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GASEOUS WASTE TREATMENT SYSTEM

by

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Gaseous Waste Treatment System

K. C. Heck, T. R. Marrero

Key Words: Decontamination, Waste Gas, Krypton, Xenon, PWR

ABSTRACT

The gaseous waste treatment system is based on the selective absorption process developed at the Oak Ridge Gaseous Diffusion Plant. Pilot plant tests indicate that the radioactive level of offgas streams of current pressurized water reactors may be reduced by a factor as large as 1000.

By isolating the problem isotopes, krypton and xenon, and collecting them in a concentrated volume for disposal, the gaseous waste treatment system provides an efficient and reliable method of reducing the radioactive levels of the effluent released to the environment.

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1. INTRODUCTION

1.1. Radioactive Gas Release

During the operation of light water nuclear reactors, radioactive gases are produced from fission products and activation products in the reactor coolant. In pressurized water reactor (PWR) systems, the bulk of these gases is vented from the reactor coolant, along with some hydrogen cover gas, and is stored in decay tanks for a period of from 45 to 60 days. During this hold-up period, activation products (principally short-lived isotopes of nitrogen and oxygen) decay to negligible levels of activity. Fission products, produced by the burnup of nuclear fuel, may leak into the coolant through defective cladding. After the hold-up period, the level of activity in the decay tank is due to fission product gases with relatively long half-lives (^{85}Kr , $^{131}\text{Xe}^{\text{m}}$, and ^{133}Xe). The half-lives of these gases are as follows: ^{85}Kr , 10.74 years; $^{131}\text{Xe}^{\text{m}}$, 11.8 days; ^{133}Xe , 5.3 days.

1.2. Selective Absorption Process

Gaseous waste stored in the decay tanks is generally a nitrogen-hydrogen mixture containing trace amounts of krypton and xenon. Figure 1-1 shows the solubility of these gases in the gaseous waste treatment system's (GWTS) process solvent. Krypton and xenon are shown to be more soluble than the usual carrier gases; this difference in solubility provides the basis for the selective absorption process. In this process, krypton and xenon are preferentially dissolved in a fluorocarbon solvent and then stripped out of the solvent as a concentrated product for storage.

1.3. Process Development

A pilot plant based on the selective absorption process was operated at the Oak Ridge Gaseous Diffusion Plant (ORGDP)*. Using

* AEC Contract No. W-7045 eng 26.

Figure 1-1. Solubility of Various Gases
in Dichlorodifluoromethane⁶

dichlorodifluoromethane as the process solvent, tests were conducted over a wide range of operating conditions to provide basic engineering data for commercial application. During the first phase of the program, data were correlated and proved to predict successfully subsequent pilot plant performance. Results of this investigation are documented in references 1 through 4. Earlier work at the Brookhaven National Laboratory⁵⁻⁷ and a parallel study,⁸⁻¹⁰ using carbon tetrachloride as the process solvent, are also referenced.

In 1971, Babcock & Wilcox contracted with the Atomic Energy Commission* to join with ORGDP to study the application of the process to reactor offgas streams. These tests included the use of krypton and xenon in the trace concentrations to be expected during commercial operation of light water nuclear reactors. Satisfactory operation was demonstrated for a variety of carrier gases, including hydrogen, nitrogen, air, helium, and argon. Krypton concentrations as low as 40 ppb and xenon concentrations as low as 3 ppb were reported.⁴

1.4. Environmental Impact of GWTS

Section 4 shows that the GWTS can reduce the level of activity of process gas released from PWR decay tanks by a factor of more than 100. This section assesses the significance of this reduction relative to the total activity released by PWR installations.

The predicted annual releases of radioactive gases from several plants are shown in Appendix A. Although the GWTS treats only the gas itemized under the column "gas processing system", Table 1-1 shows that the GWTS can reduce the overall radioactive release of some plants by as much as 75%.

To assess completely the environmental impact of the GWTS, the consequences of an accidental release of the system inventory must be considered. Assuming 0.25% failed fuel, calculations in Appendix B indicate that the body dose at the exclusion distance would be 0.38 mRem.

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* Subcontract No. 3533 to Union Carbide Corporation.

Table 1-1. Expected Reduction in Release
of Radioactive Gases by GWTS

Facility		Holdup, Ci/yr		Reduction, %
		w/o GWTS ^(a)	with GWTS ^(b)	
Three Mile Island-1	⁸⁵ Kr	845	28	97
	Total	3,329	1,917	42
Arkansas Nuclear One-1	⁸⁵ Kr	810	131	84
	Total	13,008	11,586	11
Arkansas Nuclear One-2	⁸⁵ Kr	810	27	97
	Total	4,345	2,165	50
Rancho Seco-1	⁸⁵ Kr	760	35	95
	Total	12,258	3,073	75
Virgil Summer-1	⁸⁵ Kr	782	33	96
	Total	3,261	2,491	24

(a) Data from USAEC Environmental Impact Statements.

(b) Assumed reduction factors of 100 for Kr and 1000 for Xe for gas from the "gas processing system".

2. SUMMARY

This report documents the design and performance of the GWTS designed by Babcock & Wilcox. Although the process on which the GWTS is based is applicable to offgas streams from boiling water reactors, the intent of this report is to present a system that has been standardized for PWR application. The GWTS is designed to complement the waste retention system used in commercial PWR installations. Process gas from the PWR decay tanks is treated by the GWTS to remove isotopes of krypton and xenon before the plant effluent is released to the atmosphere.

The remainder of the report is summarized as follows: Section 3 presents guidelines for the design of the GWTS. The minimum reduction of the radioactive level of PWR process gas is set at 100. Isotopes of krypton and xenon are removed and concentrated in a volume that is less than 0.2% of the volume of the process gas. Representative PWR site conditions are discussed; federal regulations and industrial standards applicable to the design of the GWTS are given.

Section 4 predicts performance of the GWTS based on ORGDP pilot plant tests conducted with typical PWR noble gas concentrations. ORGDP mass transfer correlations are presented; a sample problem is included to show how these correlations may be used in design work. Finally, the correlations are applied to the GWTS to demonstrate that process gas activity may be reduced by a factor greater than 100. The effects of solvent flow rate, absorption temperature, and absorption pressure are included.

Section 5 describes the GWTS, which is based on the ORGDP pilot plant. A process description details the selective absorption process as implemented by the GWTS. Safety features and plant operation are included. The appendixes complement the body of the report and are referred to as appropriate.

3. DESIGN GUIDELINES

3.1. Design Objectives

The design objectives for the GWTS are expressed in terms of a decontamination factor (D_p) and a volumetric reduction factor (V_F). The decontamination factor describes the effectiveness of the GWTS in reducing the activity of the PWR process gas before it is released to the atmosphere. This factor is defined as the ratio of the activity of the process gas, before treatment by the GWTS, to its activity after treatment by the GWTS. The volumetric reduction factor describes the capability of the GWTS to separate krypton and xenon from the carrier gas and to concentrate them in a small volume that can be economically stored. This factor is defined as the ratio of the volume of PWR process gas to the volume of the collected product gas in which isotopes of krypton and xenon are contained.

Based on ORGDP tests (discussed in section 4), the design decontamination factor is conservatively set at 100. Based on ORGDP tests with krypton in nitrogen (Appendix E), a typical volume reduction factor is set at 500. These design objectives ($D_p > 100$ and $V_F > 500$) establish a minimal level of performance for the GWTS.

The design conditions and criteria given in the following two sections have been established to permit the design and construction of a system satisfying these objectives.

3.2. Design Conditions

Appendix C tabulates conditions that are representative of PWR power plants. Specific conditions include ambient temperature and humidity, installation requirements for an interface between the GWTS and the plant, and feed conditions for the process gas.

3.3. Design Criteria

The general design criteria are federal regulations and industrial standards as applicable to the design and manufacture of the GWTS. Applicable federal codes are taken from the Code of Federal Regulations (Title 29), Occupational Safety and Health Act of 1970 as amended, and Atomic Energy Rules and Regulations (Title 10). Industrial standards are taken from the American Society of Mechanical Engineers Code for Nuclear Vessels (Class III) and from the National Electric Code.

The specific design criterion for the GWTS is 10 CFR Part 50, Appendix I, Numerical Guides for Design Objectives and Limiting Conditions for Operation to Meet the Criterion "as Low as Practicable" for Radioactive Material in Light-Water Cooled Nuclear Power Reactor Effluents. Applicable codes are tabulated in Appendix D.

