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**CONTAINMENT ATMOSPHERE
RESPONSE (CAR) PROGRAM
SECOND STATUS REPORT**

by
J. A. LANDONI

Prepared under
Contract DE-AT03-76ET35300
for the San Francisco Operations Office
Department of Energy

DATE PUBLISHED: MARCH 1980

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**Prepared under
Contract DE-AT03-76ET35300
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**GENERAL ATOMIC PROJECT 6400
DATE PUBLISHED: MARCH 1980**

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FOREWORD

This report is the second status report for the Containment Atmosphere Response, which is funded under the HTGR Safety Research Task, Contract DE-ATO3-76ET35300, Project No. 6400, WBS No. 2207, Task No. 500, of the HTGR Generic Technology Program.

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ABSTRACT

This report contains a summary of the work performed under the Containment Atmosphere Response (CAR) Program of the High-Temperature Gas-Cooled Reactor (HTGR) Safety Research Task since the publication of the previous status report (February 1978). The work concentrated on development of models describing containment phenomena during core heatup in support of probabilistic risk assessment studies. Models were completed for fission product iodine sorption on coated surfaces, diffusivity and retentivity of untreated concrete, iodine interaction with condensing steam on the containment atmosphere boundaries, and the cleanup filter system. These models were incorporated into a new computer program called CARCAS, a substantial extension of the CNTB computer program, and applied to Accident Initiation and Progression Analysis for Phase II core heatup sequences. Development was begun on models describing the postulated behavior of particulate fission products or aerosols within and leaking out of the containment. The model for predicting the containment atmosphere pressure response to the combustion of flammable gas was completed, applied, and incorporated into CARCAS. Effort was initiated on the containment structural response, potential failure modes, and enhanced leakage due to overpressurization. Future effort is recommended on aerosol behavior and containment structure response during core heatup.

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1. SUMMARY AND CONCLUSIONS

The CAR program analyzes the behavior of the HTGR containment atmosphere during postulated accidents which may impair the containment function. During the four years that the CAR program has been active, the various mechanical, thermal, chemical, and radioactive containment phenomena associated with accidents within and beyond the HTGR design basis have been systematically analyzed.* The present effort described in this report is directed at containment phenomena affecting the consequences of HTGR core heatup sequences studied in the Accident Initiation and Progression Analysis (AIPA) Phase II work. Specifically, the behavior of fission products released from the core to the containment atmosphere and the potential flammability effects of combustible gases released as a consequence of degradation of the prestressed concrete reactor vessel (PCRV) and subsequent reactions in the heated core are addressed. This work is a continuation of the analysis described in the previous CAR status report.

Analytical models are presented for a realistic determination of the pressure and temperature of the containment atmosphere during and after slow-combustion of carbon monoxide and hydrogen resulting from liberation of aggregational water from concrete degradation and subsequent reaction of this water vapor with the reactor graphite. Included are models for thermal radiation, heat convection, and steam condensation effects from the containment atmosphere to the boundaries during flame propagation. A new computer program called CARCAS was developed which substantially modifies the CNTB computer program for the transient state of the pressures and temperatures. This new program includes, in addition to helium (considered in CNTB), other substances which can be released from the PCRV such as

* A summary of the CAR program and achievements in the various phenomena categories is presented in the Appendix.

steam, carbon monoxide, carbon dioxide, and hydrogen as well as nitrogen and oxygen since air present in the containment may be exchanged with the PCRV atmosphere. Application of the CARCAS program to HTGR core heatup confirms previous estimates reported for AIPA Phase II studies on the pressure pulse after ignition, namely that the containment atmosphere pressure rises above the assumed median static failure pressure of the containment for a period of about 10 min. Effort was initiated on the analysis of the containment structural response, potential dynamic failure modes, and enhanced leakage due to overpressurization. This effort is recommended for continuation in future CAR program work.

In the present work, models were developed, which are relatively complete, for fission product iodine sorption on coated surfaces, diffusivity and retentivity of untreated concrete,* iodine interaction with condensing steam on the containment atmosphere boundaries, and the cleanup filter system. These models were incorporated into the CARCAS computer program and applied to AIPA core heatup sequences. Results indicate that at early times the surfaces (whether coated or not) sorb iodine. The coated surfaces are as effective as the cleanup filter system in removing gas-borne iodine, whereas the concrete is relatively ineffective. After steam begins condensing (i.e., 100 hr after the initiation of the accident), the rate of iodine removal from the containment atmosphere is dramatically increased (factor of 30 in the characteristic time) by steam mass transport to the exposed surfaces. Since iodine is soluble in water, iodine in the coated surfaces is washed away and iodine in the untreated concrete is leached out to the containment drain and sump. Thus, the gas-borne iodine concentration in the containment decreases rapidly toward zero after about 100 hr, terminating the potential iodine release to the environment through containment leaks.

* Untreated concrete refers to the usual concrete as opposed to the concrete for the floor of the containment building, which is treated in such a way as to reduce its porosity and thus the potential retentivity of radioactive products in case of accidents.

The description of the aerosol-like type PCRV releases (such as cesium, strontium, and tellurium) differs from the description of iodine in the containment atmosphere. Development was initiated on models of particulates or aerosols within and leaking out of the containment. An analytical model was developed to account for gravitational settling in addition to filtration, radioactive decay, and containment leaks, but it does not have the ability to handle the aerosol removal by steam condensation. More elaborate models are considered in the HAA-3 computer program for the Liquid Metal Fast Breeder Reactor (LMFBR) but is restricted to a log-normal distribution for the aerosol particle sizes and without consideration of steam condensation, since the program was developed for sodium fires. A computer program called DISPER enables computation of the deposition of particulate fission products through leakage paths in the containment building. Both computer programs have been obtained and implemented at General Atomic for the UNIVAC 1110.

In conclusion, the CAR program has developed capabilities in several aspects of the containment atmosphere behavior. The work on the chemical response is essentially complete, as is the description of fission product iodine behavior. Additional analytical work is needed on the behavior of particulate fission products of biological and environmental significance and on the mechanical response of the containment structure. Experimental work is needed in the area of helium jets and plumes discharging into the containment atmosphere, mainly for the determination of the entrainment and final degree of mixing in the containment atmosphere for evaluation of potential local combustion.

2. INTRODUCTION AND BACKGROUND

2.1. OBJECTIVES

In the initial years of the CAR program, primary objectives were in support of HTGR design and licensing efforts. Specifically, the objectives were to:

1. Provide the technical capability to verify that the fission product barrier formed by the containment structure will remain intact for all design basis accidents, in particular, during depressurizations, [i.e., design basis depressurization accidents (DBDAs).].
2. Reduce containment design costs by eliminating conservatisms in calculational models for the containment atmosphere and the liner thermal response, in particular, for the hot streak.

In the last two years, the objectives of the CAR program have been in support of the AIPA studies, that is, to provide the technical capability to evaluate the retention of fission products within and long-term survival of the containment during core heatup accidents to support HTGR probabilistic risk assessment (PRA) for AIPA studies.

Thus, the CAR program objectives support both HTGR licensing efforts and AIPA studies (Ref. 2-1). The CAR program is also intended to have similar applications for other gas-cooled reactor concepts, such as the gas turbine HTGR (HTGR-GT), the Gas-Cooled Fast Breeder Reactor (GCFR), and the process heat HTGR (HTGR-PH).

2.2. TECHNICAL BACKGROUND

The CAR program, a subtask of the HTGR Safety Research Task of the HTGR Generic Technology Program, was initiated in the fourth quarter of FY-75. The first phase of this subtask consisted of scoping studies on the effect of mixing of primary coolant helium depressurizing into the containment atmosphere on peak temperature and pressure (Ref. 2-2).

Table 2-1 summarizes the types of responses of the containment atmosphere and the primary phenomena associated with these responses. The CAR program is concerned with the systematic analysis of these responses. The second phase, to early FY-77, was described in the interim summary report (Ref. 2-3), dealing mainly with the thermomechanical behavior of the containment atmosphere during depressurizations. In particular, the entrainment of helium blowdown jets, impingement on the containment liner, and liner thermal response were analyzed. Computer models of jet behavior (JETWAY) and containment atmosphere response to various degrees of mixing (CNTB) were developed. A descriptive documentation of the CNTB program was recently completed (Ref. 2-4).

The third phase, to early FY-78, initiated the development of analytical capabilities to evaluate containment phenomena during core heatup Class 9 events, as described in the first status report (Ref. 2-5). This report deals primarily with the chemical behavior of the containment atmosphere, mainly for the evaluation of the flammability potential of gas mixtures containing carbon monoxide and hydrogen and the slow-combustion process. For this purpose, a new computer program called CARCAS was developed, based on the CNTB computer program with substantial modifications, to account for additional ingredients in the PCRV release because of concrete degradation and graphite reaction products. Extensive programming was added to determine the limits of flammability and detonability of the containment atmosphere mixtures and to compute the thermodynamics of the combustion process.

TABLE 2-1
PRIMARY PHENOMENA IN CONTAINMENT ATMOSPHERE RESPONSE PROGRAM

Type of Response	Primary Phenomena
Mechanical	Maximum pressure in containment due to partial mixing and compartments. Strong shock waves due to coolant system rupture.
Thermal	Containment liner hot streaking due to jet impingement.
Chemical	Local and global combustion of gases and particles released into containment atmosphere.
Radioactive	Radioactivity in containment due to fission product release from PCRV. Radioactive leak of containment atmosphere through boundaries.

The present effort concentrates mainly on the containment atmosphere response to the fission product release. The purpose of this work is to support AIPA studies (Ref. 2-1) in the area of event sequences of the core heatup accident. To complete this effort, the CARCAS computer program was considerably extended to include the different processes followed by fission product iodine (Section 3). The processes followed by particulate fission products are described in Section 5, and they will be incorporated into the CARCAS program. In addition, effort was completed on the containment atmosphere response after ignition of flammable mixtures, including models for heat radiation and slow-combustion (Section 4). Further, in connection with containment leaks (Section 6), the containment structural integrity has been re-examined (Section 7), leading to recommendation of future studies.

During FY-79, the TRAINC computer program was developed for the discharge of small helium jets into the containment atmosphere, as reported in Ref. 2-6. Examples of such jets are the PCRV release through the safety relief valve and multiple exhaust ducts and the accidental rupture of the purification system lines. The TRAIN computer program (Ref. 2-7) was linked to a reduced version (CNTBO) of the CNTB computer program (Ref. 2-4), which permits one to follow the transient state of pressures and temperatures prevailing in the containment atmosphere.

