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Light Water Reactor Hydrogen Manual

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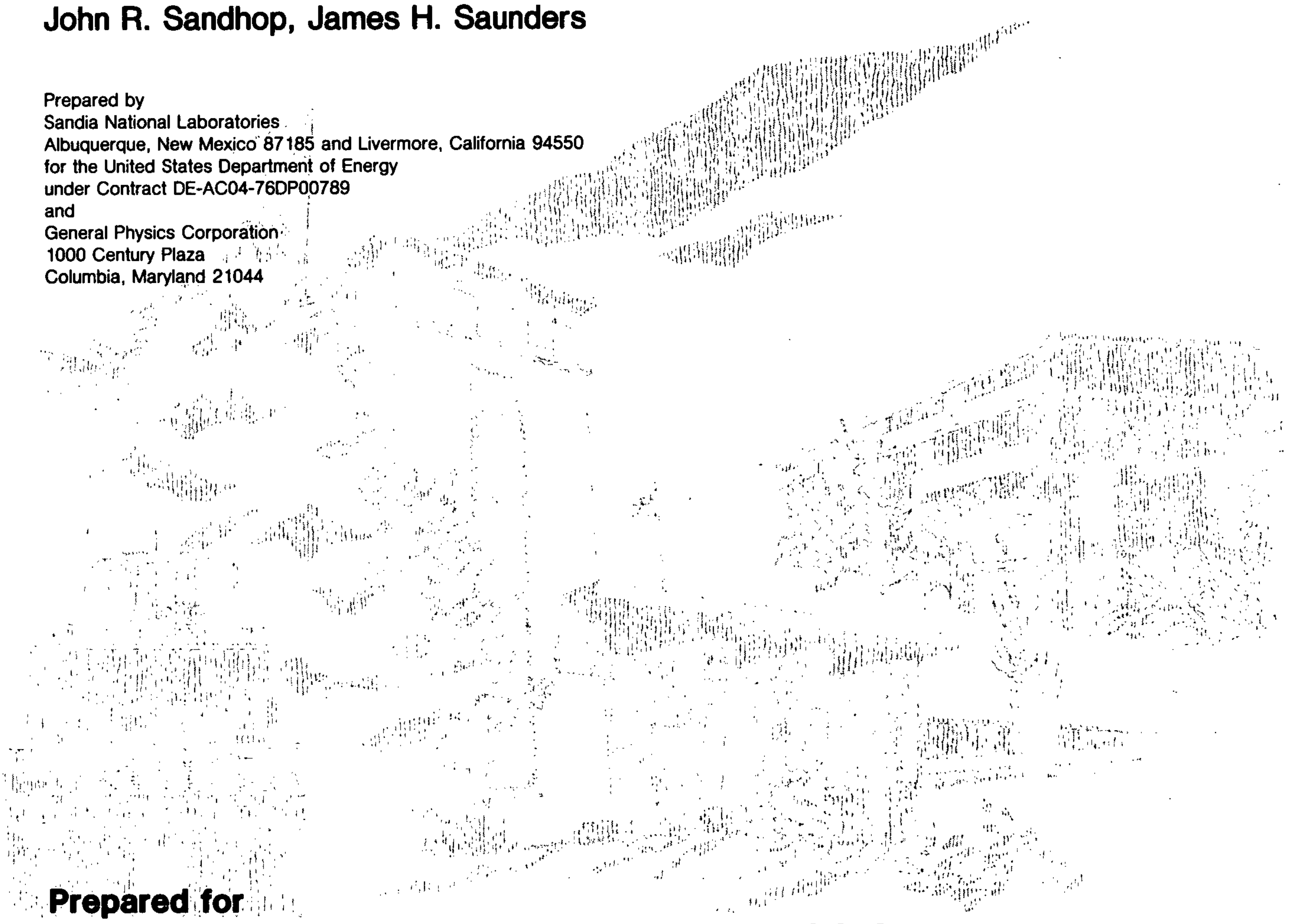

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Author's Note

While there are no current plans for updating this manual, persons who wish to point out errors or suggest revisions should send comments to the address shown below. If time and funding permits, we will attempt to pass on these comments to other recipients of the manual in an appropriate manner.

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ABSTRACT

A manual concerning the behavior of hydrogen in light water reactors has been prepared. Both normal operations and accident situations are addressed. Topics considered include hydrogen generation, transport and mixing, detection, and combustion, and mitigation. Basic physical and chemical phenomena are described, and plant-specific examples are provided where appropriate. A wide variety of readers, including operators, designers, and NRC staff, will find parts of this manual useful. Different sections are written at different levels, according to the most likely audience. The manual is not intended to provide specific plant procedures, but rather, to provide general guidance that may assist in the development of such procuedures.

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Acknowledgments

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CHAPTER 1

INTRODUCTION AND OBJECTIVES

1.1 STATEMENT OF THE PROBLEM

Since the accident at Three Mile Island (TMI), there has been a great deal of interest regarding the problem of hydrogen production and combustion in light water reactors (LWRs). As discussed in detail in Appendix I, it appears that, during the TMI accident, the core was uncovered for a time, and significant quantities of hydrogen were produced and released into containment. This hydrogen eventually ignited and resulted in about a 28 psig (192 kPag) peak pressure within containment. While this particular event did not endanger the TMI containment, there is concern that other, weaker containments might be vulnerable to hydrogen combustion or that more severe pressure rises might be seen under other accident conditions. In addition to the TMI accident, there have also been several incidents where hydrogen combustion occurred in off-gas systems.

Because of the above concerns and the interest shown regarding these problems, Sandia National Laboratories and General Physics Corporation, under the sponsorship of the Nuclear Regulatory Commission, prepared this manual. It is intended to provide information at a general but comprehensive level on the subject of hydrogen behavior. Numerous references are cited to provide more details on particular subjects. The manual is directed toward a wide variety of potential readers. The basic physical and chemical phenomena are discussed in order to provide a framework for later chapters. The phenomenological discussion also includes subjects which are topics of current research efforts, and therefore contain some uncertainties. In addition to providing background information for the remainder of the manual, the basic discussions (and the sections on mitigation systems) may be useful to plant designers. The sections on hydrogen behavior during normal operation should be useful to operators and supervisors. The sections on behavior during accidents may be of additional value to utility personnel and to NRC staff.

The manual is not intended to replace specific plant manuals, or to provide procedural directions to operators. Rather, this report is intended as a guide to utility staff when they are formulating their own plant-specific procedures. Note that it is <u>not</u> the purpose of this manual to predict the likelihood of hydrogen-generating accidents or assess the radiological consequences of such accidents.

1.2 HYDROGEN PROBLEMS IN LWRs

The major concerns regarding hydrogen are that the static or dynamic pressure loads from combustion may breach containment or that important, safety-related equipment may be damaged due to either pressure loads or high temperatures. In order to assess the possible threats, it is necessary to understand how hydrogen is produced, how it is transported and mixed within containment, and how it combusts.

The major production mechanisms are steam:zirconium reactions, steam:steel reactions, radiolysis of water, core:concrete interactions, and corrosion of zinc and aluminum. A discussion of the conditions necessary for these reactions to occur and reaction kinetics is presented in Chapter 2.

Hydrogen transport and mixing involve transport out of the primary system (accounting for the hydrogen remaining dissolved in water) and mixing within the containment atmosphere due to forced and natural convection and diffusion. Transport and mixing determine where, when, and for how long certain combustible mixtures are likely to be present. Combustion can occur if the mixture meets certain flammability criteria and an ignition source is present. The presence of steam, carbon dioxide, or other diluents can have a significant effect upon combustion. The basic processes mentioned above are discussed in Chapter 2.

Once the basics are understood, we can address hydrogen behavior in various types of reactors during different situations. As discussed in Chapter 3, hydrogen control is an important part of normal plant operations. Most reactors employ some type of gas treatment system to deal with hydrogen and other gases. Some reactors deliberately maintain certain levels of hydrogen in the coolant in order to reduce the oxygen inventory.

If a loss-of-coolant accident (LOCA) occurs, then there exists the potential to produce large quantities of hydrogen. Normally, core uncovery is necessary (but not sufficient) for significant hydrogen generation. The particular accident scenario dictates the timing and rate of hydrogen generation. Chapter 4 deals with hydrogen behavior in various types of reactors during accident situations.

1.3 HYDROGEN RESEARCH EFFORTS

There are three major research programs in progress that address issues of hydrogen behavior in LWRs: two industry-sponsored programs and one NRC-sponsored program. The industry-sponsored programs are the Electric Power Research Institute (EPRI) program[1-1] to investigate hydrogen combustion and control, and the Industry Degraded Core Rulemaking (IDCOR) program[1-2] which deals with a broad range of subjects includig hydrogen. The NRC-sponsored program[1-3] deals with hydrogen production, transport, combustion, and control.

The EPRI program focuses on hydrogen combustion behavior with studies of the deliberate ignition, water fog, and water spray approaches to hydrogen control. The primary near-term objective is to determine and demonstrate methods of effective hydrogen control so that the integrity of containment and safety-related equipment can be ensured. Several projects have been initiated for investigation of the following issues:

1. Lower flammability limits in nuclear reactor accident environments and effectiveness of various ignition sources;

2. Character of deflagrations in nuclear reactor containments and effectiveness of control or mitigation methods;

3. Nature of hydrogen mixing and distribution in large compartmentalized volumes with both natural and forced convection processes; and

4. Potential for acceleration of deflagrations or transition to detonation, and effectiveness of control methods.

The effects of hydrogen combustion on nuclear safety-related equipment have been studied in conjunction with other tests, and model development activities have been initiated. The experimental work in this program is being accomplished in test volumes ranging in size from 0.6 to 75,000 ft^3 (17 liters to 2100 m^3).

The IDCOR program is being managed by the Technology for Energy Corporation. While the IDCOR program involves many phenomena associated with degraded-core accidents in general, specific tasks related to hydrogen include:

1. Determine the rate and amount of zirconium oxidation and hydrogen generation during severe accidents;

2. Determine the hydrogen distribution in containment;

3. Determine the combustion limits of H_2:air:steam:CO_2 mixtures;

4. Survey hydrogen and oxygen detectors;

5. Evaluate pre-inerting as a mitigation scheme;

6. Evaluate fog/spray suppression;

7. Evaluate controlled burn and extinguishing systems; and

8. Identify a minimum set of equipment and evaluate the capability to survive a degraded-core environment.

Some of the above tasks are being carried out in conjunction with the EPRI program.

The NRC-sponsored program is managed by Sandia National Laboratories. The program involves assessment of the threat to nuclear power plants (containment structure, safety and control equipment, and the primary system) posed by hydrogen combustion; assessment of proposed hydrogen control and disposal methods; and development of new concepts. The program includes analytical modelling, computer simulation, and experimentation on several scales. The analysis portion of the program can be broken down into the use of existing computer codes; the development of new or significantly modified computer codes (specific to LWR hydrogen problems); and the development of simple models or correlations.

The experimental portion of the Sandia program consists of tests (and supporting analyses) in a variety of facilities ranging from laboratory scale to field scale. A large portion of the experimental work has been conducted in two cylindrical tanks. A steam:H_2 jet facility is being used to investigate autoignition and flame stability phenomena. A field-scale channel called "FLAME" will soon be available to study the effects of obstacles and venting on flame acceleration. In addition, a cooperative program with McGill University is under way to investigate flame acceleration, deflagration-to-detonation transition, and flame quenching.

1.4 DESCRIPTION OF MANUAL

Chapter 2 is intended to be a discussion of basic phenomena related to hydrogen. Production, transport and mixing, combustion, and mitigation are all discussed in some detail. Chapter 3 examines hydrogen behavior and control in reactors during normal operation, paying particular attention to chemical and off-gas systems. Chapter 4 examines hydrogen behavior and control in reactors during accident conditions. Indications of hydrogen production and combustion are discussed along with some observations and recommendations for particular types of reactors. Appendix I presents a description of what happened at TMI with regard to hydrogen, to the best of our knowledge at present. Appendix II examines the detection and sizing of gaseous voids in reactor coolant systems, and Appendix III discusses reactor vessel head venting.

References for Chapter 1

1-1 L. Thompson, "EPRI Research on Hydrogen Combustion and Control for Nuclear Reactor Safety," Electric Power Research Institute, Proceedings of the Fourth World Hydrogen Energy Conference, Pasadena, CA, New York, Pergamon Press (1982).

1-2 Personal Communication from E. L. Fuller, Technology for Energy Corporation (April 6, 1982).

1.3 J. C. Cummings and M. Berman, "Hydrogen Behavior and Control Studies at Sandia National Laboratories," SAND82-0870A, Sandia National Laboratories.

CHAPTER 2

HYDROGEN IN LIGHT WATER REACTORS

2.1 PRODUCTION OF HYDROGEN

2.1.1 Summary

There are a number of potential sources of hydrogen during a severe reactor accident. The two most important reactions producing hydrogen are:

Steam:zirconium and

Steam:steel.

Other important sources of hydrogen are:

Radiolysis of water,

Core:concrete,

Corrosion of zinc-based paint and galvanized steel, and

Corrosion of aluminum.

The steam:zirconium and steam:steel reactions are the most important early in the accident (first few hours). In the event that the core falls through the bottom of the vessel, core:concrete interactions become important. Radiolysis and corrosion can produce significant quantities of hydrogen, but over longer time periods (many hours to several days). Each of the six reactions is discussed in more detail below. The chemistry of some of these processes is very complex and not well understood. A large fraction of the information presented is taken from Ref. 2-1. Numerous other references are provided here and in Ref. 2-1 for those who wish for more details.

2.1.2 Steam:Zirconium Reaction

Steam and zirconium can react to produce hydrogen any time that the zirconium is heated to a sufficiently high temperature and an adequate supply of steam is present. Typically, a zirconium temperature in excess of 1832°F (1000°C) is required to produce a high reaction rate[2-1], indicating that the steam:zirconium reaction is only important when the reactor core is partially or completely uncovered.

The chemical formula for the reaction of zirconium with steam is:

$$Zr + 2H_2O \rightarrow ZrO_2 + 2H_2 + \text{Energy (Heat)} \qquad (2\text{-}1)$$

Thus for every mole of zirconium reacted, two moles of hydrogen are produced (or 0.044 lbm of H_2 per lbm of Zr reacted). The reaction is exothermic, releasing 2765 Btu/lbm of zirconium reacted (140 kcal/gm-mole). By assuming that all of the available zirconium reacts, one can estimate the maximum amount of hydrogen that can be released from this reaction. Note that some small amount of zirconium may react with the UO_2, and thus not be available to react with steam. Typical numbers are 2200 lbm (1000 kg) of hydrogen for a PWR and 4400 lbm (2000 kg) of hydrogen for a BWR[2-1]. These numbers will vary depending on the size of the reactor and the number of fuel assemblies in the core.

The rate at which hydrogen is produced from the steam:zirconium reaction depends upon the accident scenario, and in particular, upon the clad temperature and availability of steam. Assuming that steam is present in sufficient quantities, the amount of zirconium reacted as a function of time and temperature can be calculated from the following expression[2-2]:

$$W_{zr} = \sqrt{K(T)\,t} \qquad (2\text{-}2)$$

W_{zr} = the mass of metal reacted per unit surface area, lbm/ft^2 (kg/m^2).

$K(T)$ = an experimentally determined parabolic rate constant, $lbm^2/ft^4/s$ ($kg^2/m^4/s$).

t = the time, s

$K(T)$ is usually expressed in the following form:

$$K(T) = A \exp[-B/RT] \qquad (2\text{-}3)$$

where A is a constant, B is the activation energy, and R is the gas constant.

Numerous values for K(T) exist in the literature, but the Cathcart-Pawel[2-3] formulation is typical:

$A = 12.3\ lbm^2/ft^4/s\ (294\ kg^2/m^4/s)$

$B = 7.195 \times 10^4$ Btu/lb-mole$(1.672 \times 10^8$J/kg-mole)

$R = 1.98583$ Btu/lb-mole/°R$(8.31429 \times 10^3$J/kg-mole/K)

Knowing that the reaction of 1.0 lbm of zirconium with steam will produce 0.044 lbm of hydrogen, we can combine the previous equations in order to determine the amount of hydrogen produced per unit surface area as a function of time:

$$W_{H_2} = 0.044[12.3 \exp[-7.195 \times 10^4/1.98583/T]t]^{1/2} \frac{\text{lbm}}{\text{ft}^2} \qquad (2\text{-}4)$$

or

$$W_{H_2} = 0.044[294 \exp[1.672 \times 10^8/8.31429 \times 10^3/T]t]^{1/2} \frac{\text{kg}}{\text{m}^2} \qquad (2\text{-}5)$$

where T is in °R for the first equation and is in K for the second equation.

Figure 2-1 shows examples of hydrogen production for four different clad temperatures. The total area of cladding in a TMI-type reactor is roughly 5.27×10^4 ft^2 (4.9×10^3 m^2). Figure 2-2 shows the same examples as Fig. 2-1, while factoring in the clad surface area. These numbers will, of course, vary from plant to plant.

It should be emphasized that the reaction is exothermic and tends to drive itself once started. The heat of reaction can dominate other heating mechanisms above about 1832°F (1000°C). It should also be emphasized that the reaction rate depends very much upon the accident scenario. The temperature must be high enough (requires uncovered core) and a supply of steam must be present.

Once the core starts to slump, what happens is uncertain. If a core at a very high temperature falls into water at the bottom of the vessel, rapid production of steam and hydrogen may occur. However, the production rates will depend on how the core slumps, with the important parameters being the molten core particle size, available surface area, the temperature, and the amount of unreacted zirconium remaining.

2.1.3 Steam:Steel Reaction

Large quantities of steel are present within the walls of the reactor vessel, the core support structures, and other objects within a reactor. This steel may be oxidized to produce hydrogen when it is heated to high temperatures and exposed to steam. Oxidation of steel by high temperature steam is highly complex, and several different oxide forms are possible. Fe_3O_4 is a major product; however other forms involving Fe, Cr, and Ni are possible[2-4]. As with the oxidation of zirconium, these reactions are exothermic, releasing ~277.6 Btu/lbm of steel reacted (~8.6 kcal/gm-mole), depending upon the composition of the steel.

Normally, the oxidation of steel is not important below temperatures of about 2192°F (1200°C), and prolonged core uncovery would probably be required to achieve these temperatures. However, as the melting point of steel is approached at 2498-2732°F (1370°-1500°C), the oxidation rate of steel can become much larger than that of zirconium.

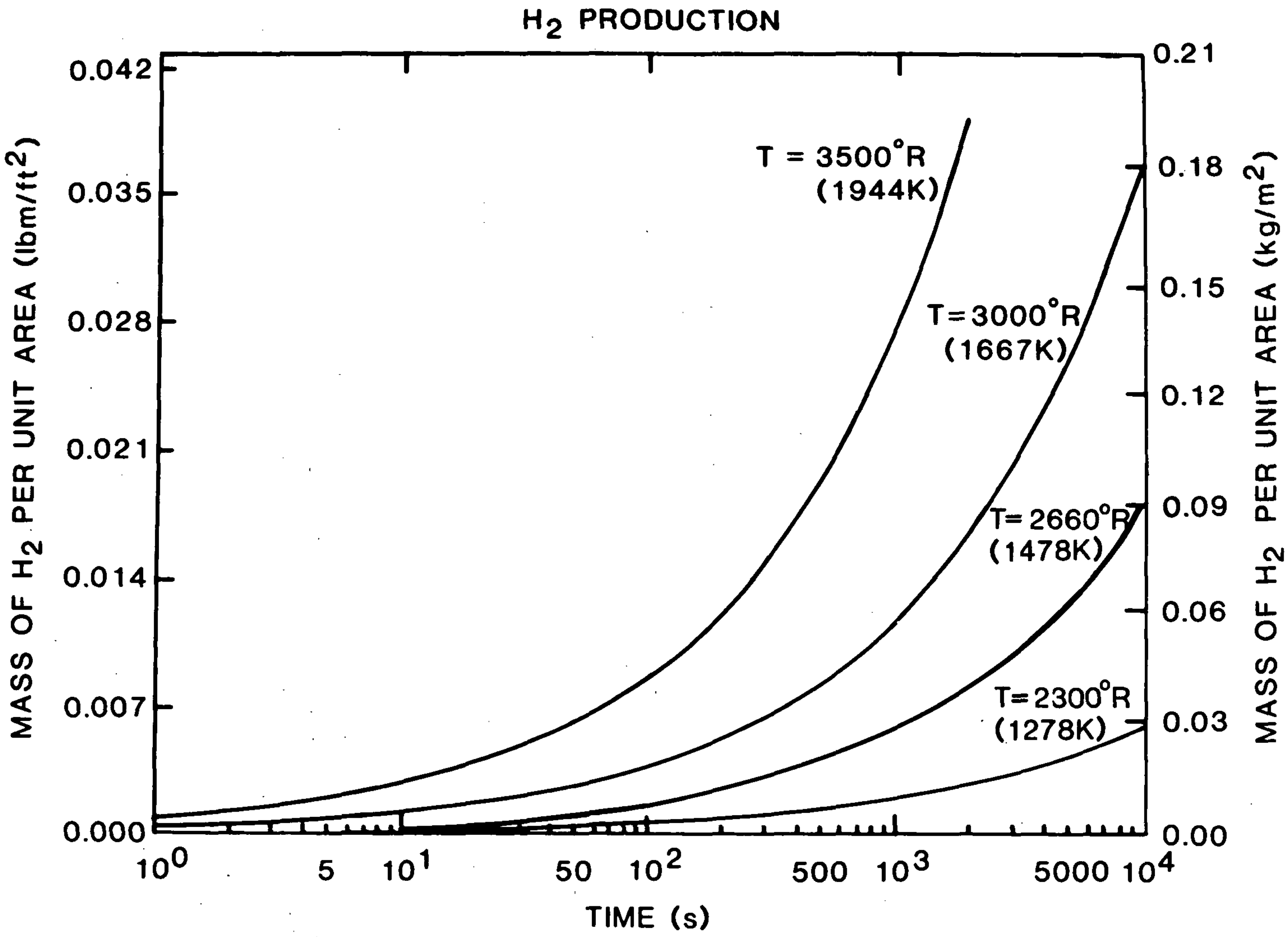

Figure 2-1. H_2 Production Per Unit Area From The $Zr:H_2O$ Reaction

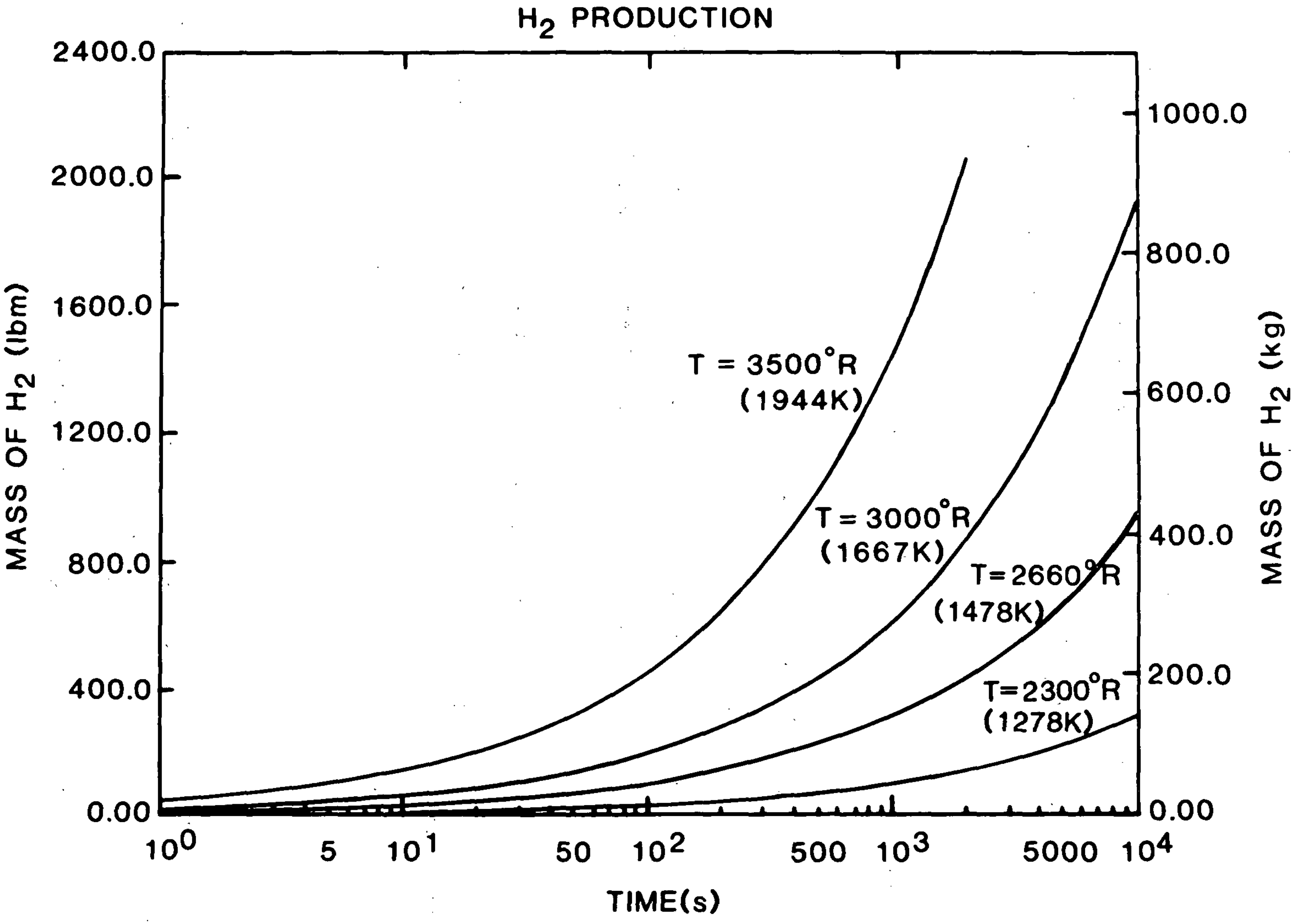

Figure 2-2. Total H_2 Production From The Zr:H_2O Reaction

Investigations into the oxidation kinetics of steel indicate that two stages of oxidation exist[2-5]. The oxidation is characterized initially (5-30 minutes) by linear kinetics:

$$\Delta W_{steel} = [225.1 \exp(-7.99 \times 10^4/RT]t \text{ lbm/ft}^2 \tag{2-6}$$

where

ΔW_{steel} = mass gained per unit of steel surface

R = gas constant = 1.98583 Btu/lb-mole/°R

T = temperature (°R)

t = time (s)

or

$$\Delta W_{steel} = [1.1 \times 10^3 \exp(-4.44 \times 10^4/RT)]t \text{ kg/m}^2 \tag{2-7}$$

where

R = gas constant = 1.98583 cal/gm-mole/K

T = temperature (K)

The second stage of steel oxidation is characterized by parabolic kinetics:

$$\Delta W_{steel} = [1.005 \times 10^7 \exp(-1.519 \times 10^5/RT)]^{1/2} t^{1/2} \text{ lbm/ft}^2 \tag{2-8}$$

or

$$\Delta W_{steel} = [2.4 \times 10^8 \exp(-8.43 \times 10^4/RT)]^{1/2} t^{1/2} \text{ kg/m}^2 \tag{2-9}$$

where the symbols are those defined above. The mass of hydrogen generated can be determined from

$$W_{H_2} = 2 \frac{M_{H_2}}{M_{O_2}} \Delta W_{steel} \tag{2-10}$$

where

W_{H_2} = the mass of hydrogen produced per unit of steel surface (in same units as ΔW_{steel})

M_{H_2} = the molecular weight of hydrogen = 2.002

M_{O_2} = the molecular weight of oxygen = 31.998

2 = the number of hydrogen moles produced for each mole of oxygen reacted.

Figure 2-3 shows a plot of hydrogen production versus time for four different temperatures. For these calculations we have assumed that linear kinetics govern the production rate.

In order to calculate the hydrogen production from the steam:steel reaction for a particular reactor we need to estimate the surface area of steel in a reactor that would be exposed to steam and could be expected to reach the necessary temperatures. Such steel surfaces as control-rod cladding, core barrels, control-rod guide tubes, and core support plates should be considered. Additionally, if core slump occurs, then the bottom of the reactor vessel and nearby structures should be considered. Typically, a few thousand square feet of steel may have the potential to participate in the steam:steel reaction.

2.1.4 Radiolysis of Water

Radiolysis of water occurs during both normal operation and accidents. Radiolysis involves the decomposition of water molecules by radiation (α, β, γ, or n). Radiolysis of water (H_2O) can produce OH, H, HO_2, and H_2O_2.[2-6] These products can subsequently react with either themselves or other chemicals present in the water to produce a variety of products. An important point to be noted is that H_2 and O_2 can be produced by radiolysis.[2-7] Radiolysis can occur in the core, or elsewhere in the primary system, or in containment (if fission products are transported to those areas).

The rate of hydrogen and oxygen generation is controlled by three factors: (1) the decay energy, (2) the fraction of this energy that is absorbed by the water, and (3) the effective rate of hydrogen and oxygen production per unit of energy absorbed by the water. The yield of a product species due to the radiolysis of water is generally expressed as that product's "G" value (molecules of product formed per 100 eV of energy absorbed). Distinction must be made between the primary or direct radiolytic yield of a species and the net yield of the same species. The direct or primary yield is usually expressed as a subscript to G while the net or actual yield is written as a parenthetical notation. Thus G_{H_2} is the hydrogen formed directly from the water by radiation, while $G(H_2)$ is the net hydrogen formed directly by radiation and indirectly by all subsequent chemical reactions. The G(x) value can be larger or smaller than G_x due to secondary reactions taking place between the various radiolytic species and the solutes. Typical values[2-8] of G_{H_2} in <u>pure</u> water are 0.44 for $\beta + \gamma$ for radiation, 1.12 for fast neutrons,

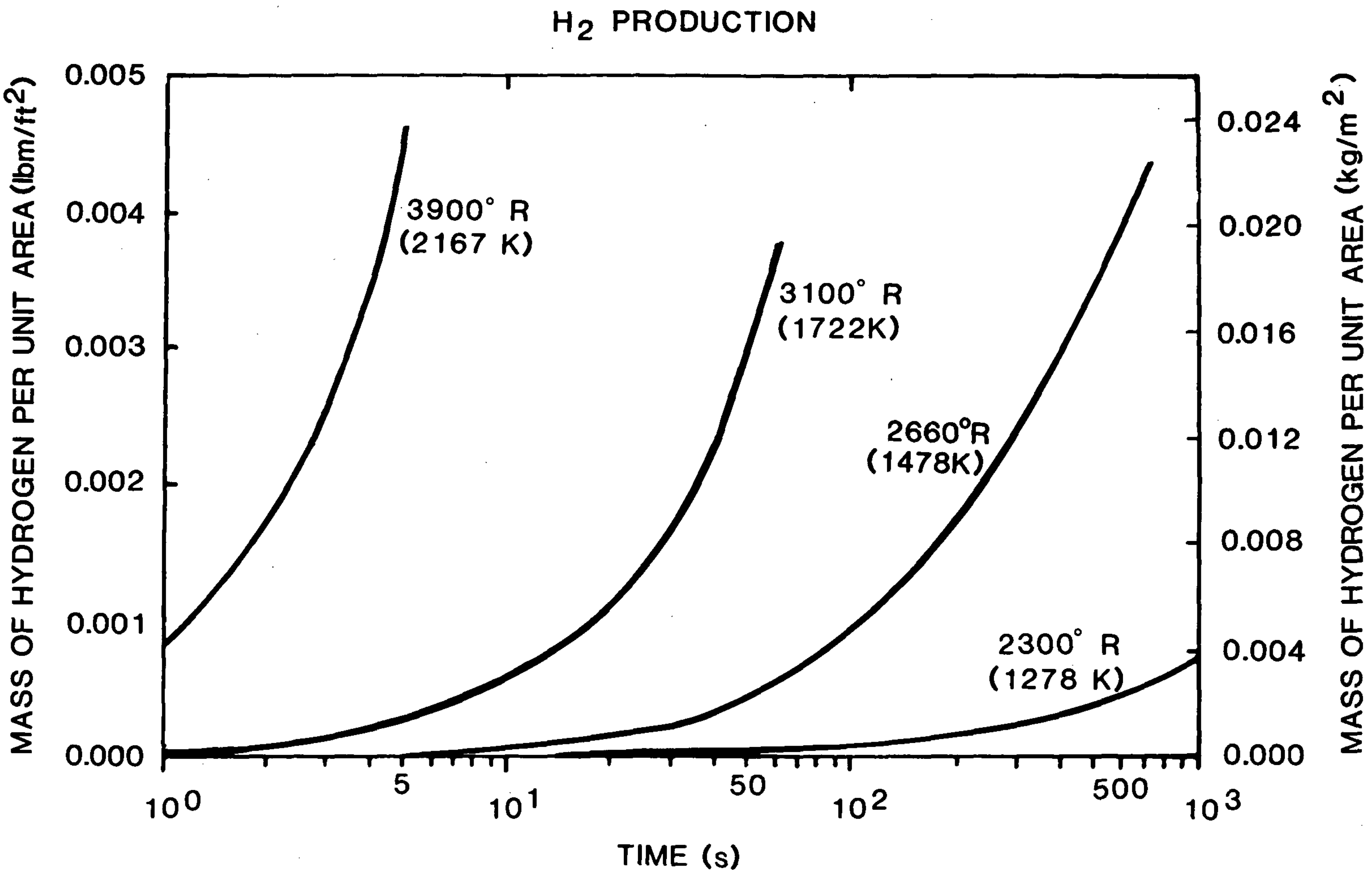

Figure 2-3. H_2 Production Per Unit Area From The Steel: H_2O Reaction

and 1.70 for the recoil nuclei from the reaction $^{10}B(n,\alpha)^{7}Li$. Since molecular oxygen is not produced directly by radiolysis, $G_{O_2} = 0$; however, $G(O_2)$ is not necessarily zero.

A closed water/gas system will eventually attain equilibrium with respect to radiolytic decomposition of the water. The concentration of gaseous products at equilibrium will be a function of the reactor power density, the water pH and temperature, and the impurity (solute) type and concentration. Once equilibrium is attained, $G(H_2) = G(O_2) = 0$ (although the concentrations of H_2 and O_2 may not be zero). It is well established that small quantities of hydrogen (less than 10^{-3} moles/liter) dissolved in pure water or boric acid solutions will effectively limit the equilibrium condition to one in which negligible O_2 is present. This technique is employed routinely in PWR nuclear plants.

An open water/gas system will not attain an equilibrium condition because the product species are being continuously removed. A typical BWR power plant operates in such a manner. If the water is boiling vigorously, H_2 and O_2 will be produced in stoichiometric portions and $G(O_2) = 1/2\ G(H_2) = 1/2\ G_{H_2}$. For pure water exposed to $\beta + \gamma$ radiation, this would result in the production of ~22 molecules of O_2 and 44 molecules of H_2 for each 10^4 eV of radiation energy.

The specific accident scenario can have a major effect on the relative importance of radiolytic production of H_2 and O_2. In order to realistically estimate the effects of radiolysis, it is necessary to know the extent and distribution of fission-product release, the water temperature and pH, the degree of bubbling and turbulence of the water, and the types and quantities of impurities dissolved in the water. Presently we cannot assess the effect of simultaneous variations in several of these parameters. We can state, however, that the rate of production of combustibles from radiolysis is slow compared to the rates from the high-temperature Zr:steam and steel:steam reactions when the latter reactions are occurring.

The rate of radiolytic decomposition of pure water increases linearly with the reactor decay power but the equilibrium concentrations of product species in a closed system increase as the square root of the power. Variations in pH have little effect on α-irradiated water, but not much is known about the effect of pH variations with other forms of radiation. It has been speculated that pH variation may have a significant effect when combined with solutes[2-8]. Increasing temperature will tend to decrease equilibrium concentrations of product species in pure water, but it has been suggested that increasing temperature will enhance solute effects due to increased reaction rates between solute molecules and radiolytically produced radicals[2-8].

The effect of vigorous boiling or bubbling of the water can be quite significant. The products of radiolysis are constantly removed from the liquid, and therefore, recombination of the H_2 and O_2 in solution is inhibited. Radiolysis of the vapor phase itself has not been studied extensively, but this may become an important issue in an accident.

The effects of the many possible solutes are not well understood. The impurities can react with the radiolytically produced radicals and upset the chemical balance. Only very small quantities of impurities are necessary to upset this balance (Ref. 2-7).

One of the key questions associated with the accident at TMI-2 concerned radiolytic decomposition of the reactor coolant water and the possibility that a combustible mixture of H_2 and O_2 might exist inside the reactor. Armed with our present understanding of the TMI-2 accident scenario, it can be stated that the probability of such an occurrence was very small[2-1] because there was probably an excess of hydrogen and steam and not enough oxygen for the mixture to be combustible. It cannot be stated, however, that the probability was zero (or would be zero for all conceivable accidents).

There are many uncertainties associated with radiolytic decomposition of water in a LOCA. It is most useful to carry out sample calculations as part of a parametric analysis. Consider the two key parameters to be the net yield G value for hydrogen, $G(H_2)$, and the fraction of reactor-shutdown (decay) radiation absorbed by the water, f (Ref. 2-7). In order to proceed we set the product $G(H_2)\cdot f$ equal to 1.0 and then all results can be scaled with the "correct" value of $G(H_2)\cdot f$. Results of calculations for a 3300 MW(t) reactor are given in Table 2-1. While these calculations probably overestimate the yield and rate by a considerable margin, there are too many unknowns to say that conclusively.

Table 2-1

CONSERVATIVE CALCULATION OF RADIOLYSIS YIELD AND RATE FOR A 3300 MW(t) REACTOR WITH $G(H_2)\cdot f = 1.0$

Time after Shutdown (s)	Integrated Decay Energy MJ/MW (Ref. 2-7)	Radiolysis Yield and Rate with $G(H_2)\cdot f = 1.0$ for a 3300 MW Reactor			
		Total Yield		Average Rate	
		lbm	kg	lbm/s	kg/s
10^2	6	8.8	4	.0881	.04
10^3	25	37.4	17	.0322	.0146
10^4	160	242.3	110	.0229	.0104
10^5	800	1207.0	548	.0106	.0048
10^6	3500	5286.3	2400	.0044	.0020

2.1.5 Core:Concrete Interactions

In the unlikely event that a reactor accident progresses to the point of gross fuel melting, the reactor vessel may be penetrated. Collapse of the molten reactor core materials into the reactor cavity could initiate vigorous gas generation as this high temperature melt attacked the concrete basemat of the reactor.

Gas generation during the interaction of molten fuel, cladding, and steel with concrete occurs in three stages[2-1]:

1. Thermal decomposition of the concrete to yield gaseous products,

2. Passage of these gases up through the melt, and

3. Chemical evolution and reaction of the gases as they emerge from the melt.

Most concrete used in reactor applications is either Type II or Type I Portland cement combined with various types of aggregate materials. When such concrete is heated, three major regions of gas generation are usually observed:

1. Release of molecular and physically entrapped water between 86° and 446°F (30°-230°C),

2. Release of water chemically constituted as hydroxides in the concrete over the interval 662° to 932°F (350°-500°C), and

3. Release of carbon dioxide from the aggregate and the cementitious phases over the interval 1112° to 1832°F (600°-1000°C).

Typically, concrete is 4 to 9 weight percent water and 0 to 45 weight percent carbon dioxide.

The rates of these three events can be determined from[2-9]:

$$\frac{d\alpha}{dt} = K \exp(-E/RT)(1-\alpha)^n \tag{2-11}$$

where

α = fraction of decomposing species lost from the concrete

t = time

R = gas constant

T = absolute temperature.

Values for the constants K, E, and n are shown in Table 2-2.

Table 2-2

KINETIC PARAMETERS FOR CONCRETE DECOMPOSITION[1,2]

Reaction	Basaltic Concrete	Limestone Common Sand Concrete	Generic Southeastern United States Concrete
Loss of evaporable water (n=1)	E=11600 (E=20899) $K=4.4x10^6$	E=11000 (E=19818) $K=1.29x10^6$	E=11000 (E=19818) $K=1.29x10^6$
Loss of chemical water (n=1)	E=41900 (E=75487) $K=2.8x10^{12}$	E=40800 (E=73505) $K=1.96x10^{12}$	E=40800 (E=73505) $K=1.96x10^{12}$
Precarboxylation (n=1)	E=42600 (E=76748) $K=3.6x10^9$	E=38300 (E=69362) $K=1.98x10^7$	E=45800 (E=82313) $K=1.73x10^9$
Decarboxylation (n=2/3)	--- --- ---	E=37000 (E=66659) $K=3.6x10^7$	E=44900 (E=80892) $K=1.94x10^6$

[1] E in units of cal/mole (Btu/lbmole); K in units of $minutes^{-1}$.

[2] Standard errors in E~10 percent; standard errors in K~30-50 percent.

In order to calculate actual gas generation rates due to thermal decomposition, detailed modelling of heat transfer from the core melt to the concrete is required. However, we can estimate that a few thousand kilograms of hydrogen might be generated under the worst conditions.

Gases generated by the attack of the molten core material on concrete will pass up through the melt and react with it. Steam and carbon dioxide released from the concrete will readily oxidize metallic constituents of the melt and produce hydrogen and carbon monoxide. Acutal rates of oxidation will depend upon the rate of gas generation, melt geometry, contact time, gas and melt composition, and temperature and pressure. Therefore, it is difficult to make quantitative statements regarding the kinetics of gas-melt reactions.

When the gases from the concrete emerge from the melt, they can continue to react. If there is sufficient air present, it appears that spontaneous ignition of hydrogen and carbon monoxide is likely. If ignition does not occur, other reactions are likely. At temperatures above 2732°F (1500°C), the gases will tend to equilibrate according to the reaction:

$$H_2 + CO_2 \rightleftarrows H_2O + CO \qquad (2\text{-}12)$$

Normally, as the gas cools, the H_2 and CO_2 content increases at the expense of the H_2O and CO. As the gas temperature falls below 1340°F (727°C), coking and hydrogenation become possible. Coking is the precipitation of solid carbon from the gas, and hydrogenation is the reaction of gases to form methane and other hydrocarbons.

In summary, quantitative predictions of hydrogen generation from core:concrete interactions are difficult. However, we can say that the potential exists to produce large quantities of hydrogen due to the large mass of water available in the concrete.

2.1.6 Other Sources

Other materials are present within containment that can react to form hydrogen. Zinc-based paint, galvanizing, and aluminum can react with water to produce hydrogen. Additionally, radiolysis of organic material may also lead to hydrogen production.

Corrosion of zinc-based paint and galvanizing is a function of temperature, composition, surface area, and pH of the spray solution. A detailed examination of the effects of these parameters can be found in Ref. 2-10. However, for example purposes it is reasonable to assume that the reactions proceed according to:[2-11]

$$W_{H_2} = C\, e^{-B/RT}\ \text{Area}\ t \qquad (2\text{-}13)$$

where

W_{H_2} = mass of H_2 produced, lbm (kg)

C = constant = 2.643×10^3 lbm/ft^2/hr = 1.292×10^4 kg/m^2/hr

B = activation energy = 26123 Btu/lb-mole = 14500 cal/gm-mole

R = gas constant = 1.98583 Btu/lb-mole/°R = 1.98583 cal/gm-mole/K

T = absolute temperature, °R (K)

Area = surface area, ft^2 (m^2)

t = time, hours.

This equation agrees well with the data presented in Ref. 2-10.

A typical PWR contains about 1.5×10^5 ft^2 (1.39×10^4 m^2) of zinc-based paint and about 3×10^4 ft^2 (2.8×10^3 m^2) of galvanized steel.[2-12, 2-13] Figures 2-4 and 2-5 show the quantity of hydrogen produced as a function of time for these reactions, assuming the above surface areas. Note that the total quantities produced are about 233 lbm (106 kg) of H_2 from corrosion of paint and about 115 lbm (52 kg) of H_2 from corrosion of galvanized steel. While in some reactors these numbers may be higher, this is still significantly less hydrogen than can be produced from other reactions discussed previously in this chapter.

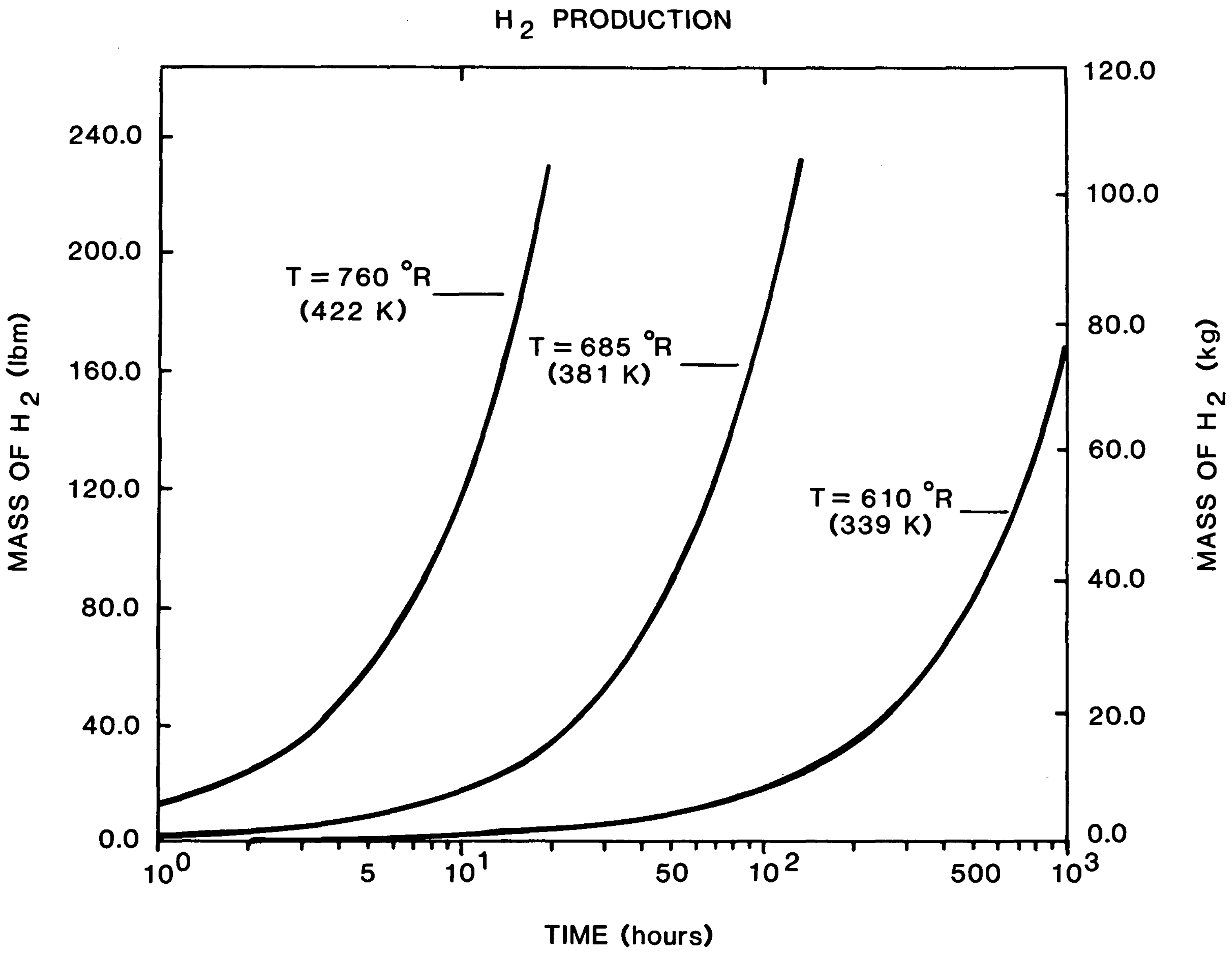

Figure 2-4. H_2 Production From Zinc-Based Paint

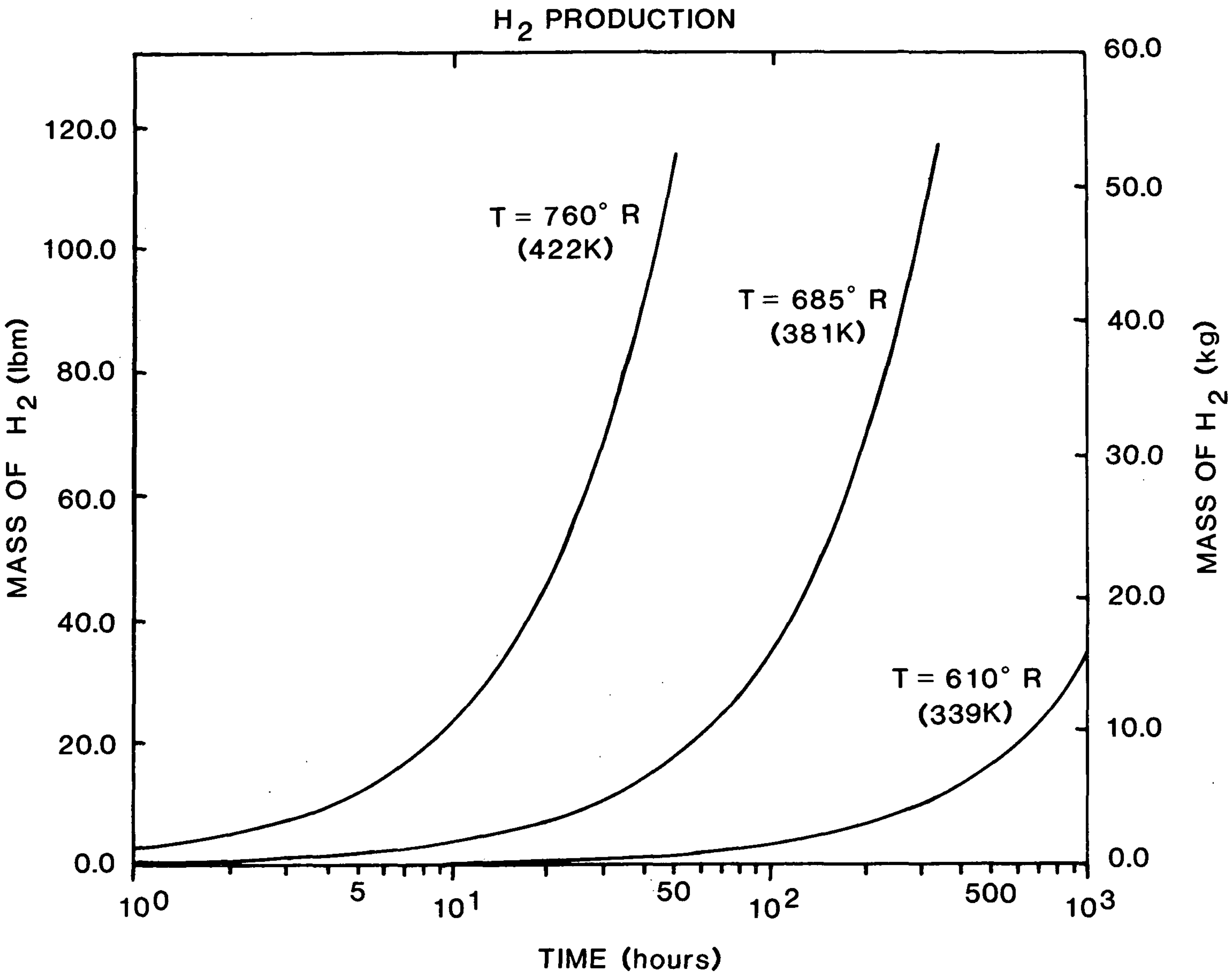

Figure 2-5. H_2 Production From Galvanized Steel

The surface area of aluminum has been estimated to be 475 ft^2 (44 m^2) in a typical containment.[2-13] The corresponding mass of aluminum is about 1250 lbm (568 kg). Under LOCA conditions of 300°F (149°C), a maximum of about 139 lbm (63 kg) of hydrogen could be produced over a 7-day period, given the surface area and mass of aluminum identified above and a production rate of 0.88 lbm/hr (0.4 kg/hr). Other estimates of the mass of aluminum in containment have been as high as 4000 lbm (1800 kg).

Organic materials such as cable insulation, epoxy paints, lubricating solutions, and gasket seals may produce combustible gases (primarily hydrogen or methane) due to radiolysis and corrosion. For most nuclear plants, the quantity of combustible gas that could be produced from organic materials inside containment is relatively small.

An example of hydrogen generation from radiolysis of cable insulation (polyethylene) follows. The yield of hydrogen, $G(H_2)$, for polyethylene is 5 molecules for 100 eV of absorbed radiation.[2-14] If we take 200 Mrad as a 30-day radiation dose for the cable insulation, then the dose per pound is roughly 6×10^{24} eV (1.3×10^{25} eV/kg). A typical containment might have 10^5 lbm (4.5×10^4 kg) of cable insulation. Therefore, roughly 220 lbm (100 kg) of hydrogen could be generated from radiolysis of cable insulation over a period of 30 days.

2.1.7 Time Sequence of Hydrogen Production

An exact calculation of hydrogen production versus time during a severe accident would require a detailed analysis of the accident scenario as well as modelling of certain physical phenomena that are not well known. However, it is useful to examine the question from a qualitative viewpoint.

Of the sources of hydrogen discussed in this chapter, the most important one is probably the steam:zirconium reaction. This reaction requires temperatures above 1832°F (1000°C) which may occur within the first few hours of a severe accident (after core uncovery).* Large amounts of hydrogen may also be produced from steam:steel reactions. These reactions are initiated after the steam:zirconium reaction due to the higher temperatures required; however, they are still initiated during the first few hours of the accident and can be concurrent with the steam:zirconium reaction.

Core:concrete interactions do not occur unless the core has fallen through the reactor vessel. Once the interactions start, vigorous gas generation results. Corrosion of paint and other surfaces within containment may begin when hot steam is released into containment or the containment sprays are activated. However, these reactions are slow, taking many hours to produce relatively small quantities of hydrogen.

---

*For the purposes of this discussion, a severe accident is one in which the core becomes uncovered for a period of time and a degraded-core situation occurs.

Radiolysis is always present in a reactor. The rate of radiolysis can increase during the accident as fission products are released from the fuel. However, radiolysis is still a long-term concern relative to the steam:zirconium reactions. Using the information presented earlier in this chapter and making certain assumptions, we can estimate the relative quantities and timing of hydrogen production for the various reactions (see Fig. 2-6). Figure 2-6 should be treated as qualitative in nature, as actual numbers depend upon the specific reactor and accident sequence.

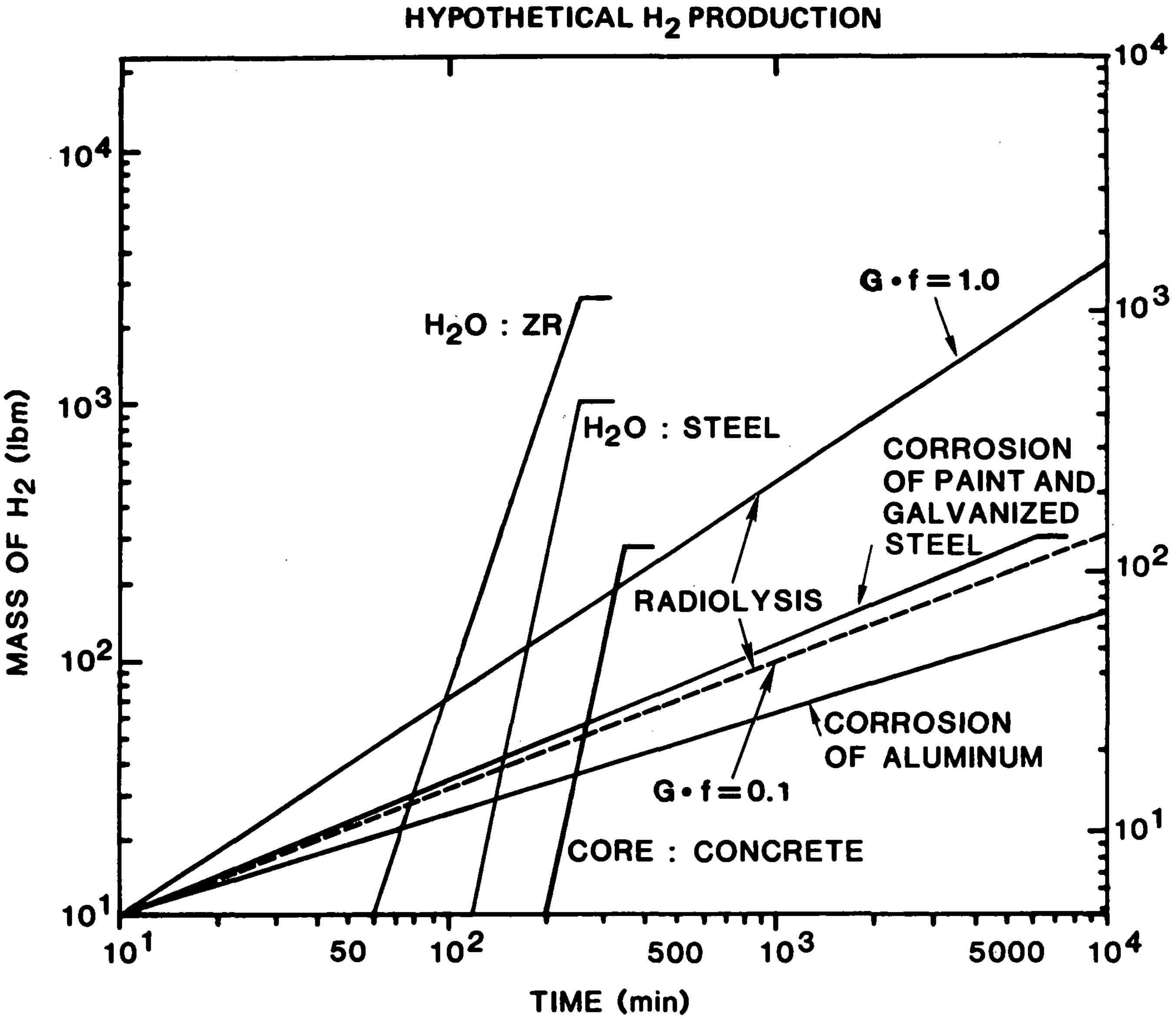

Figure 2-6. Hypothetical H_2 Production for Various Reactions

2.2 HYDROGEN SOLUBILITY, TRANSPORT, AND MIXING

2.2.1 Introduction

The transport and mixing of hydrogen determines when and where combustion is likely to occur. Some hydrogen will remain dissolved in water, with actual amounts depending upon the temperature, pressure, and composition. Hydrogen that does enter the containment atmosphere will mix with the steam and air due to forced or free convective motion and diffusion. The rate at which mixing will occur depends upon the particular mixing mechanisms at work. The following sections present discussions of solubility and mixing, followed by some observations regarding what may be expected to occur under actual accident conditions. Detailed analysis of hydrogen transport generally requires sophisticated computer modelling; consequently, many of the discussions that follow are qualitative in nature.

2.2.2 Solubility of Hydrogen in Water

The solubility of hydrogen is a measure of how much hydrogen will remain dissolved in water under various conditions. Solubility of hydrogen in water can be treated fairly well by assuming that both the gas and the liquid solution are ideal. We can then assume that Henry's law is obeyed:

$$P_{H_2} = H(T)X_{H_2} \tag{2-14}$$

where

P_{H_2} = partial pressure of hydrogen in the gas

$H(T)$ = Henry constant (this constant is also a weak function of pressure, but that effect is ignored here)

X_{H_2} = mole fraction of hydrogen in the liquid.

For a system containing a two-phase mixture of steam and hydrogen, the total pressure, P, will be the sum of the partial pressures P_{H_2} and P_{H_2O}. P_{H_2O} is approximately equal to the saturation vapor pressure of water at the mixture temperature. Therefore, P_{H_2O} can be taken directly from any set of steam tables. P_{H_2} is then

$$P_{H_2} = P - P_{H_2O}, \tag{2-15}$$

and the mole fraction of hydrogen in the liquid phase is

$$X_{H_2} = (P - P_{H_2O})/H(T). \tag{2-16}$$

H(T) has been experimentally determined over a wide temperature range and is plotted in Fig. 2-7[2-15]. Detailed expressions for H(T) can be found in Ref. 2-15. Using appropriate values for H(T), we can determine the amount of hydrogen dissolved, and Figs. 2-8 and 2-9 show some results for various conditions. The following example illustrates the use of these figures.

Example Calculation

Suppose you wish to determine the maximum amount of hydrogen that could be dissolved in a PWR reactor coolant system under normal operation conditions.

Mass of Water = 2.44×10^5 kg

Temperature = 288°C = 550°F

Pressure = 15.17 MPa = 2200 psia

From Fig. 2-9, the hydrogen concentration is approximately 7.5×10^3 $\mathrm{cm^3}$ H_2/kg H_2O. The total volume of H_2 is then

$$V_{H_2} = 7.5 \times 10^3 \, \frac{\mathrm{cm^3}\, H_2}{\mathrm{kg}\; H_2O} \cdot 2.44 \times 10^5 \;\mathrm{kg}\; H_2O = 1.83 \times 10^9 \;\mathrm{cm^3} = 1.1 \times 10^8 \;\mathrm{in^3} \tag{2-17}$$

The density of hydrogen at standard conditions, assuming ideal gas behavior, is

$$\rho_{H_2} = \frac{PM}{RT} = \frac{1 \;\mathrm{atm}\; 2.015 \;\dfrac{\mathrm{kg}}{\mathrm{kg\text{-}mole}}}{0.082056 \;\dfrac{\mathrm{atm\; m^3}}{\mathrm{kg\text{-}mole\; K}} \;\; 298 \;\mathrm{K}} = 0.0824 \;\frac{\mathrm{kg}}{\mathrm{m^3}} = 0.005 \;\frac{\mathrm{lbm}}{\mathrm{ft^3}} \tag{2-18}$$

Hydrogen concentration in water is reported in the form of cc hydrogen (at standard temperature and pressure) per kilogram of water in Fig. 2-9, therefore this density value calculated can be used in any calculations similar to those in this example. Finally, we can calculate the total mass of hydrogen dissolved.

$$\text{Mass } H_2 = 1.83 \times 10^9 \;\mathrm{cm^3} \;\; 10^{-6} \,\frac{\mathrm{m^3}}{\mathrm{cm^3}} \;\; 0.0824 \,\frac{\mathrm{kg}}{\mathrm{m^3}} = 151 \;\mathrm{kg} = 333 \;\mathrm{lbm} \tag{2-19}$$

The effect of boric acid or other chemicals present in the water is generally to reduce the amount of hydrogen dissolved. However, it appears that, in most cases, the effects are small.

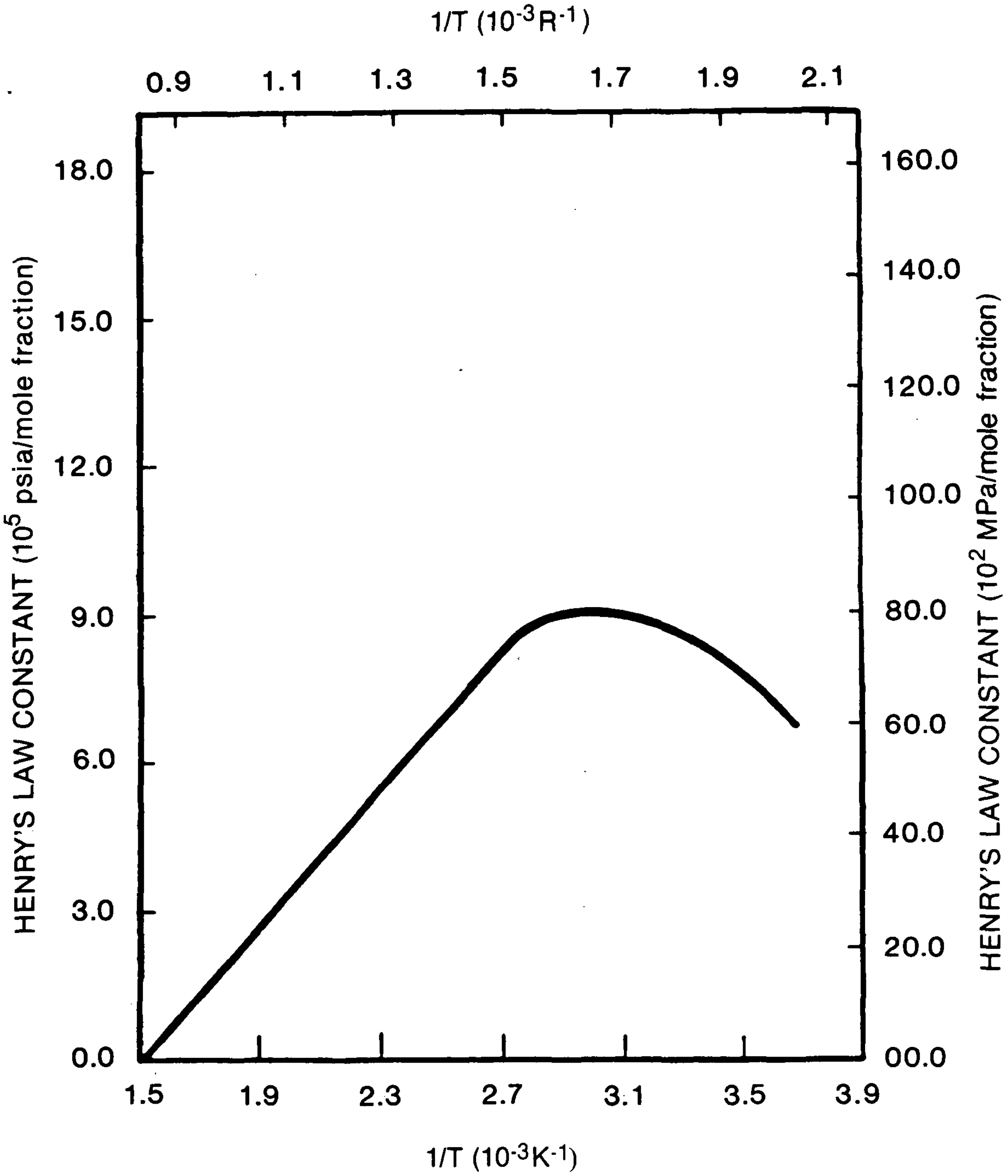

Figure 2-7. Henry's Law Constant For Hydrogen In Water

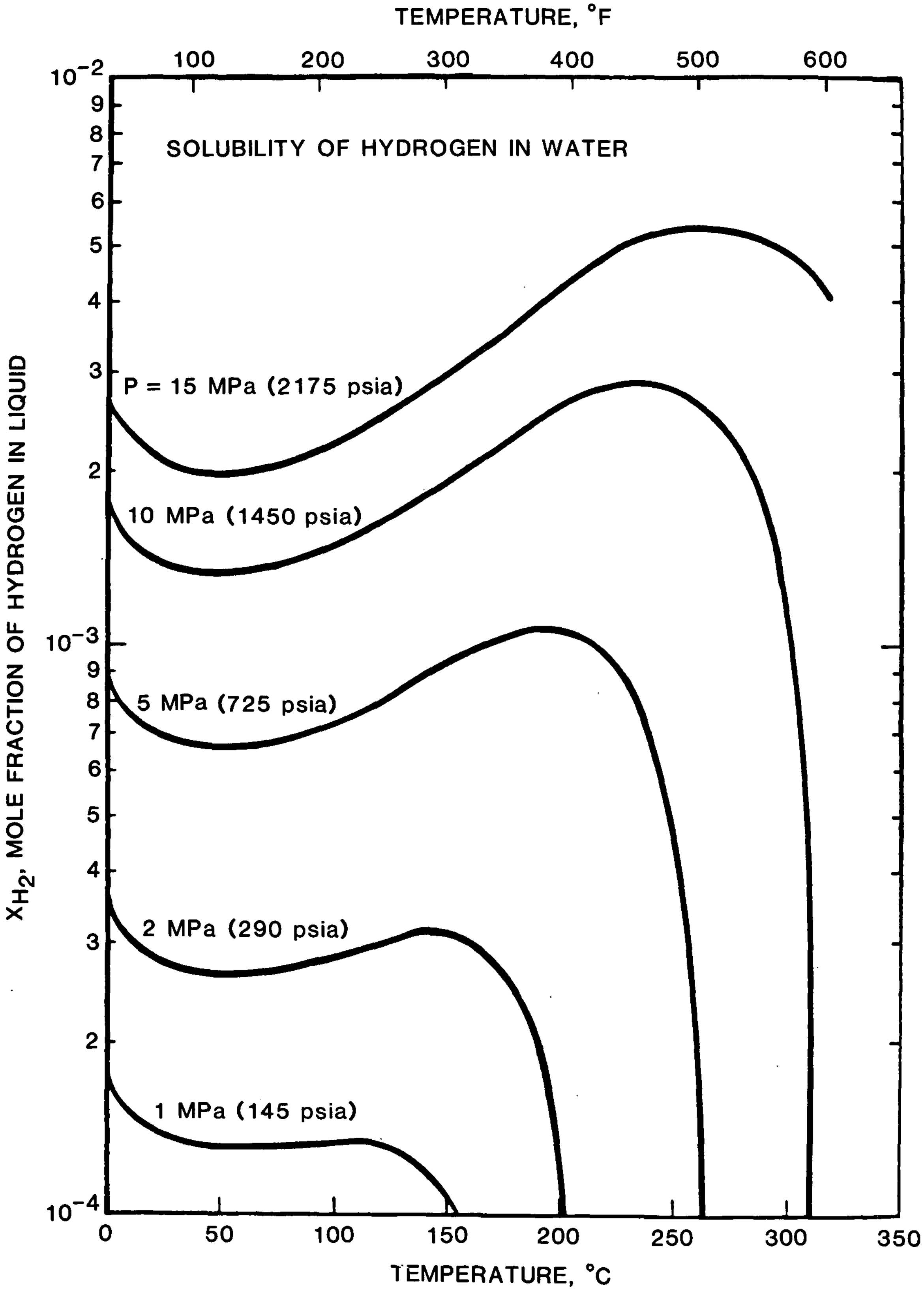

Figure 2-8. Mole Fraction Of Dissolved Hydrogen Under Various Conditions

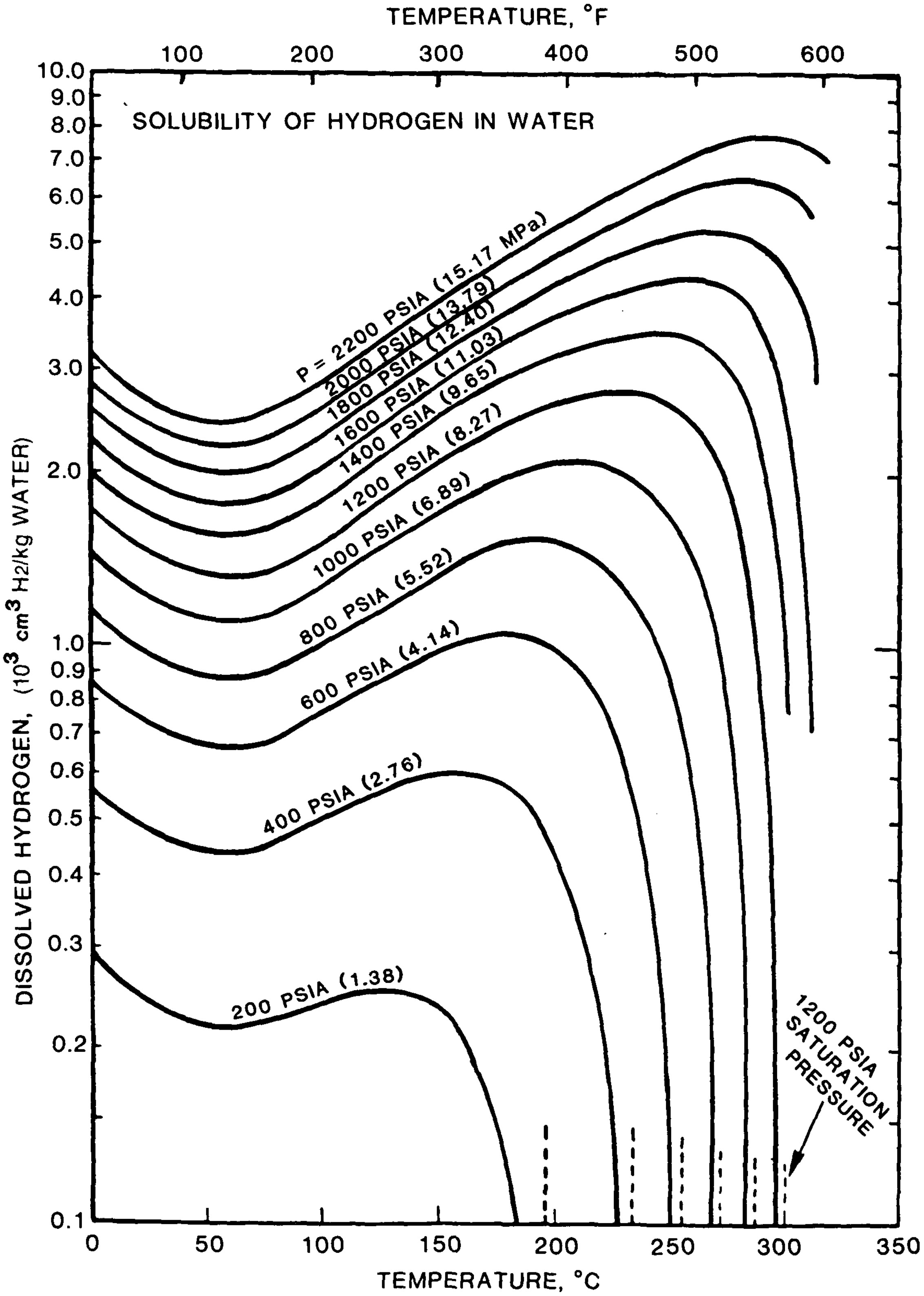

Figure 2-9. Hydrogen Concentration in Water under Various Conditions

The discussions above have dealt with closed systems at equilibrium. Little is known about the dynamics of hydrogen solubility (i.e., how fast equilibrium will be attained during a transient event). It is widely believed that turbulent effects will cause a rapid approach to equilibrium, but the details are not well known[2-16].