4. GWTS PERFORMANCE

4.1. Pilot Plant Tests (Low Concentrations of Krypton and Xenon)

In 1971, Babcock & Wilcox and the U.S. Atomic Energy Commission engaged in a cooperative program^{*} to utilize radioactive traces to study pilot plant performance. The work was undertaken to provide data for krypton and xenon concentrations typical of nuclear reactor offgas streams. Earlier tests had used nonradioactive krypton which was analyzed by gas chromatography. Consequently, the krypton concentration in the carrier gas was deliberately forced to a level high enough to yield at least a detectable krypton concentration (5 to 10 ppm) in the decontaminated gas.

To ensure that correlations developed during the earlier work could be extended to the low concentrations typical of nuclear reactor offgas streams, tests were conducted with radioisotope traces in several carrier gases. By utilizing in-line counting equipment for the detection of krypton and xenon, the previously developed mass transfer correlations were proved to be applicable to PWR design.

The correlations developed by ORGDP personnel are presented in Appendix F. These correlations, which are based on a differential mass balance of the absorber column, represent the data well enough for design purposes. For the pilot plant, calculations of the krypton and xenon removed by absorption predict the measured values within $\pm 34\%$.

Appendix E contains data taken during the ORGDP tests. The overall results of the tests were discussed by ORGDP personnel at the 12th AEC Air Conference.⁴ A summary is presented in Table 4-1. Overall

^{*} - - - -
Under Subcontract No. 3533 to Union Carbide Corporation.

Table 4-1. Overall Process Efficiencies
for Low-Concentration Tests⁴

Carrier gas	Noble gas contam	No. tests	Process feed(a)		Processing conditions			Overall process eff'cy, %
			Flow, scfm	Contam conc, ppb	Absorber press., psia	Absorber temp, F	Solvent flow, gpm	
Air	Krypton	11	1-3	50 - 200	374	-25	1.0	99.7 - 99.9
Air	Xenon	8	1-3	3 - 15	374	-25	1.0	99.95 - 99.99
Nitrogen	Krypton	30	1-6	40 - 1000	314 - 422	-35 to -23	0.75-1.0	99.0 - 99.9
Argon	Krypton	6	1-4	10 - 1400	374	-25	1.0	99.0 - 99.7
Helium	Krypton	9	2-7	100 - 4300	254 - 374	-40 to -25	0.75-1.0	99.4 - 99.9
Hydrogen	Krypton	3	1-2	300 - 600	194	-25	0.75	99.0 - 99.9

(a) Process feed plus fractionator recycle make up absorber feed.

process recoveries are shown to be better than 99% for the various carrier gases. Although most of these tests used krypton traces, tests were conducted with xenon traces in air. Table 4-1 shows that xenon removal efficiencies from 99.95 to 99.99% can be expected.

4.2. GWTS Performance

The GWTS is a commercial adaptation of the ORGDP pilot plant. The absorber design temperature (-27F) and pressure (374 psia) are consistent with the conditions used during the low concentration tests (see Table 4-1). Consequently, the results of these tests are directly applicable to GWTS design.

In Appendix F, a sample calculation demonstrates how the ORGDP correlations can be used to predict overall process performance. The particular calculations are for results published by ORGDP.⁴ As shown in Appendix F, measured and predicted values for the percentage of krypton removed in the absorber are in agreement.

In Appendix G, similar calculations performed for the GWTS predict an overall process decontamination factor ranging from 175 to 600.

4.3. Operating Parameters

For a given process gas feed rate, absorber performance is controlled by solvent flow rate, absorption temperature, and pressure. This section discusses the effects of these parameters on GWTS performance.

At low liquid-gas flow ratios, absorber performance may be considerably affected by changes in either the solvent or process gas feed rate. At high liquid-gas flow ratios, however, the effects of this parameter are negligible because essentially all the krypton (xenon) is absorbed within the first few feet of packing. The mole fraction of krypton in the carrier gas drops exponentially as the gas flows up the column. For high liquid-gas ratios, the absorption process approaches equilibrium conditions as follows:

$$y_2 = kx_2^* \quad (4-1)$$

where k = effective equilibrium coefficient,
 y = krypton mole fraction in the carrier gas,
 x = krypton mole fraction in the solvent.

The subscript 2 denotes conditions at the top of the column.

The GWTS solvent flow rate is set conservatively high to ensure that variations in flow rates will not affect system performance. Equation 4-1 suggests that absorber performance may be improved by reducing the effective equilibrium coefficient, k , or by reducing the krypton that was not stripped from the recycled solvent.

The effective equilibrium coefficient is expressed as

$$k^{**} = \exp(3.8167 + 0.010197T)/P_{\text{total}} \quad (4-2)$$

where T = absorption temperature, -F,
 P = absorption pressure, atmospheres.

The GWTS absorption temperature is -27F, and the pressure is 374 psia. Variations in temperature and pressure within the controlled operating conditions of the GWTS have only a small effect on the equilibrium constant. Perhaps the best justification for the specific temperature and pressure used for GWTS design is the excellent overall performance of the pilot plant.

Since the amount of krypton carried by the recycled solvent is determined by stripper operating conditions, which were maintained relatively constant for the ORGDP tests, it is reasonable to expect that stripper operation may be optimized for a specific application and that overall system performance will be improved.

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* This equation is discussed further in Appendix F.

** From reference 4.

5. GWTS DESCRIPTION

5.1. Background

The design of the GWTS is based on the ORGDP pilot plant,¹⁻⁴ which consists of three columns, an absorber, a fractionator, and a stripper, plus attendant heat transfer and pumping equipment. The ORGDP absorber and fractionator columns are 3 inches in diameter and are packed to a height of 9 feet; the stripper column is 6 inches in diameter and is packed to a height of 8 feet.

The diameter of the GWTS absorber column has been reduced to 2 inches, but all other packing dimensions are the same as those of the pilot plant. This reduction, which was made to accommodate the lower GWTS process feed rate (1 scfm), is discussed in Appendix H. Auxiliary components have been sized and designed to minimize cost and to meet applicable code requirements.

5.2. General System Description

The GWTS will remove isotopes of krypton and xenon from the gaseous waste produced during the operation and maintenance of nuclear power facilities. Input process gas at a flow rate of 1 scfm is accepted from plant decay tanks in which it has been held up to permit interim decay. Typical carrier gases are hydrogen-nitrogen mixtures with krypton and xenon concentrations ranging from 0.1 to 500 ppm.

The GWTS is skid-mounted in a space occupying a volume that is approximately 10 feet long by 10 feet wide by 15 feet high. The major components are the three packed columns in which absorption, fractionation, and stripping isolate and concentrate krypton and xenon. Auxiliary components include a gas compressor, a solvent pump, and refrigeration and heat exchange equipment to implement the selective absorption process. Adequate instrumentations and controls are provided to ensure safe, reliable operation of the system.

The expected exposure to personnel is approximately 1 mRem/h. Since the system contains radioactive gas, the design maximum leak rate is set at 0.01% of the process gas feed.

All parts of the system in contact with the process feed, concentrate, vapor, or distillate are constructed of austenitic stainless steels, type-304L or type-316. The components of the GWTS are manufactured in accordance with the ASME Boiler and Pressure Vessel Code, Section III, Class 3, with the Code "N" stamp. Applicable design conditions and criteria are discussed in section 3. The GWTS components are described completely in Appendix I; plant operation is described in Appendix J.

5.3. GWTS Process Description

System operating conditions are given in Table 5-1, and a diagram of the GWTS is shown in Figure 5-1.

The process gas pressure is regulated at from 15 to 18 psia and is fed to a molecular sieve dryer at a rate of 1 scfm. After drying, the gas is compressed to from 350 to 400 psi by a two-stage, metallic diaphragm compressor. The compressed gas is then cooled to from -20 to -30F and is fed to the bottom of the first process column, or absorber, where it contacts, countercurrently, chilled refrigerant-12 (R-12) as the gas flows upward through the packed column. Essentially all the krypton and xenon, and some of the carrier gas, is absorbed by the R-12 liquid. The essentially "clean" carrier gas at the top of the column may be vented to the plant stack through particulate and charcoal filters.

The "loaded" solvent is then heated and forced by differential pressure to the top of the second column, or fractionator. There, it is partially vaporized in a flash tank, and the remaining liquid solvent flows down through this lower pressure, packed column. The carrier gas absorbed in the solvent, along with some of the krypton and xenon, is driven out of the solvent by countercurrent contact with R-12 vapor from a reboiler. This gas mixture is separated from the vapor in a condenser mounted at the top of the column, and is recycled to the compressor inlet. The condensed vapor flows by gravity back to the top of column.

