ANL-78-89

ANL-78-89

FINAL SAFETY ANALYSIS ADDENDUM TO HAZARD SUMMARY REPORT, EXPERIMENTAL BREEDER REACTOR NO. II (EBR-II): THE EBR-II COVER-GAS CLEANUP SYSTEM

by

R. M. Fryer, L. R. Monson,
C. C. Price, and D. W. Hooker

U of C-AUA-USDOE

ARGONNE NATIONAL LABORATORY, ARGONNE, ILLINOIS

Prepared for the U. S. DEPARTMENT OF ENERGY
under Contract W-31-109-Eng-38

The facilities of Argonne National Laboratory are owned by the United States Government. Under the terms of a contract (W-31-109-Eng-38) among the U. S. Department of Energy, Argonne Universities Association and The University of Chicago, the University employs the staff and operates the Laboratory in accordance with policies and programs formulated, approved and reviewed by the Association.

MEMBERS OF ARGONNE UNIVERSITIES ASSOCIATION

The University of Arizona
Carnegie-Mellon University
Case Western Reserve University
The University of Chicago
University of Cincinnati
Illinois Institute of Technology
University of Illinois
Indiana University
The University of Iowa
Iowa State University
The University of Kansas
Kansas State University
Loyola University of Chicago
Marquette University
The University of Michigan
Michigan State University
University of Minnesota
University of Missouri
Northwestern University
University of Notre Dame
The Ohio State University
Ohio University
The Pennsylvania State University
Purdue University
Saint Louis University
Southern Illinois University
The University of Texas at Austin
Washington University
Wayne State University
The University of Wisconsin-Madison

Printed in the United States of America
Available from
U. S. Department of Energy
Technical Information Center
P. O. Box 62
Oak Ridge, Tennessee 37830
Price: Printed Copy $6.00

Distribution Category:
LMFBR Safety (UC-79p)

ANL-78-89

ARGONNE NATIONAL LABORATORY
9700 South Cass Avenue
Argonne, Illinois 60439

FINAL SAFETY ANALYSIS ADDENDUM TO HAZARD SUMMARY REPORT, EXPERIMENTAL BREEDER REACTOR NO. II (EBR-II): THE EBR-II COVER-GAS CLEANUP SYSTEM

by

R. M. Fryer, L. R. Monson,
C. C. Price, and D. W. Hooker*

EBR-II Project

April 1979

*Solar Energy Research Institute, Golden, Colorado

TABLE OF CONTENTS

TABLE OF CONTENTS

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

FINAL SAFETY ANALYSIS ADDENDUM TO HAZARD SUMMARY REPORT, EXPERIMENTAL BREEDER REACTOR II (EBR-II): THE EBR-II COVER-GAS CLEANUP SYSTEM

by

R. M. Fryer, L. R. Monson,
C. C. Price, and D. W. Hooker

ABSTRACT

This report evaluates abnormal and accident conditions postulated for the EBR-II cover-gas cleanup system (CGCS). Major considerations include loss of CGCS function with a high level of cover-gas activity, loss of the liquid-nitrogen coolant required for removing fission products from the cover gas, contamination of the cover gas from sources other than the reactor, and loss of system pressure boundary. Calculated exposures resulting from the maximum hypothetical accident (MHA) are less than 2% of the 25-Rem limit stipulated in U. S. Regulation 10 CFR 100; i.e., a person standing at any point on an exclusion boundary (area radius of 600 m) for 2 h following onset of the postulated release would receive less than 0.45 Rem whole-body dose. The on-site whole-body dose (10 m from the source) would be less than 16 Rem.

1. INTRODUCTION

The EBR-II cover-gas cleanup system (CGCS) is designed to remove radioactive fission products from the reactor argon cover gas and provides the capability for conducting tests with failed or vented fuel. The CGCS also incorporates a xenon-tag-trap subsystem to recover xenon-tag isotopes for failed-fuel detection. Figures 1 and 2 are block diagrams of the CGCS showing the system configuration with its major components and the flow circuit of the working fluids.

Xenon, krypton, oxygen, CH_4, and CO_2 will be removed from the cover-gas stream by the CGCS. The xenon, krypton, and oxygen will collect in the reboiler at the bottom of the distillation column, the CH_4 will condense just above the reboiler, and the CO_2 will condense in the regenerative heat exchanger. The condensed CH_4 and CO_2 will drain to the reboiler and eventually reside with the xenon and krypton. Several impurities (hydrogen, CO, and helium) will pass through the CGCS as noncondensibles. Table I lists the levels of impurities in the EBR-II cover gas.

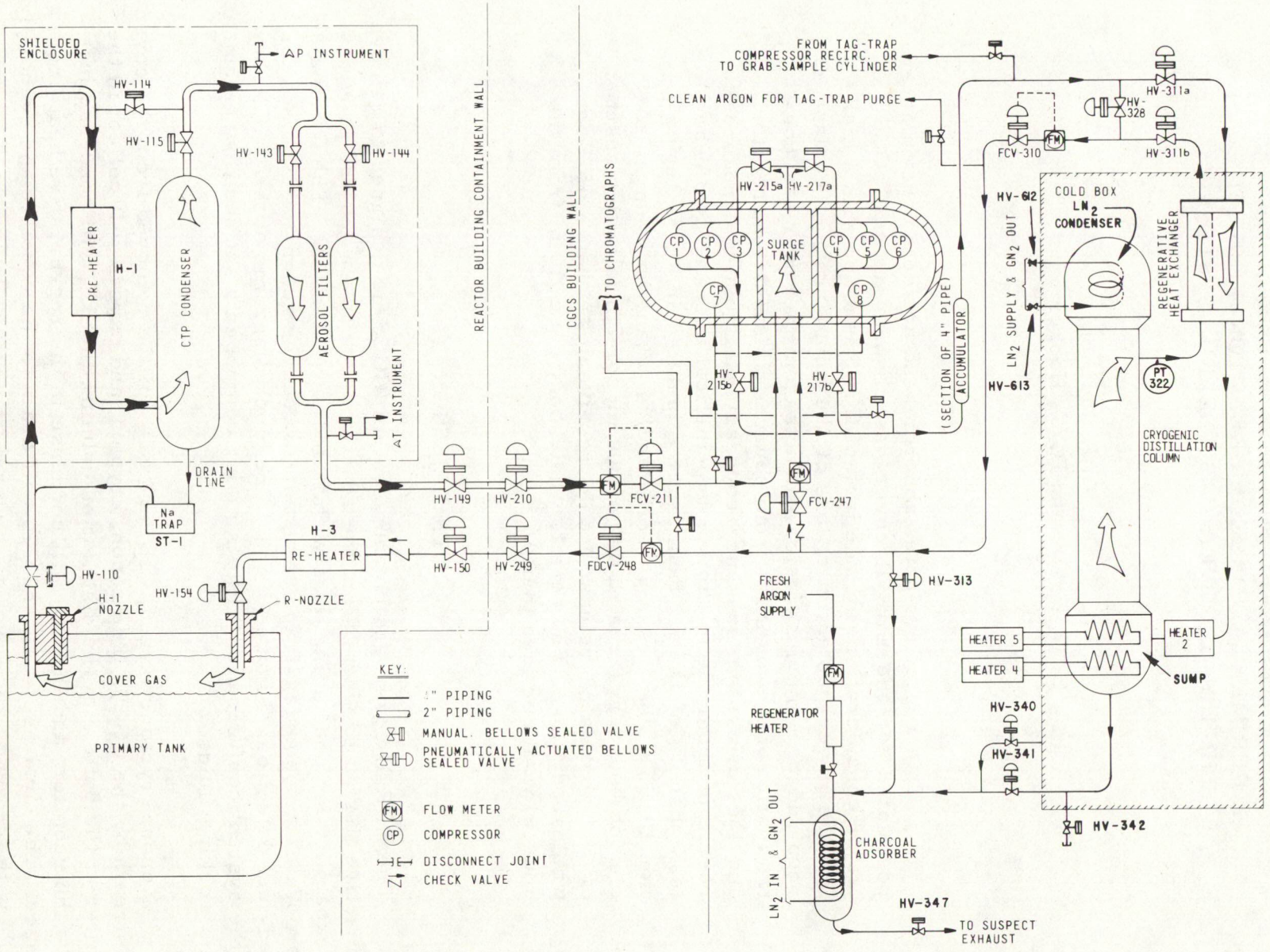

Fig. 1. Simplified Diagram of Main Loop of Cover-gas Cleanup System (CGCS). Conversion factor: 1 in. = 25.4 mm.

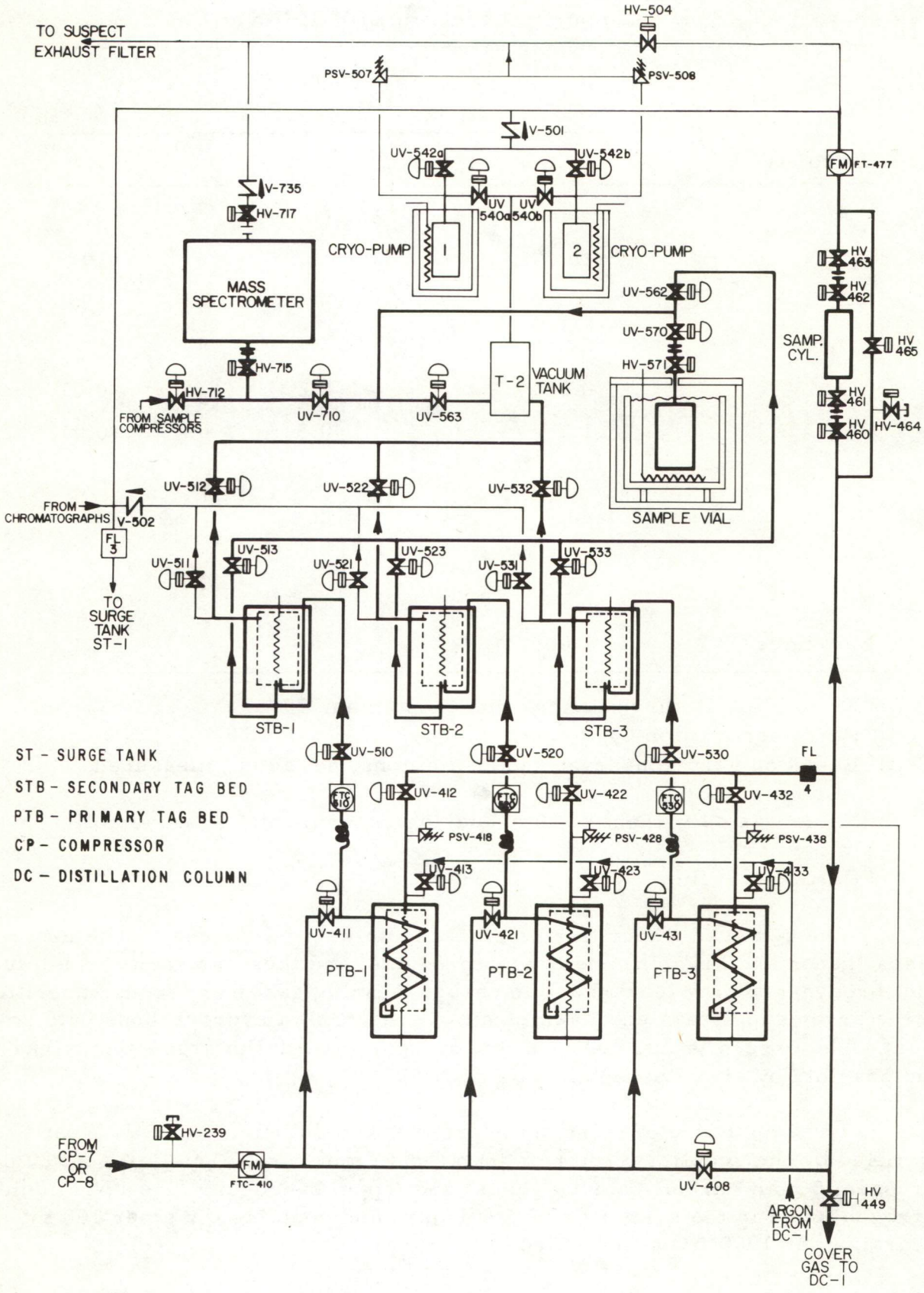

Fig. 2. Tag-trap Analysis System of CGCS

TABLE I. Impurity Levels in EBR-II Cover Gas

Impurity	Concentration, μL/L argon (ppm) High	Avg	Low
H_2[a]	>400	10	<4
O_2	<10	<10	<10
N_2[a]	>10 000	3 500	<100
CH_4[a]	8	3	<1
CO	0.35	0.2	<0.01
CO_2	1.7	0.5	<0.01
Na	1 400[b,c]	-	-
He[a]	>400	20[d]	<4
Kr	-	2[e]	-
Xe	-	12[e]	-
Na oxides	1 000[b,c]	-	-

[a]From EBR-II surveillance, June-September 1975.
[b]Parts per million by weight.
[c]Based on very conservative assumptions; not actual measured values.
[d]Value was <4 without helium-bearing experimental subassembly in the core.
[e]Parts per billion.

The removed impurities originate from several sources. The noble gases (xenon and krypton) are fission products, and their source is tramp fuel and through-cladding leakage. The carbon-bearing gases are from impurities in the argon supply gas and from chemical reaction of hydrocarbons with sodium. The oxygen is introduced to the system through the argon supply gas and possibly by air inleakage.

The impurities present in the fresh argon delivered to ANL-West are certified by the supplier to be less than 6 ppm moisture, 5 ppm oxygen, 20 ppm nitrogen, 3 ppm carbon-bearing gases, and 1 ppm hydrogen. The LN_2 (liquid nitrogen) used in the system is 99.997% pure and contains 0.5 g per 100 m^3 (2 grains per 1000 ft^3) of moisture.

The CGCS design radioisotope inventory was based on a flow rate of 4.7×10^{-3} m^3/s (10 scfm) leaving the reactor cover-gas space and 12 defective

mixed-oxide elements with 34-cm (13.5-in.)-long fuel columns operating at 52 kW/m (16 kW/ft). Twelve elements were arbitrarily chosen as a maximum number associated with the run-beyond-cladding-breach (RBCB) program. The inventory in the distillation-column sump and charcoal adsorber after 10 years of continuous operation would be about 200 TBq (5400 Ci), and this value was used as the source to analyze CGCS accident conditions. In calculating this inventory, we assumed that all the gaseous fission products released from the fuel are immediately available to the reactor cover gas and that there is zero delay in the aerosol filters and CGCS piping. These assumptions are believed to be very conservative based on the following three observations:

(1) GB-10 Sweep-gas Experiment.[1] This test was designed so that the fission-product activity at various points in the fuel element could be monitored. The data indicate that the attenuation of short-lived isotopes during transport from the fuel to the fuel-element plenum is substantial. For example, the ^{135m}Xe activity is reduced by a factor of about three in reaching the top of the fuel column and another factor of about four in moving past 10 cm (4 in.) of depleted UO_2 blanket pellets. The attenuation of krypton isotopes is less than that of xenon isotopes and decreases as the half-life increases.

(2) Holdup in the Primary Sodium. Analysis of the fission-gas activities in the EBR-II cover gas indicates a substantial holdup of krypton and xenon in the sodium. Since the amount of gas generated in a cladding-breach test is small compared to the amount of krypton and xenon that could be dissolved in the sodium flowing through the subassembly, some holdup can be expected in the primary sodium.

(3) Holdup in the CGCS. The approximate volume of gas in the CGCS upstream of the distillation column is 0.7 m^3 (24 ft^3) at STP. At the design flow rate of 4.7×10^{-3} m^3/s (10 scfm), the transit time from the cover-gas space to the distillation column would be ~2 min. This delay would reduce the concentration of many of the isotopes entering the CGCS.

Therefore, the 200-TBq (5400-Ci) inventory provides a conservative basis for a safety analysis of the CGCS. Table II shows how the radioisotope inventories are distributed in the CGCS.

The assumed presence of 12 leakers within the reactor core (which is an arbitrary assumption) is not, however, the limit precluding use of the CGCS or operation of the reactor. The radioisotope inventory as it relates directly to overall plant-safety criteria is the limiting factor, and these limits are prescribed as EBR-II technical specifications (see Sec. 5 below). The system will have to be calibrated from actual test experience to enable the number and type of defected elements in the core to be correlated with the resulting radioisotope inventories with the CGCS in operation. Sump curie content can be calculated either manually or automatically with the on-line computer system (DAS). The numerical calculation of inventory will be made according to the equation

$$N_i(t + \Delta t) = N_i(t)\exp^{(-\lambda_i \Delta t)} + \frac{\Delta t}{2}\left[Q_i(t + \Delta t) + Q_i(t)\exp^{(-\lambda_i \Delta t)}\right],$$

where

$N_i(t)$ = inventory (atoms) of radioisotope i at time t,

Δt = time since last sample point,

λ_i = decay constant of radioisotope i,

and

Q_i = source rate (atoms/s) of radioisotope i.

TABLE II. Equilibrium Radioisotope Inventory and Distribution in Cover-gas Cleanup System (CGCS)

Section	Inventory, Ci[a]	
	Gas	Liquid
Reactor Cover-gas Space	450	0
CGCS within Reactor Building		
Preheater	0.1	
CTP condenser	43.5	
Filters (2)	20.3	
Piping	6.5	
Total	70.4	0
CGCS Building (Outside Cold Box)		
Surge tank	14.4	
Tag-trap Filters (2)	1.4	
Compressors (8)	1.2	
Piping	10.7	
Tag-trap beds and sample cylinder (assumes all beds are filled simultaneously)	671.0	
Total	698.7	0
CGCS within Cold Box		
Heat exchanger	47.8	
Distillation column	61.8	
Column sump and charcoal adsorber	0	5300
Piping	3.5	
Total	113.1	5300

[a]Conversion factor: 1 Ci = 3.7×10^{10} Bq.

This method of calibration is required because the effect of geometry, differing gamma-energy levels, and shielding cannot be adequately treated in

a simple calibration of a gamma monitor. Periodically, a manual calculation of the sump inventory based on cover-gas grab samples will be performed to check the on-line calculation.

The prime purposes of this final safety-analysis addendum (FSAA) are to document the safety aspects inherent in the design of the CGCS system and to evaluate the possible effects and consequences of postulated abnormal (or upset) and accident conditions to the general public and on-site personnel. This safety evaluation does not address operator-safety aspects of normal design and operation (such as radiation shielding) that are part of the system design criteria. All necessary safety features and precautions for normal operation will be used in the CGCS to ensure operator safety, and these details will be included in the CGCS system design description and operating procedures. Such operation is designed to be well within the limiting safety envelope described in this FSAA and may be modified as operational experience demonstrates is prudent.

2. SYSTEM DESIGN: SAFETY ASPECTS

The CGCS system comprises several subsystems and components whose functions are briefly described in the following sections.

Cover gas is drawn from the primary tank at a flow rate of up to 4.7×10^{-3} m^3/s (10 scfm) and is heated to vaporize the sodium aerosols in it. The heated gas then flows through a controlled-temperature-profile (CTP) condenser, where the sodium vapor is condensed. Filters downstream of the CTP condenser remove the remaining sodium, in vapor or aerosol form. The gas then flows to a surge tank and compressors within a containment vessel. After being pressurized, the gas passes through a regenerative heat exchanger, where it is cooled to cryogenic temperatures. It then flows to a cryogenic distillation column, where xenon and krypton isotopes are liquefied and collected. The remaining argon--which is cleaned of the impurities xenon, krypton, oxygen, CO_2, and CH_4--is returned to the primary-tank cover-gas system after passing back through the regenerative heat exchanger and a reheater that raises the temperature of the gas to about 315°C (600°F)--the bulk temperature of the cover gas. The distillation column and the regenerative heat exchanger are installed in a "cold box" that serves as a containment vessel and is capable of holding, without being overpressured, all the contents of the distillation-column sump and LN_2 condenser in the event of a rupture and complete vaporization of these contents. The system also contains a xenon-tag-trap subsystem that removes and concentrates xenon to identify xenon isotope ratios. The ratios are used for ruptured-fuel identification. To protect against overpressure, relief valves set at 515 kPa (75 psig) have been placed at strategic points through the system; also, the distillation column has a rupture disk that relieves the pressure at ~825 kPa (120 psig).

Sufficient radiation shielding is provided to ensure personnel safety during normal operating conditions. Components with major radioisotope inventories are in pit areas of the CGCS building and are separated from personnel by 30-cm (12-in.)-thick high-density-concrete walls. Other radioactive areas will also be provided with shielding.

Condensed radioisotopes will be transferred by passing the contents of the distillation-column sump to the off-gas charcoal adsorber. Section 2.2.3 provides the details of the transfer of sump contents to the adsorber.

2.1. Specifications

2.1.1. System Standards

The ASME Boiler and Pressure Vessel Code, Section III, is used as the basic design code.

Section III, Class 1 designation, is used for the portions of the system connecting the primary tank to the initial CGCS isolation valves (HV-110 and -154). The valves are considered part of these portions.

Section III, Class 2 designation, is used for the portions connecting the initial CGCS isolation valves to the CGCS isolation valves at the reactor containment building.

Section III, Class 3 designation, is used for all the portions outside the reactor building. Included are all portions of the system containing argon cover gas, such as the compressor containment vessel, the cold-box containment vessel, and the xenon-tag-trap subsystem. Commercial valves will be used in analysis equipment and supporting systems.

Section 4.3.4 of RDT Standard C16-1T is applied to provide the required buffering to prevent signals from the CGCS supply-line radiation monitor from interfering with reactor-building-isolation signals.

No specific standard related to tornado loading has been applied, although the CGCS building was designed to withstand a wind load of 1.4 kPa (30 psf). The cold box, designed as a containment and isolation vessel for the distillation column and regenerative heat exchanger, would protect those components from damage from a tornado. (Almost all the radioisotopic inventory is contained in these components.)

In the extremely unlikely event of an undetected tornado damaging the building and the CGCS system, automatic isolation of the system would result (from flow mismatch). (Even if isolation were not to occur, release would be no more than for the MHA evaluated in Sec. 4.4.) Since all but one of the cold-box isolation valves are under the reinforced concrete floor of the CGCS building, the system should remain intact even if the CGCS building were destroyed.

(Only one valve extends upward through the CGCS-building floor, and it is beneath a virtually indestructible cabinet.)

2.1.2. System Containment

Capability for system isolation is provided (a) near the primary-tank nozzles, (b) at the wall of the reactor containment building, and (c) on the cold-box-vessel piping. Outside the reactor containment building, secondary containment is provided for the compressors and the cryogenic distillation column.

2.1.3. Seismic Design Criteria

The CGCS is designed to withstand the effects of earthquake ground motion at the plant site without breaching of the system integrity and without impairment of the operability of the system. Ground accelerations considered for the system within the EBR-II reactor containment building, in the pipe trench, and in the CGCS building are 0.25 g for both horizontal and vertical planes.

2.2. Operations

2.2.1. CGCS Isolation

2.2.1.1. Automatic CGCS Isolation at Primary-tank-nozzle Valves. Valves HV-110 and -154, which isolate the system at the primary-tank nozzles, automatically respond to variations or upsets caused by the CGCS. These valves are provided to automatically isolate the CGCS from the primary-cover-gas system in the event of upsets in the CGCS. Signals that initiate this automatic action are:

(1) High or low pressure of primary-tank cover gas.