Dissolved hydrogen may be released whenever a change in the temperature and pressure occur. Figures 2-8 and 2-9 clearly show that a decrease in pressure (such as when a relief valve opens) will reduce the amount of hydrogen in solution. The effects of temperature changes are more complex, depending upon the particular temperature and pressure region.

2.2.3 Transport and Mixing Within Containment

The transport and mixing of hydrogen, oxygen and steam inside containment are critical in determining how and when combustion will occur (if at all). Rapid mixing could result in burns that are global in nature, while slow mixing may lead to localized burning. Mass is normally transported around containment due to natural or forced convection and diffusion.

If significant pressure differences exist within containment there will be bulk gas motion (carrying along H_2, O_2, etc) from the high pressure to the low pressure region. This motion occurs very rapidly, with the time required to equalize pressure depending upon the pressure difference, the flow area, and the flow resistance. Mass transfer due to pressure differences will dominate other forms of mass transfer whenever large pressure differences exist.

Natural convection occurs due to density differences (buoyant effects) within the containment atmosphere. Convective motions tend to form loops with lighter gases rising up one side and heavier gases falling down the other. The convective gas velocity will increase with increasing values of

$$g \frac{\partial \rho}{\partial Z} \qquad (2\text{-}20)$$

where g is the gravitational constant and $\frac{\partial \rho}{\partial Z}$ is the density gradient in the vertical direction. For a mixture of ideal gases, the density can be found from

$$\rho = PW/RT \qquad (2\text{-}21)$$

where P is the absolute pressure, W is the average molecular weight, R is the universal gas constant, and T is the absolute temperature. The average molecular weight for a hydrogen:air:steam mixture is

$$W = 2.02X_{H_2} + 28.97X_{air} + 18.02X_{H_2O} \qquad (2\text{-}22)$$

where the X_i is the mole fraction of species i. Note that the addition of hydrogen reduces the average molecular weight. Therefore, if hydrogen is introduced low in the containment, the drop in the molecular weight and the possible higher temperature of this mixture will give it a lower density than the atmosphere in the top of the containment. This can lead to rapid natural convective motions and mixing of the containment atmosphere. The condensation of steam on containment surfaces can also produce composition and temperature gradients and thus lead to substantial natural convection.

In practice, accurate predictions of mixing due to natural convection are difficult due to the complicated geometries and the complexity of convective motions inside a containment building. Typical RALOC[2-17] calculations for a Mark III BWR containment show that natural convection, for certain accidents, could mix the containment atmosphere in about 20 minutes.[2-18] For other cases, it is fair to say that natural convection can normally be expected to mix the gases over a time period from a few minutes to a few hours. This may not be true if density inversions occur, as discussed further in this section.

Forced convection can occur due to the presence of fans or jets from a pipe break or open valve. The degree of mixing from forced convection depends, of course, upon the flow rates and velocities associated with the particular fan or jet. One can get a feel for the mixing times by comparing the volumetric flow rate with the volume of a particular containment compartment. Significant mixing will occur in a time frame on the <u>order of</u> the time required to turn over the entire compartment volume. Usually, forced convection involves higher gas velocities than natural convection. These higher velocities may induce turbulence, and thus, enhance mixing.

Forced convection mixing may also occur due to operation of the containment sprays. Current analytical capability does not allow us to model mixing due to sprays in any detail. However, observation of sprays in operation and intuition tell us that mixing due to sprays may be quite rapid. The sprays entrain air, inducing bulk mass motion, and create both large and small-scale turbulence. Complete mixing should occur within a few minutes.

Diffusion occurs due to concentration gradients. Gases will tend to diffuse from regions of high concentration to regions of low concentration according to Fick's law:

$$\bar{J}_A = -D_{AB}\nabla C_A \tag{2-23}$$

where $\bar{J}_A$ is a vector describing the molar fluxes of component A relative to the bulk gas velocity, D_{AB} is the diffusion coefficient for component A diffusing through component B, and ∇C_A is the concentration gradient for component A.

Typical values for D_{AB} at 1 atmosphere are[2-19]:

D_{AB} = 0.68 ft^2/hr (0.06 m^2/hr) for O_2 - Air at 32°F (273 K)

D_{AB} = 2.7 ft^2/hr (0.24 m^2/hr) for H_2 - Air at 32°F (273 K)

D_{AB} = 1.01 ft^2/hr (0.09 m^2/hr) for H_2O - Air at 77°F (298 K)

The diffusion coefficient goes approximately as $T^{3/2}$ and P^{-1}.

The most important thing to note about diffusion is that its effect falls off very rapidly as the size of the volume increases. The time to mix a volume is proportional to the square of the length scale. Normally, we can expect that diffusion alone would take days in order to mix the containment atmosphere.[2-20] Thus, diffusion will only be important for slow release rates.

An important issue in the discussion of mixing is whether or not locally high concentrations of hydrogen due to stratification may be expected at positions other than near the hydrogen source. Intuitively, one might expect that since hydrogen is less dense than air, it might gather at the top of containment. However, if the hydrogen is released near the bottom of containment, it will be substantially mixed before it reaches the top. Stratification of initially mixed hydrogen:air mixtures in containment is negligible. Once mixed, the gases will not appreciably unmix. Only in the case where the hydrogen is released near the top of containment, and there is no forced or natural convection, can we expect the stratified upper hydrogen layer to remain for a long time, until diffusion mixes it. The tendency to homogenize rather than stratify has been observed experimentally.[2-21] In any case, it is clear that, if substantial forced convection or mechanisms such as steam condensation that produce substantial natural convection are present, the degree of stratification and its duration will not be extensive.

Detailed calculations of hydrogen transport and mixing within containment are generally beyond the capability of any hand calculation. However, the above discussion should have given the reader a qualitative feel for the various transport and mixing mechanisms. In addition to RALOC, computer codes such as COBRA-TF,[2-22] TEMPEST,[2-23] and KFIX[2-24] are being developed or modified for transport calculations. Given the complexities of the geometries and the uncertainties in the source terms, significant uncertainties in the transport calculations will continue to be present.

2.2.4 Air:Steam:Hydrogen Concentrations Within Containment

While detailed calculations are beyond the scope of this manual, it is useful to consider qualitatively what may happen during a severe reactor accident. In most cases, hydrogen and steam will be released near the bottom of the containment and will mix with the air above. Thus initially, there will be a hydrogen concentration gradient from bottom to top. Steam may be removed using a suppression pool, an ice condenser, fan coolers, or containment sprays, depending upon the type of reactor and accident.

The degree of mixing that will occur before combustion depends upon the hydrogen release rate, available mixing mechanisms, and availability and location of ignition sources. If the hydrogen release rate is fast relative to the time required for mixing, then very steep concentration gradients would be expected. On the other hand, if the release rate is very slow, then nearly homogenous mixtures would be expected.

To determine what is a fast or slow hydrogen release rate, consider the discussion of mixing mechanisms in the previous section. Except during combustion when pressure-driven flows will dominate, the fastest mixing mechanisms available are either the containment sprays or forced convection mechanisms such as jets or fans. These mechanisms may be expected to mix the atmosphere within a time period of a few minutes to a few tens of minutes. Thus a hydrogen release over a period of seconds would tend not to be well mixed, while a release over a period of hours would probably be well mixed.

Combustion may begin near the bottom of the containment due to the higher hydrogen concentrations expected there. This depends, of course, upon the availability of ignition sources and the particular hydrogen concentration. Once combustion begins, pressure-driven flows will occur, and also the hot gases will tend to rise to the top of the containment due to buoyant forces.

The presence of steam can be very important when evaluating the behavior of hydrogen within containment. Consider an accident where no containment heat removal systems are available initially. Large quantities of steam and hydrogen may be present; however, there may be so much steam that the hydrogen, oxygen, and steam mole fractions are not within the flammability limits (see the next section). If the contaiment sprays or some other containment heat removal systems are turned on, the removal of steam will cause the hydrogen and oxygen mole fractions to increase and may make the resulting mixture combustible. This can also happen over the long term even without containment heat removal systems, as steam condenses out on the containment walls. The point of this discussion is that emergency operating procedures should address the possible effects of any actions related to containment cooling and consider the possibility of hydrogen combustion.

2.3 COMBUSTION OF HYDROGEN

2.3.1 Introduction

Combustion of hydrogen according to the reaction:

$$2H_2 + O_2 \longrightarrow 2H_2O + \text{energy (heat)} \qquad (2\text{-}24)$$

results in the release of about 5.2×10^4 Btu/lbm of hydrogen burned (57.8 kcal/gm-mole). The main concern over hydrogen combustion in nuclear reactor containments is that the high pressure generated might cause a breach of containment and a release of radioactivity. A second concern is that the resultant high temperature or pressure might damage important safety-related equipment. The pressure and temperature obtained from the complete combustion of hydrogen in air, adiabatically (without heat loss) and at constant volume, are shown in Figs. 2-10 to 2-13. The use of these figures is explained further in Section 2.3.2. The thermal response of equipment requires experiments and/or detailed modelling of heat transfer for a specific device and a knowledge of the environment the equipment will be exposed to. One analysis that assumed no containment sprays were operating has been performed indicating that a threat to equipment may exist.[2-25]

Definition

Combustion waves are usually classified either as deflagrations or detonations. The term "explosion" is somewhat ambiguous and should be avoided. Deflagrations are combustion waves in which unburned gases are heated by thermal conduction to temperatures high enough for chemical reaction to occur. Deflagrations normally travel subsonically and result in quasi-static (nearly steady state) loads on containment. Detonations are combustion waves in which heating of the unburned gases is due to compression from shock waves. Detonation waves travel supersonically and produce dynamic or impulsive loads on containment in addition to quasi-static loads. Under some conditions supersonic deflagrations and quasi-detonations may occur, resulting in a gray area between combustion waves that are definitely deflagrations and those that are definitely detonations.

In the following sections an example calculation, the conditions necessary for combustion, deflagrations, steam:hydrogen jets, and detonations are discussed in detail.

2.3.2 Example Calculation

With the aid of Figs. 2-10 and 2-11, or 2-12 and 2-13, the pressure and temperature that would be caused by an adiabatic, constant-volume, complete combustion of a homogenous hydrogen:air:steam mixture can be estimated. Figures 2-10 and 2-11 can be used for cases in which the steam mole fraction before the burn is small. This might be the case in the wetwell (or outer containment) of a Mark III BWR or the upper compartment of an ice condenser containment. Figures 2-12 and 2-13 are to be used when the conditions before the combustion are steam saturated. For initial temperatures not far above normal room temperature, the steam mole fraction is small even in a saturated atmosphere. In that case either set of figures could be used.

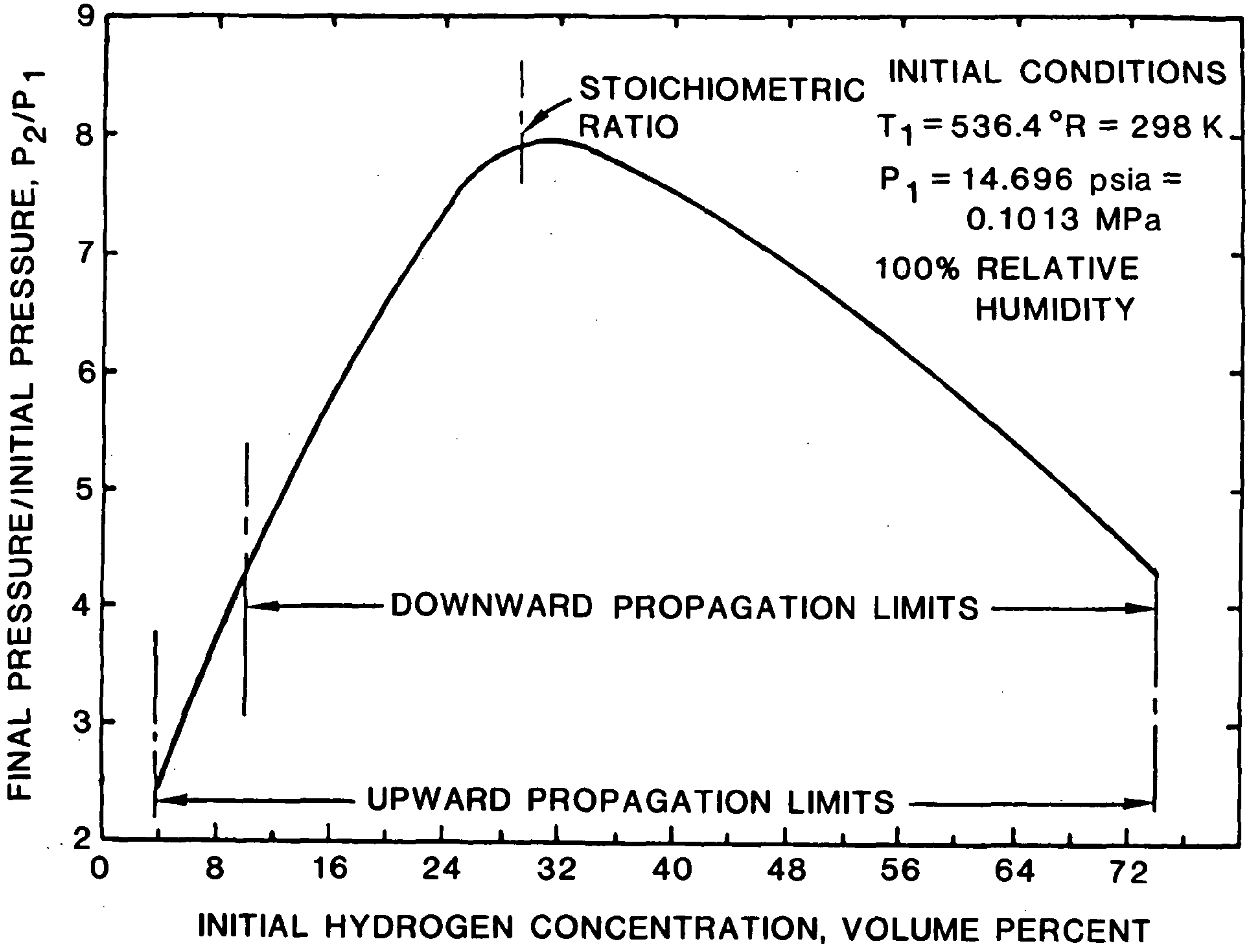

Figure 2-10. Theoretical Adiabatic, Constant-Volume Combustion Pressure for Hydrogen:Air Mixtures

3% stm mole fraction

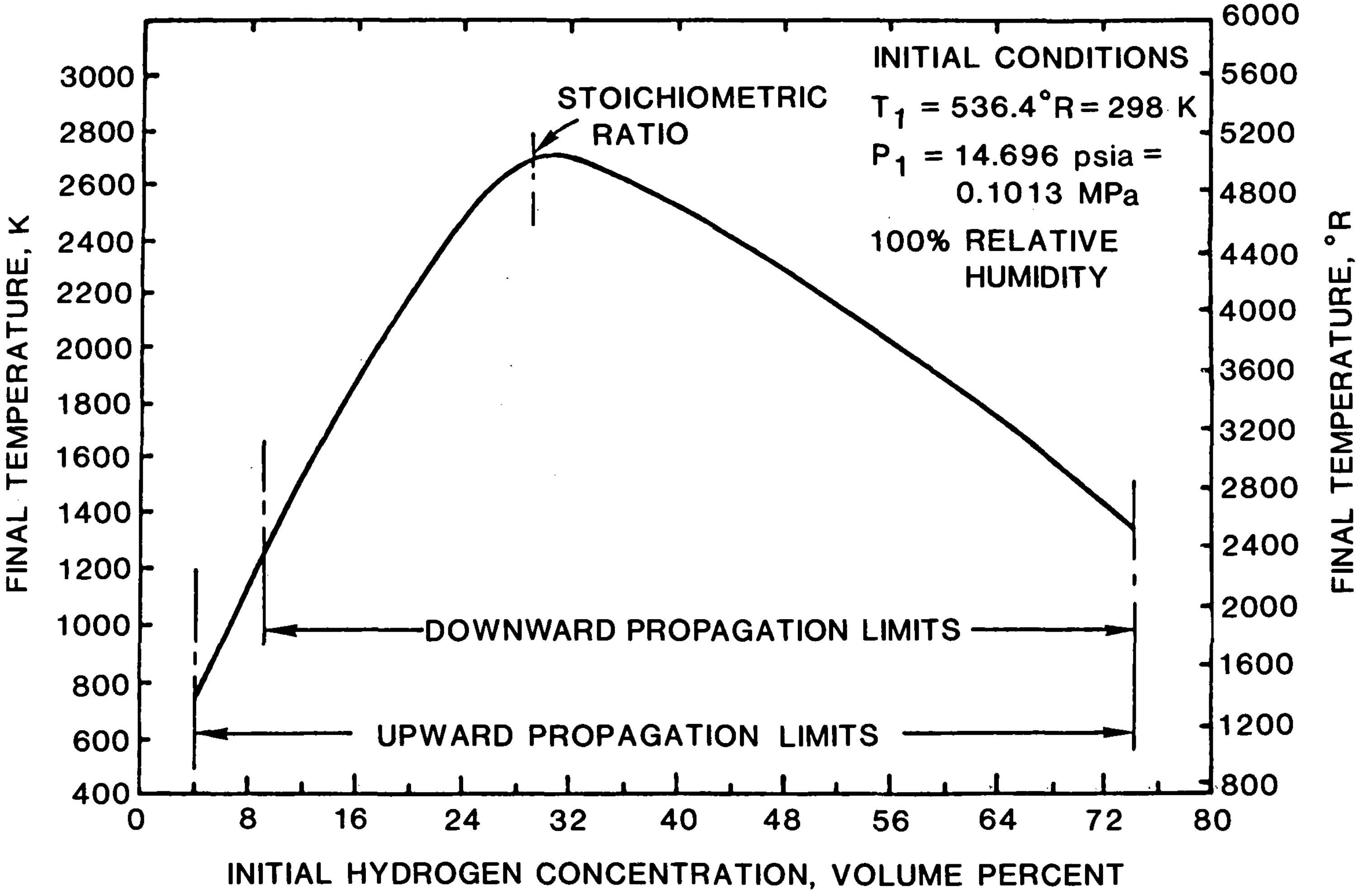

Figure 2-11. Theoretical Adiabatic, Constant-Volume Combustion Temperature for Hydrogen:Air Mixtures

100% RM

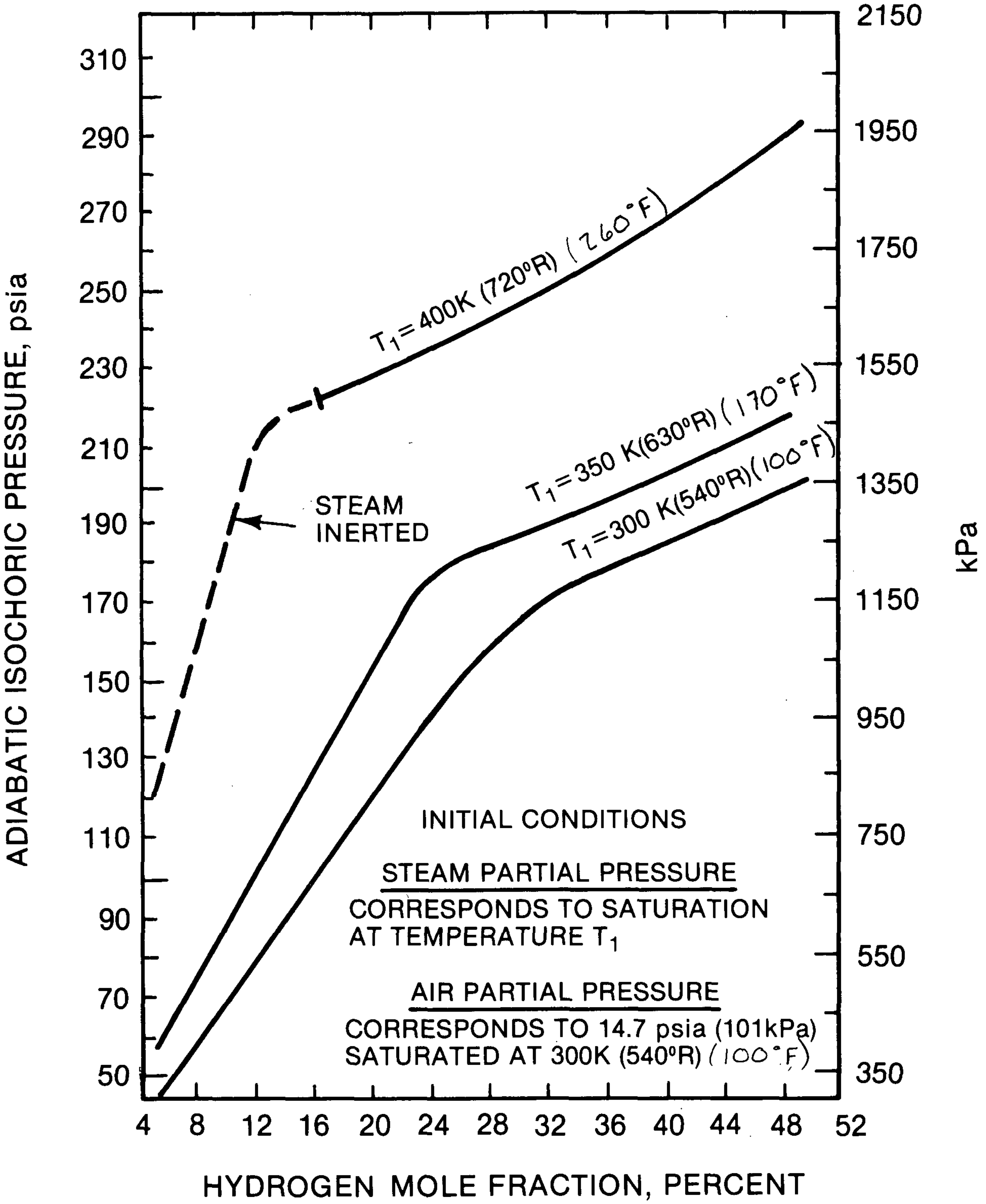

Figure 2-12. Adiabatic, Constant-Volume Combustion Pressure For Various Containment Initial Conditions

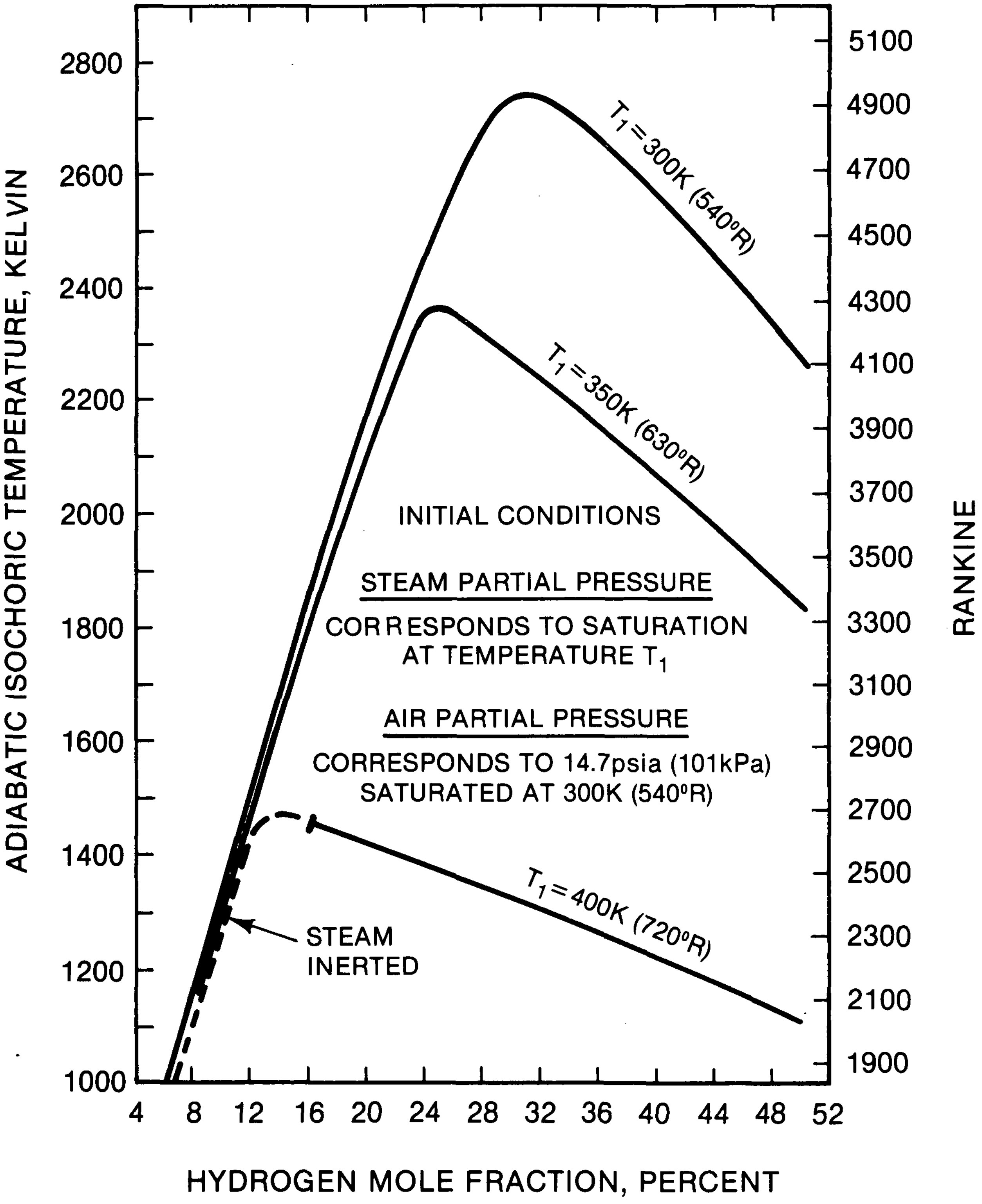

Figure 2-13. Adiabatic, Constant-Volume Combustion Temperature For Various Containment Initial Conditions

We will describe the procedure to be used in the computations in the next paragraph. For all the calculations absolute pressures and temperatures should be used.

Absolute Pressure = Gauge Pressure + Atmospheric Pressure (2-25)

Typically, for normal atmospheric pressure,

Pressure (psia) = Pressure (psig) + 14.7 (2-26)

Pressure (Mpaa) = Pressure (Mpag) + 0.101 (2-27)

For temperature,

Temperature (Rankine) = Temperature (Fahrenheit) + 460 (2-28)

Temperature (Kelvin) = Temperature (Celsius) + 273 (2-29)

The subscripts A, S and H_2 refer to air, steam, and hydrogen. The analysis considers three times: t_o, the time at the start of the accident; t_1, the time just before the combustion; and t_2, the time just after the combustion. The object of the calculation is to determine $P(t_2)$ and $T(t_2)$, the pressure and temperature just after combustion. We will assume that conditions at time t_o are known, and that sufficient information about conditions at time t_1 is known so that the unknown gas conditions at that time can be computed.

Consider the example when the conditions at the start of the accident are:

$P(t_o)$ = 14.7 psia (0.101 MPa)

$T(t_o)$ = 560°R (311 K) (100 F)

Relative Humidity = 50%

(130 F)

Just before the combustion the temperature is 590°R (328 K), the air is saturated and a hydrogen detector measures 10 volume percent (mole fraction) hydrogen (see Table 2-3).

For all three time periods, the total pressure is the sum of the partial pressures of air, hydrogen and steam,

$$P = P_A + P_S + P_{H_2} \qquad (2\text{-}30)$$

Initially, there is no hydrogen, $P_{H_2}(t_o) = 0$. The saturation steam pressures are determined from "Steam Tables" found in thermodynamics textbooks or engineering handbooks. We have

$P_{SAT}(T_O) = P_{SAT}$(560°R (311 K)) = 0.95 psia (0.0065 MPa) (2-31)

$P_S(t_o)$ = relative humidity * $P_{SAT}(T_O)$ = 0.48 psia (0.0033 MPa) (2-32)

Therefore, the initial air partial pressure is

$$P_A(t_o) = 14.7 - 0.5 = 14.2 \text{ psia } (0.098 \text{ MPa}) \qquad (2\text{-}33)$$

From steam tables we obtain, at t_1,

$$P_S(t_1) = P_{SAT}(T_1) = 2.2 \text{ psia } (0.015 \text{ MPa}) \qquad (2\text{-}34)$$

The air partial pressure at t_1 is

$$P_A(t_1) = (T_1/T_0)P_A(t_0) = (590/560) * 14.2 = 15.0 \text{ psia } (0.103 \text{ MPa}) \qquad (2\text{-}35)$$

The hydrogen mole fraction is

$$X_{H_2} = P_{H_2}/P \qquad (2\text{-}36)$$

which leads to

$$P_{H_2} = (P_A + P_S) * X_{H_2}/(1.0 - X_{H_2}) \qquad (2\text{-}37)$$

Hence

$$P_{H_2}(t_1) = 17.2 * 0.1/0.9 = 1.9 \text{ psia } (0.013 \text{ MPa}), \qquad (2\text{-}38)$$

$$P_1 = 17.2 + 1.9 = 19.1 \text{ psia } (0.131 \text{ MPa}) \qquad (2\text{-}39)$$

We now estimate the postburn conditions using Figs. 2-10 and 2-11. Figure 2-10 gives the final/initial pressure ratio for burns with a given set of initial conditions. However, the pressure ratio is insensitive to the initial pressure, and insensitive to small changes in initial temperature. The influence of initial steam mole fraction can be greater. The figures were computed using a humidity corresponding to a steam mole fraction of 3%. At 590°R (328 K) the steam mole fraction for 100% relative humidity will be higher, but will be still small enough to use Figs. 2-10 and 2-11. From Fig. 2-10, we determine that $P(t_2)/P(t_1) = 4.2$, hence $P(t_2) = 4.2 * 19.1 = 80.2$ psia (0.55 Mpa). An approximate final temperature can be estimated from Fig. 2-11 by adding to the temperature found from the figure the difference between $T(t_1)$ and 536°R (298 K).

$$T(t_2) \approx 1230 + 30 = 1260 \text{ K } (2270°\text{R})$$ (1810 F)

When applicable, the use of Figs. 2-12 and 2-13 is simpler than using Figs. 2-10 and 2-11. These figures are applicable when the conditions at the start of the accident are near $P(t_o) = 1$ atm (0.101 MPa), $T(t_o) = 540$°R (300 K), and the conditions just before the combustion are steam saturated. It should be noted that the curves for constant $T(t_1)$ in the two figures correspond to varying pressure, $P(t_1)$, and varying steam mole fraction. At all points on the curves, the composition has been adjusted to saturation conditions. Much of the work in describing the conditions at time t_1 is not needed here because that information has been incorporated into the figures. For a temperature of 590°R (328 K), we determine that $P(t_2) = 4.9$ atm = 72.0 psia (0.50 MPa), and $T(t_2) = 2340$°R (1300 K).

The results of thermochemical calculations on a computer give values $P(t_2)$ = 74.4 psia (0.51 MPa), $T(t_2)$ = 2401°R (1334 K). The difference between the results (summarized in Table 2-3) gives an indication of the accuracy to be expected from the simple graphical methods. If higher accuracy is required, results can be from one of several thermochemical computer programs such as that of Gordon and McBride.[2-26]

Table 2-3

COMPUTATION OF ADIABATIC, CONSTANT-VOLUME PRESSURE AND TEMPERATURE

	Time before Accident t_o	Time before Combustion t_1	Time after Combustion t_2 using Figs. 2-10, 2-11	Time after Combustion t_2 using Figs. 2-12, 2-13
Pressure - psia(MPa)	14.7(0.101)*	19.1(0.131)	80.2(0.55)	72.0(0.50)
Temperature - °R (K)	560(311)*	590(328)*	2270(1260)	2340(1300)
Hydrogen Mole Fraction	0.0*	0.1*		
Air Partial Pressure - psia (MPa)	14.2(0.098)	15.0(0.103)		
Steam Partial Pressure - psia (MPa)	0.48(0.0033)	2.2(0.015)		
Hydrogen Partial Pressure - psia (MPa)	0.0(0.0)	1.9(0.013)		

* Data directly from measured initial conditions

If the pressure and temperature before the combustion are accurately measured and the hydrogen mole fraction measurement is absent or less accurate, the hydrogen mole fraction can be estimated (assuming saturation) from the relations,

$$P_{H_2} = P - P_A - P_S \qquad (2\text{-}41)$$

$$X_{H_2} = P_{H_2}/P \qquad (2\text{-}42)$$

Some hydrogen detectors may remove the water vapor content of the hydrogen:air:steam mixture. In this case the measured hydrogen mole fraction (of the dry hydrogen:air mixture) will be larger than the value in the original mixture. The correction required to recover the original value is

$$X_{H_2} = (1 - X_S)X_{H_2}' \tag{2-43}$$

where X_H' is the hydrogen mole fraction the dry hydrogen:air mixture and X_S is the steam mole fraction in the original hydrogen:air:steam mixture,

$$X_S = P_S/P \tag{2-44}$$

2.3.3 Conditions Necessary for Combustion

For substantial combustion of hydrogen to take place, the gaseous mixture must be flammable, and an ignition source must be present. For a mixture of flammable gases such as hydrogen and air, the flammability limits are defined as the limiting concentrations of fuel, at a given temperature and pressure, in which a flame can be propagated indefinitely. Limits for upward propagation of flames are wider than those for downward propagation. Limits for horizontal propagation are between those for upward and downward propagation.

There is some doubt concerning the applicability of flammability limits, as defined above, to accident conditions. There may be scale effects due to the large size of reactor containments as well as variations in flammability due to the ignition source strength. It is known that flames can propagate for short distances in mixtures which are outside the standard flammability limits. Flammability limits are useful guidelines and are not expected to vary substantially, but do not appear to be fundamental quantities.

The lower flammability limit is the minimum concentration of hydrogen required to propagate a flame, while the upper limit is the maximum concentration. At the lower limit, the hydrogen is in short supply and the oxygen is present in excess. At the upper limit of flammability for hydrogen in air, the oxygen is in short supply, about 5% oxygen by volume. The behavior of the upper limit of flammability of hydrogen with various mixtures such as air: steam is more easily understood if one considers it as the lower flammability limit of oxygen.

In large PWR containments we are usually interested in the lower limit of flammability, there being large amounts of oxygen present. In the much smaller BWR containments, particularly the inerted containments, we may be interested in the upper flammability limit.

For hydrogen:air mixtures, the flammability limits of Coward and Jones[2-27] are still accepted. Values for hydrogen flammability in air saturated with water vapor at room temperature and pressure are given in Table 2-4.

Table 2-4

HYDROGEN FLAMMABILITY LIMITS IN STEAM-SATURATED AIR[2-27]

	Lower Limit, Vol %	Upper Limit, Vol %
Upward Propagation	4.1	74
Horizontal Propagation	6.0	74
Downward Propagation	9.0	74

temp

In reactor accidents the conditions inside containment prior to hydrogen combustion may include elevated temperature, elevated pressure, and the presence of steam. The flammability limits widen with increasing temperature. At 212°F (100°C) the lower limit for downward propagation is approximately 8.8% (see Fig. 2-14). In the temperature range of interest, the widening of the downward propagation limits is small. No data for the widening of the upward or horizontal propagation limits were found.

If the containment atmosphere is altered by the addition of carbon dioxide, steam, nitrogen, or other diluent, the lower flammability limit will increase slowly with additional diluent, while the upper flammability limit will drop more rapidly. With continued increase in diluent concentration the two limits approach one another until they meet and the atmosphere is inerted. A flame cannot be propagated a significant distance for any fuel:air ratio in an inerted atmosphere. Figure 2-15 shows the flammability limits with the addition of excess nitrogen or carbon dioxide. Note that for 75% additional nitrogen, the atmosphere is inert.[2-27, 2-28] This corresponds to 5% oxygen at the limit of the flammable region, a value very close to that of the upper limit for hydrogen:air combustion. Roughly speaking, hydrogen:oxygen:nitrogen mixtures will be flammable if the hydrogen concentration is above 4% and the oxygen concentration is above 5%. For carbon dioxide, the atmosphere is inerted when the carbon dioxide concentration is 60% or above, corresponding to 8% oxygen or less. The larger specific heat of the carbon dioxide reduces the flame temperature and flame velocity; hence carbon dioxide suppresses flammability more than nitrogen. It requires about 60% steam to inert hydrogen:air:steam mixtures. The triangular diagram of Shapiro and Moffette[2-29] indicates regions of flammability and detonability of hydrogen:air:steam mixtures. It has been widely reproduced and appears as Fig. 2-16.

In addition to diluents such as steam or carbon dioxide which can have a large thermal effect on a flame, certain substances react chemically to inhibit hydrogen combustion. For example, Halons (halogenated hydrocarbons) appear to cause quenching by interacting with free radicals such as H, O, and OH. Figure 2-17[2-30] shows the flammability limits for a mixture of H_2:air:CF_3Br (Halon-1301).

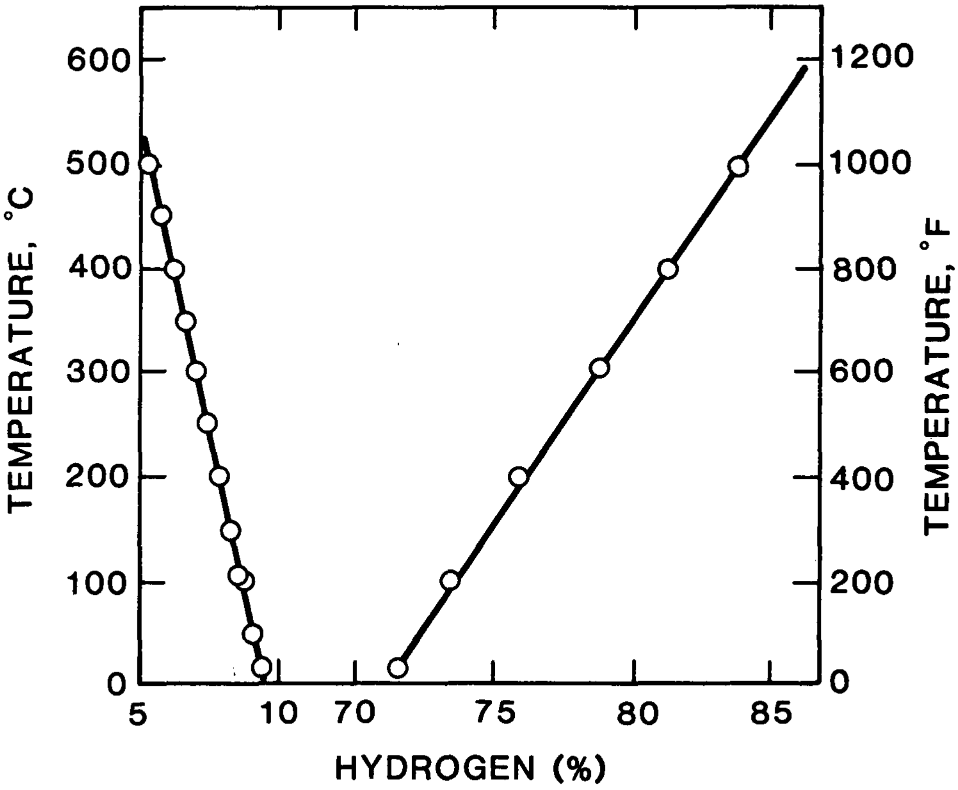

Figure 2-14. Effect of Initial Temperature on Downward Propagating Flammability Limits in Hydrogen:Air Mixtures

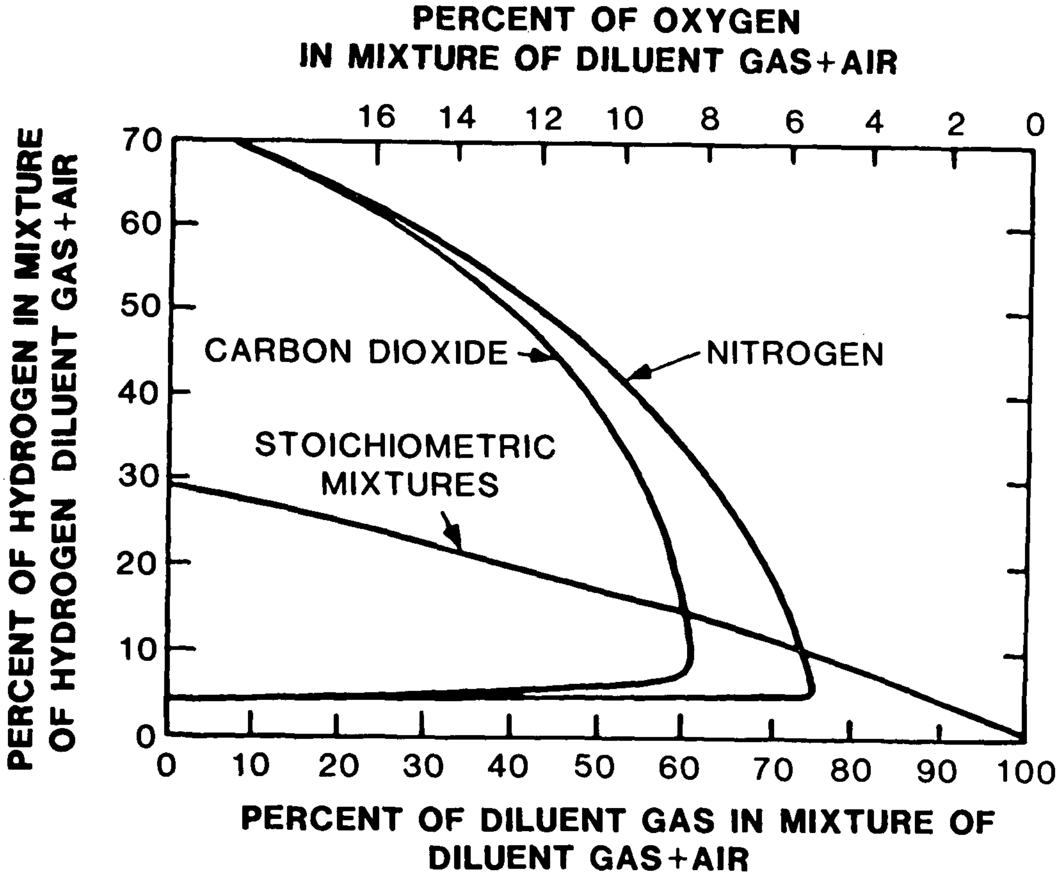

Figure 2-15. Flammability Limits Of Hydrogen In Air Diluted With CO_2 and N_2

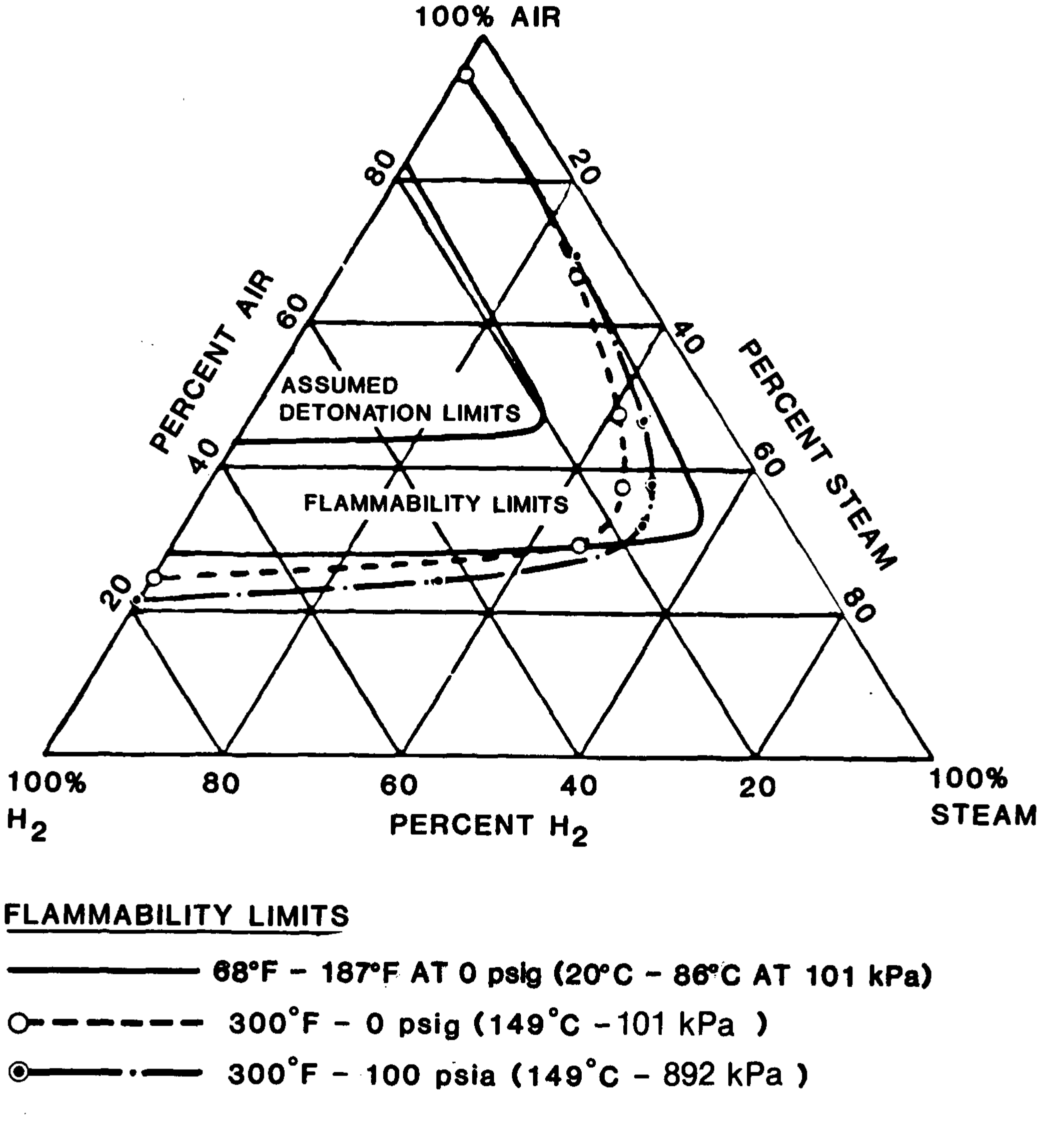

Figure 2-16. Flammability and Detonation Limits of Hydrogen:Air:Stem Mixtures

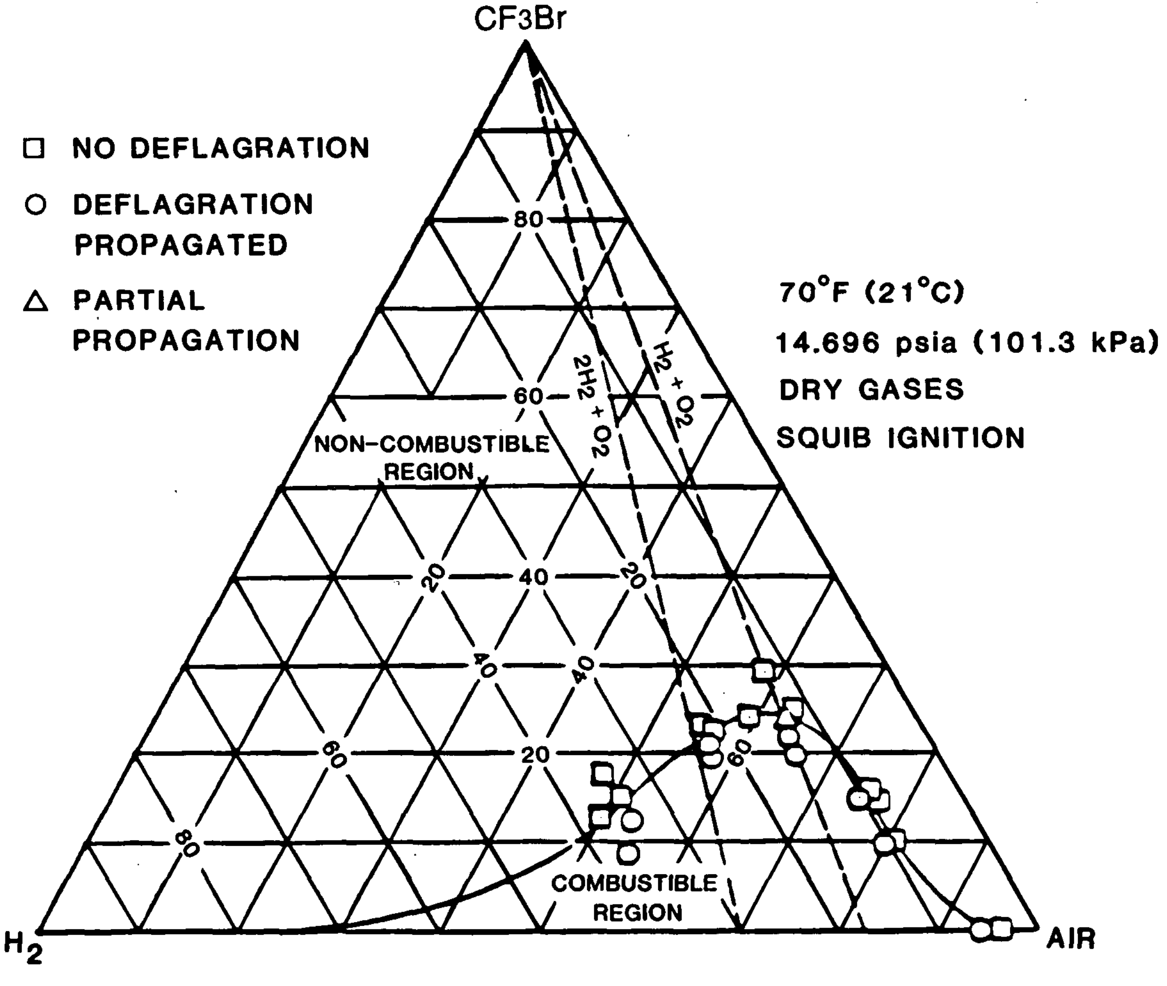

Figure 2-17. Deflagration Limits, H_2:Air:CF_3Br(Halon 1301)

Ignition of dry hydrogen:air mixtures, particularly when the mixtures are well within the flammability limits, can occur with a very small input of energy[2.29]. Common sources of ignition are sparks from electrical equipment and from the discharge of small static electric charges. The minimum energy required from a spark for ignition of a quiescent hydrogen:air mixture is of the order of tenths of a millijoule. The ignition energy required as a function of hydrogen concentration is shown in Fig. 2-18[2-31]. For a flammable mixture, the required ignition energy increases as the hydrogen concentration approaches the flammability limits. The addition of a diluent, such as steam, will increase the required ignition energy substantially. As mentioned previously, high energy ignition sources can cause mixtures outside the flammability limits to burn for some distance.

2.3.4 Deflagrations

Deflagrations are flames that generally travel at subsonic speeds relative to the unburned gas. Deflagrations propagate mainly by thermal conduction from the hot burned gas into the unburned gas, raising its temperature high enough for a rapid exothermic chemical reaction to take place. The propagation of a deflagration can be understood by examining the flammability limits discussed in the previous section. Consider a quiescent mixture of hydrogen:air. For hydrogen concentrations below about 4.1% there will be no significant propagation away from an ignition source. For hydrogen concentrations between 4.1 and 6.0%, there will be upward propagation from the ignition source. Hydrogen concentrations between 6.0 and 9.0% will produce both upward and horizontal propagation, and hydrogen concentrations above 9.0% will produce propagation in all directions, although the upward propagation may be faster than the downward propagation. Exact values for propagation limits will, of course, vary with temperature, pressure, and the presence of diluents. The degree of turbulence is also very important with turbulence tending to enhance combustion as long as the turbulence is not violent enough to "blow out" the flame.

It has been found in several small and medium-scale laboratory experiments that when hydrogen:air mixtures with hydrogen concentrations in the range 4-8% were ignited with a spark, some of the hydrogen was not burned[2-32 to 2-36]. The resultant pressure rise was below that predicted for complete combustion, as shown in Fig. 2-19[2-35]. Experimental results with a spark ignition source indicate that the completeness of combustion in quiescent mixtures increases with increasing hydrogen concentration, and is nearly complete at about 8-10% hydrogen. The range of incomplete combustion corresponds to the range in which the mixture is above the flammability limit for upward propagation, but below the flammability limit for downward propagation. In upward propagation of lean hydrogen:air flames, "separated globules" of flame have been observed.[2-37] Even when ignition occurs at the bottom of a chamber, the upward propagating flame fails to burn some of the hydrogen. As shown in Fig. 2-19 for the "fans on" cases, turbulence and mixing of the gases can significantly increase the completeness of combustion.

The phenomenon of incomplete burning of lean hydrogen:air mixtures may be of great importance in reactor safety. Combustion of lean mixtures, below 8% hydrogen, appears to be a method of partly eliminating hydrogen without significant pressure rise.

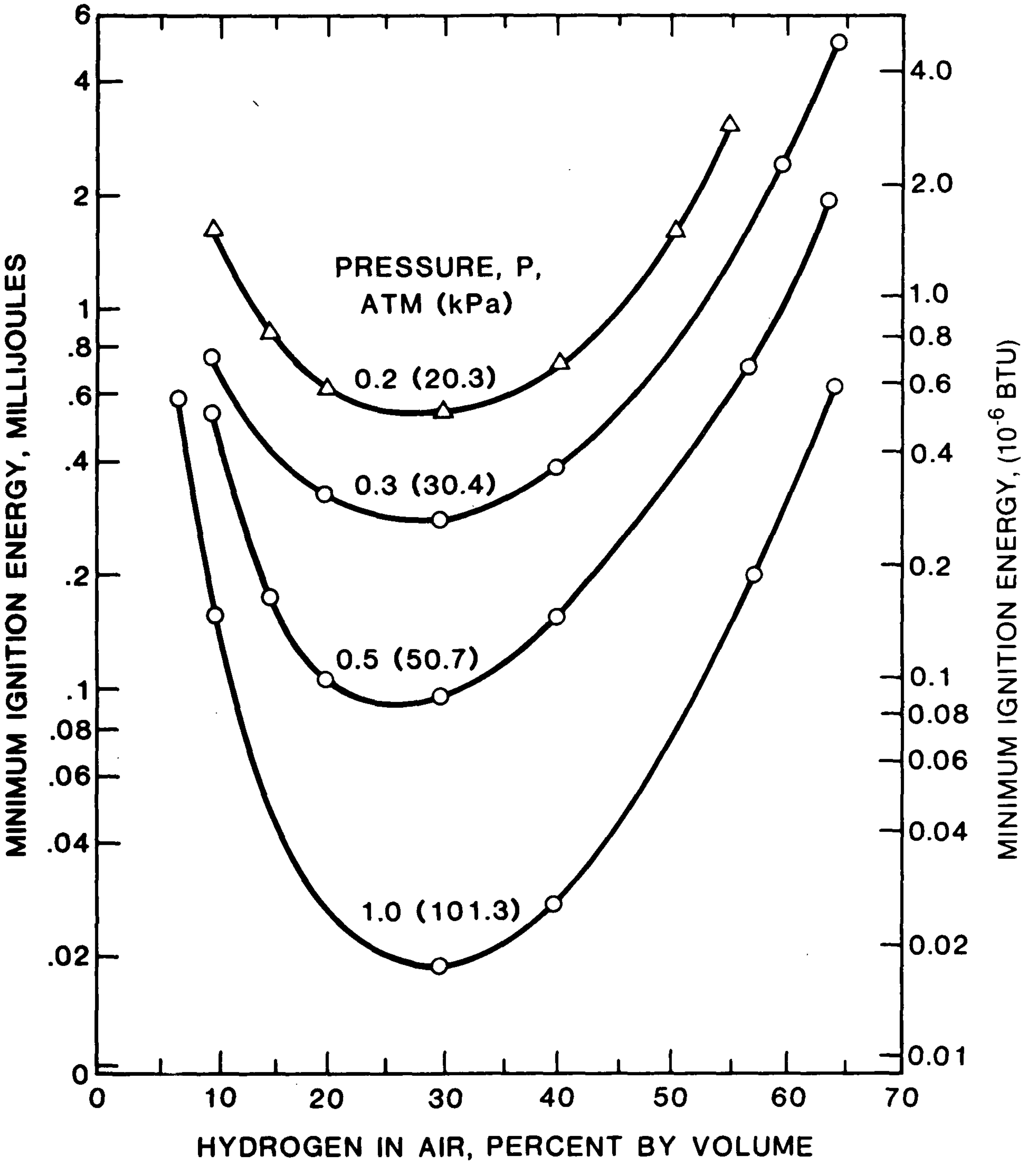

Figure 2-18. Spark Ignition Energies For Dry Hydrogen: Air Mixtures

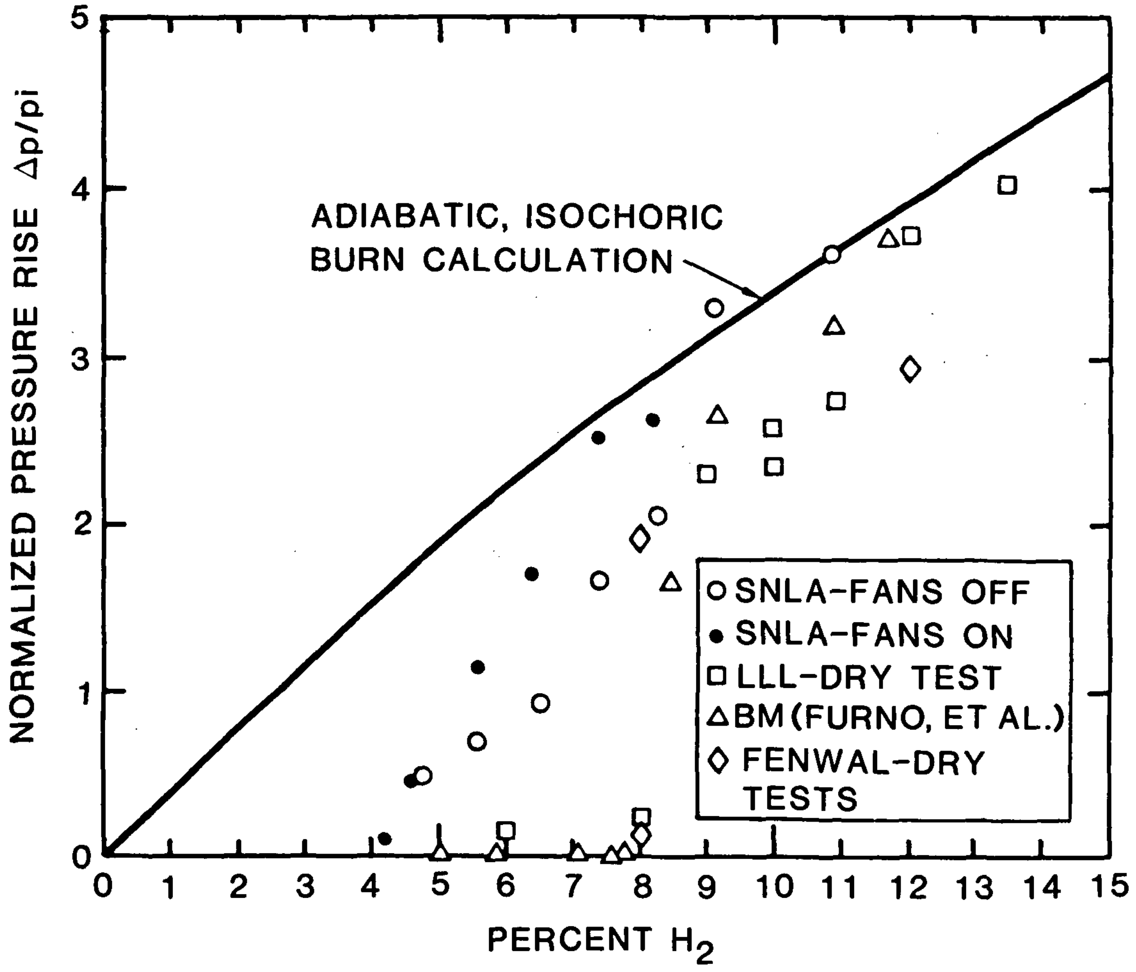

Figure 2-19. Normalized Pressure Rise Versus Hydrogen Concentration

Another important parameter when studying deflagrations is the flame speed. The flame speed determines how much time is available for heat transfer during a burn. Heat transfer results in pressures and temperatures below those predicted in Figs. 2-10 to 2-13. The dominant heat transfer mechanisms are evaporation of containment sprays, radiation, and convection. Some reactors also contain fan coolers. Normally, if the sprays are on, they will dominate the heat transfer process. Radiation heat transfer can also be important due to the high gas temperatures expected during a hydrogen burn. Convection may be less significant over the short time of a burn. One note is that the presence of sprays may significantly increase the flame speed due to the increased turbulence induced by the sprays. Typically, pressure rises above 80% of the adiabatic pressure rises are predicted for reasonable values of the flame speed, assuming complete combustion. The flame speed is discussed in detail below. Warnitz[2-38] computed the laminar burning velocity* for hydrogen:air mixtures and compared his results with those of several other workers. The results are shown in Fig. 2.20. The maximum laminar burning velocity of hydrogen:air mixtures is about 9.8 fps (3 m/s) near a concentration of about 42% hydrogen. The burning velocity becomes much smaller as the flammability limits are approached. The effect of diluents such as nitrogen is to reduce the burning velocity by reducing the flame temperature. Steam also reduces the burning velocity, but by less than the amount expected from equilibrium flame temperature considerations.[2-39,2-40,2-41]

The laminar burning velocity will be changed only slighly by moderate changes in ambient temperature and pressure.[2-31] For a 90°F (50°C) temperature rise above room temperature, the increase in laminar burning velocity is less than 0.7 fps (0.2 m/s). The variation of hydrogen:air flame speed with pressure is very small for pressure changes in the range of interest for reactor containments. Recent work by Liu and MacFarlane considering the effects of temperature and steam concentrations on burning velocities may be found in Ref. 2-42.

The plane or spherically-expanding laminar flame front has been shown to be unstable. Freely propagating laminar flame fronts, if they do not become turbulent, have complex cellular structures. Hydrogen-lean flames tend to form nonsteady cellular structures, and will eventually become turbulent. For hydrogen-rich flames, one expects "widespread wrinkled irregular steady surfaces."[2-43]

As noted above, it is likely that a laminar deflagration in containment will become turbulent. Many turbulent flames have average burning velocities in the range 2 to 5 times the laminar burning velocity. There may be a potential for large flame accelerations in fairly rich mixtures, generating "quasi-detonations."

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*The laminar burning velocity (in a Lagrangian sense) denotes the speed of gases at a steady burner. Propagating laminar flames have flame speeds (in an Eulerian sense) which are 5-7 times faster due to volumetric expansion of the burned gases.

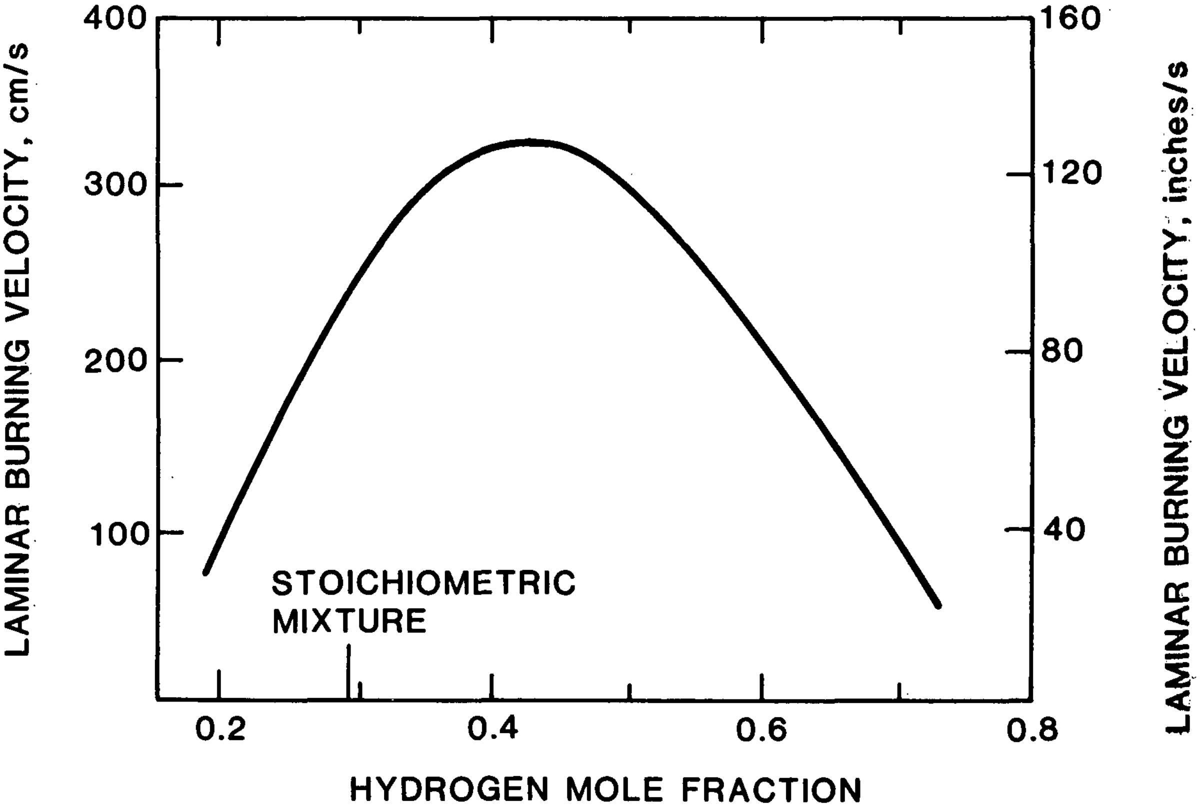


Figure 2-20. Laminar Burning Velocity of Hydrogen:Air Mixtures

If the turbulent flame speed (laboratory system) becomes greater than about one-tenth of the sound speed (the sound speed is approximately 1150 fps (350 m/s) in containment air), shock waves will be formed ahead of the flame front. Dynamic loads, in addition to static loads, will be imposed on the containment structure.

One acceleration mechanism under active study is the action of obstacles in the path of flames.[2-43] Many obstacles that might potentially cause flame acceleration, such as pipes, pressure vessels, etc, are present in the lower sections of most containments. The mechanisms governing flame acceleration in the presence of obstacles may represent a balance of positive and negative factors associated with flame folding and turbulence. Two positive factors that lead to an increase in burning rate are the increase in flame area due to folding, and the increase in the local burning velocity of the folds due to higher turbulent diffusivities associated with fine-scale turbulence. The increase in flame area is a result of the gas flow ahead of the flame being greatly perturbed by the presence of obstacles. The negative factors that lead to a decrease in the burning rate are reaction quenching due to excessive flame stretching, and rapid cooling due to turbulent mixing. Very fast burns may also occur due to the presence of a very intense ignition source. As was suggested earlier, this could be a jet of hot combustion products formed subsequent to ignition in some adjoining semi-confined volume.

The subject of fast deflagrations and quasi-detonations is one of active current research. It is currently not well understood. Further work will be needed to determine its importance to hydrogen combustion in reactor containments.

2.3.5 Combustion of a Steam:Hydrogen Jet

If the hydrogen is injected into containment in the form of a steam:hydrogen jet, it is possible that hydrogen may start to burn as a turbulent diffusion flame. A diffusion flame is one in which the burning rate is controlled by the rate of mixing of oxygen and fuel. For the jet to burn, it is necessary that at some locations the hydrogen:air:steam mixture be within flammability limits.