The solvent in the fractionator reboiler is forced by differential pressure to the top of the stripper column. The lower pressure in the

stripper column allows the krypton and xenon to be desorbed as the solvent contacts R-12 vapor from the reboiler/storage tank located at the bottom of the stripper column. This rich gas is separated from the bulk of the solvent vapor in an overhead condenser. The concentrated krypton and xenon and the remaining vapor are then passed through a subcooled condenser to further remove R-12 vapor. The condenser is maintained at about -110F by a two-stage, cascade refrigeration unit. The resultant gas stream, containing less than 10% R-12 vapor, is available for collection or for recycling.

Solvent liquid from the condenser is returned by gravity flow to the stripper reboiler. The essentially "clean" liquid R-12 is fed from the stripper reboiler/storage tank through a chiller to reduce the temperature to absorber conditions, and is pumped at about 0.6 gpm to the absorber by a single-stage, metallic diaphragm pump.

The vent from the absorber is controlled by a flowmeter signal to an exhaust control valve. The levels in the reboilers are maintained by differential pressure-meter signals to control valves. Column temperatures and pressures are controlled by temperature/pressure sensor signals to control valves at the condenser gas outlets. Reboiler heat flux is set manually. Fractionator feed heater flux is controlled by R-12 temperature sensing. The flow rate of the solvent pump is manually adjusted. The outlet pressure of the compressor is controlled by an outlet pressure sensor signal to a control valve in a compressor bypass line.

Radiation levels, as determined by in-line radiation monitors, determine whether the absorber outlet gas is vented or recycled and whether the stripper outlet gas is recycled or routed to the collection tanks.

Table 5-1. GWTS Operating Conditions

Process gas flow rate, scfm	1.0
Process gas composition	Kr and Xe (in carrier gases N, H, and Ar) (a)
Solvent flow rate, gpm	0.6
Solvent	R-12
Refrigeration requirements, Btu/h	66,000

Column operating conditions:

	<u>Absorber</u>	<u>Fractionator</u>	<u>Stripper</u>
Temperature, F	-27	+37	-13
Pressure, psia	374	54	18
Liquid-gas ratio (mole basis)	15	5	2

(a) For design purposes, a hydrogen-nitrogen mixture (9:1 volume ratio) with 1 ppm krypton was assumed.

Figure 5-1. GWTS Diagram

5.4. System Safety Features

The GWTS provides equipment to protect the public and plant personnel from transient conditions. The response of the GWTS to transients is as follows:

1. A high radiation level in the gas treated by the GWTS is detected by an in-line radiation monitor RM-2 (Figure 5-1). This monitor detects levels of activity within a range of 10^{-1} to 10^{-5} $\mu\text{Ci/cc}$ of 1 Mev gamma radiation. The detector is connected to a counting ratemeter which has a dynamic range from 10 to 10^6 cpm. The alarm setpoint is established within this range. If the setpoint is exceeded, or if the monitor malfunctions, vent valve ESV-2 closes and valve ESV-3 opens to recycle the gas to the compressor inlet. These valves are solenoid controlled and air actuated. Instrumentation includes a visual indicating meter, an alarm lamp, and a malfunction lamp which are mounted on the GWTS control panel. An electrical signal is provided for remote indication or alarm.

2. Rupture or leakage of a compressor diaphragm is detected by the leak detection system which is an integral part of the compressor. If a diaphragm failure occurs, a pressure sensitive switch, wired into the motor control circuit, shuts the unit down. Valve ESV-1, in the process feed line, is automatically closed.

3. Leakage of hydrogen into the GWTS compartment is detected by a hydrogen monitor. Instrumentation includes a visual indicating meter, an alarm lamp, and a malfunction lamp which are mounted on the GWTS control panel. An electrical signal is provided for remote indication or alarm. The alarm setpoint is established within the range of 0 to 2% hydrogen concentration, depending on site requirements.

4. In response to high system pressures, fluid is released through safety valves to the PWR containment vent (eight safety valves are installed). The GWTS has been designed to withstand pressure in excess of the maximum system pressures which are obtainable via the gas compressor. In addition, many temperature and pressure recorders continually monitor the GWTS performance.

5. The system has redundant isolation valves at the process gas inlet and the product gas outlet. Thus, the GWTS can be completely isolated from the PWR radioactive waste retention system. For items 2 through 4 above, electrical signals are provided so that these valves may be actuated under abnormal operating conditions. The GWTS may also be isolated by external signals from the NSS system.

5.5. Design Basis Accident

The design basis accident that is considered for this system is discussed in section 1.4., Environmental Impact of the GWTS, and involves the consequences of an accidental release of GWTS inventory. The calculations for the release are presented in Appendix B, Accidental Release of GWTS Inventory. The Appendix B calculations show the whole body dose at the exclusion distance to be of the order of 0.38 mRem.

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APPENDIX A

Predicted Release of Radioactive Fission Gases
From Nuclear Power Stations
(Data Taken From USAEC Environmental Impact Statements)

Table A-1. Predicted Yearly Release of Radioactive Gases From
Metropolitan Edison Three Mile Island, Unit 1

	Yearly release, Ci				
	Auxiliary bldg.	Containment purge	Condenser air ejector	Gas prcs sys	Total
^{85}Kr	5	10	5	825	845
^{87}Kr	3	--	3	--	6
^{88}Kr	9	--	9	--	18
$^{131}\text{Xe}^{\text{m}}$	5	2	5	36	48
^{133}Xe	840	140	840	460	2280
^{135}Xe	14	--	14	--	28
^{138}Xe	2	--	2	--	4

Table A-2. Predicted Yearly Release of Radioactive Gases
From Arkansas Nuclear One, Unit 1

	Yearly release, Ci					
	Auxiliary bldg.	Containment purge	Condenser air ejector	Gas prcs sys	Nitrogen cover	Total
$^{83}\text{Kr}^{\text{m}}$	1	--	1	--	--	2
$^{85}\text{Kr}^{\text{m}}$	5	--	5	--	9	19
^{85}Kr	6	12	6	686	100	810
^{87}Kr	3	--	3	--	--	6
^{88}Kr	9	--	9	--	5	23
$^{131}\text{Xe}^{\text{m}}$	5	2	5	53	65	130
$^{133}\text{Xe}^{\text{m}}$	10	--	10	--	100	120
^{133}Xe	800	130	800	690	9400	11,800
^{135}Xe	1	--	1	--	72	74
^{138}Xe	2	--	2	--	--	4

Table A-3. Predicted Yearly Release of Radioactive Gases
From Arkansas Nuclear One, Unit 2

	Yearly release, Ci				
	Auxiliary bldg.	Containment purge	Condenser air ejector	Gas prcs sys	Total
$^{83}\text{Kr}^{\text{m}}$	1	--	1	--	2
$^{85}\text{Kr}^{\text{m}}$	6	--	6	--	12
^{85}Kr	5	9	5	790	810
^{87}Kr	3	--	3	--	6
^{88}Kr	11	--	11	--	22
$^{131}\text{Xe}^{\text{m}}$	5	2	5	90	100
$^{133}\text{Xe}^{\text{m}}$	12	1	12	--	25
^{133}Xe	920	160	930	1310	3320
$^{135}\text{Xe}^{\text{m}}$	1	--	1	--	2
^{135}Xe	19	--	19	--	38
^{137}Xe	1	--	1	--	2
^{138}Xe	3	--	3	--	6

Table A-4. Predicted Yearly Release of Radioactive Gases From
Rancho Seco Nuclear Generating Station, Unit 1

	Yearly release, Ci				
	Auxiliary bldg.	Containment purge	Condenser air ejector	Gas prcs sys	Total
$^{83}\text{Kr}^{\text{m}}$	1	--	1	--	2
$^{85}\text{Kr}^{\text{m}}$	5	--	5	2	12
^{85}Kr	7	14	7	736	760
^{87}Kr	3	--	3	--	6
^{88}Kr	10	--	10	2	22
$^{131}\text{Xe}^{\text{m}}$	5	9	5	108	130
$^{133}\text{Xe}^{\text{m}}$	11	9	11	44	75
^{133}Xe	880	1150	880	8300	11,200
$^{135}\text{Xe}^{\text{m}}$	1	--	1	--	2
^{135}Xe	16	3	16	10	45
^{138}Xe	2	--	2	--	4

Table A-5. Predicted Yearly Release of Radioactive Gases From
Virgil C. Summer Nuclear Station, Unit 1

	Yearly release, Ci				Total
	Auxiliary bldg.	Containment purge	Condenser air ejector	Gas prcs sys	
$^{83}\text{Kr}^{\text{m}}$	1	--	1	--	2
$^{85}\text{Kr}^{\text{m}}$	8	--	8	--	16
^{85}Kr	6	13	6	767	792
^{87}Kr	4	--	4	--	8
^{88}Kr	14	--	14	--	28
$^{131}\text{Xe}^{\text{m}}$	7	3	7	1	18
$^{133}\text{Xe}^{\text{m}}$	15	1	15	--	31
^{133}Xe	1150	19	1150	--	2319
$^{135}\text{Xe}^{\text{m}}$	1	--	1	--	2
^{135}Xe	23	--	23	--	46
^{137}Xe	1	--	1	--	2
^{138}Xe	3	--	3	--	6

APPENDIX B
Accidental Release of GWTS Inventory

The release of radioactive gases expected from several PWR installations is shown in Appendix A. The highest release shown is for Arkansas Nuclear One-1. The analysis uses the curie level for this plant. The data, taken from USAEC Environmental Statements, assume 0.25% failed fuel. Other assumptions are as follows:

1. Total system inventory is released at ground level.
2. Typical PWR release of 50×10^3 scf/yr.
3. Typical exclusion distance of 2500 feet.