(2) High radiation in CGCS building.

(3) Mismatch of flow rates.

(4) High radiation in CGCS supply line.

(5) Full-isolation signal for reactor containment building.

Limiting conditions for the above signals are included in the EBR-II technical specifications (see Sec. 5). The alarm signal and automatic CGCS isolation will occur simultaneously.

The CGCS primary-tank-nozzle valves will not automatically close on a partial isolation of the reactor containment building. These valves, however, may be manually closed at any time.

2.2.1.2. Automatic CGCS Isolation at Reactor Containment Building. Valves HV-149, -150, -210, and -249, which isolate the CGCS at the reactor

containment building, automatically respond to high radiation signals. These signals consist of the tripping of two out of three of the radiation monitors on the CGCS supply line and any signal for full isolation of the reactor containment building. The alarm signal and automatic CGCS isolation will occur simultaneously. These valves protect the public from any radiation release associated with reactor faults within the containment and are part of the safety system (SS). As mentioned previously, these isolation signals will also close primary-tank-nozzle valves HV-110 and -154. Any of the six CGCS isolation valves may be manually closed. None of the six will automatically close on partial isolation of the reactor containment building.

2.2.1.3. Manual Override of Automatic CGCS Isolation. The capability for manual override of automatic CGCS isolation at the reactor containment building and primary-tank nozzles has been provided, but will be used only under very strict administrative control.

The override capability is an advantage to public safety. For events that may be hypothesized to result in significant fission-product contamination of the cover gas (such as meltdown of a subassembly in the fuel-unloading machine), the CGCS represents a means of containing a significant fraction of the contamination that would otherwise leak to the containment-building atmosphere. If that atmosphere were to become significantly contaminated, access would be prevented, and the only recourse would be to keep the building isolated until the levels had decayed sufficiently to allow entry. Use of the CGCS therefore represents a conservative and prudent method of reducing cover-gas activity following an assessment of circumstances initiating reactor-containment-building isolation.

Once a manual override is accomplished, and a substantial fraction of the radioisotope inventory is transferred to the CGCS, the overall safety posture of the reactor is improved. Subsequent release of the inventory would require failure of the CGCS. If, however, the CGCS were not used, the inventory would be released by normal leakage from the reactor containment building. [For safety analysis, a leakage of 28 m^3/d (1000 ft^3/d) referenced to 250 kPa (36 psia) and 0°C (32°F) is assumed for that building.] Because leakage from gas systems is more likely than from the distillation column of the CGCS, the most conservative posture of the plant relative to minimizing fission-gas release would be to contain that radioisotope inventory within the CGCS distillation column.

Note also that an assumed total release of the inventory of fission-product contaminants of the cover gas from the CGCS is no different in effect than an assumed release of the inventory from the containment building. Because the overall safety posture of the plant is improved by use of the CGCS, operation of the CGCS under emergency conditions does not need to be restricted to limits of radioisotope inventory intended to apply to normal operation. Limits for such emergency operation are related to overall safety considerations that are outside the scope of this FSAA; they are appropriately addressed as technical-specification limits for emergency operation.

2.2.1.4. Cold-box Isolation. To isolate the cold box, isolation valves HV-311a, -311b, -612, -613, -340, and -341 are closed manually from remote-control stations, and valve HV-342 is closed and capped.

Increases in distillation-column pressures or temperatures caused by system upset are alarmed and monitored. Upset conditions occur slowly enough to allow ample time for effective isolation or correction by manual closing of the valves.

2.2.2. System Monitoring and Control

The CGCS generally requires little attention after startup. System instrumentation signals are routed to the existing EBR-II data-acquisition system (DAS) for processing. The processed information is relayed to outlet terminals at local control stations in the reactor building, the reactor control room, and the CGCS building. General alarms in the reactor control room alert operators if system upset or accident conditions occur. Detailed system monitoring and control are done at the control stations in the reactor control room and the CGCS building. System alarms are tabulated in Table III.

TABLE III. System Alarms[a]

Alarm Designation	
PJRA 105	H1 Nozzle Outlet Pressure
PJRA 112	Preheater Inlet Pressure
PJRA 106	CTP Inlet Pressure
PJRA 117	CTP Outlet Pressure
PJRA 142	Aerosol Filters ΔP
TJRA 111	H1 Nozzle Supply Temperature
TJRA 108	Preheater Inlet Temperature
TJRA 118	Preheater Outlet Gas Temperature
TJRA 113	Preheater Outlet Pipe Temperature
TJRA 119	CTP Condenser Bypass Temperature
TJRA 141	Aerosol Filters Inlet Temperature
TJRA 116	Sodium Trap Temperature
TJRA 152	Reheater Outlet Temperature
TJRA 130	CTP Temperature H (Top)
TJRA 130	CTP Temperature G
TJRA 130	CTP Temperature F
TJRA 130	CTP Temperature E
TJRA 130	CTP Temperature D
TJRA 130	CTP Temperature C
TJRA 130	CTP Temperature B
TJRA 130	CTP Temperature A (Bottom)
PS-166[b]	Cover Gas Pressure Out of Limits
TIA-906	H1 Plug Temperature
TIA-911	CGCS Supply Line Temperature
TIA-916	Preheater Inlet Line Temperature
TIA-926	CTP Condenser Bypass Line Temperature
TIA-121	Preheater Temperature
TIA-921	Preheater Outlet Line Temperature
TIA-941	CTP Condenser Drain Line Temperature
TIA-936	Sodium Trap Drain Line Temperature
TIA-931	CTP Condenser Outlet Line Temperature
TIA-946	Aerosol Filter No. 2 Temperature

TABLE III (Contd.)

Alarm Designation	
TIA-951	Aerosol Filter No. 1 Temperature
TIA-157	Reheater Temperature
TIA-956	Reheater Outlet Line Temperature
XJRA-165	Isolation Annunciation
TA-900	Trace Heating Alarm
FJRA 310	Distillation Column Argon Flow
FJRA 211	Cover Gas Supply Flow
FJRA 248	Cover Gas Return Flow
FDA 248	Cover Gas Flow Mismatch
FDA 248[b]	Cover Gas Flow Mismatch Trip
FJRA 245	Balance Flow
FJRA 312	Distillation Column Nitrogen Flow
TJRA 233	Compressor Dome A Temperature
TJRA 233	Compressor Dome B Temperature
JRA 319	Distillation Column Heater H2
JRA 317	Distillation Column Heater H4
JRA 318	Distillation Column Heater H5
TJRA 392	HX3 Argon Inlet Temperature
TJRA 314	HX3 Argon Outlet Temperature
TJRA 316	Distillation Column Sump Temperature
TJRA 393	LN_2 Condenser Argon Outlet Temperature
TJRA 321	Distillation Column Outlet Temperature
TJRA 391	HX3 Clean Argon Outlet Temperature
TJRA 320	Distillation Column LN_2 Inlet Temperature
TJRA 390	Distillation Column GN_2 Outlet Temperature
TJRA 346	Charcoal Adsorber Temperature
LJRA 315	Sump Level 315B Full (30 cm)
LJRA 315	Sump Level 315C 3/4 Full (23 cm)
PJRA 213	Surge Tank Pressure
PJRA 309	Cold Box Cover Gas Inlet Pressure
PJRA 322	Distillation Column Outlet Pressure
PJRA 243	Cold Box Cover Gas Outlet Pressure
PJRA 345	Cold Box Pressure
TJRA 572	Tag Sample Vial Temperature
PJRA 239	Tag Trap Argon Inlet Pressure
FJRA 410	Tag Trap Cover Gas Supply Flow
FJRA 510	Secondary Trap 1 Flow
FJRA 520	Secondary Trap 2 Flow
FJRA 530	Secondary Trap 3 Flow
TJRA 414	Primary Tag Bed 1 Charcoal Temperature
TJRA 424	Primary Tag Bed 2 Charcoal Temperature
TJRA 434	Primary Tag Bed 3 Charcoal Temperature
TJRA 514	Secondary Tag Bed 1 Charcoal Temperature
TJRA 524	Secondary Tag Bed 2 Charcoal Temperature
TJRA 534	Secondary Tag Bed 3 Charcoal Temperature
JRA 402	Tag Trap Sequence Interrupt
PJRA 565	Vacuum Line Pressure
PJRA 564	Sample Line Pressure
YJRA 726	Gas Chromatograph 1 Helium
YJRA 727	Gas Chromatograph 2 Helium
YJRA 726	Gas Chromatograph 1 Hydrogen
YJRA 727	Gas Chromatograph 2 Hydrogen
YJRA 726	Gas Chromatograph 1 Oxygen
YJRA 727	Gas Chromatograph 2 Oxygen
YJRA 726	Gas Chromatograph 1 Nitrogen
YJRA 727	Gas Chromatograph 2 Nitrogen
YJRA 770	Anacon Oxygen Level 1
YJRA 771	Anacon Oxygen Level 2
YJRA 770	Anacon Oxygen Range 1
YJRA 771	Anacon Oxygen Range 2

TABLE III (Contd.)

Alarm Designation	
PJRA 616	Low LN_2 Back Pressure
RA 808	Cold Box Gamma Monitor
RA 801[b]	Gamma Area Monitor, East[c]
RA 801[b]	Gamma Area Monitor, West[c]
RA 802	β Particulate Air Monitor, West 25[c]
RA 802	β Gas Air Monitor, West 26[c]
RA 803[b]	β Gas Suspect Exhaust
RA 804[d], RA 805[d], RA 806[d]	High Radioactivity, Cover Gas Supply to CGCS (two out of three required for isolation)
FE-298, -299	Freon Present in Compressor Containment, FE-298 in North End, FE-299 in South End of Containment Vessel

[a]System alarm setpoints will be established during system checkout and initial operation.
[b]Alarm occurs simultaneously with automatic CGCS isolation at the primary-tank-nozzle valves (see Sec. 2.2.1.1).
[c]Located on main floor of CGCS building.
[d]Alarm occurs simultaneously with automatic CGCS isolation at the primary-tank-nozzle valves and reactor containment building (see Secs. 2.2.1.1 and 2.2.1.2).

During initial startup with the system, all instruments were operable. Subsequent operation has revealed that it is possible, and safe, to operate with some instrumentation systems temporarily out of service. All operation is controlled by approved adminstrative procedures.

The cleanup portion of the CGCS may be operated at steady state with local readout instrumentation if the DAS is not fully functional. All the instrumentation associated with the tag-trap subsystem and the Nova controller must be fully functional to enable automatic tag-trap sequencing. (The xenon-tag trap system normally functions in a sequenced, automatic mode. The Nova controller manages this sequencing function.) Even if some of the tag-trap instruments fail, tag-trap sequencing could be done manually by using those primary and secondary beds not affected by the failures.

Emergency operation of the CGCS with instrument failures is a possibility and would be contingent upon an engineering review of the state of the system and the risks/benefits of operating with other failed systems.

Because of their importance, the CGCS radiation monitors are provided with backups. Redundancy is provided for the suspect-exhaust monitor by the two area gamma monitors and the particulate-air-activity monitor. The monitors of the site suspect-air-exhaust system provide additional backup. One of the area gamma monitors is near the suspect-exhaust line and will respond to any increase in activity in the region. The CGCS building is small enough and the monitoring equipment is so located that any leakage will be "seen" by more than one monitor. High-level alarms from the above equipment will automatically isolate the CGCS at the primary-tank nozzles. In addition, a trip signal

on two of the three radiation monitors on the supply line to the CGCS will provide CGCS isolation at the primary-tank nozzles and the reactor-containment-building penetration.

As stated above, the CGCS has control centers (1) in the reactor control room in the power-plant building, (2) in the reactor building, and (3) in the CGCS building. The control center in the reactor control room can control the main argon flow in the CGCS and the sequencing of the tag-trap system, and also can isolate and safely shut down the CGCS. The control center in the reactor building controls those systems associated with the operation of the preheater, reheater, CTP condenser, aerosol filters, and trace heating. The control center in the CGCS building controls the rest of the CGCS--i.e., the compressors, cryogenic distillation column, and tag-trap subsystems--and provides system startup and shutdown capability.

2.2.3. Disposal of Distillation-column-sump Contents to Off-gas Charcoal Adsorber

The off-gas charcoal adsorber is an effective system for the retention of residual gaseous isotopes from the CGCS distillation-column sump. The adsorber system is connected to the CGCS cryogenic column by 2-cm (3/4 in.) Schedule 40 stainless steel tubing. The tubing carries the sump contents from the bottom of the sump to the top of the adsorber bed. These contents are forced out by isolating the CGCS from the reactor primary tank, shutting off the LN_2 flow, and using the buildup of argon pressure in the distillation column to push the liquid contents out of the bottom of the sump.

The sequence of events involved in dumping the sump contents to the off-gas charcoal adsorber is as follows:

(1) Isolate the CGCS from the reactor primary tank by closing valves HV-110 and -154.

(2) Close valves HV-311a and -311b, and open valve HV-328.

(3) Make sure that valves HV-340 and -342 are closed.

(4) Open valve HV-341 leading to the adsorber bed.

(5) Open valve HV-347 to allow the argon to vent from the adsorber bed during the transfer. This argon release is monitored for activity level.

(6) When the level of the distillation-column sump indicates that the sump is empty and the contents have been transferred (evidenced by a rapid pressure decrease in the sump by PT-322), close drain valve HV-341.

(7) Pressurize the distillation column to about 150 kPa (22 psia) and repeat step 6 one or more times.

The last step in the sequence ensures complete removal of the sump contents. Following the dump, the adsorber-bed vent valve, HV-347, is closed to retain the radioactive isotopes trapped in the bed.

The effectiveness of the adsorber as a receptacle for sump contents is due to the considerable adsorptive capacity of the charcoal bed for fission gas. Table IV summarizes the estimated bed capacities at ambient conditions.[2-4] Although the throughput of argon during a sump drain exceeds the bed capacity, xenon and krypton will displace argon when passing through the bed.[4]

TABLE IV. Ultimate Capacity of 280-kg (625-lb) Adsorber Bed at Ambient Conditions

Species	Fission Production[a]		Specific Charcoal Capacity,[b] mL/g	Total Bed Capacity, mL
	In 45 Full-power Days, mL	In One Year at 75% C.F.,[c] mL		
^{133}Xe	2.75[d]	2.75[d]	1200	3.4×10^8
^{85}Kr	2.75	17.0[e]	80	2.3×10^7
Xenon	220	1320	1200	3.4×10^8
Krypton	32.5	200	80	2.3×10^7
Argon[f]			9	2.6×10^6

[a] Fission production based on 12 failed 52-kW/m elements.
[b] For all but the argon, the capacities were obtained by direct laboratory measurement at EBR-II.[4]
[c] Plant capacity factor.
[d] For both 45 days and one year, equilibrium conditions in the sump were assumed. This 2.75-cm^3 volume is equivalent to 111 TBq (3000 Ci) of ^{133}Xe.
[e] This volume is equivalent to 0.925 TBq (25 Ci) of ^{85}Kr produced in one year at 75% plant capacity factor.
[f] The sump, when full, contains 3.1×10^7 mL of gaseous argon (in liquid form).

Under the flow conditions that prevail during a dump, the equation[2]

$$t_m = mk/v$$

applies, where

t_m = mean time to breakthrough (based on elution activity at 50% of maximum), h,

m = mass of charcoal in bed, g,

k = adsorption coefficient for a given element, cm^3/g,

and

v = flow rate of inert carrier gas (argon), cm^3/h.

Table V gives the values for k at three temperatures. It also gives the mean breakthrough times calculated using a value of 2.84×10^5 g for m and a coolant flow rate of about 3.1×10^7 cm^3/h (20 cfm). [Flow rate is derived from a sump volume of about 0.04 m^3 (1.3 ft^3) of liquid argon.]

TABLE V. Estimates of Adsorber-bed Breakthrough Times

Temperature,[a] °C	Approximate Adsorption Coefficient (k), cm^3/g		Corresponding Mean Breakthrough Time, h	
	Xenon	Krypton	Xenon	Krypton
20	1 200	80	10	0.7
0	2 700	120	22.5	1.1
-75	20 000	1000	165	9

[a]The value for 0 and 20°C were measured; the values for -75°C are from Ref. 2.

These values indicate that, during a dump, retention of xenon would be very high. At room temperature, some krypton might break through as dump time approaches the mean breakthrough time; thus, for sump inventories containing significant quantities of krypton radioisotopes, either delaying the dumping for one day or precooling the bed may be required. In a cooled bed, retention of both xenon and krypton should be very high during the dump sequence. Provisions are made for off-line regeneration of the bed, after suitable decay periods, to retain the original capacity of the bed.

The above discussion indicates that xenon would not pass through the adsorber during a routine sump transfer. However, depending upon conditions, some krypton could pass through to be exhausted by the stack. Also, ^{85}Kr (half-life = 10.7 yr) may be present in the adsorber from previous dumps. The ^{85}Kr will be diffused throughout the bed and the free gas space in this circumstance.

To establish a limit on the expected maximum amount of krypton isotopes that could be released, consider the following. The oxygen instrumentation may achieve a capability such that the sump contents will have to be transferred only once a year, and delay before dumping would eliminate all the short-lived isotopes. Therefore, the size of release during the transfer

would be small, but subsequent regeneration could release the total ^{85}Kr inventory from a year of reactor operation with both the RBCB and RTCB (run-to-cladding-breach) programs under way. The production per year from the design-basis 12 RBCB elements is 0.925 TBq (25 Ci); release of prior production at time of breach from both RTCB breaches and RBCB breaches could easily contribute another 1.85 TBq (50 Ci), based on 74 GBq/yr (2 Ci/yr) from each of 12 breached elements in each program. Thus, a regeneration step could conceivably release 2.8 TBq (75 Ci), all as ^{85}Kr. Call this case 1.

More frequent transfer of the sump contents would not necessarily result in an increase in released activity. A delay of a few days in transfer from the sump to the charcoal bed would effectively remove the short-lived krypton isotopes, leaving only ^{85}Kr.

For purposes of illustration, consider the release resulting from transfer of sump contents to the bed with no delay for decay of krypton isotopes in the sump. Two more scenarios will be considered in which short-lived krypton activity is involved. The first situation considered will be krypton activity produced from irradiation of two breached elements.

Activity produced during one reactor run would be 37 GBq (~1 Ci) [two elements × 74 GBq (2 Ci/yr) per element × 1/6 yr]. Release from prior production in two RBCB elements and as many as five RTCB elements during the same period could total 1.07 TBq (29 Ci); the net input would therefore be 1.11 TBq (30 Ci) of ^{85}Kr. For the same two RBCB elements, the equilibrium inventory of ^{88}Kr, ^{87}Kr, ^{85m}Kr, and ^{83m}Kr would be 1.6, 1.7, 1.5, and 0.48 TBq (43, 44, 41, and 13 Ci). From the elution data obtained by direct measurement at a bed temperature of 0°C, about 1 and 50% pass-through of krypton isotopes would occur in 30 and 60 min, respectively.[4] [A temperature of 0°C is chosen for the bed because of the substantial cooling provided by the input of the equivalent of 0.04 m^3 (1.3 ft^3) of liquid argon at a temperature just above its normal boiling point.] By interpolation, it is estimated that 481, 444, 481, and 148 GBq (13, 12, 13, and 4 Ci) of ^{88}Kr, ^{87}Kr, ^{85m}Kr, and ^{83m}Kr, respectively would be exhausted during the dump (see Table VI). Total release for this condition (case 2) would therefore be 2.7 TBq (~72 Ci) [including the 1.11 TBq (30 Ci) of ^{85}Kr discussed above].

To obtain the bounding case, assume that the full complement of 12 breached elements (rather than two) is in the core, so that the equilibrium sump inventory would be 200 TBq (5400 Ci). Further assume that an emergency transfer of the sump contents is required, not allowing for decay in the sump. The resultant release of short-lived krypton isotopes could be 9.25 TBq (~250 Ci) [six times the 1.55 TBq (42 Ci) for two elements discussed above] plus the 2.8-TBq (75-Ci) annual production of ^{85}Kr discussed previously-- a total of ~11.8 TBq (~325 Ci). These results led to the conclusions that, if the sump holds a year's accumulation of ^{85}Kr and has an initial inventory of 200 TBq (5400 Ci):

(1) A limit of 2.8 TBq (75 Ci) per transfer would allow for a routine transfer to the bed.

(2) A limit of 18.5 TBq (500 Ci) would allow for an emergency transfer to the bed. [This limit is applied to total release in a single emergency or for a year's operation; i.e., 18.5 TBq (500 Ci) is adopted as the yearly limit for routine transfers.]

TABLE VI. Whole-body Doses for Two Assumed Cases of Krypton Release

Case	Isotope	Curies[a] Released	Dose, mRem At 500 m	Dose, mRem At 5000 m
1	^{85}Kr	75	0.2	0.07
2	^{85}Kr	30	0.08	0.03
	^{88}Kr	13	0.35	0.13
	^{87}Kr	12	0.28	0.11
	^{85m}Kr	13	0.07	0.03
	^{83m}Kr	4	0	0
	Total, Case 2	72	0.8	0.3

[a]Conversion factor: 1 Ci = 3.7×10^{10} Bq.

A release of 18.5 TBq (500 Ci) would result in a dose less than 5 mRem at the INEL boundary (5000 m). Table VI lists the dose at 500 and 5000 m resulting from a release of 2.8 TBq (75 Ci).

Because transfer of sump contents to the bed could normally be delayed for 1-2 days, actual operation would be expected to result in a lower release. [As discussed above, normal release for a year would not be expected to exceed 2.8 TBq (75 Ci).] A limit on delay of transfer is not being applied as a safety limit, however. To maintain a release that is as low as reasonably achievable, we apply administrative criteria not appropriate to bounding safety considerations discussed in this document; such criteria require an evaluation of operating circumstances existing at the time of transfer. One may hypothesize, for example, a condition of high cover-gas activity that requires CGCS operation, a subsequent ingress of oxygen or methane to the CGCS that requires CGCS isolation and sump dump, and then CGCS restart at the earliest possible time to maintain control of cover-gas (and reactor-building) activity. The overall release from the early sump transfer in this situation might be lower than the release if transfer were delayed.

A further consideration for bounding safety analysis can be made by assuming that, for the worst-case emergency transfer of 200 TBq (5400 Ci) from the sump, the exhaust valve isolating the charcoal adsorber is not closed following transfer. In this case, the stagnant bed would openly communicate with the exhaust line, and isotopes of xenon as well as krypton may be released. At ambient conditions, the release fraction for a given isotope from a stagnant, saturated bed may be calculated by[5]

$$R(t,\lambda) = \frac{2D}{L^2} \sum_{n=0}^{n=\infty} \frac{1 - \exp\left\{-\left[\lambda + \frac{(2n+1)^2\pi^2 D}{4L^2}\right]t\right\}}{\lambda + \frac{(2n+1)^2\pi^2 D}{4L^2}},$$

where

R = release fraction for isotope i under ambient conditions at time t,

D = diffusion coefficient, cm^2/s,

L = bed depth (190 cm),

t = time, s,

n = eigenvalue,

and

λ = decay constant, s^{-1}.

The solution of this equation gives the release fractions shown in Table VII for 1 h.