Combustion can begin either because of an outside ignition source, or because the mixture temperature is above the spontaneous ignition temperature. Shapiro and Moffette[2-29] in 1952 presented experimental results on the spontaneous ignition temperature of hydrogen:air:steam mixtures applicable to stationary gases, or moving gases with obstacles in the path acting as flame holders (see Fig. 2-21). The spontaneous ignition temperature is in the range of 959-1076°F (515-580°C). A stable flame will occur at a distance from the orifice such that the turbulent burning velocity is equal to the gas flow velocity. There is evidence to suggest that for a particular set of conditions (temperature, pressure, and composition), there is a minimum orifice

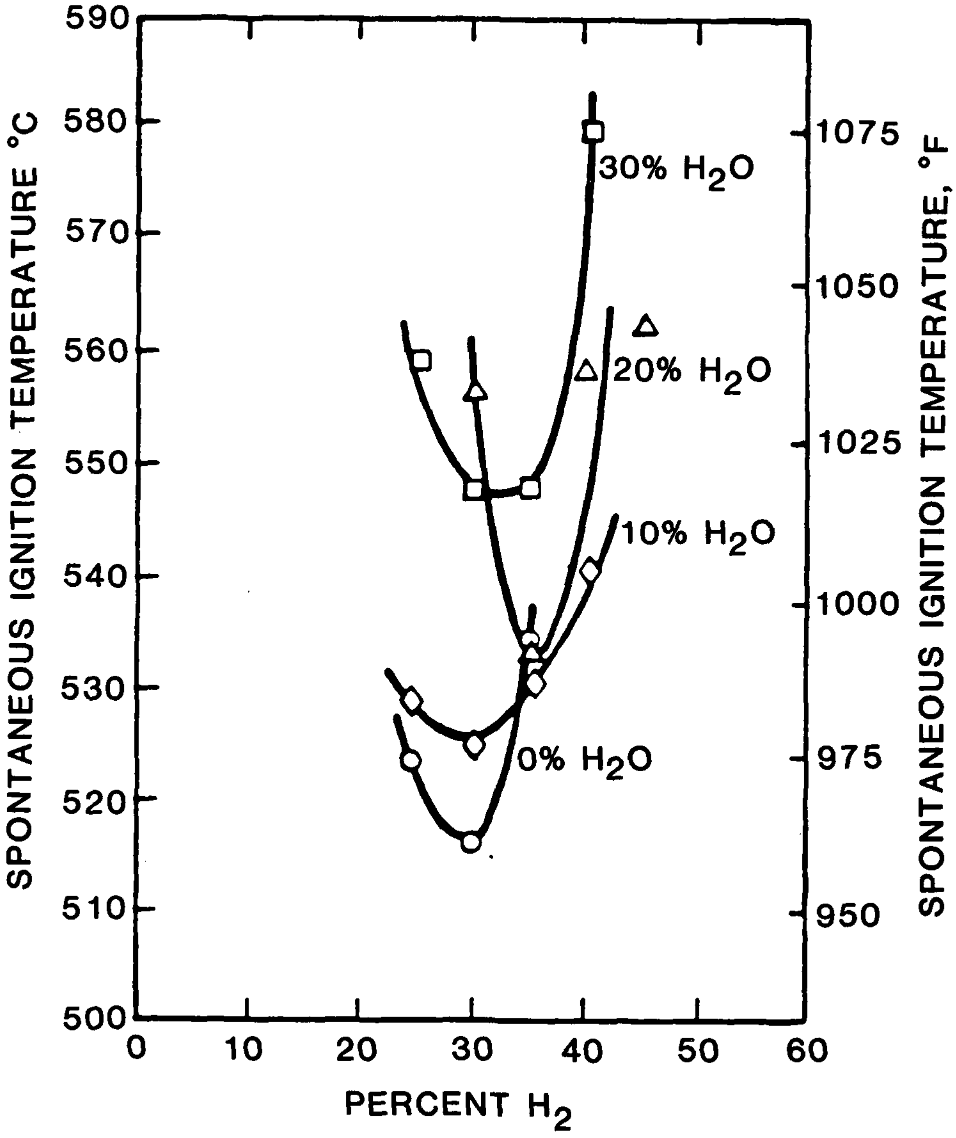


Figure 2-21. Minimum Spontaneous Ignition Temperature of Hydrogen:Air:Steam Mixtures

diameter required for flame stability.[2-44] This minimum diameter is typically on the order of a few millimeters or less, and therefore, all practical sized orifices will support a stable hydrogen flame.

2.3.6 Detonation of Hydrogen

A detonation is a combustion wave that travels at supersonic speeds relative to the unburned gas in front of it. For hydrogen:air mixtures near stoichiometric this speed is about 6600 fps (2000 m/s)(see Fig. 2-22). The compression of the unburned gas by shock waves in the detonation raises the gas temperature high enough to initiate rapid combustion.

We will attempt to answer as well as possible the following three questions:

1. Under what conditions is a hydrogen:air or hydrogen:air:steam detonation possible in containment?
2. If a detonation is possible, what is the likelihood that it will occur?
3. What pressure loads could a detonation cause?

We can answer the first question fairly well (at least with regard to hydrogen:air mixtures) and also the third question. The second question concerns the transition from deflagration to detonation and is still not well understood after more than 50 years of investigation. We can say that, in most postulated reactor accidents scenarios, deflagrations are much more likely than detonations.

2.3.6.1 Detonation Limits

Hydrogen:air mixtures near stoichiometric (about 29% hydrogen, two parts H_2 to one part O_2) are known to be detonable. Mixtures departing from stoichiometric, either in the hydrogen-lean or hydrogen-rich direction are increasingly more difficult to detonate. It has been generally believed that beyond certain mixture ratios of about 18% and 58% hydrogen, hydrogen:air mixtures could not be detonated. These "detonation limits" were measured by attempting to cause detonations in long tubes of rather small diameter. It has recently been observed, however, that the "detonation limits" are functions of the tube diameter, and not universal values at given mixture concentrations, temperatues and pressures.[2-44,2-46] Our understanding of the possibility of sustaining a detonation in hydrogen:air mixtures, as well as other gas mixtures, has greatly increased within the last few years. We will present a summary of this new understanding that replaces the older idea of fixed detonation limits.

There are three levels of sophistication used in considering detonation wave structure. For many purposes one can ignore the three-dimensional detonation wave structure and consider the wave as an infinitely thin surface

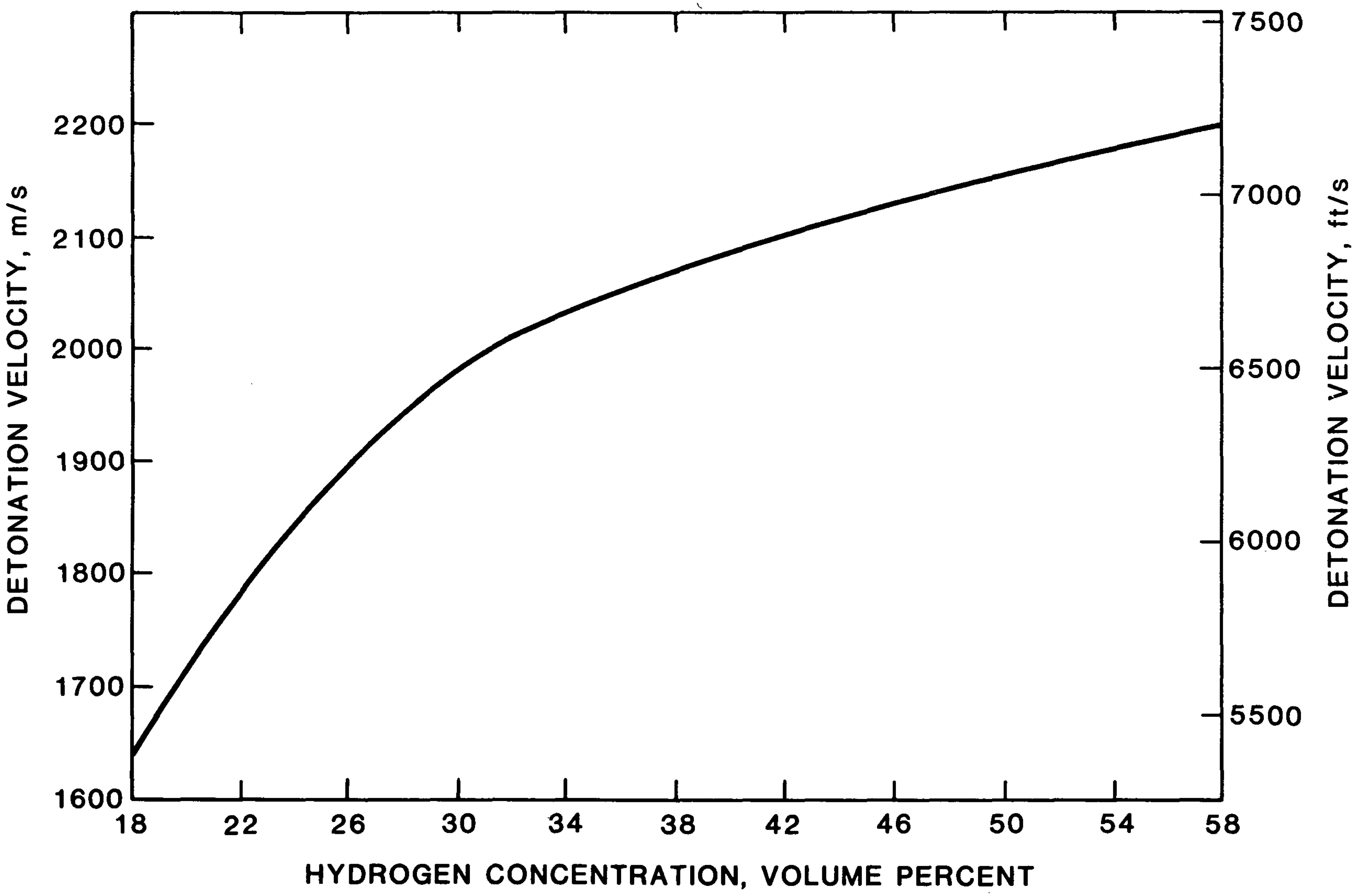


Figure 2-22. Theoretical Chapman-Jouguet Detonation Velocity for Hydrogen:Air Mixtures

separating the unburned and burned gas, the Chapman-Jouguet model (C-J model). The wave thickness for hydrogen:air at room pressure is about 0.4-4 in. (1-10 cm). The first model of detonation wave structure, the Zel'dovich, von Neumann, and Doring model (the ZND model) considered the detonation as being a normal shock wave followed by a deflagration. Within the last 20 years it has been found that the detonation wave is composed of unsteady oblique shock waves moving in an everchanging cellular structure (characterized by its transverse dimension), a "foamy" detonation front. This concern with detonation wave structure has been of interest to scientists concerned with detonations, but up to now has had little practical significance.

The cell size, λ, in a detonation is a fairly easy quantity to measure. It ties together the chemical reaction rate with the gross macroscopic propagation behavior of detonations. The farther a mixture is from stoichiometric, and hence the less energetic the chemical reaction, the larger is the detonation cell size. It appears that the smallest diameter tube in which a detonation will propagate is one whose diameter is about a third of a cell width. The cell width for hydrogen:air has been accurately measured over an extensive range of hydrogen:air ratios (see Fig. 2-23).[2-46] For example, at 16% hydrogen the cell size is about 9.6 in (24.5 cm). This means that a 16% hydrogen mixture detonation should be able to propagate down a tube 3.2 in. (8.2 cm) in diameter. The larger the tube diameter, the wider is the range of detonable hydrogen concentrations. Note that 16% hydrogen is below the usually accepted detonation limit; in fact, a detonation has been observed in a 12 in. (30 cm) tube at a hydrogen concentration of 13.8%.[2-47]

The knowledge of hydrogen:air cell size is valuable for more than tube detonation limits. It is known that if a detonation is to propagate from a tube into an open space, there is a minimum tube diameter for which the detonation will propagate, the critical tube diameter. For smaller tube diameters, the detonation will fail when leaving the tube. Experimental results show that the critical tube diameter is about 13 cell widths. For a 16% hydrogen mixture the critical tube diameter is therefore 10.5 ft (3.19 m). For a rectangular duct, the critical duct height varies from about 11 cell widths (for a square duct) to about 3 (for a wide duct). For propagation into an open space confined on one side of the duct, there is some evidence that the critical duct height lies between 1.5 and 5.5 cell widths. Figure 2-24 shows the relationship between geometry and cell size for the geometries discussed above.

The developments described above possibly answer the first question, "Under what conditions is a hydrogen:air detonation possible in containment?" The detonation limits are not fixed but depend on the geometry being wider for larger sizes. The curve of cell size versus hydrogen fraction rises steeply on the hydrogen-lean side. However, detonations have been observed at hydrogen concentrations as low as 13.8%. For the large geometrical scales in containments, detonations may propagate in leaner mixtures. Still to be answered in this area is the effect of steam, initial temperature, and initial pressure on detonation cell size.

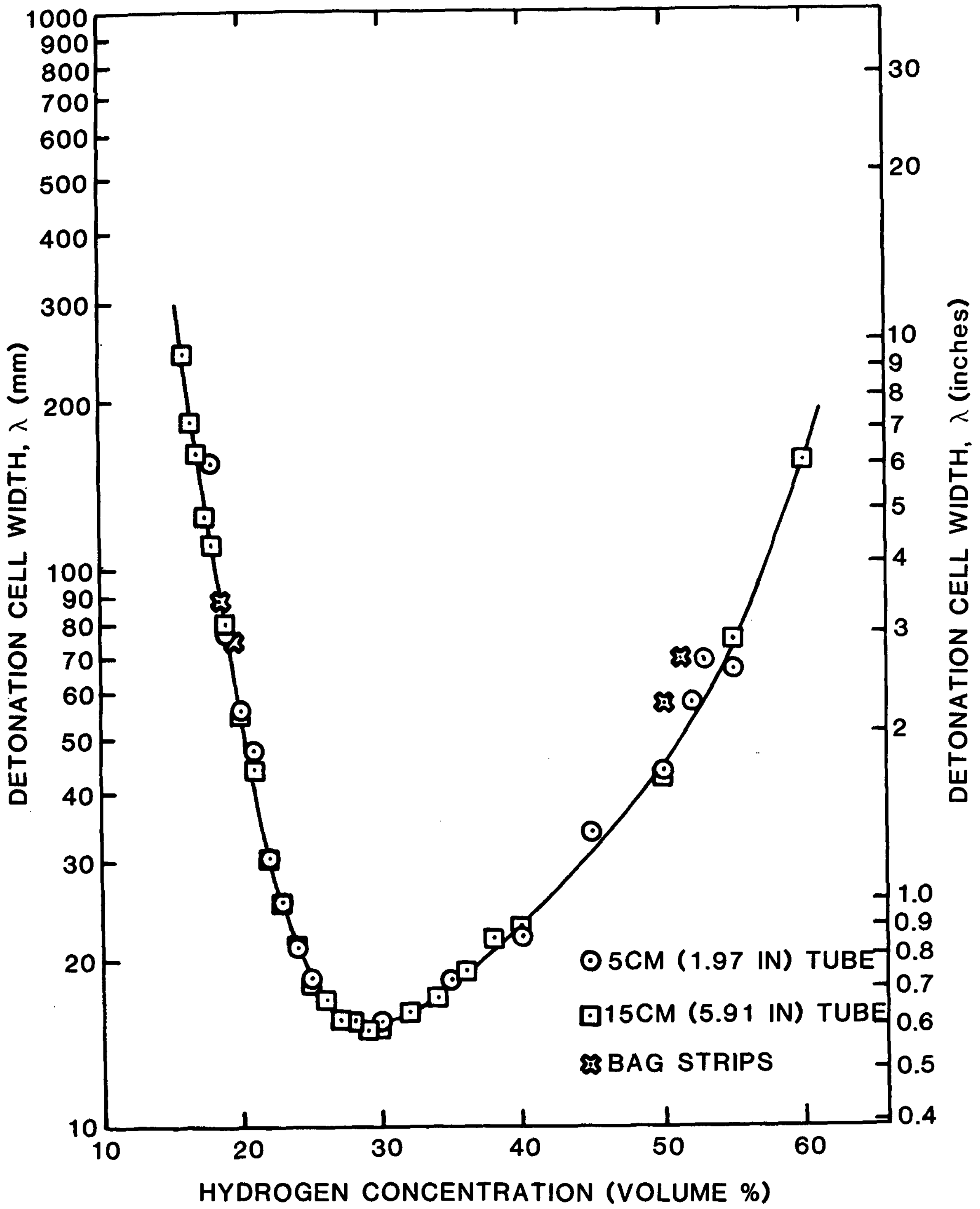
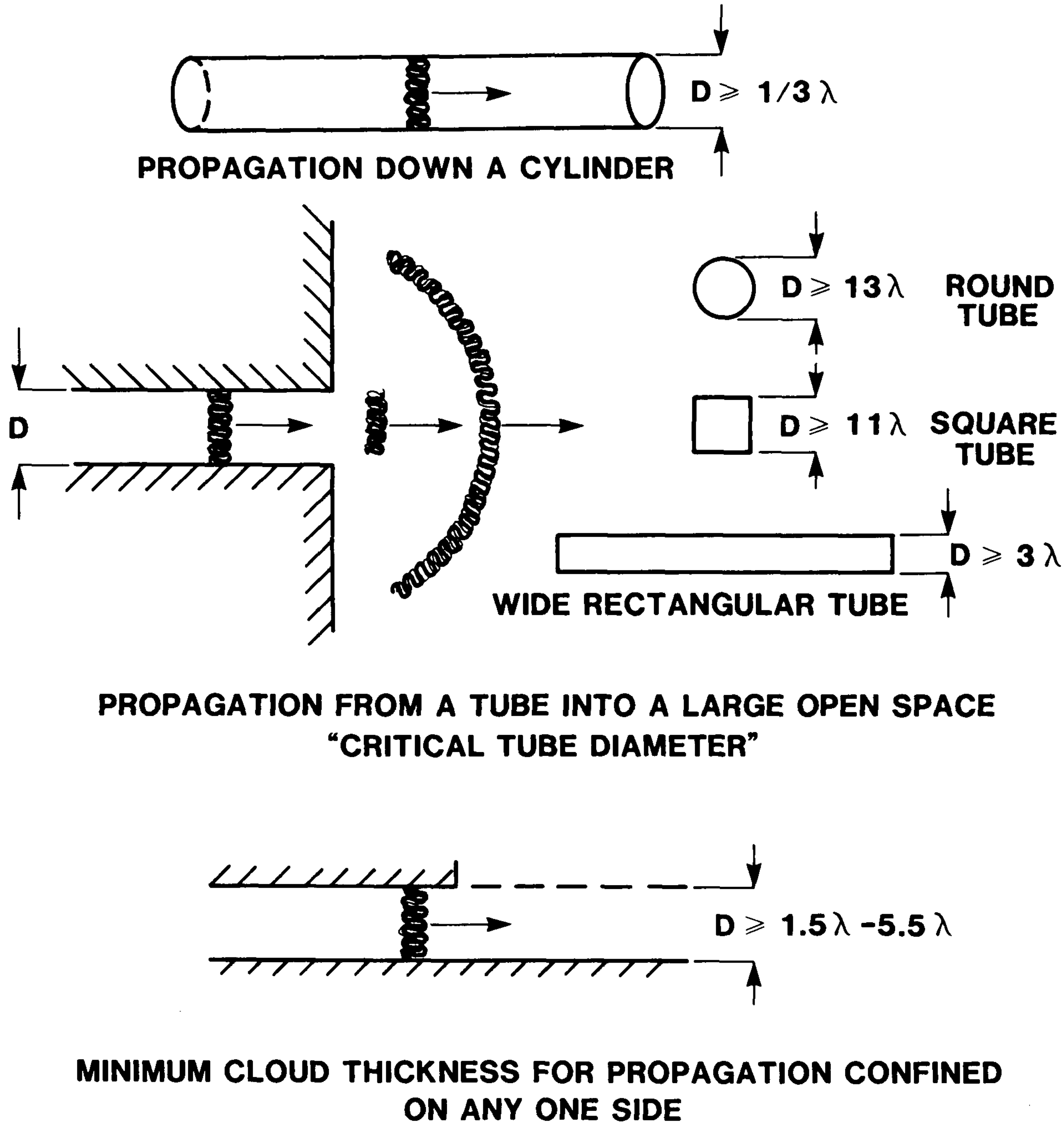


Figure 2-23. Experimental Measurement of Detonation Cell Size for Hydrogen:Air Mixtures at Atmospheric Pressure


PROPAGATION DOWN A CYLINDER

PROPAGATION FROM A TUBE INTO A LARGE OPEN SPACE
"CRITICAL TUBE DIAMETER"

MINIMUM CLOUD THICKNESS FOR PROPAGATION CONFINED ON ANY ONE SIDE

Figure 2-24. Estimates of Minimum Sizes of Various Geometries For Detonation Propagation In Terms Of Detonation Cell Width.

2.3.6.2 Transition to Detonation

A detonable mixture may only deflagrate (burn)and not detonate. Detonations can start directly by the use of a vigorous shock wave coming from a high explosive, strong spark, or laser. Approximately 1 gm of tetryl explosive will initiate a spherical detonation of a stoichiometric hydrogen:air mixture. The increase in explosive charge required as the mixture departs from stoichiometric is roughly proportional to the increase in detonation cell size. Detonations can also start from deflagrations that accelerate to high speeds pushing shock waves ahead of the burn front until at some point shock heating is sufficient to initiate the detonation. Sources of such highly accelerated flames are high speed jets coming from semiconfined regions and flames passing through fields of obstacles.

Deflagration-to-detonation transition is probably the least understood aspect of detonation theory at this time. Measurements have been made of the distance required to have transition to detonation in smooth tubes. Distances many times the tube diameter have been required. If obstacles are inserted into the tube, the required distance to detonation is greatly reduced. The motion of the expanding gases around the obstacles leads to greatly increased flame front area, rapid flame acceleration and rapid transition to detonation. Confinement greatly promotes transition, but one cannot rule out transition to detonation in a containment if a detonable mixture of sufficient size is present. The second question, "If a detonation is possible, what is the likelihood that it will occur?" therefore cannot be satisfactorily answered at present.

2.3.6.3 Detonation Pressures and Temperatures

For the purpose of studying the pressures and temperatures caused by a detonation, it is sufficient to ignore the detonation wave structure and consider it as a thin surface, a discontinuity. Chapman and Jouguet found that the conservation equations for mass, momentum, and energy, together with the appropriate thermodynamic relations and an equation of state did not lead to a unique solution for the detonation speed and hence pressure and temperature. Consequently, they assumed that the detonation traveled at a speed such that the flow behind the detonation was sonic relative to the detonation. With this assumption one can compute a unique detonation speed for each hydrogen:air mixture, and find the corresponding temperature and pressure behind the detonation wave. The results are shown in Figs. 2-25 and 2-26. It is an experimental fact that the measured speeds of detonations are approximately equal to the calculated C-J values. Various theoretical arguments have been advanced over the years to explain the near validity of the assumption of sonic speed behind the detonation. They are not totally convincing. However, the C-J theory provides reasonably correct values for detonation speed, temperature, and pressure. This theory does not give any information about the issues previously discussed, viz., detonation limits and transition to detonation.

The burned gases behind a detonation are moving in the direction of the detonation. When a detonation hits a rigid wall, the gases must be brought to rest. This is accomplished by a reflected shock wave. We will consider only the case of a detonation wave striking a wall at normal incidence. The reflected shock wave further compresses the burned gas, increasing the detonation pressure by a factor of about 2.3. The pressures and temperatures predicted behind the normally reflected shock wave are also shown in Figs. 2-25 and 2-26.

If a detonation propagates down a tube, starting from a closed end, there will be a series of rarefaction (expansion, pressure reducing) waves behind the detonation reducing the gas velocity to zero about midway between the detonation wave and the rear wall. The pressure and temperature are also reduced by the rarefaction waves. For a spherically expanding detonation, the effect of the rarefaction waves behind the detonation is even more pronounced. The case of a cylindrically expanding detonation is intermediate between the planar and spherically expanding case. Results for these cases are shown in Fig. 2-27.[2-48] R in this figure is the distance from the origin of the detonation to the detonation front. The origin is the rear wall for the planar case, the axis for the cylindrical case, and the center of the sphere for the spherical case. x is the distance from the origin to the point of interest. The abscissa of Fig. 2-27 is the ratio x/R. Note that R = Ut, where U is the detonation speed and t is the time since the start of the detonation at the origin. One can convert the results of Fig. 2-27 into a pressure history at a given position.

The above solutions for an expanding detonation are valid only for the simple geometries considered. In a containment one expects wave reflections from walls and obstacles to give rise to complex shock wave patterns. Wave interactions may lead to dissipation or, possibly, to wave focusing which can give rise to very high local peak pressures.

2.3.6.4 Local Detonations

In all the previous sections on detonations it has been assumed that the detonation is taking place in a homogeneous combustible mixture. Such detonations are global, traveling throughout the containment. With the exception of the strongest containments, containments will probably not be able to withstand the quasi-static pressures (adiabatic isochoric pressures) generated after the detonation, even without the additional dynamic loads due to detonation. It is therefore more appropriate to consider the effect of detonations when only a local portion of the containment atmosphere is detonable.

Consider a detonable cloud of hydrogen:air surrounded by air. As the detonation wave leaves the cloud, it will change into an expanding decaying shock wave. The shock wave intensity drops fairly rapidly if the shock wave expands spherically. Within a distance equal to 3 cloud radii, the shock wave pressure will drop to a value low enough to no longer threaten the containment structure. However, it has been found in detailed computer calculations[2-49,2-50] that, because of the containment geometry, the shock waves

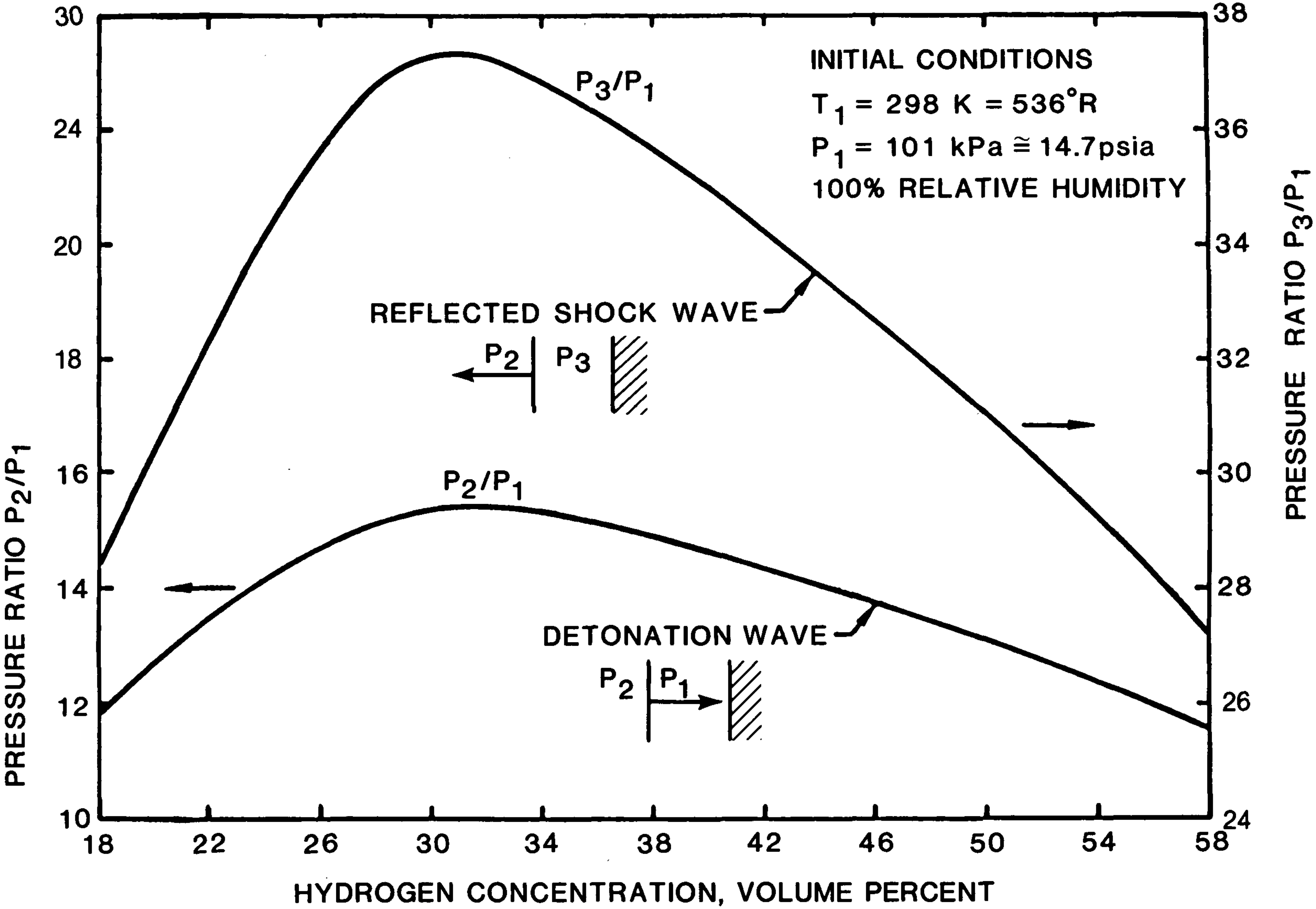


Figure 2-25. Theoretical Detonation Pressure and Normally Reflected Detonation Pressure for Hydrogen:Air Mixtures

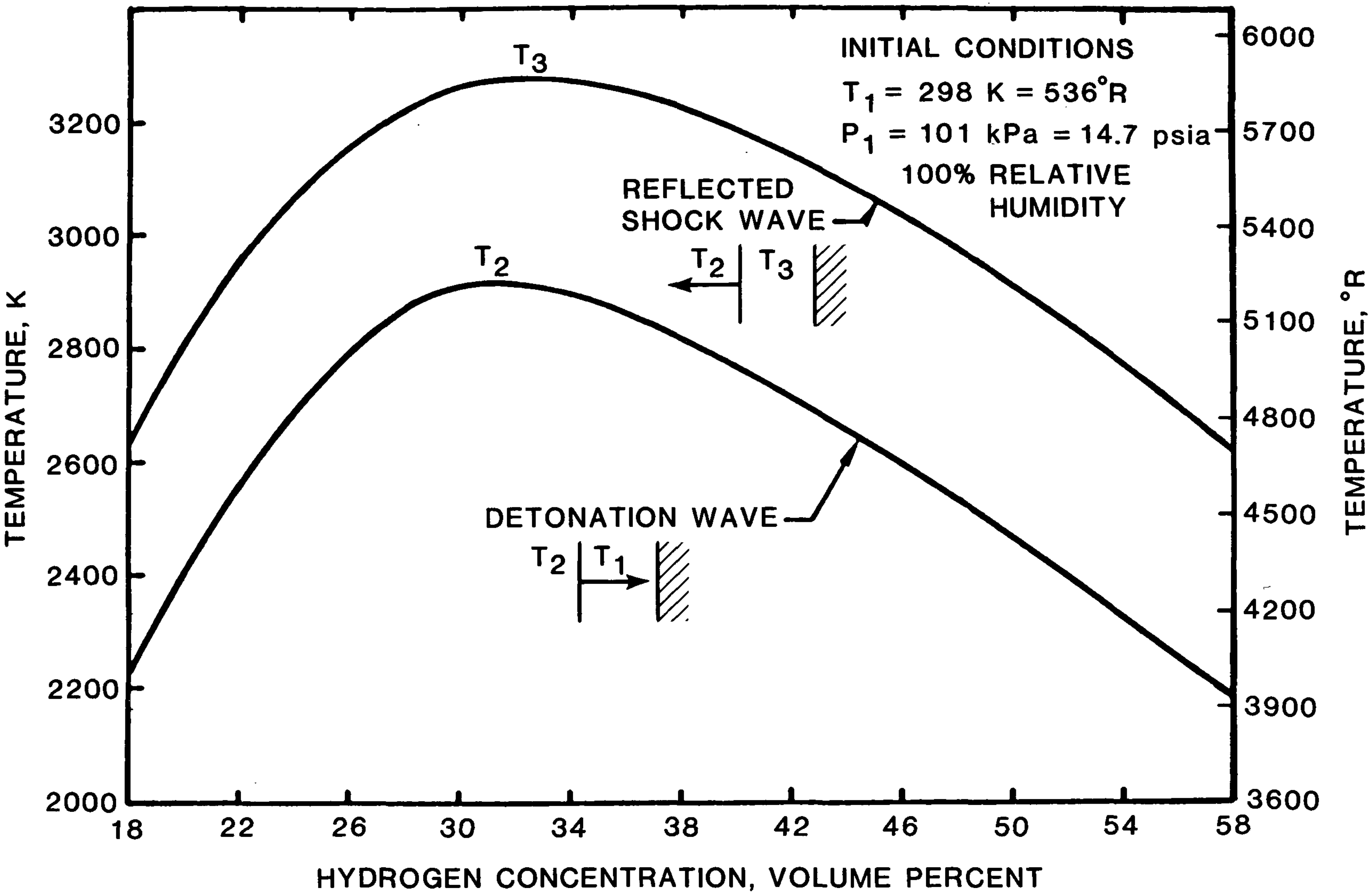


Figure 2-26. Theoretical Detonation Temperature and Normally Reflected Detonation Temperature for Hydrogen:Air Mixtures

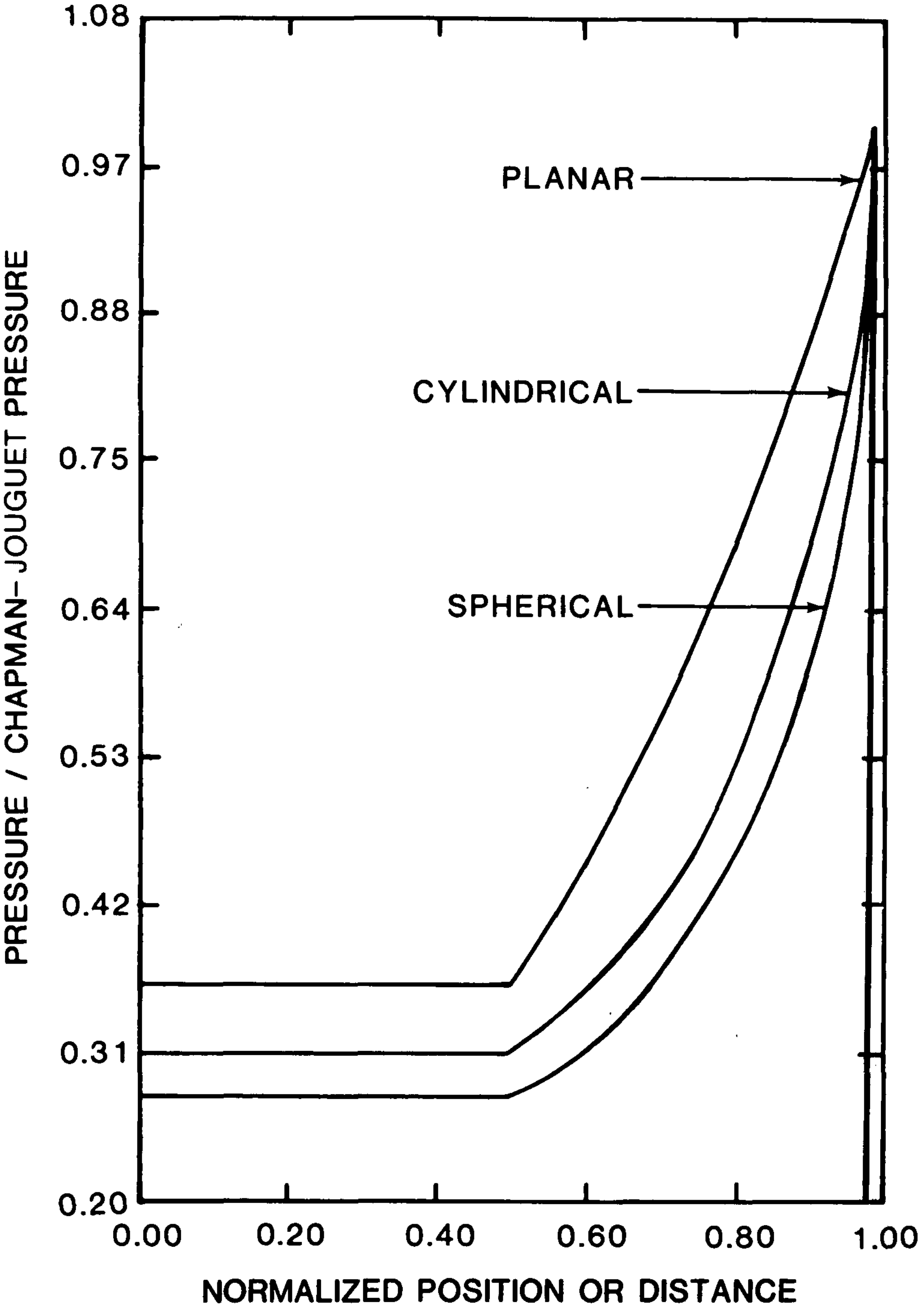


Figure 2-27. Pressure Distribution Behind Planar, Cylindrical and Spherical Detonation Fronts When $\gamma = 1.4$ (Approximation for Hydrogen:Air Mixtures)

may be focused in local regions, such as the top center of the containment dome, giving rise to large local peak pressures and impulses. Local detonations may be dangerous in and near the detonable cloud, and may be dangerous at locations farther away if shock focusing effects are significant.

2.3.6.5 Missile Generation

Missiles may be generated when combustion (deflagration or detonation) occurs in a confined region or when a propagating combustion front produces dynamic pressure loads on equipment. Such missiles may pose a threat to the containment structure itself, as well as representing a potential threat to safety and control equipment. For instance, electrical cables may not be expected to withstand the impact of a door or metal box. The actual risk to plant safety posed by missiles generated from hydrogen combustion depends upon a number of independent factors. Consequently, methods of probabilistic risk assessment need to be applied to individual plants to determine the severity of the threat.

2.4 MITIGATION SCHEMES

2.4.1 Deliberate Ignition

Deliberate ignition may be suitable for containments that are threatened by combustion of rich mixtures ($>$10% H_2) but can readily survive combustion of hydrogen at lean mixtures ($<$10% H_2). As shown previously in Fig. 2-10, the adiabatic combustion of lean mixtures will produce a lower pressure rise than rich mixtures. Additionally, combustion of lean mixtures will produce pressures and temperatures lower than the adiabatic, isochoric values due to heat transfer and, in many cases, incomplete combustion. The success of deliberate ignition methods depends primarily upon the hydrogen and steam release rates, atmosphere mixing mechanisms, and igniter performance.

The hydrogen release rate coupled with the atmosphere mixing mechanisms determine the atmosphere composition in both space and time. The hydrogen release rate depends upon the particular accident scenario. Very rapid releases of hydrogen may occur if the core slumps and falls into water below. As stated previously, a hydrogen release over a period of seconds would tend not to be well mixed, while one over a period of hours might be well mixed. The implications for deliberate ignition are somewhat unclear. If the hydrogen release is very rapid, high concentrations may be present near the release point. Deflagration will tend to be local in nature, and expansion into the rest of containment will tend to keep the pressure rises low. On the other hand, one must also consider the possibility of a detonation whenever locally high concentrations exist. It should also be noted that rapidly repeated deflagrations in a local region may eventually inert that region, leading to hydrogen being transported to the rest of containment. For the case of slow releases, global deflagrations become possible. Because of the very different phenomena that can occur depending upon how the hydrogen is released and mixed, it may be advisable to include hydrogen detectors placed at a few key locations within containment. These detectors would allow the operator to intelligently control a deliberate ignition system and perhaps even turn certain igniters off if the possibility of a local detonation exists.

Another important factor of deliberate ignition schemes is igniter performance. Most of the systems proposed have used glowplugs for the igniter. Glowplugs appear to provide reliable ignition for hydrogen concentrations of about 8% and above[2-36], while the ignition probability for hydrogen concentrations below 8% is less certain. The ability of igniters to perform reliably at lean concentrations is somewhat dependent upon the location of the igniter. An igniter located near a ceiling cannot initiate significant combustion until the downward propagation limits ($\sim$9% H_2 in quiescent mixtures, somewhat lower in a turbulent environment) are reached, while an igniter centrally located or located near a floor may initiate combustion at much leaner concentrations. Combustion initiated at the bottom of a volume will tend to be more complete for lean mixtures due to the larger volume of hydrogen that is burned.

2.4.2 Water Sprays, Fogs, and Foams

Deliberate ignition schemes can be coupled with the use of sprays, fogs, or foams to provide significant pressure reduction during a hydrogen burn. Sprays, fogs, and foams operate under similar principles. The water acts as a large thermal capacitance, with substantial amounts of energy absorbed in evaporation. Figures 2-28 and 2-29 show the theoretical temperatures and pressures expected for the complete, adiabatic, constant-volume combustion of hydrogen:air mixtures including the evaporation of water.[2-51]

The success of these methods depends upon the density of water in the atmosphere and the drop size. The drop size needs to be small enough that evaporation can occur on a time scale that is shorter than or comparable to the total burn time. Figure 2-30 shows the vaporization time versus droplet radius for various combustion conditions.[2-49]

Most American reactor containments have spray systems in place. In general, these systems will produce liquid densities less than 0.01 volume percent and drops that might be larger than optimal for hydrogen burn mitigation. However, the low densities are compensated somewhat by the large flow rates that may introduce a significant amount of water during a burn. Also, a significant fraction of the drops will evaporate even if some of them are larger than desired. Water fog systems can produce drops of the desired size; however, achieving high density may be fairly difficult.[2-51, 2-52] Foams appear promising with respect to water density; however, more research is needed regarding foam maintenance, mixing of hydrogen and air in foams, foam breakup and evaporation, and impact on other reactor systems.

One cautionary note regarding these systems is that the flame speed can be increased substantially due to the small-scale turbulence generated. However, the potential for pressure reduction is significant, and these schemes merit further attention, particularly for containments in which deliberate ignition is marginal without the addition of sprays, fogs or foams.

2.4.3 Pre-Accident Inerting

Pre-accident inerting may be an option for those reactors that have relatively small or weak containments or for other reasons cannot survive even lean combustion. Pre-accident inerting has been chosen for use in Mark I and Mark II BWR containments. Normally, the containment atmosphere is diluted with nitrogen until the oxygen concentration is below 4%. Nitrogen is the leading candidate for the diluent gas due to its low cost and nontoxic characteristics. The main problem with pre-accident inerting is that life-support systems are required for personnel entering the containment. This may impact both routine and emergency maintenance capability, although the problems associated with Mark I and Mark II BWR containments have not been severe. Another problem with inerted containments is the possibility of oxygen buildup due to leakage from outside, leakage from compressed air systems, and radiolytic decomposition of water. Oxygen monitoring systems should be used with any inerting scheme to warn of a noninert environment.

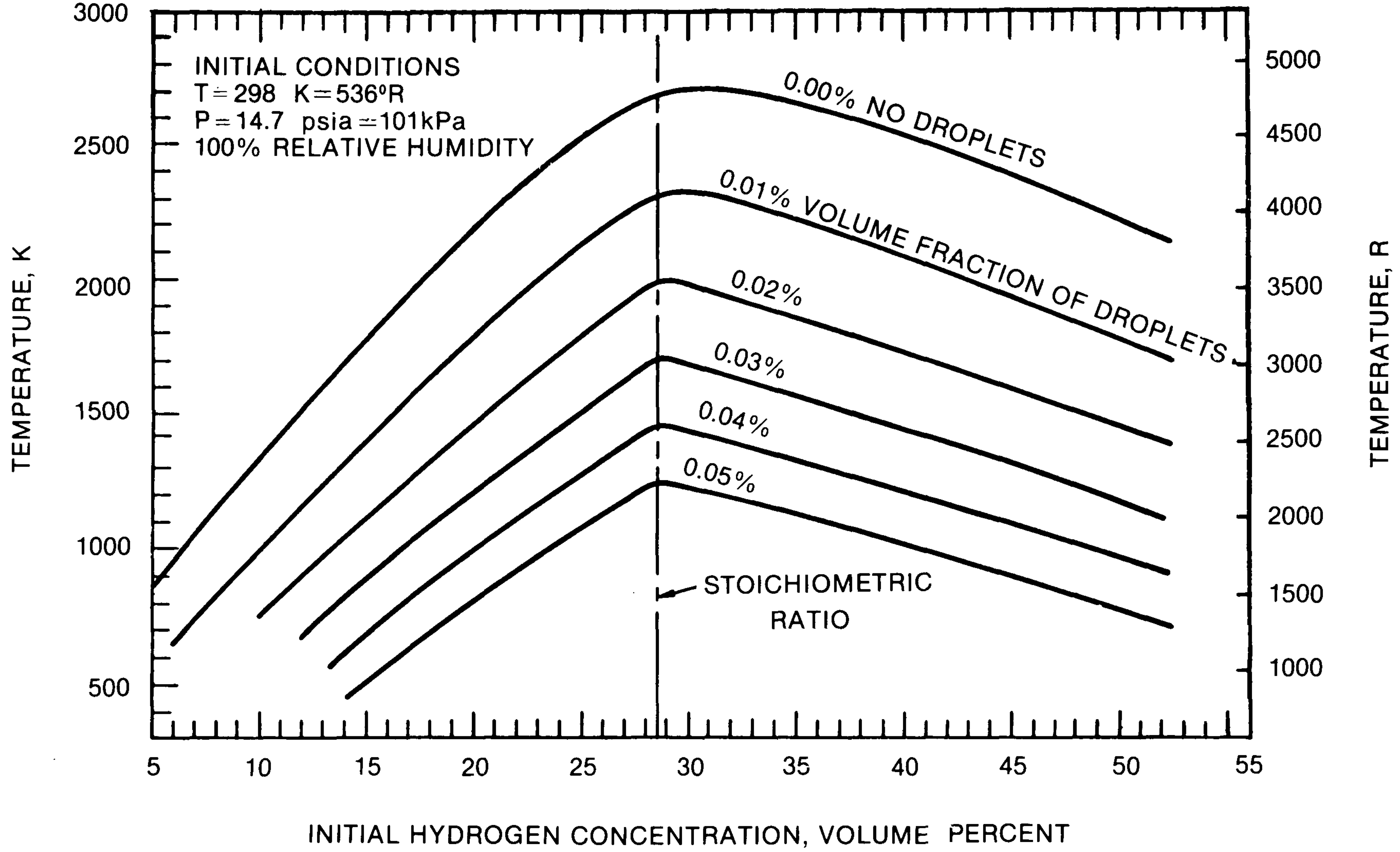


Figure 2-28. Final Temperature as a Function of Initial Hydrogen Concentration and Volume Fraction of Water Drops

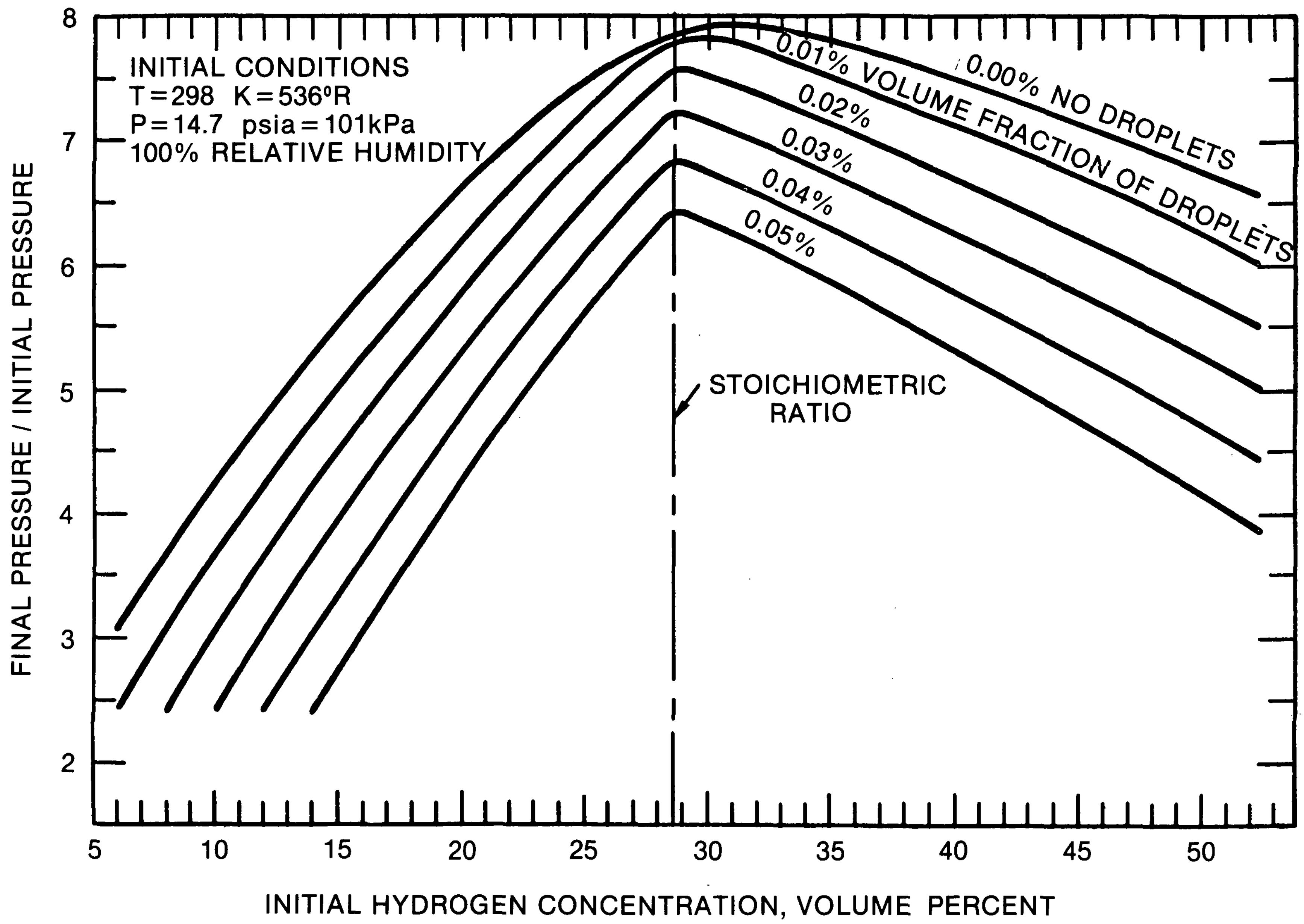


Figure 2-29. Ratio of Final to Initial Pressure as a Function of Initial Hydrogen Concentration and Volume Fraction of Water Drops

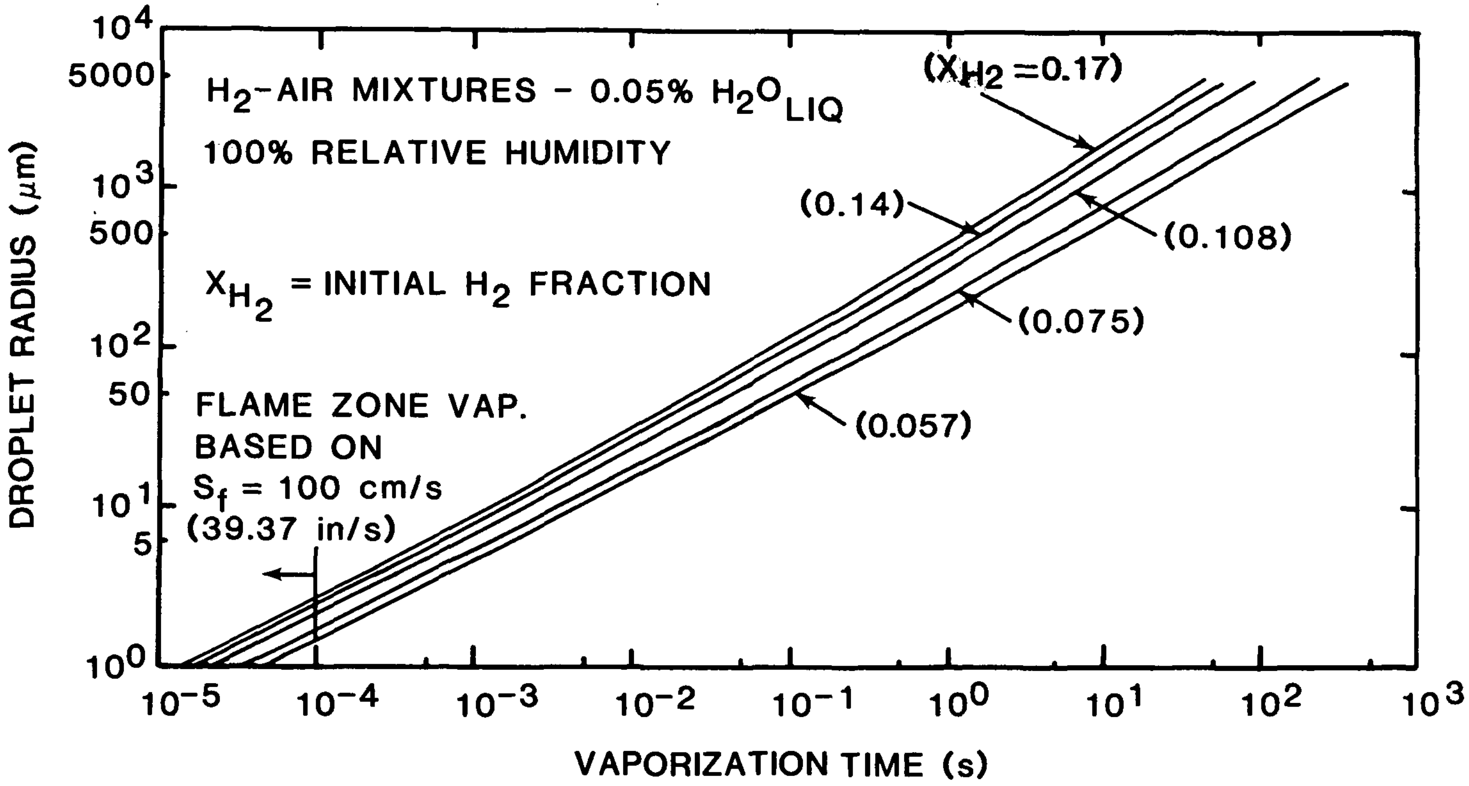


Figure 2-30. Vaporization Time Versus Droplet Radius at Various Combustion Stoichiometries

2.4.4 Post-Accident Inerting

Post-accident inerting would avoid one of the major problems of pre-accident inerting, namely, the problem of needing life-support systems for routine maintenance. Post-accident inerting could be accomplished either through oxygen depletion or through the addition of a diluent.

Oxygen depletion would involve the use of combustion chambers or engines to burn up the available oxygen. The devices could be located external to containment (connected by piping) or inside of containment with cooling provided to prevent excessive heating of the atmosphere. A major concern with such a system would be the time required to inert the containment after the onset of the accident. The containment should be inerted before the hydrogen concentration has time to reach dangerous levels. The type and number of devices should be determined by the size of containment and likely accident scenarios, and procedures for turning on the devices early in the accident should be established.

The addition of a diluent such as nitrogen, CO_2 or Halon can be accomplished very rapidly. However, a major difference between adding a diluent in a post-accident situation and adding one in a pre-accident situation is that, in the post-accident situation, it may not abe possible to bleed off excess gas and, thus, the baseline pressure will be raised. Figure 2-15 in the previous section shows the flammability limits of hydrogen in mixtures of hydrogen:air:nitrogen and hydrogen:air:carbon dioxide. Adding enough nitrogen to inert the atmosphere would raise the pressure a factor of 4, while adding enough CO_2 to inert the atmosphere would raise the pressure by a factor of 2.5, assuming that no steam is present. One way to reduce the pressure rise would be to use coupled volumes. The diluent gas would be contained either in an adjoining building or in large gas bags within containment. During an accident, the volumes would be connected, and diluent gas and air would mix with a much lower or negligible pressure rise.

Post-accident Halon injection would raise the pressure by less than a factor of 2. However, Halon may decompose either chemically, thermally, or radiolytically to produce HF and HBr acids, and these products would have to be dealt with.

2.4.5 Partial Pre-Inerting

Deliberate ignition or post-accident inerting may be coupled with partial pre-inerting. A partially inerted containment would contain 14-15% oxygen, which would allow personnel to work without additional life-support systems. For deliberate ignition schemes, partial pre-inerting would mean fewer burns before the oxygen is depleted and probably less energetic burns. For post-accident inerting, partial pre-inerting would provide a significant head start and reduce the time required to achieve an inerted condition.

2.4.6 High-Point-Vent Flaring

High-point-vent flaring allows the controlled burning of hydrogen as it exits the primary system. This technique is most useful in situations where hydrogen is collecting at specific points within the primary system and can be released in a controlled manner. The method essentially involves combustion of a steam:hydrogen jet, subject to the constraints discussed earlier. The vents should be configured such that safety-related equipment is not damaged during the flaring. This method should not be thought of as a panacea, as it will do little good in accidents involving large pipe breaks or stuck-open relief valves at random locations. Another system would be required to deal with these events. However, whenever possible, high-point-vent flaring, should provide a benign way of burning hydrogen.

2.4.7 Other Methods

Other methods, such as filtered venting, augmented cooling, or strengthened containments, may be considered if none of the methods described above appear adequate. However, it may be difficult to design vents that can handle the rapid transients involved, and augumented cooling or strengthened containments can be very expensive to implement. Additional research into mitigation schemes will be performed during the next few years. It is to be expected that different schemes will be proposed for different types of reactors, depending upon containment size and likely accident scenarios.

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Chapter 3

HYDROGEN BEHAVIOR AND CONTROL -- NORMAL OPERATION

3.1 INTRODUCTION

Chapter 2 discussed the processes and mechanisms whereby hydrogen can be produced in and dispersed throughout a light water reactor plant. It also included sections on the conditions necessary for and consequences of hydrogen combustion (or deflagration) and detonation. This chapter will discuss the behavior and control of hydrogen during normal plant operation - i.e., the specific locations at which hydrogen can be found, the problems that this hydrogen can cause, and the ways in which it can be controlled.

Hydrogen can be found in both PWRs and BWRs during normal operating conditions; its presence is not necessarily a cause for concern. To properly judge whether its presence in a particular location or at a particular concentration is unusual or undesirable requires an understanding of its role during routine conditions. That role will be examined thoroughly in this chapter.

The next section concerns hydrogen considerations common to PWRs and BWRs. Subsequent sections discuss considerations that are characteristic of one type of plant. Throughout the chapter, examples are presented based on experience at various individual plants. Readers must intepret for themselves how these examples can be related to any other plant.

3.2 HYDROGEN CONSIDERATIONS COMMON TO PWRs AND BWRs

There are major differences in some of the systems associated with PWRs and BWRs. However, from a hydrogen standpoint there are many aspects which are common to both types of plants. The objective of this section is to discuss these common considerations.

3.2.1 Radiolysis

A significant source of hydrogen and oxygen gas production during operation of a nuclear power plant is the dissociation of water when exposed to radiation. This process is known as radiolytic decomposition, or radiolysis.

As discussed in detail in section 2.1.4, radiolysis occurs when a water molecule absorbs energy in an interaction with radiation. This radiation can come from numerous different sources -- the most notable of which are products of the fission process, including neutrons, electrons, x-rays, gamma rays, protons, deuterons, helium ions, and recoil fragments. The single most important mechanism for radiolytic decomposition is dissociation initiated by proton recoils.[3-1] (These protons and hydrogen nuclei result from previous neutron interactions with the water molecules.)

The initial stages of radiolysis involve the excitation of the water molecule, and its subsequent dissociation into hydrogen and hydroxyl radicals. This is shown in Eq. (3-1) and (3-2):

$$H_2O + \text{excitation energy} \longrightarrow H_2O^* \text{ (*denotes an excited state)} \qquad (3\text{-}1)$$

$$H_2O^* \longrightarrow H^+ + OH^- \qquad (3\text{-}2)$$

An ionizing particle, in its path through the water, leaves behind a track of "spurs" or energy-rich zones. These spurs are clusters of free radicals where molecules dissociate in a short time in relation to that required for appreciable diffusion.[3-2] Once the H^+ and OH^- radicals have been liberated, two things can happen: they can react with each other immediately, or they can diffuse into the solution, where they may react with each other or with other molecules in the solution. A variety of products may be formed by these reactions, including hydrogen peroxide (H_2O_2). Although oxygen gas is not a direct product of radiolysis, it is produced by the decomposition of hydrogen peroxide.

The high radiation level in the reactor core causes the dissociation of the coolant at a very rapid rate. However, the radicals formed by this dissociation tend to recombine with each other quickly to form water; hence, the net effect is actually small.

3.2.2 Radiation Synthesis

Another process that occurs in the reactor coolant and yields undesirable by-products is radiation synthesis. Radiation synthesis reactions involve nitrogen. Nitrogen can be introduced into the coolant by air in-leakage into unpressurized auxiliary systems or into systems or components which are open during refueling or maintenance outages. (For example, in PWRs, the pressurizer is inerted with a nitrogen blanket during plant outages.)

Nitrogen gas can also be produced in the coolant by the following oxygen-hydrazine reaction:

$$O_2 + N_2H_4 \rightarrow 2H_2O + N_2 \qquad (3\text{-}3)$$

In an operating reactor, several reactions can occur involving excess nitrogen. If excess hydrogen is present, ammonia can be formed by the following reaction:

$$3H_2 + N_2 \rightleftarrows 2NH_3 \qquad (3\text{-}4)$$

The ammonia increases the pH and conductivity of the coolant, but is removed by the ion exchangers. The most adverse effect of ammonia is that it tends to exhaust the cation resins of the mixed-bed ion exchangers prematurely.

If excess oxygen is present, the formation of nitric acid could result:

$$2N_2 + 5O_2 + 2H_2O \rightleftarrows 4HNO_3 \qquad (3\text{-}5)$$

The production of nitric acid decreases the pH of the coolant and accelerates the corrosion of metals. In the absence of either excess hydrogen or excess oxygen, ammonium nitrate is formed.

$$NH_3 + HNO_3 \rightleftarrows NH_4NO_3 \qquad (3\text{-}6)$$

Ammonium nitrate is slightly acidic and lowers the coolant pH, but is present in such small amount that it has little effect.

3.2.3 Control of Hydrogen from Radiolysis and Radiation Synthesis

The problems associated with the products of radiolysis and radiation synthesis are many. If the concentrations of hydrogen and oxygen become too high, combustion may result. Excess oxygen also causes corrosion. Nitrogen reactions with either excess hydrogen or excess oxygen in the coolant also have adverse consequences. For these reasons, methods have been developed for gas control in commercial nuclear power plants.

As previously mentioned, the majority of the dissociated water molecules quickly recombine. In a PWR, the free gas that remains -- being in a closed system -- reaches an operating equilibrium pressure that depends on the nature of the radiation, radiation intensity, coolant temperature, and the presence of various dissolved substances in the water. In general, this steady-state gas pressure increases with radiation intensity, but decreases with elevated temperatures. Many dissolved impurities also cause an increase in steady state pressure. In a PWR, the solution to gas control is quite simple. A pre-determined level of dissolved hydrogen (typically about 25 cm^3/kg) is maintained in the reactor coolant. This tends to promote the recombination of free hydrogen and oxygen by the reaction:

$$2H_2 + O_2 \rightleftarrows 2H_2O \qquad (3\text{-}7)$$

This reaction may be enhanced by the intense gamma radiation present during power operation. In this way, the hydrogen and oxygen content of the coolant can be kept very low. The production of ammonia and nitric acid by radiation synthesis is also retarded.

Gas control in a BWR is somewhat more difficult. The very nature of the BWR as a single-loop power cycle (and, therefore, an open gas system) may preclude the use of dissolved hydrogen as a means of oxygen control. In a BWR, the product species are continually being removed, and the system cannot reach a state of equilibrium. For this reason, gas is continuously being produced, causing volumes of gas that far exceed those produced in PWRs. Experiments have shown representative figures for BWR gas production from beta and gamma radiation to be approximately 22 molecules of oxygen and 44 molecules of hydrogen per 10,000 eV of radiation energy.[3-1,3-5]

The gases produced in the core of a BWR are swept up with the steam through the moisture separators and steam dryers and into the turbines. As the steam loses thermal energy and condenses, the hydrogen, oxygen, and other noncondensable gases move straight through to the main condenser in gaseous form. From there, the steam jet air ejectors move the noncondensable gases into the plant's Off-Gas System. (This system is described in detail elsewhere in this chapter.) The primary device for hydrogen and oxygen control in a BWR is the recombiner. In it, hydrogen and oxygen gas recombine to form water in the presence of high heat and a platinum or palladium catalyst. Again, the hydrogen content is the limiting factor, and the reaction continues until the hydrogen is exhausted. A BWR produces a tremendous amount of gaseous waste. Approximately 100-150 SCFM of waste gas, about 90% of which is hydrogen and oxygen, is generated. One result of the large volumes of gas that must be handled is that commercial BWRs have occasionally had hydrogen combustion in the Off-Gas System. This will be discussed in detail in a later section.

In summary, water exposed to the high radiation levels in a nuclear reactor decomposes by a process called radiolysis. Although most molecules quickly recombine to form water, some remain in the water as dissolved hydrogen and oxygen. Generally, the presence of neutrons (especially high-energy neutrons) promotes the dissociation of water molecules, while gamma rays tend to aid in their recombination. Hydrogen and oxygen gases are undesirable because of their adverse effects on reactor performance, (see sections 3.2.4 and 3.3.1) both alone and in combination with nitrogen. For this reason, suppression is the primary goal of gas control in nuclear reactors. PWRs and BWRs, because of their fundamentally different designs, require different methods of gas controls. Control is easily accomplished in a PWR by maintaining a small amount of dissolved hydrogen in the reactor coolant. A BWR must employ recombiners with an extensive Off-Gas System.

3.2.4 Corrosion

At various times, hydrogen or oxygen can be present in the Reactor Coolant System of a nuclear plant, as was mentioned in section 3.2.1. Both gases affect the rate of general corrosion. In addition, hydrogen is a product of some corrosion processes. A thorough understanding of these facts requires a sound knowledge of how and why corrosion occurs, which is discussed in this section.[3-6]

Obviously, corrosion in any system is undesirable since it weakens the structure and can cause eventual failure. Most of the materials employed in the Reactor Coolant System will corrode in pure water at operating temperature. The practical utility of these materials depends on the development of protective films of corrosion products that slow down the rate of attack to values that give useful lifetimes for the materials. In addition to the general or uniform type of attack, most materials are susceptible to one or more of a variety of local forms of corrosion, such as pitting, cracking, and galvanic and crevice corrosion. These local forms of corrosion are usually caused by a specific component or impurity in the water or the mechanical arrangement of the component.

Once the tightly adherent protective film mentioned above has formed, very little general corrosion will occur in a Reactor Coolant System. Therefore, general corrosion is of little significance from the standpoint of failure of any of the metal components. However, it is important from a water purity and general cleanliness standpoint. This is because any of the corrosion products that become suspended in the coolant can eventually become activated, which would contribute to increased radiation levels.

These suspended corrosion products are in the form of a finely divided material called CRUD. The slurry of CRUD is unstable in the sense that the solids will settle out in areas of low water velocity. These areas then become the source of considerable quantities of radioactivity, causing difficulties in repair and maintenance.

In addition, it has been found that these suspended solids tend to precipitate on areas with a high heat or radiation flux. This means that the surfaces of the fuel elements may become covered with deposits of corrosion products. These deposits reduce the heat transfer efficiency and increase the internal temperature of the fuel.

The rate at which general corrosion occurs is dependent upon several controllable factors, including:

- Oxygen content of the coolant
- Hydrogen content of the coolant
- Coolant pH
- Coolant temperature
- Presence of corrosion inhibitors

The major concern of this manual is with the first two factors. Therefore, only these two will be discussed in detail. However, before proceeding with this discussion, the factors will be mentioned briefly:

- Oxygen content of the water -- The oxygen content must be kept as low as possible in order to minimize corrosion (generally below about 0.1 ppm in PWRs). This is done by using deaerated makeup water, maintaining an excess of dissolved hydrogen in the water to combine with the oxygen, or adding oxygen scavengers such as hydrazine (N_2H_4). (Hydrazine is usually added to the reactor coolant only during startup. This is because hydrogen is ineffective at removing oxygen when there is no flux field, which is the condition existing prior to startup.)
- Hydrogen content of the water -- Dissolved hydrogen in water is a weak corrosion inhibitor, but its major effect is the reduction of the oxygen content by the recombination reaction. This reaction requires a radiation field to be effective.
- pH -- The corrosion rate for most metals in water with a pH above 7 is considerably less than in that with a pH of 7 or below. Furthermore the corrosion products seem to form a more adherent film at a high pH.
- Temperature -- In general, as temperature is increased the corrosion rate increases and the protective film of corrosion products becomes less adherent.

- Inhibitors -- Corrosion inhibitors are used to reduce corrosion in relatively low temperature systems. For example, some Component Cooling Water (CCW) Systems contain potassium chromate for corrosion control. Potassium chromate produces an insoluble chromate film on the surface of the metal, which reduces the corrosion reaction rate. Corrosion inhibitors such as potassium chromate are not effective in the Reactor Coolant System since they decompose under conditions of high temperature and strong radiation flux.

For a PWR or BWR with a reactor coolant temperature above 500°F, water tends to break down into hydrogen and oxygen due to radiolysis. (A detailed explanation of the radiolysis process was presented in Chapter 2.)

In an effort to promote a hydrogen and oxygen recombination probability, PWR facilities maintain a certain level of dissolved hydrogen in the Reactor Coolant System. Typically, this is 25-35 cm^3 of hydrogen per kg of reactor coolant. Hydrogen addition to the Reactor Coolant System is not done in BWRs. Since boiling occurs continuously in a BWR, continuous hydrogen addition would be necessary to maintain an inventory in the coolant. Such a process is impractical.

The hydrogen is introduced into the PWR Chemical and Volume Control System (CVCS) in the volume control tank (VCT).* Figure 3-1 shows the letdown and charging sections, including the volume control tank, of the CVCS for the Zion Nuclear Plant, which is a Westinghouse 4-loop PWR.

In a PWR, water from one of the RCS cold legs is let down (i.e., drained or bled off) (about 70 gpm) through a purification flow path through heat exchangers, demineralizers, and filters in an effort to continually process a portion of the reactor coolant water. This purification flow path then goes to the VCT. At this tank hydrogen is added to the reactor coolant water during normal plant operation to help scavenge any oxygen present. The VCT also provides the pressure necessary for the charging pumps, which pump the water back to one of the cold legs of the RCS.