1. Calculation of Activity Released from GWTS

The GWTS has a flow-through time of about 30 minutes for an input feed rate of 1 scfm. Therefore, approximately 30 scf of radioactive gas will be released. Activity is controlled by the isotopes ^{85}Kr and ^{133}Xe . The activities released are as follows:

$$^{85}\text{Kr} = \frac{810 \text{ Ci/yr}}{50 \times 10^3 \text{ scf/yr}} \times 30 \text{ scf} = 0.486 \text{ Ci.}$$

$$^{133}\text{Xe} = \frac{11,800 \text{ Ci/yr}}{50 \times 10^3 \text{ scf/yr}} \times 30 \text{ scf} = 7.080 \text{ Ci.}$$

2. Calculation of Dose at Site Boundary

Using AEC Safety Guide No. 24, "Assumptions Used for Evaluating the Potential Radiological Consequence of a PWR Radioactive Storage Tank Failure," a value of $\chi/Q = 1.0 \times 10^{-3}$ is suggested for an exclusion distance of 2500 feet. To calculate the dose at the exclusion distance, the following equation is used:

$$D = 0.26 (\chi/Q) Q \bar{E}$$

where

D = dose, Rem,

Q = activity, Ci,

$\bar{E}$ = average energy per disintegration $\left[\begin{array}{l} ^{85}\text{Kr} = 0.24 \text{ MeV} \\ ^{133}\text{Xe} = 0.19 \text{ MeV} \end{array} \right]$.

Thus,

$$D(\text{Kr}) = 0.26 \times 1.0 \times 10^{-3} \times 0.486 \times 0.24 = 0.03 \text{ mRem},$$

$$D(\text{Xe}) = 0.26 \times 1.0 \times 10^{-3} \times 7.080 \times 0.19 = 0.35 \text{ mRem},$$

$$\text{Total dose} = D(\text{Kr}) + D(\text{Xe}) = 0.38 \text{ mRem}.$$

APPENDIX C
GWTS Design Conditions

1. General Conditions

System components shall be designed for an ambient temperature of 50F (minimum) and 125F (maximum), an ambient humidity of from 0 to 95%, and an external radiation level of 1 R/h, 3.5×10^5 R (40 years). Note that the expected exposure to personnel is about 1 mR/h.

2. Plant Interface Requirements

These requirements are as follows:

- a. Space for installation of at least 15 feet by 15 feet in a room with suitable foundations, and space for maintenance and repair.
- b. Electric power at 60 Hz; 110 V, 220 V, and 440 V; total power of 75 kW.
- c. Pipe connections to decay tanks, stack vent, and collection bottle.
- d. Cooling water flow rate of 25 gpm at a maximum temperature of 105F.
- e. Wiring path for connecting alarms in the control room to the system control panel and for connecting the system to the control panel.
- f. Instrument electric power of $117 \pm 5\%$ Vac and $60 \pm 1\%$ Hz.
- g. Instrument air.
- h. Vacuum connection (to be specified by others).

3. Feed Conditions

The conditions of the feed gas to be accepted by the system are as follows:

- a. Normal temperature of $< 100\text{F}$.
- b. Flow rate of 1 scfm on a continuous or intermittent basis.
- c. Pressure range from 15 to 150 psia.
- d. Contents as follows:
 - Moisture, 0 — saturate feed.
 - Hydrogen, 0 — 100%.
 - Nitrogen, 0 — 100%.

Air, 0 — 100% (hydrogen < 3.5%).

Krypton-85, 0.1 — 500 ppm.

Xenon-133, 0.1 — 5000 ppm.

Note that product collection bottles will be supplied by others.

4. Seismic Loadings

The seismic requirements are based on the design basis earthquake — 4.6 g horizontal component, and 3.1 g vertical component.

APPENDIX D
GWTS Design Criteria

1. U. S. Atomic Energy Commission
 - 1.1. General Criteria
 - Criterion 1 — Quality Standards and Records
 - Criterion 2 — Design Bases for Protection Against Natural Phenomena
 - 1.2. Specific Criterion
 - Safety Guide No. 26 — Quality Group Classifications and Standards
2. ASME Boiler and Pressure Vessel Code
 - 2.1. Section II — Material Specifications
 - 2.2. Section III — Nuclear Power Plant Components
 - 2.3. Section VIII — Pressure Vessels
 - 2.4. Section IX — Welding Specifications
3. National Electric Code
4. National Electrical Manufacturers' Association, Standard MG-1
5. American Standard Code for Steel Flanges and Flanged Fittings (USAS B16.5)
6. American Standard Association Code for Pressure Piping (ASA B31.1)
7. American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Standard 15-65, "Safety Code for Mechanical Refrigeration."
8. Babcock & Wilcox Specification 1107, "Seismic Design Basis for Auxiliary Equipment."

APPENDIX E

Experimental Results for Low Noble Gas Concentrations

The process performance factors used in this appendix are defined as follows: The definitions are based on material balances for a given isotope (e.g. krypton) assuming that the system is operating at steady-state conditions. The streams are indicated in Figure E-1.

The absorber decontamination factor is defined as:

$$D_a = \frac{W_f y_f}{W_v y_v} \quad (E-1)$$

where

W_f = mass flow rate of feed gas, including recycle gas, entering the absorber tower,
 y_f = concentration of specified gas component,
 W_v = mass flow rate of gas vented from the top of the absorber,
 y_v = concentration of specified gas component.

Absorber removal is the percentage of the specified gas that enters the bottom of the absorber and is dissolved in the solvent:

$$\psi = \frac{(100 D_a - 100)}{D_a} \cdot \quad (E-2)$$

The overall process decontamination factor is defined by

$$D_p = \frac{W_p y_p}{W_v y_v} \quad (E-3)$$

where

W_p = mass flow rate of contaminated gas from some PWR supplied to the absorption system,
 y_p = concentration of specified gas component.

The process recovery efficiency is defined as the percentage of the specified gas (e.g. Kr) that enters the process from some PWR and is collected in the gas product leaving the stripper tower:

$$\epsilon = \frac{(100 D_p - 100)}{D_p} \cdot \quad (E-4)$$

The process concentration factor is defined as the ratio of the concentration of the specified gas vented from the stripper tower to the concentration of the gas entering the system:

$$C_F = \frac{y_c}{y_p} \quad (E-5)$$

where y_c is the concentration of specified gas component leaving the top of the stripper column.

