NUREG/CR-3868
BNL-NUREG-51793

CONTAINMENT BUILDING ATMOSPHERE RESPONSE DUE TO REACTOR GAS BURNING UNDER REMOTE SEVERE ACCIDENT CONDITIONS

Peter G. Kroeger

Date Published — June 1984

HTGR SAFETY DIVISION
DEPARTMENT OF NUCLEAR ENERGY, BROOKHAVEN NATIONAL LABORATORY
UPTON, LONG ISLAND, NEW YORK 11973

Prepared for
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

NUREG/CR-3868
BNL-NUREG-51793
AN, R-8

CONTAINMENT BUILDING ATMOSPHERE RESPONSE DUE TO REACTOR GAS BURNING UNDER REMOTE SEVERE ACCIDENT CONDITIONS

Peter G. Kroeger

Manuscript Completed — December 1983
Date Published — June 1984

HTGR SAFETY DIVISION
DEPARTMENT OF NUCLEAR ENERGY
BROOKHAVEN NATIONAL LABORATORY
UPTON, LONG ISLAND, NEW YORK 11973

PREPARED FOR
UNITED STATES NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555
CONTRACT NO. DE-AC02-76CH00016
NRC FIN NO. A-3016

Available from
GPO Sales Program
Division of Technical Information and Document Control
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555
and
National Technical Information Service
Springfield, Virginia 22161

ABSTRACT

The formation of combustible atmospheres during unrestricted core heatup accidents in High Temperature Gas-Cooled Reactors is being investigated, considering the effects of only partially mixed atmospheres.

It is found that the previously used assumption of complete mixing presents the more severe limit in most cases. In the few cases where higher loads were obtained, these were still below the containment building failure limits, and did apply only locally. Furthermore these cases required the invocation of even more remote failure scenarios.

A qualitative discussion applying the above results to corresponding accidents at Fort St. Vrain is included.

Table of Contents

LIST OF FIGURES

LIST OF FIGURES (continued)

APPENDIX A

1. INTRODUCTION

The formation of combustible gases in the core of an HTGR cavity during Unrestricted Core Heatup Accidents (UCHA) without functioning Liner Cooling System (LCS) was recently considered in the ''Preliminary Evaluation of HTGR Severe Accident Source Terms.''[1] It had also been considered previously in References 2 and 3. In all cases completely mixed containment building (CB) atmospheres had been assumed.

The first objective of this report is to consider qualitatively for typical large HTGRs like the Lead Plant several more remote scenarios, in particular including the effect of unmixed or partially mixed regions. Several possible remedies will be pointed out in case such remote conditions are to be of concern in the licensing process. CB gas pressures and their effects on the CB structure will be discussed in terms of a uniform structure, i.e., without consideration of individual local hatches or penetrations.

The second objective is to evaluate qualitatively how these combustion scenarios relate to corresponding accidents at the Fort St. Vrain plant.

It should be noted that the scenarios presented here are far beyond the level of design basis accidents, and are only to be considered as severe accidents. The case of deflagration failure of the CB at about 5 days is part of the Category 2 accidents of Reference 1 and was assigned a probability of about 5×10^{-9} there. The events to be considered here are special cases which are even more remote than those scenarios.

2. LEAD PLANT DESIGN

2.1 Summary of Previous Severe Accident Work

In the ''Preliminary Evaluation of HTGR Severe Accident Source Terms,''1 the evolution of combustible gases from PCRV heatup during UCHA scenarios was considered as part of the Category 2 accidents. This was also found to be the only accident that could produce sufficient gas masses to cause CB failure by overpressurization or from uncontrolled burning. The most important aspects of the CB atmosphere response analysis, given in Appendix F of Reference 1, are summarized here. The evaluations were based on the core heatup and concrete degradation calculations, resulting in gas releases of about 2000 lb/hr each of CO_2 and H_2O from the degrading PCRV concrete, beginning about 70 to 90 hrs after scram. The actual fraction of concrete decomposition gases reacting with the core graphite is rather uncertain since it is primarily a consequence of the debris distribution, which can neither be predicted mechanistically nor be determined by experiment. Parametric evaluations were therefore made for the range from 10 to 70% of the concrete decomposition gases reacting with the core graphite. Up to core peripheral seal failure, expected at about 130 hrs, it was concluded that 10% of the gas reacting constitutes a reasonable assumption. Beyond seal failure, 30% of the gas was assumed to pass through the core and react with the core graphite. The CB atmosphere was assumed to be completely mixed at all times. Based on some GA results from the CARCAS code and our own estimates, a CB atmosphere temperature rise from 100°F at scram to 180°F after 10 days was assumed. Some of the results from Reference 1 are reproduced in Figures 2-1 to 2-4.

Figure 2-1 shows the expected times for the CB atmosphere to reach the overpressurization failure point of 100 psia. While overpressurization failures are not being addressed in this report, the figure is shown for completeness. At the assumed fraction reacted of 0.3 and with seal failure expected at 130 hr the CB would fail at about 240 hrs or 10 days after scram. (CB failure analyses of Appendix A of Reference 1 establish the failure pressure at about 130 psig, indicating that the value of 100 psia, used in Appendix F, is quite conservative).

Figures 2-2 and 2-3 trace the CB atmosphere evolution with respect to flammability. In HTGR UCHA scenarios, the ratio of H_2 and CO will not be

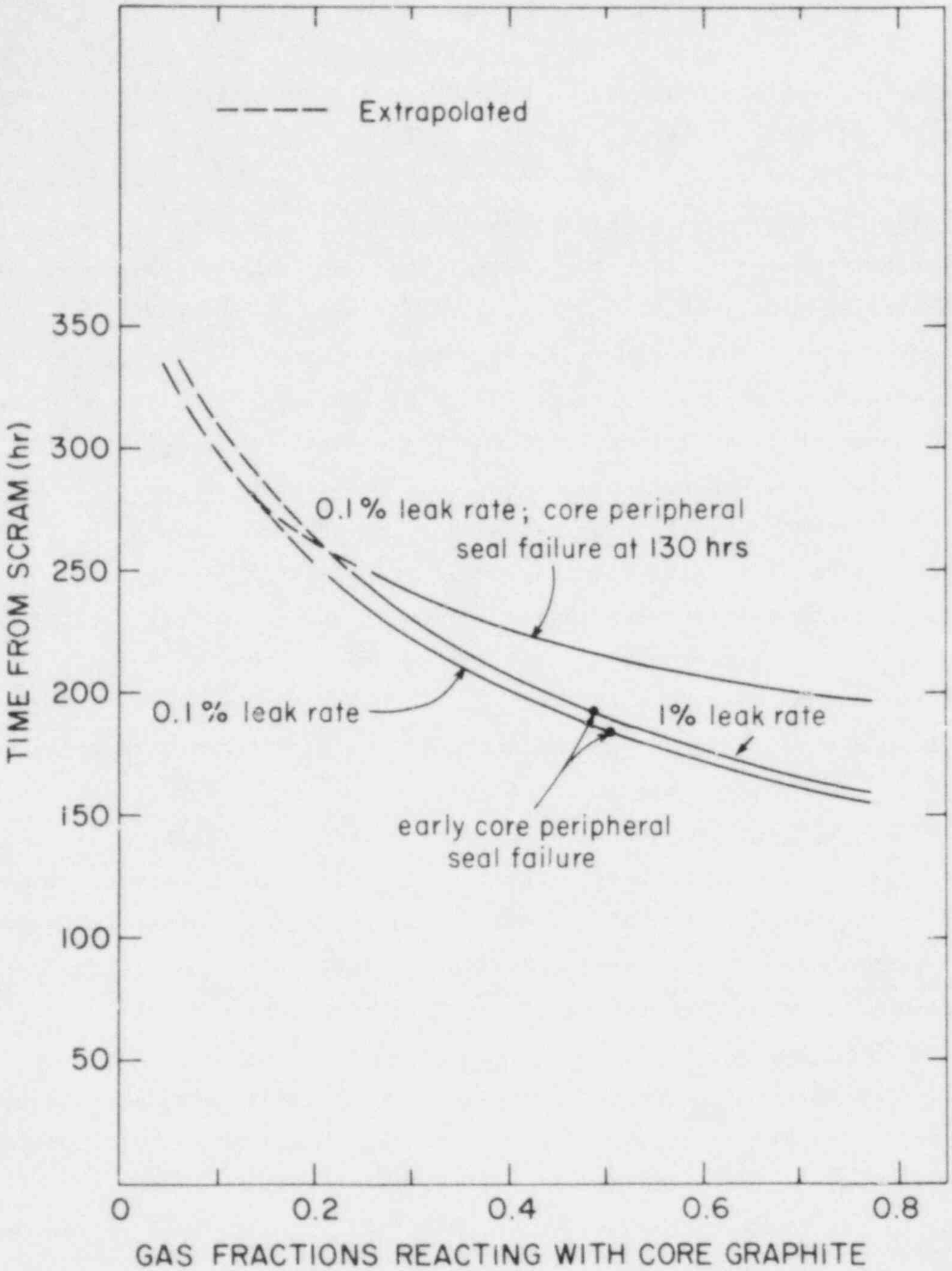


Figure 2-1 Time for CB atmosphere to reach 100 psia during UCHA without LCS operation.