Typically, a hydrogen overpressure of about 15-20 psig (100-140 kPa) in the vapor space of the VCT will serve to maintain about 25-35 cm^3/kg of hydrogen in the reactor coolant. The hydrogen will combine with the excess oxygen to form water, greatly reducing the amount of oxygen in the reactor coolant, and, hence, the amount of corrosion that occurs.

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* In general, this tank is referred to as the volume control tank for Westinghouse and Combustion Engineering plants, and as the make-up tank for Babcock and Wilcox plants. However, other names may be employed by individual plants. For example, at Duke Power Company's Oconee Nuclear Station it is called the letdown storage tank.

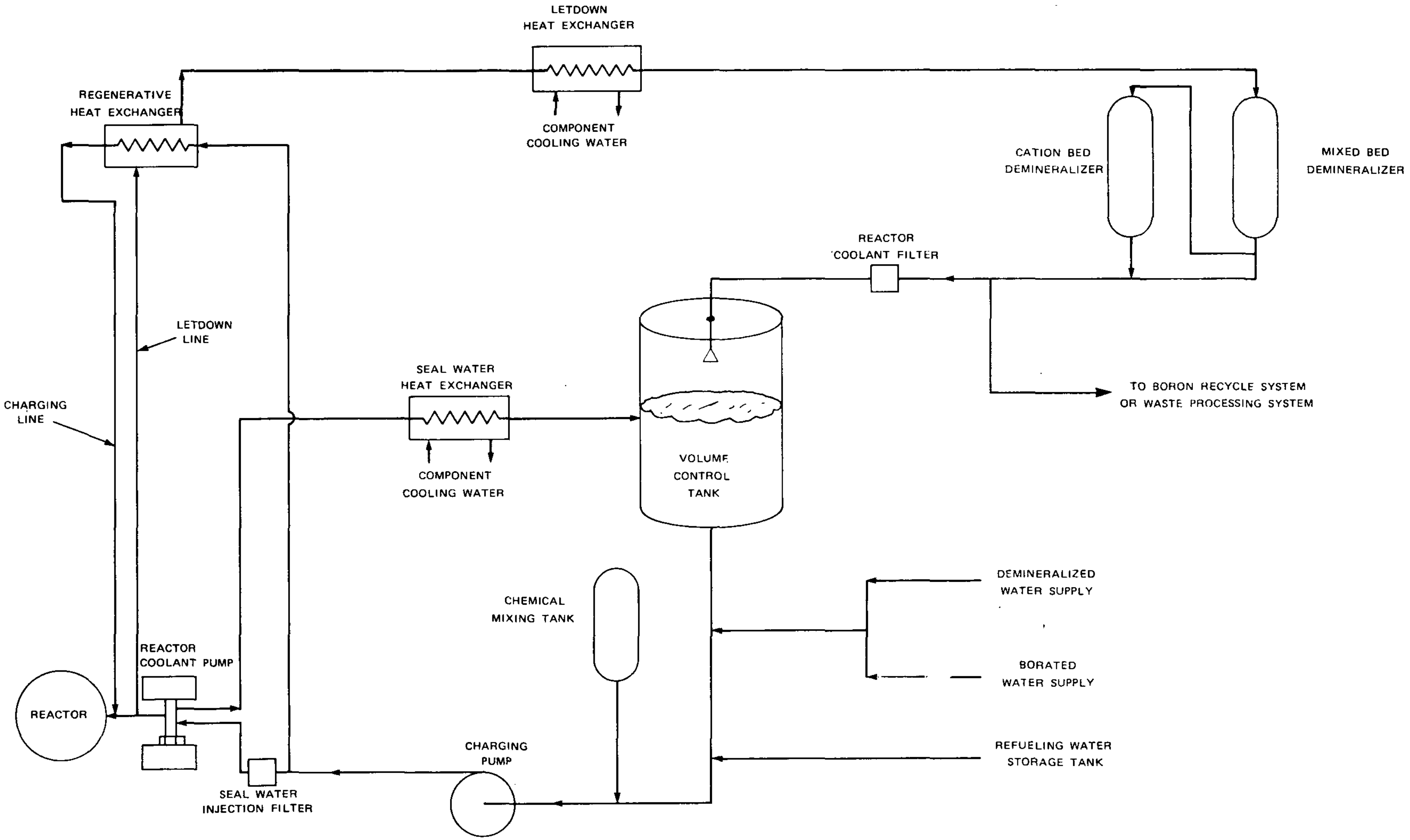

Figure 3-1. Chemical and Volume Control System

3.2.5 Electrical Generators

The electrical generator in a nuclear power station converts the rotational energy supplied by the turbine into electrical energy for commercial distribution. The generator consists of three major parts:

- The frame
- The stator
- The rotor

Figure 3-2 shows the general arrangement of a typical generator assembly.[3-7]

The generator frame supports and houses the stator core and windings and the generator rotor, and provides multiple flow paths through the generator for the hydrogen cooling gas. The frame is a casing constructed of welded steel plates. It provides an air-tight enclosure for the stator and rotor. The hydrogen coolers are mounted above the stator core in the top of the generator.

Current produced in the generator results in a significant amount of heat being developed during operation. Efficient operation necessitates dissipating this heat by cooling the generator. It is cooled by pure hydrogen pressurized to about 75 psig (500 kPa). Hydrogen was chosen as the cooling medium because it is noncorrosive and nonconductive, and has a high thermal conductivity. Also, its low density minimizes windage heating. The hydrogen is maintained in a high state of purity to prevent combustible or detonable mixtures of air and hydrogen from accumulating, and to provide the proper coefficient of heat transfer.[3-8]

Hydrogen is circulated through the interior of the generator by a blower mounted on the turbine end of the generator shaft. The generator rotor and rotor windings are ported to allow cooling gas flow. Cooling gas flow through the stator core is accomplished by spacing the core laminations intermittently with spacer blocks. Coolers mounted on the top of the generator remove the heat absorbed by the hydrogen.

Since the generator is cooled with hydrogen, which is combustible, the generator casing must be an airtight, leak-proof enclosure to prevent hydrogen leakage to the atmosphere. A shaft sealing arrangement is provided where the rotor shaft penetrates the generator casing. This seal provides a double barrier to atmosphere for the hydrogen. Figure 3-3 shows a typical shaft seal and seal oil arrangement.

In addition to preventing hydrogen leakage to the atmosphere, the shaft seal also minimizes contamination of the hydrogen with air, moisture, or oil vapor. To accomplish these purposes the seal is constructed with a dual sealing arrangement with two sources of seal oil.

Two potential problems can exist with the generator hydrogen cooling system:[3-9]

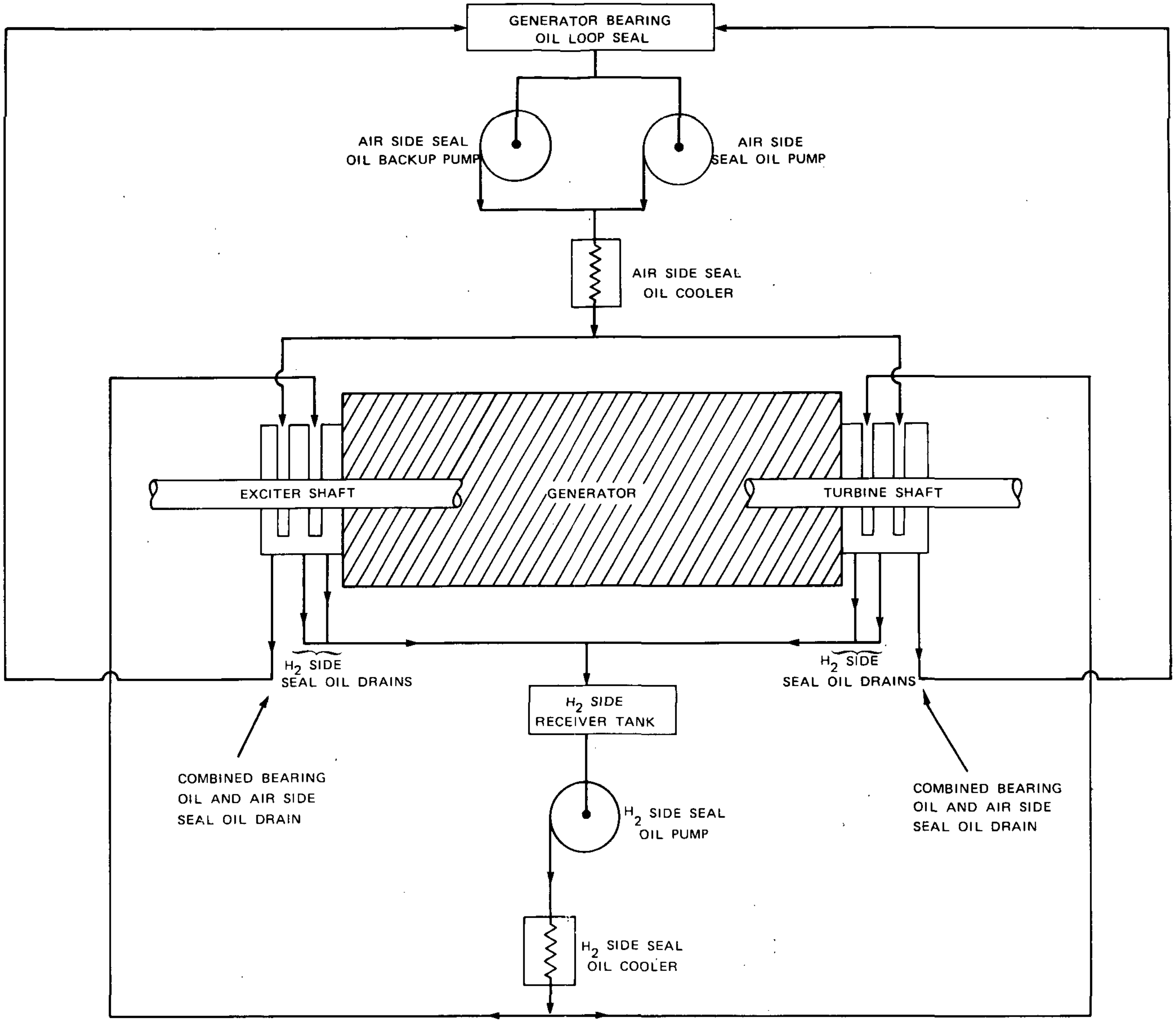

Figure 3-2. General Arrangement of a Typical Generator Assembly

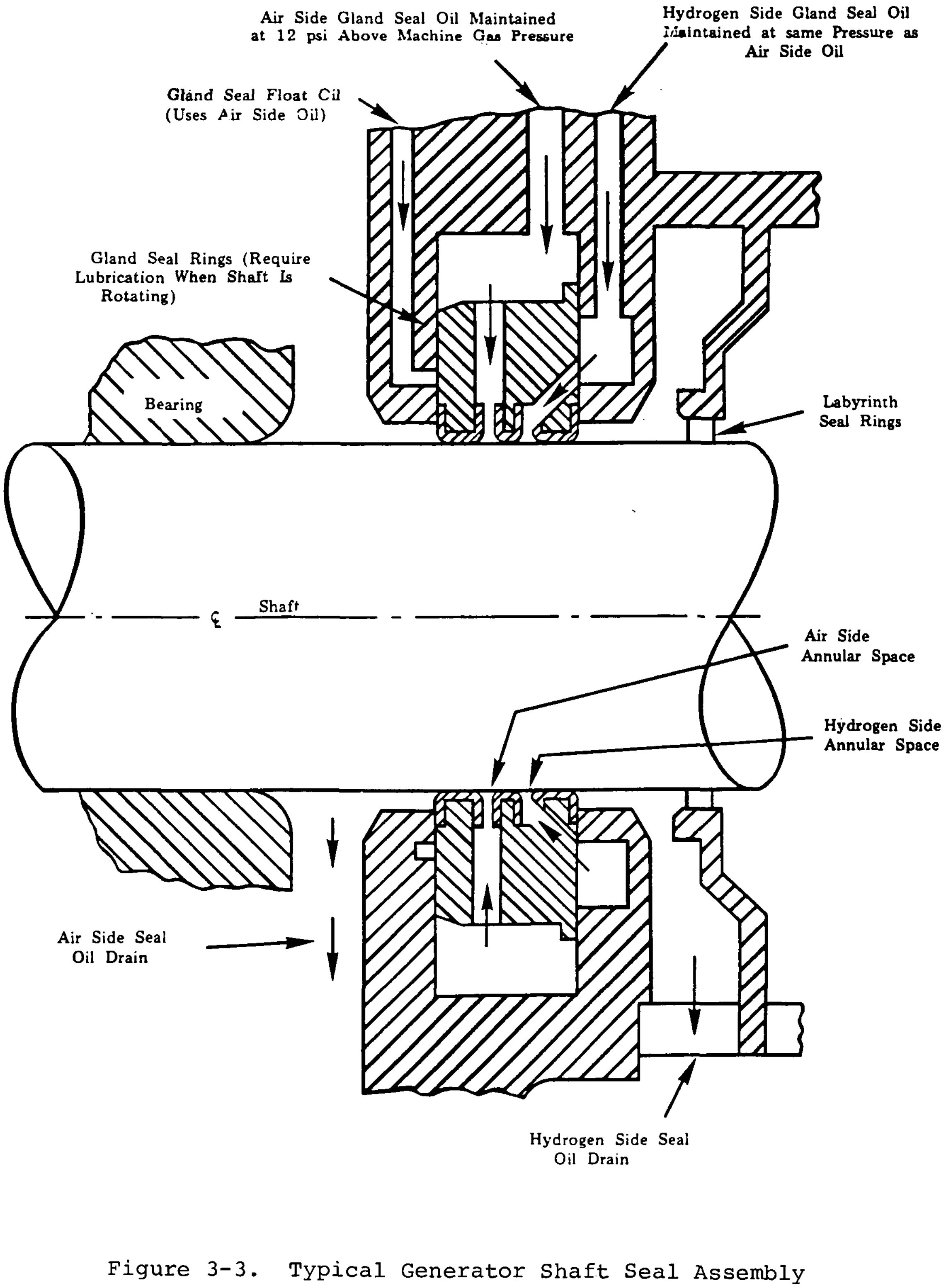

Figure 3-3. Typical Generator Shaft Seal Assembly

- Hydrogen leakage from the bulk storage facility supplying the electrical generator or from the generator itself could cause a combustible mixture to be formed in air. At one plant* where such an event occurred, hydrogen leaked from the generator's cooling system, through the seals, to the exciter area. Ignition of the hydrogen occurred, causing structural damage and one personnel injury.[3-10]
- Hydrogen can become entrained in the seal oil used for the generator. It can come out of solution where it is vented to atmosphere from the oil reservoir. One facility** had a fire in the vent stack of the roof of the turbine building. Apparently, the fire was caused by a combustible mixture of hydrogen being released through the stack.

The purity of the gas in the electrical generator is determined by a hydrogen-purity-indicating transmitter and purity-meter blower, which are normally located in a hydrogen control panel. Typically, two switch assemblies are provided with the purity-indicating transmitter. The switch assemblies are set to produce a "hydrogen purity high or low" alarm on the hydrogen control panel. Normally, the high limit is set at about 100% and the low limit at 90%.

3.2.6 Hydrogen Bulk Storage Facility

Bulk hydrogen storage is required at nuclear generating stations because hydrogen is used for the following purposes:

- Internal cooling of the electrical generator (BWRs and PWRs).
- It is added to and maintained in solution in the RCS to scavenge oxygen and thereby reduce the rate of general corrosion (PWRs only).
- Testing of some types of hydrogen recombiners (BWRs and PWRs).

Various arrangements are used at different facilities. Each arrangement typically consists of the following components:

- Hydrogen tube trailers
- Hydrogen storage tanks
- Hydrogen storage bottles

Fill stanchions are used to hook the hydrogen tube trailers to a hydrogen control cabinet. Grounding wire connections are provided for both the fill stanchion and the hydrogen tube trailers. The grounding wires run to a copper

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* Palisades Nuclear Power Station, which is a PWR in South Haven, Michigan, operated by Consumers Power Company. This event occurred on February 4, 1982.

** Zion Nuclear Plant, a PWR in Zion, Illinois, that is operated by Commonwealth Edison Company. The fire occurred during the summer of 1977.

grounding rod located away from the bulk hydrogen storage facility. These wires are intended to reduce the possibility of a hydrogen ignition due to a static electricity spark.

Hydrogen header pressure is typically in the range of 100 to 150 psig (0.7 to 1.0 MPa). The header is protected from overpressure by a relief valve. If the relief valve were to open, hydrogen and oxygen would come in contact, which could produce a combustible gas mixture. Therefore, the relief valve is fitted with a flame arrester.

3.2.7 Gas Chromatography

A gas chromatograph (GC) is an apparatus that can be used to analyze a gas sample for various constituents, such as hydrogen, oxygen, nitrogen, carbon monoxide, and carbon dioxide. At a nuclear power station, gas chromatographs may be used in two locations:

- As part of the Gaseous Radioactive Waste System
- As part of a High Radiation Sampling System (HRSS)* to sample the containment atmosphere

In a radioactive waste system the chromatograph determines hydrogen and oxygen content in the cover gases of various reactor plant tanks. When used as part of a High Radiation Sampling System, it:

- Determines the presence of selected gases in the containment during routine plant operation
- Provides backup hydrogen determination in a post-accident mode
- Determines the containment atmosphere conditions prior to personnel entry[3-11]

Hydrogen is employed in a gas chromatograph for two purposes:

- As a calibration gas to check the accuracy of the hydrogen analyzer portion of the unit
- As a carrier gas when sampling the containment for carbon monoxide

No serious problems have been recorded regarding the use of this type of gas analyzer at the time of this writing. It does, however, contain a hydrogen source, which, if not carefully controlled and operated, could create a combustible gas concern.

3.2.8 Battery Room

Another potential problem area involving the generation of hydrogen in a nuclear power plant is the battery room. A plant is typically equipped with 250 VDC and 125 VDC battery systems. Typically, the 250 VDC system consists of two banks of 120 lead-calcium storage cells, and the 125 VDC system contains four banks of 60 cells. Each bank is mounted in two rows of battery racks and located in its own battery room.[3-12]

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* Commonwealth Edison Company is installing such a system in each of its plants.

During operation, as the batteries change chemical energy to electrical energy, the sulfuric acid content of the electrolyte becomes depleted. Therefore, the batteries must be recharged if they are to be used continuously. This is done by connecting a DC charging source so that current will flow through the battery in the opposite direction, driving the acid back into the electrolyte. The by-products of this charging process, or electrolysis, can present a potential problem. As a cell becomes nearly charged, the charging current becomes greater than that necessary to force the remaining amount of sulfuric acid back into the electrolyte. This results in ionization of the water in the electrolyte, causing hydrogen gas to be liberated at the negative plate of the battery and oxygen gas to be liberated at the positive plate. Although the release of these gases is undesirable, the process is necessary to develop a full charge in the cell.[3-13]

Several simple, but extremely important methods are used to prevent hydrogen combustion in the battery rooms. First, the rooms are well-ventilated to prevent excessive hydrogen buildup. The battery room ventilation system typically limits hydrogen concentration to less than 2% of the total volume of the room and maintains a constant temperature of 77°F. The air flow rate is approximately ten air changes per hour. As an additional precaution, no open flame or smoking is allowed in the proximity of the battery room. Also, any work in the room must be performed with nonsparking tools made of brass, aluminum, or wood.[3-14]

To date there have been no major accidents involving hydrogen gas in the battery rooms at nuclear plants. However, extreme care must continue to be exercised to ensure the safe operation of this potentially hazardous system.

3.2.9 Resin Beds

In 1975, hydrogen combustion occurred in the acid day tank of the condensate demineralizer regeneration system at a BWR facility. The hydrogen was formed when moisture from the atmosphere interacted with concentrated sulfuric acid in the tank because of the depletion of the desiccant in the vent line. It is believed that combustion was caused by a spark from a nearby welding operation. The resultant ignition blew the top off the day tank and broke the vent and fill piping. As a result of this event, acid was deposited on nearby equipment, cable trays, and the floor.[3-15]

3.3 HYDROGEN CONSIDERATIONS SPECIFIC TO PWRS

The objective of this section is to discuss hydrogen concerns that are pertinent to pressurized water reactors but that, due to differences in plant design, are not directly applicable to boiling water reactors.

3.3.1 Reactor Coolant System

3.3.1.1 Pressurizer. During normal operating conditions, the pressurizer is approximately 50% full of water;* the remaining space is occupied by the steam bubble. Noncondensable gases contained in the Reactor Coolant System will tend to collect in the pressurizer steam space. Hydrogen is one of these noncondensable gases.

The pressurizer is designed to compensate for pressure transients and maintain constant system pressure. During a pressurizer outsurge (pressure decrease), electric immersion heaters in the bottom of the pressurizer are energized to convert more of the water to steam and thereby increase the pressure. In the case of a pressurizer insurge (pressure increase), a spray nozzle at the top of the vessel is activated. The cool spray condenses some of the steam, causing a reduction in system pressure. If the pressure increases to a level beyond that which can be suppressed by the pressurizer spray, power-operated relief valves (PORVs) are opened (automatically or by remote control), allowing steam to flow out of the pressurizer. This steam is piped to a pressurizer relief tank (PRT) where it is condensed. Should neither the spray nor the relief valves be sufficient to suppress the over-pressure conditions, self-actuating code safety valves will open to release the excess steam.** The presence of noncondensable gases, such as hydrogen, in the pressurizer vapor space affects the response of the pressurizer to level changes. Since hydrogen is added to the reactor coolant to scavenge oxygen and nitrogen and to help control the radiolytic decomposition of water, it can be found in the pressurizer vapor space under normal circumstances. The amount of hydrogen in the vapor space will depend upon many factors including:

- RCS hydrogen concentration
- Hydrogen addition frequency
- Spray usage
- Noncondensable gas removal rate

The solubility of a gas in water depends on:

- Temperature. At a given pressure and temperature above about 500°F (260°C), a gas will generally become less soluble as the temperature increases; at lower temperatures the reverse may be true (see section 2.2).

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* The actual percentage will vary from plant to plant. In addition, for plant's with programmed pressurizer levels, this percentage will be less at lower power levels.

** Lifting of the spring-loaded code safety valves reduces RCS pressure by reducing the water and gas inventory in the system. At one time some plants used this method to help prevent actuation of a high-pressure reactor trip during a transient. However, following the TMI-2 incident the NRC mandated that plants implement procedures to assure the reduction of the likelihood of automatic actuation of the pressurizer PORV during anticipated transients.[3-16] Thus, this method is no longer used, and lifting of the safety valves during normal operation is considered undesirable.

- Pressure. The hydrogen dissolved is linearly proportional to the partial pressure.

The pressurizer is the region of highest temperature in the RCS, and it has a large free water surface. Hydrogen can be expected to leave the water volume in the pressurizer until the partial pressure of hydrogen is sufficient to inhibit further release. At that point the concentrations of hydrogen in the water and in the steam will remain in equilibrium until conditions change.

Normal insurges and outsurges will not significantly alter the total hydrogen content of the pressurizer since the mass changes are small. The use of sprays, however, will cause large increases in hydrogen content. Spray water is relatively hydrogen-rich and, as it enters the pressurizer, it breaks into small drops and its surface area increases. The spray is rapidly heated by the steam and, at the same time, it reduces the pressurizer pressure. All of these conditions (the sudden drop in pressure, the sudden heating of a hydrogen-rich liquid, and the sudden increase in free-surface area) will promote the release of dissolved hydrogen. The total hydrogen content of the pressurizer will increase and a new equilibrium condition will result. In this new condition, more hydrogen will be contained in the vapor space.

If the hydrogen content of the vapor space increases sufficiently, it will result in what is called the "hard bubble phenomenon." This phenomenon occurs when the percentage of hydrogen (and other noncondensable gases) in the pressurizer vapor space is so large that the system reacts almost as if it were solid (i.e., as if no vapor space existed).

Sandia National Laboratories has proposed a simple rule of thumb that can be used to diagnose the presence of a hard bubble: If the pressure is greater than the saturation pressure plus 60 psig, a hard bubble exists. (The 60 psig factor is to account for the hydrogen normally present.)

The presence of a hard bubble may not be readily apparent from pressurizer behavior. Consider the following situations:

- If an insurge occurs when a hard bubble does not exist, it will result in an initial increase in pressure. This pressure increase will increase the solubility of the gas in the vapor space (solubility and pressure are directly proportional), thus forcing more of the gas into solution in the water. If the insurge is large enough, pressurizer spray will be actuated to limit the size of the pressure increase. The final result will be a new equilibrium pressure for which the pressure is close to the initial pressure prior to the insurge.
- If an insurge occurs when a hard bubble is present, it will again result in an initial increase in pressure. As in the case when no hard bubble exists, the pressure increase will force more gas into solution, and, if the increase is of sufficient magnitude, it will result in spray initiation. However, the spray will not reduce pressure because the pressure vapor space contains too large a percentage of noncondensables (recall that this was the definition

of a hard bubble). In this case the new equilibrium pressure will be higher than the initial pressure. How much higher it is will depend upon the magnitude of the insurge, and will determine whether the operator will notice any abnormality. For small insurges such as are encountered during normal operating conditions, the difference between the final and initial pressures may be small enough that the operator will not recognize the existence of the hard bubble. For a large insurge, the operator would see a rapid and large increase in pressure.

Similar conditions could be described for an outsurge.

The point to remember is that when a hard bubble is present, rapid level changes are accompanied by pressure changes that are more rapid than normal -- something the operator may not be expecting.

There are subtle indications available to the operator that will show the formation of a hard bubble before a large transient occurs. These indications include trends that may not be normally noticed. For example:

- A slow, steady decrease in RCS hydrogen concentration, accompanied by increased additions
- Frequent use of pressurizer spray, for whatever reason, raising pressurizer hydrogen content
- Slower than normal response to normal level changes, i.e., pressure taking longer than normal to stabilize
- Pressure greater than the saturation pressure corresponding to pressurizer liquid temperature

The best indication would be, of course, to sample the pressurizer vapor space for hydrogen. However, currently this is not usually done.

3.3.1.2 <u>Control Rod Drive Mechanisms</u>. One consideration to be examined when adding hydrogen to the RCS is the possibility of control rod drive mechanism (CRDM) damage due to the presence of excessive noncondensable gases collecting in the reactor vessel head region. At concentrations of 100 cm^3/kg or more, is is possible for noncondensable gases to come out of solution and collect in the CRDM housings. This can cause the hydraulic buffer to function improperly during a reactor trip (reactor scram). Figure 3-4 shows a simplified sketch of a Babcock and Wilcox CRDM.[3-17] Note that the approximate damaging concentration of gas (100 cm^3/kg) is not the maximum allowable dissolved hydrogen concentration, but the concentration of <u>all</u> noncondensable gases in the reactor coolant. It is estimated that approximately 60 cm^3/kg of additional noncondensable gases (mostly xenon and krypton) are introduced into the RCS during operation. For this reason, some stations have placed limitations of about 40 cm^3/kg on the amount of hydrogen added to the system. Although the only plant* that has confirmed the need for such a limitation is a Babcock and Wilcox facility,[3-18] a simlilar concern may also exist for Combustion Engineering and Westinghouse PWRs. If it does exist, similar limitations may be needed for these plants.

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* Three Mile Island Nuclear Station, in Goldsboro, Pennsylvania, which is operated by Metropolitan Edison Company.

NOTES:

1. The leadscrew is shown in the fully inserted position.
2. Although it is not shown, the upper motor tube extends upward a number of feet to allow for full leadscrew withdrawal.

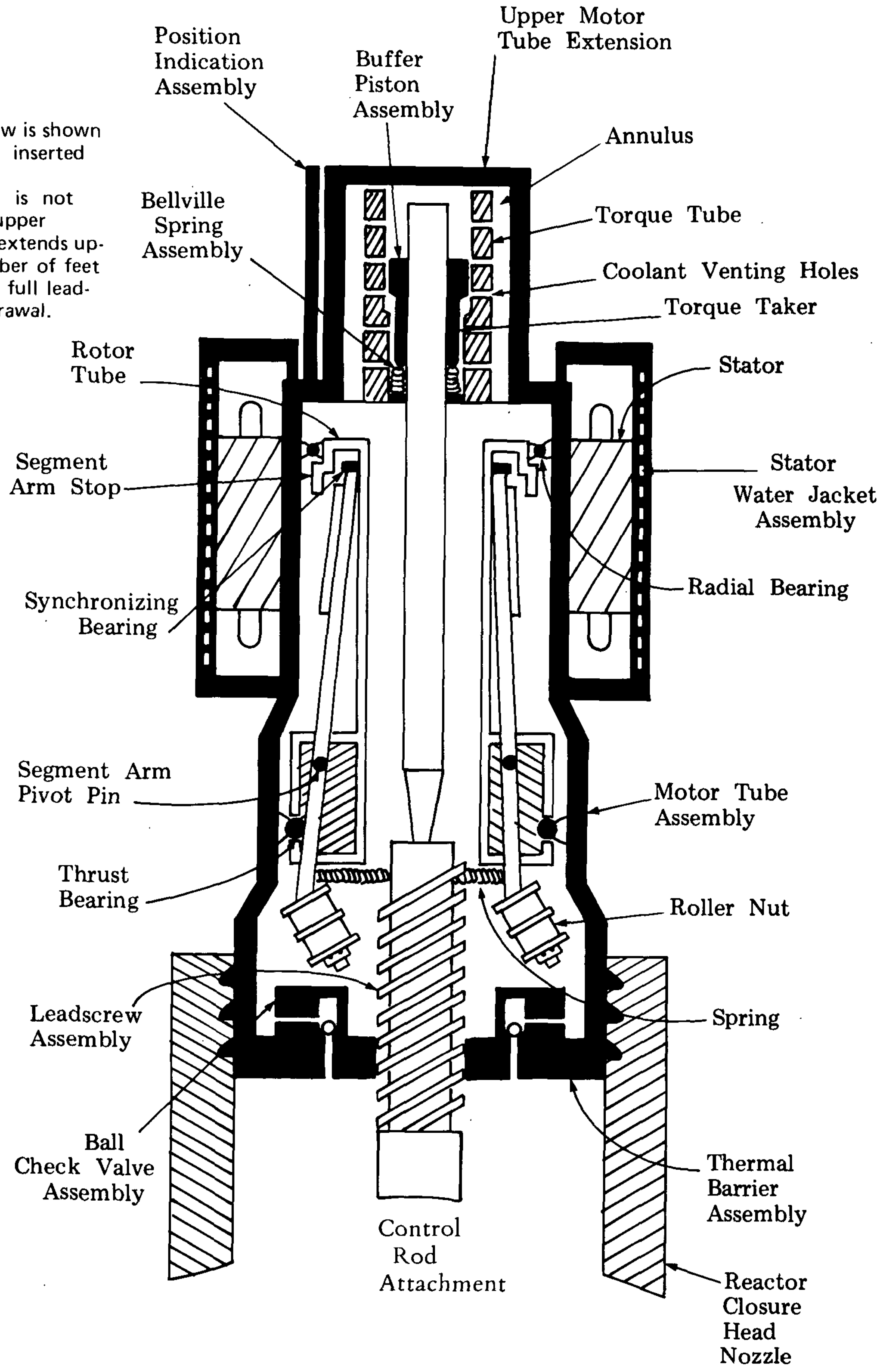

Figure 3-4. Control Rod Drive Mechanism

The control rod drive mechanism is used to raise, lower, and maintain control rod position in response to the signal sent to the control rod drive motor. Figure 3-4 shows the component parts of a CRDM.

During operation, the CRDM is filled with water. In the event of a reactor trip, the lead screw will fall while the buffer piston assembly displaces the water. The water that was originally around the leadscrew, between the torque taker and the torque tube, is forced through the control venting holes in the annulus between the torque tube and the upper motor tube extension. This arrangement cushions or buffers (hence the name) the fall of the control rod. If this water is replaced by noncondensable gases, the buffer piston action would be lost, causing possible damage to the CRDM during a reactor trip. As a result, damage to the CRDM housings could breach the RCS boundary, causing a loss of coolant.

3.3.1.3 RCS Leakage. Typically, 1 gpm of unidentified leakage and a maximum of 10 gpm of identified leakage are allowed according to the technical specifications.[3-19] Assuming an approximate water density of 1 $\mathrm{gm/cm^3}$ and about 35 $\mathrm{cm^3/kg}$ of hydrogen dissolved in the coolant, a leakage rate of 11 gpm from the RCS could result in:

$$11\ \frac{\text{gal}}{\text{min}} \times \frac{1\text{g}}{\text{cm}^3} \times \frac{1\text{kg}}{10^3\text{g}} \times \frac{35\ \text{cm}^3\text{H}_2}{\text{kg}} \times \frac{3785\ \text{cm}^3}{\text{gal}} \times \frac{60\ \text{min}}{\text{h}} \times$$

$$3.531 \times \frac{10^{-5}\ \text{ft}^3}{\text{cm}^3} = \frac{3.1\ \text{ft}^3\ \text{H}_2}{\text{h}}$$

That is, 3.1 $\mathrm{ft^3/hr}$ of hydrogen could be released into containment if the technical specification leakage rate for the RCS were occurring. This is a small rate, and is generally neglected.

3.3.2 Chemical and Volume Control System

The Chemical and Volume Control System (CVCS) at a nuclear reactor facility performs many important functions including:

- Maintenance of a programmed water level in the pressurizer
- Control of water chemistry, activity level, and soluble boric acid concentration (for reactivity control) in the RCS
- Processing reactor coolant to effect recovery and reuse of soluble boric acid and makeup water

Figure 3-1 showed water let down from the RCS being demineralized and filtered within the normal letdown and charging system. During certain plant operations it is necessary to divert a portion of the letdown flow to the holdup tanks (HUTs) where it is stored until it can be processed. A typical HUT can have a capacity of about 120,000 gallons. When nearly filled with RCS letdown water, this same holdup tank could contain about 560 $\mathrm{ft^3}$ of hydrogen.[3-6]

Normally, a small nitrogen overpressure is maintained in the holdup tanks; however, as they are filled, the fractional amount of hydrogen in the HUTs increases. One PWR facility,* for example, actually measured a hydrogen concentration of 8% in one of its tanks.[3-20] Theoretically, the presence of hydrogen in an inerted holdup tank should not create a flammability problem. However, in the process of removing hydrogen from the HUTs, large quantities of water must be shifted from tank to tank in an effort to purge a given HUT of its free hydrogen. (Not carefully venting these tanks with nitrogen during this process could result in a tank's collapsing.)

The purged hydrogen gas must then be vented to the Waste Disposal System (WDS) and be stored in gas decay tanks until it can be discharged from the plant. To avoid the possibility of hydrogen combustion in the vent header system while gas is being displaced from the holdup tanks to the vent header, components discharging to the vent header system are restricted to those containing no air or aerated liquids. The vent header, typically, is operated at a slight positive pressure (approximately 0.5 psig minimum to 2.0 psig maximum) to prevent in-leakage.

3.3.3 Containment Entry

There are three distinct types of PWR containments: large dry, ice condenser, and subatmospheric. Regardless of the type of containment employed, at every PWR facility periodic entry into containment is required. Routine containment entries are made during shutdown periods and during operation. For plants with ice condenser containments, daily entries are necessary because of the technical specification requirement to inspect the doors separating the ice bays from the rest of the containment.

Many requirements must be satisfied before an entry can be made. Some of these requirements are dependent upon the type of facility involved. However, in every case the gas concentrations in the containment atmosphere must be checked. Oxygen content must be sufficient (typically, at least 17%) to ensure a breathable mixture; otherwise, a self-contained breathing apparatus (SCBA) must be used. Hydrogen content must be such as to pose no threat of combustion. During normal conditions such a threat should not exist.

3.3.4 Gaseous Waste Disposal

The Gaseous Radioactive Waste (Radwaste) System in a PWR is designed to collect, hold, and dispose of all potentially radioactive gaseous waste generated by the station. Typically, it is designed with sufficient capacity to store the collected gases for at least 45 days, and to allow for radioactive decay prior to release to the environment. It also provides cover gases (nitrogen and hydrogen) to various holding tanks within the plant, and the means to monitor these gases within the system. Figure 3-5 shows a typical Gaseous Radioactive Waste Disposal System for a PWR.

Prior to each routine refueling shutdown the Reactor Coolant System must be degassed. Degassification is intended to reduce the hydrogen concentration in the RCS to approximately 5 cm^3/kg. During this process the hydrogen supply

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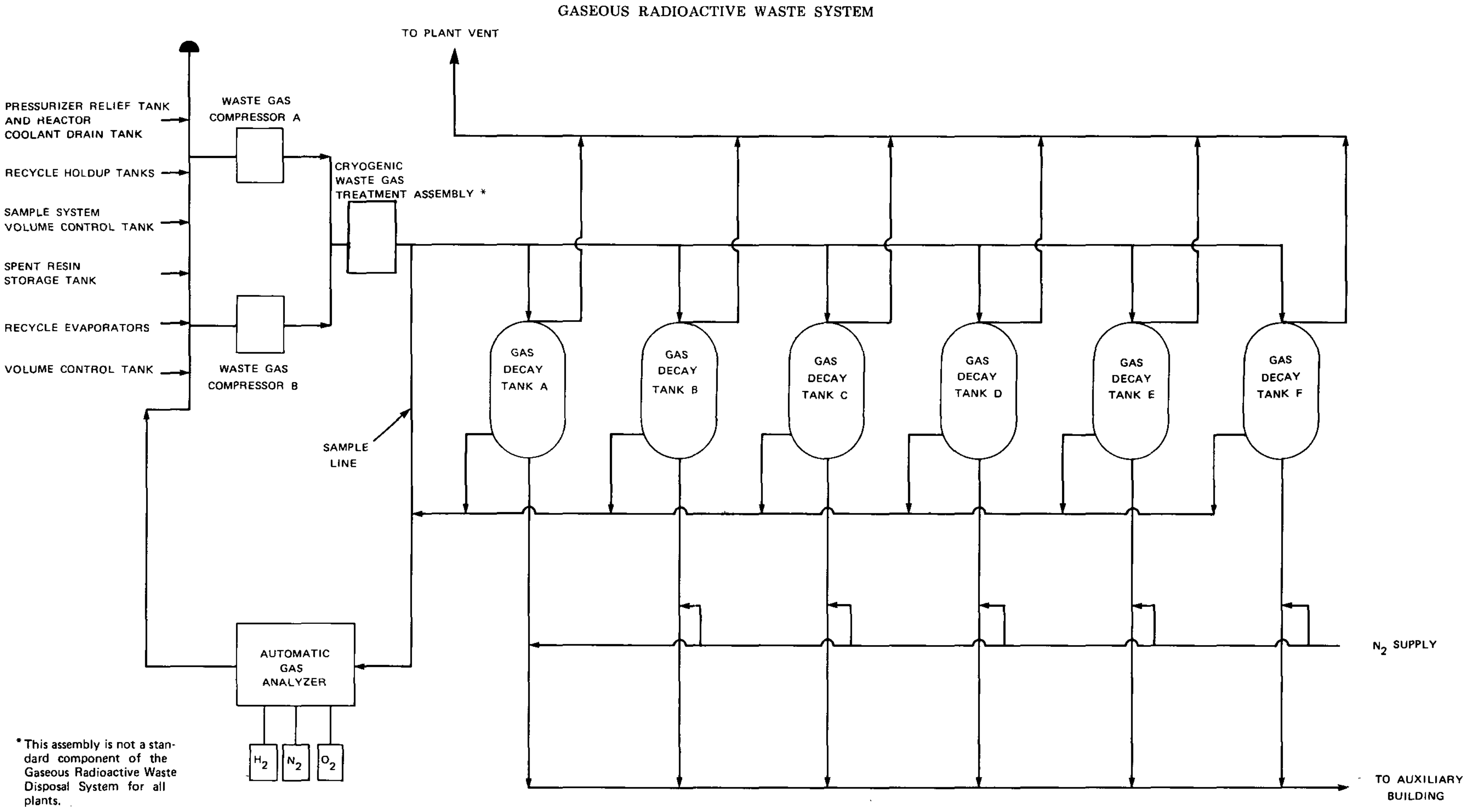
* The Donald C. Cook Plant which is located in Bridgman, Michigan. This plant is operated by Indiana and Michigan Electric Company.



* This assembly is not a standard component of the Gaseous Radioactive Waste Disposal System for all plants.

Figure 3-5. Gaseous Radioactive Waste Disposal System to the CVCS volume control tank (VCT) is secured, and the nitrogen supply to the VCT is placed in service. By using pressurizer sprays and heaters, and opening the power-operated relief valve (PORV), hydrogen can be collected in the pressurizer and subsequently vented. The hydrogen gas is vented through the PORV to the pressurizer relief tank (PRT) and, in turn, from the PRT to the Gaseous Radwaste Disposal System.

The system also contains an automatic gas analyzer that monitors all of the auxiliary system equipment where hydrogen and oxygen content must be controlled. Hydrogen and oxygen content are analyzed automatically to indicate the existence of a combustible mixture.

The tanks in which the gases are held to allow for radioactive decay prior to release are called, appropriately, gas decay tanks. One plant* experienced a hydrogen ignition in one of the gas decay tanks during a cold shutdown. This incident resulted in a release of about 8.8 curies of noble gases and in minor damage to the tank. The hydrogen combustion was made possible by the presence of air contamination in the inert nitrogen system that is used to minimize the oxygen concentration in the tank. (The increasing oxygen concentration was not detected because the gas analyzer in the system was inoperable.) The apparent source of the ignition was the oxygen recombiner in the cryogenic waste gas treatment assembly.**

In this incident, the source of air was instrument air that leaked through check valves at the cross connections between the instrument air and nitrogen lines. Leakage occurred in this direction since, under normal operating conditions, the pressure in the instrument air system is higher than that in the nitrogen system. The nitrogen system provided a backup gas supply to the air-operated steam supply valve for the steam-driven auxiliary feedwater pump. This backup was installed to provide a safety-grade auxiliary feedwater system that would satisfy the single-failure criteria. Other cross connections, which apparently did not leak, had been installed previously to provide a redundant gas supply to the air-operated pressurizer relief valves and the associated block valves.

Following the ignition, all tanks that might have been affected were sampled. It was determined that most of the tanks had oxygen levels above 10%. Generally, the gas in PWR waste gas systems is hydrogen-rich, and the oxygen concentration is controlled to prevent flammable gas mixtures. Flammable concentrations of gas mixtures can be avoided by limiting either the hydrogen or the oxygen concentration to less than the minimum combustibility limits discussed in Chapter 2.

To eliminate the possibility of recurrence at this plant, those portions of the nitrogen system that are a backup supply to the air system have been

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* This incident occurred in July 1981, at San Onofre Nuclear Generating Station Unit 1. This plant is operated by Southern California Edison Company. It is located near San Clemente, California.

** Not all PWR facilities employ a cryogenic waste gas treatment assembly as part of the Gaseous Radwaste Disposal System.

completely separated from the balance of the nitrogen system that supplies cover gas. Bottles of compressed nitrogen are now used to provide the backup to the air system.

One other instance of a flammable mixture in a gas decay tank has been reported.* Flammable concentrations of hydrogen and oxygen were discovered in the waste gas decay tanks. The flammable gas mixtures were created after the reactor coolant picked up oxygen from the air during a refueling and maintenance outage. In this case, no ignition occurred. However, the information notice issued by the NRC pointed out that licensees need to devote more attention to the potential effects of nitrogen-air system cross connections when systems are modified to use nitrogen as a backup to air systems. In cases where cross connections exist, the potential for formation of flammable gas mixtures should be evaluated. The NRC has recommended that a sampling program be considered to assure that flammable gas mixtures do not exist in tanks.[3-21]

3.4 HYDROGEN CONSIDERATIONS SPECIFIC TO BWRS

The objective of this section is to discuss hydrogen considerations that are of concern for boiling water reactors, but that, due to differences in plant design, are not pertinent to pressurized water reactors.

3.4.1 Reactor Coolant System

Figure 3-6 illustrates the basic BWR cycle. In this cycle, the reactor coolant absorbs energy as it passes up through the reactor core. The energy absorption causes a water-to-steam transformation. The steam passes through steam dryers in the upper part of the reactor pressure vessel and then flows to the turbine.

As previously discussed, some of the water passing through the core undergoes radiolytic decomposition because of the intense radiation field that is present. Some of the hydrogen and oxygen produced during this process is carried with the steam to the turbine and main condenser. These gases are removed from the condenser by the steam jet air ejectors (SJAEs), along with other noncondensable gases that are present (such as trace amounts of the noble gases, krypton and xenon), and processed through the Off-Gas System.[3-22]

3.4.2 Off-Gas System

A BWR nuclear power plant produces a substantial volume of gaseous wastes. In order to properly control these gases, plants employ an Off-Gas System that takes noncondensable gases from the main condenser and processes them in an appropriate manner before releasing them to the atmosphere. One of the most critical aspects of the Off-Gas System is the disposal of the large amounts of hydrogen contained in the off-gas mixture. The lower combustible limit of hydrogen in air is 4.1% by volume, while an off-gas mixture typically contains

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* This incident occurred at Arkansas Nuclear One Unit 1, in August 1980. This plant is located in Russelville, Arkansas, and is operated by Arkansas Power and Light Company.

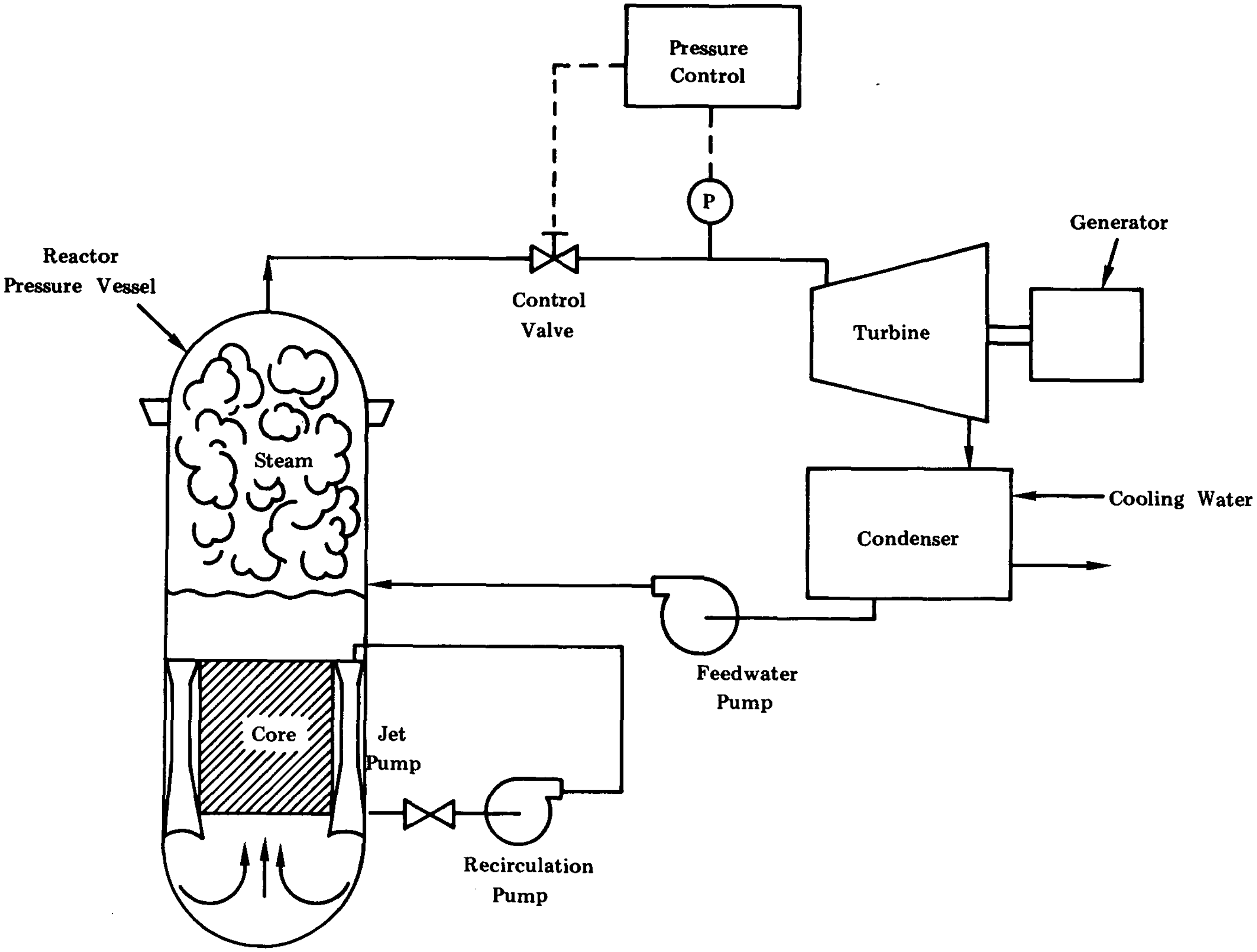

Figure 3-6. Schematic Diagram of a Typical BWR System

6 to 8% hydrogen. Thus, the Off-Gas System is a potentially hazardous area, in which a spark may cause an ignition. Combustion of hydrogen in the Off-Gas System has not been a rare occurrence during operation. The industry average has been about one combustion for every four years of plant operation.[3-23] Changes have been made in Off-Gas System design since the early BWR models to reduce the hydrogen concentration in the system, but the system still must be properly and carefully operated to ensure that hydrogen ignition does not occur.

In recent generation BWRs, the primary method of reducing hydrogen concentrations in the Off-Gas System is through the use of recombiners. A recombiner causes free hydrogen and oxygen to combine to form water. A typical off-gas recombiner is shown in Figure 3-7; its general characteristics are described below.

The Off-Gas System is divided into two sections: the recombiner section and the charcoal adsorber section. The recombiner section is designed to reduce off-gas volume by recombining hydrogen and oxygen into water. This volume reduction (typically around 90%) allows for a significant increase in the holdup time for the radioactive waste gases. Increased holdup time allows for more decay of short-lived isotopes and results in a reduction of the activity released from the stack. A recombiner unit usually consists of a feed gas condenser and two recombiner sections. Each recombiner section contains a preheater, recombiner, and condenser. The charcoal adsorber train consists of a series of filters, adsorber beds, and coolers.

All noncondensable gases in the main condenser are removed by the steam jet air ejectors (SJAEs) and passed to the feed gas condenser where any steam remaining is condensed and drained to the main condenser. The gas mixture is removed by a motive steam jet. The jet compresses and dilutes the gas to assure a hydrogen concentration of less than 4% before introduction into the primary recombiner preheater. The preheater increases the temperature of the gas to about 300°F in preparation for entry into the primary recombiner. The increase in temperature is required to promote a more efficient reaction. The primary recombiner is a pressure vessel containing a platinum/palladium catalyst cartridge. Under the proper conditions, the presence of this catalyst promotes the recombination of hydrogen and oxygen to form water. Recombination greatly reduces the volume of waste gas and decreases the hydrogen concentration to less than 1%. This results in a substantially reduced probability of hydrogen combustion. The recombination reaction is highly exothermic, causing the production, not of liquid water, but of 800°F steam. A primary recombiner condenser is included to condense the newly formed steam. The condensate is drained to the main condenser, while the remaining gas is run through the secondary recombiner section via a recycle jet. The secondary section is identical to the primary except that it handles a significantly lower volume of gas. At the conclusion of this sequence, the condensate drains to the main condenser while the remaining gases are moved into the holdup pipe.[3-24]

As was previously mentioned, BWRs have been plagued in the past with hydrogen ignitions in the Off-Gas System. They have occurred for a multitude of reasons, ranging from lightning striking the stack and sparks from static electricity to catalyst migration and sparks from recombiner flow control valves. Regardless of the cause, with the technology currently available, it

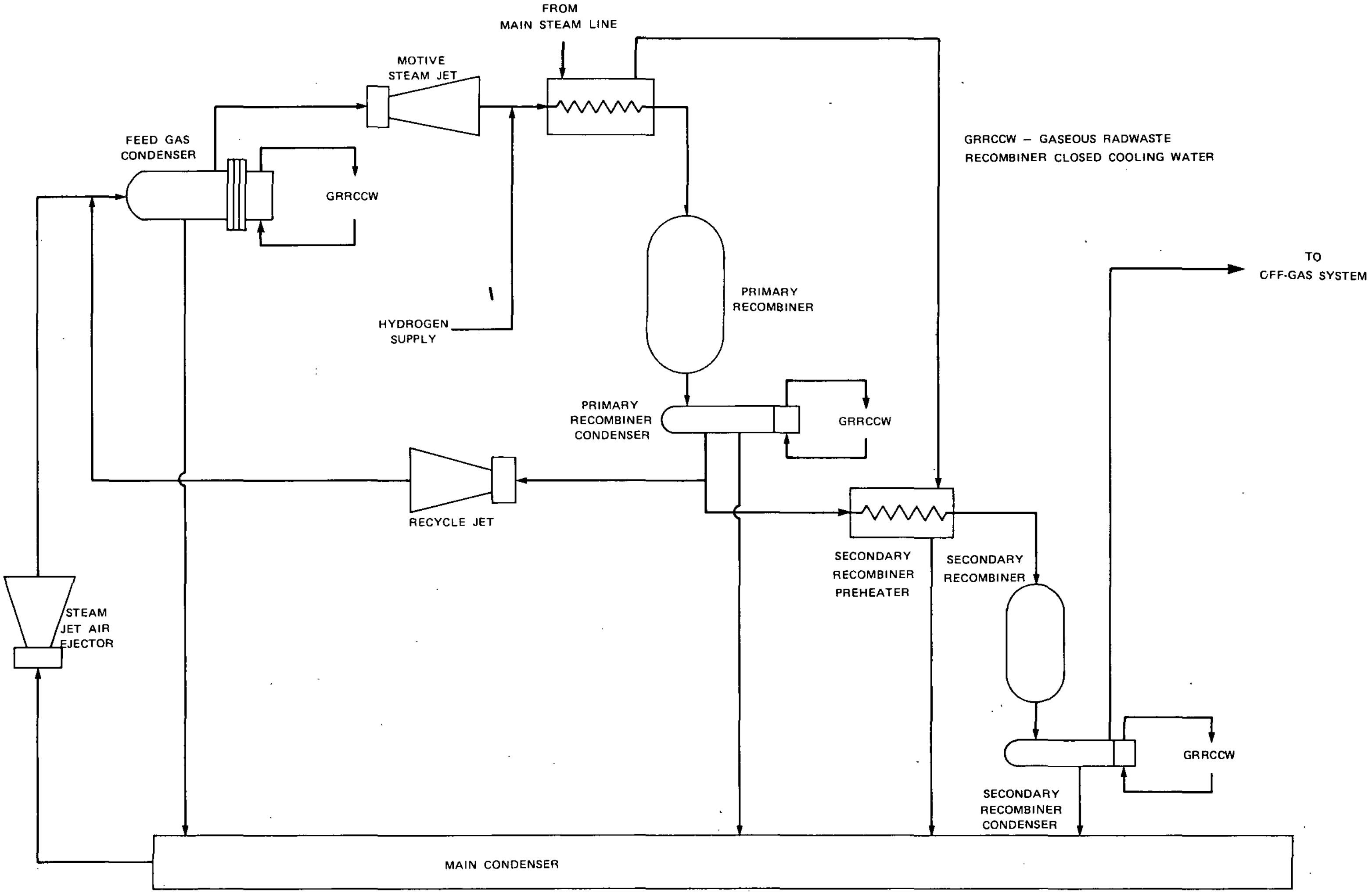

Figure 3-7. Typical Off-Gas System Recombiner Assembly

is generally agreed that such problems should not occur. The nation's only manufacturer of BWRs, General Electric (GE), has made recommendations concerning the design and operation of recombiner systems. Some of the more significant recommendations are discussed below.

Some external ignitions could be prevented if loop seals (J-tubes filled with water that are designed to handle either positive or negative pressure surges) are of adequate length and kept filled. The length of the loop seals should be compatible with system pressure and should allow for protection against potential pressure surges. In some cases it might be necessary to enlarge the discharge legs to make the seals non-siphonable. The seals should be kept full at all times and flushed periodically with demineralized water.

Ignitions have also occurred when leftover piping was used to bypass the recombiner. Once a recombiner is operable, the capability to bypass it must be rendered inoperable (and preferably removed) since there is a significantly increased probability of ignition due to migration of catalyst, leaking or sparking valves, or other related problems.

Another hazard is that of ignitions in downstream piping that is not combustion-resistant. An ignitable mixture can reach such a zone either through recombiner failure or loss of stack dilution air. According to GE, plant procedures should forbid operation unless the recombiner or the stack dilution fan is running.[3-25] Plants with operating recombiners should maintain a continuous flow of stack dilution air sufficient to dilute the full hydrogen flow (without recombiners) to below 4%. This allows for a safety margin should the recombiner become inoperable. However, extended operation with a failed recombiner is not recommended since it increases the chance of creating problems such as wetting the charcoal or blowing a loop seal. GE recommends that redundant recombiner trains be maintained in a hot-standby condition at all times during operation. In augmented off-gas systems, flow of the dilution medium entering the recombiner must be absolutely assured. Its volume should not be moderated with reactor power, and there should be no possibility of loss of diluent flow when there is off-gas flow.

Other GE-recommended operating practices are (a) non-sparking trim should be used to fabricate valves exposed to process gas to avoid acting as potential ignition sources; (b) caution should be exercised if higher than normal radiation levels are noted in the Off-Gas System area, since such conditions could be accompanied by released hydrogen; (c) the off-gas area should be a "no smoking" area; and (d) test procedures that involve instrument lines that might have a high hydrogen content should contain appropriate precautions.[3-25]

The off-gas systems have undergone considerable modification in the past several years. As a result, different generations of BWRs are equipped differently to handle the problem of hydrogen in the Off-Gas System. The most prevalent method of dealing with this problem today is the employment of recombiners in conjunction with stack gas dilution. These technological advances in hydrogen control in the Off-Gas System have significantly reduced the frequency of combustion events.

3.4.3 Chemistry

As previously discussed, the hydrogen produced by radiolysis is controlled by recombiners in the Off-Gas System. No chemical additives are introduced into the Reactor Coolant System for hydrogen control.

3.4.4 Containment Entry

Periodic entry into the containment may be necessary during normal operation. Because of the nature of the radiation and temperature environments that may be present, such entries will require special precautions. If the primary containment is inerted with nitrogen, the oxygen concentration will be too low to be breathable, and respiratory equipment will be required. All of these considerations should be (and generally are) covered by plant-specific procedures governing containment entry.

From a hydrogen standpoint, the concentration within the primary containment should be too low to present any unusual problems during normal operating conditions.

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Chapter 4

HYDROGEN BEHAVIOR AND CONTROL -- ACCIDENT CONDITIONS

4.1 INTRODUCTION

The possibility of hydrogen combustion inside the reactor vessel was a major concern of the public and of utility personnel during the Three Mile Island incident. There was no such combustion in the vessel, but the question comes to mind: "Was the fear justified?" Although the possibility exists for substantial amounts of hydrogen to be produced in the reactor vessel during accident conditions, it is highly unlikely that flammability limits would be reached because of the low oxygen concentration in the reactor coolant system (see Chapter 2). However, a large portion of the hydrogen eventually would be transferred to the containment atmostphere (e.g., via venting or through a reactor coolant system break), possibly creating an environment capable of sustaining a combustion.

This chaper is devoted to a discussion of hydrogen behavior and control under accident conditions. The principal topics covered include containment integrity, indications of a loss-of-coolant accident (LOCA), indications of hydrogen production, hydrogen transport and mixing, indications of hydrogen combustion, and mitigation schemes. An effort has been made to integrate the theoretical aspects emphasized in Chapter 2 with the operational and emergency aspects that could arise during an accident condition.

4.2 CONTAINMENT STRUCTURE AND INTEGRITY

4.2.1 LWR Containment Comparison

The principal concern over hydrogen combustion in nuclear reactor containments is that it is possible for a high pressure to be generated that could breach containment integrity and initiate a release of radioactivity to the environment. Nominal design and failure pressures vary from one containment to another; numbers for typical PWR and BWR containments for 1200 MWe plants are shown in the bar graph in Figure 4-1. Typical containment net free volumes are given along with nominal values for design pressure.[4-1]

If a LOCA occurs, hydrogen could be liberated through a metal-water reaction.* Figure 4-2 shows the resultant hydrogen concentration for each containment type solely from this source of hydrogen. Note that the curves for the smaller containment types show a gradual bending at higher hydrogen concentrations. This is because the containment atmosphere initially contains other constituents besides hydrogen; therefore, the hydrogen concentration can never reach 100%. In addition, as the volume of hydrogen generated increases, containment pressure increases due to this added gas volume. For a given

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* For most plants this would be a zirconium:steam reaction. However, several plants have fuel elements clad with stainless steel, instead of zircaloy. In these plants the reaction would be a stainless-steel:steam reaction.

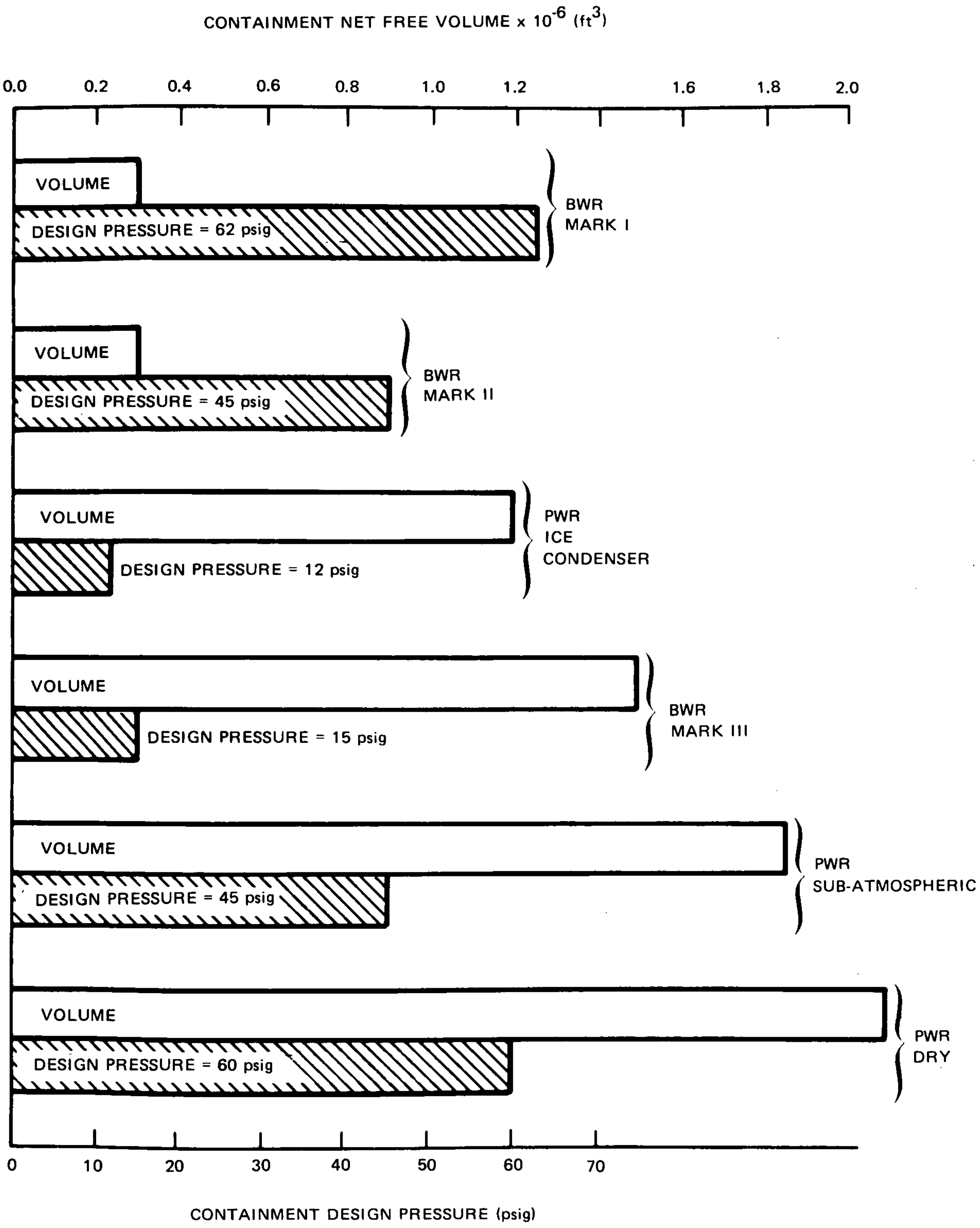

Figure 4-1. Comparison of Containment Volumes and Design Pressures (Typical 1200 MWe Plants)

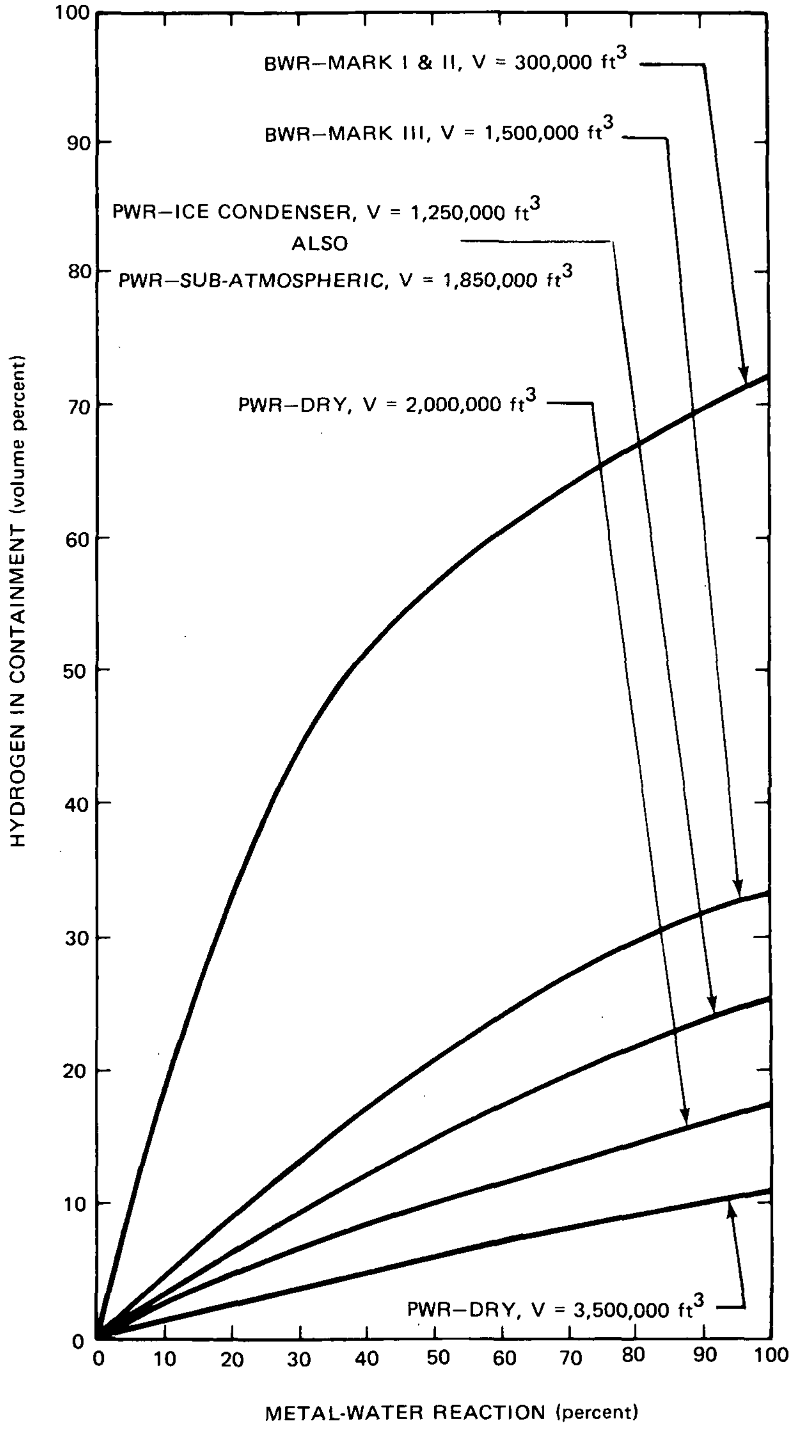

Figure 4-2. Volume Percent Hydrogen in Containment vs. Percent Metal-Water Reaction Following a LOCA

percent metal-water reaction, these effects (i.e., an increase in hydrogen concentration and the subsequent pressure rise) will be more pronounced for the smaller sized containments. The combination of these facts explains the shape of the curves in Figure 4-2.

A second concern about hydrogen combustion is that the resultant high temperature, or high pressure, might damage safety-related equipment. The pressure and temperature obtained from the complete combustion of hydrogen in air, adiabatically and at constant volume, were shown in Figures 2-10 and 2-11 respectively.

Hydrogen combustion is only one of several mechanisms that can generate high containment pressures. The release of steam that would accompany a LOCA also causes an increase in containment pressure. Further, condensing steam can react with certain metals in containment such as zinc or aluminum, to liberate additional hydrogen. This was discussed in detail in Chapter 2.

4.2.2 PWR Containments

In general, three types of PWR containment designs exist. These types are listed in Table 4-1; two of them are shown in Figures 4-3 and 4-4.

Table 4-1
PWR CONTAINMENT TYPES

Containment Types	Design Pressure (Typical)
Large Dry Atmospheric	~60 psig (500 kPaa)
Sub-atmospheric	~45 psig (412 kPaa)
Ice Condenser	~12 psig (184 kPaa)

Of primary concern in an accident situation is whether the hydrogen concentration would challenge containment integrity if a deflagration occurred. Consider the pressures involved using the large dry atmospheric containment as an example. Table 4-1 shows that a typical design pressure is 60 psig (500 kPaa). Assuming an initial pressure in containment of about one atmosphere (14.7 psia or about 100 kPaa), a five-fold pressure increase to about 75 psia (60 psig or 500 kPaa) would be required to reach the design pressure during a deflagration.

Nominally, the failure pressure for a containment (with all margins of safety removed) can be greater than twice the design pressure. For example, a probabilistic risk assessment (PRA) was performed for one station* employing a Westinghouse PWR. The dry volume containment had a design pressure of 47 psig. The PRA for this plant gives an ultimate capacity of 125 psig with

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* Indian Point Station Unit 3, near Buchanan, New York. This station is operated by The Power Authority of the State of New York.