The volumetric reduction factor, V_F , is defined as the ratio of feed gas to product gas volumes, corrected to the same temperature and pressure.

$$V_F = \frac{W_p}{W_c} \cdot \quad (E-6)$$

Table E-1. Krypton Tracer in Nitrogen

	Series (3N-1) and Date																		
	1 (4/15/71)	2 (4/15/71)	3 (4/22/71)	4 (4/22/71)	5 (4/30/71)	6 (4/30/71)	7 (5/3/71)	8 (5/4/71)	9 (5/4/71)	10 (5/5/71)	11 (5/10/71)	12 (5/10/71)	13 (5/11/71)	14 (6/16/71)	15 (6/23/71)	16 (6/24/71)	17 (6/24/71)	18 (6/25/71)	19 (6/25/71)
<u>Operating Conditions</u>																			
Tracer feed rate concentration, ppm	0.03	0.065	0.050	0.380	0.280	0.210	0.250	0.290	0.29	0.240	0.210	0.230	0.230	0.58	0.80	0.65	0.68	1.03	1.60
Absorber press., psia	314	374	410	374	374	394	314	314	314	314	374	374	422	374	374	374	374	374	374
Absorber temp, F	-30	-27	-35	-35	28	-28	-27	-26	-26	-26	-26	-25	-27	-24	-23	-27	-24	-24	-23
Tractorator press., psia	51.9	59.3	50.0	37.9	44	44	54	54	68	68	64	54	54	54	54	54	54	50	50
Tractorator temp, F	+30	+30	+26	+25	21	21	37	37	50	50	37	30	30	+20	+30	+35	+35	+34	+30
Tractorator press., psia	21.0	21.0	21.0	16.1	16.4	16.4	16.4	16.4	16.4	16.4	16.4	16.4	16.4	16.4	16.4	16.4	16.4	16.4	16.4
Tractorator temp, F	-6	-7	-8	-14	-14	-14	-14	-14	-14	-14	-14	-14	-14	-14	-14	-14	-14	-14	-14
Solver flow, rpm	1.0	1.0	1.0	0.75	0.75	0.75	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.75	0.75	0.75
Absorber gas feed, scfm	5.83	8.81	7.62	7.04	7.02	6.44	7.13	6.93	6.93	4.95	6.93	4.45	6.40	5.03	6.93	4.95	3.37	3.70	4.50
Fractionator offgas, scfm	2.51	1.18	3.32	2.20	2.62	2.67	2.72	2.67	2.57	3.34	3.27	3.69	3.63	3.32	3.37	2.37	2.18	2.08	1.08
Tractorator offgas, scfm	0.004	0.0125	0.027	0.009	0.0150	0.0044	0.0032	0.0032	0.0028	0.002	0.0021	0.0014	0.0018	0.0014	0.0049	0.0030	0.0012	0.002	0.0045
Process gas feed, scfm	6.34	5.73	4.30	4.83	4.40	4.27	4.41	4.21	4.26	2.36	3.41	4.44	3.21	2.40	3.61	1.58	1.02	1.58	1.48
<u>Process Performance</u>																			
Absorber DF (D)	11	318	390	390	359	270	230	226	205	394	344	530	326	1030	409	821	942	553	415
Absorber Kr removal (%), %	99.1	99.7	99.7	99.7	99.7	99.6	99.5	99.5	99.5	99.7	99.7	99.8	99.7	99.9	99.8	99.9	99.9	99.8	99.8
Process DF (D)	36.5	175	125	128	156	132	95	133	145	121	117	128	160	344	150	142	132	350	174
Process Kr removal (%), %	97.4	99.4	99.2	99.2	99.3	99.2	98.9	99.2	99.3	99.2	99.1	99.2	99.4	99.7	99.3	99.3	99.2	99.7	99.4
Process concentration factor (C _p)	584	245	124	403	232	643	1335	1040	1634	1099	1330	1194	1300	27.2	273	462	715	179	371
Volume reduction factor (V _p)	99.	459	158	514	291	864	1390	1320	1500	865	1700	1200	1800	27	730	526	809	678	390

Table E-2. Krypton Tracer in Air

	Series (3 Air -) and Date										
	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>	<u>6</u>	<u>7</u>	<u>8</u>	<u>9</u>	<u>10</u>	<u>11</u>
	(10/22/71)	(10/22/71)	(10/25/71)	(10/26/71)	(10/26/71)	(10/27/71)	(11/2/71)	(11/4/71)	(11/4/71)	(11/5/71)	(11/5/71)
<u>Operating conditions</u>											
Absorber feed krypton concentration, ppm	0.150	0.110	0.130	0.130	0.130	0.110	0.070	0.060	0.050	0.060	0.050
Absorber press., psia	374	374	374	374	374	374	374	374	374	374	374
Absorber temp, F	-26	-27	-25	-26	-26	-26	-25	-28	-25	-28	-23
Fractionator press., psia	49.0	49.0	49.0	49.0	49.0	49.3	49.0	49.7	50.4	49.0	49.0
Fractionator temp, F	34	39	35	35	32	35	33	30	33	34	36
Stripper press., psia	23.7	23.9	23.7	23.7	24.0	24.2	23.7	24.2	24.0	24.8	24.5
Stripper reboiler temp, F	12	11	10	10	11	11	3	5	5	6	2
Solvent flow rate, gpm	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Absorber feed gas flow, scfm	5.94	6.06	5.94	5.94	5.84	5.94	6.23	5.89	4.80	4.95	4.95
Fractionator offgas flow, scfm	3.78	3.78	3.71	3.78	3.81	3.80	3.68	3.51	3.51	3.54	3.66
Stripper offgas flow, sccm	2360	835	900	1870	2070	990	449	1200	741	281	134
Process gas flow, scfm	2.16	2.28	2.23	2.16	2.03	2.14	2.55	2.38	1.29	1.41	1.29
<u>Process performance</u>											
Absorber DF (D_A)	975	889	895	701	1164	1183	797	865	1360	1324	1168
Absorber removal (Ψ), %	99.89	99.88	99.88	99.85	99.91	99.91	99.87	99.88	99.92	99.92	99.91
Process DF (D_P)	558	400	312	333	583	453	290	387	932	344	325
Process recovery (ϵ), %	99.82	99.74	99.66	99.64	99.83	99.75	99.65	99.73	99.89	99.79	99.69
Process conc factor (C_F)	25.8	77.0	69.6	32.6	27.7	60.5	160	56.5	49.2	141	271
Volume reduction factor (V_F)	25.9	77	70	32.7	27.7	61	161	56.7	49.3	142	272

Table E-3. Krypton Tracer in Argon

	Series (3He -) and Date				
	1 (8/19/71)	2 (8/19/71)	3 (8/20/71)	4 (8/20/71)	5 (8/25/71)
<u>Operating conditions</u>					
Absorber feed krypton concentration, ppm	0.100	0.250	0.330	0.340	0.130
Absorber press., psia	374	374	374	374	255
Absorber temp, F	-30	-30	-26	-30	-27
Fractionator press., psia	49	49	49	49	49
Fractionator temp., F	30	30	30	32	35
Stripper press., psia	20	20	20	20	18.5
Stripper reboiler temp, F	3	3	2	3	-1
Solvent flow rate, gpm	1.0	1.0	1.0	1.0	1.0
Absorber feed gas flow, scfm	7.29	2.83	2.83	2.83	7.08
Fractionator offgas flow, scfm	0.74	0.74	0.74	0.74	0.59
Stripper offgas flow, sccm	330	435	673	322	251
Process gas flow, scfm	6.55	2.09	2.09	2.09	6.49
<u>Process performance</u>					
Absorber DF (D_a)	146	380	377	430	178
Absorber removal (Ψ), %	99.31	99.73	99.73	99.76	99.44
Process DF (D_p)	102	259	312	397	160
Process recovery (ϵ), %	99.02	99.61	99.68	99.74	99.37
Process conc factor (C_F)	556	135	87.8	184	727
Volume reduction factor (V_F)	561	136	88	184	731

Table E-4. Krypton Tracer in Helium

	Series (3A -) and Date					
	1	2	3	4	5	6
	(7/15/71)	(7/15/71)	(7/16/71)	(7/28/71)	(7/29/71)	(7/29/71)
<u>Operating conditions</u>						
Absorber feed krypton concentration, ppm	0.010	0.015	0.026	1.11	0.935	1.44
Absorber press., psia	374	374	374	374	374	374
Absorber temp, F	-24	-22	-23	-25	-23	-25
Fractionator press., psia	49	49	49	49	49.7	50.4
Fractionator temp, F	35	35	35	37	38	40
Stripper press, psia	18.4	18.4	18.4	18.5	18.4	18.7
Stripper reboiler temp, F	-5	-6	-3	-1	-1	-2
Solvent flow rate, gpm	1.0	1.0	1.0	1.0	1.0	1.0
Absorber feed gas flow, scfm	9.91	7.36	7.22	9.91	9.34	6.93
Fractionator offgas flow, scfm	6.01	6.01	5.93	6.05	6.05	6.04
Stripper offgas flow, sccm	249	265	163	430	217	177
Process gas flow, scfm	3.90	1.35	1.29	3.86	3.29	0.89
<u>Process performance</u>						
Absorber DF (D_a)	422	2365	1443	248	218	450
Absorber removal (Ψ), %	99.7	99.95	99.9	99.59	99.5	99.78
Process DF (D_p)	115	309	294	85.5	68.9	106
Process recovery (ϵ), %	99	99.65	99	98.81	98.53	99.05
Process conc factor (C_F)	436	143	221	249	420	140
Volume reduction factor (V_F)	443	144	223	254	429	142