TABLE VII. Calculated Release Fractions for a Stagnant Adsorber Bed at Ambient Temperatures in 1 h

n	^{133}Xe	^{85m}Kr	^{85}Kr
1	2.79×10^{-5}	5.90×10^{-4}	6.38×10^{-4}
10	1.53×10^{-4}	3.15×10^{-3}	3.40×10^{-3}
100	1.26×10^{-3}	1.15×10^{-2}	1.23×10^{-2}
1 000	2.77×10^{-3}	1.33×10^{-2}	1.40×10^{-2}
10 000	2.95×10^{-3}	1.35×10^{-2}	1.42×10^{-2}
100 000	2.97×10^{-3}	1.35×10^{-2}	1.42×10^{-2}

At ambient conditions, the cumulative release of fission gas from a charcoal bed in infinite time if the charcoal is spilled and exposed to the normal environment is given by[6]

$$R(t = \infty, \lambda) = \frac{\tanh(\beta)}{\beta},$$

where

$$\beta = \left(\frac{\lambda}{D}\right)^{1/2} L,$$

and D, the diffusion coefficient, is 7×10^{-5} cm^2/s for xenon and 1.6×10^{-3} cm^2/s for krypton.

This analysis assumes that the bed is saturated to capacity for xenon and krypton isotopes. Relative to those for unsaturated beds, the calculated release fractions for the saturated bed will be conservative. Table VIII summarizes fractional releases of the CGCS adsorber for various isotopes under the above conditions. Except for ^{85}Kr, the highest fractional release is 0.037. If, with a 200-TBq (5400-Ci) inventory, the bed were to openly communicate continuously with the site exhaust stack for infinite time, less than 7.4 TBq (200 Ci) would be released in addition to the ~11.8 TBq (~325 Ci) released during the actual emergency transfer. If the prior transfer was not carried out under emergency conditions and had been delayed for a few days, the total release would be ≤10.2 TBq (≤275 Ci).

TABLE VIII. Cumulative Fractional Release of Fission Gases in Infinite Time from a 2-m-deep Adsorber Bed at Ambient Conditions

Isotope	Half-life	Cumulative Fractional Release
^{133}Xe	5.27 d	0.037
^{135}Xe	9.2 h	0.0025
^{135m}Xe	15.7 min	0.0017
^{138}Xe	14.2 min	0.0016
^{85m}Kr	4.4 h	0.031
^{87}Kr	76 min	0.017
^{88}Kr	2.79 h	0.025
^{85}Kr	10.74 yr	0.98

If one assumes that the adsorber container ruptures and the charcoal spills to the floor and remains there for an infinite time at ambient temperatures at a depth of 20 cm (8 in.), release would be less than 66.4 TBq (1800 Ci). (Eight inches is the depth achieved if dispersal of the available charcoal is uniform.) Table IX lists the fractional releases for this event.

TABLE IX. Cumulative Fractional Release of Fission Gases in Infinite Time from a 20-cm-deep Adsorber Bed at Ambient Conditions

Isotope	Cumulative Fractional Release
^{133}Xe	0.32
^{135}Xe	0.087
^{135m}Xe	0.015
^{138}Xe	0.014
^{85m}Kr	0.29
^{87}Kr	0.16
^{88}Kr	0.23
^{85}Kr	0.9999

To release more would require the assumption of fire to heat the charcoal. Total release of the contained inventory of 200 TBq (5400 Ci) has been designated as the maximum hypothetical accident (MHA). The radiological consequences of such an event are reported in Sec. 4.4.

2.2.4. Operator Interaction

Proper operator action will combat abnormal (upset) or accident conditions, except that the operator cannot override automatic isolation of the CGCS (see Sec. 2.2.1). The EBR-II Shift Supervisor is responsible for all CGCS operations. Administrative control is provided through approved EBR-II operating instructions, check sheets, emergency procedures, and an adequate training program for personnel.

3. SYSTEM SAFETY EVALUATION

3.1. Equipment Malfunction or Failure

The consequences of postulated abnormal and accident conditions involving major CGCS components are evaluated below. System aspects that are inherently safe are considered. The design characteristics for the major components are shown in Table X.

TABLE X. Pressure and Temperature Design Characteristics

	Pressure, kPa (psig)	Temperature, °C (°F)
Reactor-building Components		
Piping and values:		
ASME Sec. III, Class 1	1035 (150)	430 (800)
Piping and valves:		
ASME Sec. III, Class 2	1035 (150)	510 (950)
Preheater and reheater	690 (100)	650 (1200)
CTP condenser	150 (22)	540 (1000)
Aerosol filters	515 (75)	205 (400)
CGCS Components		
Piping, tubing, and valves	1035 (150)	+205, -195 (+400, -320)
Tag-trap filters	1035 (150)	120 (250)
Compressor containment vessel		
Compressor sections	345 (50)	120 (250)
Surge-tank sections	1035 (150)	120 (250)
Cryogenic distillation column	1035 (150)	+120, -195 (+250, -320)
Regenerative heat exchanger	1035 (150)	+120, -195 (+250, -320)
Emergency charcoal adsorber	1035 (150)	+120, -195 (+250, -320)
Cold-box vessel	690 (100)	93, -195 (+200, -320)
Primary and secondary tag beds	1035 (150)	+205, -195 (+400, -320)

3.1.1. Rupture or Leakage of Piping and Components

Rupture or leakage of CGCS piping and components during system operation is highly unlikely. High quality of materials, fabrication, and inspection is ensured by adherence to specified codes and standards. The system operates at relatively low temperatures and pressures and is protected from impact during operation by radiation shielding, trenches, and pits. Large ruptures are not expected, but small leaks may occur during the lifetime of CGCS operation. The CGCS ventilation and radiation-detection systems were designed with the realization that argon leaks may occur.

The flow instrumentation used in the CGCS has sufficient sensitivity to detect a flow mismatch of about 4.7×10^{-5} m^3/s (0.1 scfm) between incoming and outgoing argon lines. Because of perturbations in cover-gas pressure (associated with operation of the fuel-unloading machine), some momentary perturbation in flow to and from the CGCS will likely occur. A total flow differential of 9.4×10^{-4} m^3/s (2 scfm) will result in alarm and CGCS isolation if sustained for 10 s. Isolation of the CGCS upon a flow mismatch of this

magnitude is intended to provide prompt action upon major system failure. For moderate or minor events, other detection systems provide greater sensitivity and reliability.

A total system outleakage of $\leq 9.4 \times 10^{-4}$ m^3/s (≤ 2 scfm), leading to radiation release to either the CGCS or the reactor building and reduction of argon-cover-gas pressure, would be detected by radiation-monitoring systems and the cover-gas pressure sensor. A total system inleakage at the above rate, leading to contamination by air and an increase in argon-cover-gas pressure, would be detected by the gas chromatograph and the cover-gas pressure sensor. These conditions, though undesirable, can be corrected by administrative actions and do not lead to significant safety problems. (The safety analysis presented in subsequent parts of Sec. 3 assume a flow mismatch of 4.7×10^{-3} m^3/s, or 10 scfm.)

If, because of a leak, a continual mismatch of 4.7×10^{-5} m^3/s (0.1 scfm) was present, CGCS radiation monitors should detect an increase in background level. A leak in the tag-trap system would probably take the longest to detect, although the radiation monitors would respond to a detectable leak within a few seconds in any case. The leakage of 4.7×10^{-5} m^3/s would be diluted in the 2.6×10^{-1} m^3/s (550 scfm) of clean air flowing through the CGCS building and then be swept away to the suspect-exhaust stack from areas normally occupied by CGCS personnel. Personnel exposure should be negligible under these conditions.

In addition, periodic checks will be made for leakage from the CGCS. The maximum leak rate allowed during initial helium-leak-testing of the CGCS was 1.0×10^{-9} cm^3/s (STP) per welded joint and 1.0×10^{-7} cm^3/s (STP) per mechanical joint. After the system is operating, argon leakage will be checked. The argon detector is calibrated against a standard argon leak of 7.4×10^{-4} cm^3/s (STP); argon leakage from any point in the system therefore will not be allowed to exceed this value.

Two possible consequences are evident with a postulated loss of integrity of the CGCS pressure boundary: (1) release of radioactive isotopes or (2) intake of moisture or air. Each section of the system is evaluated separately for loss of integrity of pressure boundary in the description that follows. The consequences of air contamination are discussed separately in Sec. 3.3.1.

3.1.1.1. Within Reactor Building. Rupture or leakage of either the supply or return line would allow release of radioactive gas into the reactor building and contamination of the CGCS and primary-tank cover gas with air. An offset break of a supply or return pipe could release radioisotopes from the primary-tank cover gas and portions of the CGCS. The system operates at less than atmospheric pressure from the preheater to the compressors. Upstream of the preheater, leakage would be out of the CGCS into the reactor building. Downstream of the preheater, air would leak into the CGCS.

Isolation of the CGCS from the primary tank is initiated manually by operator action in response to alarms of the reactor-building-air monitors or automatically by flow rate being mismatched or cover-gas pressure being out of limits. Isolation of the CGCS at the reactor-building containment is initiated manually by operator action or automatically by high radioactivity in the supply line of the CGCS or a reactor-building-isolation signal. (No special requirements are added to the reactor-building-isolation system because of the CGCS.) With a pressure differential of only 0.25 kPa (1 in. WG) between the primary-tank cover gas and the reactor-building atmosphere, a release rate of up to 4.7×10^{-3} m^3/s (10 scfm) is possible, but any release would be contained in the reactor building. EBR-II emergency procedures provide direct action to be taken under such conditions.

3.1.1.2. Between Reactor Building and CGCS Building. A postulated offset break of the 5-cm (2-in.) supply pipe could release radioactive gas from the cover-gas space of the primary tank and from a portion of the CGCS to the atmosphere within the valve box or corrugated pipe enclosure that houses the supply and return piping. This protective enclosure channels the released radioactive gas to the CGCS building, which contains an air monitor, two area monitors, and a monitor for the suspect-exhaust system. The CGCS is isolated automatically at the H-1 and R nozzles in response to high radiation in CGCS building, flow-rate mismatch, or cover-gas pressure out of limits.

The CGCS ventilation system pulls clean air through the valve box and corrugated pipe enclosure; then the air is routed through a HEPA filter and discharged through the suspect-exhaust system. Even if both CGCS-building ventilation blowers should fail, suction from the suspect-exhaust system would maintain an adequate flow to continuously sweep the valve box and corrugated pipe enclosure with clean air and pass it through a HEPA filter. In the highly unlikely event that argon did penetrate the valve box or the pipe enclosure, there would be no chance of contaminating natural water supplies, because the water table is about 185 m (600 ft) below the ground surface.

With an assumed, highly unlikely, total release of maximum radioactive gas inventory [about 18.5 TBq (500 Ci)] within a 2-h period from the cover-gas space in the primary tank and from a portion of the CGCS inside the reactor building, the calculated whole-body dose at a 600-m exclusion-area boundary is much less than 0.5 Rem. The corresponding limit given in 10 CFR 100 (Ref. 7) is 25 Rem. Necessary actions by EBR-II Operations personnel are outlined in the EBR-II emergency procedures.

3.1.1.3. Within CGCS Building (Excluding Cold Box and Xenon-tag Traps). A highly unlikely offset break upstream of the compressors could release radioactive gas from the cover-gas space in the primary tank and from the supply portion of the CGCS inside the reactor building to the CGCS-building atmosphere. Air inleakage to the CGCS would also occur. Leakage from a break downstream of the compressors could also release radioactive gas to the

CGCS-building atmosphere. The CGCS system is isolated at the reactor-nozzle valves in response to those parameters identified in Sec. 2.2.1.1. Operator action is according to the EBR-II emergency procedures. In an assumed, highly unlikely, total release of radioactive-gas inventory [~1.04 TBq (28 Ci)] within a 2-h period from the high-pressure (~150-kPa, or 22-psia) section of the system within the CGCS building, the calculated whole-body dose at a 600-m exclusion-area boundary is much less than 0.1 Rem, compared to the 25-Rem limit of 10 CFR 100 (Ref. 7).

3.1.1.4. Within Cold Box. A postulated pipe break or vessel rupture within the cold box is of concern because of the high concentration of liquid radioisotopes in the distillation-column sump. Nevertheless, any release would be contained within the cold box, a self-contained insulated pressure vessel [690-kPa (100-psi) design pressure] capable of holding the distillation-column inventory of radioisotopes in the sump plus the LN_2 inventory in the condenser, even at ambient temperature. Cold-box isolation and/or compressor shutdown is by operator action in response to alarms indicating abnormal conditions. Contents of the cold box can be discharged to the adsorber or discharged to the site suspect-exhaust stack under strict radiological, delayed-release control if pressure relief is necessary. The adsorber removes the radioisotopes from the argon as the distillation-column contents are discharged.

The postulated maximum accident condition--an assumed coincident rupture of the cold box, distillation column, and charcoal adsorber--is evaluated in Sec. 4.4.

3.1.1.5. Xenon-tag Beds. A highly unlikely rupture of a tag-trap bed (containment vessel) or pipe during sample collection or transfer could release adsorbed radioisotopes to the CGCS-building atmosphere. With a 4.7×10^{-4}-m^3/s (1-scfm) sampling rate, in 1 h a primary tag trap could have an inventory as high as 4.14 TBq (112 Ci) (assuming no decay). Fractional-release phenomena have been studied by Underhill.[5] The slow desorption of radioisotopes from the adsorption bed coincident with the total release of radioactive-gas inventory from the high-pressure portion of the system (see Sec. 3.1.1.3) would add to the offsite dose rate previously evaluated. However, it would still be well within the limits of 10 CFR 100.

Because of the lower inventory of radioactive isotopes, assumed rupture of a secondary tag-trap adsorption vessel is of less consequence than rupture of a primary tag-trap adsorption vessel.

3.1.1.6. Regenerative Heat Exchanger HX-3. Internal rupture or leakage of the regenerative heat exchanger, HX-3, would not release radioactivity to the atmosphere. However, part of the process feedstream would be bypassed around the distillation column, and radioactive products would be returned to the primary-tank cover gas. Cover-gas activity would therefore increase. Although they are indirect, fission-product monitors (FGM, GLASS) in the

primary-tank cover-gas system would indicate a change that would lead to investigation of the source of the increase. Manual radiation monitoring of the CGCS return line to the reactor building from HX-3 would be an additional check to determine if HX-3 had failed. A normal reading for return-line activity that could be used for comparison will be established through system surveillance. Such surveillance will normally be conducted once a shift during reactor operation.

By use of GLASS, the failure of certain types of fuel elements in the reactor could be distinguished from internal failure of HX-3. The detection by GLASS of short-lived isotopes in the reactor cover gas would be a positive indication of a fresh-element failure in the reactor core. All failed elements, however, do not leak short-half-life isotopes.

3.1.1.7. Charcoal-adsorber Vessel. A rupture or accidental leak during transfer of the contents of the distillation-column sump to the adsorption vessel could allow release of radioactive isotopes to the atmosphere. Radiological consequences would be less severe than those with the MHA presented in Sec. 4.4. (See Sec. 2.2.3 for an analysis of charcoal-adsorber rupture.)

3.1.2. Valve-position Failure

System design features that minimize the consequences of failure of a valve to open or close upon demand are primarily (a) monitoring of control parameters, (b) automatic CGCS isolation, (3) compressor shutoff, and (d) mechanical caps on all purge and sample lines not in use. All valves except the control, purge, tag-trap-system, and sampling valves have position switches that indicate whether the valve is open or closed. The consequence of single valve-position failure would generally be system upset; but, without the above-mentioned features, there is the possibility of radioactive isotopes being released to the atmosphere and of high or low argon pressure in the primary tank. Each group of valves is evaluated separately below.

3.1.2.1. CGCS Nozzle Isolation Valves HV-110 and -154. A failed-closed condition for either nozzle isolation valve causes alarms for low flow rate and mismatch of flow rate. The signal for mismatch automatically closes the isolation valves to completely isolate the CGCS and prevent high or low primary-tank argon pressure. Failure of either valve to close upon receipt of an isolation signal can be counteracted by remotely closing the appropriate isolation valves at the reactor-building containment (valves HV-149, -150, -210, -249). Failure of HV-110 or -154 to close upon system failure in the reactor building could result in release of cover gas to the reactor building.

3.1.2.2. Condenser Bypass Valve HV-114. Leakage through, or inadvertent opening of, the condenser bypass valve could eventually cause sodium-laden cover gas to plug the downstream filters. This condition is monitored by measuring the filter pressure drop. Switching to the alternative filter allows

continued CGCS operation. The position of HV-114 is displayed on the reactor-building control panel. This valve is manually operated and will be closed during operations in which condenser bypass is not required.

3.1.2.3. Condenser Discharge Valve HV-115. An inadvertent closing of this valve causes alarms for low flow rate and mismatch of flow rate, and consequently, automatic CGCS isolation.

3.1.2.4. Filter Isolation Valves HV-143 and -144. Inadvertent closing of either filter isolation valve, with its filter on stream, actuates alarms for low flow rate and mismatch of flow rate, and consequently results in automatic CGCS isolation. Leakage through, or inadvertent opening of, the valve of the filter on standby causes no hazard.

3.1.2.5. Flow-control Valves FCV-211, -247, -248, and -310. Malfunction of any flow-control valve is detected by corresponding instrumentation that indicates system upset. Alarms indicate high and low flow rates and mismatch of flow rate; if flow rate changes significantly, CGCS isolation results.

3.1.2.6. Compressor Isolation Valves HV-215a, -215b, -217a, and 217b. Leakage through these manually operated valves creates no hazard.

3.1.2.7. Distillation-column Isolation Valves HV-311a and -311b. A failed-closed condition of either distillation-column argon isolation valve at the cold box actuates alarms for low flow rate and mismatch of flow rate and leads to subsequent automatic isolation of the CGCS.

Failure of a valve to close on a manual signal for distillation-column isolation can be counteracted by manually closing the nozzle valves in the reactor building for isolating the CGCS. Although radioisotopes may migrate back into CGCS piping outside the cold box, the liquefied isotopes should remain in place, and no gas would be released to the atmosphere.

3.1.2.8. Cold-box Bypass Valve HV-328. Leakage through, or a failed-open condition of, the cold-box bypass valve allows part or all of the process feed-stream to bypass the distillation column, returning radioactive gas to the primary tank. This would be observed as a lack of gas activity (with normal CGCS operation). Detection by fission-product monitors in the primary-tank cover-gas system would alert operators to the upset condition.

3.1.2.9. Cold-box Waste-disposal Valve HV-340. Leakage through or a failed-open condition of, the isolation valve in the line connecting the cold-box atmosphere to the emergency exhaust system is of no consequence, except when a radioactive environment exists in the cold box. Such a situation is discussed in Sec. 3.1.7.

3.1.2.10. Distillation-sump Drain Valves HV-341 and -342. Leakage through, or a failed-open condition of, the sump drain valves could release radioactive gas to the CGCS-building atmosphere, which is filtered and directed to the site suspect-exhaust stack. Incorporated safety features include the connection of HV-341 to the adsorber and the use of a mechanical cap downstream of HV-342. Radiation monitors in the CGCS building and the building-exhaust system would detect HV-341 leakage.

3.1.2.11. Distillation-column Pressure-control Valve HV-313. Leakage through, or a failed-open condition of, the distillation-column pressure-control valve during normal operation could release cleaned argon gas to the adsorber. This would cause no hazard. A failed-closed condition of the valve, however, could prevent gas-pressure relief of the distillation column to the adsorber during a failure of the condenser cooling system, so the liquid inventory would vaporize. This could subject the adsorber to liquid radioisotopes or rupture the distillation-column rupture disk. Subjecting the adsorber to liquid would substantially reduce its effectiveness temporarily. Rupture of the distillation-column rupture disk would release radioactive gases to the cold box, but not to the environment.

3.1.2.12. Other Valves. Leakage through, or a failed-open condition of, any sample, purge, or drain valve is of minor consequence because of mechanical seals (caps) downstream of the valves.

3.1.3. Line Blockage

The most probable areas of line blockage are (a) between supply nozzle H-1 and the CTP condenser (including the supply line to the preheater and the sodium drain line from the condenser that contains trap ST-1), where sodium residue is present; (b) within the cold box, where cryogenic temperatures can freeze contaminants; (c) downstream of the adsorption beds of the primary and secondary xenon-tag-trap subsystems, where charcoal dust or particulates could collect; and (d) near the return nozzle R, where sodium residue from the primary-tank cover gas can collect. Line blockage causes a high pressure drop and reduction of flow rate. Consequences are not serious beyond CGCS shutdown and would not result in the release of radioactive gas to the environment.

Blockage within the main CGCS stream is monitored by pressure instrumentation and mismatch of flow rate. The system associated with sodium-aerosol-plugging identification includes instrumentation to monitor inlet pressure to the preheater, outlet pressure of the preheater, and outlet pressure of the CTP condenser. The section of the CGCS with cryogenic temperatures contains instrumentation to monitor inlet pressure to the regenerative heat exchanger, outlet pressure of the distillation column, and return-line pressure. Therefore, indication of line blockage is readily available.

Design features that reduce the possibility of sodium blockage are line heaters, relatively large pipes, and filters downstream of the CTP condenser. Other design features include filters for particulates in the return line from the primary and secondary adsorption beds, butt-welded joints, and long-radius elbows in the piping system.

3.1.4. Malfunction of Sodium-removal Subsystem

Malfunction of the sodium-removal subsystem results in the inability of the CTP condenser to remove sodium residue from the CGCS supply stream. A major release of sodium past the CTP condenser is detected by an increase in the pressure drop across the aerosol filters that trap the released sodium.

Air leakage into this portion of the system and subsequent sodium oxidation pose undesirable conditions, but the consequences are not serious, beyond ultimate system shutdown and possible addition of a small amount of sodium oxide to the primary tank.

Release of sodium oxide aerosol from the CTP condenser is detected by the increase of the pressure drop across the aerosol filters, where the aerosol would be trapped.

Air inleakage is also detected automatically by the chromatograph and O_2 analyzer. Solid sodium oxide could pass through the return line from the CTP condenser to the primary tank, or it could plug the return-line trap. Detection of air inleakage and the low rate of sodium oxide formation should allow ample time for system shutdown and CGCS isolation before significant sodium oxide forms.

3.1.5. Compressor Malfunction

Six metal-bellows compressors serve the cleanup portion of the system. Each compressor has an output of about 9×10^{-4} to 1.4×10^{-3} m^3/s (2 to 3 scfm) at about 200 kPa (30 psia). All six units are required to achieve the system design flow rate of 4.7×10^{-3} m^3/s (10 scfm). Two additional compressors serve the tag-trap portion of the system. Only one is needed to achieve the desired flow. Operation can continue at reduced flow if failures should occur.

All eight compressors are housed in a Class 3 containment vessel; therefore, any leakage due to bellows failure or system leakage would be contained. The 345-kPa (50-psia) compressor containment vessel can withstand the maximum pressure (about 235 kPa) that can be generated by the compressors. Individual compressor malfunction or failure is not a hazard. No hydraulic-oil or water-cooling systems are required for the compressors; therefore, no contamination from these sources is possible.

3.1.6. Malfunction of Adsorption System

Failure of the adsorption system is highly unlikely. However, if the transfer system malfunctions, the adsorption operation is terminated, the radioisotope contents remaining contained within the cold box or the distillation-column sump. The charcoal adsorber itself is isolated; thus, any activity within it is contained. Carryover of activity from the adsorber (which would be exhausted to the stack) is monitored continuously during the adsorption operation.