Figure 2-1 shows the boundaries to the containment atmosphere of a large HTGR-SC. The support structure of the PCRV, previously a star-shaped structure, is now a post- and ring-supported structure (with an annular gallery), or an integral-design structure. The floors of the annular gallery and the annular region between the PCRV and the containment sidewall are at different levels and connected by stair courses.

The PCRV releases into the plant containment may occur through a failed penetration, as indicated in Tables 11 and 12 of Ref. 2-3. Major PCRV releases (i.e., large jets) do not merge directly into the bulk of the containment atmosphere but into compartments, as shown in Fig. 2-1 (i.e.,

Fig. 2-1. Arrangement of a large HTGR-SC containment

the annular gallery under the PCRV and the space between the refueling platform and the top face of the PCRV). Minor PCRV releases (i.e., small jets) are of secondary importance and more susceptible to being restrained by mitigating precautions. They may occur in the bulk of the containment atmosphere. Controlled PCRV releases, such as the one produced by the opening of the safety relief valve and subsequent discharge through the specified exhaust ducts, can be categorized as minor PCRV releases, i.e., as small jets, since the PCRV discharge can be intentionally designed to produce small jets (e.g., by shower heads).

2.3. PROGRAM STATUS

For fulfillment of objectives 1 and 2 in Section 2.1, the analytical effort for DBDAs is relatively complete, except in the area of pipe whip and missiles caused by the depressurization forces. Figure 2-2 shows a diagram of depressurization phenomena for which analytical capabilities are needed to fulfill these objectives and the corresponding computer programs developed under the CAR program. The present status of the computer programs listed in Fig. 2-2 meets the requirements, except for the area of pipe whip and missiles, which is recommended for future studies. Also, experimental support for the JETWAY computer program is needed to provide data on the behavior of helium jets discharging into air-helium mixtures.

For the third objective in Section 2.1, a diagram of the core heatup phenomena for CAR program studies is shown in Fig. 2-3. The present status of the CARCAS computer program for fulfilling this objective indicates that the incorporation of particulate fission products is needed. With regard to the structural response of the plant containment to overpressurization or combustion, a much longer study is required. This study must start with the categorization of the failure models (which include the effect of missiles), followed by the description of the pertinent models and ending with the development of computer programs.

Fig. 2-2. Depressurization phenomena for CAR program consideration and corresponding computer programs

Fig. 2-3. Core heatup phenomena for CAR program consideration and corresponding computer programs

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- 2-6. "HTGR Generic Technology Program, Safety, Systems, and Component Design and Development. Quarterly Progress Report for the Period Ending September 30, 1978," DOE Report GA-A15132, General Atomic Company, October 1978, pp. 1-11 through 1-14.
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3. MODELS FOR IODINE BEHAVIOR

The models for iodine behavior are discussed in this section. Section 3.1 describes the egress of iodine from the PCRV during the core heatup accident, considering the nature of the release and the release amounts and rates. The mechanisms for the iodine removal processes are discussed in Section 3.2. Section 3.3 shows the computational results obtained for the iodine activity in the containment atmosphere and the iodine release rate to the environment during the core heatup accident. The former results are based on the removal processes described in Section 3.2, while the latter results are based, in addition, on the containment leak described in Section 6.

3.1. EGRESS FROM PCRV

Radionuclides are released from the fuel and primary coolant system as a consequence of the increase in core temperature during core heatup. Two barriers oppose the egress of these radionuclides from the PCRV:

1. The first barrier is in the fuel elements, since the fuel particle kernels and coatings per se serve as the primary barrier to the release.
2. The second barrier is the PCRV. Controlled depressurization of the PCRV takes place to prevent its overpressurization. The whole inventory released from the reactor core is not discharged into the containment atmosphere because of the plateout taking place in the PCRV.

Figure 3-1 indicates in more detail the sequence of steps for the transport of fission products from the fuel elements to the environment (under very unlikely and unmitigated circumstances). Only the aspects

Fig. 3-1. Diagram of interrelated core heatup phenomena affecting fission product source terms (from Ref. 3-1)

related to the last four steps, i.e., following the egress from the PCRV, will be considered in this report, specifically for the fission product iodine.

3.1.1. Nature of Iodine Release

The amount of iodine release during the different scenarios for the core heatup accident is variable. The worst cases correspond to (unrestricted) scenarios occurring without liner cooling which lead to the escape of the total core inventory of fission product iodine from the PCRV. This inventory is estimated at about 30 kg for a 3000-MW(t) plant, which is more than 97% stable, i.e., non-radioactive.

Most likely, the PCRV release is in the form of ferrous iodide (FeI_2), not ferric iodide (Ref. 3-2), owing to the reaction of iodine with the high-temperature steel in the PCRV. Since the chemical reaction

is endothermic (Ref. 3-3), it will proceed to the right in the PCRV, but to the left in the containment atmosphere because the exposed steel is at a lower temperature than the surrounding atmosphere.

In the PCRV, where natural circulation prevails as a consequence of large differential temperatures, the above chemical reaction can go both ways, accompanied not only by condensation of FeI_2 and I_2 but also by chemisorption of I_2 in the thin layer of ferrosferric oxide (Fe_3O_4) covering the steel surfaces (Ref. 3-4). Sorption of I_2 also occurs in Cr_2O_3 or FeCr_2O_4 but at higher temperatures than for Fe_3O_4 (Ref. 3-5).

Downstream of the PCRV safety relief valve are located the exhaust ducts. These ducts are presently specified but not designed. The specifications are mainly to avoid any reduction in the discharge flow determined by the valve and to protect instrumentation and components from that flow.

Even without design, there is no doubt that the exhaust ducts contribute to the plateout and condensation of the PCRV release by retarding and diminishing the radioactive release.

The PCRV releases are presently computed by the PADLOC program (Ref. 3-6). For iodine, the computations are restricted to the FeI_2 carried by the PCRV effluent and its sorption along the PCRV flow paths. No credit is taken for plateout on the exhaust ducts during PCRV blowdown.

The current PADLOC program is restricted to the transport of one nuclide species at a time. This restriction is satisfied by iodine, since it is the first condensable fission product released from the reactor core and the release is essentially complete before concrete degradation, when it occurs.

3.1.2. Amounts and Rate of Release During Core Heatup

Table 3-1 summarizes the key results of the plant response for each of 22 scenarios* (A through V) with sequences in the event trees greater than 10^{-9} per reactor-year. The accumulated iodine releases from the PCRV in correspondence to these scenarios are shown in Figs. 3-2, 3-3, and 3-4. The starting time for concrete degradation, mentioned in Section 3.1, is shown in correspondence to the iodine released. The normalized values are referenced to 30 kg as the weight of the initial inventory.

The iodine releases from the PCRV occur in three distinct forms:

1. An initial puff at the initiation of the helium blowdown (i.e., opening of the PCRV relief valve).
2. A continuous, low-level release immediately after the helium blowdown, which is conservatively estimated at 2% volume per hour.

* A detailed description of those scenarios can be found in Sections 4.3.1 through 4.3.5 of Ref. 3-1.

TABLE 3-1
SUMMARY OF SALIENT CORE HEAT SCENARIOS (FROM REF. 3-1)

Core Heatup Scenario	A	B	C	D	E	Q	U	F	G	H	R	V	I	J	K	P	S	L	M	N	O	T
Sequence Frequency, yr^{-1} ^(a)	1(-8)	2(-7)	1(-8)	2(-7)	2(-6)	4(-9)	2(-10)	2(-8)	4(-7)	4(-6)	8(-9)	3(-10)	1(-7)	2(-6)	2(-5)	4(-9)	4(-8)	6(-10)	1(-8)	2(-7)	2(-6)	2(-9)
Reactor trip time ^(b)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LOFC mean time	0	0	0	0	0	0	0	0	0	0	0	0	5	5	5	5	5	5	55	55	55	55
MTRC ^(c)	3	3	3	3	3	3	3	3	3	3	3	3	18	18	18	18	18	18	83	83	83	83
LCS ^(d) mean operation time	--	--	16.5	16.5	16.5	16.5	16.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CFS ^(e) mean operation time	90	90	16.5	16.5	16.5	--	--	0	0	0	--	--	0	0	0	--	--	--	0	0	0	--
PCRV relief time	7	7	7	7	7	7	7	11	11	11	11	11	35	35	35	35	35	35	125	125	125	125
Containment isolation time	≤ 7	≤ 7	≤ 7	≤ 7	≤ 7	≤ 7	--	≤ 11	≤ 11	≤ 11	≤ 11	--	≤ 35	≤ 35	≤ 35	≤ 35	≤ 35	--	≤ 125	≤ 125	≤ 125	≤ 125
Average fuel time																						
1600°C [871°F]	10	10	10	10	10	10	10	10	10	10	10	10	27	27	27	27	27	27	100	100	100	100
2000°C [1093°F]	20	20	20	20	20	20	20	20	20	20	20	20	38	38	38	38	38	38	130	130	130	130
Average top thermal barrier failure time	45	45	92	92	92	92	92	92	92	92	92	92	114	114	114	114	114	114	237	237	237	237
LCS failure time	0	0	92	92	--	--	--	92	92	--	--	--	114	114	--	114	--	--	237	237	--	--
Top concrete degradation time	50	50	97	97	--	--	--	97	97	--	--	--	119	119	--	119	--	--	242	242	--	--
Side concrete degradation time	87	87	127	127	--	--	--	127	127	--	--	--	149	149	--	149	--	--	275	275	--	--
Containment overpressurization ^(f)																						
Gas burning	143	--	190	--	--	--	--	190	--	--	--	--	212	--	--	--	--	335	--	--	--	--
Gas accumulation	--	238	--	285	--	--	--	--	285	--	--	--	--	307	--	307	--	--	--	430	--	--

(a) 1(-8) denotes 1×10^{-8} .

(b) Time to nearest hour to show trends, not significant figures.

(c) MTRC = maximum time to restore forced circulation.

(d) LCS = liner cooling system.

(e) CFS = cleanup filter system.

(f) Containment failure pressure assumed as 100 ± 15 psia, per Ref. 3-1, p. 4-224.

Fig. 3-2. Accumulated iodine release from PCRV with no forced cooling prior to core heatup (from Ref. 3-1)

Fig. 3-3. Accumulated iodine release from PCRV with 5 hr of forced cooling prior to core heatup (from Ref. 3-1)

Fig. 3-4. Accumulated iodine release from PCRV with 55 hr of forced cooling prior to core heatup (from Ref. 3-1)

3. The main release, concurrent with the PCRV release of concrete decomposition and graphite oxidation products (if occurring).

A preliminary assessment of the iodine behavior in the containment atmosphere can be performed by establishing bounds in case of a PCRV release with 100% of its total inventory. Table 3-2 lists the main characteristics of the containment atmosphere for a 3000-MW(t) reference plant before the initiation of any of the scenarios listed in Table 3-1.