Table E-5. Xenon Tracer in Air

	Series (3 Air-Xe-) and Date								
	1	2	3	4	5	6	7	8	9
	(11/10/71)	(11/10/71)	(11/11/71)	(11/11/71)	(11/12/71)	(11/12/71)	(11/16/71)	(11/16/71)	(11/17/71)
<u>Operating conditions</u>									
Absorber feed krypton concentration, ppm									
Absorber press., psia	374	374	374	374	374	374	374	374	374
Absorber temp, F	-28	-29	-25	-28	-25	-28	-25	-25	-28
Fractionator press., psia	49	49	49	49	49	49	49	49	49
Fractionator temp, F	34	35	35	35	28	35	33	35	35
Stripper press., psia	24.3	24.5	23.7	24.5	24.5	25.2	24.5	24.5	24.5
Stripper reboiler temp, F	4	5	3	5	4	5	5	3	5
Solvent flow rate, gpm	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Absorber feed gas flow, scfm	5.15	5.15	6.24	5.94	5.20	5.94	5.94	5.54	5.35
Fractionator offgas flow, scfm	3.51	3.48	3.62	3.58	3.51	3.51	3.52	3.54	3.32
Stripper offgas flow, sccm	225	165	150	160	180	180	200	155	240
Process gas flow, scfm	1.64	1.67	2.62	2.36	1.69	2.43	2.42	2.00	2.03
<u>Process performance</u>									
Absorber DF (D_a)	12,100	15,840	3180	4550	40,040	18,420	4730	4660	1260
Absorber removal (ϵ), %	99.991	99.993	99.986	99.977	99.997	99.994	99.978	99.978	99.920
Process DF (D_p)	7650	7500	2610	2220	11,410	8410	2710	4550	1060
Process recovery (ϵ), %	99.986	99.98	99.96	99.954	99.991	99.986	99.961	99.977	99.90
Process conc factor (C_F)	238	232	300	446	72.1	228	381	266	246
Volume reduction factor (V_F)	200	286	495	418	266	380	343	365	239

E-8

Babcock & Wilcox

Figure E-1. Absorption Process Flow Diagram

APPENDIX F
Absorber Column Performance — Sample Calculation

1. Introduction

At the 12th AEC Air Cleaning Conference,⁴ ORGDP personnel discussed the applicability of design equations developed for high levels of krypton concentrations to the processing of offgas streams from light water reactors. The approach, based on a differential mass balance for the absorber column, is convenient for repetitive calculations and represents the data well enough for design purposes. Data discussed at the conference were for krypton traces in air. Calculated and measured values for the krypton removed in the absorber are given in Table F-1.

In this appendix, ORGDP correlations are presented; a sample calculation for run 1, Table F-1, demonstrates how the correlations may be used. Then, in Appendix G, similar calculations are performed for the GWTS.

Table F-1. Extension of ORGDP Absorber Correlations
To Low-Concentration Reactor Cases⁴

Run	<u>Absorber feed gas (a)</u>		<u>Kr removal in absorber, %</u>	
	Flow, scfm	Kr content, ppb	Calc from correlations	Measured
1	5.9	150	99.8	99.89 to 99.90
2	6.1	110	99.7	99.88 to 99.89
3	5.9	130	99.7	99.88 to 99.89
4	5.9	130	99.8	99.85 to 99.86
5	5.8	130	99.8	99.91 to 99.92
6	5.9	110	99.8	99.91 to 99.92
7	6.2	70	99.8	99.86 to 99.88
8	5.9	60	99.8	99.87 to 99.89
9	4.8	50	99.8	99.92 to 99.93
10	5.0	60	99.9	99.91 to 99.93
11	5.0	50	99.8	99.90 to 99.92

(a) For all runs, solvent flow is 1.0 gpm, absorber pressure is 374 psia, and absorber temperature is minus 25F. The carrier gas is air.

2. ORGDP Design Correlations

The model expresses the number of absorption stages, or transfer units, as

$$N = Z \div H \quad (F-1)$$

where

N = number of transfer units accomplished over the column (packing) height,

Z = packing height, in.,

H = empirically correlated height of a transfer unit, in.

The number of transfer units, as suggested by Colburn¹¹ is

$$N = \frac{1}{1 - \frac{kG}{L}} \ln \left[\frac{y_1 - kx_2}{y_2 - kx_1} \left(1 - \frac{kG}{L} \right) + \frac{kG}{L} \right] \quad (F-2)$$

where

k = effective equilibrium coefficient,

G/L = average molar ratio of gas flow-liquid flow,

y = gas phase mole fraction of krypton (xenon),

x = liquid phase mole fraction of krypton (xenon).

Subscript 1 refers to the bottom of the column (gas inlet), and subscript 2 refers to the top of the column (gas outlet).

The height of a transfer unit, H, for krypton in refrigerant-12 is correlated by ORGDP⁴ as

$$H = \frac{1.36 \times 10^6 \ G^{1.46}}{\alpha^{0.525} \ P^{1.74} \ L^{1.61}} \quad (F-3)$$

where

H = transfer unit height, in.,

G = column feed gas flow rate, lb/min-ft²,

P = absorption pressure, atmospheres,

L = solvent feed flow rate, lb/min-ft²,

α = ratio of Henry's law constant of contaminant gas (krypton, xenon) to Henry's law constant of carrier gas.

Finally, values suggested by ORGDP for k^* and α^{**} are (Kr in air)

$$k = \exp [3.8167 + 0.010197 T] / P_{\text{total}} \quad (\text{F-4})$$

and

$$\alpha = \exp [2.0394 - 0.008253 T] \quad (\text{F-5})$$

where

T = absorption temperature, F,

P_{total} = total absorption pressure, atmospheres.

3. Sample Calculation

Run 1, from Table F-1, is selected for a sample calculation. Applicable data are included in Appendix E (Table E-2, Krypton Tracer in Air, Run 1). As a convenience for the reader, data are listed in the dimensional form suggested by the correlations

$$\left. \begin{array}{l} y_1 = 150 \text{ ppb} \\ x_2 = 0.61 \text{ ppb} \end{array} \right\} \text{molar concentration}$$

$$T = -26\text{F},$$

$$P = 374 \text{ psia} = 25.34 \text{ atm},$$

$$Z = 9 \text{ feet} = 108 \text{ inches}.$$

Substitution into equations F-4 and F-5 yields $k = 1.376$ and $\alpha = 9.526$.

Physical properties of the solvent, dichlorodifluoromethane, are generally available (e.g., Dupont Bulletin, "Freon C-30"). The parameter L , used in equation F-3, is equivalent to L_2 but is expressed in $\text{lb}/\text{min-ft}^2$:

- - - - -
* k is taken from reference 4.

** α is taken from reference 1, p43.

$$L_2 = \frac{(1.0 \text{ gpm})(93.3 \text{ lb/ft}^3)}{(7.48 \text{ gpm/ft}^3)(120.9 \text{ lb/lb-mole})(0.0513 \text{ ft}^2)} = 2.01 \frac{\text{lb - mole}}{\text{min - ft}^2}.$$

$$L = 2.01 \frac{\text{lb - mole}}{\text{min - ft}^2} \times 120.9 \text{ lb/lb-mole} = 243.009 \text{ lb/min-ft}^2.$$

$$L_1 = 2.01 \frac{\text{lb - mole}}{\text{min - ft}^2} + (5.94 \text{ scfm} - 2.16 \text{ scfm}) \left(\frac{1}{3.59 \text{ ft}^3/\text{lb-mole}} \right) \left(\frac{273^\circ\text{K}}{298^\circ\text{K}} \right) \left(\frac{1}{0.0513 \text{ ft}^2} \right) = 2.20 \frac{\text{lb - mole}}{\text{min - ft}^2}.$$

The parameter G, used in equation F-3, is equivalent to G_1 but is expressed in lb/min-ft²

$$G_1 = \left(\frac{5.94 \text{ scfm}}{0.0513 \text{ ft}^2} \right) \left(\frac{1}{359 \text{ ft}^3/\text{lb-mole}} \right) \left(\frac{273^\circ\text{K}}{298^\circ\text{K}} \right) = 0.295 \frac{\text{lb - mole}}{\text{min - ft}^2}.$$

$$G = 0.295 \frac{\text{lb - mole}}{\text{min - ft}^2} \times 29.4 \text{ lb/lb-mole} = 8.687 \text{ lb/min-ft}^2.$$

$$G_2 = \left(\frac{2.16 \text{ scfm}}{0.0513 \text{ ft}^2} \right) \left(\frac{1}{359 \text{ ft}^3/\text{lb-mole}} \right) \left(\frac{273^\circ\text{K}}{298^\circ\text{K}} \right) = 0.107 \frac{\text{lb - mole}}{\text{min - ft}^2}$$

$$\left(\frac{L}{G} \right)_{\text{avg-molar basis}} = \frac{1}{2} \left[\left(\frac{L}{G} \right)_1 + \left(\frac{L}{G} \right)_2 \right] = 13.18.$$

Substitution of the applicable parameters into equation F-3 yields H = 4.91 inches.