3.1.7. Malfunction of Distillation Column

If the distillation column malfunctions, xenon and krypton will not be stripped from the argon feed gas and maintained in the sump. Possible failures of the reboiler-level instrumentation, the heaters, the N_2 condenser, or the N_2-condenser flow control could result in system freeze-up or excessive boil-off. Upset or failure conditions are monitored by (1) flow indication, (2) temperature instrumentation at both the inlet and outlet of the distillation column and at the sump and condenser units, (3) liquid-level instrumentation at the sump, and (4) pressure instrumentation at the column outlet. The slow change of system parameters evident with well-insulated cryogenic systems allows time for manual shutdown and/or cold-box isolation. Normally, cryogenic temperatures within the cold box would be sustained and the radioisotope inventory contained until system operation is restored.

If cryogenic temperatures cannot be sustained within the cold box, radioactive material inside the distillation column and associated cold-box components is released either (1) manually to the adsorber, where it can be held indefinitely, or (2) automatically to the cold box through a rupture disk. The cold box is designed to hold the distillation-column inventory of radioisotopes in the sump plus the LN_2 inventory in the condenser, even at ambient temperature. If LN_2 continues to flow into the cold box at its normal rate, the internal pressure of the cold box will increase by about 140 kPa/h (20 psig/h). This can occur until the cold-box pressure equals the LN_2 supply pressure (about 275 kPa, or 40 psig). This pressure is well within the 690-kPa (100-psig) design pressure of the cold box. Contents of the cold box can ultimately be released through the adsorption system.

3.1.8. Malfunction of Xenon-tag-trap Subsystem

Consequences of postulated malfunction or failure of components in the xenon-tag-trap subsystem can be grouped as (a) degraded sampling operation and (b) inadvertent release of radioactive gas to the CGCS building, and then via the suspect-exhaust system to the site stack. The major components are evaluated separately below.

3.1.8.1. Xenon-tag-trap Adsorption Beds. Possible malfunctions of a tag-trap bed are plugging, streaming, or breakthrough. Plugging leads to reduced volume of samples. Streaming and breakthrough during sampling allow radioisotopes to pass through the bed, but there is little consequence other than a nonrepresentative sample, because the sampling flow is returned to the CGCS.

3.1.8.2. Leakage through Valves. Postulated leakage through a series of specific valves in the tag-trap system could release radioactivity to the site stack through the vacuum pumping system. However, the radiation monitor in the suspect-exhaust system of the CGCS building would alert operators to measurable leakage.

3.1.8.3. Cryopumping System. A postulated loss of cryopumping capability disrupts argon desorption from a secondary xenon-tag adsorber bed and precludes evacuating the sample vial. In both situations, the sampling routine ceases, but there is no hazard, because the collected radioisotopes could be returned to the CGCS.

3.1.8.4. Mass Spectrometer. Malfunction or failure of the CGCS mass spectrometer, which can monitor either the xenon-tag-trap sample or the CGCS supply stream, would be only an inconvenience. The collected sample from either the trap or the supply line can be placed in the sample vial for transfer to the laboratory for analysis.

3.1.9. Malfunction of Return-line Heater

Heater H-3 heats the CGCS return flow to essentially the temperature of the primary-tank cover gas, 315°C (600°F), before its return to the cover gas. A postulated malfunction or failure is detected and alarmed by an independent downstream temperature monitor. Because of lower gas temperatures, a heater failure could result in the increased formation of sodium aerosol residue in the cover gas in the vicinity of return nozzle R.

3.1.10. Malfunction of Gas Chromatograph and Oxygen Analyzer

A postulated malfunction or failure of the CGCS chromatographs and/or oxygen analyzers--which monitor the CGCS supply line, accumulator contents, and CGCS return line--jeopardizes monitoring for contaminants such as oxygen, hydrogen, helium, and nitrogen from inleakage. However, two chromatographs are used for redundancy, and the chromatographs for the primary-tank cover gas can back up the CGCS units. Two oxygen analyzers are dedicated to oxygen detection to minimize the potential quantities of oxygen and ozone that may accumulate in the distillation-column sump.

3.2. Loss of Support Systems

3.2.1. Liquid-nitrogen Supply

Liquid nitrogen (LN_2) is used continuously as coolant for the distillation column, intermittently as coolant for the adsorption beds in the xenon-tag-trap subsystem, and rarely as charcoal-adsorber coolant. Postulated failures of the LN_2 supply or system could be caused by delay in commercial delivery, pipe or vessel rupture, and valve failure. To ensure against supply failure, an LN_2 reserve sufficient for 4-5 days of system operation will be maintained. Postulated failures of LN_2 supply or system can cause (a) CGCS shutdown, (b) desorption or boil-off of contained radioisotopes, (c) nitrogen contamination of the CGCS and the primary-tank cover gas, and (d) release of radioactivity to the atmosphere. Cooling of the distillation column by LN_2 is monitored directly with temperature instrumentation in the distillation column and in the column outlet stream and indirectly by distillation-column pressure and level instrumentation. Manual CGCS shutdown and/or manual cold-box isolation are initiated upon evidence of system upset. Even without LN_2 cooling, isolation of the heavily insulated cold box should keep the concentrated radioisotopes liquid for several days. However, if LN_2 cooling cannot be reestablished, the contents of the distillation column would be manually released to the adsorber before ambient heating of the cold box and subsequent buildup of CGCS pressure caused automatic release through a rupture disk to the cold box.

Leakage of contaminated argon gas into the LN_2 system within the distillation column is considered highly unlikely. The argon gas in contact with the LN_2 condenser of the distillation column has been bubbled through the liquid inventory in the sump and scrubbed of contaminants as it passed through the column up to the LN_2 condenser. Also, pressure of the LN_2 system will be slightly higher than that of the argon portion of the system, so leakage would be N_2 into argon. If the LN_2 pressure fell below the argon pressure and a leak occurred, the LN_2 would flash to vapor, increasing its pressure, and again cause leakage to go from N_2 to argon. Nitrogen inleakage is monitored and alarmed by detection of nitrogen with the CGCS chromatograph, and the CGCS is shut down manually before large volumes of nitrogen can be fed into the primary-tank cover gas.

If, however, through an unforeseen mechanism the LN_2 becomes contaminated with radioactive argon, it would be detected by the suspect-exhaust radiation monitor in the CGCS building. The LN_2 is a once-through system and is not used for any purpose other than the CGCS. It is discharged through the suspect-exhaust system and cannot contaminate other systems.

Cooling by LN_2 of the primary and secondary xenon-tag-trap adsorbers is monitored with temperature instrumentation in the LN_2 cooling jacket and charcoal bed for each adsorber. Unplanned desorption from any bed is no

hazard, because the contents can be returned to the CGCS main stream. Consequences range from partial to total shutdown of the xenon-tag-trap subsystem and corresponding loss of sampling capabilities. Either inleakage of nitrogen to the argon or outleakage of argon to the nitrogen in the xenon-tag adsorbers can be postulated. Nitrogen inleakage is detected by the CGCS chromatograph, with subsequent CGCS shutdown. Argon outleakage could contaminate the N_2 system, which is exhausted to the suspect-air-exhaust system. Safety features in the N_2 cooling system include (a) relief valves and (b) the use of proven commercial storage and control equipment.

3.2.2. Electrical Power

Electrical power is required for operation of the compressors, heaters (on pipe lines, CTP condenser, distillation column, and return lines), cryopumps, automatically controlled valves, and auxiliary detector systems. With a power loss, the CGCS is automatically shut down and isolated. All power-operated valves fail closed, except the N_2 valves for the distillation-column cooling system. These valves fail open to allow manual control for continued cooling within the isolated cold box, if required, and to prevent overpressurization of the N_2 system during shutdown and subsequent heatup. The CGCS suspect-exhaust blower and radiation monitors have emergency power.

3.2.3. Instrument Air

Instrument air is required for valve operators and automatic control valves. All pneumatically operated valves, except those associated with LN_2 supply and return to the cold box and the cold-box bypass valve, are spring-driven-to-close valves. Thus, they automatically close on loss of instrument air. Loss of air automatically isolates the system. The LN_2 system for cold-box cooling remains in service.

3.3. Nonradioactive Contamination

Primary sources for nonradioactive contamination of the CGCS are air intake through compressor suction and LN_2 or Freon leakage through cooling coils.

3.3.1. Air

Leakage of air into the CGCS during operation at any point upstream of the compressors where system pressure is below atmospheric pressure could be postulated. Possible results before corrective action could be taken are (a) increased concentration of nitrogen in the primary-tank cover gas, (b) increased concentration of sodium oxide in the primary sodium coolant (also see Sec. 3.1.4), and (c) ozone buildup in the CGCS distillation-column sump. Air inleakage is detected by the chromatographs of the CGCS and primary-tank cover-gas systems, which operate continuously to detect nitrogen, oxygen, hydrogen, and helium, and the oxygen analyzers, which have a quoted detection sensitivity of ≤ 0.1 ppm.

The CGCS gas chromatographs test for impurities on a 6-min cycle, so the maximum time that air inleakage can occur without detection is 6 min. This would allow 1.7-3.4 m^3 (60-120 ft^3) of air into the CGCS (allowing for operator response time) if the full 4.7×10^{-3} m^3/s (10 scfm) of argon flow in the CGCS is replaced by air. The nitrogen in the air would pass through the distillation column as a noncondensible. Since the nitrogen is nonreactive with sodium, it would not be a safety problem. Conservatively assuming that the oxygen reacted completely to produce sodium oxide, about 1.85-3.7 kg (4.1-8.1 lb) of sodium oxide would be introduced into the system. This amount of oxides in the 325 m^3 (86 000 gal) of primary sodium would have a negligible effect. The oxygen analyzers monitor the argon gas stream continuously.

It is very unlikely, however, that 1.7 m^3 (60 ft^3) of air could leak into the system. This leakage would require a complete pipe break, with total argon flow replaced by air at the correct moment in the chromatograph cycle to avoid detection for 6 min.

Less severe air inleakage to the primary-tank cover gas would not result in oxygen being transported to the CGCS. The oxygen would react with the sodium vapor and be removed by the filter. For oxygen to reach the distillation column, a leak would have to occur in that portion of the CGCS line under vacuum (immediately upstream of the compressors). Such inleakage would be detected by the on-line oxygen monitors.

Sodium fires or explosions within the piping and vessel pressure boundaries as a result of air inleakage are highly unlikely. As shown in Table I, the cover gas normally contains about 10 ppm hydrogen and negligible amounts of oxygen. No mixture of hydrogen and oxygen in air at 0.1-0.2 MPa (1-2 atm) of pressure can propagate flame if it contains less than 4.9% oxygen or can cause an explosion if it contains less than 4.9% hydrogen,[8] and these limits should not be lower for an argon atmosphere.

Buildup of enough hydrogen or oxygen in the CGCS to allow a fire or explosion will not be possible because of the early detection of their presence in the cover gas and the lack of significant sources. Since no water is present in the sodium system, there is no source of radiolytic hydrogen or oxygen. Air inleakage is the most credible source of oxygen, but would add essentially no hydrogen to the system. However, air inleakage is detected by the chromatographs and oxygen analyzers of the CGCS and the primary tank so that the maximum buildup of oxygen in the distillation column will be less than 15 g (or 0.038% by weight of the sump contents after one year of 0.1-ppm O_2 inleakage) before detection. Hydrogen will not accumulate in the sump, since its boiling point is -253°C (-423°F). Thus, the concentrations of hydrogen and oxygen in the CGCS do not approach the required values for explosions or propagation of flame.

Since the cover gas normally contains negligible amounts of oxygen, formation of significant ozone in the distillation-column sump is also not credible under normal conditions. Assuming a constant inleakage of air that maintains a 0.1-ppm oxygen level within the CGCS supply stream, and assuming that all oxygen is converted to ozone, about 15 g of ozone could accumulate in the distillation-column sump during one year. This amount of ozone represents an O_3 concentration level of 312 ppm in the sump. Because ozone is soluble in liquid argon under the conditions in the sump, this amount of ozone does not represent a hazard to the distillation column. If the 15 g of ozone completely reacted to re-form oxygen, the reaction energy would be uniformly absorbed throughout the liquid argon, and the reaction would be isothermal. Sufficient argon could be vaporized to increase the distillation-column pressure to about 380 kPa (55 psia) (assuming the column is a closed volume of 0.03 m^3, or 1 ft^3). A detailed analysis of hazard potential due to ozone buildup appears in Appendix A.

To ensure against oxygen buildup to greater than 15 g in the distillation-column sump, the sump will be routinely dumped to the charcoal adsorber (see Sec. 2.2.3). Since assumed oxygen inleakage depends upon several variables (e.g., system operating time, system flow rate, and sensitivity of oxygen-monitoring instrumentation), no specific dumping interval has been determined. Rather, with no indicated oxygen ingress, dumps will be performed based on current operating conditions at a frequency that ensures that the 15-g limit is not exceeded. For example, an oxygen-detection sensitivity of 0.1 ppm--which is currently achievable--would require a dump after each year of operation. Instances of oxygen ingress would require whatever action is warranted to ensure that no more than 15 g of oxygen accumulates in the sump.

To preclude initial contamination by air, all piping and components exposed to air during shutdown or maintenance were purged with plant argon before CGCS startup.

3.3.2. Liquid Nitrogen

Leakage of nitrogen into the CGCS could be postulated wherever LN_2 cooling is used, e.g., in the distillation-column condenser and the xenon-tag-trap adsorbers. Probable results could be (a) increased concentration of nitrogen in the primary-tank cover gas; (b) CGCS upset, with decrease in system temperatures and possible line blockage; and (c) degraded xenon-tag sampling. Inleakage of LN_2 is monitored by the chromatographs in the CGCS and primary-tank cover-gas systems and by the temperature and pressure instrumentation of the CGCS.

3.3.3. Hydrocarbons

Less than 3 ppm of light hydrocarbons will be present as normal impurities in commercial argon. These hydrocarbons can be trapped in the

distillation column. If total trapping of these impurities in the distillation-column sump is assumed, about 2.6 g (6 mL) of hydrocarbons could be collected during one year of operation. This small amount would not degrade distillation-column operation. Furthermore, oxidation of these hydrocarbons to CO_2 and H_2O would not be expected in the absence of oxygen.

Heavy hydrocarbons could be introduced from dirty pipe and vessel surfaces, but required preventive maintenance and cleanliness during fabrication, installation, and maintenance should prevent their presence. If present, heavy hydrocarbons would generally deposit on heater and heat-exchanger surfaces or be trapped in the filters and charcoal adsorption beds.

To prevent the deposition of hydrocarbons in the primary tank, the CGCS was purged and filled with fresh argon, operated, and sampled extensively before connection with the primary-tank cover-gas system. Filters FL-3 and -4 in the lines returning argon to the cleanup system from the primary and secondary tag beds remove particulates from the argon before it enters the distillation column, where it is further cleaned up before returning to the primary tank. No requirement will be imposed beyond an occasional sample analysis for hydrocarbons during operation.

To monitor for the presence of hydrocarbon contamination in the cover gas, grab samples are routinely taken and an on-line hydrocarbon analyzer is provided. Grab samples of cover gas, which are analyzed in the laboratory, provide the most sensitive measurement. The on-line hydrocarbon analyzer does not have equal sensitivity, but would be effective in signaling a sudden increase in hydrocarbon contamination that may preclude continued CGCS operation.

The hazard potential due to hydrocarbon buildup is analyzed in Appendix A.

3.3.4. Charcoal Dust

Charcoal dust from any primary xenon-tag-trap adsorption bed is trapped in the particulate filter in the return line leading back to the CGCS. Charcoal dust from any secondary xenon-tag-trap adsorption bed is trapped in the particulate filters on the tag-trap return lines. Pressure-drop monitors for each filter detect excessive particulate collection.

3.3.5. Freon

The coils of the Freon cooling system for the eight CGCS compressors extend into the compressor containment. Therefore, a leak in the coils could cause the nitrogen atmosphere in the compressor containment to be contaminated with Freon. The nitrogen atmosphere will be continuously monitored by two Freon detectors, one on each end of the compressor containment vessel,

which will alarm on the indication of any measurable Freon concentration. The system will be manually shut down immediately after a Freon alarm. Freon contamination of the compressor containment would have no safety implications.

Freon could be introduced into the reactor cover gas if the Freon cooling coil failed simultaneously with the failure of a compressor bellows, a highly unlikely situation. Because of the multiple CGCS compressors, about 7×10^{-4} m^3/s (1.5 scfm) of the CGCS flow of 4.7×10^{-3} m^3/s (10 scfm) could be extracted from the compressor-containment region if one compressor bellows failed. The Freon leakage would be mixed into the containment nitrogen atmosphere before entering the cover gas, so only a small fraction of the 7×10^{-4} m^3/s would consist of Freon, and it would be further diluted in the 4.7×10^{-3} m^3/s of CGCS flow.

In addition to the Freon alarms, detection of this condition would be provided by the CGCS chromatographs finding the presence of nitrogen in the cover-gas flow. Because the boiling point of Freon is higher than that of argon, the Freon would be liquefied and removed from the cover-gas stream in the distillation column. Since the CGCS would be shut down in a very short time after the initiation of Freon leakage and the failure of a compressor bellows, an insignificant amount of Freon would be introduced into the cover gas, and its introduction would not affect reactor operation or safety.

3.4. Instrumentation and Control Malfunctions

Instrumentation and controls for process variables are monitored and alarmed by backup or diverse instrumentation, with more than one parameter used. Alarm circuits are independent of control circuits where necessary to provide a positive indication of control malfunction. The major process variables and associated controls are evaluated for safety in the following sections.

3.4.1. Temperature Control in Sodium-removal Subsystem

Malfunctions of the heater controls and associated temperature-monitoring system are alarmed by temperature instrumentation for the preheater and CTP condenser. Any breakthrough of sodium through the condenser is detected by an increase of pressure differential across the onstream aerosol filter. Failure of a heater control system would be detected and alarmed by temperature and pressure monitors located downstream of the condenser before the system could be damaged.

3.4.2. CGCS Flow Control

The principal area of safety concern with flow control is assurance that a mismatch between supply and return flow rates does not result in an undesirable increase or decrease in primary-tank cover-gas pressure.

Consequently, backup instrumentation and alarms and automatic CGCS isolation are provided as safety features, as noted below.

Malfunction of mainstream-flow control associated with flow controller FCV-310 is detected by alarms for high and low flow rates for flow transmitter FT-247 (bypass flow) and/or alarms for high and low flow rates for flow transmitter FT-248. (FCV and FT refer, respectively, to flow controllers and flow transmitters associated with valves of the same number as shown in Fig. 1.)

Malfunction of bypass-flow control associated with manually controlled FCV-247 is detected by alarms for high and low flow rates for mainstream flow and return flow and by an alarm for flow-rate mismatch. The CGCS is automatically isolated on excessive flow-rate mismatch.

Malfunction of supply-flow control associated with flow controller FCV-211 is detected by essentially all CGCS alarms for flow rate and pressure. Any malfunction that causes flow-rate mismatch or primary-tank cover-gas pressure to go beyond set limits isolates the CGCS automatically.

Malfunction of control of return flow associated with flow control valve FDCV-248 is also detected by essentially all CGCS alarms for flow rate and pressure. The ultimate safety features are automatic CGCS isolation on high or low pressure of primary-tank cover gas and mismatch of CGCS flow rate.

3.4.3. Compressor Control

Malfunction of the compressor control system and of the associated pressure-monitoring system is alarmed by independent pressure instrumentation upstream and downstream of the compressors. Subsequent changes in system flow rates are also monitored. Discharge pressure will not exceed 325 kPa (47 psia), the dead-head pressure for the compressors. Any resulting mismatch in CGCS flow rate or high or low pressure of primary-tank cover gas initiates CGCS isolation.

3.4.4. Distillation-column Control

A principal area of safety concern with distillation control is the assurance that sump boil-off and loss of LN_2 cooling do not result in an undesirable release of radioisotopes from the column. Consequently, backup instrumentation and alarms are provided as safety features.

A malfunction of condenser LN_2 flow control is detected by the independent temperature, pressure, and level instrumentation associated with the LN_2 system.

3.4.5. LN_2-coolant Supply and Exhaust Control

Malfunction of LN_2-coolant control is detected by temperature instrumentation in the distillation column and in each primary and secondary xenon-tag-trap adsorber. Excessive pressure is prevented by a pressure-relief valve and rupture elements throughout the LN_2 cooling system.

3.4.6. Xenon-tag-trap Flow Control

Malfunction of sample flow control results in an automatic program interruption. Inappropriate flow rates between a primary and secondary xenon-tag adsorption bed would affect the efficiency of sample collection by the secondary xenon-tag adsorber. However, no radiological hazard is evident, because any radioactive gas that passes through the adsorption bed would be returned to the CGCS.

3.4.7. CGCS-building Radiation Monitors

Several independent radiation monitors are provided for the CGCS system: (a) three totally independent gamma monitors on the argon-supply line to the compressors, (b) a monitor for gases in the CGCS-building suspect-exhaust system, (c) a monitor for gaseous and particulate radioactivity in the CGCS-building atmosphere, and (d) two area gamma monitors positioned for optimum CGCS-building surveillance. The gamma monitors on the argon supply line detect major fission-product release in the reactor; the others monitor primarily for personnel protection and system leakage in the CGCS building. All these monitors can provide automatic isolation of the primary-tank nozzle valves. These monitors, plus the site suspect-exhaust-stack monitor, provide sufficient redundancy. (Also refer to Sec. 2.2.2.)

3.5. Operator Error

The CGCS is essentially self-operating after startup, except for xenon-tag-trap sampling, and it should operate continuously with only periodic monitoring of system operating parameters. The most probable operator error would be associated with change-of-state operations, such as (a) CGCS startup and shutdown, (b) transfer of xenon-tag-trap samples, (c) switchover of parallel components, and (d) transfer of radioactive waste products from the distillation column. Only trained and qualified operators familiar with the CGCS will be involved with monitoring and operations, and they will be functioning in accordance with approved operating instructions and emergency procedures. Postulated conditions involving operator error are evaluated as follows for normal operation.

3.5.1. CGCS Startup and Shutdown

In normal startup of the CGCS, internal recirculating operation takes place before tie-in with the primary-tank cover-gas system. Premature tie-in

before pressure and flow are stabilized is prevented by the controls for mismatch of CGCS flow rate and the monitors for the pressure of the primary-tank cover gas. These controls and monitors automatically reestablish CGCS isolation if conditions are not acceptable for tie-in.

In normal shutdown of the CGCS, isolation occurs before shutdown of the compressors. Isolation ensures protection of the primary-tank cover-gas system from the CGCS system pressure that develops throughout the CGCS upon pressure equalization after compressor shutdown. A CGCS flow mismatch automatically isolates the CGCS upon compressor shutdown if the operator fails to do so.

3.5.2. Xenon-tag-trap Sampling

Obtaining xenon-tag-trap samples is essentially automatic after operator initiation, except for preparing the sample vial and the shield container for transport of a sample to the laboratory for analysis. This last operation involves disconnecting the sample vial from associated piping and is done under the surveillance of Radiation Safety personnel.

3.5.3. Switchover of Sodium-vapor Filters

The sodium-vapor filters are switched manually between on-line and standby positions. Inadvertent closure of the wrong isolation valve for the standby filter has no safety implications. Valve position is monitored by position-indicator lights at the reactor-building control station.