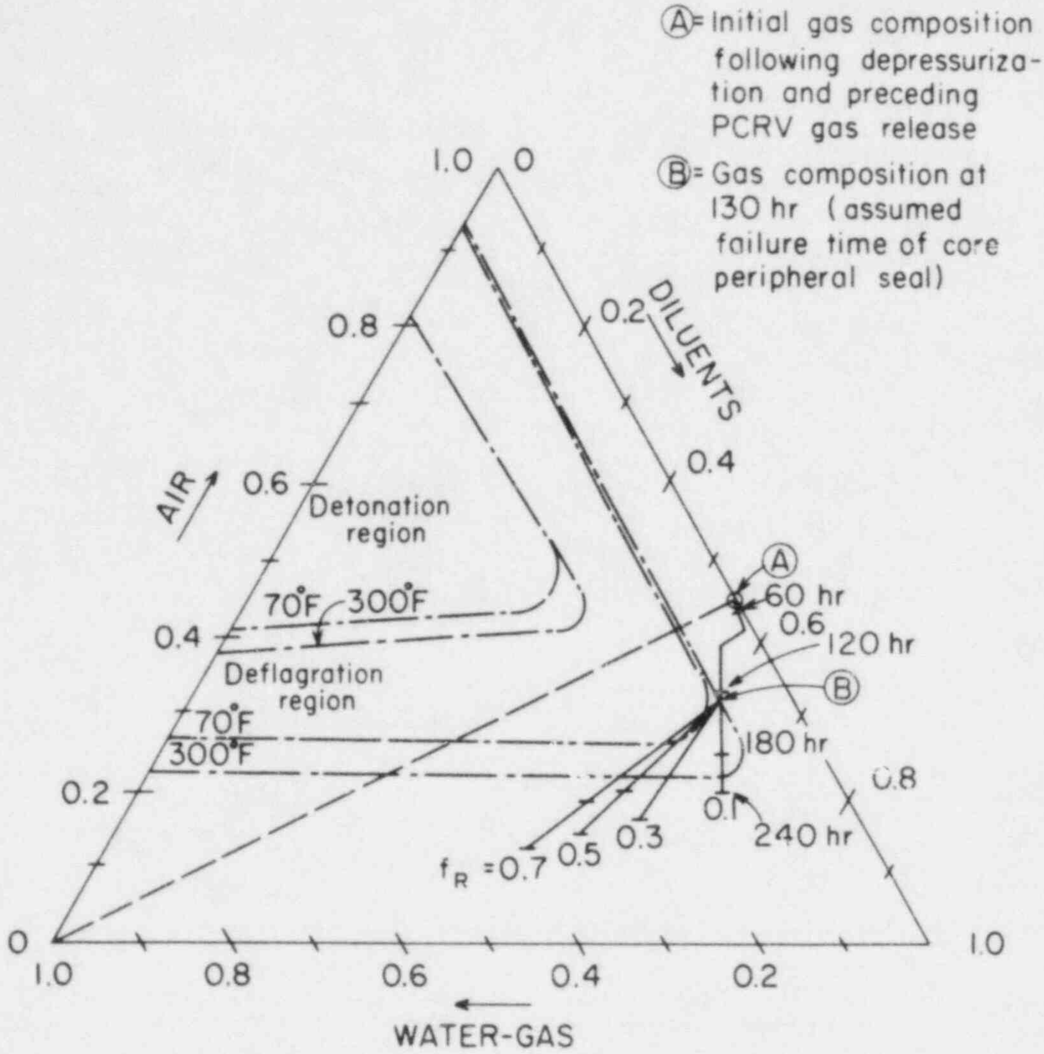


Figure 2-2 Containment building atmosphere during UCHA transient without LCS at CB temperatures gradually rising from 100 to 180°F, with 10% of released gas reacting with core graphite prior to seal failure at 130 hr and with various fractions (f_R) reacting after seal failure.

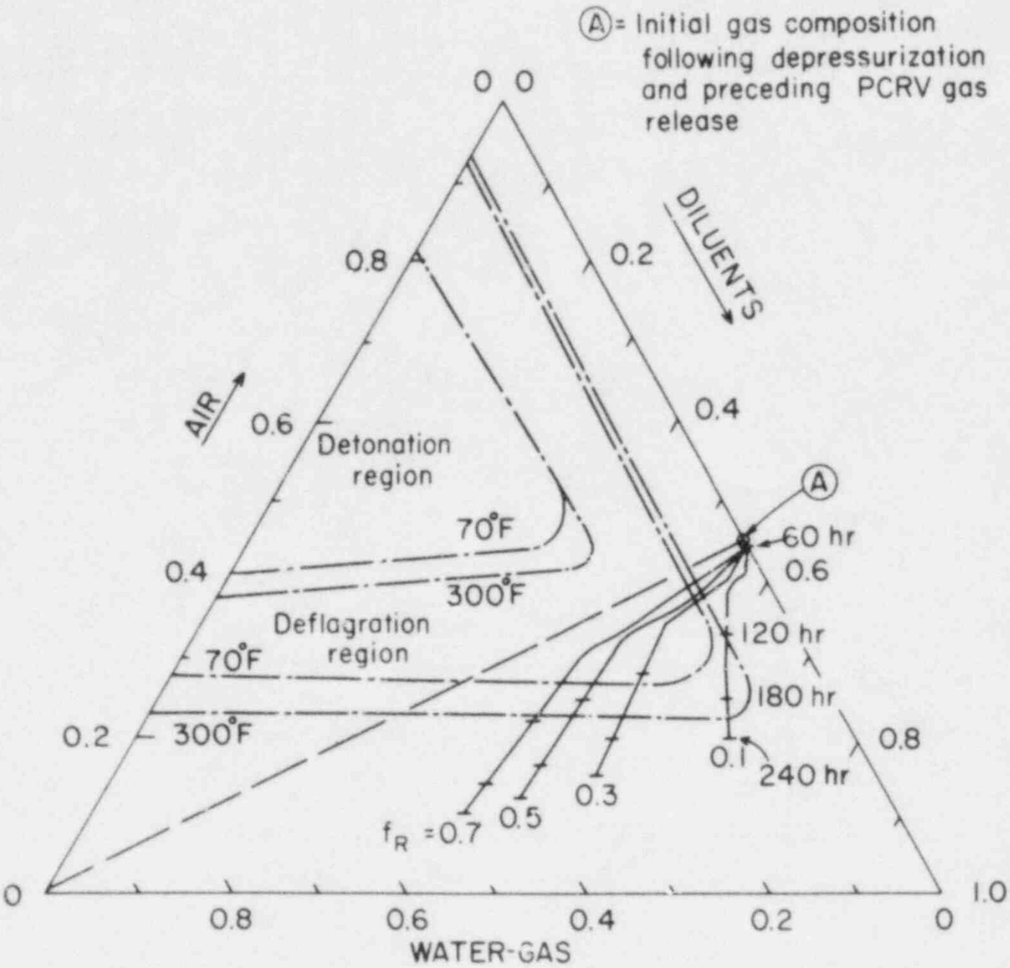


Figure 2-3 Containment building atmosphere composition during UCHA transient without LCS; at CB temperatures gradually rising from 100 to 180°F, with seal failure prior to gas ingress and with various fractions (f_R) reacting.

1:1 as in water gas, but depending on the concrete composition, about 1:2, i.e., there is a significant excess of CO. As pointed out in Reference 3, flammability limits for such gas mixtures were not available, but the use of water gas data constituted a reasonable assumption. (This aspect will be reviewed further, later in this report). Thus Figures 2-2 and 2-3 are based on water gas flammability limits.

For the case of 10% of the concrete gas reacting flammable mixtures are essentially never formed. This is the assumption recently made in Reference 4. For seal failure at 130 hrs, as assumed in Reference 1, deflagration burning is possible shortly after seal failure, as shown in Figure 2-2. In case of earlier seal failure, deeper penetrations into the deflagration region could result as shown in Figure 2-3. However, earlier seal failure requires an additional failure, thus representing an event of even lower probability. Similarly, deeper penetrations into flammable regions would be possible if some of the side cavities were open which could be possible for different designs. But this again would require the invocation of additional failures, and in general open side cavities would mitigate the complete core heatup scenario.

Figure 2-4 summarizes the time range of hypothetical deflagration failures. With seal failure expected at 130 hrs, deflagration becomes possible very shortly after seal failure, i.e., at about 133 hr. After about 170 hr, deflagration can no longer occur, as by then the remaining air fraction is too low to sustain combustion.

Thus, for the Category 2 accidents of Reference 1, deflagration burning was found to be possible within a fairly narrow time range, more than five days after scram. If burning were to occur early as the flammable mixture region is reached, the overpressures would not be as severe, since little fuel is present. Furthermore the base pressure is lower, early in the transient. The building would most likely not fail, and the net effect of early deflagration burning would be a moderate pressure spike with subsequent pressure relief. Later in the transient, as stoichiometric mixtures are reached, and with higher base pressures, deflagration burning would be more severe and could cause failure. However, burning at that later time would require the absence of an ignition source as the mixture first reaches the combustible region, plus the presence of such a source towards the end of that time