3.1.2.1. I_2 . If the iodine release is in the form of molecular iodine, its vapor pressure p_{I_2} is governed by the ideal gas law according to the values in Table 3-1, i.e.,

$$p_{I_2} = 5.40 \text{ Pa} = 0.000783 \text{ psia} .$$

Figure 3-5, based on data in Ref. 3-7, indicates that the saturation pressure of iodine p_s is, at the temperature in Table 3-1,

$$p_s = 122 \text{ Pa} = 0.0177 \text{ psia} .$$

Since the values of p_s increase more than those of p_{I_2} with increasing temperatures, it is concluded that if the entire inventory of iodine were released to the containment atmosphere in the form of I_2 , it would remain as vapor in the absence of any removal mechanism.

3.1.2.2. FeI_2 . If the iodine release is in the form of ferrous iodide, its saturation pressure p_s is as shown in Fig. 3-6, based on data from Ref. 3-8,

$$p_s < 10^{-18} \text{ Pa} = 1.45 \times 10^{-22} \text{ psia [extrapolated at } 38^\circ\text{C (} 100^\circ\text{F)}] ,$$

TABLE 3-2
CONTAINMENT ATMOSPHERE CHARACTERISTICS FOR A 3000-MW(t) RERERENCE PLANT

Parameter	Value	
	SI Units	British Units
Free volume	$56.6 \times 10^3 \text{ m}^3$	$2 \times 10^6 \text{ ft}^3$
Pressure	$1.013 \times 10^5 \text{ Pa}$	14.7 psia
Temperature	38°C	100°F
Total exposed surface	$19.8 \times 10^3 \text{ m}^2$	$213 \times 10^3 \text{ ft}^2$

Fig. 3-5. Vapor pressure of I_2

Fig. 3-6. Vapor pressure of FeI_2

or even

$$P_s = 4.69 \times 10^{-3} \text{ Pa} = 680 \times 10^{-9} \text{ psia [extrapolated at } 329^\circ\text{C (624}^\circ\text{F)}^*]$$

These saturation pressures are well below P_{I_2} , which corresponds to the metastable vaporized form of FeI_2 . Since the conditions in the containment atmosphere are far different from those required for the potential existence of metastable equilibrium, it is concluded that if the iodine is released in the form of FeI_2 , it almost totally condenses in the atmosphere (aerosol) or on its boundaries.

3.2. REMOVAL PROCESSES

The mechanisms for the removal of iodine from the containment atmosphere, with the exception of the cleanup system, occur spontaneously during the evolution of the transient states following accident situations. These mechanisms are described with the aid of analytical models which are computationally implemented to predict the transient state of radioactive iodine in the containment atmosphere and the potential leak to the environment. The consideration of detailed mechanisms for iodine removal from the containment atmosphere constitutes an appreciable improvement over previous models reported in Ref. 3-9.

The iodine release from the PCRV is assumed to be in the form of molecular iodine (I_2) for the following reasons:

1. Since the containment atmosphere is at higher temperatures than its boundaries, in contrast to the PCRV atmosphere, and since the formation of FeI_2 is produced by an endothermic reaction, it is possible that the FeI_2 reverts to Fe and I_2 , as shown by some tests.

*This temperature is the peak temperature in the containment atmosphere during helium blowdown, following the opening of the PCRV safety relief valve, and it is below the melting point of FeI_2 , i.e., $867^\circ\text{K}(1100^\circ\text{F})$.

2. Although most plateout in the PCRV is expected to be in the form of FeI_2 , small fractions released to the containment for some scenarios may be in the form of I_2 .

Advantage can be taken of studies made of molecular iodine diffusion in concrete and sorption by coated steel surfaces under HTGR containment conditions.

3.2.1. Description of Removal Processes

The models for the different iodine removal processes in the containment atmosphere are described below.

3.2.1.1. Filtration of Containment Atmosphere. Either a specified fraction f_f or the entire free volume of the containment V_c may circulate through the containment atmosphere filters when the cleanup system is operative. Thus, a non-circulating portion (i.e., unfiltering portion) can be considered.

With the efficiency of the filters denoted by λ_f and the relative volumetric rate circulating through the filters by $\dot{V}_c/V_c$, in s^{-1} , the relative (fractional) removal of iodine during the time interval Δt is given by

$$\frac{V_c}{V_m} f_f \left[1 - \exp \left(-\lambda_f \frac{\dot{V}_c}{V_c f_f} \Delta t \right) \right],$$

where V_m/V_c is the fraction of the free volume of the containment atmosphere which remains mixed. Since the internal circulation established by the cleanup system produces mixing in the portion of the free volume of the containment participating in the process, the following expression is satisfied:

$$\frac{V_c}{V_m} f_f \leq 1.$$

3.2.1.2. Sorption by Coating on Steel Surfaces. Uncoated steel seems to exhibit a limited amount of iodine sorption, according to Ref. 3-5, Fig. 12, p. 31. However, since the containment design provides for an epoxy coating on many surfaces, the sorption of iodine is intentionally promoted. Coated surfaces are provided for the containment liner and the side plate covers of the PCRV. Part of the piping and other exposed steel surfaces may also be coated. When iodine is released into the containment atmosphere, sufficient sorption sites are available in the coating. Thus, the coated surfaces behave like perfect sinks, and the gaseous concentration of iodine C_g decays according to the expression (Ref. 3-10)

$$V_m \frac{dC_g}{dt} = -C_g \left(\sum_i k_i A_i \right) dt ,$$

where A_i and k_i are the exposed area and the mass transfer coefficient of the coated steel surface i , respectively, and t is time. The relative (fractional) removal of iodine during the time interval Δt is given by

$$\frac{\sum_i k_i A_i}{V_m} \Delta t .$$

The mass transfer coefficients k_i are obtained from a similar correlation for the heat transfer coefficient for natural convection in the presence of a turbulent boundary layer (Ref. 3-11).

Sorption by applied coating is effective as long as the exposed surfaces remain dry. When the exposed surfaces are wet because of steam condensation, another iodine removal process takes over.

3.2.1.3. Steam Condensation on Containment Boundaries. Since iodine is soluble in water, steam condensation on surfaces exposed to the containment atmosphere causes the surfaces to become perfect sinks for iodine. Condensate water runs along the surfaces down to the drainage system at the bottom of the containment building.

Condensation on a specific surface occurs when the saturation pressure, at the temperature of the surface, is below the water vapor pressure prevailing in the containment atmosphere. The formulation of iodine removal by steam condensation is similar to the process described in Section 3.2.1.2:

$$V_m \, dC_g = -C_g \left(\sum_j k_j A_j \right) dt \quad ,$$

where j refers to the wetted surfaces and k_j is the mass transfer coefficient for iodine due to steam condensation.

The relative (fractional) removal of iodine during the time interval Δt is given by

$$\frac{\sum_j k_j A_j}{V_m} \Delta t \quad .$$

Again, the mass transfer coefficients are obtained from a similar correlation for the heat transfer coefficient for natural convection in the presence of a turbulent boundary layer (Ref. 3-11).

As steam condensation proceeds, the running water on the steam-condensing surfaces acts to dissolve the iodine absorbed, settled, or attached to these surfaces and to reverse the direction of the diffusive flux, as is the case for iodine diffusing through stressed concrete considered below. Furthermore, since the ionized particles and dust act as centers of condensation, the removal of iodine in the containment atmosphere layers adjacent to steam-condensing surfaces can be considered as totally effective.

3.2.1.4. Permeability and Retentivity of Stressed Concrete. Concrete surfaces exposed to the containment atmosphere are very limited in area. They are confined to the PCRV, its support structure, and the containment

floor. Furthermore, the containment floor is intentionally treated to render it impermeable to radioactive spills; thus, for practical purposes the containment floor cannot retain iodine.

Recent investigations performed for Brookhaven National Laboratory (Ref. 3-12) indicate that iodine diffuses through concrete under two different modes, which are coupled. Since the principal contributor is the slow-diffusion process, the contribution by fast diffusion is neglected. Moreover, the equilibrium ratio of iodine concentration at the concrete surface C_s to the iodine concentration in the gaseous phase C_v can be expressed by a partition coefficient K (i.e., $K = C_s/C_v$ specifies the boundary condition). The differential equation for the iodine diffusion process is taken in one-dimensional form,

$$\frac{\partial C}{\partial t} = D \frac{\partial^2 C}{\partial z^2} ,$$

where C is the concentration of iodine in the stressed concrete, t is time, and z is the coordinate in a direction perpendicular to the exposed surface ($z = 0$). The diffusion coefficient for the slow-diffusion process is D .

From Ref. 3-12, the partition coefficient is

$$K = 5 \times 10^4 ,$$

and the temperature T dependent diffusion coefficient is

$$D \left(\frac{\text{m}^2}{\text{s}} \right) = 6.76 \times 10^{-10} \exp \left(-\frac{1857}{T \text{ (}^\circ\text{K)}} \right) ,$$

where $Q = 1857 R = 3690 \text{ kcal/mole}$ is the activation energy.

The relative (fractional) removal of iodine during the time interval Δt is given by

$$-\Delta t \sum_{\ell} A_{\ell} \left(D_{\ell} \frac{\partial C}{\partial z} \right)_{z=0},$$

where the sum over the index ℓ is for the concrete surfaces exposed to the mixed portion of the containment atmosphere.

3.2.2. Quantification of Removal Processes

To establish a comparison of the different processes for iodine removal from the containment atmosphere, the processes are expressed analytically in a common form. The preceding description indicates that the comparative results must be expressed in the form of exponential decay constants, denoted by Λ .

3.2.2.1. Filtration of Containment Atmosphere. The decay constant for this process is Λ_f :

$$\Lambda_f = \frac{V_c}{V_m} \lambda_f \frac{\dot{V}_c}{V_c} = \frac{\dot{V}_c}{V_m} \lambda_f.$$

In Ref. 3-1, p. 4-248, the whole containment atmosphere is filtered. Thus,

$$\frac{V_c}{V_m} f_f = 1,$$

while

$$\frac{\dot{V}_c}{V_c f_f} = 1 \text{ hr}^{-1}$$

and

$$\lambda_f = 0.95^* .$$

Based on the above parameters, the decay constant Λ_f is estimated to be

$$\Lambda_f = 0.95 \text{ hr}^{-1} .$$

3.2.2.2. Sorption by Coating on Steel Surfaces. From Ref. 3-1, p. 4-248, the total area of the coated surfaces exposed to the containment atmosphere is

$$\sum_i A_i = 10.4 \times 10^3 \text{ m}^2 = 112 \times 10^3 \text{ ft}^2 ,$$

while the average mass transfer coefficient for iodine can be considered (Ref. 3-14) to be of the order of

$$\bar{k} = 5.5 \text{ m/hr} = 18 \text{ ft/hr}$$

and the containment free volume (Table 3-2) to be

$$V_c = 56.6 \times 10^3 \text{ m}^3 = 2 \times 10^6 \text{ ft}^3 .$$

Based on the above parameters, the decay constant Λ_c is

$$\Lambda_c = \bar{k} \frac{\sum_i A_i}{V_c} = 1.0 \text{ hr}^{-1} .$$

* Other estimates for λ_f are 0.99 and 0.90, given in Refs. 3-10 (p. VII-186) and 3-13, respectively.