3.5.4. Switchover of Compressors

The switchover between on-line and standby compressors will be manual by operator action.

3.6. Interaction with Existing EBR-II Systems

Interactions between the CGCS and the existing EBR-II and ANL-W systems are evaluated as follows.

3.6.1. Primary-tank Cover-gas System

There is direct interaction between the primary-tank cover gas and the CGCS through primary-tank nozzles H-1 and R. The cover gas carries radioactive fission products and sodium vapor along with the argon. Sodium aerosol is removed by the CTP condenser and returned to the primary-sodium tank.

Although only cleaned argon is returned to the primary tank from the CGCS, properties of the gas returned are monitored to ensure its cleanliness.

The CGCS instrumentation will detect any abnormality through temperature, pressure, and flow monitors. In addition, two gas chromatographs continually sample the argon (on 6-min cycles) to detect helium, hydrogen, nitrogen, and oxygen.

Detection devices monitoring the reactor cover gas will also indicate CGCS failures through increased concentration of radioisotopes in the cover gas, or if air inleakage is involved, gas chromatographs will detect increases in concentration of hydrogen, nitrogen, or oxygen.

The result of returning argon from which radioisotopes had not been removed would be indicated as a lack of ability to reduce the radiation levels within the cover gas and a resultant increase in the reactor-building background radiation level. The consequences of such an increase would not be serious, and actions that could be taken to reduce cover-gas activity include isolation of the CGCS and reactor shutdown. The delay time associated with the detection of such an occurrence depends upon many parameters, such as CGCS flow rate and degree of cleanup accomplished by the CGCS. Additional fuel-element failures in the presence of high activity resulting from returning noncleaned CGCS gases would be detectable by GLASS because of the presence of short-lived isotopes in the reactor cover gas. Special radiation monitoring of the CGCS return line to the reactor building would also differentiate between CGCS malfunction and additional fuel-element failures. A normal return-line-activity reading that could be used for comparison has been established through periodic system surveillance.

The CGCS flow control provides equal supply and return flow rates to maintain a stable pressure in the primary-tank cover gas. Tolerances for flow mismatch were established by the adjustment capability of the floating-head tank that maintains a constant cover-gas primary tank. If these tolerances are exceeded, a CGCS signal for flow-rate mismatch automatically initiates CGCS isolation. As a backup safety feature, signals from pressure instrumentation for the primary-tank cover-gas system do the same.

Failures of CGCS components will have no significant effect on the cover-gas system, since the returning argon quality and/or flow rate would be affected and result in CGCS isolation.

All the CGCS LN_2 is outside the reactor building and cannot impinge on any reactor system. Also, in the event of a heatup of the LN_2 and liquid argon (LAr) in the cold box, the cold box will contain the resulting pressure until the gases can be vented through the adsorber.

The CGCS gases are essentially at atmospheric or subatmospheric pressure in the reactor building. Therefore, damage of essential reactor systems by pressure or impingement is highly unlikely.

Heater H-3 automatically heats the return gas to 315°C (600°F), the normal cover-gas temperature.

3.6.2. Plant Suspect-exhaust System

The ventilation-exhaust line for the CGCS building will connect to the existing reactor-building suspect exhaust outside the reactor building.

3.6.3. Safety System

The CGCS components that are part of the safety system (SS) include the four reactor-containment-building isolation valves (HV-149, -150, -210, and -249) plus the control circuitry to operate them. These valves and controls are included in the SS because they protect the public from any radioactive releases inside the reactor containment building. All CGCS isolation valves at the reactor containment building and primary-tank nozzles (HV-149, -150, -210, -249, -110, and -154) close upon any full-isolation signal for the reactor containment building, but none of the six isolation valves close on a partial-isolation signal. Existing circuitry for the full-isolation signal for the reactor containment building will be buffered to prevent any feedback into this system from the CGCS signals.

3.6.4. Data-acquisition System

The existing data-acquisition system (DAS) will be used to process CGCS instrumentation signals for indication and alarm and for relaying the processed information to local control stations. Any adverse interaction, such as inaccurate indication or failure to alarm, depends upon the reliability of the DAS. Failure of the DAS will not terminate CGCS operation, nor in any way compromise the safety of the system.

3.6.5. Other Utilities

Site electric power, emergency electrical power, EBR-II instrument air, and plant argon are used. Prevention of operational problems depends on the continuous availability of these utilities. System safety is not compromised by utility failure.

3.6.6. Fire Protection

The CGCS building is equipped with smoke detectors that provide alarm annunciation in the coded EBR-II site fire-alarm system if a fire occurs in the building. With this alarm system, Fire Department personnel are only about 1 min away. Portable fire extinguishers are in the CGCS building.

3.7. Alpha Contamination

To date, EBR-II operation with fuel containing breached cladding has not resulted in any sustained indication of plutonium in the primary sodium. In addition, no fissile material, no fission products other than xenon and krypton nuclides, no corrosion products, and no ^{24}Na activity have been detected in cover-gas samples (with sodium aerosols filtered out) taken during the operating history of EBR-II.[9]

This experience is parallel to that of the Dounreay Fast Reactor (DFR), since the DFR has never encountered problems from plutonium becoming airborne or contaminating equipment or work areas, even though many grams of plutonium have been released into the coolant.[10] The only situations in which alpha contamination of the EBR-II cover gas could occur would be during handling of irradiated and possibly alpha-contaminated fuel subassemblies in the fuel-unloading machine (FUM) and the fuel transfer port (FTP). Cover-gas contamination could occur in the extremely unlikely situation of a rupture or meltdown of a fuel subassembly in the FUM or during the "hold and blow" phase of fuel handling in the FUM and FTP, when alpha-contaminated sodium aerosols could be transferred to the cover gas. Because subassemblies in "hold and blow" will be sodium-wetted, any alpha contamination entering the FUM/FTP argon cooling during this period should be contained within sodium aerosols.

The probability for a fuel-subassembly-meltdown accident in the FUM has been analyzed.[11] Due to its low probability of occurrence, this accident can be reasonably discounted as a credible source of alpha contamination in the CGCS within the anticipated lifetime of EBR-II.

In the event that alpha-contaminated sodium particles are introduced into the FUM/FTP argon cooling during "hold and blow," they would first be transported to the primary-tank cover-gas region. Above the primary-tank sodium, the cover-gas volume is about 20 m^3 (700 ft^3) and contains about 8.5 m^3 of argon at standard conditions. After the sodium particles are introduced into the cover-gas space, the 30-min holdup time should cause a substantial portion of any particulates present in the argon to settle to the surface of the primary sodium before being entrained into the CGCS flow of 4.7×10^{-3} m^3/s (10 scfm).

Furthermore, the CGCS inlet nozzle from the primary tank (H-1) is about 7 m (22 ft) from the FTP, the location where argon cooling from the "hold and blow" cycle enters the primary tank. This distance further ensures that most of the particulates introduced into the cover gas through the FTP will settle to the surface of the primary sodium before reaching the CGCS inlet. The cover-gas region of the primary tank is disk-shaped and is about 0.4 m (1.33 ft) high and 8 m (26 ft) in diameter. This geometry provides a short vertical settling distance and a large settling area for particulates.

In the event that (a) alpha-contaminated sodium aerosols reach the CGCS inlet nozzle, (b) the CGCS is not isolated, and (c) sodium aerosols are entrained in the CGCS inlet argon flow, the sodium and alpha particles would be deposited on the inner surfaces of the piping between the H-1 nozzle and CTP condenser, on the preheater, on the Raschig rings and inner walls of the CTP condenser, and possibly in the aerosol filters immediately downstream of the condenser. Between the H-1 nozzle and the preheater, the argon will also be partially cleansed of particulates by the reflux of liquid sodium flowing back to the primary tank from the CTP condenser. No sodium aerosols, and therefore no alpha contamination, will be transported further into the CGCS than the aerosol filters.

Since all the components mentioned above are within the EBR-II containment building and are separated from the portion of the CGCS outside the containment by isolation valves in the event of an incident, alpha contamination does not represent a public hazard in any region of the CGCS located outside the containment building. In addition, because of the leak-tightness of the system, no on-site personnel exposure problem would result, unless maintenance activities were necessary that required the portion of the system within containment to be opened. In this event, very strict radiological personnel-protection procedures would be required, such as bag-in and bag-out procedures, wearing protective clothing, and the use of face masks with breathing-air supply.

4. EVALUATION OF POSTULATED ACCIDENTS

Safety evaluation of the CGCS as presented in Sec. 3 emphasizes the individual safety features to be incorporated. Four general-category accident conditions are postulated and evaluated in this section, with expected sequences, corrective action, and consequences. In addition, the capability of the CGCS to withstand the EBR-II design-basis accident (DBA) is discussed.

4.1. CGCS Emergency Shutdown with LN_2 Cooling Available

This condition results from a manual or automatic emergency shutdown of the CGCS. This situation could be caused by any of several CGCS malfunctions and failures previously postulated, such as loss of valve-position control, line blockage, instrumentation-and-control malfunction, and loss of electrical power.

Shutdown of CGCS would primarily be associated with an automatic or manual signal for CGCS isolation, whereby CGCS isolation valves HV-149, -150, -210, and -249 (at the reactor containment building) and/or HV-110 and -154 (adjacent to the primary-tank nozzles) will close. Normally the CGCS compressor-and-gas system in the CGCS building remains operating in the internal-recirculating mode until manual shutdown is accomplished.

Special operating procedures associated with high cover-gas and/or reactor-building activity guide the EBR-II Shift Supervisor in his decision concerning anticipatory reactor shutdown or power reduction on shutdown of the CGCS. (There are many conditions of reactor operation for which operation of the CGCS is not required or desirable.)

The distillation column is isolated manually by closure of valves HV-311a and -311b when the Shift Supervisor is assured, after operator surveillance of postshutdown conditions, that a long-term shutdown of the CGCS will be necessary for maintenance.

With the distillation column isolated and with sustained LN_2 cooling, the concentrated radioisotope inventory within the column remains liquid.

With the CGCS isolation valves closed, the primary-tank cover-gas system is protected from the CGCS pressure.

4.2. CGCS Shutdown with Coincident Loss of LN_2 Cooling

This condition, with loss of LN_2 cooling of the distillation column, is unlikely. If it were to occur, the CGCS would be shut down manually or automatically, as evaluated in Sec. 4.1. The LN_2 system has two 22.7-m^3 (6000-gal) supply tanks to maximize reliability.

Even without LN_2 cooling, isolation of the heavily insulated cold box should keep the concentrated radioisotopes liquid in the column sump for several days, so there would be ample time for corrective action. In the unlikely event that LN_2 cooling cannot be reestablished, heatup within the cold box and subsequent buildup of pressure in the CGCS would occur, but be contained. The cold-box contents would be manually released from the distillation column to the charcoal adsorber, or, for the worst case, automatically released from the distillation column through a rupture disk to the cold-box interior if an unforeseen pressure buildup occurs. In the former case, radioisotopes are adsorbed by the charcoal bed. In the latter, the radioactive material remains within the cold box. Consequently, there would be no uncontrolled release of radioactivity to the atmosphere in either situation.

One possible undesirable consequence that has been evaluated is the increase of radiation level inside the CGCS building when the center of the radioactivity is moved from the sump to the center of the cold box. This increase could amount to a factor of about five, based solely on geometric considerations, but sufficient shielding is provided to prevent a personnel-exposure problem. Scoping calculations indicate that one day of decay would reduce by more than five times the radiation level at the time of CGCS shutdown. Thus, after one day of decay, the radiation level within the CGCS building due to radioisotopes dispersed evenly in the cold box would be less than that during normal CGCS operation.

Any radioactive material in the cold box is ultimately discharged to the charcoal-adsorber system, under strict radiological and administrative control. The charcoal adsorber holds the radioisotopes for long-term decay. It does not require LN_2 cooling to retain fission gases or to maintain pressure within acceptable limits.

Therefore, CGCS shutdown with a postulated loss of LN_2 cooling would result in no uncontrolled release of radioactivity to the atmosphere.

4.3. Major Fission-product Release from Reactor

A major release of fission products from the reactor resulting from a postulated core meltdown or massive fuel failure, neither of which causes loss of primary-tank integrity (these occurrences are of less severity than the DBA), would result in much higher concentrations of radioisotopes in the primary-tank cover gas; the CGCS might therefore be subjected to radioisotope concentrations above its design value, if its isolation valves were not closed. The higher concentrations would reduce system efficiency and substantially increase radiation levels, but no release to the atmosphere would occur. Temporary shielding or limited access may be required for this type of operation.

Three independent gamma-radiation monitors are provided to protect the CGCS from such an occurrence. Located in the valve box between the

CGCS building and the reactor building, they provide automatic isolation of the CGCS at the reactor containment building and primary-tank nozzles when two of the three monitors reach a preset trip level. Manual override of the trip signal allows cleanup of the cover gas to continue at acceptable rates (see Sec. 2.2.1.3) if advantageous to overall plant safety.

4.4. CGCS Maximum Hypothetical Accident

The maximum hypothetical accident (MHA) postulated for the CGCS is the complete release to the atmosphere of the complete inventory of radioactive noble gas and 1% of the inventory of particulate daughter products in the CGCS building. This highly unlikely multiple failure relates to a postulated rupture of the distillation column, coincident rupture of the cold box and the charcoal-adsorber containment, and simultaneous failure of the CGCS suspect-exhaust system. Automatic CGCS isolation occurs upon a signal for mismatch of CGCS flow rate. Thus, the radioactive noble gas in the reactor building would not be included in this atmospheric release.

The inventory assumed to be released during the MHA was 200 TBq (5400 Ci). Figure 3 shows the calculated 2-h whole-body dose for the MHA as a function of distance between the receptor and the CGCS building. The curve for the INEL site shows that the 2-h whole-body dose would be about

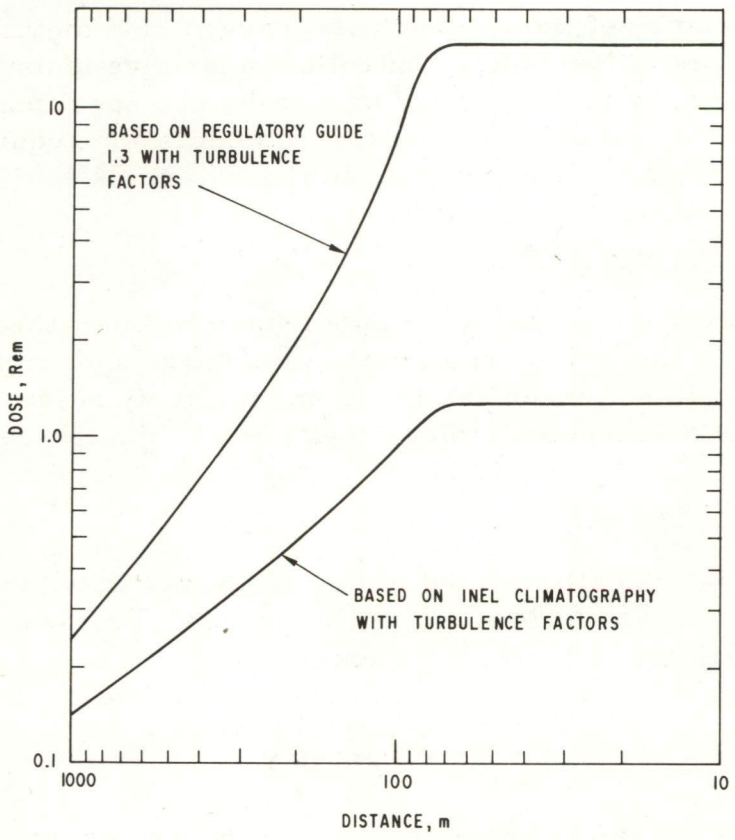

Fig. 3. Calculated 2-h Whole-body Dose for Postulated CGCS Maximum Hypothetical Accident (MHA)

0.45 Rem at the exclusion-area radius of 600 m, which is significantly less than the 25-Rem limit given in 10 CFR 100 for accidental releases. An operator 10 m from the CGCS would receive a dose of 16 Rem, still below the limits of 10 CFR 100. The detailed dose calculations appear in Appendix B.

4.5. EBR-II Design-basis Accident

The design-basis accident (DBA) hypothesized for EBR-II was calculated to result in a pressure to the top structure of the primary tank of no greater than 263 kPa (38.2 psia) for a time of no more than 2 ms.[12,13] Outside the reactor containment building, the minimum design pressure in the CGCS is 345 kPa (50 psig). (This is the pressure for the compressor containment.) Integrity of the CGCS is therefore not endangered by the assumed DBA. Note also that the CGCS would be isolated from the containment building upon the occurrence of the DBA.

5. REVISIONS TO PRACTICES AND DOCUMENTATION

5.1. Technical Specifications

The basic limits derived from these safety analyses have been implemented as two new sections of the EBR-II technical specifications. Specific limits on the inventory of fission products, oxygen, and methane are established. Fission-gas effluents are controlled, and valve isolation of the CGCS under specified conditions is ensured by a technical-specification requirement. Since the CGCS is an entirely new system, its operation requires the application of additional, rather than revised, limits.

5.2. Administrative Controls

Administrative controls are implemented by operating procedures that specify operator action. The argon-cover-gas purge system formerly used to control activity in the cover gas is administratively restricted to be used only when the CGCS is not available.

5.3. Hazard Summary Report

No material directly related to the CGCS was listed in the Hazard Summary Report[12] or its Addendum.[13] The present document is an extension, rather than a revision, of those documents.

6. SUMMARY

No significant safety hazard will result to the general public from normal conditions or postulated abnormal and accident conditions in the CGCS. All postulated releases of radioactivity fall within the requirements of U. S. Regulation 10 CFR 100. Calculated exposures resulting from the assumed

maximum hypothetical accident (MHA) are less than 2% of the 25-Rem limit of 10 CFR 100 at an exclusion-area radius of 600 m. This radius is conservative relative to the minimum 5000-m radius to the site boundary of the Idaho National Engineering Laboratory (INEL). Total containment is not required, because an assumed rupture of the uncontained CGCS does not require an increase in exclusion radius. The maximum hypothetical accident (MHA) is postulated as (1) rupture of the distillation column and the charcoal adsorber, which contains the removed fission-product inventory; (2) rupture of the cold-box containment, which surrounds the distillation column; and (3) subsequent release of the inventory of accumulated or contained fission products to the atmosphere.

In addition, on-site personnel will not be exposed to any significant safety hazard during normal or abnormal conditions in the CGCS. Operator safety during normal conditions will be ensured by system design features and operating procedures consistent with EBR-II operating instructions and safety requirements. During abnormal or accident conditions, the on-site exposure resulting from the MHA, 10 m from the CGCS building, is less than 64% of the 25-Rem limit of 10 CFR 100.

APPENDIX A

Calculation of Hazard Potential due to Buildup of Oxygen, Ozone, and Methane in CGCS Sump

1. Introduction

This appendix analyzes the hazard potential due to buildup of methane (CH_4), oxygen (O_2), and ozone (O_3) in the cryogenic sump of the CGCS.

2. Summary of Analysis

Since methane is present in the reactor cover gas, it will be drawn into the CGCS system, where it will be trapped in the cryogenic sump.

During one year of CGCS operation, about 2.6 g (6.0 mL in liquid phase) of methane could accumulate in the CGCS sump. This amount would give a CH_4 concentration of 160 ppm in the sump liquid. During normal operation of the CGCS, no O_2, and therefore no O_3, would be introduced into the distillation column. Oxygen in the primary cover gas should react with sodium aerosols and penetrate the CGCS only as far as the CTP condenser or filters.

Air inleakage to the subatmospheric portion of the CGCS is the only postulated method for O_2 to enter the distillation column and be trapped in the sump. The CGCS has welded piping and bellows-sealed valves, but air inleakage can still be postulated. If a continual 0.1-ppm oxygen inleakage is assumed, 15.0 g of O_2 could be trapped in the sump (which contains 39 kg of argon) during one year of operation with a 70% plant capacity factor. In the presence of radioisotopes, this amount of O_2 may be ionized by the decay energy of fission products in the sump and converted to O_3. The 320 ppm of O_3 that would then be in the sump would be completely soluble in the sump argon and uniformly dispersed throughout the sump.

If only CH_4 is concentrated in the sump, then no hazard exists for a one-year operating period. If O_3 is also built up in the sump, then it is postulated that the O_3 completely and instantaneously reverts to O_2 and further combines with the CH_4 present. This reaction liberates 1.75×10^5 J (4.15×10^4 cal) of heat that, because of the complete solubility of O_3 in argon, will cause isothermal boiling of argon throughout the sump volume. The vaporized argon will increase sump pressure to 9.0 atm (133 psia), which does not exceed the 10.1-atm (150-psia) design pressure of the column. Thus, it is concluded that, for the maximum possible accumulation of CH_4 and O_3 in the cryogenic sump of the CGCS, instantaneous and total release of the stored energy in the O_3 and CH_4 will not result in a pressure that exceeds the design limits for the sump and column.

We have analyzed the potential hazard of an O_3 reaction in an off-gas adsorber bed during a dump of the distillation-column-sump contents to these

beds. The large heat capacity of the adsorber-bed charcoal and the long duration of the sump dump (about 1 h) will easily distribute the energy release from reversion and complete combustion of 15 g of O_3.

3. Methodology

3.1. Consultation

EBR-II has had no experience in the operation of cryogenic systems in the presence of ionizing radiation. However, Allied Chemical Corporation has operated a somewhat similar system on the INEL site. Dr. Robert Hammer of Allied Chemical was invited to EBR-II to discuss the company's experience with CH_4 and O_3 and to review these aspects of the CGCS design. The following paragraphs summarize the information gathered in this meeting.

Allied Chemical has a cryogenic distillation column similar to the CGCS column, and Dr. Hammer discussed the amounts of CH_4 and O_3 they have measured in their system. (Their sump liquid is composed mainly of xenon rather than argon, and the sump volume varies from 2 to 10 L, or 35% or less than the CGCS volume.) The Allied Chemical system has a 14.2-L/s (30-scfm) stream containing about 1.33 ppm CH_4; therefore 2.32 g of CH_4 could accumulate in the two days before the sump liquid is changed. Dr. Hammer indicated that, for a substantial time, the Allied Chemical system had about 50 g of O_3 in the sump. The system is now emptied at two-day intervals so that less than 2 g of O_3 may accumulate in the sump (compared to 15 g of O_3 out of 39 kg total contents in the CGCS sump, or 0.04 wt % after one year). During the entire history of the Allied Chemical system (it began operation in the 1950's), there has never been an observable explosion. Therefore, Allied Chemical has operated a cryogenic distillation column for several years with both CH_4 and O_3 present in the sump and has never had operational or safety problems caused by their presence. The O_3 concentrations in the sump were much larger at times than are possible in the CGCS.

Dr. Hammer examined the CGCS design and the potential amounts of CH_4 and O_3 that could accumulate in the sump during one year of operation. He concluded that the amounts involved were small and that no problems should result if the O_3 remained at concentrations at which it is completely soluble in the argon.