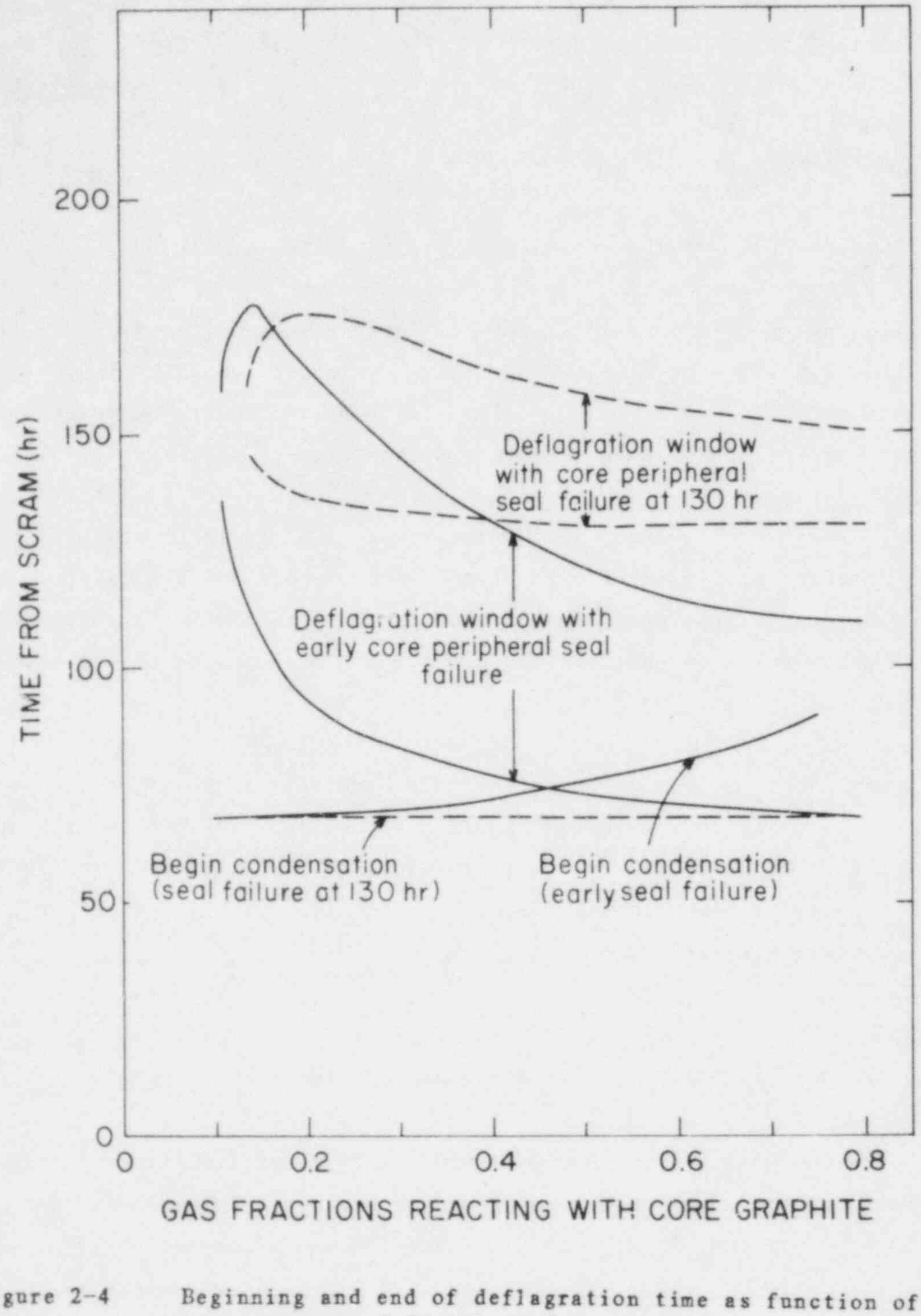


Figure 2-4 Beginning and end of deflagration time as function of CB temperature and fraction of gas having reacted during UCHA transient without functioning LCS.

''window''. For that reason, CB failure from deflagration burning was judged to be about one order less likely than failure from overpressurization, the more dominant Category 2 event, which was estimated to have a probability of only 5×10^{-8}/yr.

There was no plausible scenario found that could lead to the formation of detonable mixtures.

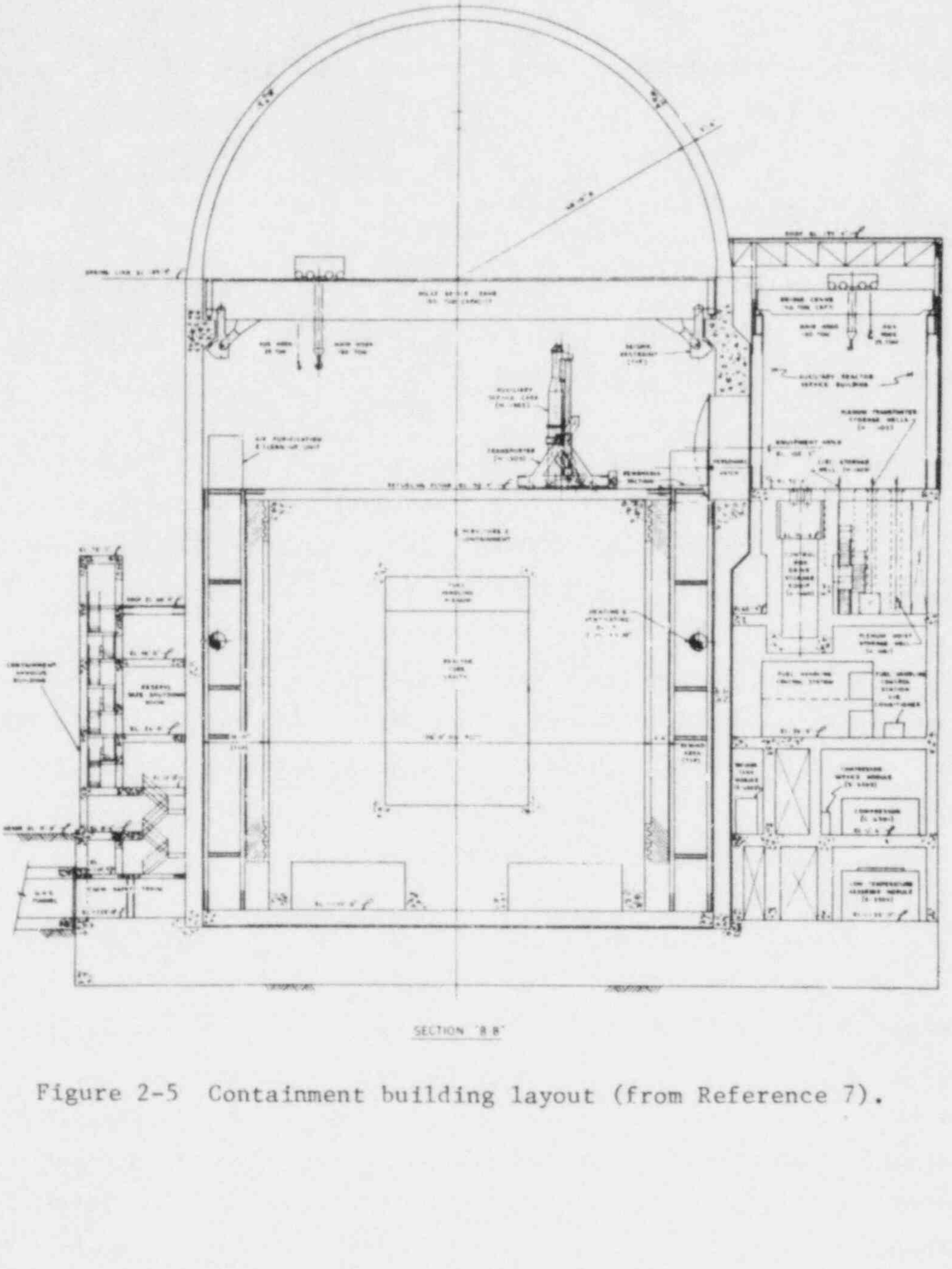
2.2 Additional Scenarios

Based on the previous assessment of deflagration in the CB during UCHA scenarios without functioning LCS, several more remote possibilities will be considered in this section.

A schematic of the CB is shown in Figure 2-5. The building is of about 140 ft in diameter, about 240 ft high, including the hemispherical top. Its total air volume is about 2,030,000 ft.^{3} The space above the refueling platform appears to be fairly free of flow obstructions. The lower part is occupied by the PCRV with an annular space of about 12 ft width between the PCRV and the CB walls which contain a steel structure with various kinds of equipment, an elevator, access platforms, and stairs. The air volume of this more obstructed area represents 25% of the total air volume.

2.2.1 Restricted Mixing with Air from Side Annulus

The completely mixed atmosphere assumption of the work of Reference 1 to 3 has often been questioned. The first effect of non-mixing to be considered would be the fact that some of the more restricted annular space around the PCRV as well as some gas space underneath the PCRV would not participate in the gas mixing during blowdown. As pointed out already in Reference 2, the net effect of this would be a reduction in the amount of available air in the CB atmosphere. In terms of Figures 2-2 and 2-3, considering this effect would move the atmosphere composition to higher diluent fractions and lower air fractions, thus reducing the possibility for burning. While it is to be expected that some of the air from these obstructed regions will not mix with the gas emerging from the PCRV, the simplifying assumptions of not excluding this air from the CB atmosphere is clearly conservative.



SECTION 'B-B'

Figure 2-5 Containment building layout (from Reference 7).

2.2.2 Helium/Air Stratification

PCRV depressurization will generally occur early in the accident, between 2 to 5 hrs after scram. Reactor gases from concrete decomposition and graphite/gas reactions only enter the CB after liner failure, around 70 to 90 hrs after scram. (Minor amounts of CO due to failed fuel enter the CB between about 20 and 70 hrs. While those amounts of CO are sufficient to transport fission products into the CB, they are not sufficient to constitute any combustion hazard).

At the time of depressurization, the helium inventory from the primary loop is being discharged into the CB. The discharge location is typically somewhere in the annular space between the PCRV and CB walls. The exact location for the lead plant design has not been established yet. Almost all of the gas discharged during blowdown will occur as choked flow, with a high speed jet ejecting hot helium into the ambient temperature air. As the helium is injected into the CB atmosphere, mixing between the hot helium jet and the surrounding air will occur. But due to its lower density, some helium could also penetrate the air and accumulate in the upper dome region of the CB. For the consideration of later combustion scenarios, the question arises whether and how much of the helium could be stratified in the top dome of the CB.

Initial air inventory in the CB is about 145,000 lbs. The helium inventory in the primary loop is about 25,000 lbs. The total volume fractions in the CB after blowdown are 55% helium and 45% air. For practical purposes, one would anticipate that large parts of the helium will mix during blowdown with the air in the large volume above the refueling floor, and that the ventilators would provide for further gas mixing between blowdown and the beginning of combustible gas ingress (70 to 90 hrs).

However, considering the hypothetical and extreme scenario of large parts of pure helium being accumulated in the reactor dome during blowdown, and assuming no co[illegible] r [illegible] exist thereafter, the only mechanism for mixi[illegible].

[illegible] on the mixing of helium an[illegible] .ely separated gas

[illegible]

volumes of helium and air being put into contact at blowdown time is being considered. The diffusion coefficient for He and air was estimated based on References 5 and 6 as $D = 6 \times 10^{-4}$ ft^2/s. The concentration field for two semi-infinite regions in contact and for a constant diffusion coefficient, is

$$c = .5 \text{ erfc } \frac{x}{2\sqrt{Dt}}$$

where c is the concentration of the diffusing species, i.e., of helium in the air volume, or of air in the helium volume. A numerical solution of one-dimensional molecular diffusion for a finite CB volume was applied here, but semi-infinite results based on the above equation are very close to the finite solution up to 10 days. Results are shown in Figures 2-6 and 2-7.

Even in this completely hypothetical upper bound case, at the anticipated liner failure time of 70 to 90 hrs about 25% of the containment atmosphere would be more than 50% mixed, and almost half of the CB atmosphere would be more than 20% mixed (''n percent mixed'' is defined here as the region in which the volume fraction of diffusing gas (i.e., helium in the lower air region or air in the upper helium region) exceeds n% of its final equilibrium volume fraction of 0.5)

These results show that while molecular diffusion will not result in complete mixing during the time frame of 1 to 10 days, it alone would result in mixing of significant parts of the CB atmosphere prior to liner failure, even in the hypothetical case of complete gas separation and absence of all convective flows.