Substitution of the calculated H into equation F-1 yields N = 108/4.91 = 22.0 absorption stages.

To calculate y_2 , equation F-2 is rearranged in the form

$$y_2 = kx_2 + \frac{(y_1 - kx_2) (1 - k \frac{G}{L})}{\exp \left[N \left(1 - k \frac{G}{L} \right) \right] + k \frac{G}{L}} = (0.849 + \approx 1.0 \times 10^{-6}) \text{ ppb.} \quad (\text{F-6})$$

For the low concentration tests, summarized in Table 4-1, the second term is generally negligible when compared to the first term of equation F-6.

From the data listed in the beginning of this section,

$$\begin{aligned} k &= 1.376, \\ \left. \begin{aligned} y_1 &= 150 \text{ ppb} \\ x_2 &= 0.61 \text{ ppb} \end{aligned} \right\} &\text{molar concentration,} \\ L/G &= 13.18. \end{aligned}$$

Since

$$\begin{aligned} y_1 &\gg kx_2 = 0.849 \text{ ppb}, \\ 1 &\gg k \frac{G}{L} = 0.0759. \end{aligned}$$

Equation F-6 may be approximated as

$$y_2 = kx_2 + \frac{y_1}{\exp(N)}. \quad (\text{F-7})$$

This equation is considerably simplified and yields the same significant numerical value as does equation F-6. The number of transfer units, N , calculated for the low concentration tests (Table 4-1) is typically about 20 (H is typically 4 to 5 inches). The data for x_2 , krypton in air, are within the range 0.18 ppb (run 10) to 0.61 ppb (run 1).

For this range of x_2 s, we may approximate equation F-7 by

$$y_2 = kx_2. \quad (\text{F-8})$$

This equation implies that the krypton has essentially equilibrated between the liquid and gas phases before reaching the top of the column. Hence, absorber performance is primarily limited by the extent to which krypton is driven from the "clean" solvent before entering the top of the column. Note that for sufficiently high L/G ratios (as in the ORGDP tests), variations in L/G will not affect column performance. Using equation F-8 y_2 is calculated as

$$y_2 = kx_2 = 1.376 \times 0.61 \text{ ppb} = 0.849 \text{ ppb}.$$

The amount of krypton removed in the absorption process may be calculated by a mass balance. Since the gas enters and exits through identical cross-sectional areas, the percentage of krypton removed may be expressed as

$$\frac{G_1 y_1 - G_2 y_2}{G_1 y_1} \times 100\%. \quad (\text{F-9})$$

Further, since the absorption process is both isothermal and isobaric, the volumetric flow rates of the absorber feed and vented gas may be conveniently substituted for G_1 and G_2 . (The fact that the other terms cancel out may be seen by inspecting the calculations of G_1 and G_2 .)

$$\% \text{Kr removed} = \frac{5.94 \text{ scfm} \times 150 \text{ ppb} - 2.16 \text{ scfm} \times 0.849 \text{ ppb}}{5.94 \text{ scfm} \times 150 \text{ ppb}}.$$

The calculated 99.8% is shown in Table F-1 for run 1. This value is seen to agree with the measured value.

Data for run 10 are also included in Table E-2, run 10. The range of x_2 values for the low-concentration tests was from 0.61 for run 1 to 0.18 for run 10. Using the approximation for y_2 ,

$$y_2 = kx_2 = 1.57 \times 0.18 \text{ ppb} = 0.25 \text{ ppb},$$

and %Kr removed = 99.9% as shown in Table F-1.

APPENDIX G
GWTS Performance Calculation

The absorber decontamination factor, D_a , as defined by equation E-1, may be expressed as

$$D_a = \frac{G_1 y_1}{G_2 y_2} . \quad (G-1)$$

Manipulation of equation F-9 results in

$$\% \text{ Kr removed} = \left(1 - \frac{1}{D_a}\right) \times 100\% .$$

A D_a of 100 would result in a krypton removal of 99.0%; a D_a of 1000 would remove 99.9%.

The x_2 s in the ORDGP tests discussed in Appendix F varied from 0.18 to 0.61. Since the GWTS design is based on the pilot plant's configuration and operating conditions, it is reasonable to expect a similar range for the GWTS.

It must be noted that the efforts at ORDGP were concentrated on the absorption process; less attention was given to the stripping process.

It is reasonable to assume that the krypton content (x_2) of the "clean" solvent may be reduced and that overall performance may be improved. Consequently, the following calculations of the expected performance of the GWTS, based on the ORDGP data and correlations, represent a realistic estimate of system performance. The reader is referred to section 2 of Appendix F for a detailed sample calculation.

The range of $x_2 = 0.18$ to 0.61 ppb, and

$$y_2 = kx_2 = 1.37 x_2 .$$

Therefore, the range of $y_2 = 0.25$ to 0.85 ppb.

GWTS absorber vent gas flow rate = 1 scfm

GWTS absorber feed gas flow rate = 1.6 scfm (process gas + recycle gas).

Using the krypton concentration (150 ppb) in air at the same absorber pressure and temperature as the sample calculation in Appendix F, section 2,

$$D_a = \frac{G_1 y_1}{G_2 y_2} = \frac{1.6 \times 150}{1 \times y_2 (\text{ppb})} \quad (\text{G-2})$$

Therefore, the approximate range of D_a s is from 300 to 1000.

The overall process decontamination factor (equation E-3) may be expressed as

$$D_p = \frac{G_p y_p}{G_2 y_2} \quad (\text{G-3})$$

where the subscript 'p' denotes the fresh feed from the PWR decay tank. During steady-state operation, this flow ratio is unity. Therefore, the decontamination factor becomes the ratio of the respective krypton concentrations:

$$D_p = \frac{150 \text{ ppb}}{y_2}$$

The range of D_p s is from 175 to 600.

APPENDIX H
GWTS Absorber Column Diameter
Design Basis

Since the GWTS design gas flow rate (1 scfm) is about one-third of the pilot plant flow (see Table 4-1), the absorber column diameter was scaled down from 3 inches (pilot plant) to 2 inches. This method of scaling increases the absorber gas velocities to velocities comparable to those of pilot plant tests conducted at process feed rates between 2 and 3 scfm. The calculated gas velocity for the GWTS is 0.036 fps.

To ensure proper column performance, it is important that this velocity does not exceed the maximum recommended* vapor velocity. The maximum vapor velocity ($u_{\max}$) calculated for any given set of column conditions represents the flooding velocity for that set of conditions.

The correlation provided by the packing manufacturer is expressed by

$$u_{\max} = \frac{0.0942K}{\mu_L^{0.33}} \left(\frac{\rho_L - \rho_V}{\rho_V} \right)^{0.57}$$

where

$u_{\max}$ = maximum vapor velocity, fps,

μ_L = liquid viscosity, cp,

ρ_L = liquid density, lb/ft³,

ρ_V = vapor density, lb, ft³,

K = nondimensional correction factor for liquid-to-vapor mass flow rate ratios other than 1.0.

Using nitrogen as the carrier gas at -27F and 374 psia, the applicable physical properties** are

$$\rho_V = 2.25,$$

$$\rho_L = 93.4,$$

$$\mu_L = 0.383.$$

At $(L/G)_{\text{molar}} = 15$ or $(L/G)_{\text{mass}} = 64.7$, K, as obtained from a graph provided by the manufacturer, is 0.216.

* Packed column corporation, Bulletin No. A711.

** For example, from Dupont Bulletin, "Freon C-30."

Performing the required mathematical operations, we obtain a maximum vapor velocity $u_{\max}$ of 0.231 fps. The actual gas velocity, 0.036 fps, is approximately one-sixth of this recommended maximum allowable flooding velocity.

APPENDIX I
GWTS Component Description

In describing components, the notation following the component refers to Figure 5-1.