3.2. Methane Accumulation in CGCS Distillation-column Sump

The CH_4 accumulation in the CGCS distillation-column sump may be calculated by comparing the CH_4 concentration in the cover gas and the gas-purge rate for current EBR-II operating conditions with those expected while the CGCS is in operation. A CH_4 mass balance on the EBR-II primary-cover-gas system gives the following:

Rate of change of CH_4 mass = source rate - leak rate (purge), or, in equation form,

$$V\frac{dC}{dt} = S - FC, \qquad (1)$$

where

V = cover-gas volume, 8490 L (300 ft^3) STP,

F = cover-gas purge rate, L/s STP,

C = concentration of CH_4 in cover gas, g/L STP

and

S = CH_4 source rate, g/s.

On the average, the CH_4 concentration in the EBR-II cover gas is about 3 ppm under equilibrium conditions. The cover gas leaving the system goes either to the reactor building by seal leakage or to various gas-monitoring systems and then up the stack in the following quantities:

Seal leakage	10.7 mL/s
GeLi detectors	6.71
Chromatographs	1.3
Fission-gas monitor	1.3
GLASS II	18.3
	38.3 mL/s

Under steady-state, equilibrium conditions, the CH_4 concentration in the cover gas is constant; therefore,

$$\frac{dC}{dt} = 0$$

and

$$S = FC. \qquad (2)$$

The CH_4 source rate for EBR-II cover gas, S, may now be calculated, since F and C are known under equilibrium conditions without the CGCS in operation. The calculation gives

$$S = 38.3\frac{mL}{s} \times 3 \times 10^{-6}\frac{L\ CH_4}{L} \times 10^{-3}\frac{L}{mL}$$

$$= 1.15 \times 10^{-7}\frac{L\ CH_4}{s},$$

or, on a mass basis,

$$S = 1.15 \times 10^{-7} \frac{\text{L } CH_4}{\text{s}} \times \frac{1 \text{ g·mol}}{22.4 \text{ L}} \times 16.04 \frac{\text{g}}{\text{g·mol}}$$

$$= 8.23 \times 10^{-8} \frac{\text{g } CH_4}{\text{s}}.$$

Now consider operation of EBR-II with the CGCS also in operation. Under equilibrium conditions,

$$V\frac{dc}{dt} = 0 = S - FC \text{ as before, and}$$

$$C = \frac{S}{F}. \qquad (2')$$

In this case, F will be 4.72 L/s (10 scfm), the CGCS design flow rate. (Conservatively assume that there is no other possible gas purge, since the EBR-II seal leakage is being reduced and the gas-monitoring systems could be modified so that the gas is returned to the primary-cover-gas system rather than sent up the stack.) The CH_4 source rate, S, should remain at the same level as before CGCS operation. The CH_4 concentration in the cover gas with the CGCS operating is then

$$C = \frac{1.15 \times 10^{-7} \text{ L } CH_4/\text{s}}{4.72 \text{ L/s}}$$

$$= 0.024 \text{ ppm } CH_4.$$

The reduction in CH_4 concentration in the cover gas resulting from the CGCS is

$$\frac{\text{C with CGCS}}{\text{C without CGCS}} = \frac{0.024 \text{ ppm}}{3.0 \text{ ppm}} = 8 \times 10^{-3}.$$

Thus, the operation of the CGCS reduces the CH_4 concentration by a factor of 125.

The amount of CH_4 accumulating in the CGCS distillation-column sump annually may now be computed. This may be expressed as

$$A = V(C_0 - C_f) + St, \qquad (3)$$

where

A = CH_4 accumulation, g,

V = cover-gas volume = 8490 L (300 ft^3) STP,

C_0 = initial CH_4 concentration in the cover gas

$$= 3.0 \times 10^{-6} \frac{\text{L } CH_4}{\text{L}} (3 \text{ ppm}),$$

C_f = equilibrium concentration of CH_4 = $2.4 \times 10^{-8} \frac{\text{L } CH_4}{\text{L}}$ (0.024 ppm),

S = CH_4 source = $8.23 \times 10^{-8} \frac{\text{g } CH_4}{\text{s}}$,

and

t = time = 1 year.

The CH_4 accumulation in one year is therefore equal to

$$A = 8490 \text{ L gas}(3.0 - 0.024) \times 10^{-6} \frac{\text{L } CH_4}{\text{L}} \times \frac{16.04 \text{ g}}{22.4 \text{ L}} + 8.23 \times 10^{-8} \frac{\text{g } CH_4}{\text{s}}$$

$$\times 3.15 \times 10^7 \text{ s/yr} \times 1 \text{ yr} = 2.6 \text{ g } CH_4 (\text{or } 5.7 \times 10^{-3} \text{ lb}_m \text{ } CH_4).$$

In liquid phase, this amount of CH_4 will occupy 6.0 mL.

3.3. Accumulation of Oxygen and Ozone in CGCS Distillation-column Sump

Oxygen (O_2) may be postulated to enter the CGCS gas feed stream by air inleakage to the subatmospheric portion of the system. The cover gas leaving the EBR-II primary tank should not be a source of O_2, because O_2 reacts with sodium vapors in the primary cover gas. Once the O_2 enters the CGCS distillation column and then enters the sump, it will be exposed to ionizing radiation from the fission products in the sump liquid argon. This exposure may result in the formation of O_3.

First, consider the amount of O_2 that may accumulate in the sump in one year. It is assumed that the sensitivity of the CGCS oxygen chromatograph is 0.1 ppm O_2 and that air is inleaking at a rate sufficient to provide 0.1 ppm O_2 in the 4.72-L/s (10-scfm) CGCS feed stream of cover gas. (Only 0.0023 mL/s of air is required to provide 0.1 ppm O_2.) The O_2 accumulation is

$$O_2 = 4.72 \text{ L/s} \times 0.1 \times 10^{-6} \frac{\text{L } O_2}{\text{L}} \times \frac{1 \text{ g·mol}}{22.4 \text{ L}} \times \frac{32 \text{ g}}{\text{g·mol}} \times 3.15 \times 10^7 \text{ s/yr}$$

$$= 21.2 \frac{\text{g}}{\text{yr}} O_2 \text{ (for an EBR-II plant capacity factor of 100\%).}$$

For a plant capacity factor of 70% for EBR-II and the CGCS, the O_2 accumulation will be 15.0 g in one year (13.0 mL O_2 liquid). For conservatism, it is assumed that all the O_2 will be retained in the sump (i.e., the distillation-column efficiency will be 100% for O_2).

Once the O_2 is present in the sump, it is postulated to be completely converted to O_3 by the fission-product ionizing radiation. Reference 14 gives a correlation for the G value of O_3 (the number of O_3 molecules formed per 100 eV absorbed). The correlation is

$$G(\epsilon) = 12.5\epsilon + 8.05 + 1.29 \log_{10} \epsilon \frac{\text{molecules}}{100 \text{ eV}}, \tag{4}$$

where

ϵ = the electron fraction for O_2 in the O_2-N_2 mixture.

If the correlation is valid for an O_2-Ar mixture, the maximum amount of O_3 that may be produced in the CGCS sump per year may be calculated with it. With a 0.1-ppm O_2 inleakage, the fraction of O_2 molecules will vary from 0 to 4.7×10^{-4} (235 ppm) over a one-year period. The electron fraction is then

$$\epsilon = \frac{\text{number } O_2 \text{ electrons}}{\text{total number electrons}} = \frac{NO_2}{NO_2 + NAr}, \tag{5}$$

where

$NO_2 = 16f$ = number of O_2 electrons,

$NAr = 18(1 - f)$ = number of argon electrons,

and

f = fraction of O_2 electrons = 2.35×10^{-4}.

Therefore,

$$\epsilon = \frac{16 \times 2.35 \times 10^{-4}}{16 \times 2.35 \times 10^{-4} + 18(1 - 2.35 \times 10^{-4})},$$

$$= 2.1 \times 10^{-4}$$

and

$$G(\epsilon) = 12.5 \times 2.1 \times 10^{-4} + 8.05 + 1.29 \log_{10}(2.1 \times 10^{-4})$$

$$= 3.3 \frac{\text{molecules } O_3}{100 \text{ eV absorbed}}.$$

The ionizing power in the CGCS sump must now be determined. Table XI lists the equilibrium CGCS fission-product inventories and average energies for the three main sections of the CGCS. Since xenon and krypton comprise most of the radioactive sump nuclides, the energy for the ionizing radiation may be computed from the following:

	Inventory, Ci (TBq)	Energy, MeV/dis		
		Gamma	Beta	Total
^{133}Xe	3029 (112.3)	0.081	0.346	0.427
^{135}Xe	938 (34.7)	0.25	0.92	1.17

When both gamma and beta energy are considered, the average rate of decay-energy emission is

$$\frac{0.427 \times 3029}{3029 + 938} + \frac{1.17 \times 938}{3029 + 938} = 0.6 \frac{\text{MeV}}{\text{dis}}$$

and

$$5000 \text{ Ci} \times 0.6 \frac{\text{MeV}}{\text{dis}} \times 3.7 \times 10^{10} \frac{\text{dis/s}}{\text{Ci}} = 1.1\ 10^{14} \frac{\text{MeV}}{\text{s}}.$$

For beta radiation only, the average rate of energy emission is 7.1×10^{13} MeV/s.

The maximum possible O_3 production rate in the sump if all beta energy is absorbed is

$$7.1 \times 10^{13} \frac{\text{MeV}}{\text{s}} \times 3.3 \frac{\text{molecules}}{100 \text{ eV}} O_3 \times 10^6 \frac{\text{eV}}{\text{MeV}} = 2.3 \times 10^{18} \frac{\text{molecules}}{\text{s}} O_3,$$

or on a mass basis, in one year,

$$2.3 \times 10^{18} \frac{\text{molecules}}{\text{s}} O_3 \times \frac{1 \text{ g·mol}}{6.023 \times 10^{23} \text{ molecules}} \times 48 \frac{\text{g}}{\text{g·mol}}$$

$$\times 3.15 \times 10^7 \frac{\text{s}}{\text{yr}} \times 1 \text{ yr} = 5.77 \text{ kg } (12.72 \text{ lb}_m) O_3.$$

This assumes an unlimited supply of O_2 for conversion to O_3 and the presence of 12 leakers in the EBR-II core to produce the required ionizing power. Since this is a much larger amount of O_2 than can be postulated to enter the CGCS sump, it is assumed that the entire 15.0 g of O_2 introduced by the 0.1-ppm inleakage is converted to O_3 in the sump and is present in the form of a liquid. Under those conditions, the argon sump would contain 320 ppm O_3.

TABLE XI. CGCS Fission-product Inventories and Average Energies

Isotope	Inventory, Ci				Energy, MeV/dis		
	CGCS Outside Cold Box	CGCS in Cold Box	Sump	Total	Gamma	Beta	Total
^{23}Ne	-	-	-	Negligible	-	-	-
^{41}Ar	-	-	-	Negligible	-	-	-
^{83m}Kr	10.1	1.63	68	79.7	0.041	0	0.041
^{85m}Kr	14.5	2.35	227	243.9	0.186	0.27	0.46
^{85}Kr	-	-	136[a]	136	0.007	0.22	0.227
^{87}Kr	45.4	7.3	208	260.7	1.06	1.05	2.11
^{88}Kr	23.4	3.8	230	257.2	1.74	0.66	2.40
^{89}Kr	64.3	10.4	12	86.7	0.39	1.53	1.92
^{90}Kr	28.1	4.6	0.9	33.6	0.85	1.52	2.37
^{88}Rb	0.23	0.04	2.3	2.6	1.22	1.52	2.74
^{89}Rb	0.64	0.10	0.12	0.9	2.39	0.60	2.99
^{90}Rb	0.28	0.05	0.01[b]	0.34	1.85	2.2	4.05
^{89}Sr	0.64	0.10	0.12	0.9	0	0.58	0.58
^{90}Sr	0.28	0.05	0.01[a]	0.34	0	0.20	0.20
^{131m}Xe	0.02	-	15	15	0.164	0	0.164
^{133m}Xe	0.29	0.05	57	57.3	0.233	0	0.233
^{133}Xe	6.9	1.1	3029	3037	0.082	0.115	0.197
^{135m}Xe	20.4	3.3	19	42.7	0.564	0	0.564
^{135}Xe	29.3	4.7	938	972	0.261	0.31	0.571
^{137}Xe	46.8	7.6	11	65.4	0.97	1.31	2.28
^{138}Xe	55.6	9.0	46	110.6	0.56	0.8	1.36
^{139}Xe	13.2	2.1	0.5	15.8	0.73	1.53	2.26
^{140}Xe	4.1	0.7	0.1	4.9	0.8	0.29	1.09
^{137}Cs	0.47	0.08	0.014[b]	0.56	0.62	0.19	0.81
^{138}Cs	0.56	0.09	0.46	1.11	2.14	0.87	3.01
^{139}Cs	0.13	0.02	0.01	0.16	0.64	1.33	1.97
^{140}Cs	-	-	-	Negligible	-	-	-
^{140}Ba	-	-	-	Negligible	-	-	-
^{140}La	-	-	-	Negligible	-	-	-
Total	365.8	59.2	5000.6	5425.6	-	-	-

[a]After 10 years of operation at 60% capacity factor. Inventories for all other fission products are at equilibrium.

[b]Includes all components within the CGCS building, but the daughter products are 1% of total inventory, according to the MHA definition.

3.4. Estimation of Solubility of Liquid Ozone in Liquid Argon

The following calculations and discussion describe the method of estimating the solubility of O_3 in the argon (Ar) in the sump of the CGCS.

The operating temperature of the CGCS sump is -182°C (-295.6°F); this is 3.8°C (7.0°F) higher than the boiling point of Ar at standard pressure, -185.8°C (-302.4°F). The boiling temperature is higher in the CGCS because the system is slightly pressurized above ambient.

A computerized literature search by the National Bureau of Standards did not uncover any measured data on the solubility of O_3 in Ar. We therefore had the options of calculating the solubility levels or setting up a test to make the measurements. Consultation on the subject with Dr. Hildebrand,[15] an expert in the field, indicated that, if pursued in the proper way, a calculated estimate of the solubility of O_3 in Ar should yield a reliable estimate of the solubility limit. Dr. Hildebrand further suggested that, because the solubility characteristics of O_2 and Ar are similar, a good way to determine the solubility of liquid O_3 in liquid Ar would be to use the theoretical relationship developed for liquid-liquid solubility to estimate O_3-Ar solubility from existing experimentally measured O_3-O_2 solubility data. He indicated that an estimate obtained in this manner would be considerably more accurate than an estimate made from calculation alone. The following discussion covers the method used to estimate the solubility of O_3 in Ar from the theoretical solubility relationships and the experimentally measured solubility data for O_3 in O_2.

From Hildebrand et al.,[16] p. 173, the general relationship governing liquid-liquid solubility is

$$RT \ln(a_j/x_j) = v_j \varphi_i^2 (\delta_j - \delta_i)^2, \qquad (6)$$

where

R = molar gas constant, 1.99 cal/K·g·mol,

T = temperature, K,

a_j = activity of liquid j,

x_j = mole fraction of liquid j,

v_j = molal volume of liquid j, cm^3/mol,

φ_i = volume fraction of liquid i,

δ_i = solubility parameter for liquid i $(cal/cm^3)^{1/2}$,

δ_j = solubility parameter for liquid j $(cal/cm^3)^{1/2}$,

and

i, j = the two liquid components.

Equations of this form exist for each component i and j of the solution and each phase A and B of the solution when more than one phase is present.

The solubility parameters, δ, for this calculation are best determined from the relationship (p. 207 of Ref. 16)

$$\delta_i = \left(\frac{\Delta H^v_{bi} - RT}{v_{bi}} \right)^{1/2}, \tag{7}$$

where

H^v_{bi} = heat of vaporization of liquid i at its boiling temperature

and

v_{bi} = molal volume of liquid i at its boiling temperature.

This form of the solubility relationship permits the solubility parameter δ_i to be adjusted to the first order to the Ar-boiling-point temperature in the CGCS. Hildebrand points out (p. 207 of Ref. 16) that to seek high precision in the term $(\delta_j - \delta_i)^2$ is a waste of effort, but that the term should be evaluated in a consistent way. Thus, the solubility parameters will be evaluated only at the Ar boiling point in the CGCS, and these values will be used over the temperature range (78-93 K) investigated. That this is an acceptable approximation can be clearly seen from Eq. 7, where it is evident that ΔH^v_{bi} is the dominant parameter of the numerator. A second approximation is made by assuming

$$v^{CGCS}_{bi} \simeq v_{bi} \simeq v^0_{bi},$$

where

v^{CGCS}_{bi} = molal volume of liquid i in the CGCS at the CGCS boiling temperature

and

v^0_{bi} = molal volume of the liquid i at its boiling point in the pure state.

This approximation is good for nonelectrolyte solutions (see p. 11, Ref. 16) and will introduce negligible error when used for such solutions.

The solubility parameters, δ_i, for O_2, Ar, and O_3 were calculated at the CGCS temperature of 91.3 K from Eq. 7 and compiled in Table XII. For comparative purposes, the table also gives the solubility parameters at the normal boiling point of the pure liquid at standard pressure.

TABLE XII. Solubility Parameters (δ_b) for O_2, Ar, and O_3 and Data Used to Calculate Them

	ΔH_b,[a] cal/mol	v_b,[a] cm^3/mol	δ_b,[b] $(cal/cm^3)^{1/2}$	δ_b^{CGCS}, $(cal/cm^3)^{1/2}$
O_2	1630	27.9	7.21	7.20
Ar	1550	28.6	6.94	6.92
O_3	3410	30.5	10.17	10.29

[a]Data obtained from Ref. 17, Vols. 10 and 14.
[b]Value at boiling point of the pure liquid at standard pressure.

Table XIII lists the solubility data for O_3 in O_2. These data are plotted in Fig. 4. Also marked on Fig. 4 are the various normal phase-change temperatures of O_2, Ar, and O_3 that fall within the range of the O_3-O_2 solubility curve.

To estimate the solubility of O_3 in Ar based on the measured solubility of O_3 in O_2 (Fig. 4), we use Eq. 6 and write relationships for O_3 in O_2 and O_3 in Ar as

$$RT\ \ell n\left(a_j^{O_2}/x_j^{O_2}\right) = v_j^{O_2}\left(\varphi_i^{O_2}\right)^2\left(\delta_j^{O_2} - \delta_i^{O_2}\right)^2 \tag{8}$$

and

$$RT\ \ell n\left(a_j^{Ar}/x_j^{Ar}\right) = v_j^{Ar}\left(\varphi_i^{Ar}\right)^2\left(\delta_j^{Ar} - \delta_i^{Ar}\right)^2, \tag{9}$$

where the superscripts O_2 and Ar designate the respective systems. Now, using the definitions

$$\varphi_i = \frac{n_i v_i}{n_i v_i + n_j v_j},$$

and

$$x_i = \frac{n_i}{n_i + n_j},$$

noting that

$$x_i + x_j = 1,$$

and making the approximation that

$$a_j^{O_2} = a_j^{Ar},$$

TABLE XIII. Solubility of O_3 in O_2[a]

Temperature		Mol % of O_3 in O_2	
°C	K	Oxygen-rich Phase (A)	Ozone-rich Phase (B)
-195	78	5.3	65
-188	85	10.0	58
-183	90	18.5	48
-182	91		44
-181	92		24

[a]From Ref. 18.

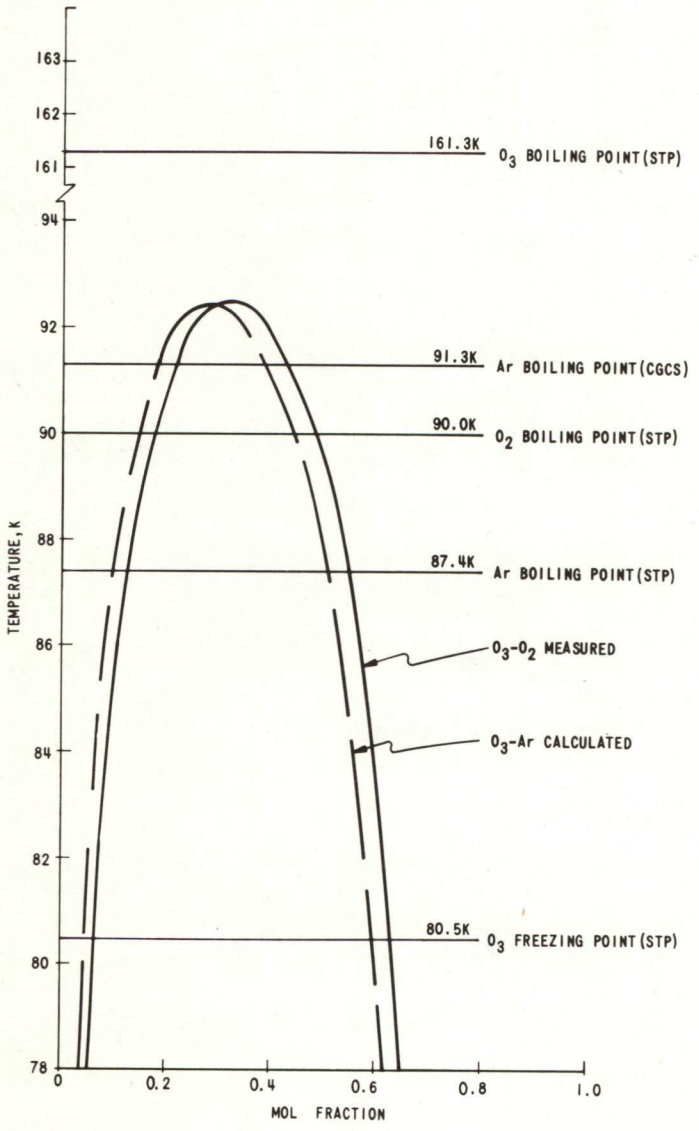

Fig. 4

Solubility of Liquid Ozone in Liquid Oxygen and Liquid Argon. ANL Neg. No. 103-V5659.

we can combine Eqs. 8 and 9 to yield

$$x_2^{Ar} = x_2^{O_2} e^{-z}, \tag{10}$$

where

$$z = \frac{\left.\dfrac{v_j (v_i n_i)^2 (\delta_j - \delta_i)^2}{n_i c_i + n_j v_j^2}\right|_{Ar} - \left.\dfrac{v_j (v_i n_i)^2 (\delta_j - \delta_i)^2}{n_i v_i + n_j v_j^2}\right|_{O_2}}{RT} \tag{11}$$

and the Ar and O_2 are simplified notations indicating the O_3-Ar and O_3-O_2 systems.

Now, if we assume a fixed volume in which the major constituent is Ar and O_3 is an impurity,

$$n_i^{Ar} \simeq n_i^{O_2} = n_i \tag{12}$$

and

$$n_j^{Ar} \simeq n_i^{O_2} = n. \tag{13}$$

Thus,

$$\frac{n_j}{n_i} = \frac{x_j^{O_2}}{1 - x_j^{O_2}} = \frac{x_j^{Ar}}{1 - x_j^{Ar}}. \tag{14}$$

Substituting into Eq. 6 using Eq. 14 yields the relationship

$$z = \frac{\dfrac{v_j^{Ar}\left(\delta_j^{Ar} - \delta_i^{Ar}\right)^2}{\left(1 + \dfrac{x_j^{O_2}}{1 - x_j^{O_2}} \dfrac{v_j^{Ar}}{v_i^{Ar}}\right)^2} - \dfrac{v_j^{O_2}\left(\delta_j^{O_2} - \delta_i^{O_2}\right)^2}{\left(1 + \dfrac{x_j^{O_2}}{1 - x_j^{O_2}} \dfrac{v_j^{O_2}}{v_i^{O_2}}\right)^2}}{RT}. \tag{15}$$

Now, since we realize that

$$\delta_j^{Ar} = \delta_j^{O_2} = \delta(O_3),$$

$$\delta_i^{Ar} = \delta(Ar),$$

and

$$\delta_i^{O_2} = \delta(O_2),$$

that these values are available in Table XII with the molal volumes, and that $x_j^{O_2}$ can be obtained from Table XIII or Fig. 4, the solubility of O_3 in Ar can be estimated from Eq. 10. The O_3-Ar curve shown in Fig. 4 was generated by this procedure.