[illegible] at the beginning of concrete decomposition gas ingress, some CB [illegible] stratification could still exist if there would have been no venti[illegible] all during this 3-day time period, but large parts of the CB would [illegible] due to mixing during the initial blowdown, and due to molecular diffusion. The assumption of completely separated gas regions above the refueling flow does not appear to be realistic.

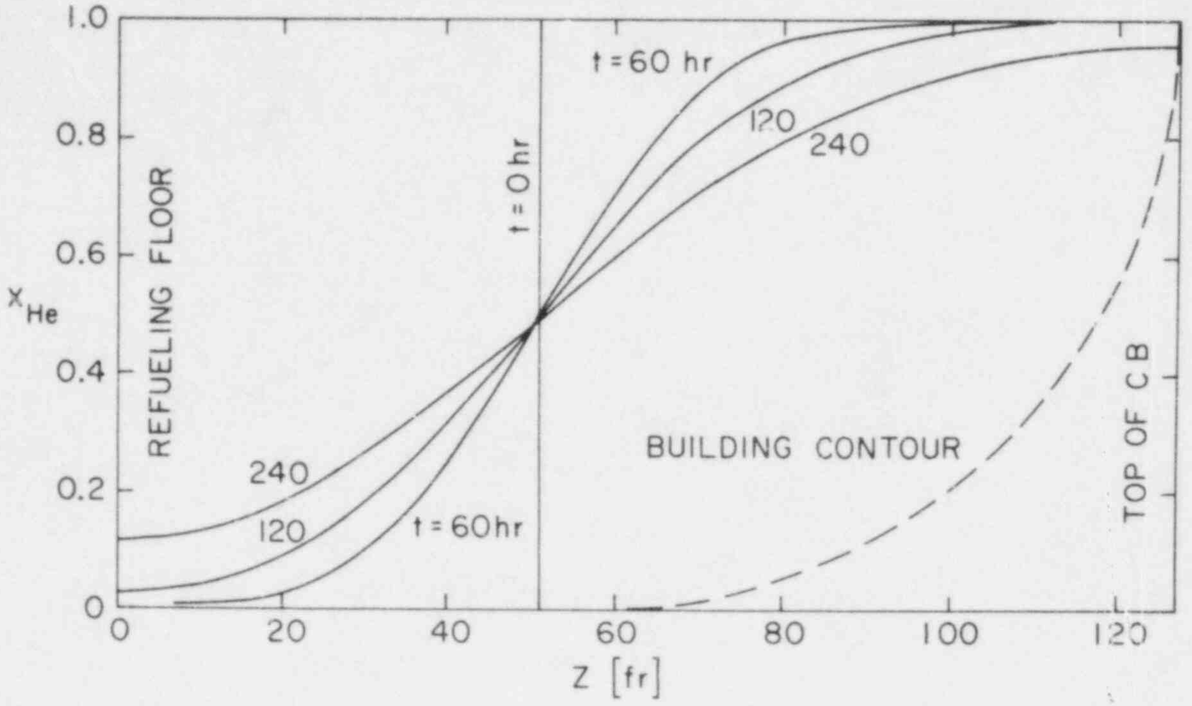


Figure 2-6 Axial distribution of volume fraction of helium (x_{He}) in containment building atmosphere at various times (t) after blowdown for hypothetical case of complete stratification at blowdown (t=0) with subsequent mixing due to molecular diffusion only; (total volumes of air and helium are equal; $D_{AB} = 0.4 \times 10^{-3}$ ft^2/s).

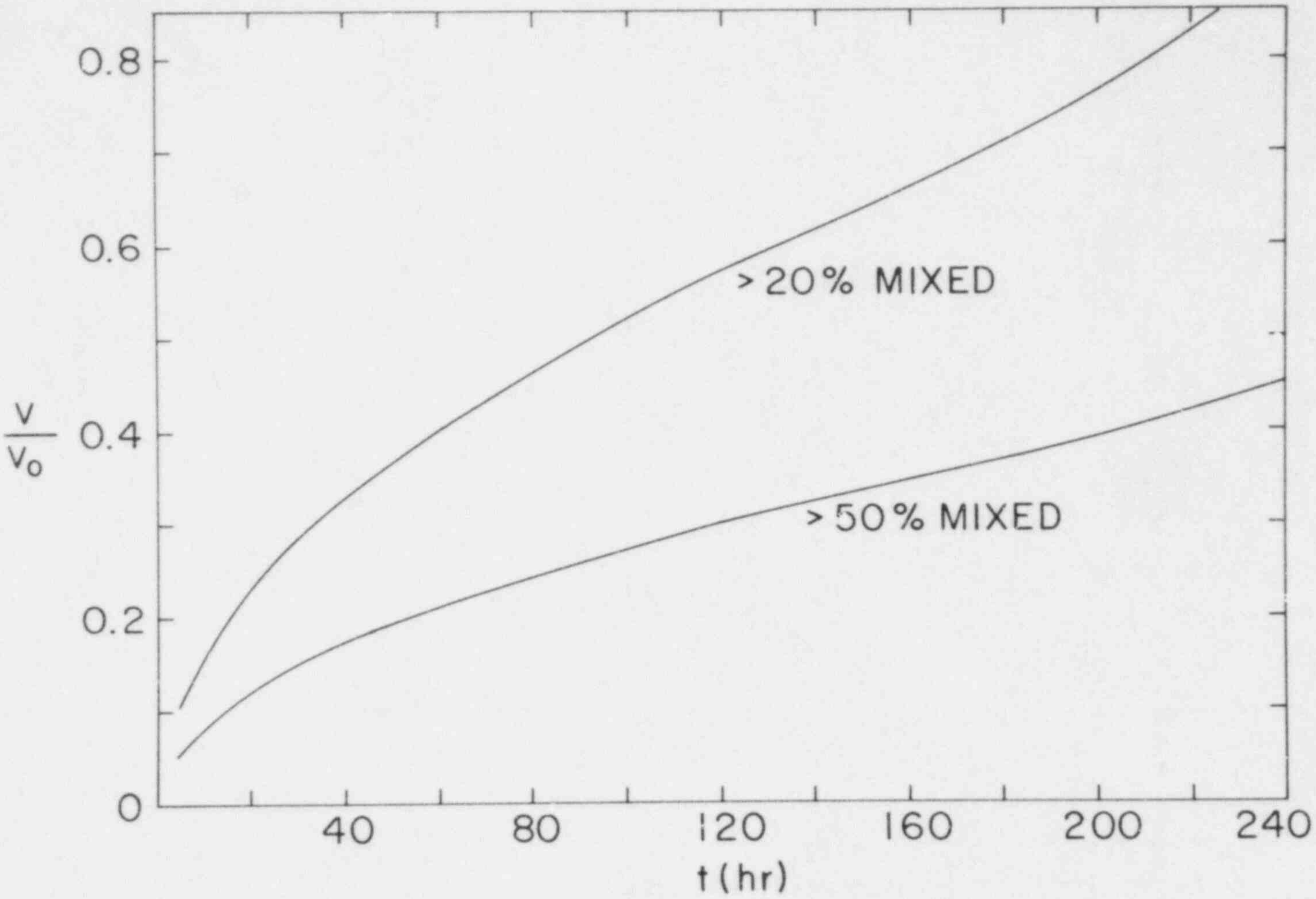


Figure 2-7 Fraction of containment building atmosphere volume in which mixing of helium and air exceeds specified value for hypothetical case of complete stratification at blowdown ($t=0$) with subsequent mixing due to molecular diffusion only; (total volumes of air and helium are equal; $D_{AB} = 0.4 \times 10^{-3} ft^2/s$).

2.2.3 Local Formation of Combustible Mixtures Prior to Core Peripheral Seal Failure

Subsequent to liner failure at about 70 to 90 hrs concrete decomposition gases (CDG) will enter the core. As long as the core peripheral seal remains intact, only small fractions of these CDG's can react with the hot core graphite, forming combustible gas mixtures of H_2, CO, H_2O, and CO_2 to be called ''reactor gas'' here. As was shown in Appendix F of Reference 1 combustible mixtures between reactor gas and CB air are not expected to be formed until seal failure at about 130 hrs. That result was obtained based on completely mixed atmospheres. As was pointed out above, the first effect of partial mixing would be to exclude some of the side annulus air from mixing, resulting in even less potential for the formation of combustible mixtures.

To arrive at potentially worse conditions, there would have to be a mechanism for reactor gas to mix with relatively pure air resulting in higher fuel and air concentrations. At the exit point from the relief valve train to the CB atmosphere, where the original helium blowdown occurred, one cannot expect such high air concentration. Failure of the relief valve train ducts can occur as the core gas temperatures exceed 2000°F and approach the melting point of steel. This is expected to occur around 130 to 150 hrs. Only an earlier duct failure, i.e., an additional failure, could plausibly lead to a shift in the reactor gas discharge point. If that were to occur it would most likely be at the hottest point in the ducting, i.e., in the open space above the refueling platform elevation. At that elevation, pure air, again, cannot reasonably be expected. However, if for some even less likely reason duct failure were to occur in the annular side space at a point where relatively pure air still exits, then a local pocket of combustible gas could be formed. (Note that this event requires duct failure earlier than expected, and at a point other than the most likely failure point). Up to seal failure at about 130 hrs the reactor gas contains about 12% water gas; 7% additional CO; and 81% of H_2O and CO_2.

Flammability diagrams for water gas and CO mixtures are not available and - as before - the ones for water gas will be used.[2,3] Two limiting cases will be considered: once it is assumed that as far as flammability limits are concerned the additional CO acts as diluent and only the water gas represents fuel (Cases 1.1 and 2.1); in the other case the additional CO is treated as fuel in considering flammability limits (Cases 1.2 and 2.2). In the evaluation of peak pressures the additional CO is always burnt with the remaining fuel and does contribute to the resulting pressures. Actual conditions would be expected to lie between these two extremes.

Figure 2.8 shows the progression of such fuel mixing with pure air and with all water exceeding saturation being condensed and removed from the mixture at all times.