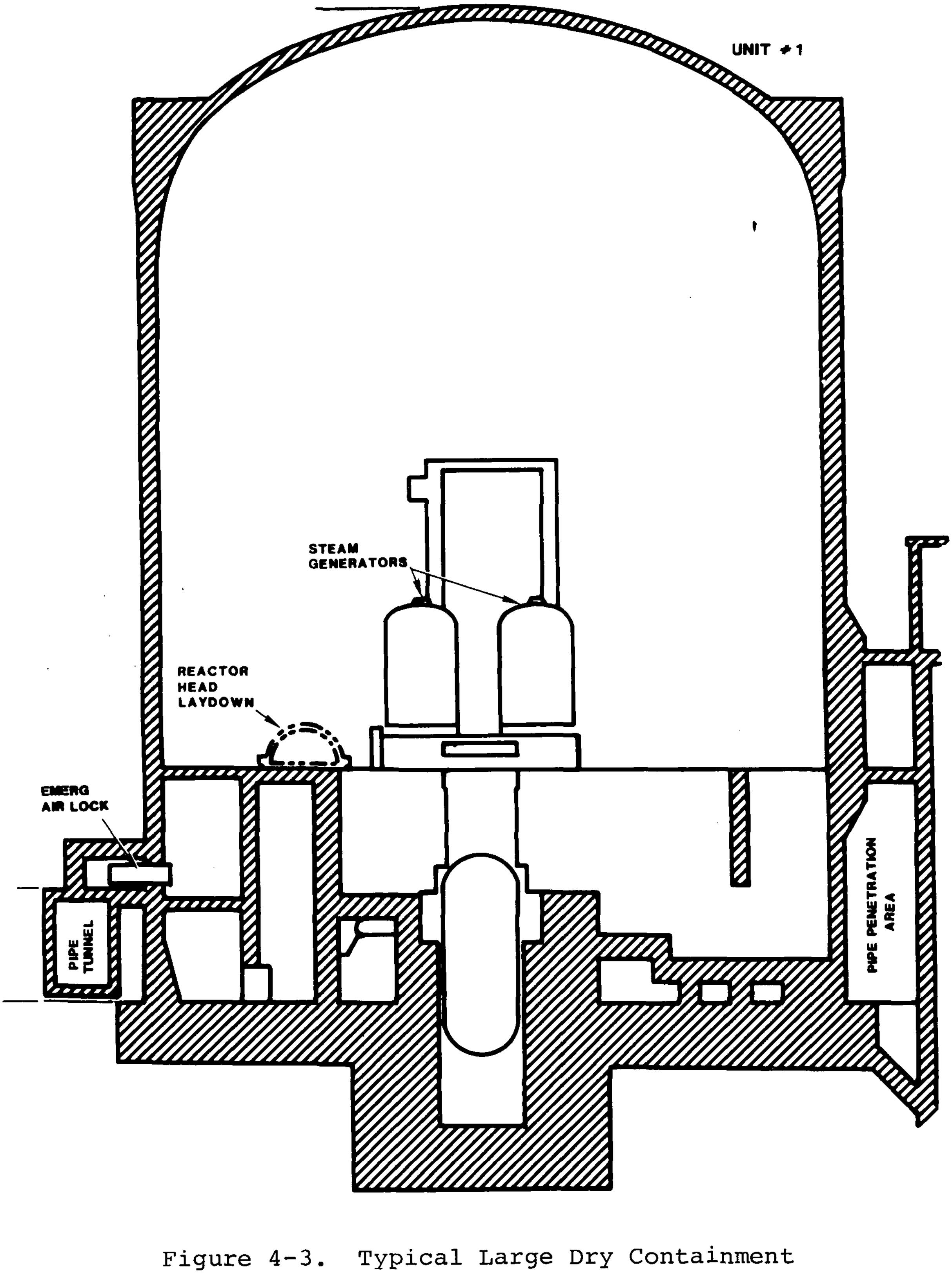

Figure 4-3. Typical Large Dry Containment

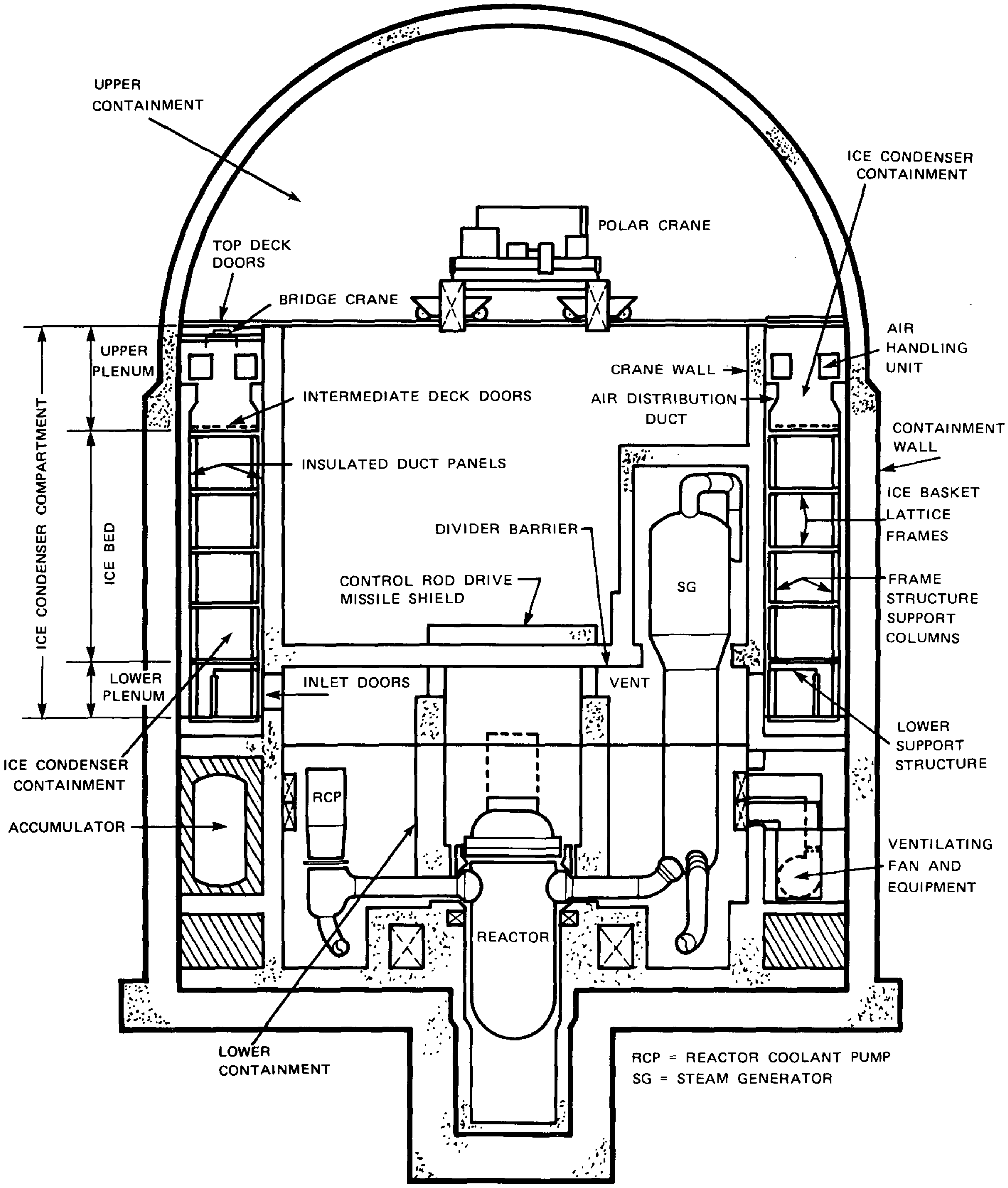

Figure 4-4. Simplified Diagram of Ice Condenser Containment

100% confidence, and 145 psig with 95% confidence. In addition, one specialist's opinion rates the ultimate capacity of Stone and Webster sub-atmospheric containments (typical design pressure of 45 psig) as 100 psig.[4-2] In general, the ultimate capacity of a containment structure is two-to-three times the design pressure. Some PWRs employ ice condenser containments, such as that shown in Figure 4-4. These containments have smaller volumes and lesser design pressures than other PWR containments. This is because the ice is used as a heat sink in the event of the design basis accident. The ice will reduce the containment pressure by condensing the steam liberated during such an incident.

An example of how the hydrogen concentration can increase in containment is given in Figure 4-5, which shows the postulated post-LOCA hydrogen concentration versus time for the Maine Yankee Atomic Power Station.*[4-3] Figure 4-5 makes the simplifying assumption that the zircaloy-water reaction for the LOCA occurs all at once, and, similarly, that all of the aluminum in containment oxidizes at the onset of the incident. Note that Figure 4-5 assumes less than 1% of the cladding has reacted.

4.2.3 BWR Containments

As a result of the requirements in section 50.44 of 10CFR, all Mark I containments are inerted. In the Federal Register of October 2, 1980, the NRC stated that a long-term rulemaking proceeding related to the consideration of degraded or melted cores in safety regulation was in progress. This review would include a reevaluation of positions on the inerting of reactor containments. Pending completion of this process, the NRC felt that it would be prudent to establish certain inerting requirements for operating plants and those that would become operational in the near term. Therefore, at the time of this writing, the NRC is considering amending Section 50.44 to require that:

- All operating Mark I and Mark II BWRs be inerted.
- Mark I and II BWRs under construction be inerted upon operation.
- Licensees now operating PWR plants or Mark III BWR plants, or license applicants that plan to operate these plants study the various methods of controlling the behavior of large amounts of hydrogen before the containment is threatened, or of mitigating the consequences of accidents, involving the generation of large amounts of hydrogen.[4-5]

If a LOCA occurred at a BWR facility, a steadily increasing pressure in the primary containment/drywell would result. If operation of the Emergency Core Cooling System and other water delivery systems are compromised in some manner, the possibility exists for an inadequate core cooling (ICC) condition to develop. If an ICC condition arose, it would be possible for a metal-water reaction to commence in the core. In the event that a metal-water reaction

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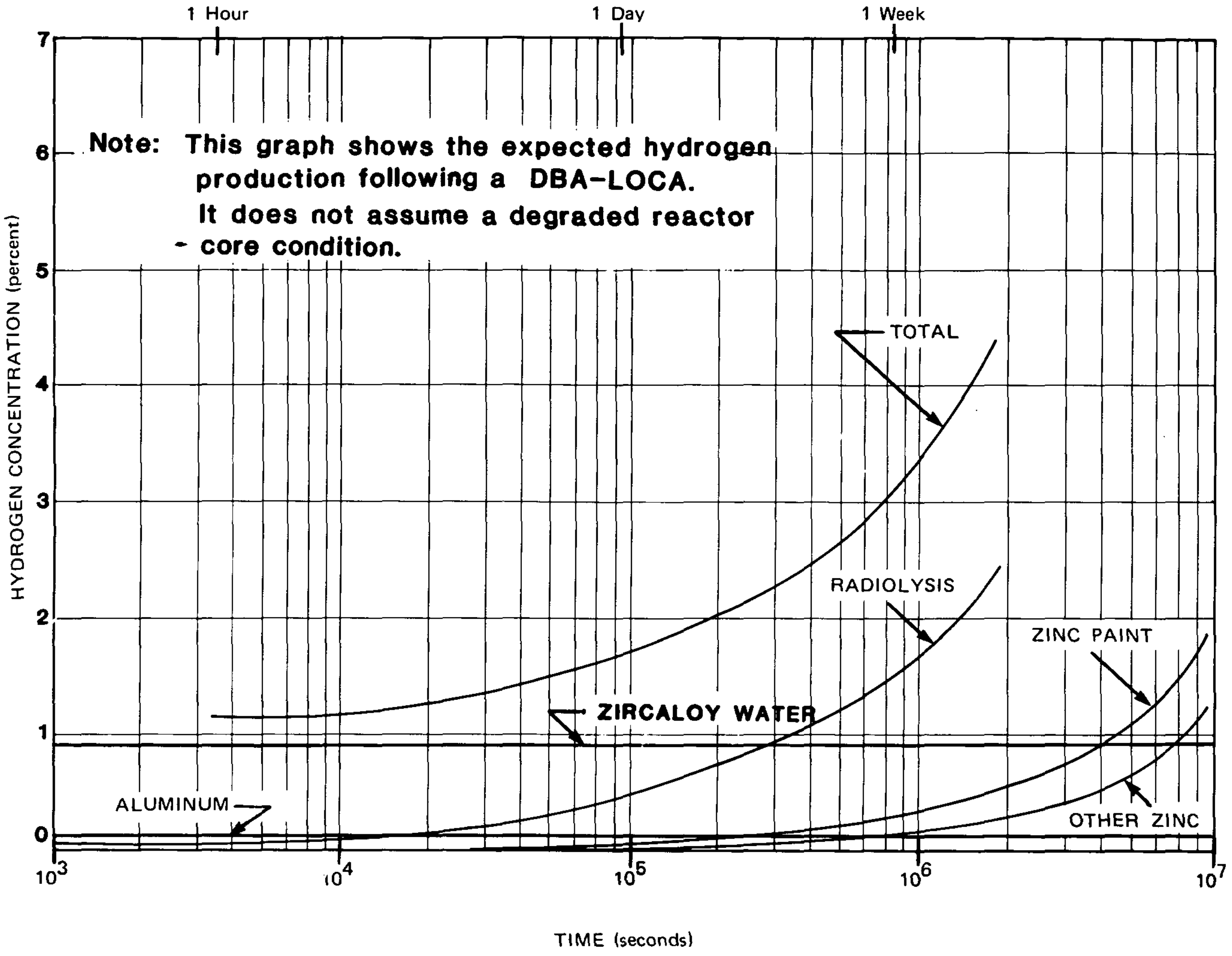
* A PWR facility located in Wiscasset, Maine, and operated by the Maine Yankee Atomic Power Company.



Note: This graph shows the expected hydrogen production following a DBA-LOCA. It does not assume a degraded reactor core condition.

Figure 4-5. Maine Yankee Containment Post-LOCA Percent Hydrogen Concentration vs. Time occurred, hydrogen would be liberated, as was discussed in Chapter 2. The approximate volume percent of hydrogen which could fill the containment was shown in Figure 4-2. In this figure, the top curve represents the volume percent in a Mark I or II containment/drywell as a function of percent metal water reaction in the reactor core. One of the lower curves in Figure 4-2 is for a Mark III containment. Note that Mark III containments are substantially larger than either the Mark I or II type. Further information is given in Table 4-2, which shows some possible hydrogen pressure effects in BWR containments.[4-6] For those cases where a hydrogen burn occurs, this table assumes that only a single hydrogen burn occurs (and that sufficient oxygen exists for this burn to occur). The table does not take into account any hydrogen recombiner system or specially installed hydrogen igniter system (HIS). In addition, the values for design and failure pressures are the nominal published values. The pressures listed in Table 4-2 incorporate a safety factor. These values are only intended to give a general notion of the possible effects on a BWR containment where it is assumed that no mitigation scheme is employed; they should be regarded in this light.

Table 4-2

HYDROGEN PRESSURE EFFECTS ON BWR CONTAINMENT TYPES
(ASSUMING NO MITIGATION SCHEMES ARE EMPLOYED)

Parameters	Mark I	Mark II	Mark III
Design Pressure, psig (nominal)	60	45	15
Failure Pressure, Est., psig	120	140	72
Estimated Pressure 50% Metal-Water Reaction, No Burn, psig	19	19	4-5
Estimated Pressure, 30% Metal-Water Reaction, With Burn, psig	>>200	>>200	55
Estimated Pressure, 50% Metal-Water Reaction, With Burn, psig	>>200	>>200	100
Percent Metal-Water Reaction To Reach Estimated Failure Pressure With No Burn	>100	>100	100
Percent Hydrogen Necessary To Reach Estimated Failure Pressure With Burn	13-16	15-20	8-12

Note that from a containment failure pressure point-of-view, a hydrogen deflagration is worse in Mark I and Mark II containments because of their smaller volumes. If a hydrogen ignition occurred, however, the resultant pressure increase as a function of initial hydrogen concentration would be as shown in Figure 2-10.[4-7] It should be emphasized that both the Mark I and II containments are inerted. For facilities with Mark I or II containments, the operating oxygen concentration in the containment/drywell must be less than 4% by volume to meet technical specification requirements. This essentially guarantees that a hydrogen deflagration could not take place within this environment.

Figure 4-6 shows a typical BWR Mark I containment; a Mark II design is shown later in Figure 4-32.

Figure 4-7 shows a profile view of a typical BWR Mark III containment. Mark I and II containments are inerted. For Mark III containments, where no inerting is used, methods of controlling large amounts of hydrogen may be necessary to ensure that the hydrogen does not threaten containment integrity.

4.3 INDICATIONS OF A LOSS-OF-COOLANT ACCIDENT

4.3.1 Introduction

Examination of those parameters that are indicative of a LOCA is the first step in detecting the onset of an inadequate core cooling condition. It is the ICC condition that ultimately can result in hydrogen production within the reactor vessel. Further, as previously discussed, the liberation of high temperature water or steam into containment can produce oxidation reactions that can liberate hydrogen.

In this section, those key parameters that are indicative of a LOCA will be considered for both PWRs and BWRs. The discussion will identify those parameters that, when considered collectively, can normally be used to identify the presence of a LOCA. It should be emphasized, however, that where these same parameters are considered individually the indications are not necessarily exclusive to a LOCA. Individual subsections discuss indications of conditions internal and external to the Reactor Coolant System separately for PWRs and BWRs.

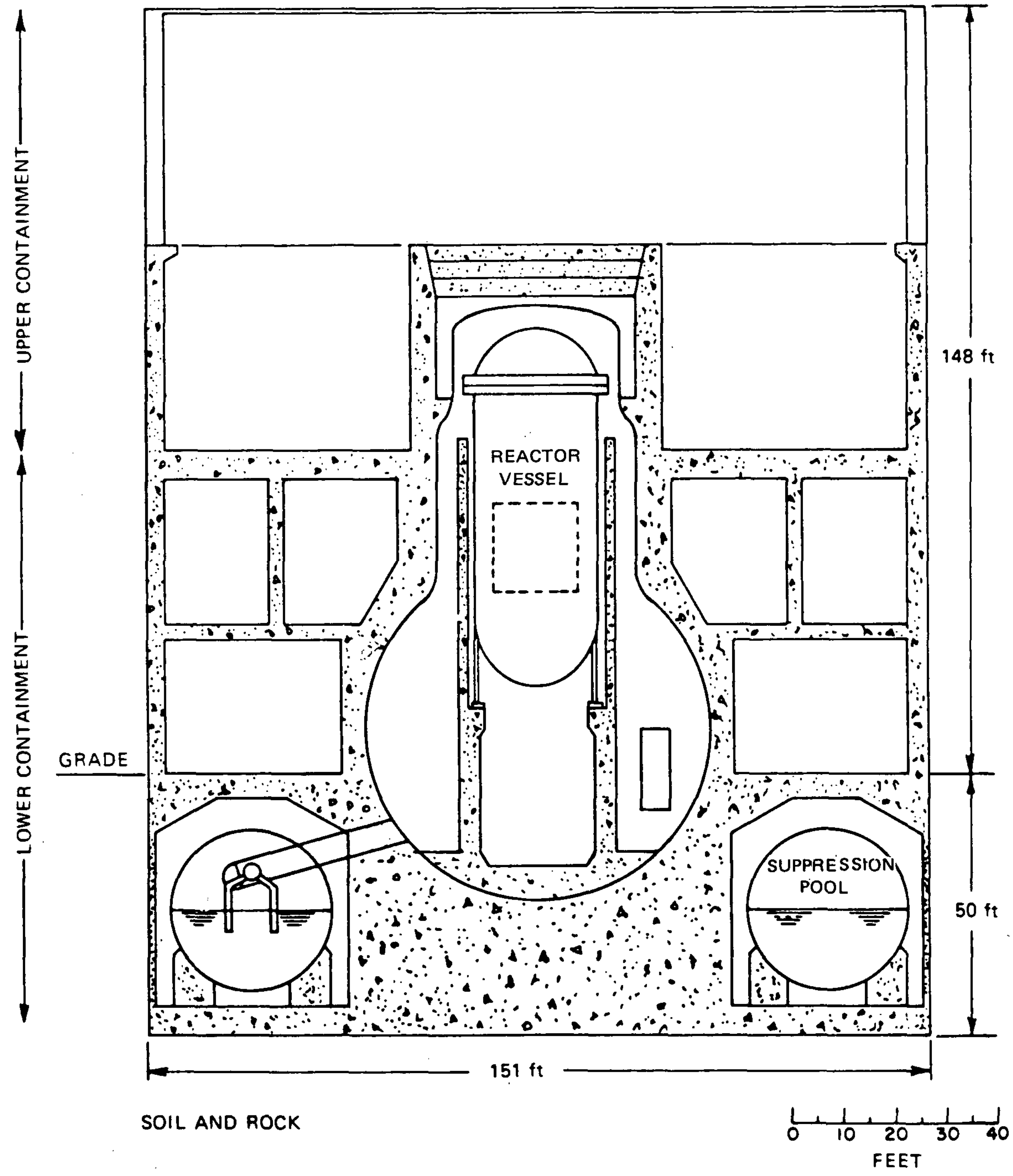


Figure 4-6. Mark I BWR Drywell/Primary Containment

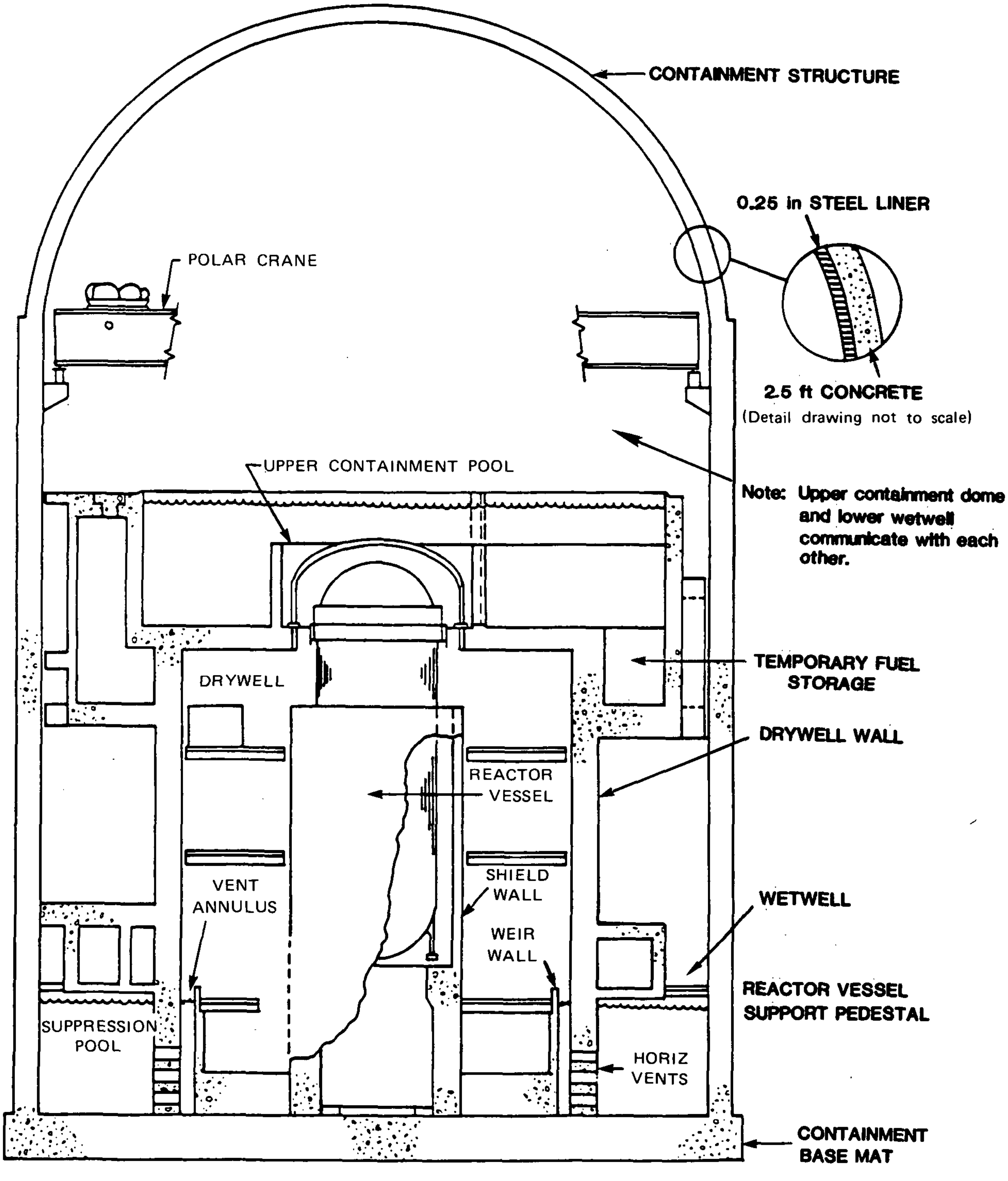


Figure 4-7. Section View of a Mark III Containment Structure and Internals (Grand Gulf Nuclear Station)

4.3.2 PWR Indications Internal to the Reactor Coolant System

Indications of conditions internal to the Reactor Coolant System (RCS) that are measured in operating nuclear plants and can provide evidence or a LOCA include:

- Temperature
- Flow
- Pressure
- Pressurizer level
- Reactor vessel level
- Nuclear instrumentation

4.3.2.1 Temperature. Temperatures within the primary system are measured by incore thermocouples and RCS hot leg resistance temperature detectors (RTDs). The incore thermocouple system continuously monitors coolant outlet temperatures of selected fuel assemblies in the reactor core. These temperatures are used for control room indication and plant computer analysis. The thermocouples are positioned at the top of the core to measure fuel assembly outlet temperatures. A simplified drawing of a thermocouple channel as used in the incore thermocouple system is shown in Figure 4-8.[4-8] A LOCA could be accompanied by abnormally large increases in the indicated temperatures.

Abnormally high thermocouple temperatures may be indicative of voiding in the reactor core which may be followed by the production of superheated steam. In the event of a drop in RCS inventory, heat transfer from the excessively hot cladding will also contribute to an increase in the measured temperatures. The hot leg RTDs will also experience an increase in temperature shortly after the core exit thermocouples show a temperature rise, because they are located 15 to 20 feet downstream from the core exit thermocouples.

Those PWRs (e.g., many Westinghouse facilities) employing RTD bypass manifolds may not show this temperature rise. These manifolds sample a fraction of the RCS hot leg and cold leg flow. An RCS break (or tripping reactor coolant pumps (RCPs)) will cause a drop in flow to the RTD manifold. Thus, there will be little or no change in the hot leg or cold leg temperatures sensed by these RTDs, and, hence, little or no change in the indicated temperatures. Therefore, core exit thermocouples tend to be the better indication of possible voiding in the reactor vessel. Those RTDs installed in the reactor coolant hot-leg piping itself will provide similar temperature indications, however, the RTDs provide a less accurate measure of reactor core temperature conditions.

4.3.2.2 Flow. The power production rate in a LWR is limited not by the amount of fuel, but by the ability to transfer energy from the fuel. A given power level will require a minimum core flow rate to ensure adequate core cooling to prevent exceeding thermal design limits. Reactor coolant flow typically is found by one of two methods.[4-6,4-8]

- Measuring differential pressure across the steam generator
- Measuring differential pressure in a 90° piping elbow in the RCS piping to the steam generator

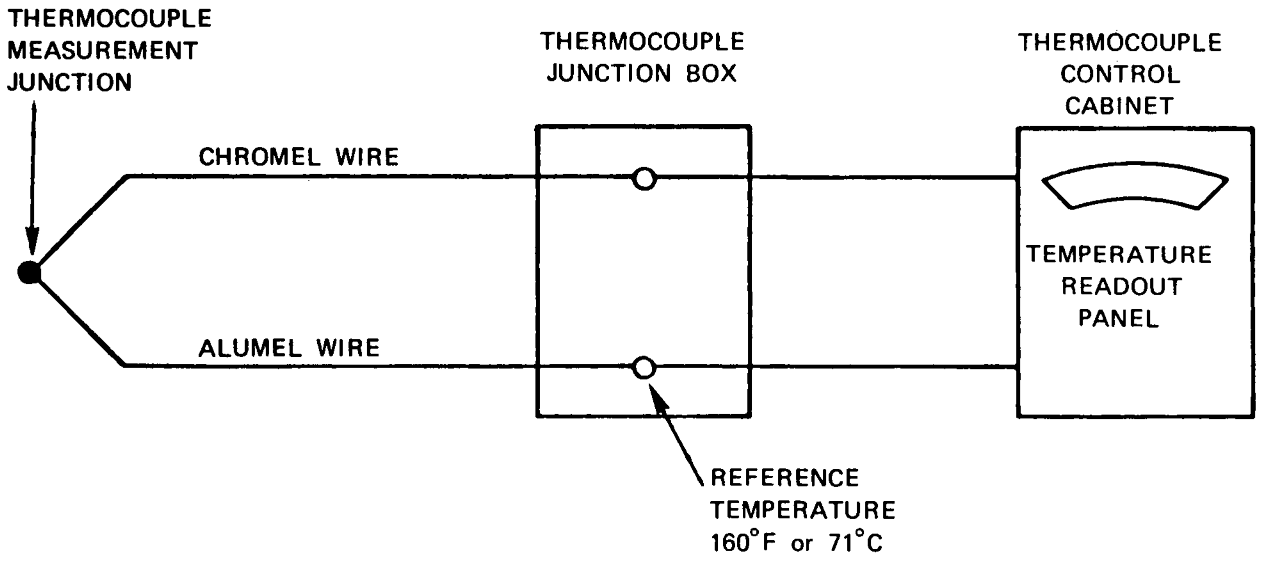


Figure 4-8. Typical Incore Thermocouple System

If a LOCA occurred there would be a lesser mass flow rate through the system. Further, as the RCS pressure dropped to saturation conditions, some flow anomalies would result because of the lesser mass flow rate. The abnormal reactor coolant pump flow indications seen by the operator could include:

- Decrease in pump motor current
- Increase in pump temperature
- Increase in pump vibration

4.3.2.3 Pressure. A LOCA, depending upon its magnitude, can result in a drop in RCS pressure. A reactor trip and ECCS actuation could both be initiated by a low pressure condition. ECCS actuation on low pressure can be an indication of a LOCA.

In general, RCS pressure is measured at the pressurizer (see Figure 4-9). Pressurizer pressure can be compared with the saturation temperature corresponding to the hot leg temperature to ensure that a subcooled system exists within the reactor vessel and, thus, an adequate heat removal rate exists. Post-TMI-2, PWR facilities have installed subcooling margin monitors (SMMs) to monitor the margin to saturation within the reactor vessel. Typically, a subcooling margin monitor receives input signal data from pressurizer pressure transmitters, core exit thermocouples, and hot and cold leg RTDs. Data from each input source is processed as a temperature signal. The monitor obtains the highest temperature from the various inputs. This temperature is a measure of the margin to saturation in the reactor vessel or RCS. The SMM would provide one of the first indications that pressure had dropped and that the RCS was at saturated conditions if a LOCA occurred. There is a multiplicity of inputs to the SMM. The SMM must be well maintained, otherwise, its usefulness could be marginal. (For example, input from an aging thermocouple that has become noisy could result in invalid signals.)

4.3.2.4 Pressurizer Level. Pressurizer level is another potential indication of a LOCA. Classically, it was assumed that if a LOCA occurred, the pressurizer would empty first because it is the highest elevation point in the RCS. In fact, in previous years, many PWR facilities initiated safety injection (ECCS actuation) on low pressurizer level coincident with low pressurize pressure.

However, since then it has been shown that some LOCA scenarios do not necessarily result in a rapid pressurizer level drop. A notable example was the TMI-2 incident. Here the loss of coolant occurred through the pressurizer power-operated relief valve (PORV) at the top of the pressurizer. In this incident (described more fully in Appendix I) pressurizer level initially dropped, and then, about one minute into the incident, it rose rapidly. This rapid rise in pressurizer level confused the operators, causing them to reduce makeup flow to the RCS and to reinitiate letdown flow. These actions caused a reduction in RCS inventory that ultimately led to an ICC condition.

In general, pressurizer level should drop due to a LOCA -- especially for a large LOCA that is not in the pressurizer steam space. However, "peculiar" pressurizer behavior can also be an indication of a LOCA (such as the small-break LOCA at TMI-2) -- but in this case other indications such as

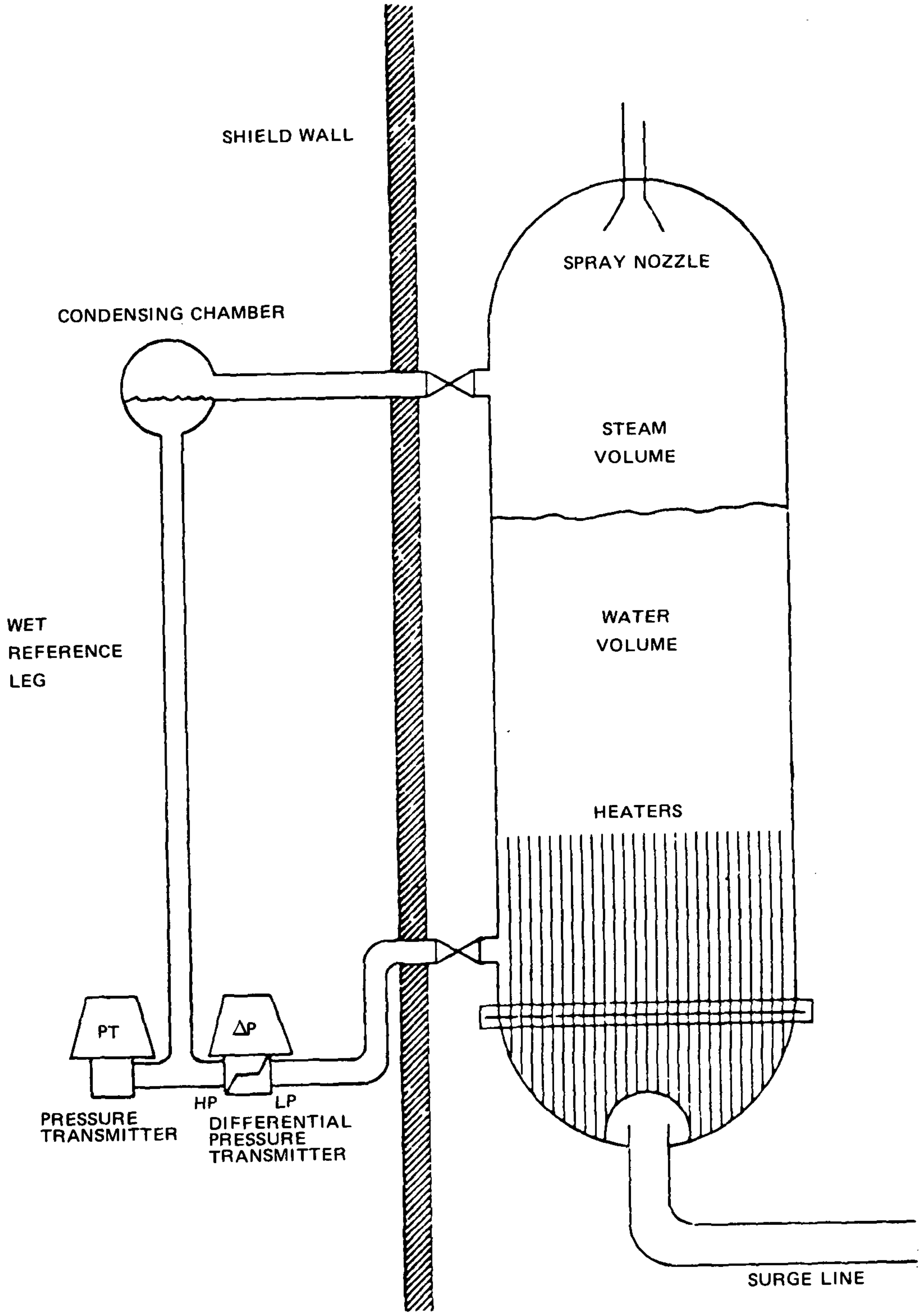


Figure 4-9. Typical Pressurizer Pressure and Level Transmitter Arrangement (Byron & Braidwood - Westinghouse)

those considered in this section must be used in conjunction with pressurizer level to verify the existence of the LOCA.

4.3.2.5 Reactor Vessel Water Level. In the past, PWRs have not measured reactor vessel water level. It has been assumed, since the pressurizer is at the highest elevation in the RCS, that if pressurizer level is maintained it can be assumed that the core is covered. However, as demonstrated during the TMI-2 incident, a rapid RCS pressure drop caused steam formation in the reactor vessel that resulted in water being forced into the pressurizer. Thus, voiding may exist in the core while pressurizer level is maintained. The potential for misinterpretation as to whether the core is covered (such as could occur with an existing pressurizer level with voiding in the core), has led to the installation of systems to provide an unambiguous measurement of reactor coolant inventory above the reactor core. One such system involves the use of heated-junction thermocouples.

The basic heated-junction thermocouple system consists of a heater and two thermocouple junctions, as shown in Figure 4-10a.[4-8] Under normal operating conditions, the two thermocouples would be near the same temperature since core flow will remove energy from the heater. Thus, the differential voltage between the thermocouples will be small. If the water is replaced by a steam/water mixture (which has less efficient heat transfer characteristics), the thermocouple nearest the heater will heat up very rapidly, resulting in a much larger output potential than that of the unheated thermocouple. If the core becomes uncovered at the height of the thermocouple, a substantial rise in output voltage will occur with a response time of about 1 second. Acceptance tests have shown that the heated junction exhibits a sharp response similar to that of an electronic bistable device. Figure 4-10b shows a typical heated-junction thermocouple response curve.

Thus, the heated-junction thermocouple system, by providing an indication of reactor vessel water level, can indicate the existence of a LOCA. In the case of a large-break LOCA, this indication would be rapid (a matter of seconds, perhaps). For a small-break LOCA, it may take minutes to hours to see the drop in reactor vessel water level. In either case, it would disclose when the core could become uncovered, which is of concern because if an uncovered core becomes inadequately cooled a fuel cladding metal-water reaction could occur.

4.3.2.6 Nuclear Instrumentation. Nuclear instrumentation at PWR stations includes the:

- Excore Nuclear Instrumentation System
- Incore Instrumentation System

These systems provide vital information to the reactor operator and process computer, and supply input (trip) signals to the Reactor Protection System. The use and importance of the nuclear instrumentation systems in the evaluation of the nuclear (and power generating) behavior of the core is obvious. However, these systems can also provide additional information concerning adverse core cooling conditions. If water level drops in the reactor core, both the excore and incore nuclear instrumentation, will be affected. Much

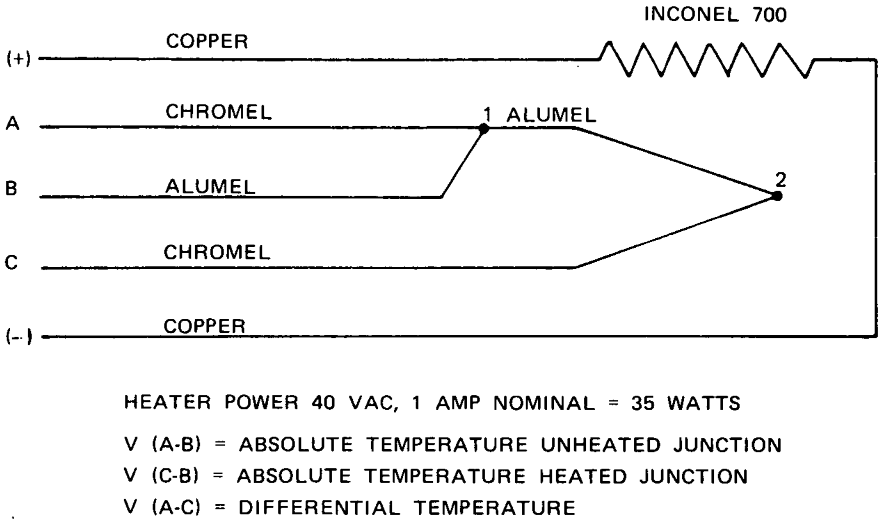


Figure 4-10a. Heated-Junction Thermocouple Arrangement

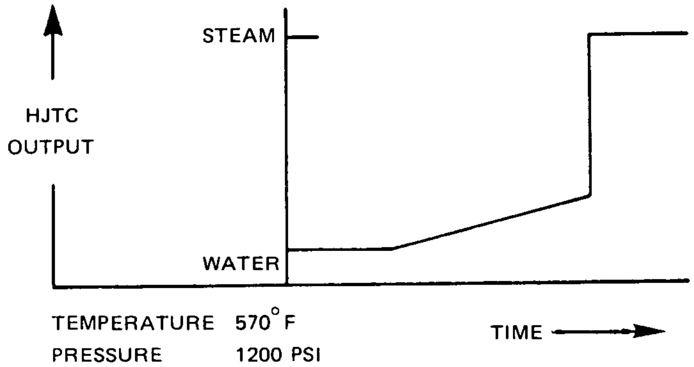


Figure 4-10b. Heated-Junction Thermocouple (HJTC) Response

could be said about the possible behavior of this instrumentation during a LOCA of this magnitude, however, one fact is certainly clear: the readings will be off-normal. Some examples of this possible off-normal behavior are discussed below.

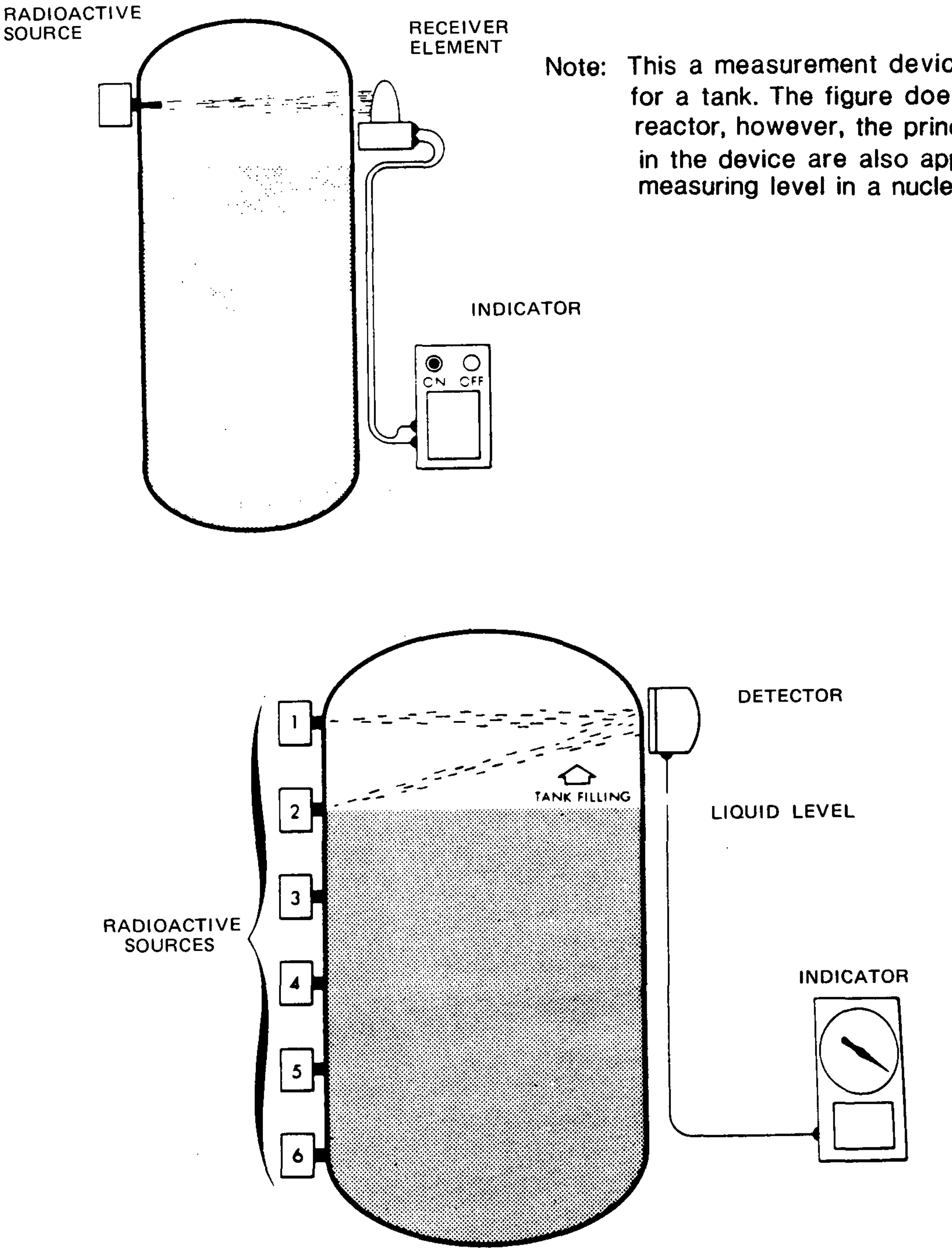
If the core is uncovered by a LOCA, increased neutron and gamma leakage will result. This increase in leakage would be seen by the excore nuclear instrumentation, and would be indicated by an increased signal strength. In fact, during the incident at TMI-2, the excore nuclear instrumentation indicated that a two-phase mixture had developed in the reactor core. At about 20 minutes into the incident, a greater neutron leakage caused these detectors to show an increased count rate (as shown in Appendix I, Figure I-28). To better understand this phenomenon, consider a system which employs radioactive sources for level measurement in a tank, as shown in Figure 4-11. In this system as long as the water level in the tank is high, the detector output will be low, since the water acts as a radiation shield. As the water level drops, the shielding decreases, and the detector output increases. A similar effect can be observed with the excore instrumentation associated with PWR cores.[4-8] These detectors (Figure 4-12) measure a fraction of the fast neutrons that leak from the core. If the only variable is reactor power (indicated by neutron population), changes in detector output correspond to changes in power. However, if the water level in the core drops, the reduction in neutron shielding results in a higher detector output. Thus, unexpected increases in indicated power could be due to the core being uncovered.

The Incore Instrumentation System uses either movable or fixed miniature fission chambers, or fixed miniature self-powered neutron detectors (SPNDs). Both detectors could show an increase in signal strength due a two-phase water-steam mixture in the reactor vessel. The SPNDs are primarily sensitive to the neutron flux, and are uncompensated for gamma radiation. In general, a drop in signal strength might be expected during core uncovery, however, because the SPND exhibits thermionic behavior, it will yield an output current proportional to the detector temperature. Theoretically, as the core became uncovered, the fission chambers should indicate a smaller signal strength, while the self-powered neutron detectors can actually indicate a larger signal. (See Appendix I and Figure I-25 for a brief discussion of SPND thermionic behavior.)

The fission chambers may be movable through the height of the core, or permanently installed at prescribed locations. Note that these detectors exhibit a response to both thermal neutrons and gamma radiation. The detector response to gamma radiation is smaller in amplitude because the detector is less sensitive to gamma radiation. Ordinarily, the gamma ray component of the detector output is reduced or removed by one of the following techniques:

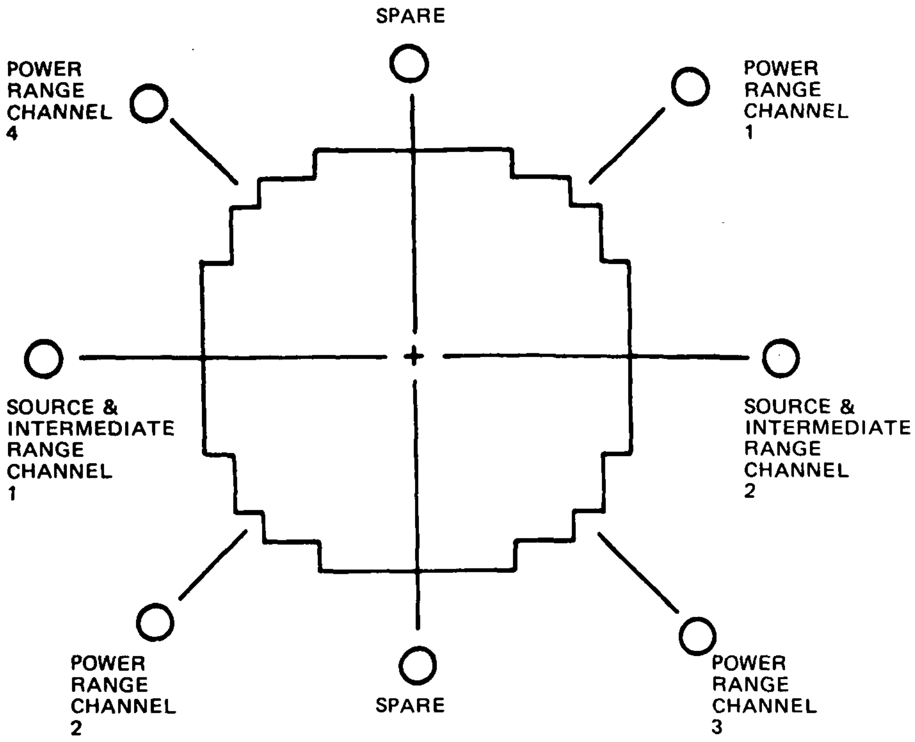
- Setting a pulse discriminator in the detector circuit to remove the smaller amplitude gamma ray-induced pulses
- Employing a counting statistics technique which results in making the gamma response negligible (the Campbelling Technique)

Thus, during normal conditions the system indication would be proportional to neutron leakage from the core, and, hence, to core power level.

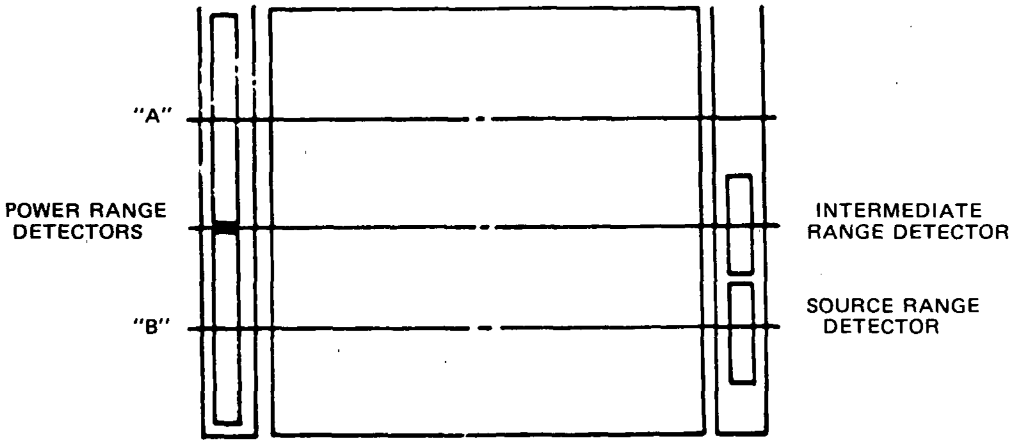


Note: This a measurement device designed for a tank. The figure does not show a reactor, however, the principles employed in the device are also applicable for measuring level in a nuclear reactor.

Figure 4-11. Radioactive Sources Used for Continuous Level Measurement



PLAN VIEW



ELEVATION

Figure 4-12. Detector Locations for the Excore Nuclear Instrumentation (Typical Westinghouse PWR)

If the core was uncovered during a LOCA, however, the indicated power would change. The relative number and magnitude of the gamma-induced pulses would increase so that the detector circuitry would not eliminate all of them. However, the dominant effect would be the sharp drop in neutron-induced pulses because of the sharp decrease in the number of thermal neutrons. Because of these effects, the fission chamber detector output would drop during a LOCA.*

The self-powered neutron detectors generally are installed at fixed elevations and specific radial positions throughout the reactor core. This type of detector yields a given output current for a specific neutron flux in the reactor core. However, it was found during the TMI-2 incident that SPNDs that became uncovered indicated very high output currents by comparison with those SPNDs that remained covered during the incident. This behavior was due to the thermionic effect on this detector.

During normal conditions, the neutron flux causes the SPND center wire to become radioactive. This rhodium wire then emits beta particles. The net positive charge on the wire causes a current flow, which is used as the output signal.

When the core is uncovered by a LOCA, the rhodium wire will heat up and emit electrons. This emission results in a net positive charge on the wire, again causing a current flow. Thus the SPND output would indicate an increase in power.

In summary:

- Excore nuclear instrumentation can read high during a LOCA.
- Incore nuclear instrumentation can read high or low depending upon the detector type and the degree of voiding. In either case, "peculiar" instrumentation behavior coupled with other control board RCS indications can be used to detect a LOCA.**

4.3.3 PWR Indications External to the Reactor Coolant System

There are several indications of conditions external to the Reactor Coolant System that can indicate the onset of a LOCA. These are:

- Containment pressure
- Containment temperature
- Containment humidity
- Containment activity
- Containment sump water level

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* It is possible that heating of the detector could result in an increased output indication due to a thermionic effect. However, insufficient information is available on this point.

** For those plants with both fission chambers and SPNDs, a LOCA could cause the fission chamber output to drop and the SPND output to rise: a prime example of "peculiar" behavior! (See Appendix I for a discussion of how SPND behavior following a LOCA compared to the normal plant shutdown behavior.)

4.3.3.1 Containment Pressure. A LOCA will discharge water and steam into the containment atmosphere, thereby causing a containment pressure increase. This pressure increase can cause safety injection actuation (ECCS initiation). The containment pressure increase coupled with an RCS pressure decrease is indicative of a LOCA.

4.3.3.2 Containment Temperature. During a LOCA, a sharp temperature rise in containment will accompany the pressure rise caused by the discharge of high temperature coolant.

4.3.3.3 Containment Humidity. If a LOCA occurred, containment humidity should increase along with the pressure and temperature in containment. However, many PWR containments operate with fairly high humidities during normal operations. As a result, an increase in relative humidity is not nearly as significant as increases in containment pressure and temperature as an indication of a LOCA.

4.3.3.4 Containment Activity. A main steam line break will cause many of the same indications as a LOCA. Containment activity is one of the best indications to differentiate between the two occurrences. Containment activity is normally low. During a LOCA, activity from the RCS will be discharged to the containment atmosphere. This activity will cause the area radiation monitors in containment to read high during a LOCA.

4.3.3.5 Containment Sump Level. Rising sump levels are indicative of some type of pipe break in containment. If this is coupled with high containment activity levels it is an indication of a break in the RCS; i.e., of a LOCA.

4.3.4. BWR Indications Internal to the Reactor Coolant System

The indications of a loss of reactor coolant in a BWR are similar in many respects to those for a PWR. The presently measured indications of conditions internal to the Reactor Coolant System include:

- Temperature
- Flow
- Pressure
- Reactor vessel level
- Nuclear instrumentation

4.3.4.1 Temperature. Temperature indications in BWRs are not as abundant as in PWRs, nor are they relied upon as heavily as in PWRs. Typically, temperature is inferred from pressure since normal operation is at saturation conditions. Recirculation loop temperatures are available; steam line temperatures may be available at some plants. Overall, temperature is not a primary indicator of a loss-of-coolant accident.

4.3.4.2 Flow. As with a PWR, the power production rate in a BWR is limited not by the energy production rate, but by the energy removal rate. Thus, BWRs require a minimum flow rate for a given reactor power. Typically, the reactor coolant mass flow rate is monitored by measuring the differential pressure across a venturi in the steam line piping leaving the reactor vessel.

BWRs have abundant core flow information available. Total core flow is obtained by summing the flow through each jet pump (see Figure 4-13), and is displayed in the control room. Individual jet pump flows are available at a remote panel. Core plate differential pressure is recorded and can be used to determine gross changes in core flow or flow distribution. Recirculation loop flow, which provides the driving flow to the jet pumps, also is displayed.

A LOCA would reduce the flow rate through the core. As previously stated, inadequate core flow would result in an increase in cladding temperature, which could lead to an ICC condition. However, flow anomalies could also indicate the onset of core cooling problems. For example, variation in the individual jet pump flow rates could indicate an abnormal distribution of reactor coolant entering the reactor core.

4.3.4.3 Pressure. Reactor vessel pressure is sensed using the reactor vessel level reference legs. Pressure signals are provided to the ECCS and Feedwater Control System. A rapid pressure drop is one of the principal indications of a LOCA.

4.3.4.4 Reactor Vessel Level. Reactor vessel level indications are abundant in BWRs. Typically, four or more ranges are available; use of a particular range depends on the operating conditions in the core. Figure 4-14 is an example of the level ranges.[4-9] Since the detectors for each range are separate, and since overlapping exists between ranges, there is redundant level indication in the control room. Level is measured by comparing the pressure exerted by a fixed column of water in a reference leg to the pressure exerted by the height of water in the vessel, as schematically shown in Figure 4-15. The reference leg is at a lower temperature than the vessel, and, thus, there will be a density difference between the water in the vessel and the reference leg. This difference will result in an error in the indicated level. Various methods are employed to account for the density effect during normal operation, including:

- Correcting the signal from the level transmitter with a milliampere signal proportional to vessel pressure
- Calibrating the level range instruments with respect to the containment environment that would exist when the range would normally be used
- Making no correction, since error makes level indication more conservative (acutal level > indicated level)

If a LOCA occurred, a rapid drop in reactor vessel water level would occur. This drop would be an immediate indication of a LOCA.

Once the released coolant enters the containment it will heat up the atmosphere and surroundings, including the reference leg. This would reduce the temperature, and density, difference between the two legs, causing a higher than actual level indication. For the postulated DBA-LOCA, the reactor vessel water level indication can be 10 to 15% in error for the expected temperature rise in containment. If the reference leg water should flash to steam, the reactor vessel water level indication can become useless. Therefore, it is important to remember that once a LOCA has started the indicated vessel level may become invalid.

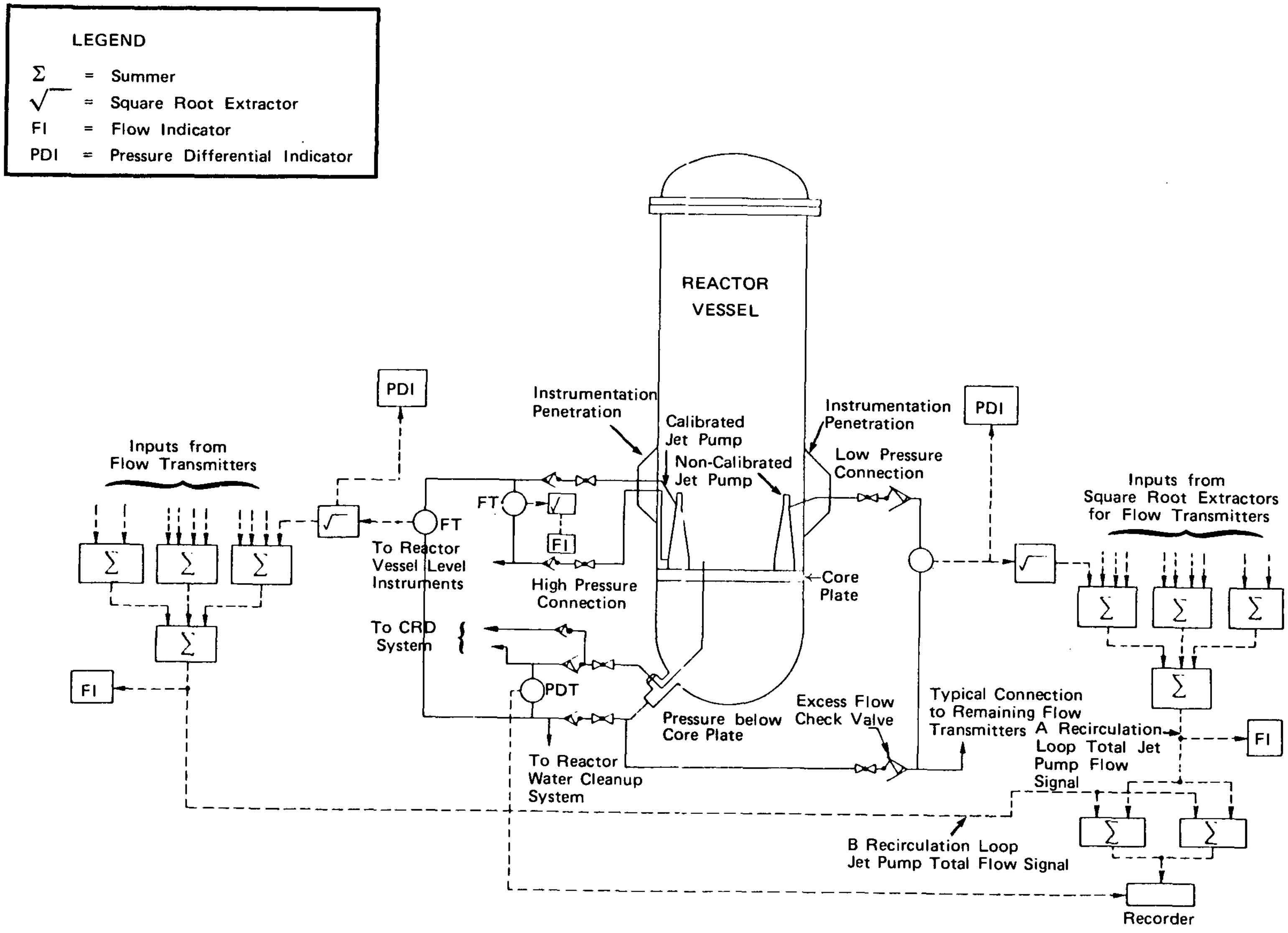


Figure 4-13. Jet Pump Instrumentation Block Diagram

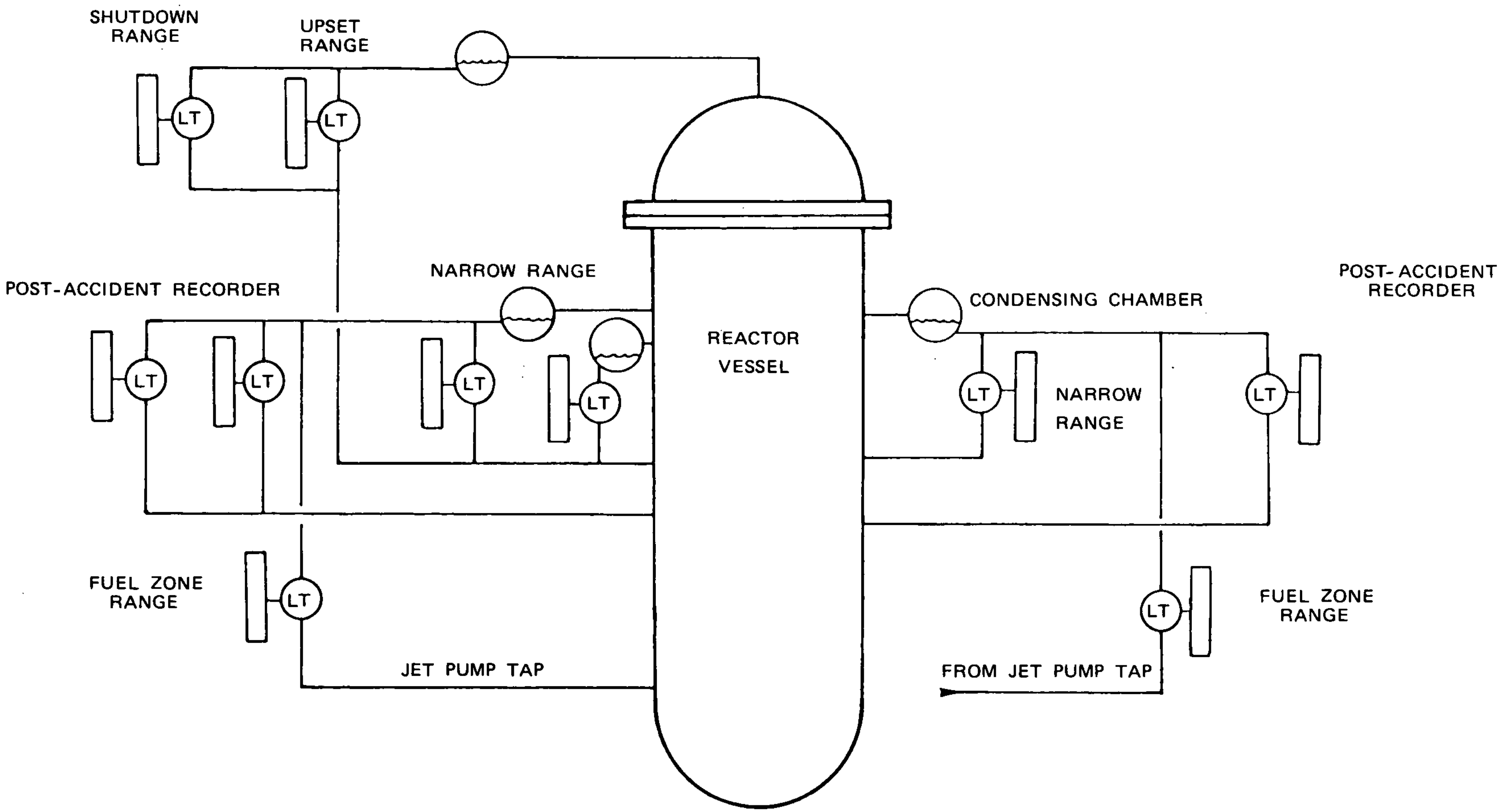


Figure 4-14. Reactor Vessel Level Instrumentation - Simplified Diagram

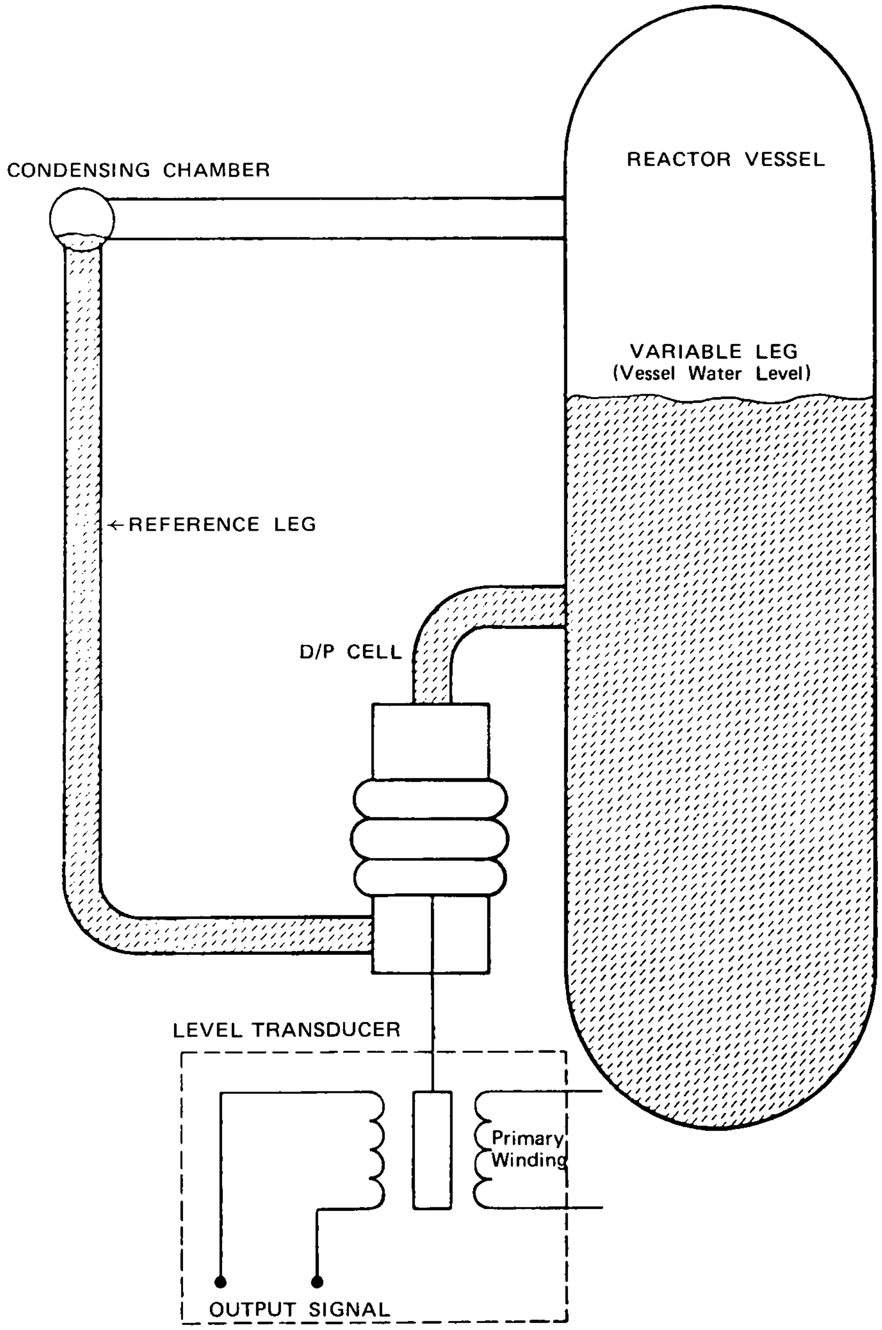


Figure 4-15. Typical Reactor Vessel Level Detector

4.3.4.5 Nuclear Instrumentation. The Neutron Monitoring System (NMS) for a BWR consists exclusively of incore instrumentation. The source range monitors (SRMs) and intermediate range monitors (IRMs) are both movable detector systems. They employ miniature fission counters (pulse-type output) and miniature fission chambers (current-type output) respectively. BWR facilities also employ fixed incore fission chambers in the Local Power Range Monitoring (LPRM) System.

Because of their greater sensitivity, it is the source range and intermediate range nuclear instrumentation systems that can be of most value in ascertaining the severity of a LOCA. Note that these detectors exhibit a response to both thermal neutrons and gamma radiation. The detector response to gamma radiation is pulses of a smaller amplitude than those caused by neutrons, due to a lesser detector sensitivity to gamma radiation. Ordinarily, the gamma ray component to the detector output may be reduced or removed by one of the following techniques:

- Setting a pulse discriminator in the detector circuit to remove the smaller amplitude gamma ray-induced pulses.
- Employing a counting statistics technique that results in making the gamma response negligible (the Campbelling Technique)

Thus, during normal operation, the detector output corresponds directly to the neutron flux, and, hence, to the core power level.

If a LOCA occurred, two-phase flow through the core would increase. Thus the fluid density in the core would be less. Since the neutrons are slowed down by the coolant, a decrease in density would increase the mean free path of the neutrons. This increased mean free path would result in a higher neutron flux at the detectors, and therefore, in an increase in detector output.

However, as the detector itself becomes uncovered and the two-phase flow becomes pure steam, detector output should drop because the fission detector is more sensitive to thermal neutrons than to the high energy neutrons initially emitted by the fission process.

4.3.5 BWR Indications External to the Reactor Coolant System

There are several indications external to the Reactor Coolant System that are indicative of a LOCA in a BWR. These are:

- Drywell/containment pressure
- Drywell/containment temperature
- Drywell/containment activity
- Suppression pool water level

(Note: Drywell/containment refers to the drywell in Mark I or II BWR designs, but to both the drywell and containment in a Mark III BWR design.)