Examination of the O_3-Ar solubility curve shows that, at the CGCS operating temperature (-182°C), O_3 is soluble in Ar up to a mol fraction of 0.18. Beyond the 0.18 point, an O_3-rich phase containing 0.38 g·mol separates out; thus the O_3 fraction must remain below 0.18. Based on the estimate in Sec. 3.3 in this appendix of a maximum O_3 concentration of 320 ppm (0.000266 mol fraction) in the CGCS Ar in one year, the argon will be capable of dissolving about 677 times the anticipated yearly accumulation of O_3 in the CGCS.

4. Hazard of Methane and Ozone Buildup

If the maximum CH_4 and O_3 accumulations calculated in the preceding work are realized, at the end of one year the sump will contain 2.6 g of CH_4 and 15 g of O_3. The maximum energy release from these components would occur if they were to combine to produce carbon dioxide (CO_2) and water (H_2O) as follows:

$$4O_3 + 3CH_4 \rightarrow 3CO_2 + 6H_2O. \quad (16)$$

Any unreacted ozone would revert to O_2 and thereby liberate its stored energy. In essence, the reaction can be viewed as follows:

$$2O_3 \rightarrow 3O_2 + \text{Energy } E_1; \quad (17)$$

$$2O_2 + CH_4 \rightarrow CO_2 + 2H_2O + \text{Energy } E_2. \quad (18)$$

In the first reaction (Eq. 17), all O_3 decomposes to O_2; in the second (Eq. 18), the O_2 combines with the CH_4 to the limit of the availability of the components. Since 0.16 (2.6/16.04) g·mol of CH_4 and 0.47 (15/32) g·mol of O_2 are available, the extent of the reaction will be limited by the availability of CH_4, and only 0.32 mol of O_2 will be used. The following paragraphs describe the method used to estimate the maximum energy released by the maximum reaction postulated.

If the O_3 is soluble in the liquid Ar under the conditions in the CGCS sump, the reaction energy will be distributed evenly throughout the mixture. Distribution of the reaction throughout the liquid Ar in the sump should result in an essentially isothermal reaction, since the energy will immediately be

transferred to the O_2 and Ar liquids and cause vaporization of some liquid and a pressure increase in the distillation column. The energy released in the reaction of Eq. 17 is 36.0 kcal/g·mol.[19] The latent heats for O_2 and Ar are 1630 and 1550 cal/g·mol,[19] respectively. The energy release from 15.0 g of O_3 will be

$$\frac{15\ \text{g}}{48\ \text{g/g·mol}} \times 3.6 \times 10^4 \frac{\text{cal}}{\text{g·mol}} = 11\ 250\ \text{cal.}\quad \text{(Note: 1 cal = 4.19 J.)}$$

The energy necessary to vaporize the 15.0 g of O_2 is

$$0.47\ \text{g·mol} \times 1630 \frac{\text{cal}}{\text{g·mol}} = 766\ \text{cal.}$$

This leaves 10 484 cal of energy to vaporize Ar. The amount of Ar vaporized is then 6.76 g·mol.

To estimate the amount of Ar vaporized by reaction of the O_2 and CH_4, the net heat of combustion and the change in enthalpy of the reactants and products must be taken into consideration. The heat of combustion for O_2 and CH_4 is 1.92×10^5 cal/g·mol.[19] The change in enthalpy is essentially due to the change in the internal energy of the reactants and products, which is small compared with the heat of combustion. A rough calculation shows that the change in internal energy of reactants and products will add about 2242 cal/g·mol (1.2%) to the energy from combustion. Thus,

$$0.16\ \text{g·mol}(1.92 + 0.02) \times 10^5 \frac{\text{cal}}{\text{g·mol}} \times \frac{1}{1550\ \text{cal/g·mol}} = 20\ \text{g·mol}$$

of Ar will be vaporized by the O_2-CH_4 reaction. In addition, 0.15 g·mol of O_2 in the gaseous state is not consumed in the combustion.

The pressure increase resulting from the vaporization of 26.8 g·mol (20.0 + 6.76) of Ar and 0.15 g·mol of O_2 in the distillation column, the free volume of which is taken at 28.3 L (1 ft^3), is estimated from the relationship

$$P = MRT/V,$$

where

M = number of mols = 27.0 g·mol,

R = 0.0821 L·atm/mol·K,

V = 28.3 L (1 ft^3),

and

T = 91 K (-295°F).

Thus,

$$P = \frac{27.0\ \text{g·mol} \times 0.0821\ \text{L·atm/mol·K} \times 91\ \text{K}}{28.3\ \text{L}} = 7.2\ \text{atm (106 psia).}$$

Since the column is designed for 10.1 atm (150 psia), this pressure in addition to the 1.83 atm (27 psia) normal operating pressure produces a pressure of 9.0 atm (133 psia), which does not exceed the column's design pressure.

4.1. Evaluation of Ozone Hazard Potential in Dumping Sump Contents to Off-gas Adsorber Bed

When the sump contents of the CGCS are dumped into the off-gas adsorber bed, the 15 g of O_3 will be transferred into the bed. The potential energy released by this amount of O_3 by reversion from O_3 to O_2, followed by complete combustion with carbon in the charcoal bed, is analyzed below.

The energy release by the reversion of 15 g of O_3 to O_2 was found earlier to be 43 900 J (10 484 cal). Complete combustion of the oxygen in the charcoal by the relation

$$O_2 + C \rightarrow CO_2 + \text{Energy } E_3 \qquad (19)$$

is determined from the heat of combustion of carbon in charcoal form, which is 33.9 kJ (8100 cal) per gram of substance.[19] Since 15 g is 0.47 g·mol of oxygen in its O_2 state, the reaction (Eq. 19) will consume 5.64 g (0.47 × 12) of carbon. The combustion-energy yield is 191 kJ (45 700 cal). The total energy release for the above reaction is 235 kJ (56 200 cal).

The specific heat of charcoal at 273 K is 0.69 J/g·K (0.165 cal/g·K).[19] The CGCS off-gas adsorber bed contains a minimum of 283 kg of charcoal. If the combustion reaction is uniform throughout the bed, the maximum temperature rise of the bed is

$$\frac{56\ 200\ \text{cal}}{0.165\ \text{cal/g·K}} \times \frac{1}{283\ 000\ \text{g}} = 1.2\ \text{K.}$$

If the combustion reaction takes place in the first 1% of the bed, the maximum temperature rise will be 120 K.

In either case, the temperature rise will be mitigated by cooling from the Ar gas and distributed over the duration of the sump dump (about 1 h). As a consequence, no hazard from O_3 during a sump dump exists if the O_3 is uniformly dispersed in the sump contents.

Earlier analysis led to the restriction of the sump O_2 content to ensure solubility and hence uniform dispersion of the liquid O_3 in the Ar of the sump.

The situation is less clear for the gaseous phase of the O_3-Ar mixture. At the sump operating conditions (145 kPa, -182°C) and the vapor pressure of O_3 (36.5 Pa), the equilibrium mixture of O_3 and Ar gas is determined to be 250 ppm by Dalton's rule of partial pressure. This is somewhat less than the 320 ppm an accumulation of 15 g of O_3 represents. Under worst-case conditions, where fractional distillation is fully effective, 22%, or 3.3 g, of the 15 g of O_3 could remain in the sump. Because of the method and dynamics of the dump, however, a significant residue of O_3 will probably not remain in the sump.

Dumping of the sump contents, described in Sec. 2.2.3 of the body of this report, involves forcing the sump contents out of the sump in a liquid state through a pipe. This pipe is insulated until it reaches a horizontal run, where any condensed droplets of O_3 will be pushed by the expanding gas flow.

That the uniform distillation of O_3 in both the gaseous and liquid phase is a valid assumption is supported by data gathered from a test dump with activated isotopes in the sump. Figure 5 shows activity level in the charcoal bed during the test dump. These data show that the activity buildup in the off-gas adsorber bed is essentialiy uniform with flow and time. Most of this activity is due to the xenon isotopes. Since the partial pressure of xenon is very close to that of O_3 over the entire range of the dump, the activity of the xenon, acting as a tracer, shows that any O_3 in the sump will be removed to the adsorber as a uniform mixture in the Ar.

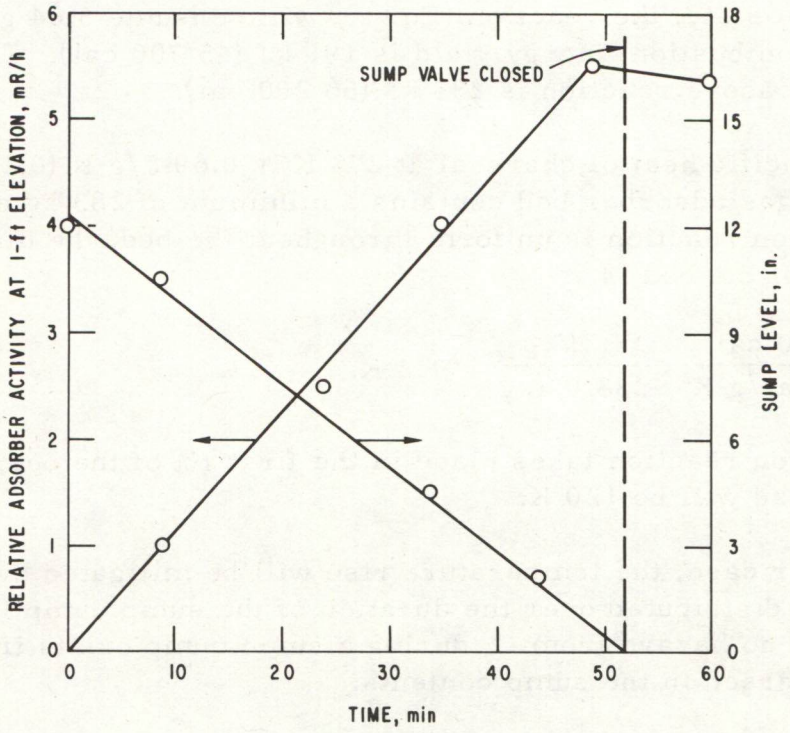

Fig. 5

Adsorber Activity during CGCS-sump Dump of June 15, 1977. Conversion factors: 1 ft = 0.3048 m; 1 in. = 25.4 mm; 1 R = 2.58 x 10^{-4} C/kg.

4.2. Evaluation of Potential Oxygen and Methane Trapping in Off-gas Adsorber Bed

At ambient conditions, activated charcoal adsorbs CH_4 poorly and O_2 extremely poorly. In many applications, air is used as the normal carrier gas for the impurities for which the charcoal trap is intended. Charcoal can be used to effectively adsorb paraffin hydrocarbons of greater than C_6 molecular weight, whereas low-mass hydrocarbons such as methane, ethane, and propane are more weakly adsorbed. This difference in adsorption magnitude as a function of mass is used under certain circumstances to separate low- and high-mass hydrocarbons. Further, the adsorption is a dynamic process that is directly related to the partial pressure of the component. Thus, at trace compositions, adsorption will be further weakened.

It should not be inferred from the above, however, that CH_4 will not be adsorbed to some slight extent by the approximately 2-m-deep bed of charcoal. During at least the early stages of use, the total capacity of the bed will exceed the input of xenon and krypton isotopes. This means that downstream of the zone, where preferential deposition of the xenon and krypton occurs, adsorption sites will be available for impurities. However, as more xenon, krypton, and possibly Ar are added, the CH_4 will be displaced. The excess of Ar from the sump drain may preempt adsorption of CH_4. Although comparative adsorption isobars for Ar and CH_4 have not been obtained, the low partial pressure of CH_4, compared to that for Ar, means that adsorption of the former will be minor.

APPENDIX B

Calculation of Exposures for CGCS Maximum Hypothetical Accident (MHA)

1. Introduction

The CGCS MHA is defined as the complete atmospheric release of the radioactive noble-gas inventory and 1% of the particulate daughter-product inventory located within the CGCS building. The release is presumed to occur over a 2-h period following a component failure. Table XI (in Appendix A) summarizes the CGCS inventory and the average beta and gamma energies per disintegration for each isotope.

2. Methodology

U. S. Atomic Energy Commission Regulatory Guide 1.3, Rev. 1, presents specific guidance for whole-body-dose calculations resultant from postulated loss-of-coolant accidents in boiling-water reactors.[20] The parts of that guide that appear applicable to this case are as follows:

"A. INTRODUCTION

"Section 50.34 of 10 CFR Part 50 requires that each applicant for a construction permit or operating license provide an analysis and evaluation of the design and performance of structures, systems, and components of the facility with the objective of assessing the risk to public health and safety resulting from operation of this facility. The design basis loss of coolant accident (LOCA) is one of the postulated accidents used to evaluate the adequacy of these structures, systems, and components with respect to the public health and safety. This guide gives acceptable assumptions that may be used in evaluating the radiological consequences of this accident for a boiling water reactor. In some cases, unusual site characteristics, plant design features, or other factors may require different assumptions which will be considered on an individual case basis. The Advisory Committee on Reactor Safeguards has been consulted concerning this guide and has concurred in the regulatory position.

"B. DISCUSSION

"After reviewing a number of applicants for construction permits and operating licenses for boiling water power reactors, the AEC Regulatory staff has developed a number of appropriately conservative assumptions, based on engineering judgment and on applicable experimental results from safety research programs conducted by AEC and the nuclear industry, that are used to evaluate calculations of the radiological consequences of various postulated accidents.

"This guide lists acceptable assumptions that may be used to evaluate the design basis LOCA of a Boiling Water Reactor (BWR). It requires that the offsite dose consequences be shown to be within the guidelines of 10 CFR Part 100.

"C. REGULATORY POSITION

"1. The assumptions related to the release of radioactive material from the fuel and containment are as follows:

"a. The effects of radiological decay during holdup in the containment or other buildings should be taken into account.

"2. Acceptable assumptions for atmospheric diffusion and dose conversion are:

"a. No correction should be made for depletion of the effluent plume of radioactive iodine due to deposition on the ground, or for the radiological decay of iodine in transit.

"b. External whole body doses should be calculated using 'Infinite Cloud' assumptions, i.e., the dimensions of the cloud are assumed to be large compared to the distance that the gamma rays and beta particles travel. 'Such a cloud would be considered an infinite cloud for a receptor at the center because any additional (gamma and beta) emitting material beyond the cloud dimensions would not alter the flux of gamma rays and beta particles to the receptor' (Meteorology and Atomic Energy, Section 7.4.1.1--editorial additions made so that gamma and beta emitting material could be considered). Under these conditions the rate of energy absorption per unit volume is equal to the rate of energy release per unit volume. For an infinite uniform cloud containing χ curies of beta radioactivity per cubic meter, the beta dose in air at the cloud center is:

$$_{\beta}^{\infty}D' = 0.457\overline{E}_{\beta}\chi$$

The surface body dose rate from emitters in the infinite cloud can be approximated as being one-half this amount (i.e.,

$$_{\beta}^{\infty}D' = 0.23E_{\beta}\chi). \qquad (20)$$

For gamma emitting material the dose rate in air at the cloud center is:

$$_{\gamma}^{\infty}D' = 0.507\overline{D}_{\gamma}\chi \qquad (21)$$

From a semi-infinite cloud, the gamma dose rate is:

$$\gamma_{\infty}D' = 0.25\overline{E}_{\gamma}\chi \qquad (22)$$

where

$\beta_{\infty}D'$ = beta dose rate from an infinite cloud (rad/s)

$\gamma_{\infty}D'$ = gamma dose rate from an infinite cloud (rad/s)

$\overline{E}_{\beta}$ = average beta energy per disintegration (MeV/dis)

$\overline{E}_{\gamma}$ = average gamma energy per disintegration (MeV/dis)

χ = concentration of beta or gamma emitting isotope in the cloud (Ci/m^3).

"c. The following specific assumptions are acceptable with respect to the radioactive cloud dose calculations.

"(1) The dose at any distance from the reactor should be calculated based on the maximum concentration in the plume at the distance taking into account specific meteorological, topographical, and other characteristics which may affect the maximum plume concentration. These site related characteristics must be evaluated on an individual case basis. In the case of beta radiation, the receptor is assumed to be exposed to an infinite cloud at the maximum ground level concentration at that distance from the reactor. In the case of gamma radiation, the receptor is assumed to be exposed to only one-half the cloud owing to the presence of the ground. The maximum cloud concentration always should be assumed at ground level.

"(2) The appropriate average beta and gamma energies emitted per disintegration, as given in the Table of Isotopes, Sixth Edition, by C. M. Lederer, J. M. Hollander, I. Perlman; University of California, Berkeley; Lawrence Radiation Laboratory, should be used.

"d. For BWR's without stacks the atmospheric diffusion model should be as follows:

"(1) The 0-8 h ground level release concentrations may be reduced by a factor ranging from one to a maximum of three for additional dispersion produced by the turbulent wake of the reactor building in calculating potential exposures. The volumetric building wake correction factor, as defined in Sec. 3-3.5.2 of Meteorology and Atomic Energy 1968, should be used only in the 0-8 h period; it is used with a shape factor of 1/2 and the minimum cross-sectional area of the reactor building only.

"(2) The basic equation for atmospheric diffusion from a ground level point source (for the 0-8 h period) is :

$$\chi/Q = \frac{1}{u\sigma_y\sigma_z} \qquad (23)$$

where

χ = the short term average centerline value of the ground level concentration (Ci/meter^3)

Q = amount of material released (Ci/s)

u = windspeed (meter/s)

σ_y = the horizontal standard deviation of the plume (meters). See Fig. V-1, page 48, Nuclear Safety, June 1961, Volume 2, Number 4, "Use of Routine Meteorological Observations for Estimating Atmospheric Dispersion," F. A. Gifford, Jr.

σ_z = The vertical standard deviation of the plume (meters). See Fig. V-2, page 48, Nuclear Safety, June 1961, Volume 2, Number 4, "Use of Routine Meteorological Observations for Estimating Atmospheric Dispersion," F. A. Gifford, Jr.

"(3) The atmospheric diffusion model for ground level releases is based on the information below:

Time Following Accident	Atmospheric Conditions
0-8 h	Pasquill Type F, Windspeed 1 meter/s, uniform direction.

"(4) Figures 3A [Fig. 6 of this report] and 3B give the ground level release atmospheric diffusion factors based on the parameters given in h(4)."

The CGCS structure will be within ~5 m (16 ft) of the shell of the EBR-II reactor containment building. The average projected dimensions of the CGCS building are 4.1 m (13.5 ft) high and 7.3 m (24 ft) wide. The information presented to this point provides the basis for three assumptions:

(1) The release is at ground level (7-m-high building).

(2) The CGCS building is within the turbulent eddy region of the reactor containment building (5 m from building). Turbulence caused by other buildings in the area is not considered, so that additional conservatism is provided.

(3) Credit is taken for fission-product decay during the release period. Assumption 2 is derived from dispersion studies near buildings, which indicate that eddies occur to the lee side for a distance about three times the building height.[21] The projected average dimensions of the EBR-II reactor building are 26.4 m (86.7 ft) high by 24.4 m (80 ft) wide. This information, in fact, provides the basis for a model to calculate χ/Q values at distances near the source (<100 m away).

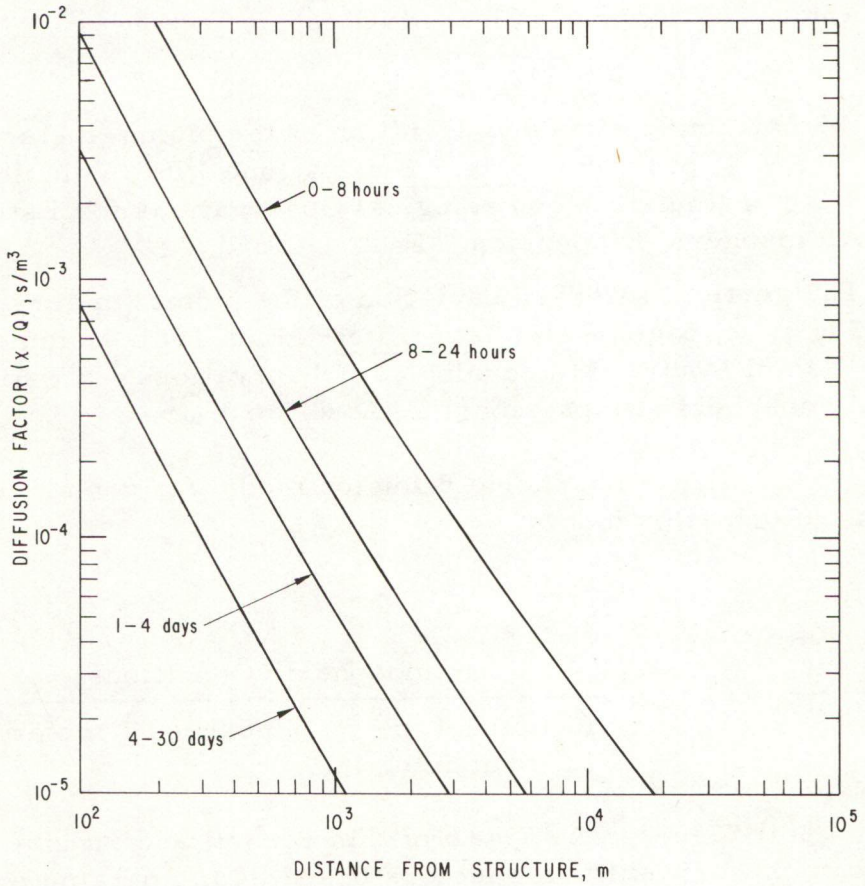

Fig. 6. Atmospheric-diffusion Factors for Various Times Following a Ground-level Release

The χ/Q data presented in Regulatory Guide 1.3, and for that matter in most other sources, do not include estimates at distances less than 100 m, even without building turbulence. Therefore, it is assumed that in the turbulent zone (to ~75 m downwind) the air is completely mixed, and the concentration may be calculated from

$$\chi = Q/cAu, \tag{24}$$

where

A = vertical cross-sectional area of the building (645 m^2 for EBR-II containment building and 30 m^2 for the CGCS building),

c = building wake factor (0.5 for poor mixing, 2 for strong mixing),

u = horizontal wind speed (m/s),

and χ and Q are as previously defined.[21]

In reality, the above equation will not provide χ/Q estimates that couple directly with those given in Fig. 6. However, for distances beyond the turbulent-mixing zone ($d \geq 75$ m), dispersion can be computed from a modified Sutton formula:

$$\chi/Q = \frac{1}{u[0.5\pi C_y C_z (d - 75)^{2-n} + cA]}, \qquad (25)$$

where n, C_y, and C_z are Sutton's parameters, and d is the horizontal distance from the source in meters.[21]

Using Eqs. 24 and 25, we can establish ratios of the χ/Q values at distances less than 75 m to the χ/Q value at 100 m. These ratios can be multiplied by the χ/Q value at 100 m from Fig. 6 to extend the useful range of the data to less than 100 m. Values of downwind concentration developed specifically for the INEL can also be used and compared to the values derived from Eqs. 24 and 25.