As the reactor gas enters the pure air atmosphere, the gas/air mixture moves down from the tip along lines 1.1 or 1.2. As the flammable region is reached, with about 6% fuel in the mixture, combustion could occur if an ignition source were present. At entry into the flammable region, Case 1.1 represents the more severe case since in that case combustion occurs with more fuel and less excess air.

At that point, if the local compartment contained a uniform mixture, the isochoric adiabatic complete combustion (IACC) pressure ratio would be about 3.6 for Case 1.1 and 2.9 for Case 1.2. Experimental results referred to in Appendix A indicate that at these low fuel concentrations, actual pressure ratios are significantly lower. Assuming the actual pressure ratio to be 70% of the theoretical one, and with CB pressures ranging from 40 to 50 psi over the time span of 80 to 130 hrs where such local burning might occur, and using the more severe Case 1.1 a peak pressure of 50 x .7 x 3.6 = 126 psia could occur locally. This is less than the maximum CB pressure of 130 psig or 145 psia given in Appendix A of Reference 1. Thus, such burning of local pockets would not be expected to affect CB integrity. Since any compartment in the side annulus would not be hermetically sealed, gas would expand into surrounding areas and the actual peak pressure would be lower. Furthermore, the whole compartment would have to be uniformly mixed to reach the above pressure, and the effect of significant amounts of condensed water would be to further reduce the temperature and pressure spikes.

The local peak pressures would last on the order of seconds. As the natural frequency of CB structures is of the order of 10 cycles, these local

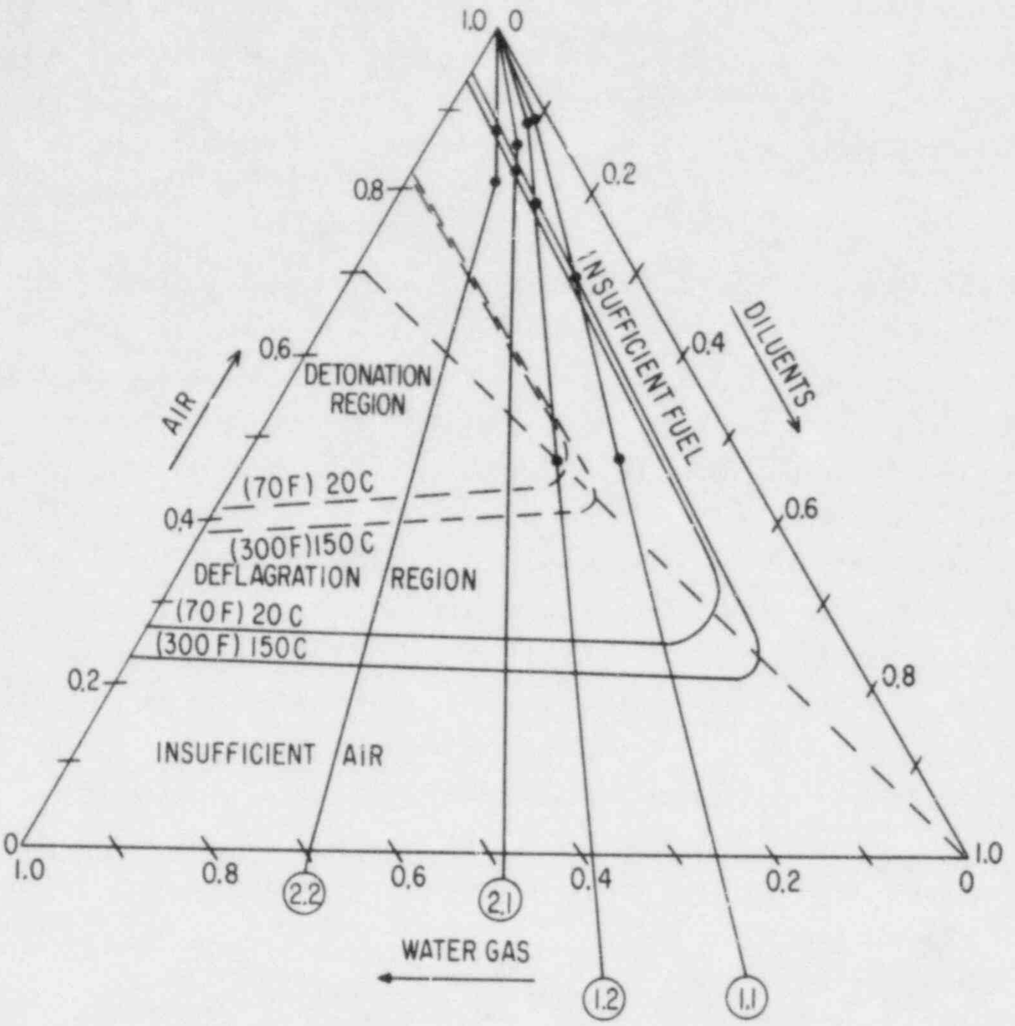


Figure 2-8 Flammability limits for reactor gases mixed with undiluted air from the CB atmosphere.

Case 1: Gas composition up to core peripheral seal failure (0.1 of CDG reacting with core graphite)

Case 1.1 Treating additional CO as diluent

Case 1.2 Treating additional CO as water gas

Case 2: Gas composition subsequent to core peripheral seal failure (0.3 of CDG reacting with core graphite).

Case 2.1 Treating additional CO as diluent

Case 2.2 Treating additional CO as water gas .

peaks can impose quasi-static loads. While this report does not include any CB stress analysis, simple first order arguments can be used to show that the wall stresses induced by local static peak pressures will always be lower than those from the same pressure applied uniformly for the whole CB. Thus, even if the local pressure in a compartment were to exceed the building failure pressure transiently by a moderate amount, CB failure would not be anticipated.

If there were no ignition source in the above compartment, and more fuel were to mix with its air until the gas just reached stoichiometric conditions, than the IACC pressure ratio could be as high as 5.3. At that point the diluent concentration is about 35%, and again the actual pressure spike would be significantly lower. However, the resulting local peak pressures could now reach levels of 150 to 180 psi between 90 to 130 hrs. Figure 2.8 indicates that for Case 1.2 even detonations are possible within very narrow limits. However, in addition to all other remote assumptions this would now also require the initial absence of an ignition source plus its sudden occurrence just as the stoichiometric point is reached. Local compartment pressures of 150 to 180 psi imposing only local stresses on the CB structure would not be expected to result in structural damage to the CB since, as pointed out above, the wall stresses resulting from local peak pressures are generally lower than those resulting from the same pressure applied uniformly to the total pressure vessel. These pressure levels have also been arrived at by imposing several worst case assumptions on top of worst case assumptions.

It should also be noted that the base CB pressure of 50 psi, used above for the time span of 80 to 130 hrs is only reached at 130 hrs, and building failure of about 135 hrs due to deflagration burning is already considered. I.e., for the <u>earlier</u> failures that are being looked for here, a lower base pressure should actually have been applied.

Thus, in summary, the local formation of combustible gas pockets is of much lower probability than the considered event of deflagration burning after seal failure. And, even if it were to occur, it would only apply local stresses on the CB structure which are less severe than the building failure stress levels.

An alternate scenario for early combustion would be to assume reactor gas egress at the refueling platform level, for instance, due to early duct failure at that point. In completely mixed CB atmospheres, combustible mixtures could not be formed prior to seal failure. But assuming a layer of relatively concentrated air at the refueling platform level, and assuming the reactor gas to mix only with that layer, one can reach combustible mixtures of the same composition as Cases 1.1 or 1.2 in Figure 2.8. However, this gas volume is now part of the total upper gas dome. As it burns, it will initially compress the upper inert gas layers. Thereafter, temperature equalization between the two regions would lead to a further gradual pressure rise, if there were no heat transfer to the surroundings. The initial pressure rise is less than the pressure rise for combustion with the two regions completely mixed. The final pressure after temperature equalization and without heat transfer to the surroundings would be equal to that for combustion of the two gas regions being mixed. In actuality, as the temperature equalization takes a significant amount of time, more heat transfer to the surroundings would occur, and thus, any burning in the top volume area of local combustible regions results in a less severe pressure-spike than the corresponding case of burning a completely mixed gas. However, <u>initiation</u> of burning may become possible under stratified circumstances, when fuel or air concentrations for mixed atmospheres are outside of the flammability limits. This process is analyzed in more detail in Appendix B.

For reactor gas prior to seal failure and assuming 50% of the top dome to be pure helium and 50% to be pure air, the instantaneous IACC pressure ratio after pressure equalization would be 2.5 as first flammable conditions with 6% fuel are reached. Assuming the actual peak to be 70% of this, and a base pressure of 50 psi, one obtains a peak pressure of 89 psi. The IACC pressure ratio after temperature equalization would be 3.0 for this case, but as pointed out above, significantly lower pressure ratios would be expected in practice, and the peak pressures from such early burning would not be expected to reach 100 psi.

If ignition were not to occur in this air fuel layer until it reached uniformly mixed stoichiometric concentration, while still not mixing with the inert gas on top and with water condensation based on the air-fuel layer partial pressure alone- a completely hypothetical scenario- than the initial

IACC pressure ratio would be 4.0. Again using 70% of this and a base pressure of 50 psia, one obtains a peak pressure of 140 psia, which would apply for the whole dome. While this pressure would be in the range of assumed failure pressures, the scenario used to invoke it is highly hypothetical, and also uses the base pressure which is only reached at seal failure time.

The more reasonable scenario to be expected for gas emissions at the refueling platform level would be as follows: reactor gases begin to emerge at about 80 hr, with a temperature of about 2000°F and at a rate of about 3000 lb/hr. The CB atmosphere at that point is most likely to be fairly well mixed, about 55% helium and 45% air. All mixtures of reactor gas before seal failure with such an atmosphere are non-flammable in accordance with Figure 2.8, and no burning would be expected. If the CB atmosphere were not well mixed, and higher air concentrations were available locally, then it would be most likely that a flammable mixture would be formed at the point of gas entry into the CB, with the gas temperature being sufficient for self-ignition. Such local combustion as reactor gas is entering the CB would result in controlled local burning for a limited time, until the available air concentrations drop below about 25%. Such temporary controlled burning would reduce the actual CB gas volume slightly and would eliminate the possibility of later uncontrolled burning, since it would deplete the available air.