3.2.2.3. Steam Condensation on Containment Boundaries. In addition to V_c , from Table 3-2 the value of the total exposed area of the containment boundaries is

$$\sum_j A_j = 19.8 \times 10^3 \text{ m}^2 = 213 \times 10^3 \text{ ft}^2 .$$

Using also an estimate for the mean mass transfer coefficient from Ref. 3-1, p. 4-249,

$$\bar{k} = 91.4 \text{ m/hr} = 300 \text{ ft/hr} ,$$

it follows that the decay constant Λ_s is

$$\Lambda_s = \bar{k} \frac{\sum_j A_j}{V_c} = 32.0 \text{ hr}^{-1} .$$

3.2.2.4. Permeability and Retentivity of Stressed Concrete. A pragmatic estimation of Λ_d was attempted in Ref. 3-1, pp. 4-250 through 4-252, based on computational results for the iodine in the containment atmosphere with acting and suppressed diffusivity in the untreated concrete boundaries. A different estimation of Λ_d is given below.

Table 3-3 describes the untreated concrete boundaries exposed to the containment atmosphere for a 3000-MW(t) reference plant. The temperature of these surfaces is about 55°C (130°F) while remaining unwetted before steam condensation. The coefficient of diffusion is then

$$D = 2.34 \times 10^{-12} \text{ m}^2/\text{s} = 0.252 \times 10^{-10} \text{ ft}^2/\text{s} .$$

From Table 3-1, the containment atmosphere boundaries remain unwetted during the time Δt (from the opening of the PCRV safety relief valve

TABLE 3-3
UNTREATED CONCRETE SURFACES OF A 3000-MW(t) REFERENCE PLANT

Description	Surface Area		Thickness	
	m ²	ft ²	m	ft
PCRV wall	1,090	11,735	2.74	9
PCRV lower face	299	3,216	2.74	9
PCRV support structure	704	7,576	1.52	5
Total area	2,093	22,527		
Average thickness			2.33	7.65

until steam condensation begins), so that

$$\Delta t = 50 - 7 = 43 \text{ hr} .$$

From arguments of dimensional analysis, the significant penetration of iodine in the untreated concrete boundaries is of the order of

$$\sqrt{D\Delta t} = 6.02 \times 10^{-4} \text{ m} = 1.98 \times 10^{-3} \text{ ft} ,$$

which is much shorter than the average thickness of those boundaries (2.33 m = 7.65 ft, Table 3-3). Consequently, those boundaries can be considered as semi-infinite plane boundaries. Considering next those boundaries exposed during Δt at a constant concentration (i.e., constant bulk concentration in the containment atmosphere), the amount diffused into the boundaries referred to the initial concentration is (Ref. 3-15)

$$\frac{V_c \Delta C}{C} = K \int_0^{\Delta t} \sqrt{\frac{D}{\pi t'}} \left(\sum_{\ell} A_{\ell} \right) dt' = 2K \left(\sum_{\ell} A_{\ell} \right) \sqrt{\frac{D}{\pi} \Delta t} ,$$

where (from Table 3-3)

$$\sum_{\ell} A_{\ell} = 2093 \text{ m} = 22,527 \text{ ft}^2 .$$

Thus, for a first approximation,

$$\frac{V_c \Delta C}{V C} = 2 \frac{K}{V_c} \left(\sum_{\ell} A_{\ell} \right) \sqrt{\frac{D}{\pi} \Delta t} = 1 - \exp(-\Lambda_d \Delta t) ,$$

assuming that the diffused amount is small compared with the initial amount in the atmosphere. This assumption is valid only for Δt of the order of a few hours since, approximately,

$$\Lambda_d \text{ (hr}^{-1}\text{)} = \frac{0.191}{\sqrt{\Delta t \text{ (hr)}}} .$$

Table 3-4 lists the estimates for Λ_d from

$$\Lambda_d = \frac{\ln \left[1 - 2 \frac{K}{V_c} \left(\sum_{\ell} A_{\ell} \right) \sqrt{\frac{D}{\pi}} \Delta t \right]}{\Delta t}$$

for the first few hours from the opening of the PCRV safety relief valve. For practical purposes, it can be concluded that $\Lambda_d < 0.1 \text{ hr}^{-1}$.

To corroborate the last conclusion, computer runs were performed for scenario A (Table 3-1) with acting and suppressed diffusivity of iodine in the untreated concrete boundaries. After

$$\Delta t = 2.16 \times 10^4 \text{ s} = 6 \text{ hr} ,$$

the iodine in the containment atmosphere is

$$V_c C = 0.832 \text{ kg} = 1.834 \text{ lb (acting diffusivity)} ,$$

$$V_c C' = 0.883 \text{ kg} = 1.998 \text{ lb (suppressed diffusivity)} .$$

Thus,

$$\Lambda_d = \frac{\ln \frac{C'}{C}}{\Delta t} = 0.010 \text{ hr}^{-1} ,$$

which is well below the previous estimate (Table 3-4) because of the distinct forms of the iodine release as described in Subsection 3.2.1.

Table 3-5 lists the decay constant values for iodine removal processes. The dominant process for iodine removal is steam condensation, while the least effective process for iodine removal is permeability and retentivity of concrete. The iodine removed from the containment atmosphere by steam condensation is dissolved in the water running along the

TABLE 3-4
ESTIMATE OF DECAY CONSTANT FOR IODINE REMOVAL BY UNTREATED CONCRETE
IN A 3000-MW(t) REFERENCE PLANT

PCRV Relief Time (hr)	Decay Constant, Λ_d (hr ⁻¹)
0	∞
1	0.212
2	0.157
3	0.134
6	0.105

surfaces down to the containment building sumps. The iodine removed from the containment atmosphere by diffusing into the untreated concrete boundaries may be returned to the containment atmosphere if its iodine concentration reduces, diffusing out of the concrete. However, if steam condensation is present, the iodine is first leached out by the water running along the untreated concrete surfaces.

TABLE 3-5
DECAY CONSTANTS FOR IODINE REMOVAL PROCESSES

Process	Decay Constant (hr ⁻¹)
Containment atmosphere filters	0.95
Sorption by coating on steel surfaces	1.0
Steam condensation	32
Permeability and retentivity of concrete	<0.1

3.2.3. Restrictions

Two minima for the iodine activity in the containment atmosphere restrict the computational results obtained by the previously described removal processes:

1. The minimum amount of molecular iodine in the containment atmosphere is at least 0.1% of the total iodine release from the PCRV, in agreement with the results shown in Fig. 7 of Ref. 3-14.
2. Unless the containment atmosphere filters are able to remove methyl iodine to lower limits, a minimum value of 1% of the iodine release from the PCRV is considered to be in the form of methyl iodine. Organic iodides plate out slowly and are more difficult to clean up. The available information on the formation of organic iodides under accident conditions in HTGRs

has been reviewed in Ref. 3-16. The conservative upper bound estimate was 10.1% for containment atmospheres containing oxygen, such as during an HTGR core heatup. A realistic estimate of less than 1% formation of organic iodide under accident conditions in water-cooled reactors was also projected in Ref. 3-17. There is no experimental basis for concluding that the percentage conversion would be higher or lower in an HTGR containment than in a light water reactor (LWR) containment. Thus, 1% methyl iodine formation was assumed for HTGR core heatup sequences.

In addition to the above-mentioned processes, there exists a concurrent plateout and fallout of dust suspended in the containment atmosphere. This dust is difficult to specify since it has a complex generation: concrete decomposition, re-entrainment of carbon deposits on the primary cooling system, etc. Iodine was assumed to behave as a vapor; less volatile fission products are expected to be in particulate form or be plated out on dust. Therefore, natural deposition of elements other than iodine must be treated differently and is closely associated with aerosol behavior.

3.3. COMPUTATIONAL RESULTS FOR CORE HEATUP

The following results were obtained with the aid of the CARCAS computer program, which contains the iodine removal models (Section 3.2) and the containment leak models (Section 6). The reported results update previous ones in Ref. 3-1 for AIPA studies, because of the above-mentioned model improvements.

Two type of results are reported for radioactive iodine during unrestricted core heatup scenarios A and B from Ref. 3-1 (concrete degradation sequences):

1. Iodine in the containment atmosphere.
2. Iodine leaked from an isolated containment.

The activities and activity rates for (1) and (2), respectively, do not account for the minimum iodine in the containment atmosphere, as mentioned in Section 3.2.3.

3.3.1. Iodine in Containment Atmosphere

Figure 3-7 shows the activity, in curies, of the five significant radioactive isotopes of iodine, I-131, I-132, I-133, I-134, and I-135, versus time. The initial peak in activity at the opening of the PCRV safety relief valve is due to the activity carried by the helium blowdown. The containment atmosphere becomes wet about 43 hr after the initiation of helium blowdown owing to the release from the PCRV of concrete decomposition products (Table 3-1). However, the removal of iodine is not concluded until steam condensation begins (about 100 hr after the initiation of helium blowdown in Fig. 6-5). Before the initiation of steam condensation, iodine removal is governed by spontaneous processes and the cleanup filter system, whose operation is restored 83 hr after the initiation of the helium blowdown (Table 3-1). Figure 3-7 shows two substantial decreases in the activities of I-131 and I-133 due to first the restoration of the cleanup filter system and later the beginning of steam condensation on the containment atmosphere boundaries.

3.3.2. Iodine Released to Environment

For isolated or closed containments, a constant leak rate specified as a fraction of the containment free volume per unit time is representative of licensing requirements, permitting no more than 0.1% per day for the computation of the radioactive release of air-borne particulates to the environment (Ref. 3-18).