1. Gas Feed Components

Process Gas Dryer (D-3) — The gas dryer is a solid desiccant type with provisions for regeneration. The drying agent is a molecular sieve, type-4A. For the two drying towers, 2 inches in diameter and with 80 inches of desiccant, the regeneration cycle is 8 hours. The desiccant reduces the dew point of the process gas feed to -150F.

Gas Compressor (P-1) — The process and fractionator gas streams are compressed to the operating pressure of the absorber by a metallic diaphragm compressor. Units similar to this compressor have been used in many nuclear plants throughout the world. The compressor features a triple diaphragm construction and an integral leak detection system. The capacity of the compressor is 3.0 scfm with a discharge pressure of 374 psia.

Gas Chiller (H-5) — The gas chiller cools the absorber feed gas to a temperature of less than -27F. The total thermal duty is approximately 1400 Btu/h with a surface area of 2.6 ft².

2. Packed Columns and Auxiliaries

Absorber (C-1) — The absorber is a column, 2 inches in diameter, with 9 feet of Goodloe packing. In the absorber, krypton and xenon fed to the GWTS dissolve into the solvent. The design L/G (molar) ratio is 15. The absorber operating pressure is 374 psia. The gas stream leaving the top of the absorber has been decontaminated and may be released to the atmosphere. The solvent, loaded with dissolved gases, travels from the bottom of the absorber to the fractionator.

Fractionator — The fractionator separates the less soluble non-radioactive gases from the more soluble radioactive gases. The fractionator consists of five components: packed column (C-2), feed heater (H-6), flash tank (F-1), condenser (H-2), and a reboiler (R-2). The 3-inch-diameter column contains 9 feet of Goodloe packing. The operating conditions are as follows: pressure, 54 psia; temperature, 37F, and L/G (molar) ratio, 5. The gas-solvent feed is heated to allow approximately

20% of the solvent to flash in the tank. The condenser has a thermal duty of 15,100 Btu/h and a surface area of 11.6 ft². The reboiler is a cylindrical tank, 6 inches in diameter, with external electrical heaters of 3 kW capacity. The solvent, carrying the krypton and xenon, leaves the fractionator reboiler and enters the top of the stripper column.

Stripper — The stripper consists of a packed column (C-3), condenser (H-1), and reboiler (R-1). In this column, 6 inches in diameter with 8 feet of Goodloe packing, the solvent vapor generated in the reboiler removes krypton and xenon from the liquid phase. The vapor carrying the radioisotopes is partially condensed in the overhead condenser. The column operates at a pressure of 18 psia and an L/G (molar) ratio of 2. The reboiler is large enough to serve as a storage tank for all the solvent in the system; the reboiler has external electric heaters of 12 kW capacity.

3. Solvent and Auxiliary Equipment

The solvent is dichlorodifluoromethane, CCl₂F₂, which is better known by various trade names such as Freon-12, Genetron-12, and Refrigerant-12. This solvent, the first commercially available fluorinated organic compound, is still widely used as a refrigerant.

Liquid Metering Pump (P-2) — This pump is a metallic diaphragm type unit. The pump circulates solvent through the system at a throughput of 0.6 gpm. The pump has a discharge head of up to 400 psig. The solvent pump has a variable speed motor with manual control for flow adjustments. The pump is installed between the stripper reboiler and the liquid feed inlet to the absorber.

Solvent Chiller (H-4) — The solvent chiller cools the solvent feeding the liquid metering pump to temperatures of less than -27F. The chiller brings the solvent temperature down to absorber operating conditions and prevents cavitation in the metering pump. The solvent chiller has a total surface area of 2.6 ft².

Solvent Filter (D-1) — This filter removes impurities that may be present or generated in the solvent. The solvent is supplied at a purity of about 99%; the solvent filter will trap impurities such as moisture, oils, and acids. In addition, the filter removes most of the

degradation products (hydrogen halides) of the solvent resulting from radiation. The solvent filter is a cartridge-type unit with an expected life of 30 days; provisions are made for the convenient replacement of the filter cartridges.

4. Product Gas Drier (D-2)

The product gas drier removes the residual solvent vapor from the krypton and xenon leaving the stripper condenser. The product drier is essentially a cold trap located downstream of the stripper condenser. This cold trap has a volume of approximately 1 liter and a duty of 50 Btu/h. The cold trap has an integral refrigeration unit capable of reducing the product gas temperature to -110F.

5. Refrigeration Unit (H-3)

The unit provides 66,000 Btu/h (55 tons) of refrigeration at -40F suction temperature. Secondary refrigerant is supplied to the gas and solvent chillers and to the fractionator and stripper condensers. The refrigeration unit is water cooled.

APPENDIX J
GWTS Plant Operation

The GWTS operating procedure, as briefly outlined here, is based on the procedures and experience gained in the pilot plant over more than 3 years of tests. The pilot plant could be started up within a few hours, and operation rapidly approached steady-state conditions with a minimum of transients. The GWTS, with components of similar size and improved instrumentation and controls, should respond even more smoothly and quickly. Nomenclature for the following discussion is shown in Figure 5-1.

Startup of the plant involves the use of the condensers, cooled gas, and cooled solvent. Nitrogen gas rather than contaminated effluent is used to bring the plant to normal operating conditions. Then, the nitrogen is shut off and effluent gas is introduced to the GWTS. This procedure minimizes radioactive discharge to the environment. This startup procedure assumes that all columns were isolated and bled at shutdown; therefore, each column will be at approximately 100 psia due to R-12 vaporization.

The startup procedure is as follows:

1. Open ESV-15 and actuate PCV-1 to automatic; this action will provide nitrogen gas.
2. Start compressor P1, energizing all controls for the compressor. The compressor will pump feed gas to increase the absorber pressure to about 374 psia and thus reduce the R-12 content in the absorber column. At this point, the compressor will recycle the total flow rate in the bypass circuit (ESV-2 closed and ESV-3 open).
3. Turn on refrigeration unit. Refrigeration will be initially supplied to the stripper and fractionator condensers. The refrigerant flow of the secondary system is controlled to prevent the refrigeration units from decreasing the temperature (pressure) in these columns below a value slightly less than operating conditions.
4. At this time, the solvent chiller will have been operating for several minutes, subcooling the solvent at the inlet of the liquid metering pump and thus providing a net positive suction head. Turn on the solvent pump, P-2, and open FCV-3 and FCV-4 to allow circulation of solvent through the entire loop. Open PCV-3 and FCV-2 to

allow the fractionator and stripper to operate normally when operating pressure and temperature are reached.

5. Turn on heat to the fractionator feed heater to initiate flashing in the fractionator flash tank. A portion of the absorbed nitrogen will be released in both the fractionator and stripper columns. Since the control valves at the exhaust of the stripper and fractionator condensers are in operation, the exhausted gas will be recycled to the compressor until the column operating temperature and pressure are reached.

6. Adjust the heat input to both reboilers to the normal operating input power to bring the fractionator and stripper column to normal operating conditions.

7. Close ESV-15, which shuts off nitrogen and opens shutoff valves "by others" from the decay tanks. Open ESV-1, which permits the intake of process feed gas.

8. Energize FCV-1, ESV-3, and ESV-2 to allow the absorber to vent or recycle the input gas as determined by radiation monitor No. 2. When the process gas flow rate stabilizes, the absorber will be cooled to operating temperature and the system will be on line.

In steady-state operations the system maintains the release of radioisotopes of krypton and xenon to the atmosphere at a level as low as practicable. Periodically, it may become necessary to adjust the heat to the reboilers or to the fractionator feed heater. The feed gas driers are regenerated automatically. There are provisions to add fresh solvent to the system to account for any losses. The normal operating conditions are indicated in Table 5-1.

The system can be shut down when the treatment cycle is completed, as indicated by low pressure in the decay tank or by low levels of radioactivity. To prevent holdup of contaminated gas in the system, the feed gas should be isolated and the system run with nitrogen until the concentrated gas in the stripper is forced out, as controlled and indicated by RM-4.

The system can then be shut down as follows:

1. Shut off the liquid metering pump.
2. Shut off heat in the reboilers.
3. Isolate the stripper column.
4. Isolate the fractionator column.
5. Stop the compressor and isolate the absorber when pressure drops to 30 psi.

Thus, shutdown of the system is shut down by closing ESV-1, PCV-1, ESV-3, PCV-3, FCV-2, ESV-4, ESV-5, FCV-3, FCV-4, ESV-2, FCV-1, the pump bypass valve, and redundant valves at each end of the system.