4.3.5.1 Drywell/Containment Pressure. BWRs employ a pressure monitoring system that continuously monitors the pressure in the drywell and suppression pool (torus at some facilities). This system is capable of detecting a leak in the Reactor Coolant System and of measuring the pressure increase arising from a LOCA.

4.3.5.2 Drywell/Containment Temperature. The drywell containment temperature monitors measure drywell atmosphere, suppression pool atmosphere, and suppression pool water temperature. The temperature sensors are situated to ensure that representative measurements are obtained. A rapid rise in temperature can be an indication of a LOCA. (The general vicinity of the break can be determined if a rise is seen on one sensor, followed by rises on nearby sensors.)

4.3.5.3 Drywell/Containment Activity. BWRs employ a fission product radiation monitoring subsystem that monitors air particulate iodine and noble gases within the drywell containment. If the detected radiation exceeds a predetermined value, an annunciator is energized in the control room. If a LOCA occurred, this alarm should be energized.

In addition, there are drywell/containment and suppression pool gamma radiation monitors. These monitors are intended to be operable following a design basis accident. High level alarms associated with this instrumentation would also be annunciated in the control room.

4.3.5.4 Suppression Pool Water Level. Water level in the suppression pool is continuously monitored. The instrument provides trip logic for the reactor and for Emergency Core Cooling System actuation if a high level is reached. A high level in the suppression pool is yet another indication of a LOCA.

4.4 INDICATIONS OF HYDROGEN PRODUCTION

The previous section emphasized those parameters that should be examined to determine whether a loss-of-coolant accident has occurred. The existence of a LOCA is of great concern because it can be the first step toward an inadequate core cooling condition. An ICC condition could ultimately develop into a condition in which hydrogen could be liberated by the steam reaction with the fuel cladding, and, eventually, by other reactions if the accident is not terminated (see Chapter 2). If this occurred, there are a great number of potential indications, in addition to hydrogen detectors within the containment, of the presence of hydrogen or of whether a hydrogen combustion occurred. The following discussion examines each of these parameters individually, and discusses their behavior if hydrogen were liberated during an accident condition.

The indications of hydrogen production internal to the Reactor Coolant System will be considered first, followed by those indications that are external to the Reactor Coolant System. Keep in mind when reading this section that instrumentation varies from plant to plant, thus not all indicators will be available at every nuclear power station.

Further, various indications of an inadequately cooled core and the resultant production of hydrogen will be discussed. The existence of any one of these indications may or may not indicate hydrogen production. One must examine all available data, and then make a knowledgeable assessment of the actual core conditions.

One of the principal lessons learned from the TMI incident was that key operational or safety decisions should not be made based on a single parameter;

instead all available data should be evaluated before rendering an important safety decision during a plant emergency. This lesson should be kept in mind when reading the subsequent material.

It will be seen later in this chapter that it is not necessary to be absolutely sure that hydrogen is present. Not every mitigation scheme requires the absolute certainty of the presence of hydrogen before it is initiated. For example, one scheme, a hydrogen igniter system, may be placed in service if only the possibility of hydrogen production exists.

4.4.1 Indications of Hydrogen Production Internal to the Reactor Coolant System of a PWR

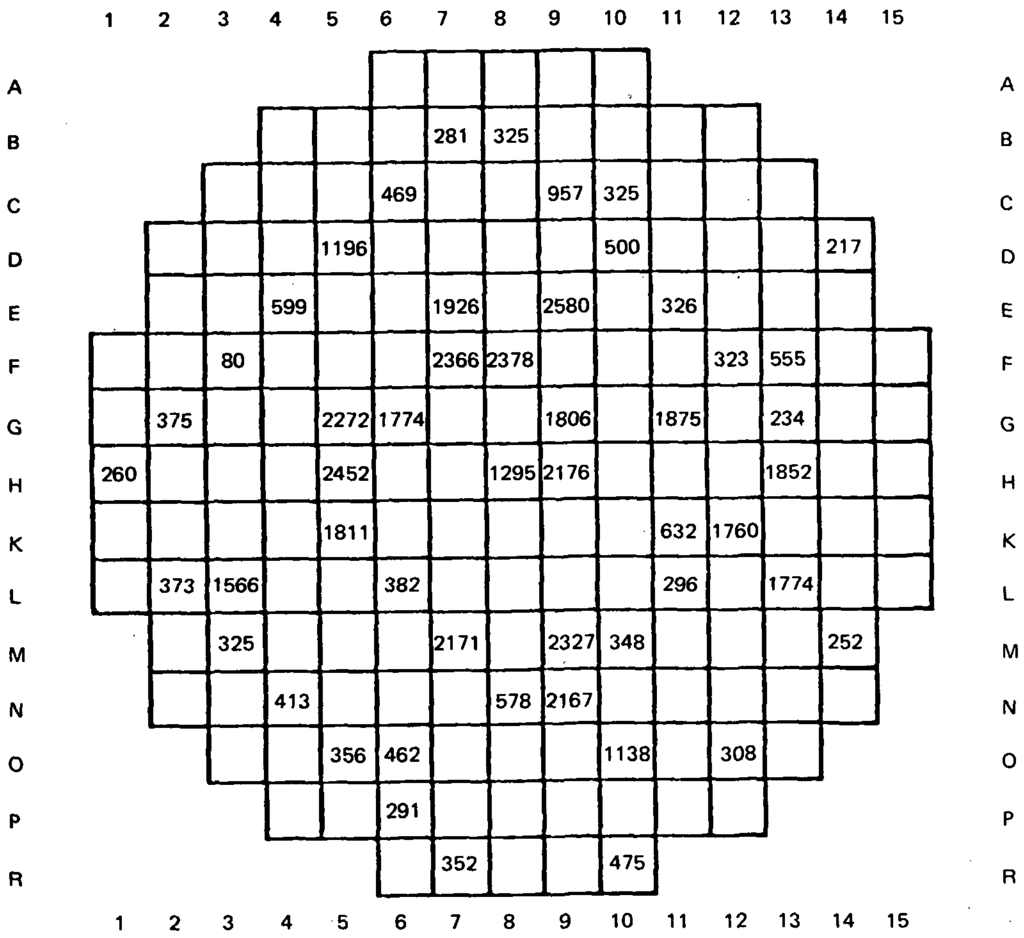
4.4.1.1 Temperature. The incore thermocouple system may be helpful in determining if a hydrogen-producing environment exists within the reactor vessel. For example, Figure 4-16 shows the core exit thermocouple readings that occurred during the TMI-2 incident. From these data taken at approximately 1000 psig, it can be seen that reactor coolant inventory must have been low and superheated conditions must have existed at various core locations. Thus, a distinct probability existed that hydrogen production had commenced.

Temperature can provide a first indication of the extent of core damage (hence, of hydrogen production). The thermocouple system provides a map of core exit temperatures and can thus be used to determine if the entire core is inadequately cooled or if the phenomenon is localized (see Figure 4-16). An abnormally low temperature reading (such as F3 in Figure 4-16) may be due to thermocouple failure caused by excessive core damage.

Another indicator of poor thermal-hydraulic conditions and of possible hydrogen production in the core is the hot leg temperature, which is measured by an RTD. RTDs can be installed in a thermowell directly in the RCS hot leg piping (Combustion Engineering and Babcock & Wilcox plants) or in a bypass manifold connected to the RCS (Westinghouse design). The most frequently used metal for the RTD is platinum, which has a resistance linearly dependent on temperature to about 1250°F. A temperature above saturation temperature for the operating pressure would be indicative of a significant amount of voiding in the core and the production of superheated steam. This abnormal thermal hydraulic condition would not adequately remove the stored energy of the cladding. Thus, an increase in cladding temperature and, possibly, in the metal-water reaction rate would occur. Obviously, if this reaction rate increases, more hydrogen is produced. (Above 1800°F one may assume that the hydrogen generation commences as a result of the water reaction with the clad.)

4.4.1.2 Flow. Reactor coolant flow indication does not by itself indicate that hydrogen production is occurring. However, if adequate core cooling (i.e., coolant flow) is not maintained for the existing power level, the cladding temperature will increase. If this situation continues to the point that an ICC condition develops, hydrogen production can occur.

Flow anomalies may also indicate the onset of an ICC condition that could lead to hydrogen production. There are several potential causes of flow anomalies,



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
A															
B							281	325							
C						469			957	325					
D					1196					500				217	
E				599			1926		2580		326				
F			80				2366	2378				323	555		
G		375			2272	1774			1806		1875		234		
H	260				2452			1295	2176				1852		
K					1811						632	1760			
L		373	1566			382					296		1774		
M			325				2171		2327	348				252	
N				413				578	2167						
O					356	462				1138		308			
P						291									
R							352			475					

Figure 4-16. Map of Core Exit Temperatures (^{O}F) at 240-300 Minutes for the TMI-2 Incident

one of which is the collection of steam or noncondensable gases (such as hydrogen) at high points in the RCS. During the incident at TMI, gases collected in the "candy cane" regions of the RCS piping at the steam generator inlets (see Figure 4-17).

Abnormal reactor coolant pump indications may indicate flow anomalies. Abnormal indications may include:

- Decrease in pump motor current
- Increase in pump temperature
- Increase in pump vibration

During operations, if indications of less than normal flow or of flow anomalies are present, other instrumentation should be checked for evidence of hydrogen production.

When reactor coolant pumps (RCPs) are secured and natural circulation cooling is employed, core flow is determined from a differential temperature measurement.

Using the abundant temperature information available from PWR process instrumentation, an estimate of the flow rate can be calculated using the simple heat transfer relationship:

$$\dot{Q} = \dot{m} c_p \Delta T \qquad (4\text{-}1)$$

where: $\Delta T = T_h - T_c$ (4-2)

T_h = hot leg temperature (°F)

T_c = cold leg temperature (°F)

$\dot{Q}$ = rate of energy transfer (Btu/h)

m = mass flow rate ($lb_{m/h}$)

c_p = specific heat capacity of water at constant pressure (Btu/lb_m-°F)

A high ΔT (e.g., greater than full power ΔT) would indicate an inadequate core flow rate for the power generation rate. Hence, cladding temperatures may rise above the threshold for the metal-water reaction. This ΔT is an extremely important indication of cooling flow during natural circulation cooldown. Further, any noncondensable gas binding of the RCS piping would be manifested by a high ΔT during a natural circulation cooldown.

4.4.1.3 Pressure. By itself, pressure cannot be used to verify the presence of hydrogen. However, the operator may be able to use pressure in conjunction with other parameters to verify that hydrogen is present. For example, assume that a LOCA has occurred that resulted in an inadequate core cooling condition and hydrogen production. Further, assume that RCS pressure has been restored and that there is a void in the upper part of the reactor vessel (determined by measuring reactor vessel water level). If under these circumstances, the Reactor Coolant System is rendered subcooled and the void remains, then it can be assumed that this is a noncondensable gas void. Further, if in trying to increase RCS pressure a sharp pressure increase is observed, this noncondensable gas is displaying the hard bubble phenomenon previously described in Chapter 3.

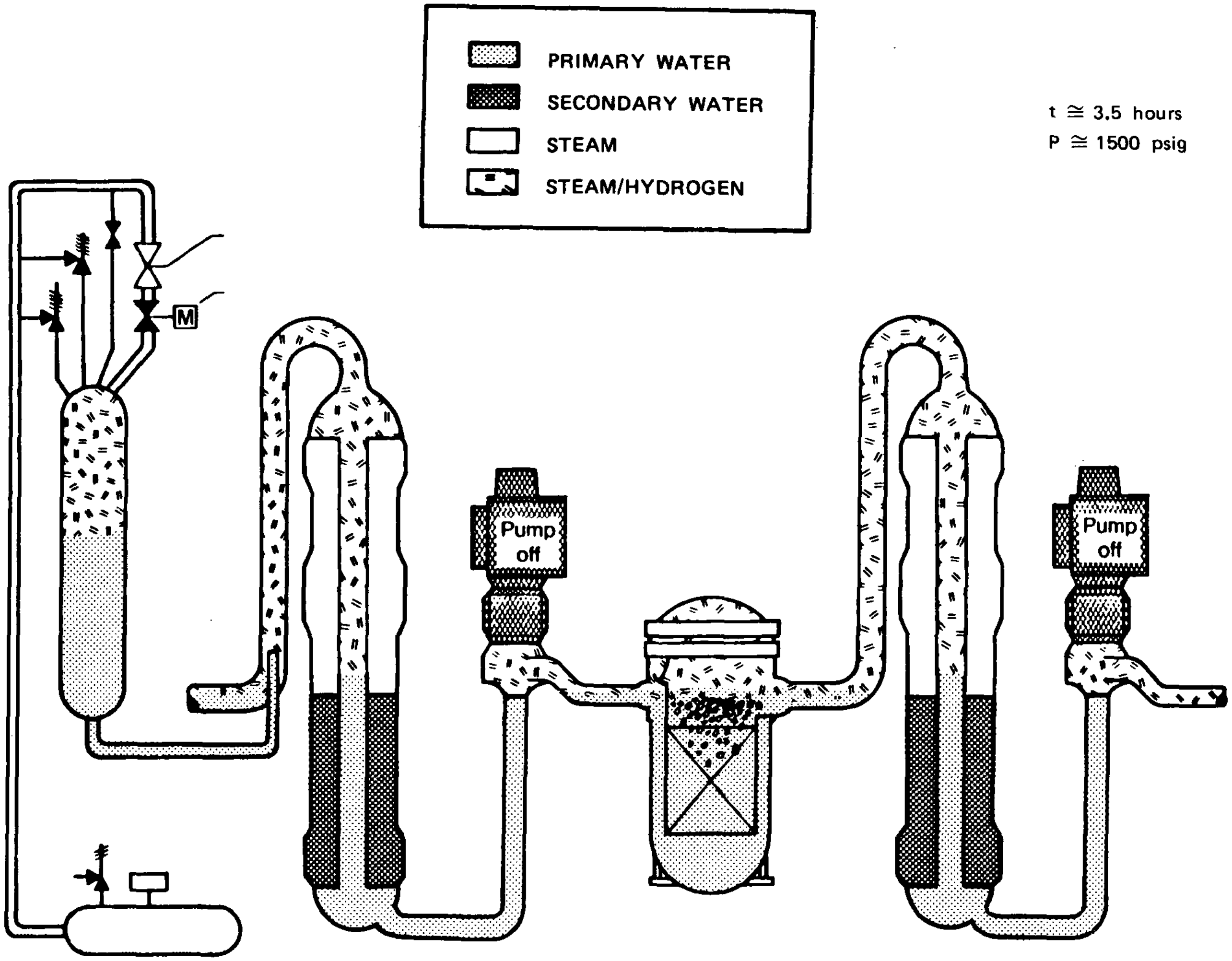


Figure 4-17. Reactor Vessel Refilled by Manual Initiation of Safety Injection Core Temperatures Decreasing

The non-condensable gas void may also be comprised of nitrogen from the ECCS nitrogen accumulators (or safety injection tanks or core flood tanks, depending on the plant) used at many PWR facilities. To know whether this is so, one must know whether these tanks, which use compressed nitrogen gas, actually discharge into the RCS.

In summary, with noncondensable gases present in the RCS, pressurizer pressure control would not respond normally. If this is the case, the guideline in Appendix II may be used to determine the size or the gaseous void.

4.4.1.4 Pressurizer Level. The presence of hydrogen in the Reactor Coolant System will cause pressurizer pressure and level controls to respond abnormally. As has been mentioned, the presence of noncondensables (such as hydrogen) creates a hard bubble phenomenon. That is, from a pressure viewpoint, the hydrogen void almost appears as a solid water volume.

In general, pressurizer level must be used in conjunction with other parameters, such as temperature and pressure, to indicate the presence of hydrogen. Abnormal behavior, such as a sharp RCS pressure rise resulting from a small pressurizer level increase, would be expected if the hard bubble phenomenon exists.

4.4.1.5 Reactor Vessel Water Level. A major concern during accident transients is to ensure that the core is covered by reactor coolant. High and low pressure safety injection systems are designed to ensure coolant is available even during the most limiting accident conditions. Obviously, without enough water to cool the core, cladding temperatures will rise, resulting in hydrogen production from the metal-water reaction. Thus, reactor vessel level is an extremely important parameter to observe to ensure adequate core cooling.

PWR facilities are currently installing or planning to install either differential pressure sensors or heated-junction thermocouple systems to determine reactor vessel water level.

4.4.1.6 Reactor Coolant Sampling. The reactor coolant can be sampled for many items, including hydrogen concentration. When the coolant is sampled for hydrogen, a liquid sample is drawn. While this will indicate the presence of hydrogen in the RCS, it will not be an accurate measure of the concentration in the pressurizer steam space. To obtain such a measurement, a gaseous sample would have to be drawn.

4.4.1.7 Reactor Coolant Activity. The reactor coolant normally will contain activation products. The source of these radionuclides may be the water itself, structural material in the core, a suspended (insoluble) solid, a soluble neutron absorber such as boron, a soluble corrosion product, or other impurities in the water. The major sources of long-lived radioactivity identified in the RCS are activation products.

These activation products should not be confused with fission products that could be released into the reactor coolant if an ICC condition led to fuel damage. Inadequate core cooling can result in fuel damage from a steam reaction with the fuel cladding (see Chapter 2). Therefore, abnormally high RCS activity could denote fuel damage.

The presence of fuel damage, then, is a potential indicator of a steam-cladding reaction; such a reaction would liberate hydrogen. Therefore, it is safe to say that any time there is significant fission product leakage into the RCS, there should be an ever-present concern about hydrogen production.

Differentiating between activation products and fission products is relatively straightforward. It is a matter of utilizing standard laboratory counting techniques to identify the individual radionuclides in an RCS sample. Table 4-3 lists the primary coolant activation products, along with their major source in the RCS.

Table 4-3

PRIMARY COOLANT ACTIVATION PRODUCTS

Nuclide	Half-life	Reaction	Major source
^{3}H	12.26 yr	$^{10}B(n,2\alpha)^{3}H$	Boron in coolant
		$^{6}Li(n,\alpha)^{3}H$	Lithium in coolant
^{14}C	5730 yr	$^{14}N(n,p)^{14}C$	Nitrogen in water
^{16}N	7.1 s	$^{16}O(n,p)^{16}N$	Water
^{17}N	14.4 s	$^{17}O(n,p)^{17}N$	Water
^{18}F	110 min	$^{18}O(p,n)^{18}F$	Water
^{13}N	9.96 min	$^{16}O(p,\alpha)^{13}N$	Water
^{24}Na	15 h	$^{23}Na(n,\gamma)^{24}Na$	Impurity in water
^{31}S	2.6 h	$^{30}Si(n,\gamma)^{31}Si$	Impurity in water
^{32}P	14.3 d	$^{31}p(n,\gamma)^{32}p$	Impurity in water
^{41}Ar	1.83 h	$^{40}Ar(n,\gamma)^{41}Ar$	Air in water
^{51}Cr	27.8 d	$^{50}Cr(n,\gamma)^{51}Cr$	Steel & high-nickel alloys
^{54}Mn	312 d	$^{54}Fe(n,p)^{54}Mn$	Steel & high-nickel alloys
^{55}Fe	2.7 yr	$^{54}Fe(n,\gamma)^{55}Fe$	Steel & high-nickel alloys

^{56}Mn	2.6 h	^{55}Mn(n,γ)^{56}Mn	Steel & high-nickel alloys
^{59}Fe	45 d	^{58}Fe(n,γ)^{59}Fe	Steel & high-nickel alloys
^{59}Ni	8×10^{4} yr	^{58}Ni(n,γ)^{59}Ni	Steel & high-nickel alloys
^{63}Ni	92 yr	^{62}Ni(n,γ)^{63}Mo	Steel & high-nickel alloys
^{65}Ni	2.6 h	^{64}Ni(n,γ)^{65}Ni	Steel & high-nickel alloys
^{58}Co	71 d	^{58}Ni(n,p)^{58}Co	Steel & high-nickel alloys
^{60}Co	5.24 yr	^{59}Co(n,γ)^{60}Co	Stellite steel
^{64}Cu	12.9 h	^{63}Cu(n,γ)^{64}Cu	17-4 pH steel
^{95}Zr	65 d	^{95}Zr(n,γ)^{95}Zr	Zircaloy-4
^{97}Zr	16.8 h	^{96}Zr(n,γ)^{97}Zr	Zircaloy-4
^{110m}Ag(a)	253 d	^{109}Ag(n,γ)^{110m}Ag	Control rod (b)
^{115}Cd(a)	53.5 h	^{114}Cd(n,γ)^{115}Cd	Control rod (b)
^{181}W	130 d	^{180}W(n,γ)^{181}W	Steel, carbides, stellite
^{187}W	24 h	^{186}W(n,γ)^{187}W	Steel, carbides, stellite

(m) Denotes a metastable state.
(a) In plants with B_4C control rods fission is the only source of these nuclides.
(b) Also a fission product.

From Table 4-4, it can be seen that hydrogen, in the form of radioactive tritium, can be produced within the reactor coolant. Tritium, however, can also be produced in the nuclear fuel by means of ternary fission. (Ternary fission results in three fission products instead of the usual two from binary fission.) Ternary fission occurs approximately once out of every 12,000 fission events in the reactor.

Table 4-4

SOURCES OF TRITIUM FROM NEUTRON REACTIONS

Reaction	Threshold
$^{10}B(n,2\alpha)T$	1 MeV
$^{10}B(n,\alpha)^{7}Li(n,n\alpha)T$	Thermal;3 MeV
$^{10}B(n,2\alpha)T$	10.0 MeV
$^{7}Li(n,n\alpha)T$	3 MeV
$^{6}Li(n,\alpha)T$	Thermal
$^{2}D(n,\gamma)T$	Thermal

The list of fission products is extensive; Table 4-5 shows a partial listing in order of decreasing escape rate coefficients. (Those with the greatest probability of escape have the highest escape rate coefficients.) Those that escape most readily are the fission product gases, or volatile fission products. Table 4-5 also includes the semi-volatile fission products, such as the iodine isotopes, and the non-volatile fission products.

Table 4-5

FISSION PRODUCTS

Nuclide	Half-life	Nuclide	Half-life
^{131m}Xe	11.96 h	^{137}Cs	30.2 yr
^{133m}Xe	2.26 d	^{138}Cs	32.2 min
^{133}Xe	5.27 d	^{89}Sr	50.8 d
^{135m}Xe	15.70 min	^{90}Sr	28.9 yr
^{135}Xe	9.16 h	^{91}Sr	9.67 h
^{138}Xe	14.20 min	^{92}Sr	2.69 h
^{85m}Kr	4.40 h	^{88}Rb	17.7 min
^{85}Kr	10.74 yr	^{89}Rb	15.2 min
^{87}Kr	76.00 min	^{99}Mo	66.6 h
^{88}Kr	2.79 h	^{139}Ba	84.0 min

$^{131}\mathrm{I}$	8.065 d	$^{140}\mathrm{Ba}$	12.8 d
$^{133}\mathrm{I}$	20.8 h	$^{140}\mathrm{La}$	40.2 h
$^{141}\mathrm{Ce}$	32.5 d	$^{143}\mathrm{Pr}$	13.6 d
$^{143}\mathrm{Ce}$	33.0 h	$^{144}\mathrm{Pr}$	17.3 min
$^{134}\mathrm{I}$	52.30 min	$^{90}\mathrm{Y}$	64.0 h
$^{135}\mathrm{I}$	6.70 h	$^{91}\mathrm{Y}$	58.8 d
$^{134}\mathrm{Cs}$	2.06 yr	$^{92}\mathrm{Y}$	3.54 h
$^{136}\mathrm{Cs}$	13.00 d	$^{93}\mathrm{Y}$	10.1 h
$^{95}\mathrm{Nb}$	3.5 d	$^{144}\mathrm{Ce}$	284.4 d
$^{102}\mathrm{Ru}$	39.4 d	$^{132}\mathrm{Te}$	78.0 h

4.4.2 Indications of Hydrogen Production External to the Reactor Coolant System of a PWR

4.4.2.1 Containment Pressure. If hydrogen is liberated into containment following a LOCA as a result of a steam reaction with the fuel cladding, there would be an increase in containment pressure. However, a containment pressure increase will also occur as a result of reactor coolant flashing to steam following a Reactor Coolant System break. Therefore, a pressure increase in containment is not, by itself, a sufficient indicator of the presence of hydrogen. However, the existence of a LOCA should caution the operational staff that the potential for hydrogen production exists.

4.4.2.2 Containment Temperature. If a LOCA occurred containment temperature would rise as coolant was released into the containment building. If hydrogen is created within the reactor core by a fuel cladding-steam reaction, and subsequently released to the containment, it would be impossible to detect its presence from temperature effects alone. However, as with a containment pressure increase, the containment temperature increase indicates the potential for hydrogen production.

4.4.2.3 Containment Humidity. Since many pressurized water reactor stations operate with high relative humidities in containment during normal full-power operation, the use of this parameter as an indicator of the presence of hydrogen seems somewhat unlikely. However, for those facilities whose relative humidity in containment is significantly less than 100%, a sudden increase in humidity is indicative of a loss-of-coolant condition (although, it may be only an excessive RCS leakage condition). As a result, a sudden increase in containment humidity should be compared with other parameters discussed in this section, because a possible ICC condition may be approached. Approaching an ICC condition could ultimately result in hydrogen production from the reaction between the hot steam in the core and the hot fuel cladding.

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4.4.2.4 Containment Sampling. Post-accident sampling of the containment is, of course, a direct method of determining the presence of hydrogen. During examination of the containment atmosphere sample it is important to determine the oxygen concentration as well, since this measurement can be used to determine the amount of hydrogen initially present in the containment atmosphere. This is true because a drop in the oxygen concentration would occur during a hydrogen combustion. In order to use this technique, however, the containment must be sampled with sufficient frequency to ensure that an accurate measure of the oxygen concentration exists. If it is known then any sudden drop in oxygen concentration clearly would be indicative of a reaction with the hydrogen in containment.

For example, during the TMI-2 incident, the hydrogen and oxygen concentrations were measured 3 days following the onset of the incident. On March 31, 1979, at 0600 hours, the hydrogen and oxygen concentrations of a sample of dry air in containment were measured to be:[4-11]

- H_2 concentration = 1.7%
- O_2 concentration = 16.1%

(Note: These data are from a dried air sample. In the sample, hydrogen oxygen, and nitrogen concentration are measured; the sum of their concentration equals 100%.)

Because the precise oxygen concentration was not known prior to the start of the incident, the TMI staff engineers assumed that it was the normal concentration in dry air, i.e., 20.9%. With this assumption, the oxygen concentration would have dropped a total of:

20.9% - 16.1.% = 4.8%

Since 2 moles of hydrogen react with one mole of oxygen to form water, the amount of hydrogen that was initially burned would have been:

2 x 4.8% = 9.6%

These calculations are based upon the oxygen concentration in containment being 20.9%. However, there is reason to believe that the oxygen concentration in a dry atmospheric containment is less than the standard concentration for normal air. The oxygen in containment can react with many type of metals; the resultant oxidation of the metals in containment would tend to reduce the free oxygen concentration to less than 20.9%. If this was the case at TMI-2, then the drop in the oxygen concentration would have been less that 4.8%, and, hence, the actual hydrogen concentration would have been less than 9.6.*

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* Because of the conditions existing at TMI, this calculation may be considered valid. In any case, it should have been conservative. However, it should be emphasized that this method cannot be used at all times. Oxygen concentration may be reduced by other methods besides reaction with hydrogen. For example, injection of a gas into containment will lower the oxygen mole fraction. Therefore, it cannot always be assumed that the difference between the final and initial oxygen concentrations corresponds to the amount of oxygen that reacted with hydrogen.

4.4.2.5 Steam Line Radiation. The steam generator tube rupture has the potential for a large off-site radioactivity release. If the Emergency Core Cooling System (ECCS) capabilities are hampered in some way, this particular accident could ultimately result in a degraded-core condition. If an ICC condition were to exist, then hydrogen could be produced by steam reaction with the hot fuel cladding. Releasing hydrogen through the ruptured steam generator tube(s) is highly undesirable because it could be released to the environment along with the fission product radioactivity from the damaged fuel. If ignited by some spark upon its release (through a steam line power-operated relief valve (PORV), for example), it could damage the valve through which release was taking place. This could also provide a fission product release path from the RCS to the steam line (via ruptured steam generator tubes) and directly to the environment through a damaged relief valve.

The presence of high steam line radiation is not a sufficient indicator of hydrogen production, but it is a good warning to key the operations staff to ensure that emergency core cooling is maintained to guarantee sufficient core cooling, so as not to allow an emergency condition such a this to result in a degraded-reactor-core condition.

4.4.2.6 Gross Radiation Level Detection. A previous section discussed the nuclides in the RCS that could indicate potential reactor core damage. It should be emphasized that at any time when RCS activity levels are rising, the vital RCS parameters should be monitored and evaluated to determine the source of this activity. An increasing RCS activity could point to existing or potential fuel damage which could ultimately lead to hydrogen generation.

An example where radiation level detection could have been used as a potential indication of a degraded core condition and possible hydrogen production occurred during the TMI-2 incident. Here an RCS sample was being taken during the morning of the incident and was being recirculated in the sample line in an effort to get a representative sample. As a result of the sampling operation, radiation levels became unusually high in the sample area. This unusually high radiation level warranted notification of the shift supervisor. If the shift supervisor had known about the high RCS activity, he would have had an additional clue that a possible damaged core situation existed.

Gross radiation indications from reactor coolant samples are one measure of potential core damage that could lead to hydrogen generation. High radiation in the containment is another measure of potential reactor core damages. In an effort to be better prepared to monitor this, nuclear power stations are installing higher range area radiation monitors in containment.

At TMI-2, the radiation monitor in containment had a range of 10^6 R/hr, which was adequate to meet the conditions of the accident. In a review of the monitoring capabilities of other plants shortly after the TMI-2 incident, however, it was found that very few operating facilities had instrumentation capable of measuring in excess of 10^6 R/hr.[4-5] For this reason, the NRC recommended that high range monitors capable of reading up to 10^8 R/hr be installed.[4-12]

Sharply increasing radiation levels from RCS samples or containment area radiation monitors are a possible measure of a degraded reactor core. These levels can, in fact, indicate the likelihood of hydrogen generation. Therefore, they should be considered as yet another indication for operations personnel to consider in analyzing the severity of an emergency condition.

4.4.3 Indications of Hydrogen Production Internal to the Reactor Coolant System of a BWR*

4.4.3.1 Temperature. Temperature instrumentation for the BWR Reactor Coolant System is found in the recirculation loops, where thermocouples mounted on the piping measure the temperature of the recirculation flow. In addition, thermocouples are mounted in a pre-determined pattern over the outside of the reactor pressure vessel to monitor vessel skin temperatures. During heatup and cooldown conditions these thermocouples are used to ensure that thermal stresses applied to the vessel walls do not exceed the prescribed limitations of the reactor vessel brittle fracture considerations that are outlined in Appendices F and G of 10CFR50.[4-13]

It has been suggested[4-2] that reactor vessel temperature instruments not be utilized during large scale LOCas. The vessel thermocouples provide heatup or cooldown information for normal evolutions where one is concerned with reactor vessel stresses; they do not give an accurate measure of core temperature. On the other hand, recirculation flow temperature is indicative of core temperature during periods of recirculation pump operation. However, during a LOCA in which recirculation pump flow is lost, these loop temperatures will not provide an accurate measure of core temperature.**

For these reasons, the usefulness of the Reactor Coolant System temperature instruments as an indicator of hydrogen production is quite limited.

4.4.3.2 Flow As mentioned in section 4.3, abundant core flow information is available for a BWR. For example, core plate differential pressure is recorded and can be used to determine gross changes in core flow or flow distribution. Recirculation loop flow, which provides the driving flow to the jet pumps, is also displayed. Jet pump flows are also monitored.

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* In BWR facilities employing an inerted drywell (primary containment), oxygen detection is also important because the possibility of oxygen production during the radiolysis process will exist following a LOCA.

** This is based on several discussions concerning the use of skin temperature thermocouples as a potential indicator of an ICC condition. These discussions were with members of the operational staffs of several BWR facilities, including:

- Susquehanna Steam Electric Station (January 1981)
- James A. FitzPatrick Nuclear Power Plant (April 1981)
- Grand Gulf Nuclear Station (September 1981)

Inadequate core flow will result in an increase in cladding temperature that could lead to hydrogen production. Similarly, an abnormal distribution in core flow can indicate a possible cooling restriction that may lead to an ICC condition and to hydrogen production.

Finally, abnormal operation of the recirculation pumps may indicate a flow anomaly such as two-phase flow. This, too, could indicate a possibility of hydrogen production as a result of inadequate core cooling.

4.4.3.3 Pressure. Operating experience has shown that reactor pressure is a good indicator of the conditions existing in the BWR core during many accident conditions.4-14 For example, during a DBA-LOCA, a rapid depressurization will take place as soon as the liquid inventory in the downcomer and separator region is depleted and steam exits the break. Typically, this would require only about 9 seconds from the time the break occurs; within approximately 30 seconds, the reactor vessel would be completely depressurized. During the period of almost zero vessel pressure, the core would still be generating a large amount of heat and would most likely have fuel temperatures approaching 2000°F in the most severely affected areas. The effect of high temperature coupled to low system pressure may result in a superheated steam bubble region in the core although natural circulation may preclude this. Although the pressure instrumentation would still indicate actual core pressure, it definitely would not be representative of core temperature under these conditions and thus, should not be used as a measure of reactor coolant temperature. Therefore, when considering the probability of hydrogen production, pressure should be compared against other parameters such as temperature and reactor vessel water level.

4.4.3.4 Reactor Vessel Water Level. To ensure that the probability of hydrogen production is minimized, reactor vessel water level must be maintained sufficiently high to provide adequate core cooling. To monitor this, the reactor vessel water level instrumentation is used. However, during an accident condition this level instrumentation may become inaccurate. One problem encountered with the reactor vessel level instrumentation in older BWRs during post-accident use is related to the physical location of the heated reference column.[4.15] Differences between measured and actual vessel level can result when large changes in drywell temperature occur as a result of a DBA-LOCA, due to the fact that at most plants the heated reference leg is located outside the reactor vessel as shown for the Yarway-type instrument in Figure 4-18. This effect could also be encountered during a steam line break inside the drywell. As a large increase in drywell temperature occurs, the reference leg heats up. As the temperature of the reference leg increases, the density of the water in it decreases.

Since actual level measurement is a function of differential pressure (Δp), a density decrease in the reference leg would be sensed as a decreasing pressure and, therefore, would indicate an increasing vessel level.[4-16] The magnitude of the false level increase would be a function of three factors: (a) the temperature transient in the drywell, (b) the thermal response time of the reference leg, and (c) the total length of the reference leg. It has been calculated that the maximum level error while assuming the worst possible conditions would result in 12.7% level error. A maximum level error of 12.7% x 227 inches or +29 inches results. (The calculation is considered conservative since it assumed an equilibrium maximum drywell temperature and instantaneous

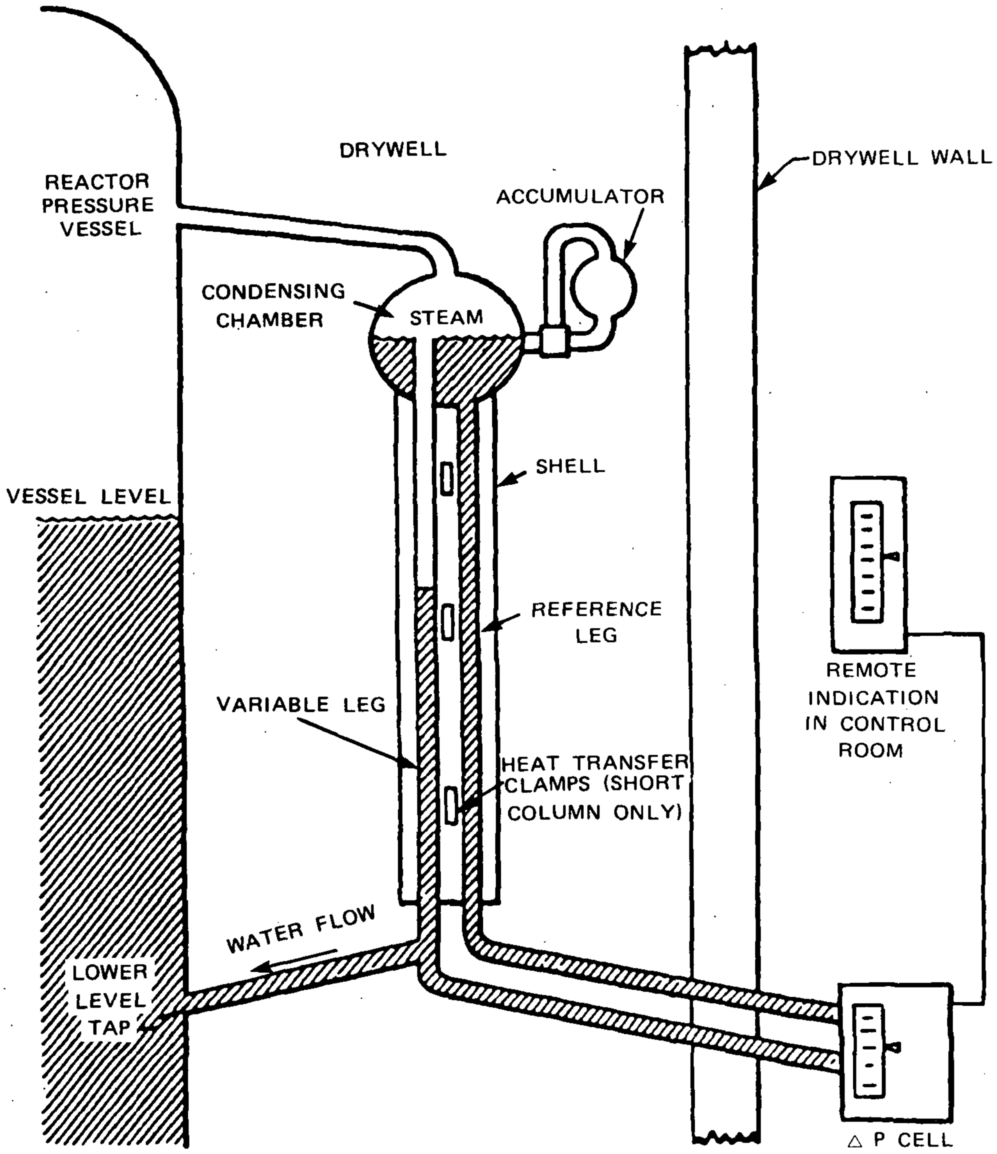

Figure 4-18. Typical Heated Reference Leg Level Instrument Inside Drywell (Referred to as a Yarway Instrument)

thermal response of the reference leg, as previously stated.) This level error means that the indicated level would be 29 inches higher than the actual level. This error could give an operator a false sense of security about reactor vessel level. This calculation was performed assuming the existence of the maximum expected drywell temperature, and instantaneous thermal response of the reference leg, and a 227 inch reference leg. The level indication changes resulting from increasing drywell temperature occur slowly since the thermal time constant of the Yarway level instrument reference leg in on the order of 20 to 30 minutes.

One solution to this problem is to use level instrumentation without a reference leg inside the drywell, as shown in Figure 4-19. This method is used on newer BWRs. Such instruments should not be adversely affected by drywell accident conditions.[4-15]

In the final analysis, reactor vessel water level alone is not a sufficient indication of the presence of hydrogen. Because the reactor vessel water level indications could be erroneous during an accident condition, other instrumentation should be consulted to ensure adequate reactor core cooling exists so as to minimize the possibility of hydrogen production. However, it should be emphasized that, since an uncovered core is a necessary condition for hydrogen production, reactor vessel water level is an extremely important indication.

4.4.3.5 Reactor Coolant Activity. The discussion regarding RCS activity for PWRs is also applicable for boiling water plants. The key point is to be aware of which radionuclides are activation products derived from the reactor coolant itself and from its associated corrosion and erosion products, and to differentiate these activation products from the fission products. This differentiation is necessary because it is the fission product activity in the reactor coolant that provides a measure of fuel cladding damage. Abnormally high reactor coolant activity can be caused by fuel cladding damage. Hence, if cladding damage has occurred, then there is a distinct possibility that hydrogen could have been produced.

4.4.4 Indications of Hydrogen Production External to the Reactor Coolant System of a BWR*

4.4.4.1 Drywell/Containment Pressure. An increase in drywell/containment pressure as a result of a LOCA was discussed in section 4.2. The pressure increases resulting from the presence of hydrogen that might be expected for each primary containment type were shown in Figure 4-2 and tabulated in Table 4-2.

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* The term "drywell/containment" has two somewhat different connotations in the discussion that follows:

- Mark I or Mark II designs - It refers to the drywell or as it is sometimes termed, the primary containment.
- Mark III design - It refers to both the drywell and the surrounding containment structure, which become one and the same (because they communicate with each other during a post-LOCA environment).

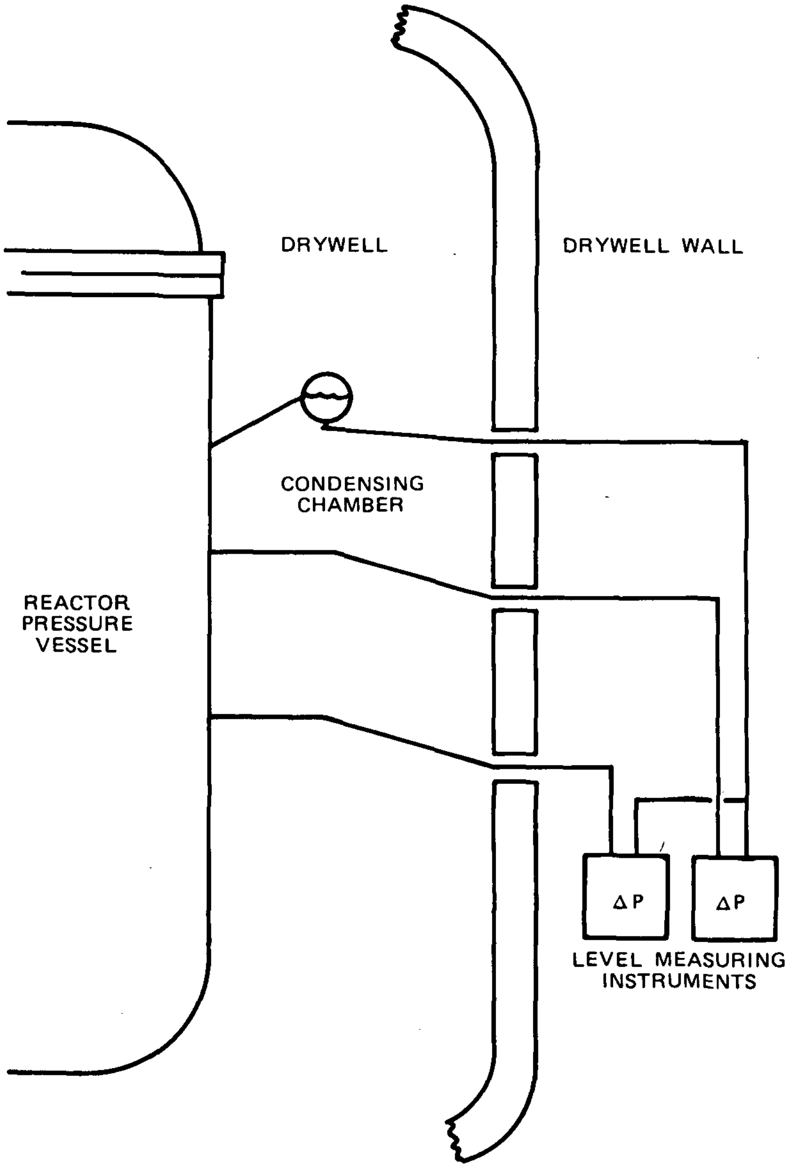

Figure 4-19. Typical Cold Reference Leg Level Instrument

The pressure increase caused by liberation of the hydrogen into the drywell containment is not a singularly sufficient indicator of the presence of hydrogen. It should be used in conjunction with other Reactor Coolant System data to evaluate the possibility for hydrogen production.

4.4.4.2 Drywell/Containment Temperature. Drywell/containment instrumentation does not provide indications of actual core damage. Post-accident use of this instrumentation does, however, provide indications that can be used to observe changing plant conditions to identify if the possibility for hydrogen production existed. Increasing drywell/containment temperatures and pressures can be used in conjunction with reactor vessel instruments to identify energy-release-type accidents as they occur, as discussed in section 4.3. Post-accident use of these instruments provides indications of the turning point of the transient, and indicates whether safety systems are functioning properly to control the transient. Proper functioning of the safety systems is necessary to minimize the probability of hydrogen production.

4.4.4.3 Drywell/Containment Humidity. Typically, the drywell/containment contains a high relative humidity under normal operating conditions. If a LOCA occurred, the humidity would naturally increase to 100%. However, this marginal increase tends not to be very significant when viewed at the main control board. Hence, as for PWRs, the increase in containment humidity can be added to the lengthening list of indications that could indicate the existence of an ICC condition where hydrogen could be generated, but that cannot be relied upon exclusively to indicate such a condition. Drywell/containment humidity must be considered in conjunction with other available indications to determine the possibility for hydrogen generation.

4.4.4.4 Drywell/Containment Sampling. Post-accident liquid and gas sampling can determine both the extent of reactor core damage and the extent of hydrogen gas production during the accident.

Liquid samples from the drywell or suppression pool which disclose high fission product activity are, in fact, a direct clue to the onset of nuclear fuel damage. (A review of fission products, listed in the order of decreasing escape rate coefficients, was presented earlier in this chapter.) It is, of course, this fuel damage that may be an early clue to possible hydrogen production in the reactor core.

BWR facilities typically employ a Hydrogen Analyzing System that monitors and records the hydrogen concentration in the primary and secondary containments following a postulated LOCA. The Hydrogen Analyzing System generally is considered to be one of the subsystems that comprise the Combustible Gas Control System. The Hydrogen Analyzing System typically provides control room indication of the hydrogen concentration, and alarms when the concentration limit is reached or exceeded. A warmup time will be associated with the use of these systems.

As the name implies, the Post-Accident Sampling System can be used for liquid and gaseous sampling in a post-accident condition. For example, a gaseous sample may be taken from the primay containment to determine the existing concentration.

4.4.4.5 Steam Line Radiation Monitoring. Steam line radiation monitoring is one of the functions of the Process Radiation Monitoring System at a BWR facility. The main steam line radiation monitoring subsystem, typically, consists of four identical gamma monitoring channels. Each channel monitors the gross gamma radiation level of all four main steam lines at a point inside the steam tunnel, close to the containment, normally in proximity to the outboard main steam isolation valve (MSIV). (The Reactor Coolant System for a BWR ends at the outside of the MSIV.) The radiation level is sensed by monitoring channels that control the trip circuits that provide inputs to the Reactor Protection System.

A high radiation level signal from the main steam line radiation monitoring subsystem can indicate the possibility of hydrogen production due to the onset of fuel rod damage. The presence of high steam line radiation in conjunction with other confirmatory data could indicate hydrogen production.

Note that once a reactor SCRAM has occurred, the steam line radiation monitor is isolated on most plants. Hence, core damage following a SCRAM ordinarily would not be detected by these monitors. As a result, their usefulness is limited to times of power operation.[4-17]

4.4.4.6 Gross Radiation Level. Another possible indication of hydrogen production is the presence of high radiation, as indicated by reactor coolant or drywell samples. As discussed previously in the section for PWRs, an unusually high radioactivity in a reactor coolant or drywell sample, or a high radiation level in the drywell can be an indication of degraded reactor core conditions.

It should be emphasized that high radiation level indications do not in themselves indicate a hydrogen presence, but, instead, denote a potentially damaging operating condition. Other vital instrumentation for the Reactor Coolant System and containment should be consulted to verify or rule out the presence of hydrogen.

4.4.4.7 Sump Leak Detection. Typically, the drywell floor in a BWR facility has two sumps for the collection of potentially radioactive wastes in the drywell. Normally, these are of low capacity (200 to 300 gallons each), and are fed by sources such as:

- Vent cooler drains
- Control rod drive flange leakage
- Chilled water drains
- Cooling water drains
- Floor drains
- Overflow from the drywell equipment drain tank[4-18]

Each sump contains level detectors that provide control board indication, with an associated level alarm. Typically, each drywell sump has two AC motor driven pumps for transferring collected wastewater to the liquid radwaste (LWR) collection tanks.

High sump levels in the drywell are potential indications of RCS leakage. A high sump level alarm could be an early indication of a potentially damaging condition for the reactor core due to a loss of coolant. It is the coolant loss that could lead to a degraded core condition that could result in hydrogen production. Therefore, if high sump levels exist, other vital instrumentation should be consulted to ensure that adequate reactor core cooling exists.

Water from this sump can be transferred to the LRW collection tanks outside the drywell, therefore, a sample of this liquid could be drawn to check for indications of possible core damage.

4.4.4.8 Suppression Pool Temperature. The pressure suppression pool provides an adequate heat sink in the event of a design basis LOCA. Suppression pool water temperature is monitored during normal operations to ensure that this temperature is maintained within prescribed limits. (A typical temperature limitation during normal operation is 100°F although it may be much higher during an accident.[4-19]) If the suppression pool temperature exceeds the normal operating limit, the reactor must be scrammed, and operation may not be resumed until pool temperature is reduced to below the maximum allowable operational limit prescribed in the technical specifications. (This pool temperature is normally less than 90°F.)

Typically, RTDs are installed at several locations in the suppression chamber water to provide signals for temperature indicators and recorders in the control room.

A sudden rise in suppression pool temperature can result from a LOCA condition. This is another indication of a potentially damaging operating condition. Other vital instrumentation should be monitored to verify the presence and seriousness of the emergency condition. It should be emphasized again that it is the LOCA condition that can degenerate into a degraded cooling condition for the reactor core, and it is the degraded core condition that can result in hydrogen production through the metal-steam reaction with the BWR fuel bundles.

4.5 HYDROGEN DETECTION

Several methods are employed to reduce the risks associated with high hydrogen concentrations, however, proper implementation requires an accurate measurement of the concentration; a variety of hydrogen detectors currently are being marketed for use in nuclear power plants, each of which has its own relative strengths and weaknesses. The purpose of this section is to discuss the criteria that must be met for a detector to be adequate in a LOCA situation, and to identify the characteristics of some of the more promising detector designs.

Reference 4-20 lists nine desirable characteristics for remote hydrogen sensing in the containment:

(1) Insensitivity to ambient pressure, temperature, and humidity
(2) Reliability and stability
(3) High sensitivity
(4) High specificity (i.e., insensitivity to the presence of other gases)
(5) Not an ignition source
(6) Suitability for remote monitoring

(7) Not affected by nuclear radiation
(8) Rapid response and recovery
(9) Ability to measure large ranges of hydrogen concentration[4-20]

The list explicitly mentions only these nine items, but a tenth entry is also implied: reasonable cost.

The importance of each of these criteria can easily be seen. However, there are situations in which trade-offs between desirable characteristics can become particularly crucial in the selection of a detector. One of these situations is the conflict involving detector sensitivity. Usually, the higher the minimum detectable hydrogen concentration (for any type of sensor), the less expensive, more durable, and faster responding that sensor will be. Although a relatively high minimum detectable limit can be advantageous in these respects, the limit must, obviously, be low enough that the detector can identify hydrogen levels in the appropriate range. An example of this is the case where deliberate ignition is employed as a means of hydrogen control. If the minimum detectable limit of the sensor is greater than the specified upper bound for safe ignition, the detector is of little value. It is estimated that an appropriate conservative minimum detectable limit is 1% hydrogen, with the corresponding accuracy specification of 0.5% for LWR service.[4-21]

If hydrogen detectors are used in the future by operators to control ignition systems, then there is another problem to consider. This problem related to deliberate hydrogen ignition concerns the trade-off between the measurement time constant of the detector and the time allowed for the decision to ignite to be made. For a LOCA where hydrogen is being produced rapidly, the time allowed for this decision is estimated to be about one minute. Assuming that it is reasonable to allow no more than the first half of the time delay for decision to be consumed with obtaining measurements, and that the measurement must be taken twice to confirm its accuracy, the detector time constant should be no more than one-fourth of the time delay allowed for the decision to actuate the igniter. In the scenario involving rapid hydrogen buildup, this amounts to 15 seconds or less for the system response to an increase in local hydrogen concentration. To obtain such a response time, it is necessary to locate the sensors inside containment, where they must be able to survive the high temperature, high humidity, and radiation effects present in the post-LOCA environment.[4-21] Note, however, that many of the criteria for accurate and reliable hydrogen measurement cannot be met with currently available equipment.

There are numerous devices on the market for the detection of hydrogen. However, most are expensive and designed specifically for laboratory use. As a result, many are relatively useless for applications in nuclear power plants. Those detectors that are feasible can be classified into the following major groups: (1) combustion, (2) solid state, (3) electrochemical, (4) thermal conductivity, and (5) absorption.

4.5.1 Combustion Detector

To date, the most widely used detector has been the combustion detector. In this device, a hot wire, or catalyst, that forms one segment of a Wheatstone bridge electrical network, ignites the combustible gas mixture. The heat released during the combustion process produces a change in resistance that is measured to determine the composition of the mixture. This method is effective because of the very high heat of combustion of hydrogen.

There are several disadvantages to the combustion detector. Since it operates by igniting the gas, it must be separated from its surroundings by a flame arrestor. Also, because the combustion process is dependent upon oxygen, any disruption in the air supply can lead to erroneous readings. The facts that calibration can be affected by exposure to radiation and that the detector can only measure up to 7% hydrogen are other characteristics that detract from the performance of the combustion type of detector.

4.5.2 Solid-State Detector

Solid-state detector is an all-encompassing term used to refer to any of a multitude of hydrogen detectors that operate by using the electrical phenomena of crystalline substances. These detectors are very much in vogue at present. They are too numerous for all of them to be described here. There are, however, some characteristics common to all solid-state detectors that can be mentioned: the upper limit of detectable hydrogen concentration is typically around 10%, and the detectors are likely to experience calibration change when subjected to nuclear radiation or a high moisture environment.

4.5.3 Electrochemical Detector

The electrochemical detector consists of two electrodes immersed in an electrolyte that dissolves hydrogen. The cell is covered by a membrane that is relatively permeable to hydrogen. As the gas passes through the membrane, the gas reacts with the electrolyte to produce an output current proportional to the rate of hydrogen diffusion through the filter. In this type of detector, the rate of sample air flow should be kept constant and the temperature of the film must be known.

The greatest shortcoming of the electrochemical detector is its inability to operate properly in the presence of water vapor. Its calibration may also be affected when the detector is subjected to nuclear radiation.

4.5.4 Thermal Conductivity Detector

The high thermal conductivity of hydrogen is utilized in a device called, appropriately, a thermal conductivity detector. In this device, the passive elements of a Wheatstone bridge are exposed to a reference gas stream; the sensing is done by the two active elements. This detector actually has very poor specificity for most gases, but the thermal conductivity of hydrogen is so great (seven times that of air -- only helium is comparable) that it is actually quite suitable.

4.5.5 Absorption Detector

The final major type of hydrogen detector is the absorption detector. When hydrogen dissolves in a palladium-silver alloy, it causes a volume expansion that is easily detectable. Several methods have been developed to translate this expansion into a corresponding hydrogen concentration. These detectors are not currently used at nuclear reactor facilities. But, since the absorption processes will occur under harsh (i.e., post-LOCA) conditions and is virtually unaffected by steam, this type of detector is a likely candidate for future service inside containment.

4.5.6 Detector Availability

According to a survey of all the types of detectors currently available, only two are on the market* that are specifically tested for service in nuclear power plants. One is a thermal conduction detector (TCD) and the other is a diffusion-limited electrochemical cell (DEC). The latter is a type of electrochemical detector. At the time of the survey, the DEC units were undergoing tests to qualify them as safety-grade units for service inside LWR containments. The TCD units had already completed the tests.

The primary operational difference in these systems is the manner in which they are employed. The TCD sensors are located outside containment, and sample containment air by circulation through pipes (two per sensor) that penetrate the containment wall. The DEC detectors, on the other hand, are located inside containment where air sampling time can be short. The signal processing equipment, however, is not able to withstand the environmental conditions expected after a LOCA and, therefore, is located outside containment. Specific performance data for these detectors, as well as location diagrams for currently employed systems, can be found in Ref. 4-21.

4.6 TRANSPORT AND MIXING OF HYDROGEN

4.6.1 Introduction

An inadequate cooling condition can create a degraded reactor core in which hydrogen may be liberated (as described earlier in this chapter). This degraded core would be the principal source of hydrogen that could be liberated into the containment and transported to other buildings or structures. For example, during the TMI incident (described in Appendix I) the hydrogen generated, principally by the zirconium-steam reaction in the reactor core, was transported throughout the RCS, as shown in Figure 4-20. This figure shows a sketch of the TMI Reactor Coolant System at a time when hydrogen was most probably being generated.[4-22] The great loss of reactor coolant inventory enabled hydrogen to spread freely throughout the system. The lack of water inventory also made it impossible to establish single-phase natural circulation once the reactor coolant pumps (RCPs) had been tripped.

There are many potential hydrogen release paths through components in the RCS or through systems that interface with the RCS. For a PWR these paths include, but are not necessarily limited to, the following:

- Reactor vessel head vent (as required by NUREG-0737).
- Through the hot leg or cold leg piping (as might occur because of a break in one these piping sections).

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* As of January 1981. See Ref. 4-21.

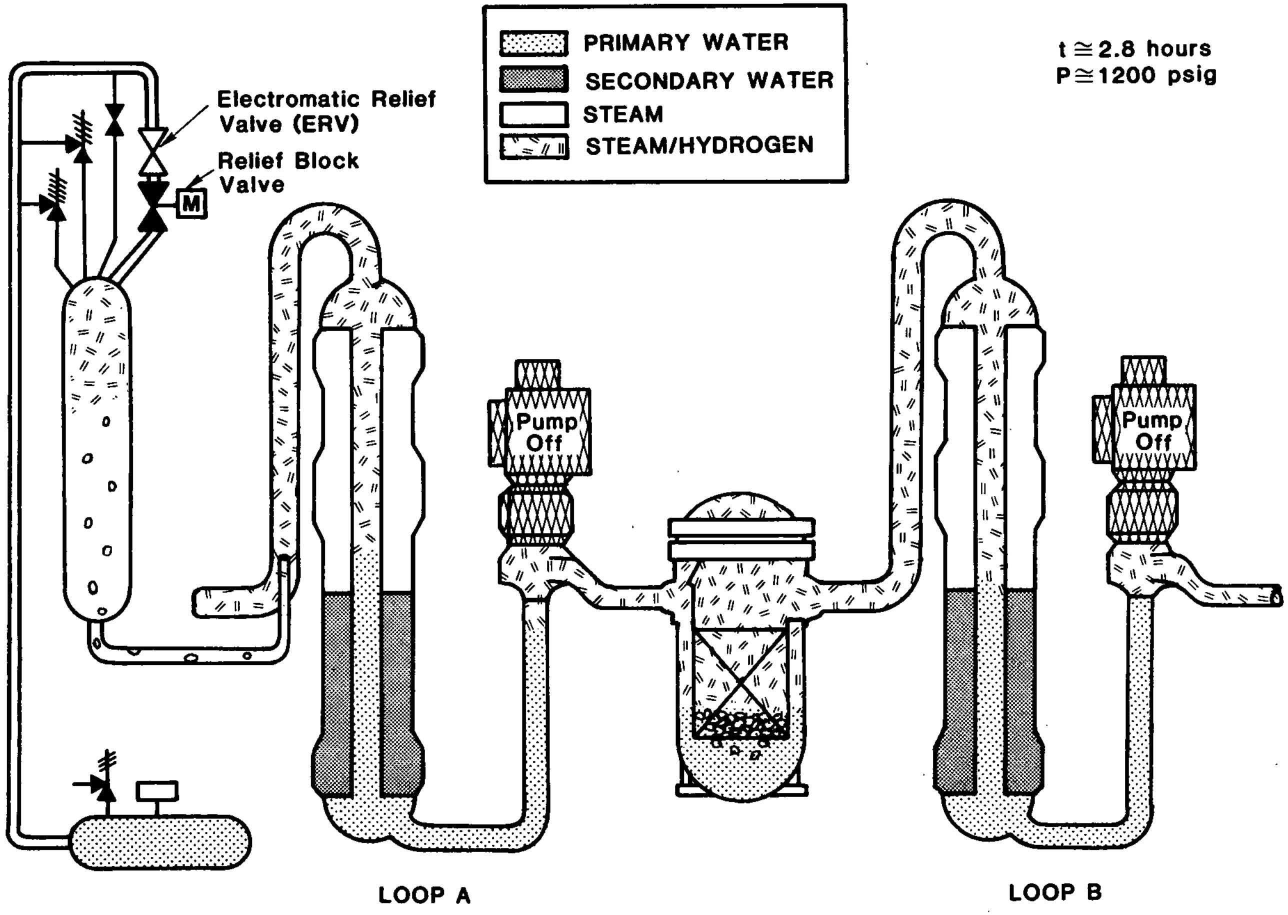

Figure 4-20. The TMI Reactor Coolant System Showing Hydrogen Generation During the Inadequate Core Cooling Condition

- By way of pressurizer and pressurizer relief tank (quench tank).
- By way of auxiliary and emergency systems that interface with the RCS. These include:
  - Chemical and Volume Control System (CVCS)
  - Emergency Core Cooling System (ECCS)
  - Residual Heat Removal System (RHR)
  - Sampling System (SS)

These PWR release paths will be examined in section 4.6.2.

Similarly, for a BWR, a number of potential hydrogen release paths exist including:

- Through a Reactor Cooling System break into the containment.
- By way of auxiliary, emergency, and steam systems from the drywell to the secondary containment (or another building).

These potential bypass leakage paths include:

- Main steam lines
- Feedwater lines
- Reactor water cleanup line
- Recirculation pump seal mini-purge line
- Main steam line drains
- Suppression pool purification line
- Drywell Ventilation and Purge System
- High Pressure Coolant Injection (HPCI) lines (when there is a suction taken from the suppression pool)
- Reactor Core Isolation Cooling (RCIC) lines (when there is a suction taken from the suppression pool)
- Residual Heat Removal (RHR) lines
- Core Spray (CS) lines
- Drywell Reactor Building (primary-to-secondary containment) Vacuum Breaker System
- Drywell floor and/or equipment sump to Radwaste System
- Control Rod Drive Hydraulic System

4.6.2 Hydrogen Transport Pathways in a PWR

4.6.2.1 Hydrogen Transport through the Reactor Vessel Head Vent. With reference to Reactor Coolant System vents, the NRC has stated that:

> Each applicant and licensee shall install reactor coolant system (RCS) and reactor vessel head high point vents remotely operated from the control room. Although the purpose of the system is to vent noncondensable gases from the RCS which may inhibit core cooling during natural circulation, the vents must not lead to an unacceptable increase in the probability of a loss-of-coolant accident (LOCA) or a challenge to containment integrity. Since these vents form a part of the reactor coolant pressure boundary, the design of the vents shall conform to the requirements of Appendix A to 10 CFR Part 50, "General Design Criteria." The vent system shall be designed with sufficient redundancy that assures a low probability of inadvertent or irreversible actuation.[4-12]

Although the exact reactor vessel head vent arrangement (installed or planned) may vary somewhat among PWR facilities, the general arrangement is similar. Figure 4-21 is a typical reactor vessel head vent arrangement. This figure shows a sketch of the Reactor Vessel Head Vent System (RVHVS) for the Trojan Nuclear Plant.*

The Trojan RVHVS is designed to remove noncondensable gases or steam from the reactor vessel via remote manual operation from the control room. Venting during plant startup and system venting during shutdown on post-accident mitigation of non-design-basis events are possible periods of RVHVS usage. The Trojan RVHVS is designed to vent a volume of hydrogen, at system design pressure and temperature, approximately equivalent to one-half of the Reactor Coolant System Volume in one hour. It discharges into a well-ventilated area of the refueling cavity to enable good mixing within the containment building. This particular RVHVS consists of two parallel flow paths with redundant isolation valves in each flow path. The venting operation uses only one of the flow paths at any one time.[4-23]

As of this writing, it appears that most PWR facilities do not have a finalized procedure for operation of the reactor vessel head vents.[4-24] However, the Donald C. Cook Plant** has prepared a procedural guideline that contains an outline of background information for Reactor Vessel Head Vent operation.[4-25] Because most of this information appears to be generic in nature and thus has potential applicability to all PWRs, (although not for all situations) it is presented, in part, in the rest of this section. Each reader can determine its applicability to his or her specific plant.

The purpose of the RVHVS is to remove noncondensable gases from the reactor vessel head. The specific design of the RVHVS includes a single connection to the reactor vessel head, with redundant flow paths and isolation valves extending from a common line, as shown in Figure 4-21. It seems to be generally accepted that any venting operation should be performed only with an accurate vessel level indication. For those PWR plants with a reactor vessel water level detection system, the performance of the calculation in Appendix II may provide an estimate of the total volume of gaseous voids in the RCS (other than the pressurizer).

It is important that RCS conditions be stabilized, with a constant pressurizer level and an adequate subcooling margin established, prior to commencing reactor vessel venting. Further, it is possible that an adverse containment environment can affect pressurizer level conditions. Therefore, to use pressurizer parameters to verify the existence of a stabilized RCS condition, either the containment temperature must be at or near that for normal operating conditions, or the pressurizer parameters must be corrected to reflect

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* Located In Prescott, Oregon, and operated by Portland General Electric Company.

** Located in Bridgman, Michigan; operated by Indiana and Michigan Electric Company. This was the only plant, of approximately ten PWRs contacted, that had such a procedure.

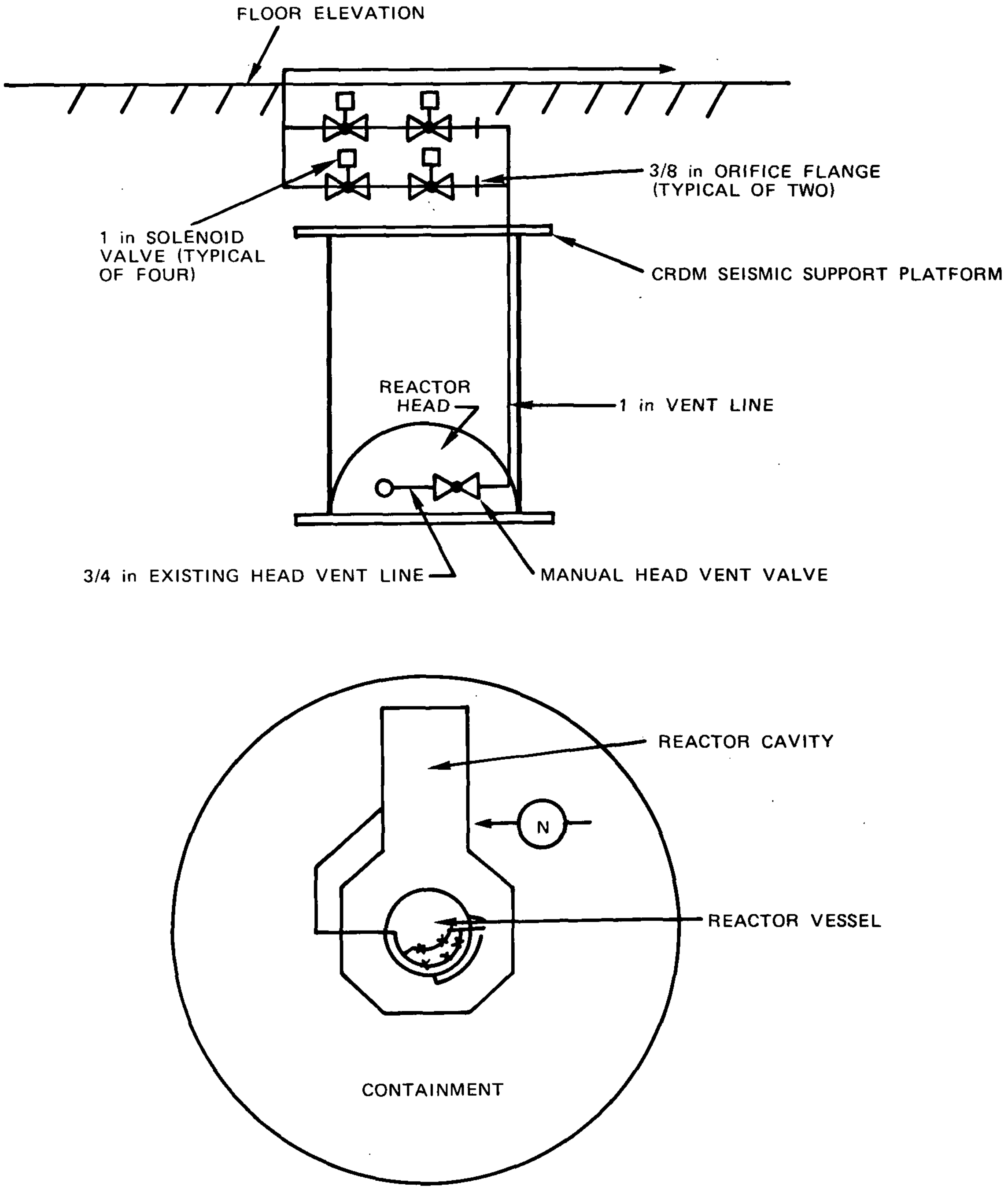

Figure 4-21. Reactor Vessel Head Vent

possible changes resulting from containment conditions. Also, any venting operation must be performed prior to the initiation of safety injection (SI) flow throttling during a post-LOCA cooldown and depressurization operation.

An important consideration relative to use of the RVHVS is that it is not designed to be, and should not be used as, the primary means to mitigate an ICC event. The vent flow path is not sized to provide this capability, and should only be used in conjunction with the plants ICC guidelines.

There are several symptoms denoting the possible presence of a gaseous void in the reactor vessel head. These include:

- Peculiar pressurizer behavior due to the presence of a gaseous void in the reactor vessel.
- High differential temperature across the reactor core which indicates that the coolant is spending too much time in the core and, hence, is not providing the proper amount of cooling.
- The presence of superheat conditions, as determined by the core exit thermocouples or the subcooling margin monitor.
- Greater letdown flow commensurate with a lesser charging (or make-up) flow into the RCS while maintaining a constant pressurizer level.

Once a gaseous void is detected or suspected in the RCS, any changes being made to the RCS should be terminated and steady-state conditions should be established. This refers to such events as post-LOCA cooldown, normal plant cooldown, or plant recovery from a design basis event. The intent is to allow the RCS to stabilize so that the size and position of the void can be determined.