For "worst-case" calculations of this type, always assume the climatological conditions that result in the minimum dispersion of the fission products. This assumption produces maximum cloud concentration and maximum dose to the receptor, who is assumed to stand on the centerline of the downwind cloud. The basic assumptions are strong inversion, generally called Class F conditions, coupled with a low wind speed (1 m/s) and no wind meandering during the release. The atmospheric-dispersion data are presented in reference to defined sets of atmospheric conditions.

For other atmospheric conditions, for example, weak inversion or strong or weak lapse, the concentration functions predict lesser concentrations of the fission products (i.e., better dispersion). Figure 7 presents χ/Q data developed for the INEL climatography by class (A-F) of atmospheric condition.[22] These curves were derived from INEL ground-level-diffusion experiments and represent effluent releases of about 15- to 60-min duration. For releases of longer duration, effluent-plume meander in the crosswind direction becomes a significant factor in the dispersal of effluents.[22]

Inspection of Figs. 6 and 7 reveals that the χ/Q values developed at the INEL (for Class F conditions) are nearly a factor of 10 less than the 0-8-h curve from the Regulatory Guide at 100 m from the source. This difference would indicate that the χ/Q data from the Regulatory Guide are very conservative; i.e, the dispersion is better than that predicted by the values in Fig. 6.

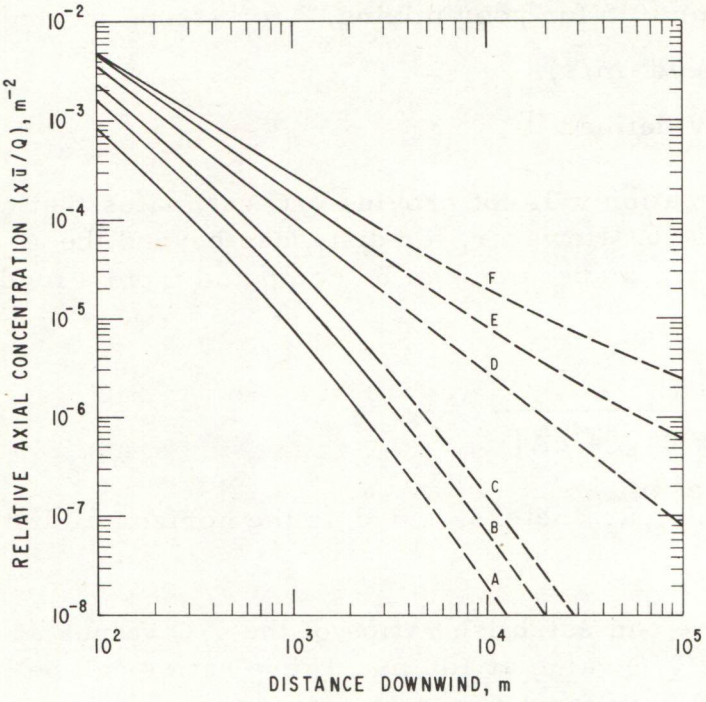

Fig. 7

Relative Axial Concentration vs Distance Downwind by Stability Class: Release Time of 15–60 min

3. Equation Development

The equations for dose rate (Eqs. 20 and 21 above) must be summed over all isotopes and integrated over the time of release to obtain the integrated dose. The resultant equations yield dose in rads. The desired dose unit is Rem; the appropriate relationship between rad and Rem is[23,24]

Dose in Rem = Dose in rad × quality factor,

where

quality factor = 1 for whole-body dose from beta/gamma radiation.

For all isotopes, the gamma dose rate is

$$ {}_{\gamma}D = 0.25 \sum_{i=1}^{n} \chi_i \overline{E}_{\gamma,i}. \tag{26} $$

Figures 6 and 7 give χ/Q values. Since

$$ \chi = \frac{\chi}{Q} \cdot Q, \tag{27} $$

where

Q = release rate of an isotope (Ci/s),

Eq. 26 can be written as

$$ {}_{\gamma}D = 0.25\frac{\chi}{Q}\sum_{i=1}^{n} Q_i\overline{E}_{\gamma,i}. \tag{28} $$

Here, we must recognize that χ/Q is independent of isotope and can be taken out of the summation. This form still gives dose rate. The release occurs over 2 h, and the receptor is assumed to receive the dose for the 2-h period. Therefore, the integral to yield dose is

$$ \left.\begin{aligned} {}_{\gamma}\text{Dose}_{\text{int}} &= 0.25\frac{\chi}{Q}\sum_{i=1}^{n}\frac{C_i}{\Delta T_1}\overline{E}_{\gamma,i}\int_0^{T_2} dt \\ \text{or} \\ {}_{\gamma}\text{Dose} &= 0.25\frac{\chi}{Q}\left(\sum_{i=1}^{n}\frac{C_i}{\Delta T_1}\overline{E}_{\gamma,i}\right)(\Delta T_2) \end{aligned}\right\}, \tag{29} $$

where

C_i = curies of isotope i,

ΔT_1 = time of release (2 h),

ΔT_2 = time of exposure (2 h),

and

$$ Q_i = C_i/\Delta T_1. $$

Since $\Delta T_1 = \Delta T_2$, Eq. 29 reduces to

$$ {}_{\gamma}\text{Dose} = 0.25\frac{\chi}{Q}\sum_{i=1}^{n} C_i\overline{E}_{\gamma,i}. \tag{30} $$

This equation is essentially identical to those used in the ZPPR FSAR[21] for gamma doses.

By identical development, the equation for beta dose rate (Eq. 20) yields, for surface body beta dose,

$$ {}_{\beta}\text{Dose} = 0.23\frac{\chi}{Q}\sum_{i=1}^{n} C_i\overline{E}_{\beta,i}, \tag{31} $$

where $\overline{E}_{\beta,i}$ is the average beta energy in MeV/dis for the given isotope.

With a small measure of conservatism, the 0.23 factor in Eq. 31 can be rounded up to 0.25. This small correction allows the two equations for integrated dose to be combined into

$$_{tot}\text{Dose} = 0.25\left(\frac{\chi}{Q}\sum_{i=1}^{n} C_i\overline{E}_i\right), \tag{32}$$

where $\overline{E}_i$ is now the sum of the average beta energy and average gamma energy.

The form of Eq. 32 assumes a constant source of curies (C_i) released uniformly over a given time span. Therefore, the equilibrium inventories of each isotope can be directly substituted to obtain doses without credit for isotopic decay. Since many of the isotopes involved have half-lives equal to or less than the release time, decay during the release period substantially reduces the integrated dose to the receptor.

For all noble-gas parents in the system, the concentration of an isotope as a function of delay time is given by

$$C_i/C_{0,i} = \exp(-\lambda_i t), \tag{33}$$

where

C_i = curies of isotopes i at time t after start of release,

$C_{0,i}$ = equilibrium curies of i at time of start of release,

and

λ_i = decay constant.

Decay of daughters of the noble gases in the system during release can be discounted as negligible for two reasons:

(1) Only 1% of each daughter product is assumed to be released; therefore the contribution to total dose by the daughters is minor.

(2) Decay of the parent tends to maintain the total daughter inventory in the system near original levels.

Equation 33 simply defines the decay characteristics of the noble gases after the release begins. [And, it must be added, the CGCS system is assumed to isolate from its gas source (the reactor cover gas) at the time the release begins.] To obtain an average value of C_i during the release, we must time-average C_i.

The time-averaged inventory of a parent noble gas is given by

$$C_{i,\,avg} = \frac{\int_0^t C_i\,dt}{\int_0^t dt} = \frac{\int_0^t C_{0,i}\exp(-\lambda_i t)dt}{t} = \frac{C_{0,i}}{\lambda_i t}\left[1 - \exp(-\lambda_i t)\right]. \qquad (34)$$

4. Calculations and Discussion

The CGCS building is in the wake-dispersal-influence region of the reactor building as well as that of the Hot Fuel Examination Facility/South (HFEF/S), the sodium boiler building, and the EBR-II power plant, and any on-site receptor is likely to be in another structure downwind of the source. Downwind structures can, in general, introduce more dispersion by turbulence around the structure. As a basic assumption, the influence of structures other than the CGCS building and the reactor containment building will be ignored; i.e., the receptor is assumed to be at ground level in open terrain, and the reactor building is assumed to be the only major structure that can influence the downwind concentrations.

Calculations of the total dose with Eq. 32 is straightforward when the χ/Q functions are defined. Thus, the key to definition of the receptor doses lies in the best definition of the χ/Q data, particularly those for distances of less than 100 m from the source. For this reason, χ/Q values developed from the sources--Eqs. 24 and 25 and Figs. 6-8--were used in parameter studies to scope the problem and establish the best definition of the dose rates.

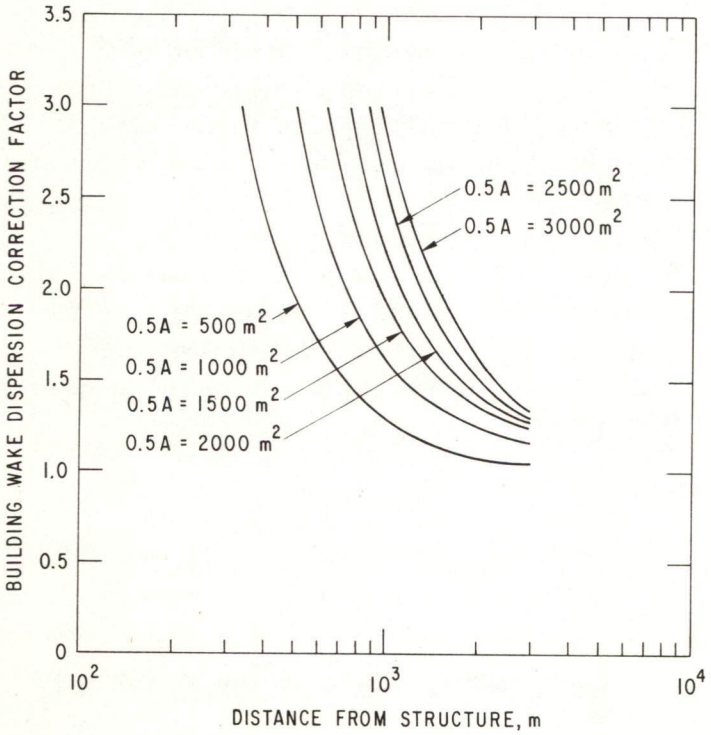

Fig. 8

Wake-correction Factors for Reactor Buildings of Various Cross-sectional Areas

Equations 24 and 25 were used with combinations of the building's projected areas (645 and 30 m^2) and mixing factors (C = 0.5 and 2) to assess the effects of these factors on the χ/Q functions.

The Sutton data used in these equations were derived from

$$\sigma_y^2 = \tfrac{1}{2}C_y^2 X^{2-n}$$

and

$$\sigma_z^2 = \tfrac{1}{2}C_z^2 X^{2-n},$$

where n = 0.50 for strong inversion and X is the distance from the source. Values of σ_y and σ_z were taken from Figs. 3-5 and 3-6 of Ref. 22. The σ_y and σ_z values are standard deviations of effluent concentrations in the cross-wind and vertical directions, respectively.

Next, the χ/Q data of Fig. 6 were corrected for the wake-correction mixing factors of Fig. 8, assuming a building projected area of 645 m^2, and the doses were calculated for constant source and source with decay.

In accordance with the guidance quoted earlier, the maximum wake-correction factor used was three. Inclusion of decay during release reduces the dose by about 30%

The paired parameters of A = 30 m^2 and C = 1 yielded χ/Q values (via Eq. 25) at distances ≥100 m that were similar to those derived from Fig. 6 and 8. Therefore, these values of C and A were used to calculate values for χ/Q at <100 m with Eq. 24 as well as with Eq. 25. The ratio of these two values was then multiplied by the χ/Q value taken from Figs. 6 and 7 at 100 m to yield an estimate of χ/Q at <100 m.

Finally, using the χ/Q data from Fig. 7 developed specifically for the INEL with correction for reactor-building turbulence, we generated another pair of χ/Q sets for comparison with the earlier estimates. Use of the parameter set A = 645 m^2 and C = 1 in Eqs. 24 and 25 gave comparable results to those from Fig. 7 corrected for turbulence.

5. Summary and Conclusions

The results for source with decay are plotted in Fig. 9. The conditions that apply to each curve are:

(1) The upper boundary curve is primarily based on the regulatory guidance presented earlier, corrected for building turbulence, but extrapolated to distances of less than 100 m from the source. This curve also represents estimates from Eqs. 24 and 25 with the parameter set C = 1 and A = 30 m^2.

(2) The lower boundary curve represents doses calculated from the χ/Q data developed at the INEL,[22] but corrected for the effects of reactor-building turbulence. This curve also represents the results of Eqs. 24 and 25 when full credit is taken for the reactor-building projected area (645 m^2).

(3) As permitted by the regulatory guidance, the exposures presented in Fig. 9 take credit for decay during the release period of 2 h.

(4) Both curves represent doses for a ground-level release under Class F (strong-inversion) conditions, with low wind speed (1 m/s) and no wind meandering during the release period. Other assumed weather conditions yield calculated doses less than the assumed conditions. The receptor is assumed to be on the centerline of maximum cloud concentration for the 2-h duration in open terrain.

(5) The effect of air mixing due to turbulence around structures downwind of the source has not been included in these estimates.

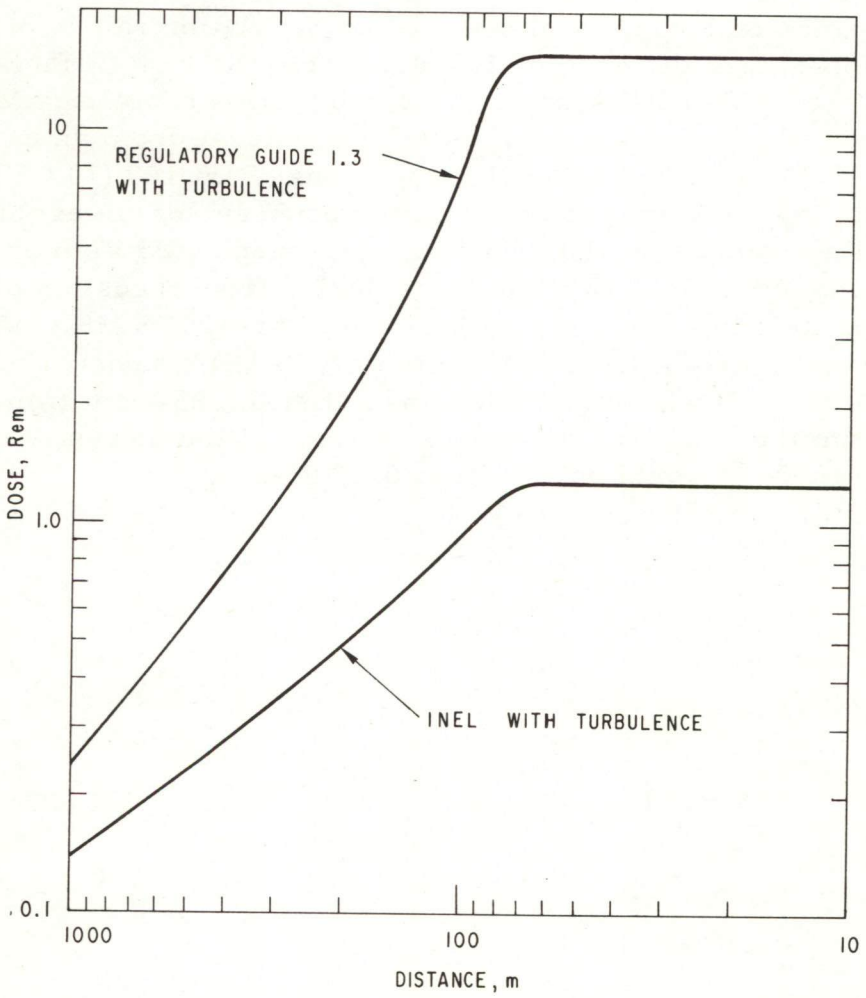

Fig. 9. Calculated Exposures, Including the Effect of Isotopic Decay during Release Period

For use in conjunction with Fig. 9, Table XIV gives approximate distances from the CGCS building to various on-site facilities.

TABLE XIV. Distances from CGCS to Other On-site Facilities

Facility	Distance, m
HFEF/S	40
EBR-II control room	55
HFEF/N	90
L&O building	140
ZPPR south wing	275
TREAT control building	550

An exclusion boundary of 600 m, low-population radius of 1600 m, and population-center distance of 48 000 m from the EBR-II facility have been established. These limits were defined from a postulated MHA within the reactor core corresponding to the energy release from an excursion of 10^{20} fissions. The Code of Federal Regulations, Part 100 (10 CFR 100),[7] requires that any individual standing on the boundary of the exclusion zone for 2 h shall not receive a whole-body dose exceeding 25 Rem or a thyroid dose exceeding 300 Rem. Thyroid doses derive from ingestion of iodine isotopes, and no iodine species are involved in the CGCS MHA. Therefore, from Fig. 9 the whole-body dose from the CGCS MHA, under "worst-case" conditions, falls well within this once-in-a-lifetime 25-Rem limit for all distances from the source. The maximum dose at the boundary of the exclusion area (600 m) would be less than 0.45 Rem.

REFERENCES

1. R. J. Campana, General Atomic, personal communication (Feb 1976).
2. T. J. Kabele et al., *FFTF Fission Gas Delay Beds: Engineering Scale Test Report,* HEDL 73-26 (May 1973).
3. R. Villarreal, Argonne National Laboratory, personal communication (Jan 1978).
4. E. R. Ebersole, Argonne National Laboratory, personal communication (June 1977).
5. D. W. Underhill, "Effect of Rupture in a Fission Gas Holdup Bed," *Proc. of 12th AEC Air Cleaning Conference,* Oak Ridge, Tenn., Aug 28-31, 1972, CONF-720823, pp. 60-69 (Jan 1973).
6. D. W. Underhill, *Release of Adsorbed Krypton and Xenon from Spilled Charcoal,* Nucl. Sci. Eng. *63,* 133-142 (1977).
7. *Reactor Site Criteria,* Title 10, Code of Federal Regulations, Part 100 (10 CFR 100) (Apr 1966).
8. H. F. Coward and C. W. Jones, *Limits of Flammability of Gases and Vapor,* U. S. Bureau of Mines Bulletin 503, U. S. Government Printing Office (1952).
9. E. R. Ebersole, Argonne National Laboratory, personal communication (Jan 1978).
10. J. P. Kirk, DFR Manager, personal communication (Dec 1975).
11. *Reactor Development Program Progress Report: August 1974,* ANL-RDP-31, pp. 1.11-1.17 (Sept 27, 1974).
12. L. J. Koch et al., *Hazard Summary Report, Experimental Breeder Reactor II (EBR-II),* ANL-5719, p. 339 (May 1957).
13. L. J. Koch, W. B. Loewenstein, and H. O. Monson, *Addendum to Hazard Summary Report, Experimental Breeder Reactor II (EBR-II),* ANL-5719 (Addendum) (June 1962).
14. J. C. Gault et al., *Ozone Formation and the Radiolysis of Liquid Nitrogen: Calculation and Measurement,* Nucl. Safety *14*(5), 446-451 (Sept-Oct 1973).
15. J. H. Hildebrand, University of California, personal communication (June 1976).
16. J. H. Hildebrand et al., *Regular and Related Solutions,* D. Van Nostrand-Reinhold, New York (1970).
17. Kirk-Othmer, *Encyclopedia of Chemical Technology,* 2nd Ed., Interscience Publishers, New York (1963).
18. G. M. Schab, J. Phys. Chem. *110,* 599-625 (1922).
19. C. D. Hodgman, Editor in Chief, *Handbook of Chemistry and Physics,* 39th Ed., The Chemical Rubber Publishing Co., Cleveland (1957-1958).
20. U. S. Atomic Energy Commission, *Assumptions Used for Evaluating the Potential Radiological Consequences of a Loss of Coolant Accident for Boiling Water Reactors,* Regulatory Guide 1.3, Rev. 1 (June 1973).
21. H. Lawroski et al., *Final Safety Analysis Report on the Zero Power Plutonium Reactor (ZPPR) Facility,* ANL-7471 (June 1972).

22. G. R. Yansky et al., *Climatography of the National Reactor Testing Station*, IDO-12048 (Jan 1966).

23. S. Glasstone, *Principles of Nuclear Reactor Engineering*, D. Van Nostrand, Princeton, N.J., pp. 547-548 (1955).

24. Hans Kiefer et al., *Radiation Protection Measurement*, Pergamon Press, New York (1972).

Distribution for ANL-78-89

Internal:

J. A. Kyger
R. Avery
L. Burris
D. W. Cissel
S. A. Davis
B. R. T. Frost
E. V. Krivanec
R. J. Teunis
C. E. Till
R. S. Zeno
C. E. Dickerman
H. K. Fauske
S. Fistedis
J. F. Marchaterre
H. O. Monson
R. Sevy
A. E. Allen
W. N. Beck
D. B. Berg
P. R. Betten
W. F. Booty
J. H. Bottcher
F. L. Brown
T. N. Buchanan
L. K. Chang
D. C. Cutforth
E. M. Dean
J. W. Driscoll
E. E. Feldman
A. J. Foltman
R. J. Forrester
F. C. Franklin
R. M. Fryer (6)
J. G. Gale
J. L. Gillette
G. H. Golden
K. N. Grimm
K. C. Gross
B. L. Hansen
G. L. Hofman
E. Hutter
J. M. Keeton
F. S. Kirn
J. F. Koenig
J. A. Koerner
D. A. Kucera
J. D. B. Lambert
H. A. Larson
W. K. Lehto
G. L. Lentz
R. J. McConnell
R. P. McCormick
D. Meneghetti
F. E. Metcalf
D. Mohr
L. R. Monson (2)
W. H. Olson
W. H. Perry
K. E. Phillips
R. H. Rempert
R. E. Rice
W. E. Ruther
J. I. Sackett (3)
W. R. Simmons
R. M. Singer
R. N. Smith
R. R. Smith
B. Y. C. So
R. V. Strain
J. E. Sullivan
L. C. Walters
T. S. Wu
E. R. Ebersole
J. P. Kirk
A. B. Krisciunas
ANL Contract File
ANL Libraries (5)
TIS Files (6)

External:

DOE-TIC, for distribution per UC-79p (251)
Manager, Chicago Operations and Regional Office, DOE
Chief, Office of Patent Counsel, DOE-CORO
Director, Reactor Programs Div., DOE-CORO
Director, INEL, DOE-CORO
Director, DOE-RRT (2)
President, Argonne Universities Association:
EBR-II Project Review Committee:
E. L. Alexanderson, Detroit Edison Co.
J. R. Calhoun, Tennessee Valley Authority
D. T. Eggen, Northwestern University
W. H. Jens, Detroit Edison Co.
L. J. Koch, Illinois Power Co.
H. Pearlman, Atomics International
G. K. Knolls, U. of Michigan

☆ U.S. GOVERNMENT PRINTING OFFICE: 1979—650-068/12