As explained in Section 6.1.1, the variable leak rate from the containment building is obtained after attributing the above value to the peak pressure conditions prevailing in the containment atmosphere

Fig. 3-7. Iodine activity in containment atmosphere (scenarios A and B)

during a hot leg DBDA. Thus, according to Fig. 6-1, the variable leak rate is

$$\frac{0.001}{24 \times 47.75} = 0.8726 \times 10^{-6} \frac{1}{\text{hr} \cdot \text{psig}} = 0.1266 \times 10^{-9} \frac{1}{\text{hr} \cdot \text{Pa}}$$

Figure 3-8 shows the activity release rates for significant radioactive isotopes of iodine from an isolated containment versus time. The activity release rates were obtained by using the above-derived variable leak rate. The curves shown in Fig. 3-8 are not proportional to those in Fig. 3-7 because of the variable containment atmospheric pressure during the transient.

Approximately 100 hr after the opening of the PCRV relief valve, the containment sidewall remains wet and the leak rates are nil.

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Fig. 3-8. Iodine release rate activity from isolated containment (scenarios A and B)

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4. CONTAINMENT ATMOSPHERE RESPONSE TO COMBUSTION

A few areas were not completely covered for the thermal transient response of the containment atmosphere, in case of combustion, at the time the relevant material for Refs. 4-1 and 4-2 was published. Those areas are thermal radiation to the containment boundaries and items related to the slow-combustion process (flame propagation and imperfect combustion), and they are needed for a more realistic computation of the transient state of pressures and temperatures in the containment atmosphere after combustion initiation. The pertinent models are described in this section.

4.1. THERMAL RADIATION

Computer programs developed at General Atomic for the transient behavior of pressures and temperatures in the containment atmosphere (Refs. 4-3 and 4-4) did not account for the radiant heat between the containment atmosphere and its boundaries. As a result, higher pressures and temperatures are computed for the containment atmosphere, but lower temperatures for its boundaries.

Since radiant heat follows the fourth power of the absolute temperature, so far as its transmission is concerned, its effect is more important at high temperatures. In the absence of combustion, heat radiation mainly arises during DBDAs (a) at the initial release of the PCRV helium blowdown and (b) around the peak temperature of the containment atmosphere. The former case (a) is more important if the containment atmosphere remains totally unmixed; however, high temperatures during the initial release of the PCRV are not associated with high pressures in the containment. For the latter case (b), peak temperature and pressure are not simultaneous.

The peak temperature occurs earlier (Ref. 4-4, Figs. 5-3 and 5-4) because of the heat transfer to the containment boundaries. An attempt to account for heat radiation for the peak temperature event is not only insignificant [peak temperature = 310°C (590°F), Ref. 4-4, Fig. 5-4], but also prolongs the time interval between the peak temperature and peak pressure events, diminishing their interrelation.

In the event of combustion of flammable gases in the containment atmosphere, high temperatures become associated with high pressures, with the potential overpressurization of the containment building. Therefore, a realistic estimate for the transient state requires the computational implementation of the radiant-heat process. Consequently, the radiant-heat model is applied only after combustion initiation.

The containment atmosphere after combustion can be considered as non-diathermanous because of the presence of water vapor and carbon dioxide. After combustion the main constituents of water gas, hydrogen and carbon monoxide, become water vapor and carbon dioxide, respectively. The gaseous suspension of solid or liquid particles, called aerosols, in the containment atmosphere contributes to its opacity, although these particles are essentially non-luminous.*

Relevant material for the heat radiation model can be found, for instance, in Refs. 4-5 and 4-6. Figure 4-1 shows the simplified model for radiant heat from a uniformly burnt containment atmosphere. This model allows one to define the beam length L , which is approximately (Ref. 4-5, p. 89)

$$L = (0.85) (2R_c) = 1.7 R_c ,$$

* The potential combustion of carbon dust carried by helium during blow-downs is considered both analytically and computationally (SILT computer program) in Ref. 4-1, Sections 5.5 and 6.3.

$$R_c = \sqrt[3]{\frac{3 V_c}{4 \pi}}$$

V_c : FREE VOLUME OF THE CONTAINMENT ATMOSPHERE

R_c : RADIUS OF SPHERE WITH VOLUME V_c

Fig. 4-1. Simplified model for radiant heat from a uniformly burnt containment atmosphere

where (Fig. 4-1)

$$R_c = 23.8 \text{ m} = 78.2 \text{ ft} .$$

Thus,

$$L = 40.5 \text{ m} = 133 \text{ ft} .$$

Since the containment atmosphere is at higher temperature than its boundaries after combustion initiation, only the radiant heat from the atmosphere to the boundaries is considered, which can be expressed, in terms of the heat rate per unit area $\dot{q}$ for the boundary surfaces s ,^{*} as approximately

$$\dot{q} = \sigma \frac{1 + \epsilon_s}{2} \left(\epsilon_A T_A^4 - \alpha_{As} T_s^4 \right) ,$$

where σ = Stefan-Boltzmann constant,

ϵ = emissivity, ϵ_s for surface s , ϵ_A for the containment atmosphere,

α = absorptivity, α_s for surfaces, α_{As} for the containment atmosphere for radiation from surface s ,

T = absolute temperature, T_s for surface s , T_A for the containment atmosphere.

Numerical values are

$$\sigma = 5.67 \times 10^{-5} \frac{\text{erg}}{\text{cm}^2 \cdot \text{s} \cdot \text{K}^4} = 4.758 \times 10^{-13} \frac{\text{Btu}}{\text{ft}^2 \cdot \text{s} \cdot \text{R}^4} ,$$

* The sum of all the boundary surfaces s is not equal the area of the sphere of radius R_c in Fig. 4-1. There is no contradiction in this inequality, since (1) Fig. 4-1 is only for the purpose of obtaining the beam length L , and (2) the boundary surfaces s only receive radiant heat from the containment atmosphere, without exchanging heat among themselves.

$$\epsilon_s \approx \begin{cases} 0.96 & \text{for wetted boundaries by condensing steam} \\ 0.65 & \text{for unwetted boundaries (average value)} \end{cases},$$

$$\epsilon_A \approx 0.9,$$

$$\alpha_{As} \approx \epsilon_A \sqrt{\frac{T_s}{T_A}}.$$

The approximate values for ϵ and α refer to the conditions prevailing for scenario A after initiation of combustion.

4.2. SLOW COMBUSTION

No computational model was operative at the time of calculating the results for Ref. 4-2 in the areas of:

1. Flame propagation.
2. Imperfect or partial combustion.

Actually, in reference to Fig. 4-67 of Ref. 4-2, cases 1 and 2 (i.e., for instantaneous and total combustion and for instantaneous and partial combustion, respectively) are obtained by computational results. Also in that figure, cases 3 and 4 (i.e., to account for flame propagation during total and partial combustion, respectively) are plotted with broken lines, which correspond to estimates supported by the arguments given on pp. 4-209 through 4-218 of Ref. 4-2.

To present a more realistic solution, in particular for the transient state of pressures in the containment atmosphere after ignition, the two above-mentioned alleviating factors are computationally taken into account according to the models described below.

4.2.1. Flame Propagation

A model for flame propagation was devised in the OXIDE-2 computer program (Ref. 4-7) and was later used for the results reported in Ref. 4-2, p. 4-210. This model has been improved for present purposes.

There are two aspects of flame propagation, the speed and the direction of propagation, which are separately considered below.

4.2.1.1. Speed of Flame Propagation. An estimate of the finite speed of the propagation of flame, disregarding the influence of suspended particles and the increasing pressure in the containment atmosphere during flame propagation, can be performed. The burning rate b is referred to the air (a) to water gas (f) ratio, which becomes

$$\frac{a}{f}$$

for the stoichiometric mixture. An interpolatory formula for $b = b(a/f)$, conservatively based on experimental data for carbureted water gas (Ref. 4-8), is used for computational purposes. This formula yields

$$b = 0 \text{ for } \begin{cases} a/f = 0 \\ a/f = \infty \end{cases}$$

and

$$b = b_{\max} \text{ for } a/f = 2.38$$

4.2.1.2. Direction of Flame Propagation. The limits of flammability for downward propagation of flame for the single constituents of water gas in air are reported in the literature. For hydrogen, the limit is 9% (Refs. 4-9 and 4-10), while for carbon monoxide, the limit is about 15%. This latter value is extrapolated from Fig. 10 of Ref. 4-9 for large tube diameters.

To determine the minimum burning time if the concentrations of the single constituents of water gas are below the above flammability limits, a single or multiple ignition source at the bottom of the containment building is required for burning the whole containment atmosphere. By contrast, if the concentrations of the single constituents of water gas are above the above flammability limits, then an ignition source(s) at the elevation of the top face of the PCRV can produce a flame front reaching the top and bottom of the containment building almost simultaneously. Figure 4-2 shows, for a vertical cross section of the containment building, the location of the ignition sources which minimize the burning time depending on the direction of flame propagation. Distances covered by the flame front are of the order of 36.5 to 73 m (120 to 240 ft), depending on whether it propagates in any direction or only upward, respectively.

Structures encountered by the flame front will oppose flame propagation and prolong the burning time. Such structures include, in particular, the grating at different levels in the annular space between the PCRV and the containment sidewall. This grating consists of an array of bars [usually 3.2 cm (1-1/4 in.) long, 0.32 cm (3/16 in.) thick, spaced 2.54 cm (1 in.) apart]. The bars are sufficiently far apart to be comparable in effect to flame propagating in tubes, but not as effective as the gauge in Davy safety lamps.

The flame front may be imagined initially as cylindrical or spherical. The ignition source could be a portion of bare electrical wire in the former case or a point spark in the latter case. In any event, the

Fig. 4-2. Location of ignition sources to minimize burning time

burned zone starts growing gradually as the square or the cube of its radius, respectively. Later, as the flame front propagates, it becomes irregular in form, impinging on obstacles and wiggling. However, no self-combustible pockets, such as those occurring during car engine knocking, exist for the following reasons:

1. The containment atmosphere is off the detonation region.
2. The temperature rise in the unburned pocket due to compression by the burning atmosphere falls below the ignition temperature of water gas.*

4.2.2. Imperfect or Partial Combustion

A revision of the model reported in Ref. 4-2 was effected by referring to the individual limits of flammability of the water gas components (carbon monoxide and hydrogen), rather than the limit of flammability of water gas (as in Ref. 4-2). Hydrogen exhibits incomplete combustion in air at its lower limits of flammability. Table 4-1 lists the results reported in Ref. 4-9. Based on these results, an interpolatory formula can be used for the combustion fraction of the form

$$1 - e^{-46.21\Delta f},$$

where the factor 46.21 in the exponent is based on the first two points in Table 4-1, and Δf is the fraction of hydrogen departing from the limit of flammability. In fact, for the third point in Table 4-1,

$$\Delta c = 0.10 - 0.041 - 0.059$$

*The ignition temperature of the individual constituents of water gas in air is over 570°C (about 1060°F) according to Ref. 4-11. Adiabatic compression of the unburnt portion of the containment atmosphere by the burning one is not able to reach this temperature.