In summary, gas egress at the refueling platform level and the formation of combustible mixtures there is also not expected to result in damage to the CB structure. The more likely effect would be temporary controlled burning with beneficial side effects.

2.2.4 Combustible Mixtures After Core Peripheral Seal Failure

Beyond the time of liner failure (70 to 90 hrs), if one were to assume earlier core peripheral seal failure, the analysis of Reference 1 showed that for completely mixed atmospheres deflagration burning was possible and could begin shortly after seal failure. This scenario includes an additional failure and is, therefore, less likely to occur. If one were now to assume non-mixed regions such that the incoming reactor gas mixes with pure air, and that no burning occurs as the gas mixtures become flammable, but with ignition as these mixtures reach stoichiometric concentration, then even detonable mixtures can be obtained. (Case 2.1 and 2.2 in Figure 2.8) The same, of course, also applies for seal failure at 130 hrs or later.

The possibility of CB failure from deflagration burning subsequent to seal failure has already been considered in Reference 1 and failure due to detonation does, therefore, not constitute an additional failure. At first glance it might appear to cause a more severe failure. However, the detonation pressure spikes are very fast and can therefore be considered as dynamic loads, while the slower deflagration pressure spikes constitute full static loads. The typical lead plant CB structure is of the type of Indian Point CB's (Reference 1, App. A). Reference 8 analyses severe accident loads for such buildings and includes a case of hydrogen detonation of 25 vol % hydrogen in air occupying the whole hemispherical dome, under several conservative assumptions. The results show that while concrete cracking would occur, the building liner integrity would be maintained and the pressure boundary would not fail. Also, the dynamic load is more affected by the long-lasting overpressure step than by the dynamic impulse load. In HTGR's the base pressures in the CB are higher at the times at which burning can occur, and the results do not directly apply to HTGR's. However, they indicate qualitatively, that even if detonations were to occur, their accompanying stress loads are hardly more severe than those from deflagration waves having the same step change in overpressure.

Thus, after core seal failures, CB failures from deflagration burning can occur with mixed or stratified atmospheres. Even detonations could occur, but are less likely. It is not at all certain that CB failure would occur but it is conservatively assumed to occur.

2.2.5 Potential Mitigating Features

While the accidents discussed here are of extremely low probability, there analysis is afflicted by significant uncertainties, since for instance the debris distribution in the core which has a significant effect on the ultimate gas composition cannot be determined accurately by analysis or experiment.

If these accidents were ever to be considered in the design of a plant, one could reduce their likelihood even further by use of enhanced safety features, like a further improved liner cooling system.

Another way to eliminate uncontrolled burning from consideration would be by inerting the atmosphere, either as a permanent feature, or due to the time scale of such HTGR accidents by inducing controlled burning of the CB air subsequent to blowdown and prior to liner failure (70 to 90 hrs after beginning of the accident). This would slightly increase the gas masses in the CB and, thus, slightly advance the time point of CB failure from overpressurization, but it would prevent any uncontrolled burning.

A system of glow plugs, causing ignition and thus preventing accumulation of combustible gases would be another option, as would be catalytic recombiners.

Division of the CB into subcompartments separated by gravity controlled check valve-like doors could also be used to control the atmosphere, separating large parts of the original air from the later arriving combustible gases.

Concretes of low carbon dioxide content are readily available, and specifying the use of such a concrete would drastically reduce the severity of the accident scenarios considered here.

This list does not imply that either of these features should be used. They are only listed as possible items that could be used if uncontrolled combustion were ever to be considered ir the design of the CB.

3. QUALITATIVE APPLICATION TO FORT ST. VRAIN

The FSV reactor uses a vented Reactor Building (RB), with the ventilation system generally providing for about 1/4 in wg negative pressure to assure that all leakage is inward.[9] In a DBDA sequence, about 1/3 of the primary coolant will be lost from the RB to the atmosphere through the ''relief device'' at the top of the building. The relief device closes after blowdown, and the building ventilation system can filter the remaining 2/3 of the primary coolant. These analyses assumed complete mixing at all times, which is conservative, as actually initially more air would be ejected, resulting in less air and more helium in the RB after blowdown. The RB gas composition after cooldown then corresponds to about 50 vol % helium, which is roughly the same as in the lead plant.

A UCHA analysis for FSV is not available at this time. It is, therefore, assumed that such an accident qualitatively follows the same route with reactor gas ingress into the RB beginning after several days. As the RB is not pressurized, gas and fission product release from the RB will be continuous once this reactor gas release from the core begins.

The various scenarios of non-mixed gas pockets being formed remain essentially unchanged from those of the lead plant. However, with beginning reactor gas emission into the RB, the gas escaping from the RB will contain air, thus making burning even less likely. As the base pressure in the RB remains atmospheric, the resulting peak pressures from any burning will be much lower, certainly 42 psi or less, using the highest pressure ratios of Section 2. While such pressure spikes may cause local damage where they occur, their effect on RB integrity is not of concern here, since the building is already open to the environment.

Thus, such remote burning accidents as considered here for the lead plant would be even less likely in FSV as there is only a net outflow and escape of combustion air subsequent to reactor gas ingress, and even if it were to occur, it would not significantly impact the source term since the building is vented at all times, and the RB does not provide a fission product release barrier.

The FSV reactor core does not have the same flow arrangement as the lead plant, and as the side thermal barrier fails and even as the core barrel steel sheet melts, there is still no direct flow path for concrete decomposition gases to enter the core, as there is in the lead plant subsequent to core peripheral seal failure. In the FSV core the only path from the side thermal barrier to the core would be via leakage through the steam generators, circulators, and the gravity closed flapper check valves, an extremely arduous path. Concrete decomposition gas from the side thermal barrier would, therefore, be much more likely to exit to the RB via the upper plenum and not pass through the core. Thus, a UCHA at FSV might form significantly less combustible gases than would be expected in the lead plant. On the other hand, it is not clear up to what time one can assume that the integrity of the core support floor is maintained. Beyond that time any such conclusions would most likely not be valid.

4. CONCLUSIONS

This report extends the previous work on potential uncontrolled burning of gas in the CB during UCHA scenarios. One of the basic assumptions in the previous work, which is summarized in Section 2.1, was to assume complete mixing of the gases at all times. In contrast, this report considers the potential effects of only partial mixing, gas stratification and the potential formation of local combustible pockets.

It was found that in most cases the completely mixed scenario presents a worse case than the burning of only partially mixed atmospheres. In particular, the air contained in the side annulus of the CB represents about 25% of the total original air volume, and only part of this air will be mixing with the arriving fuel. Considering all of it to mix makes more air available for burning and results in mixtures closer to the flammable region.

Comparing the ignition of a completely mixed gas volume, to the case of the same gases but with the inert components being stratified prior to ignition it is shown that the completely mixed case will cause the higher peak pressure and be, thus, a more severe load.

If the absence of all convective currents and complete stratification is assumed, over the time scale of UCHA accidents (2 to 10 days), molecular diffusion will cause significant but not complete mixing.

Previous analyses assumed that deflagration burning in the CB becomes a possibility shortly after core peripheral seal failure, with CB failure at that time being possible. The possibility of earlier failures from local mixing of reactor gas with pure air was investigated. If one assumes a separated local compartment where only reactor gas and pure air mix, such that all gas in this compartment is uniformly mixed and all water beyond saturation is removed, then pressures of 120 to 130 psia could be reached locally, if burning occurs as the flammability limits are reached. These pressures are still below the building failure pressure. If burning is further delayed until a stoichiometric fuel/air ratio is reached, then one can reach local peak deflagration pressures of 150-180 psia, which exceed the building failure pressure of Appendix A of Reference 1. However, these pressures apply only locally, and thus cause lower static stresses in the CB structure then would be imposed by a uniform pressure of 144 psia in the whole CB pressure vessel. This case also requires additional failures of gas ducting at unexpected points, plus a well sealed side compartment, with complete mixing inside of it, plus no ignition until the stoichiometric point is reached, with a spark arising at that time. Thus, this event is less likely than the already remote burning accidents, and it still does not impose any fatal loads on the CB structure.

If reactor gas were to mix with pure air at the refueling level, the peak pressures would generally not reach 100 psi. If one assumes complete mixing of the fuel and air but complete stratification of the inert gas plus delay of ignition until the stoichiometric point is reached, then a peak pressure of 140 psi could be reached. While this is in the range of failure pressures, the scenario to reach this condition is highly hypothetical.

If one were to extend the partially mixed analyses beyond the point of core peripheral seal failure, one could obtain even detonable mixtures from mixing of reactor gas with pure air. But at that time building failure is already assumed to occur anyhow, and the loads from detonation burning appear to be dominated by the static load which is the same as that from deflagation burning.

Considering how these results apply to FSV, it is found that as long as the integrity of the core support floor is maintained, there is less potential in FSV for the in-core formation of combustible gas mixtures. Furthermore, the continuing gas outflow out of the CB as reactor gas ingress begins will reduce the available air and make uncontrolled burning accidents even less likely. Of course, as the CB does not have a pressure boundary it cannot act as a fission product release barrier.

REFERENCES

1. ''Preliminary Evaluation of HTGR Severe Accident Source Terms,'' NUREG/CR-3429, 1982.

2. ''HTGR Accident Initiation and Progression Analysis Status Report - Phase II Risk Assessment,'' Report No. GA-A15000, General Atomic Company, April 1978.

3. P. Bogorinski and H. Wagner,''Thermodynamik Einschliesslich Moeglicher Verbrennungsvorgaenge Im Reaktorschutzgebaeude,'' (Thermodynamics including possible combustion in the Containment Building), Section B.1 of Fachband II of Sicherheitsstudie fur HTR-Konzepte unter deutschen Standortbedingungen (Safety Analysis for HTR concepts under German Siting Conditions), KFA, Julich, JUL-SPEZ-136, Vol. 3, April 1982.

4. GA Document 906392, ''Safety Risk Assessment for the 2240 MW(t) SC/C Plant.''

5. Transport Phenomena, R. Byron Bird, W. E. Stewart, and E. N. Lightfoot, Department of Chemical Engineering, University of Wisconsin, Madison, Wisc., J. Wiley & Sons, Inc., N. Y.