The first action taken to remove any gases from the RCS is to attempt to recombine any condensable gases by increasing RCS pressure. The venting operation will result in RCS gases being vented to the containment. Therefore, the Containment Purge and Exhaust System should be isolated to prevent the possibility of a gaseous radioactivity release to the environment.

It is very important that the RCS not reach saturation conditions during the venting process. Typically, this can be prevented by increasing the subcooling margin over the minimum plant-specific value and by limiting the RCS pressure decrease as much as possible during the venting process. If these two constraints are adhered to, the reactor coolant should remain in the subcooled condition while venting is taking place.

In an effort to keep the hydrogen concentration in containment less than three volume percent to ensure that a flammable concentration is not created, the allowable venting time must be determined. A general guideline for the venting time period is presented in Appendix III.

It is also advisable to maintain pressurizer level greater than about 50% during the venting process to maintain RCS mass inventory. It is suggested that RCS letdown to the Chemical and Volume Control System (CVCS) be isolated during the venting process to ensure that presurizer level is maintained.

A possible decrease in RCS pressure during the venting process could initiate safety injection (SI) if the venting occurred at a pressure near the low pressure SI setpoint. Generally, it would be advisable to block low pressure SI actuation if or when the block permissive is energized to prevent an inadvertent SI initiation during the venting process.

The venting process should be terminated when the reactor vessel head is refilled or when containment hydrogen concentration has reached a concentration of three volume percent.

4.6.2.2 Hydrogen Transport through the Hot Leg and and Cold Leg Piping. Any time that hydrogen is produced in a PWR reactor vessel during an ICC condition, it has a tendency to be transported first to the hot legs of the RCS. From there it can enter the pressurizer as well as the primary side of the steam generator. A break in any of this piping or these components can result in a hydrogen release to the containment atmosphere.

In general, the cold leg of the RCS will see the hydrogen gas last. Naturally, a cold leg RCS break will result in a hydrogen release to the containment through the break. Figure 4-22 shows a profile view of a Reactor Coolant System hot leg and cold leg in which the postulated break has occurred in the cold leg.[4-26] The plant arrangement shown in this figure is typical for Combustion Engineering and Westinghouse PWRs.

Forced circulation through the RCS tends to keep any steam/noncondensable gas voids mixed in a nearly homogeneous manner in the RCS as water inventory is lost through the break. However, where it becomes necessary to secure the reactor coolant pumps, the hydrogen will have a tendency to rise to the highest points in the system. For Babcock and Wilcox (B&W) units, the hydrogen has a tendency to rise to the top of the:

- Reactor vessel
- Pressurizer
- "Candy cane" inlet piping to the once-through steam generator (OTSG)

For example, Figures 4-23 and 4-24 show two types of RCS configurations for the B&W stations. From a natural circulation standpoint, the lowered loop configuration (Figure 4-23) is less desirable because a loss of RCS inventory followed by the tripping of RCPs tends to separate the RCS water in three places: the reactor vessel and the two steam generators.[4-27] The lowered loop arrangement is used at most B&W facilities, including TMI Units 1 and 2. The installation of vent valves in the "candy cane" section can be useful in venting any noncondenable such as hydrogen that could hamper the natural circulation process.

The raised loop configuration, shown in Figure 4-24, is used at the Davis-Besse Nuclear Power Station.* This arrangement is more favorable for natural circulation, if there is a loss of RCS inventory and RCPs must be tripped. Here, reactor coolant has a tendency to flow back into the reactor vessel where it is needed most to help ensure reactor core coverage, and,

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* A B&W plant located in Oak Harbor, Ohio, and operated by The Toledo Edison Company.

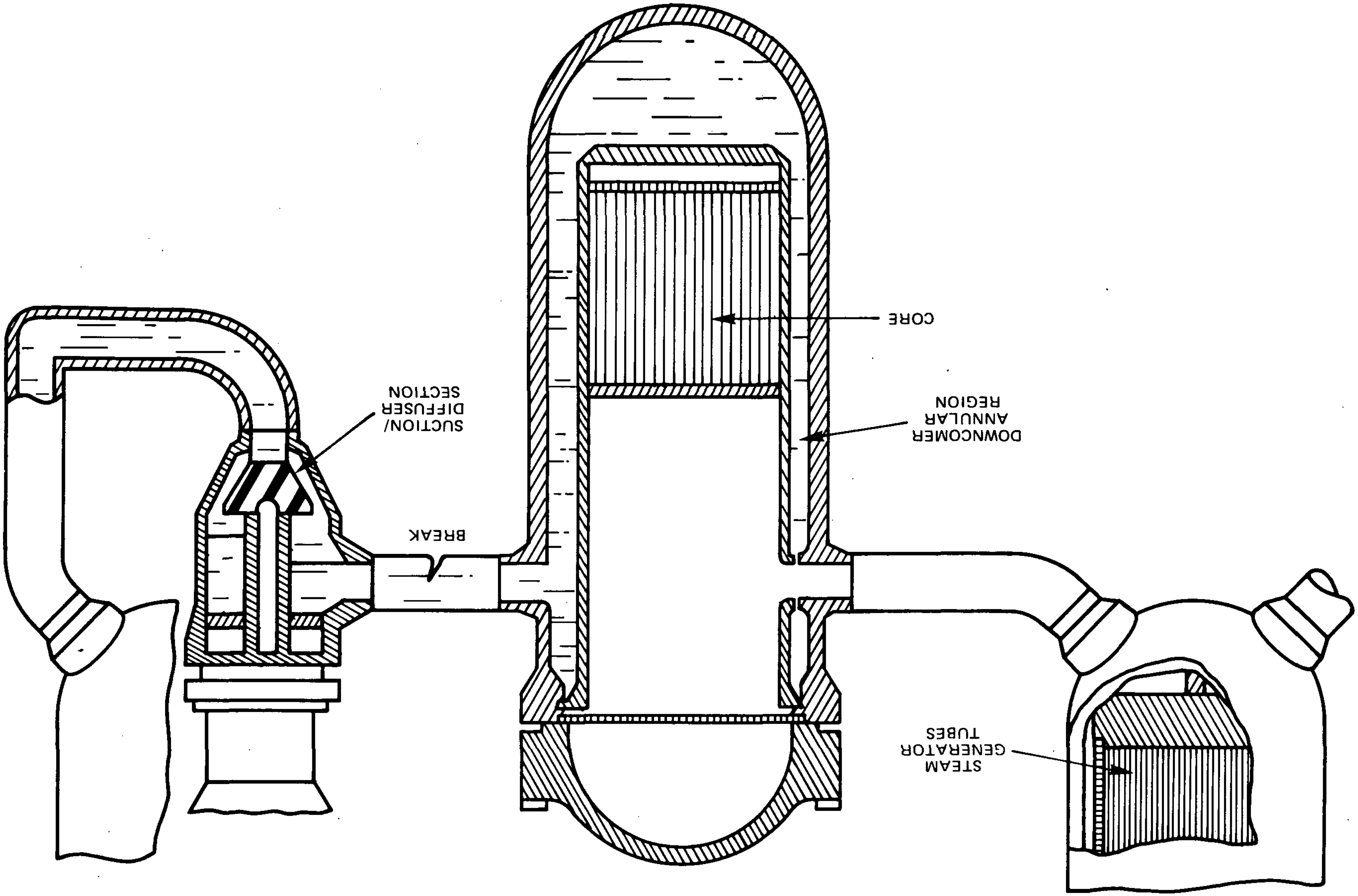

Figure 4-22. Cold Leg Break Steam Flow Path Schematic

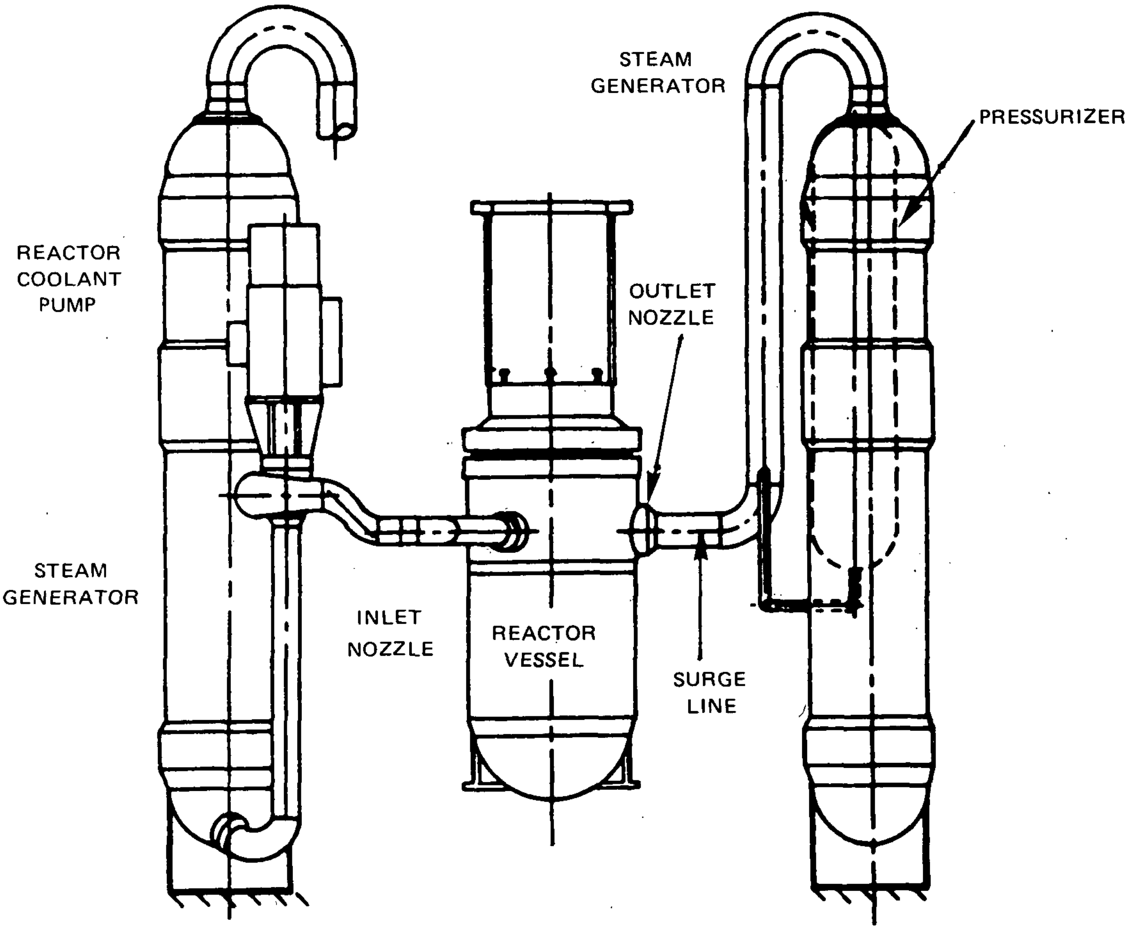

Figure 4-23. Babcock and Wilcox Reactor Coolant System Arrangement Low Profile or Lowered Loop Configuration

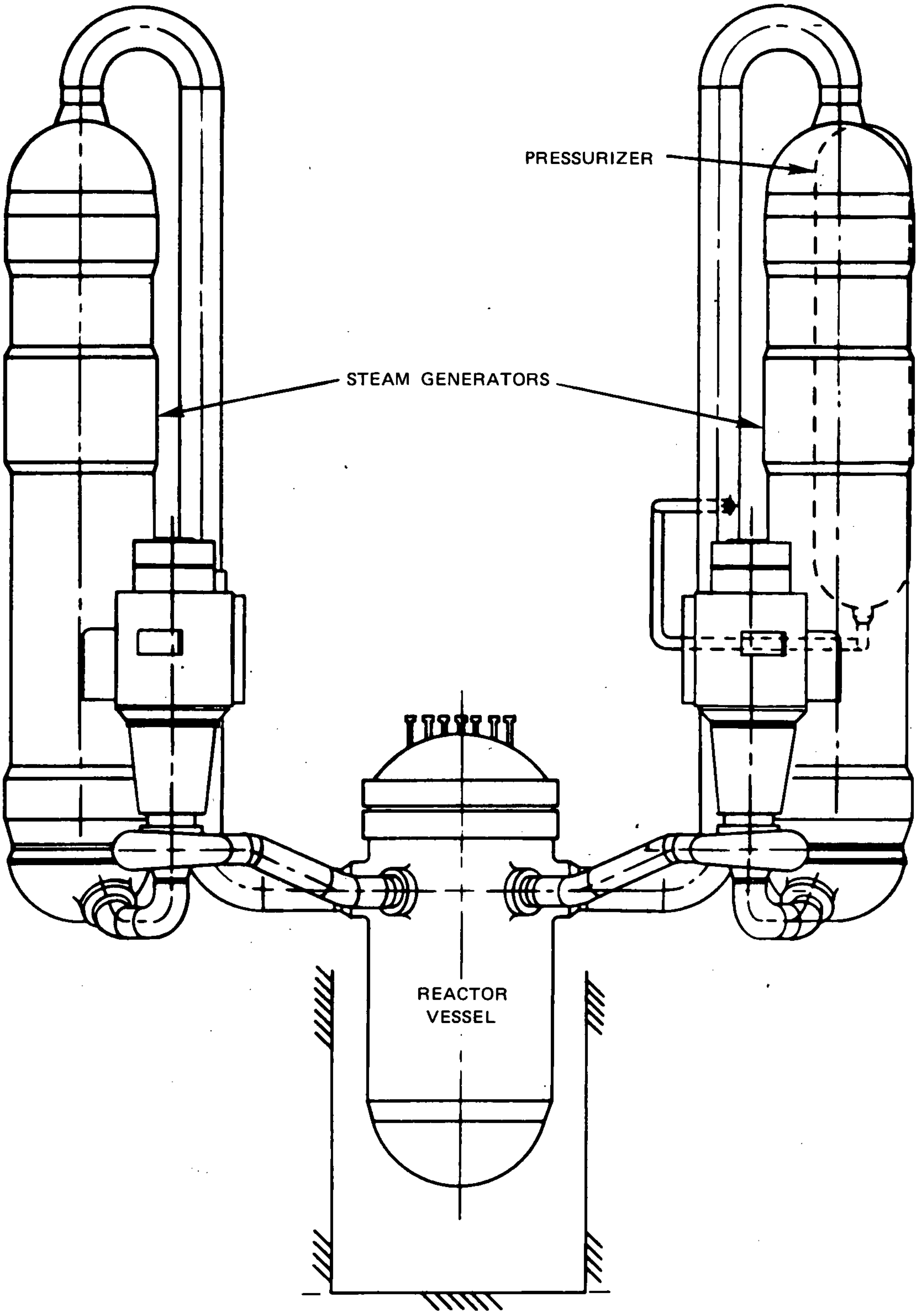

Figure 4-24. Babcock and Wilcox Reactor Coolant System Arrangement High Profile or Raised Loop Configuration

thereby, avoid an ICC condition that could generate hydrogen. Combustion Engineering and Westinghouse PWRs are also of the high profile or raised loop design.[4-28]

4.6.2.3 Hydrogen Transport into the Pressurizer and Pressurizer Relief Tank. Hydrogen that is generated during an ICC condition can be transported through the RCS hot leg and into the pressurizer. As a result, the pressurizer is another location from which noncondensable gases (including hydrogen) can be vented to containment. Some facilities, therefore, are incorporating both a Reactor Vessel Head Vent System such as that previously discussed, and a Pressurizer Vent System. These two venting subsystems would then comprise an overall Reactor Coolant Vent System (RCVS) whose basic function would be to remove noncondensable gases or steam from the reactor vessel head and the pressurizer.[4-29] The combination of these two vent paths would serve to mitigate an ICC condition, impaired natural circulation, or inability to depressurize the RCS to residual heat removal initiation conditions, any of which could result from any accumulation of noncondensable gases in the RCS. Venting capability of the RCS hot legs is not required at Westinghouse or Combustion Engineering facilities because the hot legs are not the high point in the system. For B&W facilities, the inlet piping to each of the once-through steam generators does, in fact, constitute a high point in the system and is a desirable location for a vent (see Figure 4-23 and 4-24).

A typical Pressurizer Vent System is shown in Figure 4-25. This system is connected to the pressurizer relief line and, typically, incorporates two valves in series in each flow path. Using two valves in series minimizes the possibility of reactor coolant pressure boundary leakage.

In general, the Pressurizer Vent System is intended for use in venting noncondensable gases from the pressurizer vapor space. This path also may be used as an alternate method of depressurizing the RCS if this is required by another instruction, as when pressurizer spray and the power-operated relief valves (PORVs) are not available.

There are a number of points that should be considered in using the Pressurizer Vent System. First, the system is not designed for, and should not be used as, the primary means to mitigate an ICC event. The vent flowpath, shown in Figure 4-25, is not sized to privide this capability.

In order to use this system it is necessary to obtain accurate pressurizer level and pressure indications. Therefore, if the containment temperature is not near normal operating temperature, it is necessary to make the appropriate instrumentation correction.

As with the Reactor Vessel Head Vent System (RVHVS), use of the Pressurizer Vent System should be initiated with stable plant conditions. Further, the use of this system while safety injection is operating may result in the pressurizer's becoming water-solid, which is an undesirable condition.

A prerequisite to use of this system is that a larger than normal concentration of noncondensable gases be present in the pressurizer vapor space. It is quite possible that variations from the normal pressurizer pressure and level response due to normal charging and spraying operation may be observed. In the event that noncondensable gases are present in the vapor space, spraying

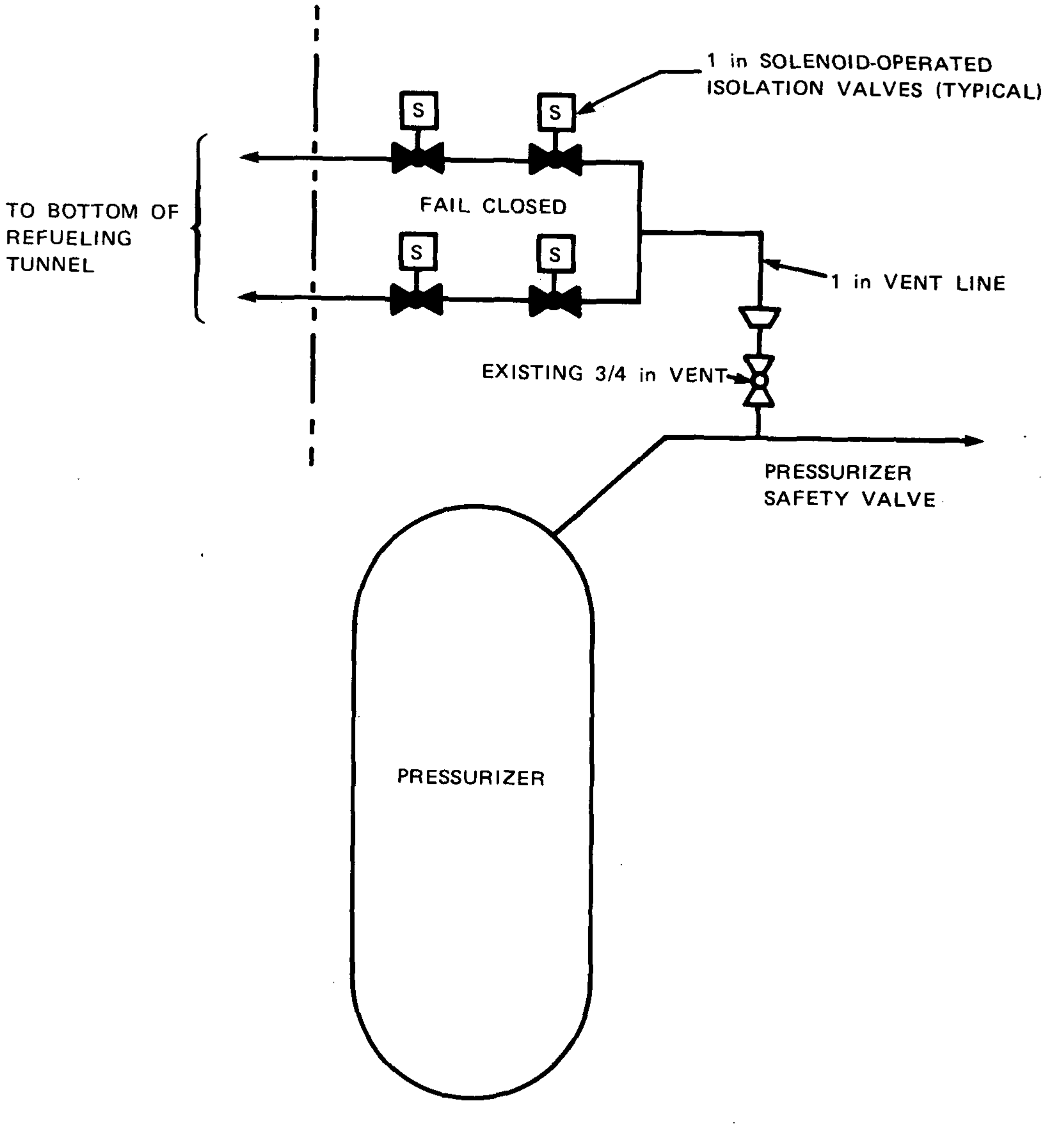

Figure 4-25. Typical PWR Pressurizer Vent System

will not condense the gases and the normal depressurization will not occur. (Recall, from Chapter 3, the discussion regarding a hard bubble in the pressurizer.)

If noncondensable gases are present in the RCS and the reactor vessel head, it is advisable to vent the reactor vessel head first. If the pressurizer were vented first, the depressurization might result in the reactor vessel head gas bubble expanding to the point where natural circulation core cooling could be disturbed.

Some important steps that should be considered during the venting process include (but are not necessarily limited to) the following (These steps are excerpted from information provided by the D. C. Cook Station on pressurizer venting operation.[4-10, 4-30] They should not be used verbatim by other plants without being verified for applicability.)

> Note: Those steps marked by an asterisk are not applicable if the pressurizer is being vented because large quantities of noncondensable gases are preventing an RCS depressurization.

1. Once noncondensable gases are detected or suspected in the RCS, any changes being made to the primary system should be terminated and a steady-state condition should be established. This step refers to events such as a post-LOCA cooldown, normal plant cooldown, or plant recovery from a design basis event.
2. If large amounts of gases are not detected in the vapor space, there is no need to vent the pressurizer unless the vent system is being used as an alternate depressurization method.
3. The venting operation will result in pressurizer gases being vented to containment. Therefore, the containment Purge and Exhaust System should be isolated to prevent release of any radioactive gases to the environment. All available containment air circulation equipment should be started to prevent hydrogen from forming a gas pocket, so that proper mixing will take place, and to ensure a representative hydrogen concentration is obtained in step 5.
4. Increasing the reactor coolant subcooling above the minimum plant-specific valve ensures that reactor coolant subcooling will be maintained over the entire range of RCS operating conditions if the venting operation is terminated following a decrease in RCS pressure.
5. The actions of Appendix III determine the maximum allowable time period for venting that will limit the containment hydrogen concentration to less than three volume percent. This limit is required to prevent a potentially flammable hydrogen concentration from being developed inside containment.
6. RCS pressure will decrease during the venting, and, if initial pressure is near the low pressure safety injection actuation set point, SI may be initiated automatically during the venting. The operator should block low pressure SI actuation if the block permissive is energized, to prevent an inadvertent SI.
7. Charging flow is increased to maximum to limit the net mass depletion of the RCS during the venting period.

8. Both isolation valves in one vent flowpath must be opened to initiate the venting operation.
9. The venting operation is terminated when enough gases have been removed to restore normal pressurizer control or when the time limit determined in step 5 is met.
10. Normal pressurizer pressure and level control is restored after completion of venting.
11. If venting was terminated prior to removing enough gases to restore normal pressurizer control or to reduce pressure to the required condition, then the operator should return to step 4 and repeat the venting.

    Note: The hydrogen concentration could be reduced through use of the containment hydrogen recombiners (where applicable) or the purge and exhaust system if radioactive gas concentrations are within limits. The new venting period will be based upon the reduced hydrogen concentrations.

4.6.2.4 Hydrogen Transport from Containment to Other Buildings. In Chapter 3, it was discussed that hydrogen can be removed from the RCS even during normal plant operations. Much of the information on hydrogen transport paths and mechanisms that was discussed in this connection with regard to such sytems as the Chemical and Volume Control System (CVCS) (or Charging and Letdown System) and the Gaseous Waste Disposal System also has general applicability during an accident scenario.

First, one must be aware that the bulk of the hydrogen generated during an ICC condition has its origin in the reactor core (see Chapter 2). As discussed previously, care must be exercised in releasing the hydrogen into containment. Care is necessary because, if a combustible mixture were present, an accidental deflagration could occur in containment, which could be undesirable. As a result, it could be more desirable to remove the hydrogen through one of the plant auxiliary systems and to transport it to the Gaseous Waste Disposal System for final removal from the plant. Such decisions would have to be made on a plant specific basis and according to NRC guidance. The specific choice would be based on several factors, which include:

- Location of hydrogen
- Amount of hydrogen
- Availability of the auxiliary systems to be used as the release path

This section explores the release paths available to remove hydrogen from the reactor containment and transport it to the Gaseous Waste Disposal System.

One of the more obvious paths for hydrogen removal is through the CVCS. In this case, letdown water from the RCS is sent to the volume control tank (Westinghouse and Combustion Engineering plants) or makeup tank (Babcock and Wilcox plants). Here, noncondensable gases, including hydrogen, may be vented to the waste gas decay tank (see release path #1 in Figure 4-26). (Note that Figure 4-26 is not intended to represent any given plant, rather it denotes a multiplicity of release path possibilities that are, in general, representative of B&W, CE and Westinghouse PWRs alike.)

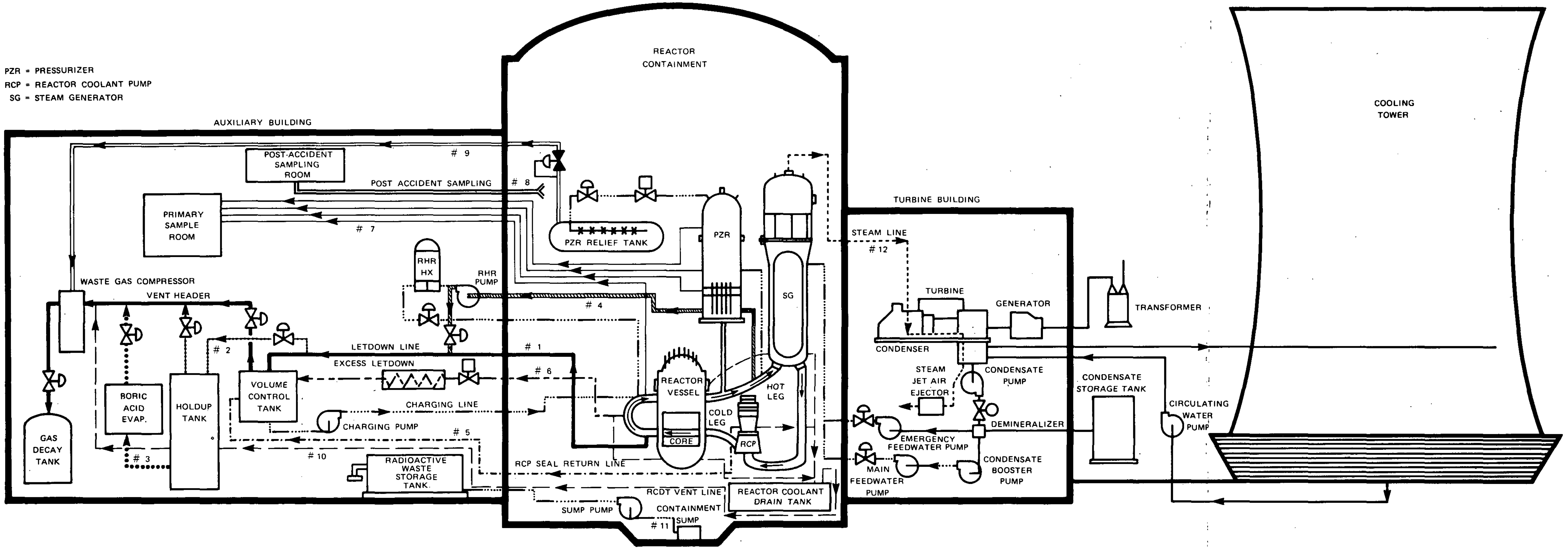

Figure 4-26. Possible Hydrogen Release Paths from the Containment Building to the Auxiliary Building (PWR)

In addition, this letdown flow from the RCS can be diverted to a holdup tank that can also be vented to the waste gas decay tank, as shown in path #2.

Water in the holdup tank that contains some hydrogen can be processed further by a boric acid evaporator unit. A gas stripping column in the boric acid evaporator removes noncondensable gases, such as hydrogen, and vents them to the waste gas decay tank, as shown by release path #3 in Figure 4-26.

When it is possible to place the plant on the Residual Heat Removal System (RHR) during a plant cooldown, RHR generally can serve as an additional release path via a cross-connect valve to the CVCS (depicted by release path #4 in Figure 4-26).

Those PWRs employing controlled seal leakage RCPs have a seal return line back to the volume control tank (makeup tank). Although it would be a relatively minor consequence, this return line is another possible path for hydrogen to be transported from the containment to an auxiliary building. Release path #5 in Figure 4-26 shows the seal return line path.

PWR facilities can also utilize an excess letdown path (generally, this comes from a drain line (or lines) from the RCS). Therefore, hydrogen entrained in the reactor coolant also can be letdown through this path. The excess letdown release path is shown in Figure 4-26 as release path #6.

Sample lines from the RCS hot legs, cold legs, or pressurizer can provide another hydrogen release path from the RCS. In this case, however, the release path goes to the primary sample sink directly. See release path #7 in Figure 4-26.

Post-accident sampling of the containment or of the RCS provides another release path for hydrogen. This is shown by release path #8 in Figure 4-26.

Hydrogen gas can also be vented from the pressurizer relief tank (PRT) to the waste gas compressor, and thence to the waste gas decay tank (release path #9 in Figure 4-26).

The reactor coolant drain tank in the plant containment can, typically, collect reactor coolant from:

- RCP seal leakoff
- Reactor vessel flange seal leakoff
- Reactor coolant loop drain header
- Accumulator drains

Hydrogen could be removed from the containment building by one of these paths, via the waste gas compressor, and then stored in the gas decay tank, as shown by path #10 in Figure 4-26.

Any gas entrained in the reactor coolant that flows to the containment sump also can be transported to the Auxiliary Building by the sump pump (path #11 in Figure 4-26).

All of the potential paths discussed so far would release hydrogen to the Auxiliary Building. The possibility exits that a steam generator tube repture would occur. For such a rupture, a potential hydrogen release path through the failed steam generator tube(s), through the steam line, and into the main condenser can be postulated. The hydrogen would be removed from the condenser by either the steam jet air ejectors (SJAEs) or the Off-Gas System vacuum pumps (often referred to as "hoggers"). It would then be release to the turbine building (see Figure 4-26, release path #12).

4.6.2.5 Considerations to Minimize Hydrogen Transport to Other Buildings. During the TMI-2 incident, noncondensable gases, such as radioactive krypton and xenon, escaped the containment by way of the containment sump and were pumped to a radioactive waste storage tank in the Auxiliary Building. These gases ultimately were released through a blown rupture disc in this tank. The result was an airborne radioactivity release to the environment by way of the Auxiliary Building.

As a result, one of the lessons learned from the incident was that the containment sump pump should not have any automatic actuation features, but should, instead, be manually controlled. This consideration for noncondensable radioactive fission products holds true for hydrogen as well, since the potential for hydrogen release from containment by way of the containment sump is certainly a viable one.

In addition, a radioactivity release occured at TMI-2 via a leaking vent header off the makeup tank. This resulted in a second release of noncondensable gases, such as xenon, krypton, and hydrogen to the Auxiliary Building several days after the onset of the incident. From this another lesson was learned: surveillance testing of vent headers should be incorporated to ensure that leakage is limited to negligible amounts. If vent header leakage contains a combustible hydrogen concentration, its subsequent leakage into containment poses both a personnel hazard and a hazard to equipment. In the TMI-2 case, hydrogen and other noncondensable gases were transported to the makeup tank (of the CVCS) via the letdown line.

Any fluid system has the potential for leaks, especially in pump rooms due to the types of system connections found there. Thus, one potential consideration is to have several hydrogen monitors in pump rooms within the Auxiliary Building. The monitors could be placed in those areas where hydrogen could accumulate in the event an accident occurred that was of sufficient magnitude to generate hydrogen.

Precautions also should be exercised in the use of sampling systems, not only because of the potential for high radioactivity but also because hydrogen could be present in the sample or released into the sampling room itself. Therefore, mention of the potential hydrogen hazard in these areas of the Auxiliary Building is appropriate as part of any emergency procedure on the use of the systems mentioned in this section. It should be emphasized that each plant should specifically assess its own situation in this regard, since the potential release paths and related concerns discussed here are presented only as a representative sample of hydrogen-release possibilities for a PWR.

The only postulated release path previously discussed by which hydrogen can enter the Turbine Building is via a steam generator tube rupture. At each facility, the details of the interface piping between the Containment Building and the Turbine Building should be examined with this in mind. In this regard, it would appear appropriate to have hydrogen monitors in the Turbine Building to ensure that no measurable quantities of hydrogen exist if a steam generator tube rupture incident occurs.

4.6.3 General Hydrogen Transport Pathways in a BWR

4.6.3.1 Hydrogen Transport through a Reactor Coolant System Break. BWR stations employ a direct cycle design, in which steam produced by the reactor core leaves the reactor vessel and is passed directly to the turbine, as shown in Figure 4-27. The steam then passes through the turbine to the condenser. From here it is ultimately pumped back to the reactor vessel as feedwater; it is heated and its pressure is increased in the process.[4-31]

A second pumping system, also shown in Figure 4-27, is the recirculation system, which features two large motor-driven pumps arranged in two parallel recirculation loops attached to the vessel. In addition, there are a series of jet pumps that circumferentially surround the core in the shroud region.

A design basis accident (DBA) is a hypothetical accident in which a complete and circumferential rupture of the largest pipe connected to the reactor vessel occurs, with displacement of the ends so that blowdown from the Reactor Coolant System occurs from both pipe segments. (Figure 4-28 shows an example of the break location for the DBA-LOCA[4-32]).*

It should be mentioned that as long as proper ECCS operation occurs, sufficient water should be pumped into the reactor core to ensure a minimum coverage of two-thirds of the reactor core, i.e., water should be at least as high as the jet pump suction inlet. This should ensure adequate core cooling, although adequate core cooling can probably be maintained with somewhat lower water levels. If an ICC condition occurred, the hydrogen produced would be released into the drywell through this break in the system piping.[4-32] If a LOCA occurred as shown in Figure 4-28, and hydrogen was produced as a result of inadequate core cooling, the hydrogen would be discharged into the drywell through the break. Once hydrogen enters the drywell, it is contained in Mark I and II BWR facilities. However, the possibility of its being released to other buildings does exist, until it can be purged from the drywell. Its inadvertent release may be undesirable. For a Mark III containment, the drywell and containment building communicate in a post-LOCA condition. Hence, hydrogen that enters the drywell has a tendency to enter the surrounding containment via the suppression pool (wetwell). The following subsection discusses the various bypass leakage paths via which the hydrogen may be released from the drywell/containment.

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* In general, the most severe nuclear system effects and the greatest release of radioactivity to containment result from the complete circumferential break at the pump inlet. However, the individual plant's FSAR should be consulted for possible variations from this.[4-6]

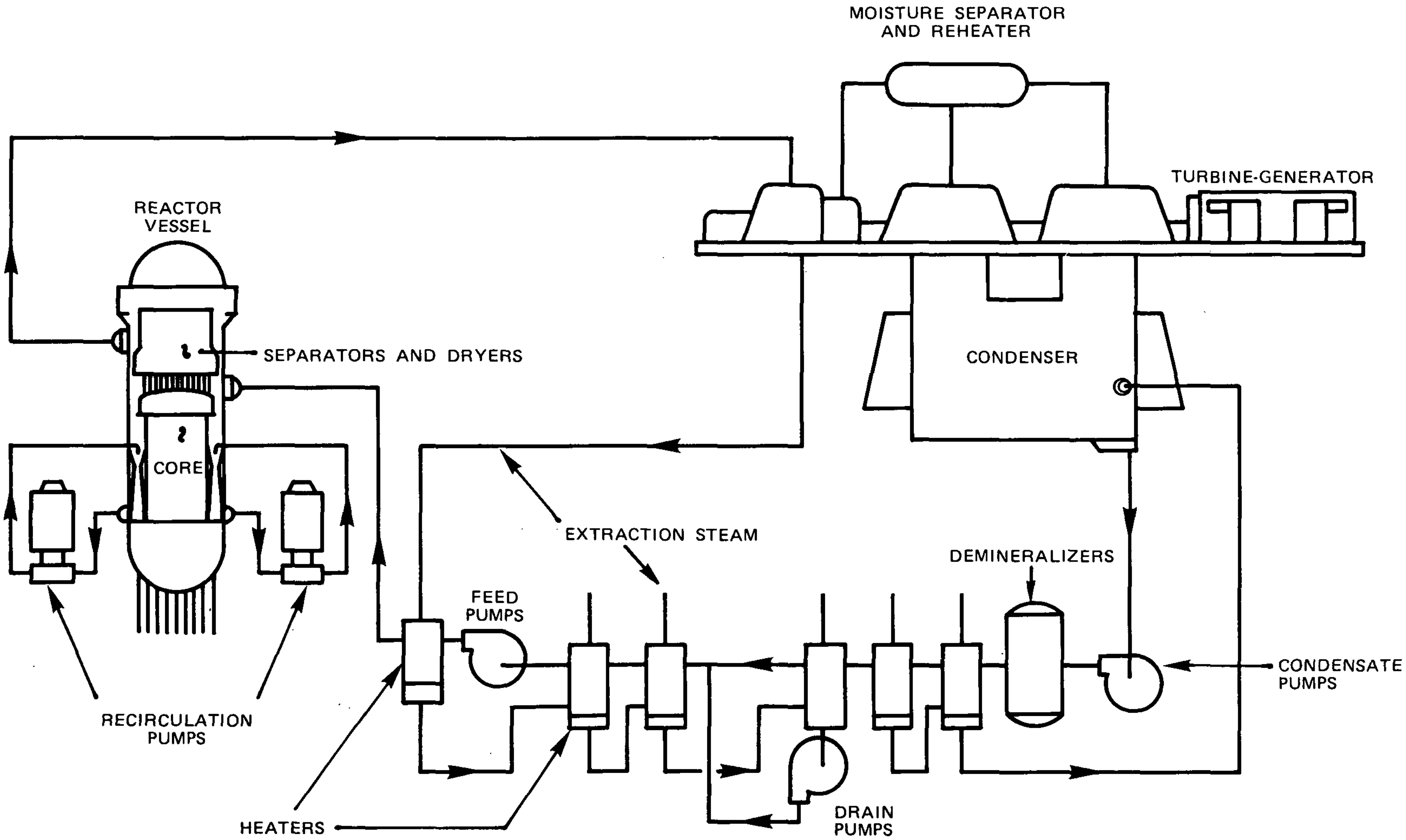

Figure 4-27. Direct Cycle Reactor System

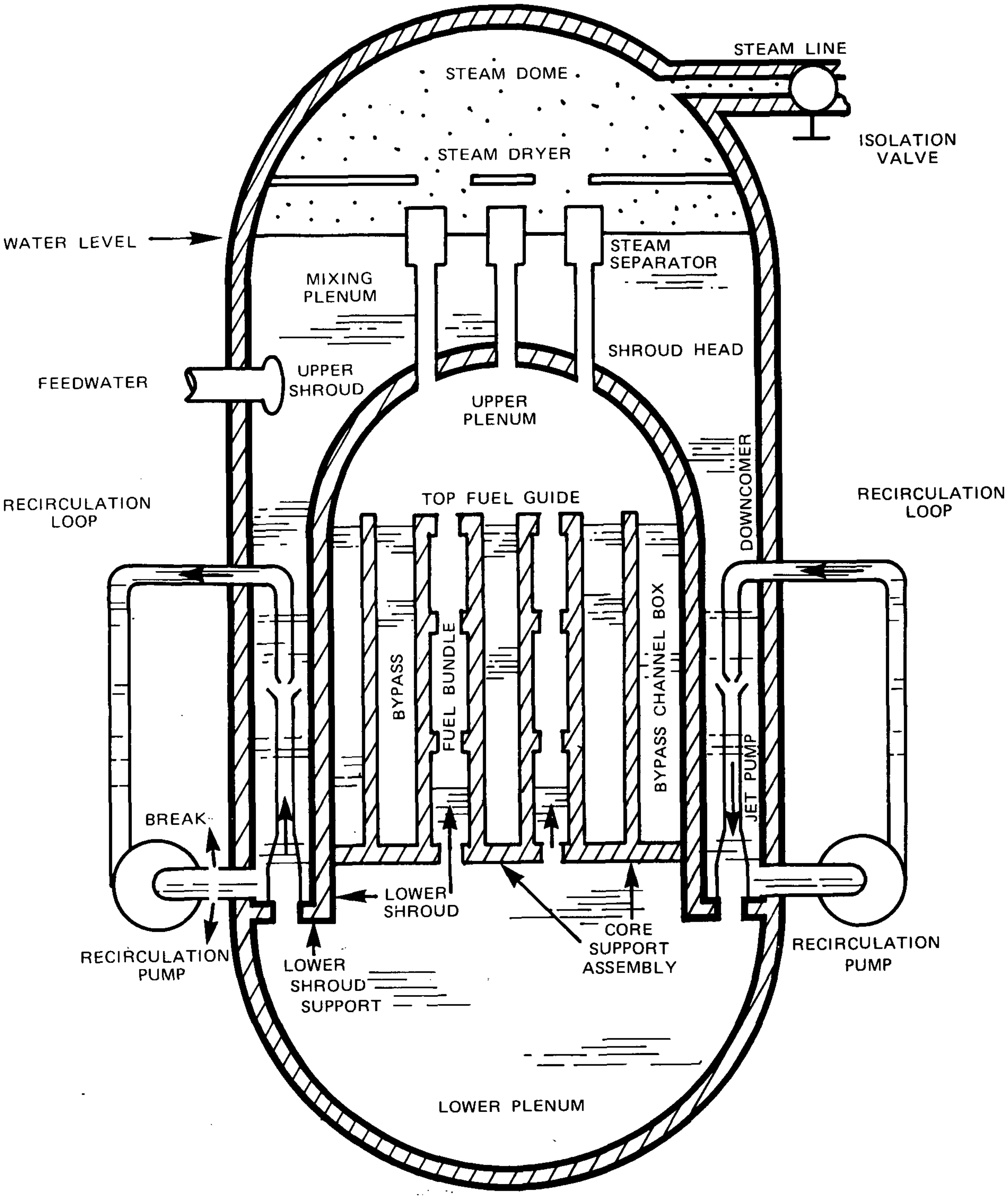

Figure 4-28. Reactor Vessel Water Level and Primary System Flows Immediately After a Loss-of-Coolant Accident

4.6.3.2 Hydrogen Transport through a Stuck Open Safety/Relief Valve to the Suppression Pool. Each main steam line for a BWR is provided with safety/relief and spring-loaded safety valves to relieve any overpressure condition and prevent a possible failure of the reactor coolant pressure boundary.

Most BWR facilities employ four main steam lines that go directly to the high pressure turbine. Each steam line has two kinds of valves located inside the primary containment. One is a spring-loaded safety valve with a setpoint that is independent of the backpressure. The pressure setpoint of the safety valves is generally between 1210 and 1275 psig. The other valve is a dual-purpose, safety/relief valve.

The main safety/relief valve section is a hydraulically-operated, reverse-seated, globe valve that, when activated by the pilot valve, provides the pressure relief function. These safety/relief valves open at a lower pressure than the spring-loaded safety valves. Generally, the safety/relief valves are set to open between about 1085 and 1105 psig.[4-31]

If a small break occurs it should be handled by the High Pressure Coolant Injection (HPCI) System. However, if the HPCI System malfunctions, the safety/relief valves provide an automatic depressurization capability. This depressurization will allow operation of the Low Pressure Coolant Injection (LPCI) System* and the Core Spray System to protect the fuel cladding integrity.

In the event that an ICC condition is reached, hydrogen could be produced. This hydrogen could contribute to an overpressure condition if a degraded core condition were to develop. The release of hydrogen through a stuck-open safety/relief valve is shown in Figure 4-29. (Figure 4-29 is a simplified sketch of the BWR Main Steam System for a facility incorporating a Mark I primary containment design.[4-31]) Note that the relief valve will discharge to the suppression pool (often referred to as the torus for Mark I primary containments). The safety valve would discharge either to the drywell volume, thereby increasing the hydrogen concentration of the drywell itself, or to the suppression pool, depending upon the containment type.

4.6.3.3 Primary Containment Leakage to the Secondary Containment (Mark I and II BWR Designs). The primary containment is designed to maintain its functional integrity during and following any postulated LOCA. The primary containment, in combination with other accident mitigation systems, also is designed to limit the fission product leakage during and following the postulated DBA to values less than those prescribed by 10CFR100.[4-33]

The drywell is protected by the Combustible Gas Control System (CGCS), which controls the concentration of hydrogen within the drywell and secondary containment following a LOCA. If any overpressure condition developed due to the presence of hydrogen in the drywell, the CGCS would minimize the consequences of the event. It should be emphasized, however, that the Combustible Gas Control System cannot handle large amounts of hydrogen, such as could be generated during a severe accident.

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* LPCI mode of the Residual Heat Removal System at some facilities.

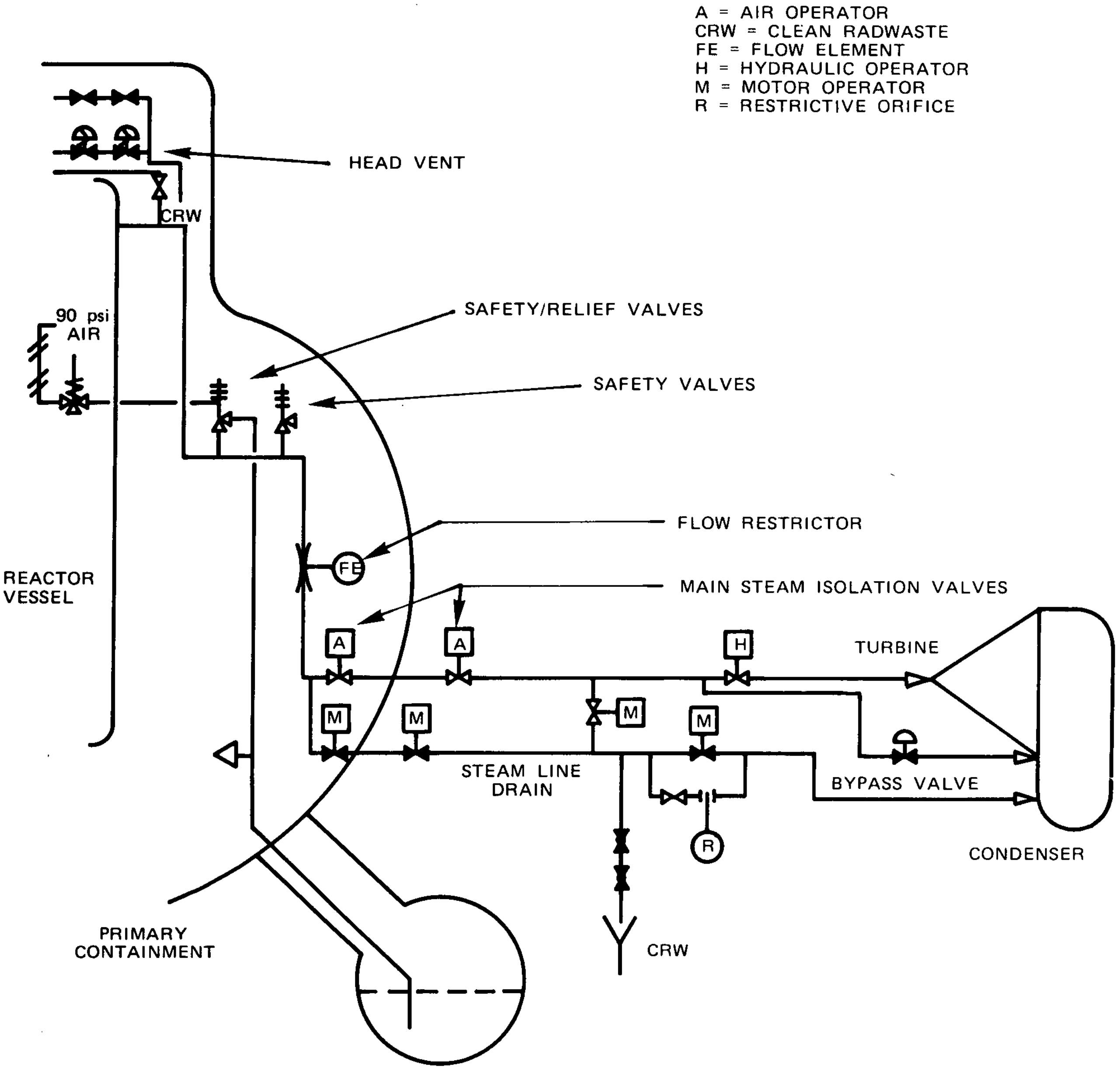

Figure 4-29. Main Steam System (Mark I BWR)

The CGCS ensures that the hydrogen concentration is maintained below a level that could endanger drywell integrity. The CGCS provides the capability to monitor and control the concentration of hydrogen in the drywell by incorporating the following subsystems for combustible gas control:[4-33]

- A subsystem to monitor the concentrations of hydrogen and oxygen within the containment.
- A hydrogen recombiner subsystem (in some plants) to maintain the hydrogen concentration below the lower combustible limit.
- A containment hydrogen purging system to limit the concentration of hydrogen. This is a backup to the hydrogen recombiner system.

For Mark I and Mark II containment designs, there is no intended path for hydrogen to take from the drywell (primary containment) to the reactor building (secondary containment). Therefore, for these two designs, leakage from the drywell to the secondary containment could only take place via bypass leakage paths that were discussed in a previous section. Every effort is made to minimize the probability of an accident's proceeding to the point that drywell integrity could be breached.

Mark III BWR containment designs, on the other hand, incorporate a Drywell Purge/Vent System that can vent the drywell to the surrounding containment volume. This system is provided for the expressed purpose of utilizing the full capacity of both the drywell and containment volumes in containing any hydrogen liberated by a severe accident that resulted in a degraded reactor core condition. (It is designed to handle the hydrogen release from a DBA LOCA; there may be other accident scenarios for which it would be unable to handle the release.) It forces the hydrogen from the drywell to the surrounding containment, in an effort to reduce the hydrogen concentration below flammability limits.[4-14]

Figure 4-30 shows a Drywell Purge System and Post-LOCA Vacuum Relief System for the Grand Gulf Nuclear Station, which has a Mark III containment. The vacuum relief portion of this figure will be discussed in the next section.

4.6.3.4 Hydrogen Transport via the Drywell Purge System* and Vacuum Breaker (Mark I and II BWRs). Another method of relieving a hydrogen gas buildup in the drywell at a facility with a Mark I or II containment is via the drywell hydrogen purge subsystem. A line penetrating the primary containment (or drywell) is provided with power-operated isolation valves. This particular purge system discharges to the Standby Gas Treatment System (SGTS) recirculation supply plenum, where it is filtered and exhausted to the turbine building exhaust vent stack. The Drywell Purge System is provided as a backup to the Hydrogen Recombiner System at most BWR facilities. It would be used only in a post-LOCA situation, in the unlikely event of a failure of the existing Hydrogen Recombiner Systems. (Again, it is intended to handle the release from a

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*This terminology has different meaning for different plants, and these discussions may not be applicable for all plants.

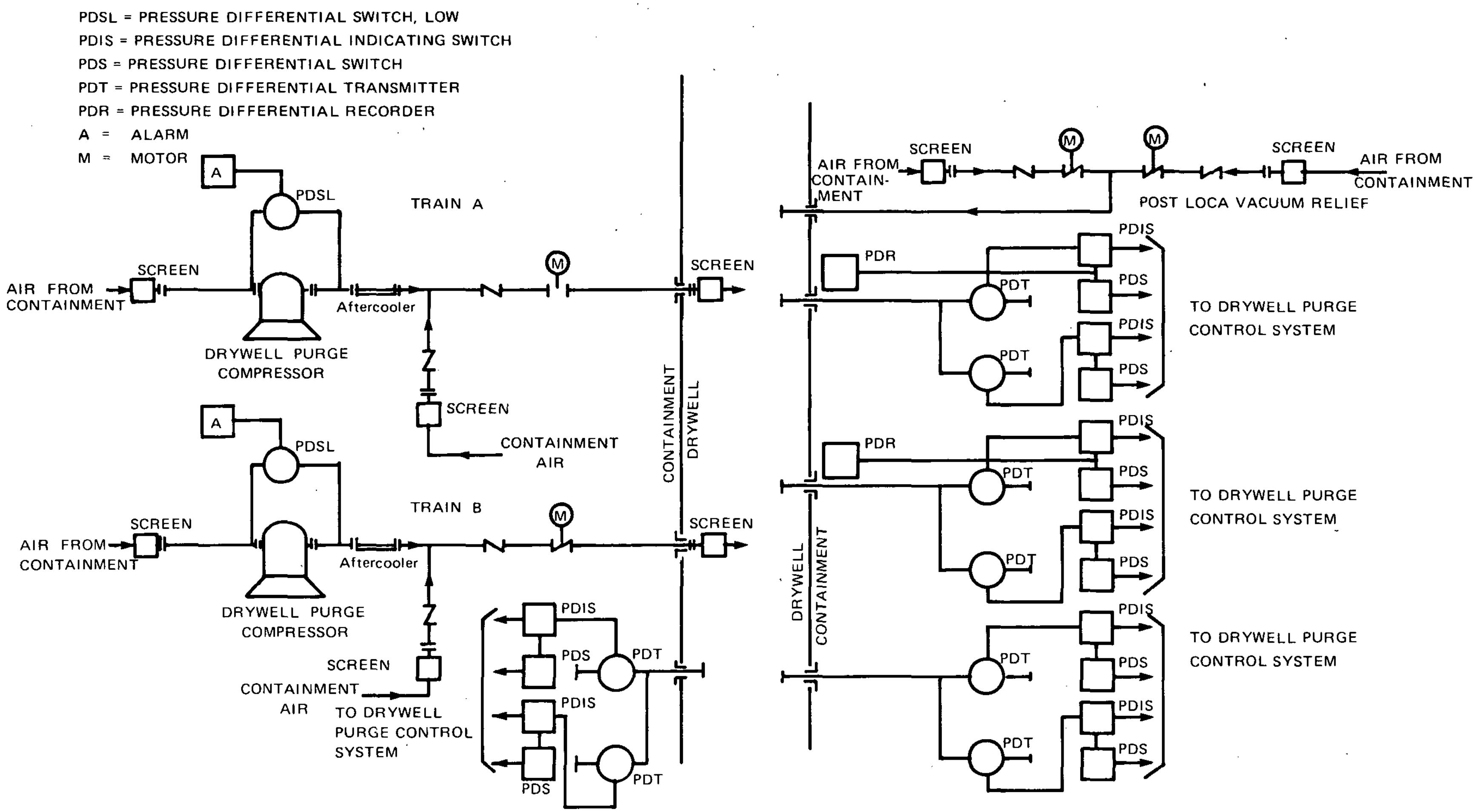

Figure 4-30. Drywell Purge System and Post-LOCA Vacuum Relief System

DBA-LOCA; it may not be able to control the releases from some other accidents.)

The purge system controls the hydrogen concentration by dilution of the post-LOCA drywell atmosphere. The drywell is purged of hydrogen gas; nitrogen is supplied to the drywell during the purging process. Calculations show that radiation doses at the site boundary as a result of a DBA-LOCA will not exceed the guideline values of 10CFR100.[4-33]

Protection of the drywell from exceeding the design maximum external pressure of about 2 psig is provided by a system of self-actuating swing-check vacuum relief valves. Figure 4-31 shows a simplified Containment Ventilation and Inserting System showing the vacuum relief valves to the suppression chamber (torus) for a Mark I containment design.[4-32]

Mark II containment vacuum relief is accomplished in much the same way. The suppression pool, however, is directly below the reactor vessel within the same structure, which is referred to as the drywell. Mark III containment designs also incorporate a vacuum relief system. Figure 4-30 shows the arrangement of this system for the Grand Gulf Nuclear Station.

In each case, the flow through the vacuum relief check valves is into the drywell, not out of it. However, if there were a failure of these check valves, or possibly some bypass leakage, hydrogen gas contained in the drywell atmosphere could escape to the secondary containment. For the Mark III design this is acceptable. It is not desirable in the Mark I and II designs because the reactor building secondary containment is not designed for an elevated pressure condition.

4.6.3.5 Hydrogen Transport through the Bypass Leakage Paths from the Drywell. An important consideration examined by BWR facilities is that of primary containment bypass leakage. If a LOCA occurs, the Standby Gas Treatment System (SGTS) is automatically activated and begins to process all air flow streams from the secondary containment ventilation system. Therefore, if a LOCA occurs, any airborne radioactivity and hydrogen gas that exfiltrates the steel-lined primary containment is collected and passed through the SGTS.* The system is designed to operate during and after a DBA-LOCA. Although one of the principal functions of the SGTS is to maintain the off-site radiation dose within limits prescribed by 10CFR20, it also filters and exhausts the atmosphere from the primary containment for the purposes of purging, ventilation, and pressure relief. The filtered exhaust is sent to the turbine building exhaust vent stack.[4-33]

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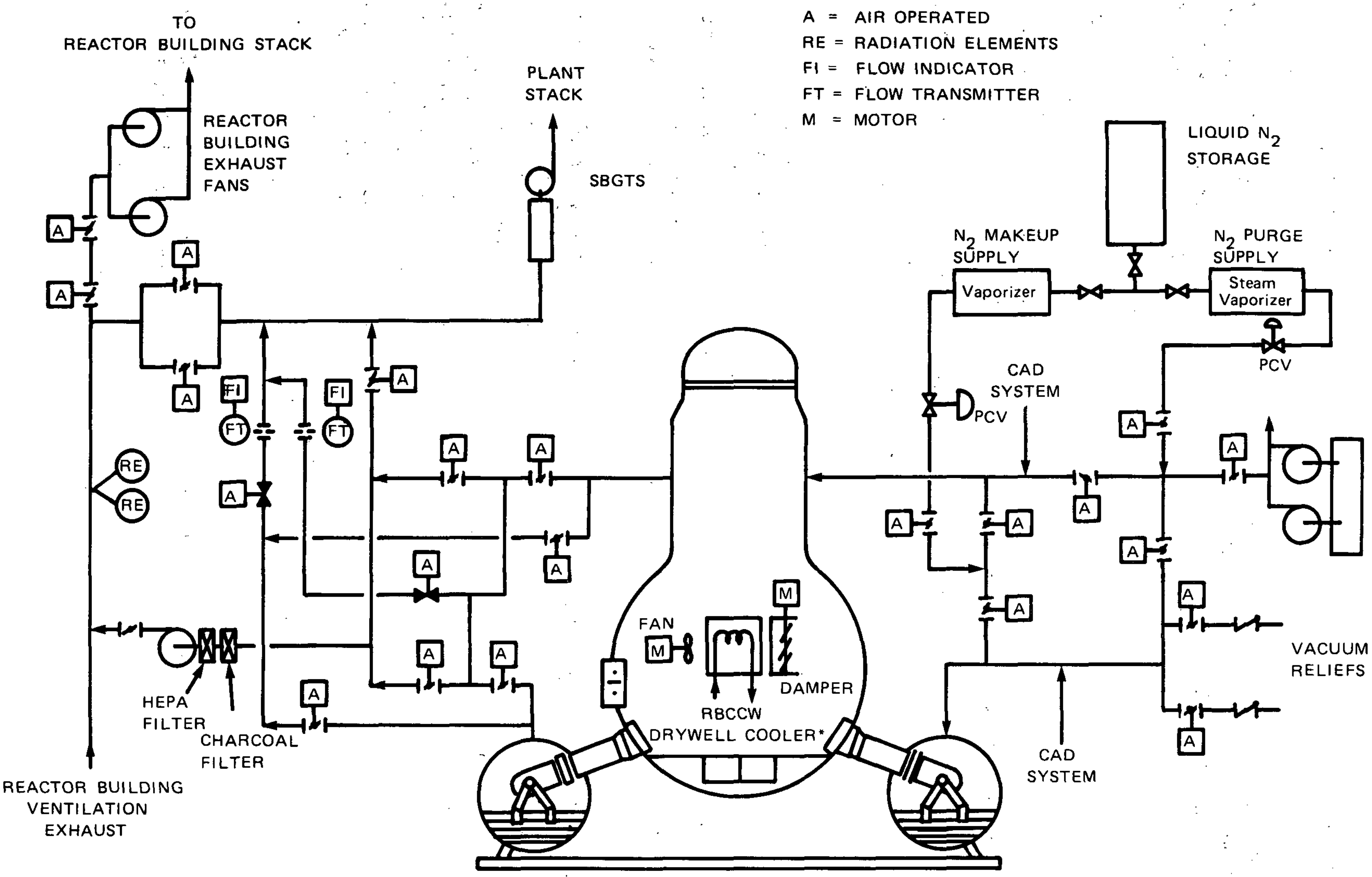
* While such containment leakage is possible, its existence is considered unlikely because of the stringent periodic testing requirements that must be met in this area.



* TYPICAL OF 10

Figure 4-31. Mark I Drywell/Primary Containment Ventilation and Inerting

The potential bypass leakage paths from the primary containment include the following*:

- Main stream lines (#1)
- Feedwater lines (#2)
- Reactor water cleanup line (#3)
- Recirculation pump seal mini-purge line (#4)
- Main steam line drains (#5)
- Suppression pool purification line (#6)
- Drywell Ventilation and Purge System (#7)
- High Pressure Coolant Injection (HPCI) lines (when there is a suction taken from the suppression pool) (#8)
- Reactor Core Isolation Cooling (RCIC) lines (when there is a suction taken from the suppression pool) (#9)
- Residual Heat Removal (RHR) lines (#10)
- Core Spray (CS) lines (#11)
- Drywell-Reactor Building (primary-to-secondary containment) Vacuum Breaker System (#12)
- Drywell floor and/or equipment sump to Radwaste System[4-33,4-34] (#13)
- Control Rod Drive Hydraulic System (#14)

Figure 4-32 shows a simplified sketch of the containment bypass leakage paths described here. A BWR Mark II containment design was chosen as an example.**

4.6.3.6 Considerations to Minimize Hydrogen Release to Other Buildings. Figure 4-32 showed potential hydrogen release paths from the drywell. In general, for hydrogen to be released from the drywell, there must be a breach of system integrity. (Except in a Mark III facility, for which hydrogen could be released via the suppression pool vents.) To maintain system integrity, the necessary surveillance requirements to ensure proper system operation must be consistently and punctually carried out. Further, the awareness that each system that penetrates the drywell serves as a potential hydrogen, as well as radioactivity, release boundary during a severe accident may create an interest in increasing either process radiation monitoring or additional hydrogen monitoring at these boundaries.

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* There are other possible leakage paths that can exist. However, because they require the existence of two breaks in the system, one in the primary containment and another in the secondary containment, their probability of occurrence is not considered to be significant. Hence, they are not discussed in this section. These paths include:

- Nitrogen supply lines
- Reactor building closed cooling water (RBCCW) lines
- Traversing Incore Probe (TIP) System

** Mark I and Mark III designs have similar considerations for bypass leakage paths. Chapter 6 of the plant FSAR should be consulted for more detail on the containment leakage paths for a specific plant.

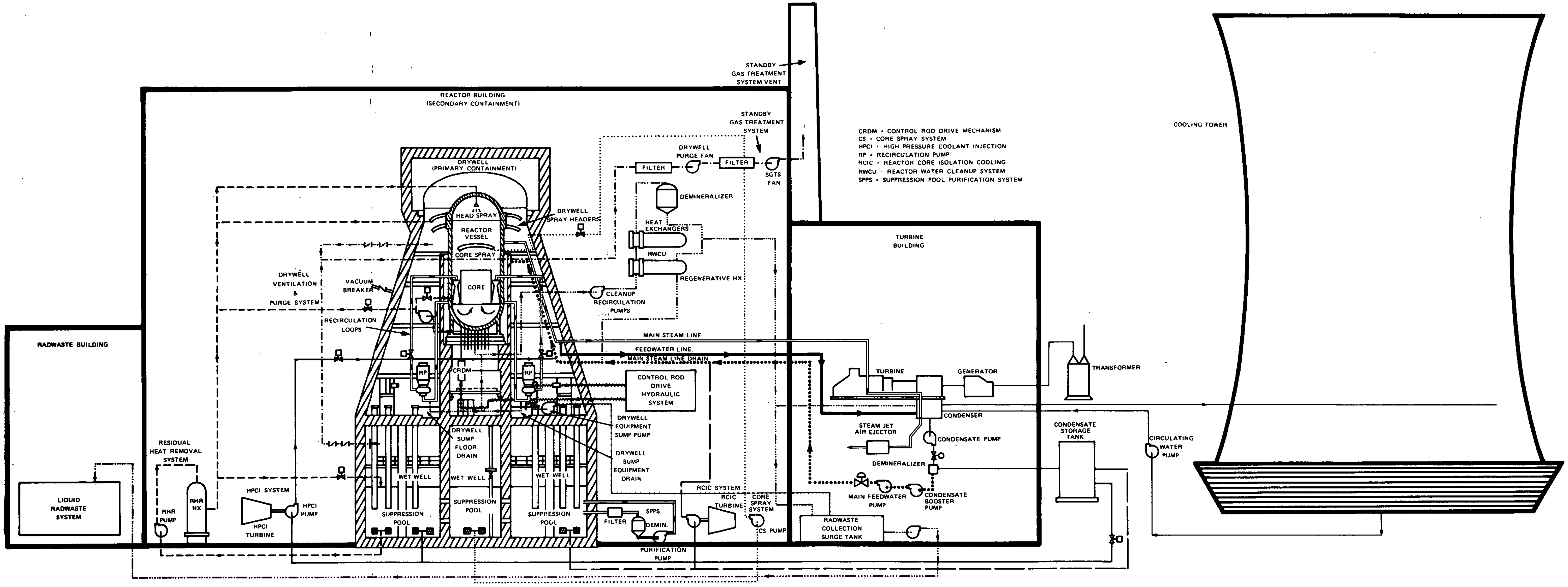

Figure 4-32. Potential Drywell Leakage Paths for Hydrogen from a BWR Mark III Design.

4.6.4 Air Handling Fans

Following a LOCA that results in the release of hydrogen to the containment (for a PWR) or drywell (for a BWR), measures must be provided to assure that the hydrogen mixes throughout the volume and does not "pocket" in dangerous concentrations. The transport and mixing of hydrogen is assisted by cooling and recirculating fans in containment. The degree of mixing achieved is dependent upon fan size (or compressors) and hydrogen release rate.

Some BWR facilities have a hydrogen mixing system, that consists of drywell purge compressors that obtain suction from the drywell and exhaust to the containment. A typical mixing system consists of two compressors, each with 500 SCFM capacity. Automatic valves open when drywell pressure is 0.5 psi less than secondary containment pressure, and shut when it is 0.25 psi less than secondary containment pressure. Initiation of the system is manual after a 30 minute delay, and manual operation of the valves may override automatic operation ten minutes after system initiation. Air flow through the drywell is upward and rotary, which enhances mixing in the drywell. Mixing in the containment may be accomplished by other fans.

Reactor building cooling fans and sprays introduce considerable turbulence to the building atmosphere to enhance mixing. In addition, there also may be stairwells, elevator shafts, and gratings in the building that will help to promote good circulation. (It should be mentioned that accident scenarios may exist in which these fans are unavailable. Such situations are not discussed here.)

The fans and fan motors used should be designed to withstand post-LOCA temperatures and pressures, and exposure to radiation, depending upon their location in containment. The fans are either vane, axial, or centrifugal, and are either belt-driven or direct-coupled to the motor shaft.

4.7 HYDROGEN COMBUSTION

4.7.1 Introduction

An inadequate core cooling condition can produce hydrogen if fuel cladding temperatures reach 1832°F (1000°C). Combustion of this gas in the containment building could pose a threat to safety-related equipment and, possibly, to the containment itself. At TMI, the 28 psig (290 kPa) peak pressure pulse that occurred was substantially less than the 60 psig (510 kPa) containment design pressure. However, for a containment building with a smaller volume or a lower design pressure a more severe threat could have resulted.

This section will examine the potential sources of accidental hydrogen ignition, and will review the methods and instrumentation that may be used to determine whether a hydrogen combustion actually took place.

The combustion properties for hydrogen:air:steam mixtures on a large scale are not well known. However, this section will examine some current work pertaining to hydrogen distribution and combustion following an accident. It also will introduce information regarding hydrogen flame acceleration channels that may occur in a reactor containment and some work currently being performed to further study flame acceleration.

4.7.2 Potential Sources of Accidental Hydrogen Ignition

Accidental ignition of hydrogen could be caused by several sources in a containment structure if the hydrogen concentration in air were to reach sufficient levels. In air at standard temperature and pressure (25°C, 1 atm), and 100% relative humidity, the lower limit for hydrogen combustion is 4.1% hydrogen concentration by volume.[4-1] Table 4-6 indicates the approximate hydrogen concentrations required for combustibility in air.

Table 4-6

HYDROGEN CONCENTRATION VS. POSSIBLE REACTIONS

Hydrogen Concentration in Air*	Possible Reaction
0% - 4%	Noncombustible
4% - 14%	Combustible
14% - 59%	Combustible (possibly detonable)
59% - 75%	Combustible
75% - 100%	Noncombustible

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* These numbers are currently accepted values. Recent experiments have indicated that the range of concentrations for which detonations may be achieved may be wider than that indicated.

Some containment systems include intentional ignition devices, glow plugs, to keep the hydrogen concentration in containment between 4% and 9% in the event of a LOCA. These systems are discussed in a later section of this chapter.

Hydrogen generation, and its subsequent release to the containment structure, is a concern only in a post-accident mode. In the event of an accident, hydrogen will either collect in the reactor head or vent to containment through the reactor head relief valves or a coolant pipe break. If this happened, any unsealed electrical component or any valve movement that created a spark could provide the necessary energy for ignition. Depending on the location of the leakage, the vented hydrogen might pass or remain near many possible ignition sources as it left the RCS.

If hydrogen is vented from the reactor vessel head, the many motors and valves near it could provide the necessary spark for ignition. The control rod drive motors (in a PWR) and power-operated relief valve motors (in both PWRs and BWRs) are located near the reactor vessel head relief valves. In addition, in a PWR, there are the control rod drive mechanism (CRDM) cooling fans.