TABLE 4-1
PARTIAL COMBUSTION OF HYDROGEN IN AIR

Hydrogen Fraction (%)	Combustion Fraction (%)
4.1	0
5.6	50
10	100

TABLE 4-2
PARTIAL COMBUSTION OF CARBON MONOXIDE IN AIR

Carbon Monoxide Fraction (%)	Combustion Fraction (%)
17.8	93.1 (lower limit)
19.0	97.0
21.0	100.0

and

$$1 - e^{-(46.21)(0.059)} = 0.935$$

instead of one, but in agreement with 0.94 burning at 10% hydrogen at 1.01×10^5 Pa (10 atm) (Ref. 4-12 p. 559). Partial burning of hydrogen at its upper limit of flammability was also determined in Ref. 4-12 (p. 560), and the determination close to that limit indicates 0.53 partial burning at 73.4% hydrogen at 5.06×10^6 Pa (50 atm).

Carbon monoxide seems to partially burn with air. The values in Table 4-2 at 1.01×10^5 Pa (10 atm) (Ref. 4-12, p. 568) can be interpolated by the expression

$$0.931 + 0.069 (1 - e^{-69.41\Delta f})$$

where Δf is now the fraction of carbon monoxide departing from the limit of flammability. This interpolatory formula satisfies the first two points of Table 4-2. The third point in Table 4-2 yields 0.993 as the burning fraction, instead of one. Thus, the interpolatory formula can be considered satisfactory for small departures from the limits of flammability.

4.3. TRANSIENT STATE OF PRESSURES AND TEMPERATURES DURING CORE HEATUP

In this section, the application of the thermal radiation and slow-combustion models is shown for core heatup scenarios A and B by following the transient state of pressures and temperatures in the containment atmosphere. A summary of the events for scenarios A and B (for burning and non-burning conditions, respectively) is given in Table 3-1. For these scenarios, the containment atmosphere remains under flammable conditions between 111 and 161 hr after the initiation of the helium blow-down. The former time corresponds to the limit of flammability for lean mixtures, and the latter time corresponds to the limit of flammability

for rich mixtures. For scenario A, successful ignition of the containment atmosphere is assumed to occur at about mid-time, 136 hr, which is close to stoichiometric proportion for water gas and air in the containment atmosphere. Stoichiometric mixtures are shown to maximize the pressure increase due to combustion, as discussed in Ref. 4-1, Section 5.3.

Figure 4-3 shows the transient state of pressures prevailing in the containment atmosphere around the ignition time. The results shown in Fig. 4-3 render obsolete the results shown by curves 3 and 4 in Fig. 4-67 of Ref. 4-2, for flame propagation with total and partial combustion, respectively. These two curves were estimates rather than computational results, since at the time Ref. 4-2 was published the CARCAS computer program was not able to account for a finite speed of flame propagation.

Burning time, i.e., the minimum time required for the flame to propagate through the containment atmosphere (as described in Section 4.2.1), is almost 2 min, and it corresponds to a flame-front traveling trajectory as shown on the left side of Fig. 4-2.

Figure 4-4 shows the transient state of temperatures prevailing in the containment atmosphere around the ignition time. The results shown in Fig. 4-4 render obsolete the results in Table 4-33 of Ref. 4-2, in which temperatures over 1550°C (2830°F) are reported for an instantaneous combustion.

The temperatures shown in Fig. 4-4 during the burning time correspond to neither the burnt nor the unburnt portions of the containment atmosphere, but to the whole containment atmosphere. The decreasing pressures and temperatures after burning are due to the combined effects of heat transmission to (by radiation and convection) and steam condensation on the containment atmosphere boundaries.

Fig. 4-3. Containment atmospheric pressures during scenarios A and B

Fig. 4-4. Containment atmosphere temperatures during scenarios A and B

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5. DEVELOPMENT OF PARTICULATE BEHAVIOR MODELS

Work on the radioactive response of the containment atmosphere is expected to be completed with the Third Status Report, to be published by the end of FY-81. Thus, that report and the present report will completely cover the radioactive response of the containment atmosphere.

There are differences between the behavior of iodine and the other fission products of environmental and biological significance, i.e., cesium, tellurium, and strontium. The removal processes for iodine are, as discussed in Section 3.2, filtration, sorption by coating, steam condensation, and permeability and retentivity of stressed concrete. The removal processes for cesium, tellurium, and strontium are those typical of aerosols, i.e., filtration, gravitational settling, attachment to walls, coagulation, steam condensation, etc. Filtration and steam condensation are the common processes for radioactivity removal from iodine and the aerosol-like fission products.

This section summarizes the preliminary work performed on the methods and computer programs for the aerosol-like fission products in the containment atmosphere.

5.1. PRELIMINARY MODEL

A preliminary model for the consideration of aerosol-like fission products is described in Ref. 5-1, pp. 4-255 and 4-256. This model indicates that only two removal processes are dominant: filtration and gravitational settling. Other removal processes are considered of secondary importance for the containment atmosphere.

The PCRV release is actually a polydisperse (or heterodisperse) aerosol; however, it is treated here as a monodisperse (or homogeneous) aerosol. The particle size is expected to vary during the PCRV release, according to containment system experiments (CSEs) (Ref. 5-2). Reference 5-3 uses information obtained from the CSEs (i.e., an initial particle diameter of 15 μm , which a few hours later decreases to an average size of about 5 μm), as does Ref. 5-1 (p. 4-256) for AIPA studies.

Results reported in Ref. 5-1 (Table 4-42, p. 4-272) are based on computations performed by the TDAC computer program (Ref. 4-5), which was slightly modified to accommodate the gravitational settling behavior by its corresponding decay constant (Ref. 5-1, p. 4-255). This decay constant for gravitational settling is added to the decay constant for the containment atmospheric filtration (Ref. 5-1, p. 4-255). Thus, TDAC is able to account for radioactive decay, filtration, and gravitational settling in addition to containment leaks.

5.2. METHODS FOR AEROSOL BEHAVIOR

A description of the different processes for aerosol removal can be found in Refs. 5-5 and 5-6. Most of these processes are present in the containment atmosphere in a passive or active form. However, according to the preliminary model for the results reported in Ref. 5-1 for the AIPA studies, the two dominant processes for aerosol removal are filtration and gravitational settling. This conclusion is correct for dry containment conditions, because when steam condensation begins, it becomes a dominant process for aerosol removal.

A re-examination of the release from the PCRV of particulates and radioactive fission products used for Ref. 5-1 must be performed. The PCRV release used for Ref. 5-1 (Table 4-39, p. 4-244) is based on the fractional releases reported for the Windscale accident (Ref. 5-7) because of the present inability of the PADLOC computer program (Ref. 5-8) to simulate chemical reactions with metallic surfaces of the PCRV.

5.3. COMPUTER PROGRAMS FOR AEROSOL BEHAVIOR

Two computer programs were implemented for use in the UNIVAC 1110 computer at General Atomic. They are the HAA-3 and DISPER computer programs, whose applicability is discussed below.

5.3.1. HAA-3 Computer Program

This computer program (Ref. 5-9) was developed for hypothetical accidents in the LMFBR, mainly for sodium fires. The size distribution of particles is assumed to be log-normal, and the parameters characterizing this distribution are functions of time. Different physical processes for the aerosol behavior are followed, such as Brownian and gravitational agglomeration, settling, wall plating, leakage, and constant or variable rate for the log-normal source. Three factors restrict the use of the HAA-3 computer program in conjunction with the CARCAS computer program:

1. The restriction of one log-normal distribution for the suspended material (aerosol).
2. The extensive memory size of the HAA-3 computer program (about 60K), which is larger than the memory size of the CARCAS computer program (about 45K).
3. The absence of the steam condensation process.

5.3.2. DISPER Computer Program

This computer program (Ref. 5-10) permits one to determine the source strength outside of a leaky enclosure caused by the release of aerosol particles inside the enclosure. Therefore, its implementation for use in the UNIVAC 1110 is for the purpose of computing the environmental leaks from the containment atmosphere for cesium, tellurium, and strontium through isolated containments.

The memory size of the DISPER program is about 12K, which indicates that it can be used in conjunction with the CARCAS computer program, with minor modifications. However, the running time of DISPER should be observed, since presently the running time for core heatup scenarios A and B with the CARCAS computer program is about 20 min.

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6.. CONTAINMENT STRUCTURE

The release of radioactive fission products to the environment which may be present in the containment atmosphere depends upon several factors, such as closed or open (i.e., isolated or non-isolated) conditions for an intact containment, steam condensation on the leaking containment boundaries, integrity of the containment building, etc. In this section, first the leaks occurring in intact containments are considered, then the structural failure modes. To provide for either gas accumulation or flammable gases (i.e., water gas) during the pertinent core heatup scenarios which lead to failure of the containment, the degradation of the concrete in the PCRV is required.

6.1. INTACT CONTAINMENT LEAKAGE

Consideration of the following cases does not require concrete degradation in the PCRV, but these cases lead to containment leaks under closed or open conditions.

6.1.1. Closed Containment

The leak rate of a closed containment is determined by the requirement, typical of licensing proceedings, which permits no more than 0.1% per day as the constant leak rate of the free volume of the containment atmosphere for the computations of the radioactive release of air-borne particulates to the environment (Ref. 6-1). The variable leak rate from the containment building is then obtained after attributing its maximum value at the peak pressure conditions prevailing in the containment atmosphere during a hot leg DBDA.

Figure 6-1 shows the transient state of containment atmospheric pressures during a hot leg DBDA for a 3000-MW(t) Reference plant, as computed by the aid of the CNTB program (Ref. 6-2). The peak pressure is

$$p_{\max} = 4.306 \times 10^5 \text{ Pa} = 62.45 \text{ psia}$$

for a completely immiscible (0% mixing with helium accumulating in the top of the building) atmosphere. Since the environmental pressure is

$$p_{\text{env}} = 1.013 \times 10^5 \text{ Pa} = 14.7 \text{ psia} ,$$

the differential pressure, for containment leak purposes, is then

$$\Delta p = p_{\max} - p_{\text{env}} = 3.292 \times 10^5 \text{ Pa} = 47.75 \text{ psig} .$$

The leaking flow through the concrete walls of the containment is along cracks, whose fluid flow resistance is mainly away from the inner (pressurized) boundary, which consequently renders the leaking flow essentially isothermal. Figure 6-2 shows the temperature profiles in the containment sidewall, above the elevation of the PCR, at different times after initiation of helium blowdown during a hot leg DBDA with an immiscible containment atmosphere. The temperature profiles confirm the conclusion of an isothermal leaking flow.