6. J. O. Hirschfelder, C. F. Curtiss, R. B. Bird, Molecular Theory of Gases and Liquids, Wiley, New York, 1954.

7. ''High Temperature Gas-Cooled Reactor Steam Cycle/Cogeneration, Lead Plant Design and Cost Report,''Volume III Balance of Plant, Gas Cooled Reactor Associates, July 1982.

8. T. A. Butler, L. E. Fugelso, ''Response of the Zion and Indian Point Containment Buildings to Severe Accident Pressures,'' NUREG/CR-2569, LA-9301-MS, 1982.

9. Final Safety Analysis Report, Fort St. Vrain HTGR.

APPENDIX A

Pressure Peaks During Combustion in Closed Volumes

The wave propagation through combustible mixtures is considered in many texts on gas dynamics.[A-1,A-2] Based on the conservation equations it can be shown that detonation waves cause severe pressure rises across shocks, but deflagration waves are waves reducing the pressure. In closed volumes, deflagration waves are formed behind an advancing shock,[A-2] and after several wave passages and reflections, significant pressure rises are also observed. Detonation waves propagate at supersonic speeds, with peak pressure arising in the order of milliseconds. Pressure spikes from deflagration burning take longer to build up, typically of the order of 0.1 to 1 second.

The pressure rise during deflagration burning depends on local heat and mass transfer conditions during and after the propagation of the flame front, and the actual prediction of the pressure peaks is relatively complex, depending on geometry, local gas composition, convective currents and initial temperature distribution. An upper limit, which can never be approached is the isochoric and adiabatic complete combustion (IACC) temperature and pressure, which can be computed readily, assuming zero heat transfer from the gas, and maximum combustion, limited only by the available fuel or air.

Figure A-1 to A-2 show the IACC pressure peaks computed for several gas mixtures as function of available air for combustion based on gas internal energy data from Reference A-1. The abscissa air factor λ is the ratio of volume fractions of air over volume fraction of air required for stoichiometric combustion. I.e., at values $\lambda<1$ there is insufficient air and only partial combustion occurs, (region below stoichiometric line of flammability diagram in Figure 2-8), while at $\lambda>1$ excess air is available and complete combustion is possible but the excess air reduces the combustion temperature and the pressure peak (region above stoichiometric line in Figure 2-8).

The gases emitted from the PCRV to the CB due to concrete decomposition with subsequent partial chemical reaction of the gas with core graphite are typically water gas (equal volume fraction mixture of H_2 and CO) plus excess CO. The typical mixture of 2/3 water gas and 1/3 CO (1/3 H_2 and 2/3 CO) will be referred to here for convenience as ''reactor gas''.

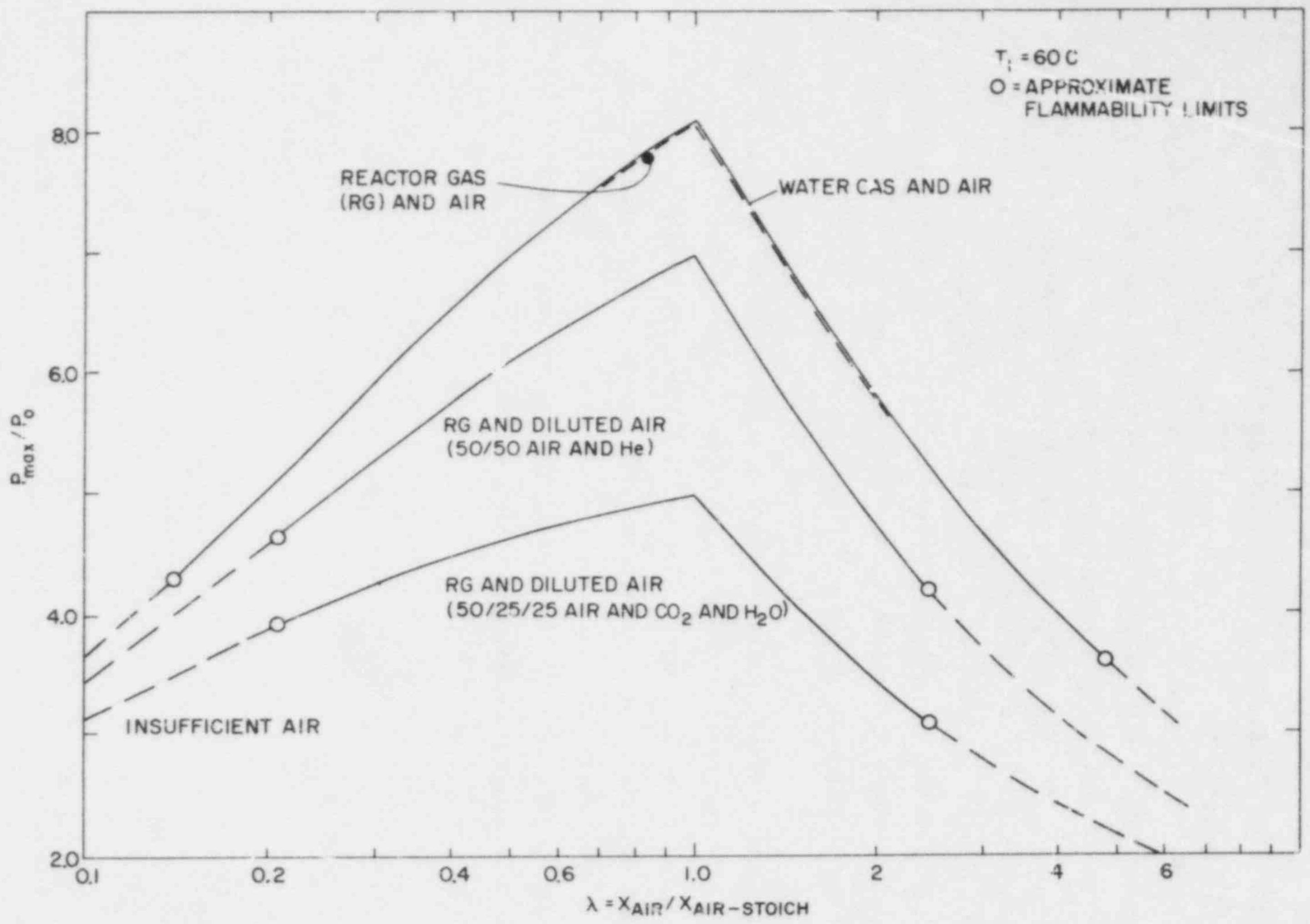


Figure A-1 Peak pressures for theoretical isochoric/adiabatic combustion of water gas and reactor gas (2/3 water gas; 1/3 CO) mixed with pure air or with diluted air (initial mixture temperature 60°C = 140°F).

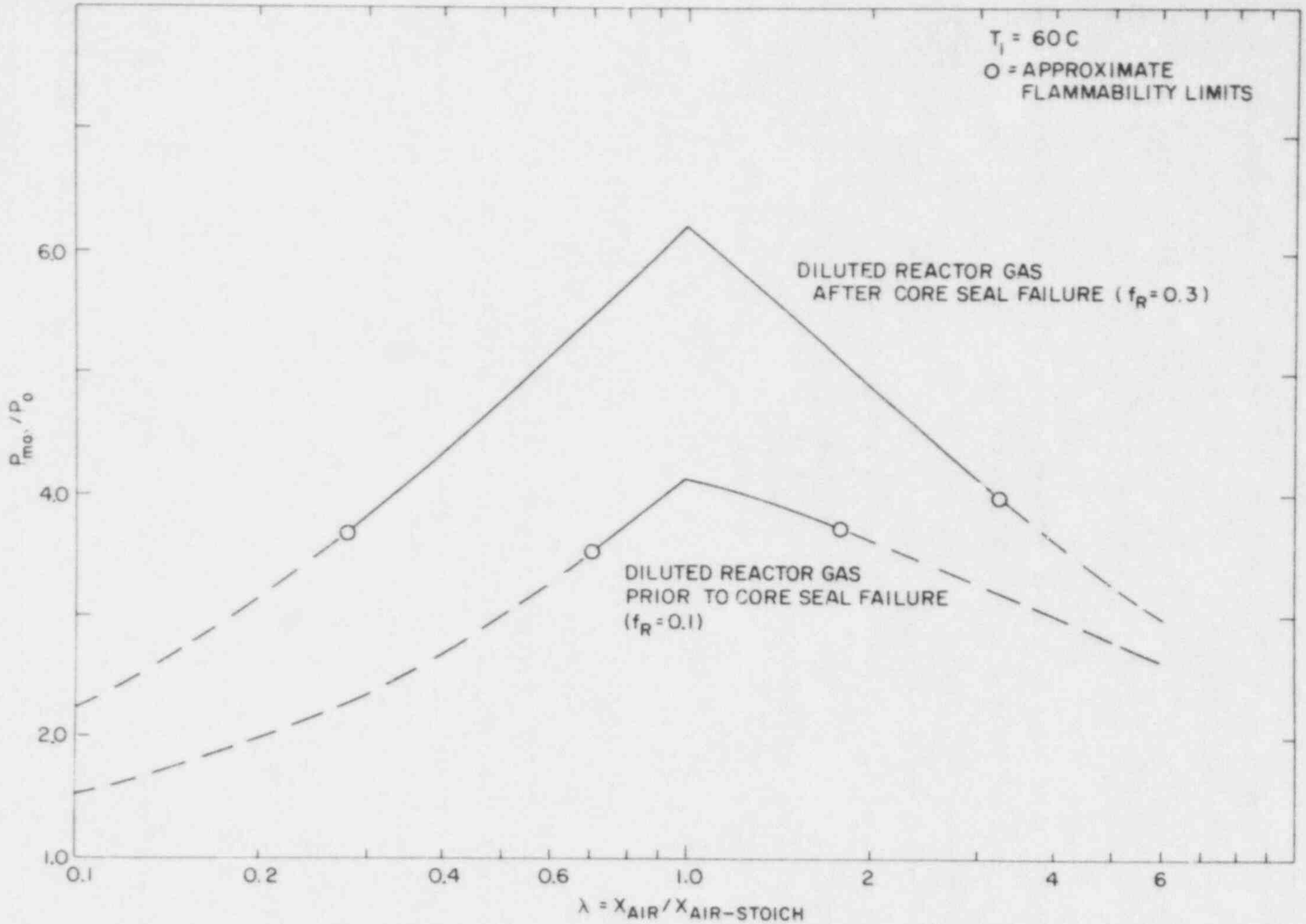


Figure A-2 Peak pressures for theoretical isochoric/adiabatic combustion of typical diluted gas prior and subsequent to core peripheral seal failure mixed with pure air (initial mixture temperature 60°C = 140°F).

Figure A-1 shows the IACC pressure ratio p_{max}/p, of pressures before and after combustion for pure water gas mixed with pure air, and for reactor gas mixed with pure air. It is seen that the additional CO has essentially no effect on the IACC peak pressures. Also shown are the peak pressures for reactor gas mixed with 50/50 mixtures of air and helium as well as with 50/25/25 mixtures of air with CO_2 and H_2O.

Figure A-2 shows the IACC peak pressures for partially reacted reactor gas, i.e., H_2 and CO diluted with H_2O and CO_2 being mixed with pure air. Shown are the cases of typical reactor gas prior to core peripheral seal failure, where 10% of the concrete decomposition gas is assumed to react with the core. Typical composition for this gas is 12% water gas, 7% additional CO, 26% CO_2 and 55% H_2O. Also shown is reactor gas subsequent to core peripheral seal failure, assuming 30% of the concrete decomposition gas to react with core graphite. The composition for that gas is 31% water gas, 16% additional CO, 17% CO_2 and 36% H_2O.

(Whether the diluents are part of the original air/diluent mixture or enter the CB with the reactor gas is, of course, irrelevant as far as the IACC pressures are concerned. Showing peak pressures once for pure fuels entering diluted air, and once for diluted fuel entering pure air is strictly done for convenience, to provide data for the bounding cases to be considered in the body of this report).

The IACC pressure ratios are upper limits, assuming closed volumes with no heat transfer from the gas and for complete combustion. Typical experimental data for burning of hydrogen in large tanks have shown that the actual peak pressures are significantly lower.[A-3,A-4] For pure fuels and air close to the stoichiometric point, the observed pressure ratios can be as high as 85% of the IACC pressure ratio, but with diluents and for non-stoichiometric mixtures the observed pressure ratios are only around 50 to 60% of the IACC values. Corresponding ratios will be applied in the body of this report.

The peak combustion pressures tend to decrease with increasing temperature of the initial mixture. Thus evaluations at lower than actual initial mixture temperatures will tend to be conservative.

References

A-1. J. A. Owczarek, ''Fundamentals of Gas Dynamics,'' International Textbook Co., Scranton, Pa., 1964.

A-2. L. D. Landau, E. M. Lifshitz, Fluid Mechanics, Pergammon Press, London, 1959.

A-3. M. R. Baer, A. C. Ratzel, ''A Hydrodynamic Model of Flame Propagation in Reactor Vessels,'' Proceedings of the Second International Conference on the Impact of Hydrogen on Water Reactor Safety, Albuquerque, New Mexico, pp 757, 1982.

A-4. W. B. Benedick, J. C. Cummings, P. G. Prassinos, ''Experimental Results From Combustion of Hydrogen: Air Mixtures in an Intermediate Scale Tank,'' Proceedings of the Second International Conference on the Impact of Hydrogen on Water Reactor Safety, Albuquerque, New Mexico, pp 665, 1982.

APPENDIX B

Burning of Flammable Region in Contact with Inert Region

The objective of this appendix is to show qualitatively that the peak pressures reached in burning a completely mixed volume will always be higher than those resulting from burning if the same gas were separated into a region containing a flammable mixture and an inert region.

To be compared here are the cases of:

1. burning of a mixture of fuel, air, and diluents all being completely mixed before burning, versus
2. burning of the same amount of gas, but some or all of the diluents now being stratified in region B, while the air-fuel mixture, plus remaining diluent, if any, occupying region A.

The IACC pressure ratio p_2/p_1 for Case 1 is readily computed. The actual peak pressure is reached rapidly in the order of seconds or faster. Even during this short period, the radiative and convective heat transfer to the surroundings are significant and the actual peak pressure-ratio will be only 50 - 80% of the IACC value.

In Case 2, only region A burns. Containing less diluents than the mixture of Case 1, a higher IACC pressure, p_2 is reached theoretically. However, the region A gas will now expand, compressing the region B gas, and establishing a uniform pressure for both regions, p_3. This expansion/compression process is rapid, of the same order as the combustion process, and can be considered as adiabatic compression/expansion. Thereafter, within seconds after ignition, regions A and B are at the same pressure, but at different temperatures. Temperature equalization due to convection and/or conduction between the two regions will take much longer, in particular for the large gas volume of interest here.

From ideal gas laws and energy conservation, it can be shown that if regions A and B have the same specific heats, then the pressure will remain constant during temperature equalization ($p_4 = p_3$). If the colder region has a lower molar specific heat (as helium does) the pressure will always increase during temperature equalization, $p_4 > p_3$. For real gases with temperature dependent specific heat this is not necessarily so, but for the temperature ranges and gas composition of interest here, hot region A always has a much higher specific heat, and for all practical cases the pressure will rise during temperature equalization, if there is no heat loss to the surroundings. Assuming that the temperature equalization indeed proceeds without any heat transfer to the surroundings, the ultimate pressure after full temperature equalization (p_4) would be identical to the IACC pressure of Case 1. I.e., we have reached the same theoretical peak pressure as in Case 1, but in a slower process. Since it is the heat transfer to the surroundings which strongly affects the actual peak pressures, these must be lower in Case 2 since significantly more time is available for heat losses to occur.

Thus, if there are two regions, region A containing a fuel-air mixture and some diluents, plus region B containing diluents, then burning of region A with subsequent pressure and temperature equalization with region B will result in a lower peak pressure p_4 then would have been reached, had all gas been mixed prior to combustion. Therefore, regarding peak pressures, the completely mixed case constitutes an upper limit.

It should be noted though, that considering flammability, the completely mixed assumption is not an upper limit. A stratified sub-region may contain a flammable mixture, while the same gas, completely mixed, may not be flammable.

Table B-1 summarizes computed IACC pressures and temperatures for specific gases.

Table B-1

IACC Pressures and Temperatures for Burning of Region A and Equalization with Region B[*]

Gas	P_{2A} (bar)	P_3 (bar)	P_4 (bar)	T_{3A} (C)	T_{3B} (C)	T_4 (C)
Pure Reactor Gas						
stoichiometric	8.1	5.2	7.0	2630	370	2260
Reactor Gas(F_r=.1)						
stoichiometric	4.0	3.4	3.8	1120	270	1060
low fuel limit(8%)	3.3	2.5	2.8	790	210	710
low air limit(25%)	3.6	3.1	3.4	960	250	910
Reactor Gas (F_r=.3)						
stoichiometric	6.2	4.4	5.6	1910	330	1720
low fuel limit(8%)	3.5	2.4	2.8	840	200	690
low air limit(25%)	3.8	3.3	3.6	1020	260	970

[*] NOTE: Initial Temperature 60°C
Initial Pressure 1 bar

FUEL GAS COMPOSITION

	H_2	H_2O	CO	CO_2
Pure Reactor Gas =	.33	0	.67	0
Reactor Gas (F_r=.1) =	.06	.56	.12	.26
Reactor Gas (F_r=.3) =	.16	.36	.31	.17

Inert Region = helium; with initial helium volume equal to air volume.

DISRIBUTION

Brookhaven National Laboratory

P. G. Kroeger (10)
C. A. Sastre
D. G. Schweitzer
H. J. Kouts
W. Y. Kato

R. Foulds (NRC)
J. Glynn (NRC)
T. King (NRC)
H. Reilly (EG&G)
P. Williams (NRC)

☆U.S. GOVERNMENT PRINTING OFFICE: 1984 717 032 10003

NRC FORM 335
(11 81)

U.S. NUCLEAR REGULATORY COMMISSION

BIBLIOGRAPHIC DATA SHEET

1. REPORT NUMBER *(Assigned by DDC)*
NUREG/CR-3868
BNL-NUREG-51793

2. *(Leave blank)*

3. RECIPIENT'S ACCESSION NO.

4. TITLE AND SUBTITLE *(Add Volume No., if appropriate)*
Containment Building ATmosphere Response Due to Reactor Gas Burning underRemote Severe Accident Condition

5. DATE REPORT COMPLETED

MONTH	YEAR
December	1983

DATE REPORT ISSUED

MONTH	YEAR
June	1984

6. *(Leave blank)*

7. AUTHOR(S)
P. G. Kroeger

8. *(Leave blank)*

9. PERFORMING ORGANIZATION NAME AND MAILING ADDRESS *(Include Zip Code)*
Brookhaven National Laboratory
Upton, N.Y. 11973

10. PROJECT/TASK/WORK UNIT NO.

11. FIN NO.
A-3016

12. SPONSORING ORGANIZATION NAME AND MAILING ADDRESS *(Include Zip Code)*
R. Foulds
Office of Accident Evaluation
U.S. Nuclear Regulatory Commission
Washington, DC 20555

13. TYPE OF REPORT
Formal

PERIOD COVERED *(Inclusive dates)*

14. *(Leave blank)*

15. SUPPLEMENTARY NOTES

16. ABSTRACT *(200 words or less)*

The formation of combustible atmospheres during unrestricted core heatup accidents in High Temperature Gas-Cooled Reactors is being investigated, considering the effects of only partially mixed atmospheres.

It is found that the previously used assumption of complete mixing presents the more severe limit in most cases. In the few cases were higher loads were obtained, these were still below the containment building failure limits, did apply only locally, and required the invocation of even more remote failure scenarios.

A qualitative discussion applying the above results to comparable accident at Fort St. Vrain is included.

17. KEY WORDS AND DOCUMENT ANALYSIS

17a. DESCRIPTORS

Containment Building Atmosphere
Combustion

17b. IDENTIFIERS/OPEN-ENDED TERMS

18. AVAILABILITY STATEMENT
unlimited

19. SECURITY CLASS *(This report)*
unclassified

20. SECURITY CLASS *(This page)*
unclassified

21. NO. OF PAGES

22. PRICE
$

NRC FORM 335 (11 81)

120555078877 1 1ANIR8
US NRC
ADM-DIV OF TIDC
POLICY & PUB MGT BR-PDR NUREG
W-501
WASHINGTON DC 20555