The expansion losses are small in comparison with the friction losses, i.e.,

$$\ln \frac{p_{\max}}{p_{\text{env}}} \ll \frac{fL}{g} .$$

Fig. 6-1. Transient state of containment atmospheric pressures after hot leg DBDA

Fig. 6-2. Temperature profiles in containment sidewall after hot leg DBDA

In fact, since according to Fig. 6-1,

$$\ln \frac{P_{\max}}{P_{\text{env}}} = 1.45$$

and with

$$f > 0.02 \text{ (laminar flow, Ref. 6-3) } ,$$

$$L \approx 106.7 \text{ cm (3.5 ft (Fig. 4-2) } ,$$

$$g \approx 2.54 \times 10^{-3} \text{ cm (0.001 in.) } ,$$

one has

$$\frac{fL}{g} > 840 .$$

Thus, approximately,

$$\Delta p \propto Q ,$$

if laminar flow prevails along the cracks, which are idealized as broad parallel plates, i.e., no turns, enlargements, or contractions. Figure 6-1 renders for the proportionality constant omitted above

$$\frac{\Delta p}{Q} = 3.29 \times 10^6 \frac{\text{Pa day}}{\text{free vol \%}} ,$$

or

$$\frac{\Delta p}{Q} = 477.5 \frac{\text{psig day}}{\text{free vol \%}} .$$

Figure 6-3 shows the leak rate from a 3000-MW(t) reference plant closed containment to the environment, assuming 0% mixing (stratified atmosphere), and compares its values with the nominal values used in Ref. 6-4, p. 4-258^{*} (0.05 vol %/day). This nominal leak rate value compares favorably with design values specified for lined HTGR containments, i.e., 0.1 vol %/day for the first 24 hr and 0.05 vol %/day for all remaining time after the first day (Ref. 6-5).

6.1.2. Open Containment

An open containment situation occurs if the isolation valves of the containment atmosphere ventilation system fail to close after opening of the PCRV safety relief valve.

The CNTB computer program was used to estimate the duration of the PCRV primary system depressurization transient into the reactor service building. Figure 6-4 shows the vented volumes from the containment building for two possible cases for the ventilation fans: stopped or running at normal operating speed. No appreciable difference in the vented volume is shown to result from the differing behavior of the fans. The duration of the transient is estimated in 900 s, which is the value used for the AIPA studies (Ref. 6-4, p. 4-259).

6.2. STEAM CONDENSATION

Steam condensing on surfaces exposed to the containment atmosphere reduces the amount of radioactive release to the environment through the containment. The condensing steam removes radioactivity not only from the containment atmosphere (Section 3.2) but also through the surfaces exposed to the containment atmosphere in which sorption or diffusion of radioactive material has occurred. In core heatup accidents, steam in the containment atmosphere is due to degradation of PCRV concrete in certain low-probability sequences.

^{*}The abscissa of this figure in Ref. 6-4 incorrectly indicates 10 times the actual time values.

Fig. 6-3. Containment leak rate to the environment for closed containment (0% mixing)

Fig. 6-4. Vented volume from open containment (0% mixing)

Figure 6-5 shows the amount of condensed steam on the containment atmosphere boundaries for core heatup scenario B. The containment atmosphere is assumed to remain dry (i.e., 0% relative moisture) until the release of concrete decomposition products from the PCRV begins. From then on (i.e., 43 hr after the initiation of the helium blowdown), the containment atmosphere remains humid; however, water vapor does not condense on the boundaries of the containment atmosphere until approximately 100 hr after the initiation of the helium blowdown. The uncertainty regarding the precise time is due to the uncertain degree of mixing in the containment atmosphere.

The two curves shown in Fig. 6-5 for stratified and homogeneous atmosphere limit the range of uncertainty of condensed steam versus time. This figure shows that the uncertainty in the time for moisture to start condensing in the containment atmosphere boundaries is between 95 and 117 hr. From this time on, the containment leaks do not contain radioactive particulates or iodine because they have acted as centers for water condensation or the iodine is already dissolved. Failure of the containment by either burning (scenario A) or gas accumulation (scenario B) restarts the environmental leaks.

6.3. STRUCTURAL FAILURE MODES

The failure of the plant containment did not receive a substantial analysis in Ref. 6-4. Failure was attributed to a cause similar to that for the PCRV, where the liner fails due to high temperatures before the collapse of the concrete.

Since the publication of Ref. 6-4, additional information has become available in the open literature about the failure of plant and reactor containments. This information is not only descriptive but also methodological, and it permits a more complete examination of the failure process.

Fig. 6-5. Condensed steam on containment atmosphere boundaries versus time (scenario B) (from Ref. 6-4, p. 4-223)

Structural failure modes are actually a responsibility of the architectural-engineering firms. Related material has been included here to provide a better understanding of the potential failure of the plant containment in order to mitigate its effects, mainly with regard to containment leaks to the environment.

6.3.1. Gross and Restrained Failures

The reactor enclosure, i.e., the PCRV, and the plant containment have common aspects in their configurations. Both structures are made of concrete with their internal surface covered by a steel liner. However, the liners are subjected to different types of loads, as discussed below.

PCRV Loading. In the HTGR-SC, high pressures in the PCRV cause the opening of the safety relief valve. Thus pressure loads are not responsible for liner failure in PRA accident sequences; thermal loadings are of greater concern.

Plant Containment Loading. Pressure loadings, rather than thermal loadings, are the mechanism of interest for the failure of the containment liner. Pressure loadings can be discontinuous, in time and/or space (e.g., pipe whip, burning), or uniform (e.g., buildup of pressure by gas accumulation).

With regard to the concrete structure, it is prestressed in the PCRV, but may be reinforced and/or prestressed in plant containments.

PCRV Rupture. A restrained rupture of the PCRV during core heatup conditions is anticipated on the basis that the liner collapses first under thermal loading. Subsequent cracks develop in the concrete because the dissimilar expansion of concrete and steel allows the escape of the PCRV atmosphere into the containment, reducing the pressure on the concrete and subsequently closing the cracks. This process can be repeated ad libitum by a continuous pressure buildup inside the PCRV. This description follows

the arguments given in Ref. 6-4. Failure then occurs in a "controlled" manner. The ultimate pressure of the PCRV is not reached, and failure is more like that in a brittle material.

Plant Containment Rupture. Alternatives to the above explanation, if the liner collapses first, are reported in the literature. Reference 6-6 describes gross failure of the structure produced by crumbling of the concrete when subject to slow overpressurization. The lower and upper bounds for the failure pressure are "when the steel liner and the inner layer of reinforcing are stressed to yield," and "when subjected to their ultimate tensile strength," respectively (Ref. 6-6). Reference 6-7 qualifies as "explosive" the rupture at the ultimate strength, i.e., a rupture more like that in a ductile material.

6.3.2. ECT (Elementary Catastrophe Theory) Interpretation for Containment Failure

Relatively recent developments in catastrophe theory provide a basis for a formal categorization of the failure modes for the plant containment. Attention will be restricted here to the two simplest types of catastrophes from the list of seven elementary catastrophes (Ref. 6-9, table on p. 78): the fold and the cusp.

For a detailed presentation on this subject, Ref. 6-8 is recommended. For a brief but illustrative presentation of ECT (elementary catastrophe theory), which is restricted to gradient vector fields, Ref. 6-9 is recommended. Catastrophe theory is based on arguments of topology and predicts cases of unstable behavior, allowing their classification depending on the number of control and behavior parameters.

6.3.2.1. Fold. Only one control dimension and one behavior dimension are required for the fold. The potential function V is given by

$$V = \frac{x^3}{3} - ax \quad ,$$

and its first derivative when equalized to zero

$$x^2 - a = 0 \quad ,$$

defines the behavior line x as a function of the control parameter a . The fold has two branches as shown in Fig. 6-6, one stable branch and one unstable branch, which merge at the critical point $x = a = 0$. The load-displacement characteristic at the point of ultimate strength (Ref. 6-7, Fig. 3, p. 158) corresponds to this type of catastrophe. In fact, the load P is related to the stress σ and cross-sectional area A by

$$P = \sigma A \quad .$$

At the point of ultimate strength σ_u ,

$$\sigma = \sigma_u = \text{const} \quad ;$$

thus,

$$dP = \sigma_u dA \quad .$$

With $A = (1/4)\pi D^2$ for a circular cross section,

$$dP = \sigma_u \frac{\pi}{4} dD^2 \quad .$$

Around the point of ultimate strength, the correspondence is

$$P - P_u \leftrightarrow a \quad ,$$

$$D - D_u \leftrightarrow x \quad .$$

Fig. 6-6. The fold catastrophe

The two branches around σ_u are for

$$dD > 0 \text{ (stable)}$$

and

$$dD < 0 \text{ (unstable)}$$

6.3.2.2. Cusp. Two control dimensions (a and b) and one behavior dimension (x) are required for the cusp. The potential function V is given by

$$V = \frac{x^4}{4} - ax - b \frac{x^2}{2} ,$$

and its first derivative when equalized to zero,

$$x^3 - a - bx = 0 ,$$

defines the behavior surface x, as a function of the control parameters a and b (Fig. 6-7). The bifurcation set in the a,b plane is determined by

$$4b^3 = 27a^2 .$$

Inside the cusp,

$$4b^3 - 27a^2 < 0 ,$$

there are two stable modes and one unstable mode, which correspond to the three sides of the behavior surface (Fig. 6-7). Outside the cusp,

$$4b^3 - 27a^2 > 0 ,$$

Fig. 6-7. The cusp catastrophe

there is only one stable mode, which corresponds to one side of the behavior surface (Fig. 6-7).

From here on it is clear that the control plane, with the cusp drawn on it, is sufficient to indicate the behavior (continuous or discontinuous) during any evolution determined by the control variables. Examples of cusp catastrophes are known in numerous fields. Here, a case of buckling instability which may occur with an improperly designed containment liner will be considered. This case has already been analyzed by Alesso (Ref. 6-10) within the frame of ECT. The total potential energy equation was developed by Jaeger (Ref. 6-11), while the buckling and post-buckling behavior of the liner was examined by Kicher et al. (Ref. 6-12). Alesso used the total potential energy equation and arguments of ECT to reexamine the cases of liner instability (Ref. 6-10).

Figure 6-8(a) shows a sketch of the portion of the containment liner between anchor points which is susceptible to buckling. Figure 6-8(b) shows the cusp in the control plane according to the control variables selected by Zeeman (Ref. 6-9, p. 76, and Ref. 6-13, p. 374), compression and load, rather than those used by Alesso (Ref. 6-10), which depend on the circumferential strain and the angle of arc of buckle (again, two control variables). Figure 6-8(a) and 6-8(b) are presented for illustrative purposes and not for quantitative interpretation. Since a rigid wall (actually the reinforced concrete) impedes the motions of the containment liner from expanding the cavity (i.e., the free volume of the containment atmosphere), only one branch of the cusp represents the possible motions of the liner. The behavior variable stands for the amplitude of the liner displacements. The circumferential strain or compression [Fig. 6-8(a)] may be produced by the hot streak of an impinging jet while the load or internal pressure remains essentially constant. If this is the case, the evolution of the liner displacements in the control plane is given by the trajectory from 1 to 2 and the liner will try to buckle inward. At point 2, if the circumferential strain or compression remains stabilized but the load or internal pressure increases, then the liner displacements in the

Fig. 6-8. Buckling instability of the liner sidewall

control plane are given by the trajectory from 2 to 3 and the liner will try to buckle outward. However, the rigid wall impedes the last buckling instability, and the liner trajectory stops before reaching the dotted branch of the cusp.

The above description assumes that the liner does not collapse and remains without permanent deformations after buckling. It should be emphasized that the actual case of liner buckling is more complicated than the above-described situation. In fact, longitudinal as well as circumferential strains develop in the liner, which increases to three the number of control variables.

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7. RECOMMENDATIONS FOR FUTURE WORK

For FY-80, the completion of work on the radioactive response of the containment atmosphere is indicated in Section 5. The recommendations in this section are for future work in the CAR program beyond FY-80 and are in agreement with the conclusions presented in Section 1.2 and Table 2-1. For practical purposes, they are divided into the following items:

1. Documentation of computer programs.
2. Test plans for helium jets and plumes.
3. Containment failure modes.
4. Mechanical analysis for missiles and fragments in the containment atmosphere.*

7.1. DOCUMENTATION OF COMPUTER PROGRAMS

Some computer programs which have been developed and applied in the CAR program are incompletely documented or not documented at all. The following computer programs are included in this category:

CNTB Program. The CNTB version for helium blowdowns in partially mixed containment atmospheres is described in Ref. 7-1. However, to complete its documentation, a user's manual must be issued.

CARCAS Program. The CARCAS computer program is operative at General

* There is no present provision for the analysis of external impacts from aircrafts, tornadoes, explosions, etc., on the containment since they do not originate in the containment atmosphere. However, the CAR program can be expanded to cover these areas.

Atomic, and some of its results are reported in Ref. 7-2 and the present report (for flammability studies and radioactive behavior of the containment atmosphere, respectively). Its documentation is needed for peer review and production status. For purposes of the flammability studies, the computer program is complete. However, for the inclusion of the radioactive behavior of fission products other than iodine, development on the computer program will be continued in FY-80.

TRAINC Program. The work for this program was concluded with the linking of the TRAIN program (Ref. 7-3) and the CNTB program (Ref. 7-1). References 7-1 and 7-3 serve as descriptive documents for the TRAINC program, whose main application is for PCRV releases from the safety relief valve and ruptured lines in the helium purification system. This program indicates whether hammering develops in the affected line during depressurizations. A user's manual needs to be issued.

RCA Program. This program was developed for the analysis of the hot streak on the liner attached to the containment sidewall and was obtained by linking the CNTB4 version (when the affected compartmental space under the PCRV is considered) and the JETWAY program (for jet trajectories). Results obtained with the RCA program are reported in Ref. 7-4. The documentation of the RCA program should be preceded by an update, since the program is based on the now obsolete star-shaped PCRV support structure. Moreover, the closed form expression for the intact core of helium jet, as given by Abramowich (Ref. 7-5), should be reviewed to incorporate experimental results when available.

Miscellaneous Short Programs. Several short programs developed for the CAR program may be documented after review if it is deemed necessary. In this category are the BLAST and SILT programs, whose results are reported in Refs. 7-4 (for shock waves due to pipe rupture) and 7-6 (for detonation waves caused by combustion of carbon dust suspensions), respectively.

7.2. TEST PLANS FOR HELIUM JETS AND PLUMES

The objective of the test plans is to provide:

1. A better prediction for the hot streak due to the impingement of helium jets on the liner of the containment sidewall.
2. Information about the thermal effects of helium plumes (i.e., by heat radiation and convection) emanating from the top of the PCRVR on the liner of the containment dome.
3. A suitable design for the helium discharge from the exhaust ducts downstream of the PCRVR safety relief valve during controllable depressurizations of the PCRVR.
4. A better understanding of the behavior of underexpanded (or overpressurized) jets produced by rupture of small lines (e.g., rupture of the helium purification system line).
5. From the above tests, a better understanding of the entrainment by jets and plumes, which will finally determine the degree of mixing (air-helium) or layering in the containment atmosphere after helium blowdowns.

A preliminary effort for the tests is reported in Section 6.2 of Ref. 7-4.

7.3. CONTAINMENT FAILURE MODES

Knowledge of the containment failure modes is an important prerequisite for the estimation of the radioactive leaks to the environment. Uncertainty exists concerning the modes of failure for the plant containment, whereas the failure of the PCRVR appears to be known. Section 6.3

presents a way to categorize the different forms of instability leading to potential containment failure by using arguments of ECT and giving two examples. After the different forms of plant containment failure are known, their quantification and subsequent action to mitigate their effects must follow.

7.4. MECHANICAL ANALYSIS FOR MISSILES AND FRAGMENTS IN CONTAINMENT ATMOSPHERE

Damage to the plant containment may be inflicted by missiles and fragments through the containment atmosphere. Typical cases are turbine deblading and pipe whip. A preliminary effort was initiated at General Atomic by considering the entrainment of fragments by isobaric turbulent jets of incompressible fluids. The DRAG program (Ref. 7-7) was developed for plane-parallel and circular jets, with a very simple version for entrainments in pipes which is capable of verification by closed-form expressions.

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APPENDIX
CAR PROGRAM SUMMARY OF ACHIEVEMENTS AND GOALS

TABLE A-1
CAR PROGRAM SUMMARY OF ACHIEVEMENTS AND GOALS

Document	Thermomechanical Response of the Containment Atmosphere and Its Boundaries	Chemical Response of the Containment Atmosphere	Radioactive Response and Environmental Impact of the Containment Atmosphere
Scoping study FY-75, GA-A13727	<ol style="list-style-type: none"> 1. Examination of CONTEMPT-G computer program limitations. 2. Nonmixing estimated to result in: <ol style="list-style-type: none"> a. Up to 55.16×10^3 Pa (8 psi) lower containment design pressure if helium fills from bottom, but more than 27.58×10^3 Pa (4 psia) higher if helium ascends instantaneously to the top. b. Up to 556°C (1000°F) higher containment atmosphere temperature compared with perfect mixing. 3. Estimation of jet impingement to be important for containment liner local integrity by predicting the hot streaking from helium and steam jets. 4. Development of recommendations and program plan for FY-76. 	Recommendations for the study of combustion phenomena.	Recommendation for the study of the effect of localized radioactive gases on containment leaks.
Interim summary report FY-76, GA-A 4262	<ol style="list-style-type: none"> 1. Conclusion that shock waves caused by sudden depressurization of the primary or secondary coolant system are not hazardous for containment integrity. 2. Analysis of turbulent jet characteristics for isobaric and underexpanded situations. 3. Extension of the CNTB computer program to analyze partial mixing of helium blowdown to the containment with compartment. 4. Justification of the use of quasi-steady models for the analysis of transient jets during depressurization. 5. Deflection of isobaric turbulent jets caused by buoyant forces. Development of the JETWAY computer program for helium jets discharging into helium. 6. Computation of the hot streaking on the containment liner by linking the CNTB and JETWAY computer programs. Maximum temperatures concluded acceptable by architect/engineer firms. 	Recommendation of work on the chemical response of the containment atmosphere during core heatup and other class 9 accidents in support of probabilistic risk assessments.	

TABLE A-1 (Continued)

Document	Thermomechanical Response of the Containment Atmosphere and Its Boundaries	Chemical Response of the Containment Atmosphere	Radioactive Response and Environmental Impact of the Containment Atmosphere
Interim summary report FY-76, GA-A14262 (continued)	<ol style="list-style-type: none"> 7. Analysis of large jet effects on containment mixing and heat transfer. Significant reduction of peak containment pressure. 8. Analysis of small high-velocity jets. Comparison of capabilities of three existing computer programs for isobaric high-velocity small jets. 9. Investigation of the entrainment coefficients limited to the main region of isobaric turbulent jets. 10. Preparation of the test plan for data and verification of jet behavior, recommended to be performed for <ol style="list-style-type: none"> a. Support of CAR program models. b. Licensing credit for local effects on containment design. 	Recommendation of work on the chemical response of the containment atmosphere during core heatup and other class 9 accidents in support of probabilistic risk assessments.	
First status report FY-77, GA-A14699	<ol style="list-style-type: none"> 1. Recommendation for future work on computational models for small jets and blowdown into dissimilar media in conjunction with the test program on jet behavior. 2. Recommendation of a test program to be performed to obtain JETWAY input. 3. Development of the SILT computer program for the analysis of carbon dust combustion in the containment atmosphere. 	<ol style="list-style-type: none"> 1. Development of the CARCAS computer program to include the consideration of steam and concrete decomposition products for combustion potential effects. 2. Evaluation of the flammability and detonability limits of water gas in air as a function of diluents and temperature for computational purposes. 3. Documentation of the time-dependent air ingress model into the PCRVR for the OXIDE-3 computer program. 	Recommendation of work on aerosol behavior for the determination of the air-borne activity of radioactive nuclides in the containment atmosphere.
Second status report FY-79, GA-A15582	<ol style="list-style-type: none"> 1. Incorporation of the thermal radiation model after combustion into the CARCAS computer program. 2. Development of the TRAINC computer program for the discharge of small jets into the containment atmosphere. 	Incorporation of the slow-combustion model (e.g., flame propagation, imperfect combustion) into the CARCAS computer program.	<ol style="list-style-type: none"> 1. Incorporation into the CARCAS computer program of the processes followed by the release of fission product iodine in the containment. 2. Incorporation into the CARCAS computer program of iodine leaks from the containment to the environment. 3. Initiation of containment failure studies and recommendation of future studies.
Future work from FY-80 on.	As above, plus mechanical analysis of missiles and fragments through the containment atmosphere as a consequence of accidental rupture of the primary or secondary cooling system.	No further work recommended.	<p>Completion of the processes followed by radioactive nuclides (other than iodine in the containment atmosphere).</p> <ol style="list-style-type: none"> 1. Completion of the radioactive leaks (other than iodine) to the environment. 2. Continuation of containment failure studies.

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