Solenoids, which actuate many motors, generally are not considered to be a probable ignition source because most solenoids are sealed, thus preventing exposure of any sparks to the vented hydrogen. A motor, however, is not completely sealed and can be an ignition source.

Hydrogen releases to the containment atmosphere from the pressurizer vessel could be exposed to sparks from PORVs and PORV motors at the vessel head. Hydrogen venting from the pressurizer to the containment atmosphere is not probable, however, because the pressurizer would vent to the pressurizer relief tank (PRT) first. This is a closed venting system (i.e., it is not open to the atmosphere) and, therefore, no oxygen would be present for combustion.

In the event of a pipe rupture in any system directly connected to the reactor vessel, or pressurizer (in a PWR), hydrogen could be introduced anywhere inside the containment structure. There are many pumps, motors, and fans located inside containment, all of which could provide sparks to ignite the hydrogen. Depending upon local hydrogen concentrations and the strength of the spark, the hydrogen could either deflagrate or detonate.

It is most probable that ignition would be caused by a spark rather than by spontaneous combustion on a hot surface. The reason for this is that for jets or plumes of hydrogen:steam mixtures, a temperature of at least 959°F (515°C) is required for spontaneous combustion autoignition.[4-35] It is highly unlikely, even in an accident mode, that any surface inside the containment or drywell would reach this temperature.*

Once the hydrogen concentration in the containment atmosphere is over 4%, a spark anywhere in the containment structure could initiate combustion. Depending upon the hydrogen concentration, a global hydrogen combustion could cause a sharp increase in containment pressure. If the initial hydrogen concentration were high enough, this pressure increase could challenge the integrity of the containment.

In a related context, there have been instances of unplanned hydrogen combustion in the off-gas systems of BWR plants. These events have been caused, in many cases, by motors sparking, and also by welding sparks, by lightning striking the exhaust stack,[4-36] and by improperly grounded equipment[4-37,4-38] in the Off-Gas System. (Hydrogen in BWR off-gas systems was discussed in Chapter 3.)

4.7.3 Evidence of Hydrogen Combustion in PWRs

In the event of a hydrogen deflagration or detonation, rapid changes in containment temperature and pressure can occur. Data from the TMI-2 event disclose that a hydrogen deflagration occurred approximately ten hours after the onset of the LOCA. From the data obtained from this incident it was learned that some instrumentation (e.g., steam generator pressure) responded to the hydrogen combustion process.

Additional sampling of the containment atmosphere two days after this event also showed that a hydrogen combustion had taken place.

This section will consider various methods that may be employed to determine whether a hydrogen combustion has occurred.

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*A possible exception would be at a break location where high temperature steam and hydrogen are exiting.

4.7.3.1 Containment Pressure Effects. If a combustible concentration of hydrogen were present in containment and an accidental ignition occurred, creating a deflagration, then a rapid pressure rise could occur as discussed in Chapter 2 and depicted in Figure 2-10. The containment pressure detectors would sense the deflagration. For example, Figure 4-33 shows a containment pressure vs. time graph from one of the trend recorders in the TMI-2 control room during the incident. It shows that there was a pressure change, in the TMI-2 containment, from ~2 psig (115 kPa) to ~28 psig (294 kPa) (a differential pressure of 26 psig) and then back down again. This was seen as a pressure spike on the control board recorder. The whole process lasted about 200 seconds. This "peculiar" behavior confused personnel in the control room because there was, literally, no emergency or accident condition analyzed in the Final Safety Analysis Report (FSAR) or discussed in their training that postulated a containment pressure behavior such as this. As a result, personnnel in the control room thought that it might have been caused by an electrical transient. After the indicated spike, everything appeared to be "normal." A key feature of the pressure spike was that all three containment pressure meters on the control board showed the same pressure behavior as the recorder. This was another indication that a deflagration had occurred. That this behavior could have been caused by an electrical transient is virtually impossible because the instrument power supplies for each pressure detector utilize separate electrical power sources. Therefore, an almost simultaneous rapid pressure rise on all three pressure channels must be believed as being a genuine pressure increase,[4-8] as opposed to some sort of electrical transient.

4.7.3.2 Pressurizer Pressure Effects. If a hydrogen deflagration (or possibly a detonation) occurred in the reactor containment, any pressure sensor or differential pressure device that measures pressure relative to the pressure in containment will be affected, i.e., if the reference pressure of the sensor is that of the containment atmosphere, then any change in this pressure will effect the indicated system pressure that registers in the control room.

For example, from Figure 4-9 it can be seen that the pressure transmitter for the pressurizer senses the pressurizer on one side and the containment volume on the other side.[4-8] That is, from a pressure sensing point-of-view, it interfaces with both the pressurizer and the reactor containment. The actual pressure monitored by this instrument is the differential pressure between the pressurizer and the reactor containment. Therefore, if the containment pressure were to rise suddenly (as a result of a hydrogen deflagration for example), the pressurizer pressure detector would show a rapid drop in pressurizer pressure. This sudden deviation from the normal pressurizer pressure behavior could be compared with the behavior of other parameters such as containment pressure, containment temperature, or steam generator pressure to determine whether the possibility of a hydrogen ignition in containment exists.

4.7.3.3 Steam Generator Pressure Effects. The previous discussion for the pressurizer applies to the steam generators as well. Pressure transmitters monitoring steam pressure for the steam generators are also present in the containment building. Hence, a sudden increase in containment pressure can

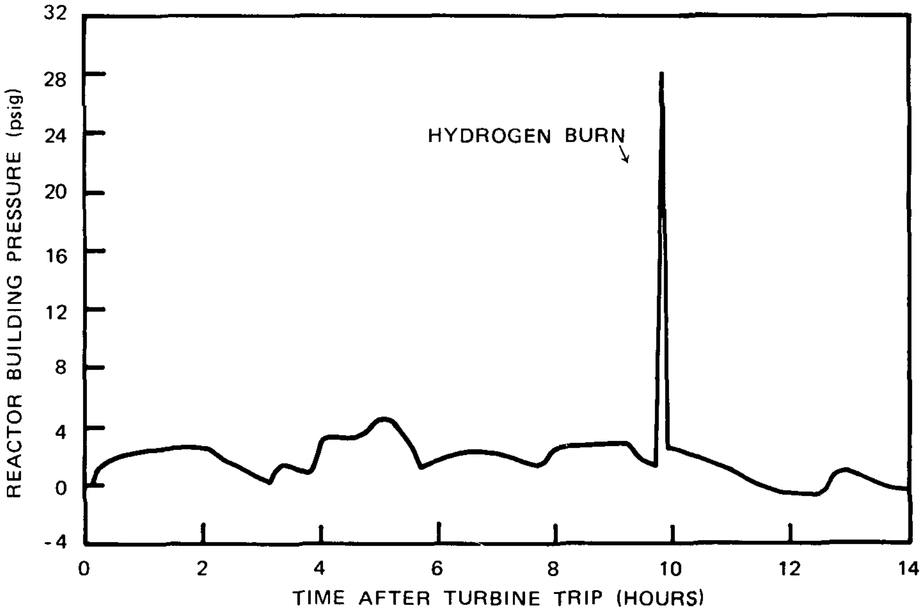


Figure 4-33. Reactor Building Pressure vs. Time

manifest itself in a sudden drop in the indicated steam generator pressure. Actual steam generator pressure data are presented in Figure 4-34.[4-8] Further discussion of this point is presented in Appendix I.

As can be seen in Figure 4-34, the sharp drop in steam generator pressure that occurred during the TMI incident occurred at about 1350 hours on March 28, 1979. The incident started at 0400 hours that morning. At 9 hours and 50 minutes into the incident (at 1350 hours) there was a sharp pressure spike noted on the containment pressure detectors.[4-8] The rapid rise in containment pressure (about 26 psid; see Figure 4-33) was matched by the rapid drop in steam generator pressure (see Figure 4-34).

4.7.3.4 Containment Temperature Effects. If hydrogen is created within the reactor core by a fuel cladding-steam reaction and subsequently released to the containment, it would be impossible to detect its presence from temperature effects alone. However, if the hydrogen concentration increased to a level that could be ignited, a hydrogen combustion would definitely be detected from the temperature effects. This was discussed in Chapter 2 and depicted in Figure 2-11. For example, during the TMI incident, the hydrogen deflagration that occurred at 1350 hours caused a rapid temperature rise on most of the temperature monitors in the containment, as shown in Figure 4-35.[4-8] This suddenly rising temperature, in conjunction with changes in other parameters such as containment pressure, pressurizer pressure, and steam generator pressure could be used to determine that a hydrogen combustion had taken place. The temperature in containment is typically measured by RTDs which have a slow response time. Therefore, temperature data should not be relied on exclusively; rather it should be considered carefully in conjunction with other available information. (Refer to Appendix I for further information regarding the TMI-2 incident.)

4.7.3.5 Containment Gaseous Sampling. In section 4.4.3.4, it was pointed out that a containment gas sample can provide a direct indication of the presence of hydrogen.

If a hydrogen combustion takes place, the oxygen concentration must decrease. The post-accident sampling of the TMI-2 containment atmosphere (dry gas sample) showed that the oxygen concentration dropped by approximately 4.8%. This oxygen was consumed by a chemical reaction. Such a drop in oxygen concentration could be another clue that a hydrogen combustion had taken place; however, the possibility must also be considered that the oxygen was consumed in reactions with substances other than hydrogen (although these reactions are generally long term).

4.7.4 Evidence of Hydrogen Combustion in BWRs

If a hydrogen deflagration or detonation occurred, rapid temperature and pressure changes would occur in the primary containment. Some of the same instruments that provide indications of hydrogen production will also provide key indications of hydrogen combustion.

4.7.4.1 Drywell/Containment Pressure Effects. Table 4-2 gave some general pressure effects caused by hydrogen for each containment type. These pressure effects included estimated final pressures that might be expected if a hydrogen combustion occurred. These pressures were presented as a function of the

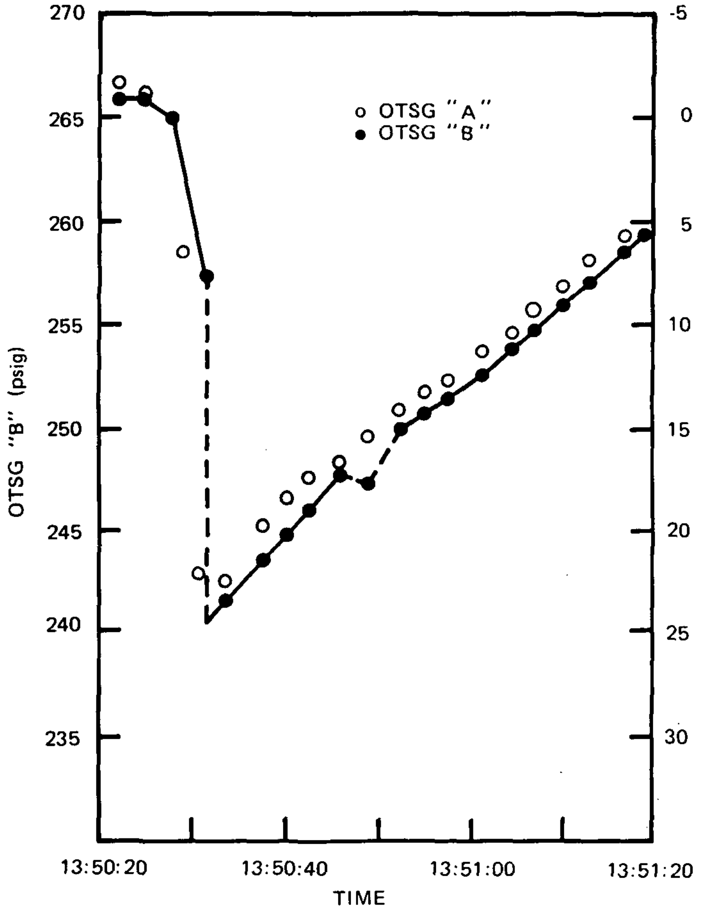
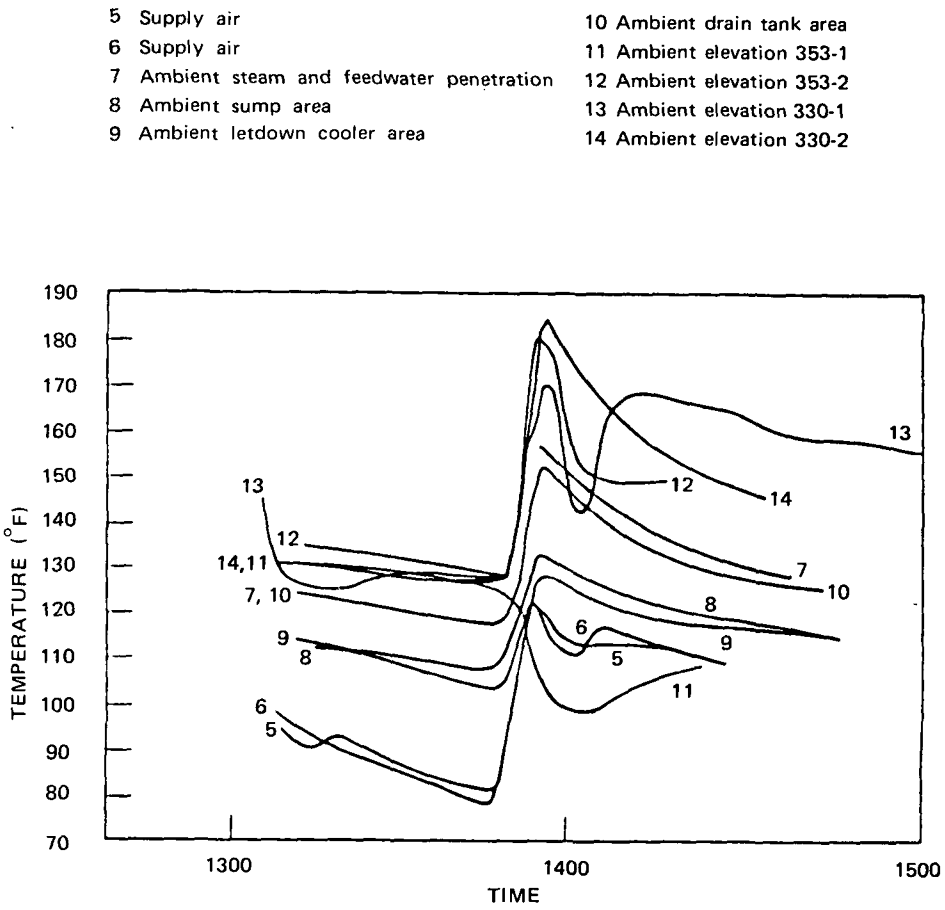


Figure 4-34. Effect of Hydrogen Ignition on Measured Steam Pressures



Note: The variation in response time for the various instrumented regions is due, in part, to their different elelvations and specific locations in containment. Further, these data were sketched from recorder data showing point-by-point temperature readings. This graph is intended to show general temperature trends only.

Figure 4-35. Reactor Building Temperature During Hydrogen Ignition at Three Mile Island Unit 2 percent metal-water reaction. This table assumed that all of the hydrogen was liberated and that a single global deflagration occurred.

For a BWR Mark III containment where no inerting is used, other methods of controlling hydrogen behavior can be employed to ensure that containment integrity is not threatened. (The anticipated pressure increase for a global hydrogen combustion for the complete range of hydrogen concentrations in containment was shown in Chapter 2.) As for PWRs, the pressure increase caused by the liberation of hydrogen into the containment is not a singularly sufficient indicator of the presence of hydrogen. However, global deflagrations are evidenced by sharp pressure spikes, such as those in Figure 4-36. Local deflagrations will also cause sharp pressure spikes; however, the pressure rises will be lower in magnitude due to volumetric expansion of gases in the burned region into the unburned region (see Figure 4-38). Continuous burning of a steam:hydrogen jet could cause a steady pressure rise, as shown in Figure 4-40. (Note that Figures 4-36 to 4-41 should be treated as qualitative rather than precise quantitative examples.)

4.7.4.2 Drywell/Containment Temperature Effects. There has never been a hydrogen ignition in a BWR drywell/containment as of this writing. One should be aware of the TMI containment temperature results previously discussed for PWRs, since this sort of temperature behavior might be possible in a BWR containment that is air-filled. For nitrogen-inerted Mark I and II drywells, the possibility of oxygen production by radiolysis must also be considered during a severe accident. An indication of the temperature effects due to hydrogen combustion is given in Figs. 4-37, 4-39 and 4-41, which show the temperature response to deflagrations.

The temperature spikes shown in Fig. 4-37 would result from successive global deflagrations. Local deflagrations could produce locally high temperatures (not far below the temperatures from global deflagrations), as shown in Fig. 4-39. Regions not adjacent to local burns would see much smaller temperature rises. Figure 4-41 shows a gradual rise in temperature due to burning of a steam:hydrogen jet. Regions close to the jet may see a much more rapid and severe temperature rise.

4.7.4.3 Drywell/Containment Gas Samples. For those BWR facilities whose drywell/containments are not inerted, the possibility exists for hydrogen ignition to occur. If the hydrogen concentration exceeds the flammability limit of 4% discussed in Chapter 2, it can be ignited either by a Hydrogen Igniter System (HIS)[4-39] or by other ignition sources in the primary containment. If part of the hydrogen is burned, the oxygen concentration will drop. Hence, a sudden drop in oxygen concentration (dry gas sample) could be indicative of a hydrogen combustion. (It could also be due to reactions with substances other than hydrogen.) Verification that a hydrogen combustion has occurred would require comparison of this indication with other potential indications of hydrogen combustion being examined in this section. Maintenance of good records of oxygen concentration in a non-inerted drywell would be necessary for this indication to be noticed.

4.7.5 Possible Flame Acceleration Channels

Every effort is made to minimize the probability of the hydrogen concentration reaching the flammability limit. However, if the hydrogen concentration in

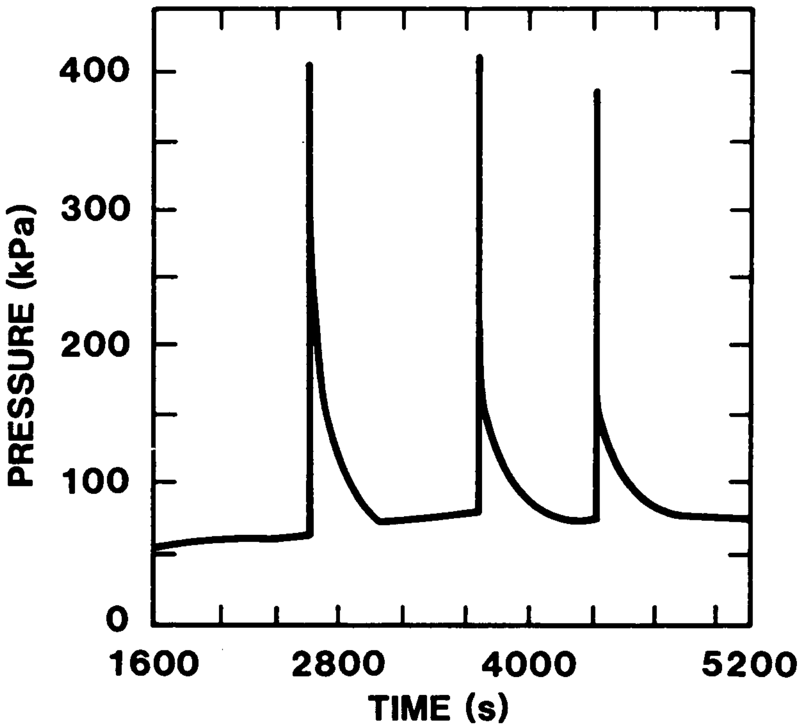


Figure 4-36. Pressure Response to Global Burns.

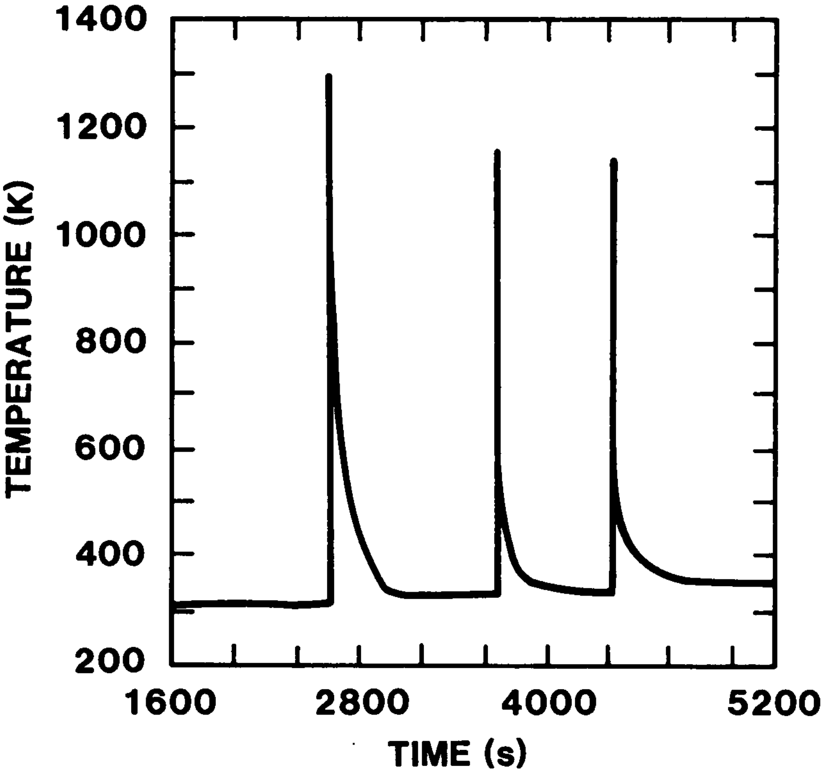


Figure 4-37. Temperature Response to Global Burns.

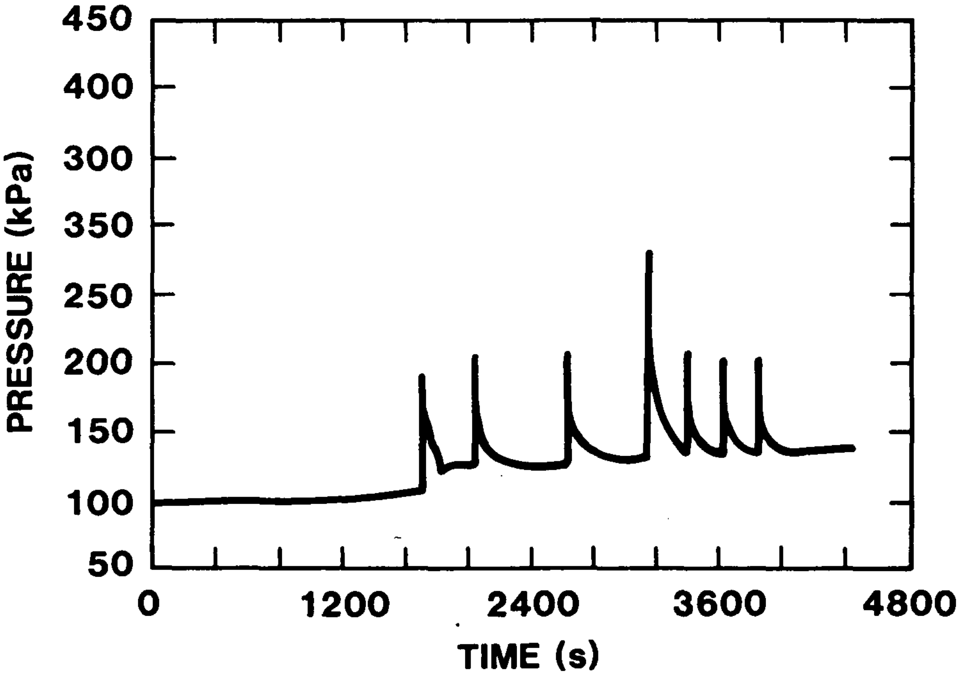


Figure 4-38. Pressure Response to Local Burns.

Figure 4-38. Pressure Response to Local Burns

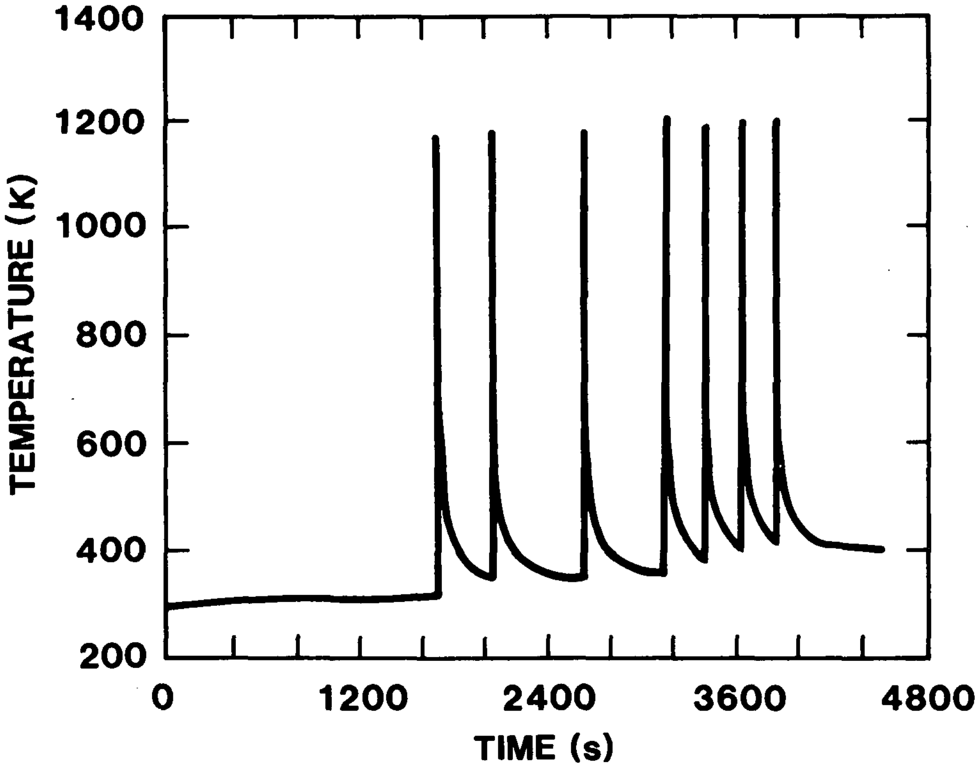


Figure 4-39. Temperature Response to Local Burns

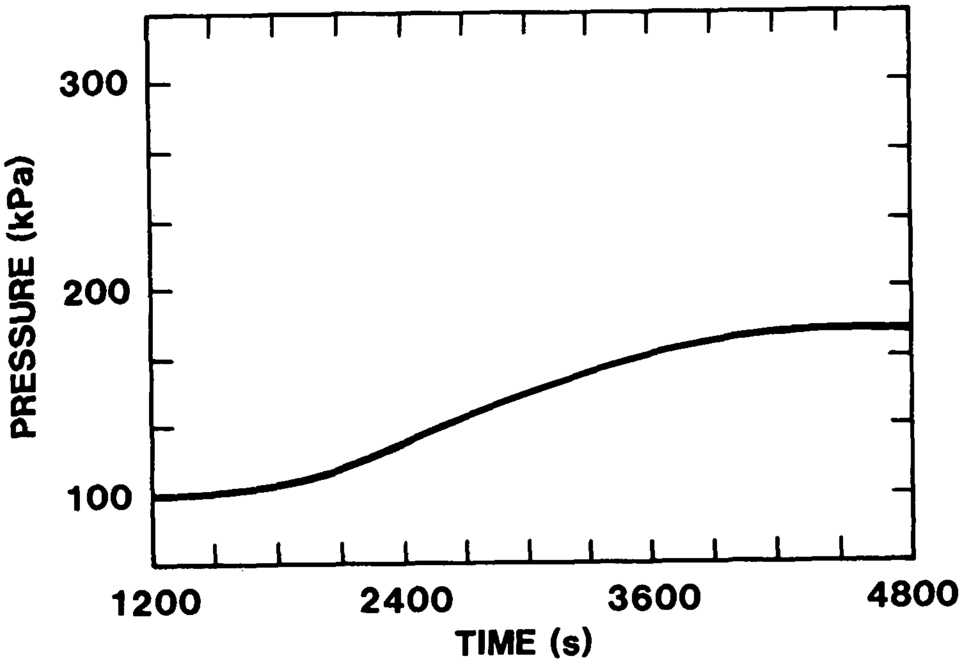


Figure 4-40. Pressure Response to Continuous Burns

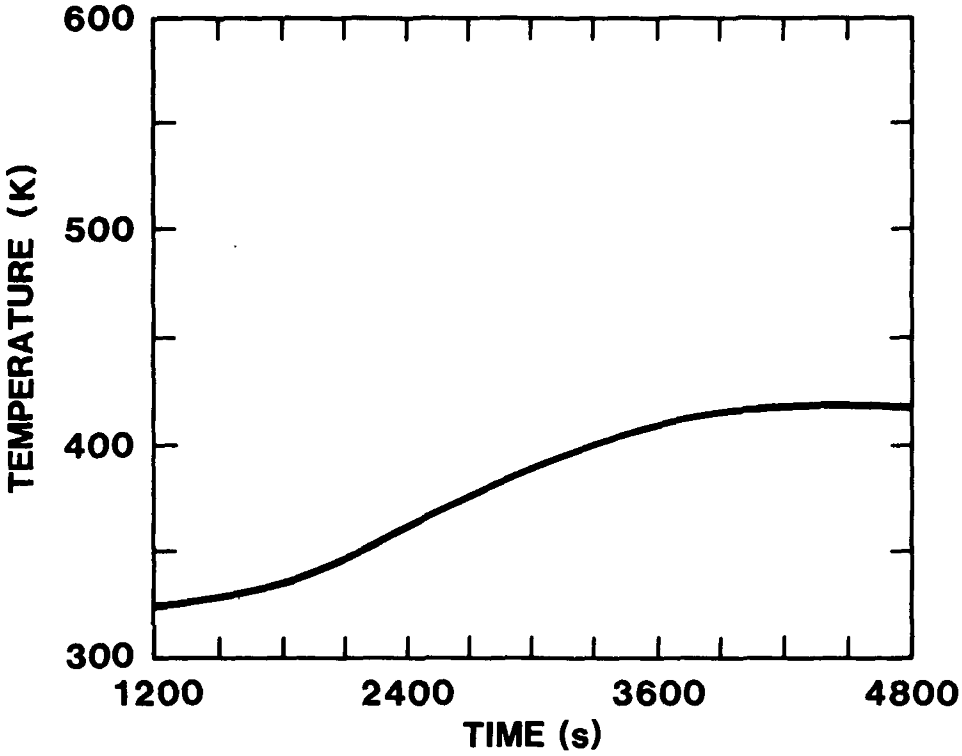


Figure 4-41. Temperature Response to Continuous Burns

containment reached a combustible level, a deflagration could occur. If a hydrogen deflagration takes places, the ability of the flame velocity to cause possible shock damage to systems or components in containment becomes a concern.

If the hydrogen has had time to completely mix with the containment atmosphere before combustion, the combustion will be a premixed flame or, possibly, a detonation, depending upon the hydrogen concentration.[4-1] The actual speed of the combustion front may be as slow as 1 m/s for a laminar deflagration or as high as 2000 m/s for a detonation. As discussed in Chapter 2, deflagrations are flames that travel at subsonic speeds relative to the unburned gas, and propagate mainly by thermal conduction from the hot burned gas into the unburned gas, raising the temperature high enough for a rapid exothermic chemical reaction to take place. Detonations, on the other hand, are supersonic relative to the unburned gas and involve unsteady shock wave phenomena in their structure. In a detonation, the unburned gas is heated primarily by shock compression in contrast to the heat conduction operating in deflagrations.[4-1]

If the speed of the combustion front is low relative to the speed of sound, the pressure within containment generally will rise uniformly throughout the volume of the enclosed gas within several seconds. The pressure will decay slowly due to heat transfer from the gas to the walls and other surfaces in containment, with a time constant of a few minutes. If containment spray is actuated, the decay of the gas temperature and pressure will be more rapid. For slow flames the pressure effects on the containment building are quasi-static. That is, the containment will respond principally to the magnitude of the pressure effects. The transient pressure effects will tend not to be important. In referring to the stresses placed on the containment, it may be said that if the duration of a pressure pulse is short with respect to the lowest relevant mode of vibration of a structure (its natural frequency) the load or stress placed upon it is called impulsive. The severity of the load is governed mainly by the impulse per unit area (the time integral of the pressure pulse), rather than by the peak value of the pressure. When the variation in pressure is long compared to the period of vibration of the structure, the load is called quasi-static. The severity of the load is governed mainly by the peak pressure; the impulse is irrelevant. When the pressure-pulse duration and structure period are of roughly the same magnitude, the severity of the load is governed by both peak pressure and impulse.

For a detonation, however, the initial containment stresses are large and dynamic, and will be followed by quasi-static stresses, as previously mentioned. During a detonation, the pressure seen by the containment wall will be an intense pressure pulse followed by a series of reflected pressure pulses due to shock wave reverberations within the containment. Once these reverberations have decayed, the residual pressure will be approximately equal to that produced by a slow deflagration.[4-1]

In a study performed by Sandia National Laboratories, calculations of the pressures caused by a postulated detonation were made for various points in the Zion containment (assuming a simplified geometry[4-43]). For purposes of the calculation, it was assumed that the detonation was initiated at the center of the containment bottom, with a 20% hydrogen concentration throughout.

The detonation was assumed to propagate no faster than the Chapman-Jouguet detonation speed (see Chapter 2). For this simplified example, the pressure history at the top of containment is shown in Fig. 4-42. This theoretical behavior denotes a strong initial pulse due to focussing along the axis of symmetry, followed by other smaller pressure pulses.[4-1,4-44]

Although for a postulated DBA-LOCA the hydrogen concentration in a PWR containment should not reach the detonable limit, the proposed changes to 10CFR50[4-5] on this matter assume that a 75% zirconium-steam reaction has occurred. For some facilities a potentially detonable mixture (>14% hydrogen concentration) is approached based on these revised assumptions. In an accident, however, it is much more probable that combustion will begin as a deflagration. Experimental results indicate that deflagrations, rather than detonations, are often observed up to hydrogen concentrations of 24% in air.[4-42] Also, the presence of steam will make detonations less likely.

In this regard, there has been a great deal of work on the deflagration-to-detonation transition (DDT) over the past 50 years; however, the subject is still not well understood. What is known is that a deflagration begins in an enclosed volume. The resultant expansion of the hot burned gas creates a compression wave of the gas ahead of the deflagration front. The compressive heating of the unburned gas increases the flame speed, causing further increases in compression until a shock wave is developed. If the unburned gas behind the shock wave is heated above its autoignition temperature, a detonation can occur, assuming the hydrogen concentration is greater than the detonation limit.[4-44] It is generally accepted today that the transition mechanism must involve the formation of a turbulent flame and perhaps reflected shock waves.[4-45,4-46,4-47] This type of transition mechanism has been studied in closed tubes in laboratory experiments.

There is, however, an important second mechanism to consider for a deflagration-to-detonation transition. This is the acceleration that the deflagration flame front experiences as it passes obstacles in its path. Laboratory experiments using tubes containing obstacles have produced detonations where, under identical circumstances without obstacles present, there would have been no detonation.[4-48] The fact that the plant containment will contain many obstacles (such as pumps, piping, reactor vessel, steam generators, reactor containment fan coolers, etc.) is important to consider with regard to a DDT if a detonable concentration of hydrogen is ever reached in containment.

In studies currently being performed by EPRI and Sandia National Laboratories (SNL), the topic of possible flame acceleration is being addressed. One of the objectives of these studies is to determine the potential for the acceleration of deflagrations or for the transition to detonation in turbulent mixtures. For example, it is known that grating systems can promote turbulence and can conceivably accelerate a burn.[4-40] The structures and equipment in containment have the potential to create flame turbulence that could accelerate the burn. The EPRI and SNL studies will examine these phenomena to determine their possible effects.[4-49]

It, therefore, is advisable to take measures to maintain hydrogen concentrations as low as practicable during an accident or emergency condition so as to minimize the consequences of combustion. Note, however, that structures and equipment may have a substantial capacity to survive a local detonation

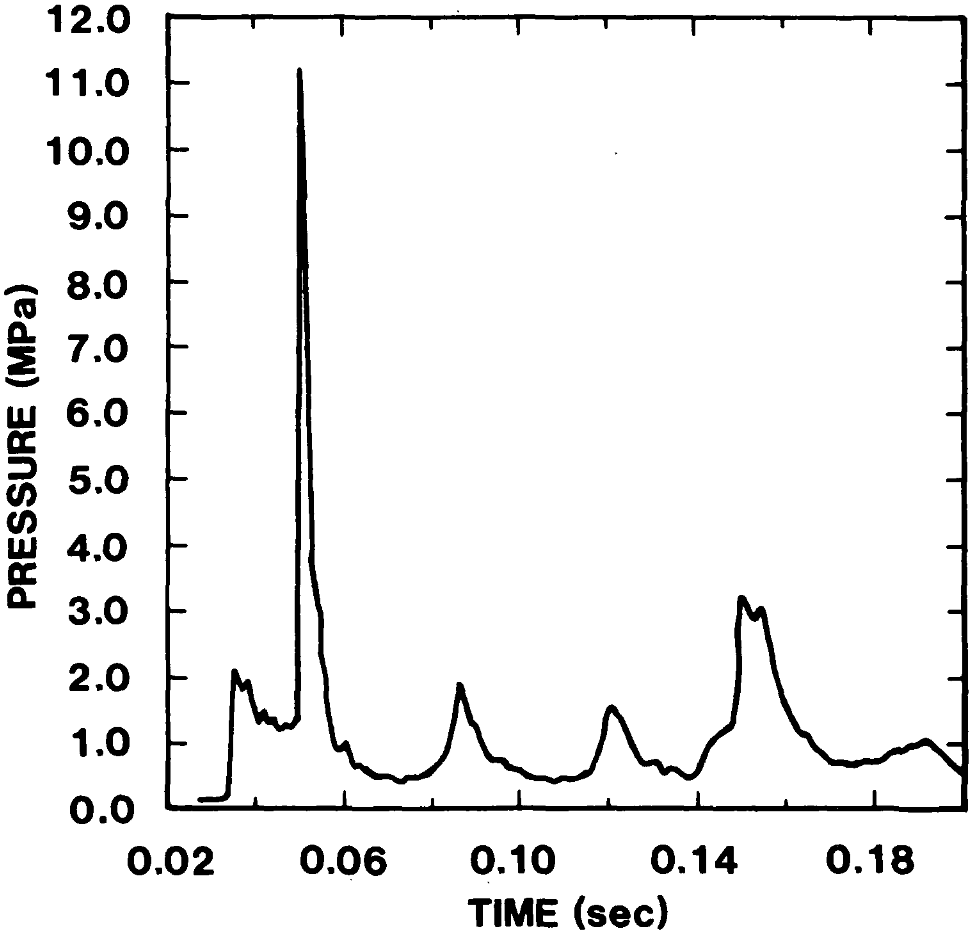


Figure 4-42. Pressure at Center of Roof in Zion Calculation

since the pressure and temperature decay when the compression wave enters a leaner hydrogen mixture; control means such as water sprays may sufficiently mitigate the phenomenon. (Water sprays may quench detonations and raise the lower detonation limit.[4-51])

In one PWR study,* it was found that the possibility of developing uniform hydrogen concentrations in excess of 18% (previously thought to be the detonability limit) seems very remote, if not impossible.[4-7] While it is now known that detonations can occur in lower hydrogen concentrations, the possibility of a global detonation is still remote. Local hydrogen accumulations, however, could conceivably reach detonable concentrations. The top of the ice condenser (see Figures 4-43 and 4-44) may be such a location. The mechanism aiding in concentrating this hydrogen is the condensation of steam out of the steam-hydrogen mixture that could flow up an ice condenser duct following a LOCA in which severe core damage occurred. If a deflagration was initiated at the base of the ice condenser duct, the combination of ostacles, along with the distinct possibility of an increasing hydrogen concentration vertically within the duct, renders this particular arrangement a possible candidate for DDT.

Other possible PWR locations in which hydrogen could concentrate include containment fan cooler ductwork, the cubicle area of the pressurizer relief tank (quench tank), the compartment immediately above the reactor vessel head, or, perhaps a reactor coolant loop cubicle, such as is present for some PWR facilities (shown in Figure 4-45).[4-52] Hydrogen could concentrate in comparable areas in BWR containments.

4.8 Residual Hydrogen (Post-Burn) Considerations in Containment

The burning of hydrogen in containment would result in large, short-duration temperature and pressure increases. Multiple burns would result in an increase in containment ambient temperature and pressure. Any systems and equipment inside containment whose use may be required after a burn must be able to survive both burn and post-burn environments. Following is a list of systems and equipment for a BWR6/Mark III facility whose use may be required after a burn:

- Containment isolation valves, penetrations, locks, and hatches
- Hydrogen Igniter System
- Hydrogen recombiners
- Containment Spray (CS) System
- Safety/relief valves
- Low pressure core spray, low pressure coolant injection, and residual heat removal systems
- Reactor level and pressure instruments
- Hydrogen analyzers
- Containment pressure and high-range radiation instruments
- Containment and suppression pool temperature instruments

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* Performed for the Sequoyah Nuclear Power Plant, a Westinghouse plant with an ice condenser containment, that is located in Daisy, Tennessee, and operated by the Tennessee Valley Authority.

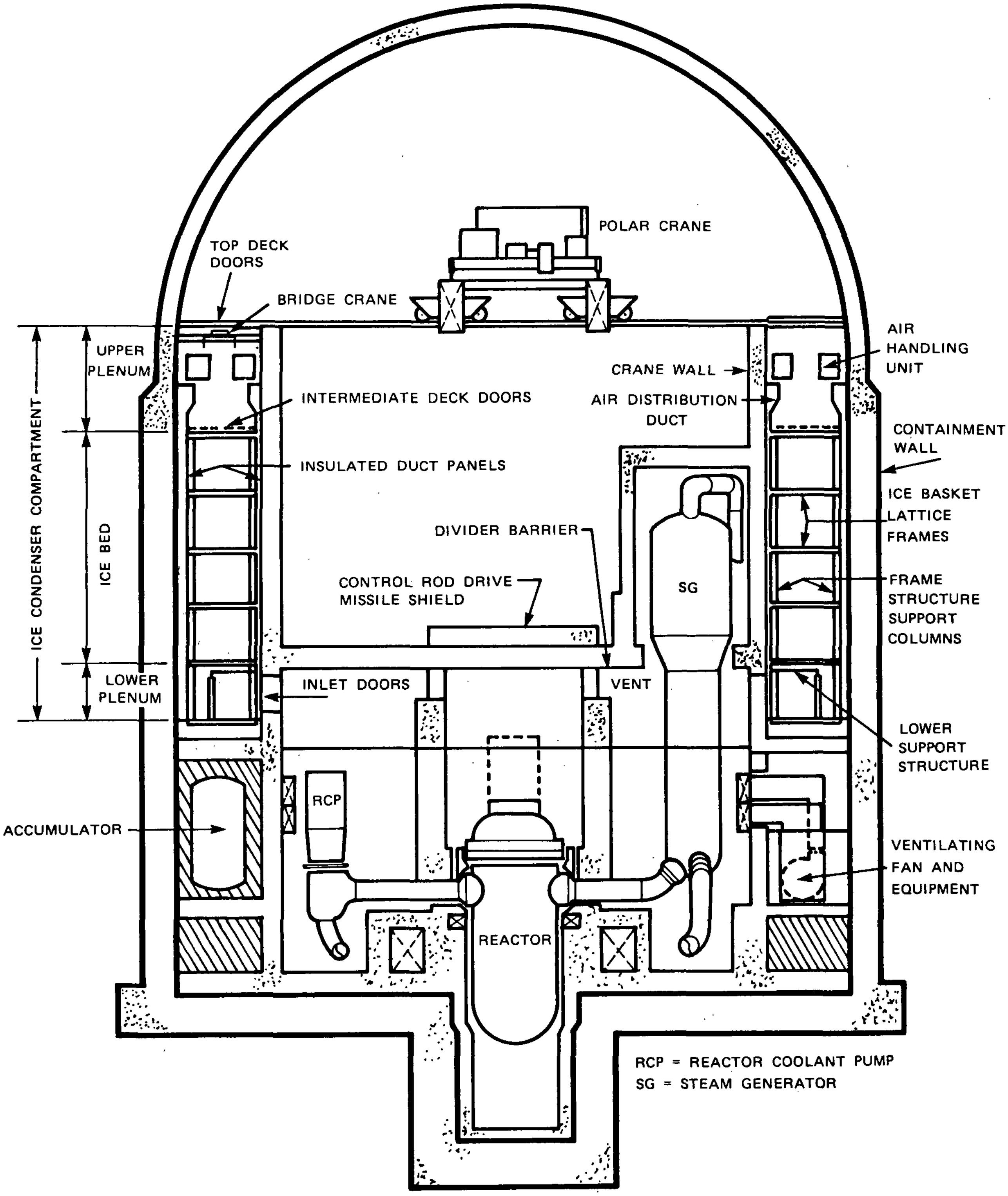

Figure 4-43. Simplified Diagram of Ice Condenser Containment

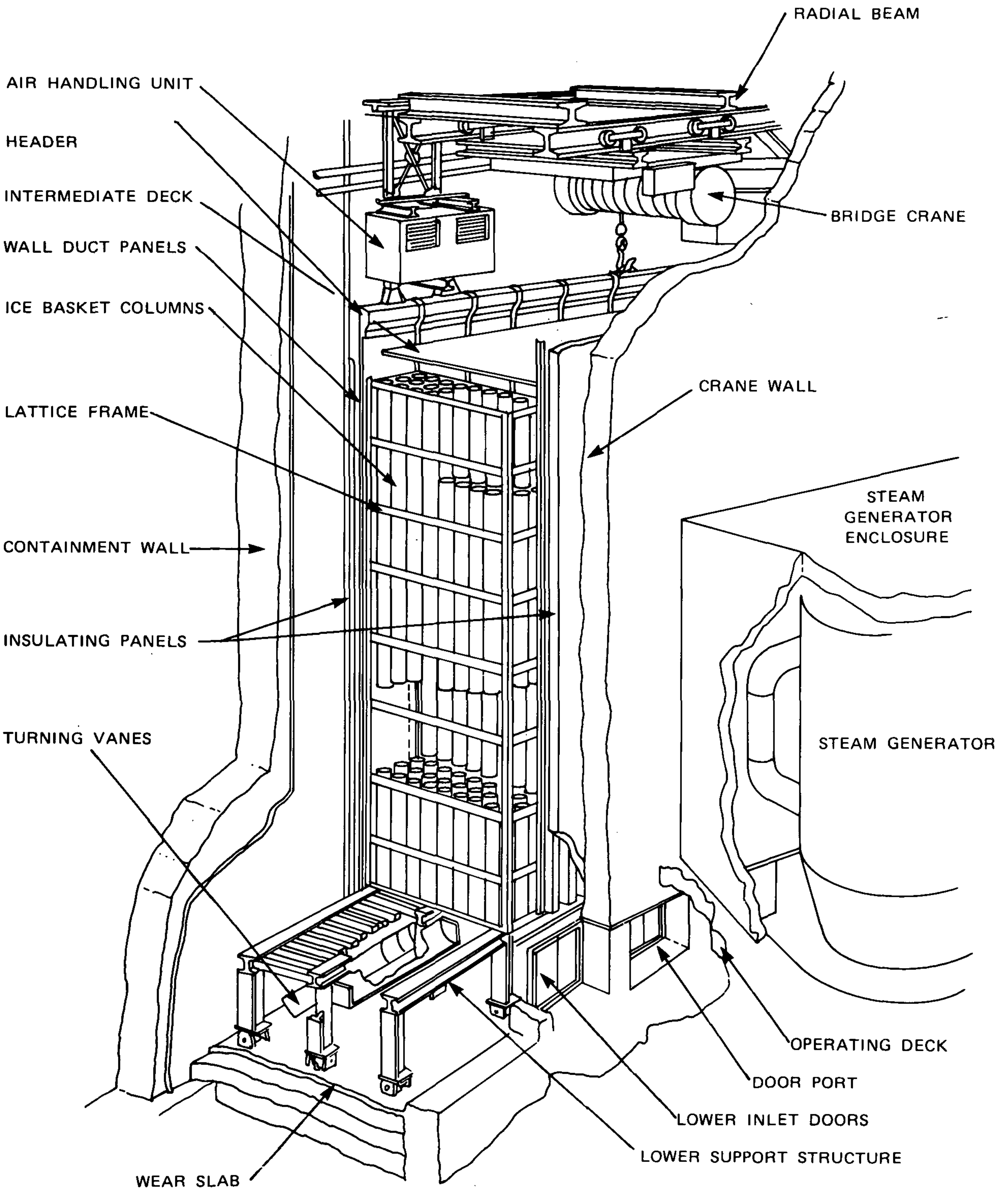

Figure 4-44. Cutaway View of Ice Condenser

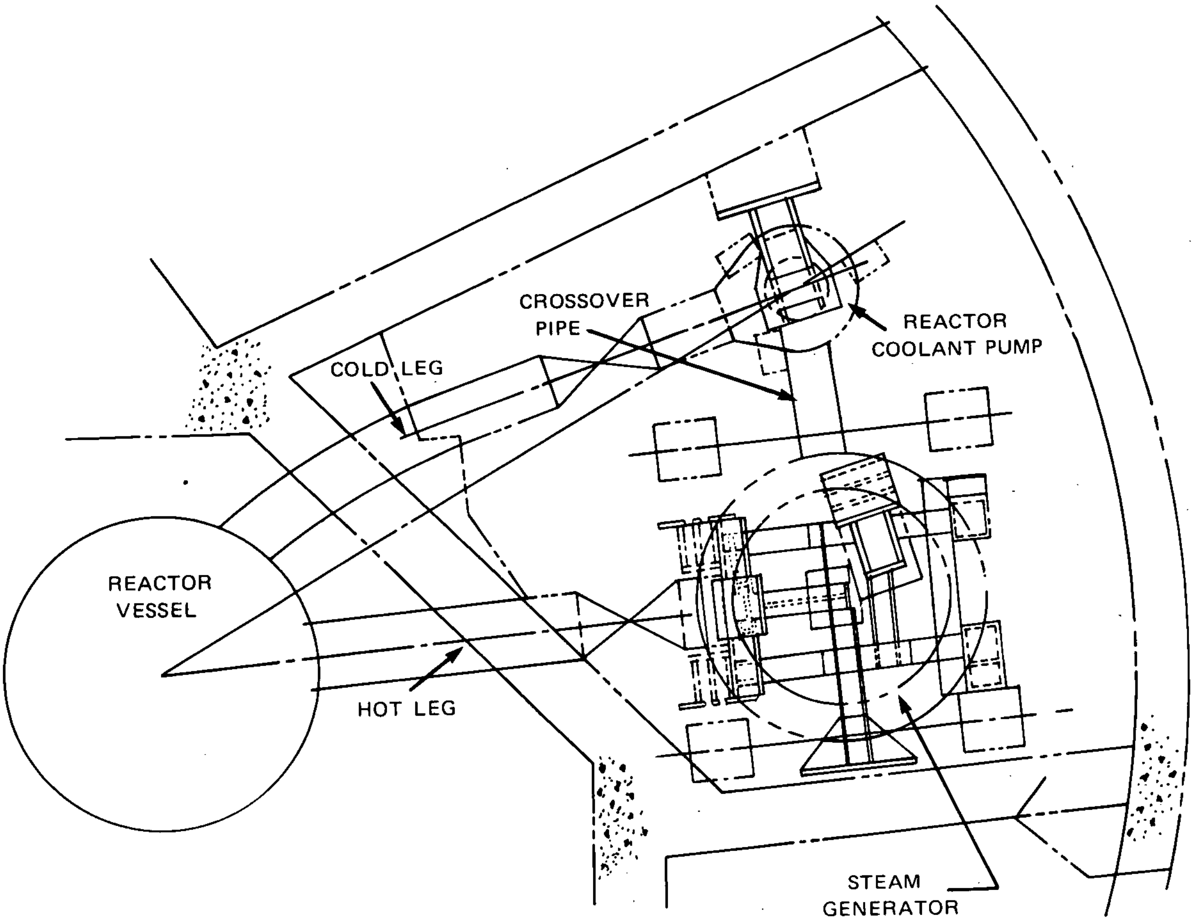

Figure 4-45. Plan View - Cubicle Loop (Typical)
North Anna Power Station Units 1 and 2

- Drywell pressure instruments
- Associated instruments and controls
- Associated power and control cables
- Low pressure core spray, low pressure coolant injection, containment spray, residual heat removal, and containment isolation valve position indication

The list for a PWR facility would be similar, minus the drywell equipment, and with the addition of pressurizer and steam generator equipment and instruments.

During the TMI-2 accident, the pressurizer level transmitters, pressurizer pressure transmitters, and RCS flow transmitters, all located at the six-foot elevation in containment, failed when the water level rose to the seven-foot elevation. The TMI-2 staff has recommended that any transmitters positioned at lower elevations in the containment building be repositioned at a higher elevation to prevent a transmitter failure by submergence in water. An alternate solution to this problem would be to enclose transmitters in watertight casings.

Also of concern in burn and post-burn environments are radiation, pressure and temperature effects. Although this was probably not a cause of any instrument failure at TMI, it is certainly one of the factors to be considered in instrumentation reliability. Up to the present time, there have been very little data regarding the integrated dose required for given vital instrumentation to fail. It is expected that more data will be made available regarding this parameter in the future.

During a hydrogen burn there is a rapid temperature increase in the vicinity of the burn. For a short duration, temperatures may exceed 1000°F, causing concern over radiation heat transfer. Radiation heat transfer can be adequately controlled by shielding susceptible instrumentation with a cover insulated on the inside.

As a result of multiple burns, the ambient containment temperature would rise. Typically, vital instrumentation designs have been submitted to (and have survived) test sequences that include exposures to temperatures as high as 300 to 330°F for periods up to a few hours. Analyses have indicated that under some circumstances severe accidents in reactor containments may produce temperatures higher than these tests. Therefore, the survivability, i.e., the ability to function adequately during and after such accidents, of safety related equipment needs to be carefully evaluated. In general, the instrumentation, probably as a result of having been designed to rigorous seismic requiremements, appears not to be threatened by the pressures expected in reactor accidents.

4.9 METHODS OF CONTROLLING LIBERATED HYDROGEN

4.9.1 Hydrogen Recombiners

The recombiners that now exist are capable of dealing effectively with the relatively small amounts of hydrogen and oxygen that result from radiolysis and corrosion following a LOCA. They are, however, incapable of handling the hydrogen produced in an extensive zirconium-steam reaction. Current recombiners can only process gas that is approximately 4 to 5% hydrogen or less. Higher hydrogen concentrations can be handled by diluting the mixture before it enters the recombiner. They are also limited to about 200 SCFM input flow per unit.[4-1]

4.9.1.1 Types. A recombiner is a device that reduces the hydrogen concentration in the containment atmosphere by combining free hydrogen and oxygen to form water. There are three different classifications of recombiners: flame, thermal, and catalytic. All three types perform the same function. They differ primarily in the way that they initiate the recombination reaction. The thermal recombiner uses radiant heat to bring about recombination, while flame recombiners depend on a self-maintaining, exothermic combustion process. Catalytic recombiners use a noble metal catalyst bed to promote recombination at relatively low temperatures.

The flame recombiner has the advantage of negligible heat input, but is more difficult to start than the other two types. In addition, it requires supplementary hydrogen and oxygen for reliable ignition and flame control. Also, the addition of hydrogen and oxygen to the input stream makes flame arrestors necessary. This type of recombiner has found very limited use in containment applications.[4-53]

The catalytic recombiner is widely used to recombine radiolytically generated off-gas during normal operation of BWRs. Extensive testing has indicated that it can also be effective in the less predictable post-LOCA environment.[4-1]

Two kinds of thermal recombiners are currently available for use in post-LOCA situations. One is for location inside containment; it uses convective gas flow that is regulated by the size of built-in orifices. The other is for location outside containment; it allows control over several operating parameters.[4-21] Since the flame recombiner has limited use in containment applications and since operation of the catalytic recombiner has already been described in some detail in the Chapter 3 discussion of BWR off-gas recombiner systems, only the two types of thermal recombiners will receive extended attention here.

The first type of thermal recombiner is that employed inside the containment building. The recombiner consists of a thermally insulated, vertical metal duct with electric resistance heaters to heat a continuous flow of containment air to a temperature that is sufficient to cause a reaction between hydrogen and oxygen. It has an outer enclosure to keep out containment spray water. The recombiner consists of an inlet preheater section, a heater-recombination section, and a discharge mixing chamber that lowers the exit temperature of the air (see Figures 4-46 and 4-47).

Air is drawn into the recombiner by natural convection, and passes through the preheater section. This section consists of a shroud placed around the central heater section; it takes advantage of heat conduction through the walls to preheat the incoming air. This serves to reduce heat losses from the recombiner and to preheat the air.

The warmed air passes through an orifice plate and enters the electric heater section where it is heated, thus causing recombination to occur. Tests have

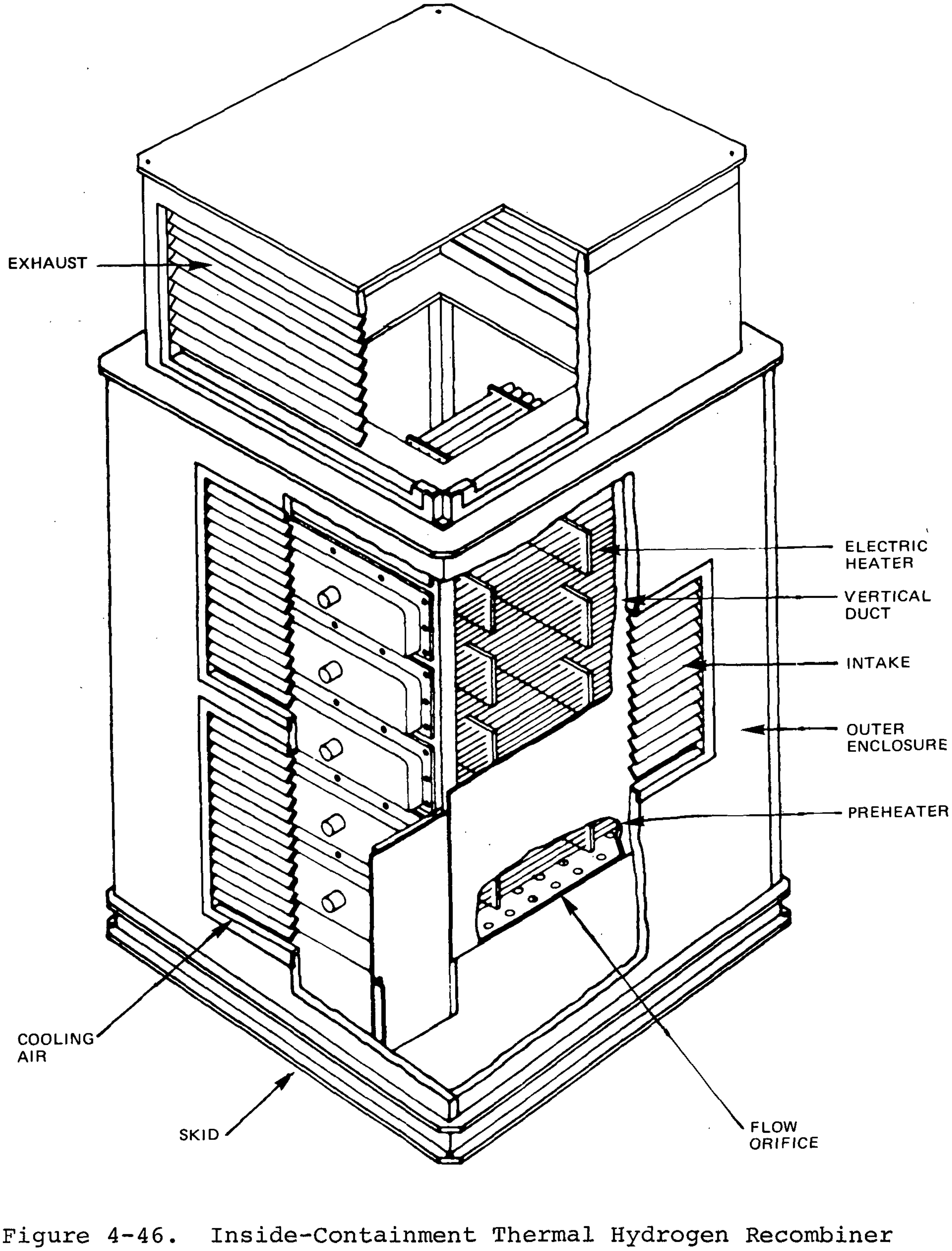

Figure 4-46. Inside-Containment Thermal Hydrogen Recombiner

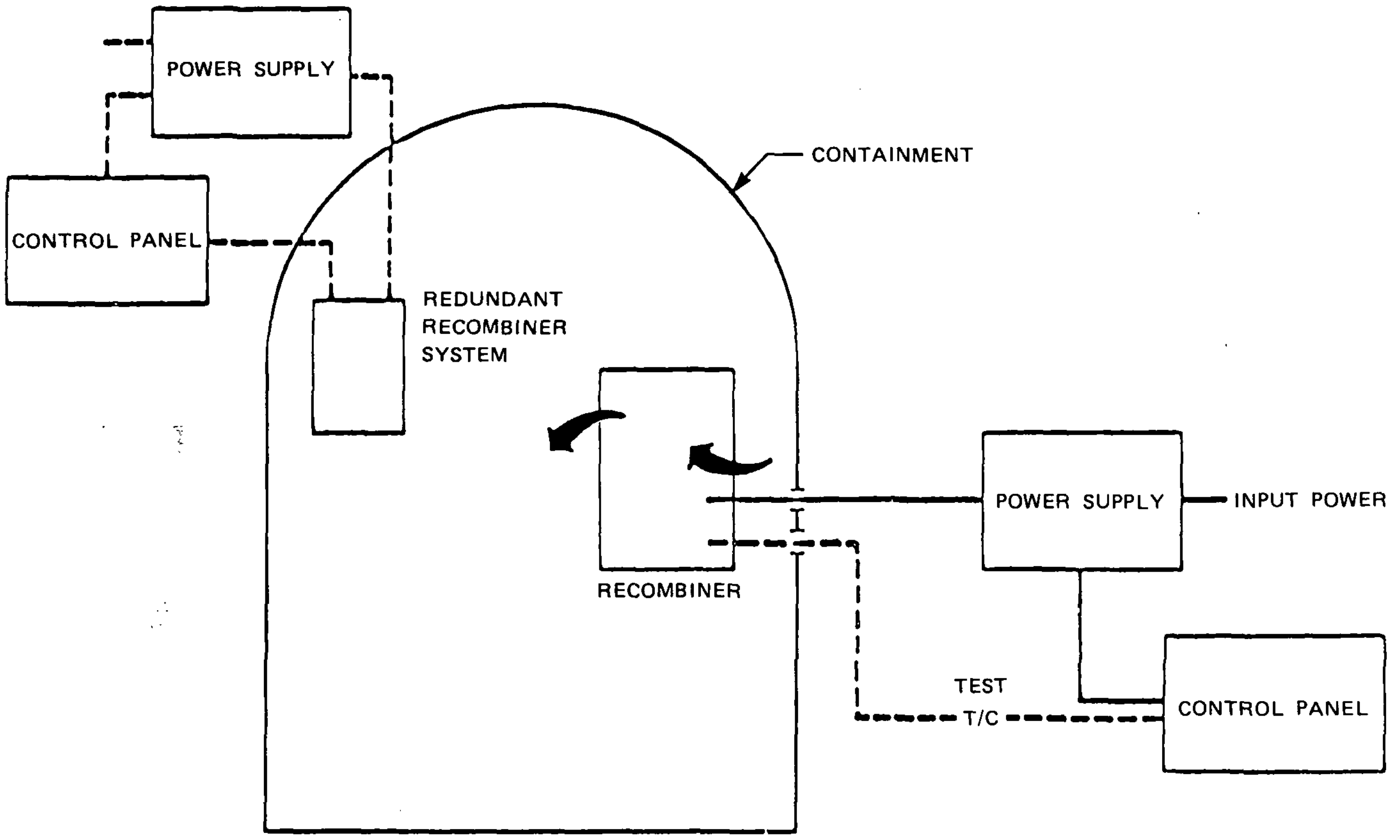

Figure 4-47. Schematic of Recombiner System

verified that the recombination is not a catalytic surface effect associated with the heaters but, rather, occurs due to the increased temperature of the process gases; therefore, catalytic poisoning is not a problem.

Catalytic poisoning is the process whereby a substance within the recombiner unit itself inhibits the activity of the catalyst. Such poisoning has not been demonstrated to be a problem in these thermal recombiners.

The power panel for the recombiner is located in the auxiliary building where it is not exposed to the post-LOCA environment. The control panel is located in the control room. To control the recombination process, the correct power input that will bring the recombiner above the threshold temperature for recombination is set on the controller. This power depends on containment atmospheric conditions, and must be determined whenever recombiner operation is required. A thermocouple readout instrument is also provided in the control panel for monitoring temperatures in the recombiner.

The recombiner units are located in the containment such that they process a flow of containment air containing hydrogen at a concentration that is typical of the average concentration throughout containment. The recombiners will be started manually after a LOCA. They are capable of continually processing a minimum of 100 SCFM of containment air per unit. The hydrogen and oxygen in the processed atmosphere are converted to steam, thus reducing the overall containment hydrogen concentration.[4-1]

The other type of thermal recombiner is designed for employment outside containment (see Figures 4-48 and 4-49). This device is very similar to that previously described; it has only a few variations. The process gas is drawn from the containment building, into and through the recombiner system, and back to containment by either a positive displacement blower or regenerative blower directly driven by an induction motor. The flow rate of the containment gas through the system is measured by a flow tube. In addition to the heater, reaction chamber, and cooler sections employed in the inside-containment type, this recombiner also uses a "trickle heater." During periods of non-operation, it is possible for moisture to accumulate in the gas containing piping. To preclude this, and thereby inhibit corrosion, an auxiliary heater control system trickle heater is provided. The heaters operate continuously to maintain heated-section temperatures at about 150°F (66°C).

All instrumentation and control equipment is, of course, located outside containment. An adjustable timer provides for a low-alarm cutout during start-up. Interlocks are provided to turn off the heater if the heater or reaction gas temperature exceeds the normal control range. A low-flow blower and heater cutoff, that receives its signal from the gas flow meter, completes the safety instrumentation for the system.[4-1]

One of the concerns about the use of external thermal hydrogen recombiners is that hydrogen control penetrations should be dedicated solely to this purpose. For example, TMI-2 had provisions for post-accident installation and operation of an external hydrogen recombiner for combustible gas control. However, the design of the external recombiner hookup at TMI-2 used the

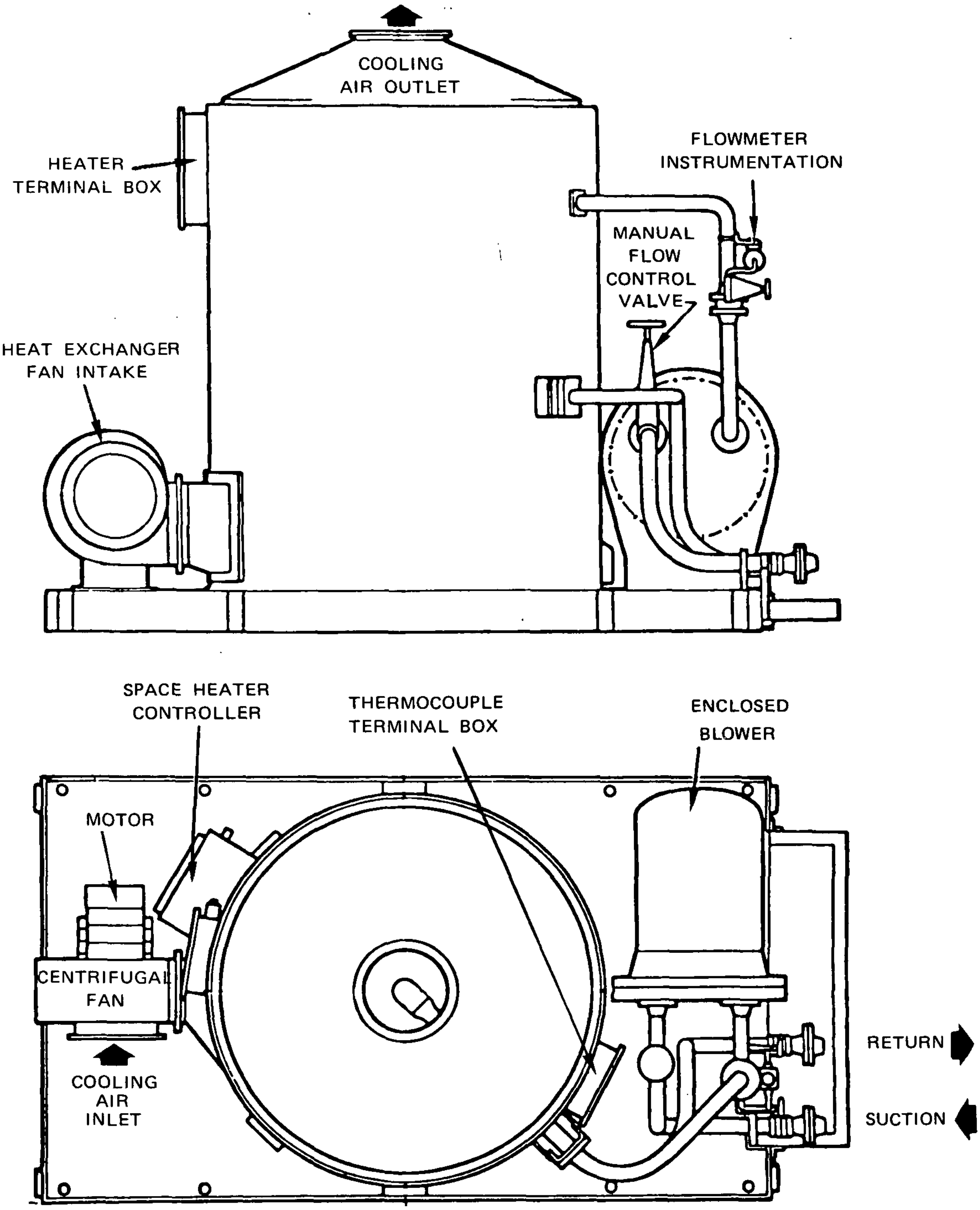

Figure 4-48. Thermal Recombiner Package

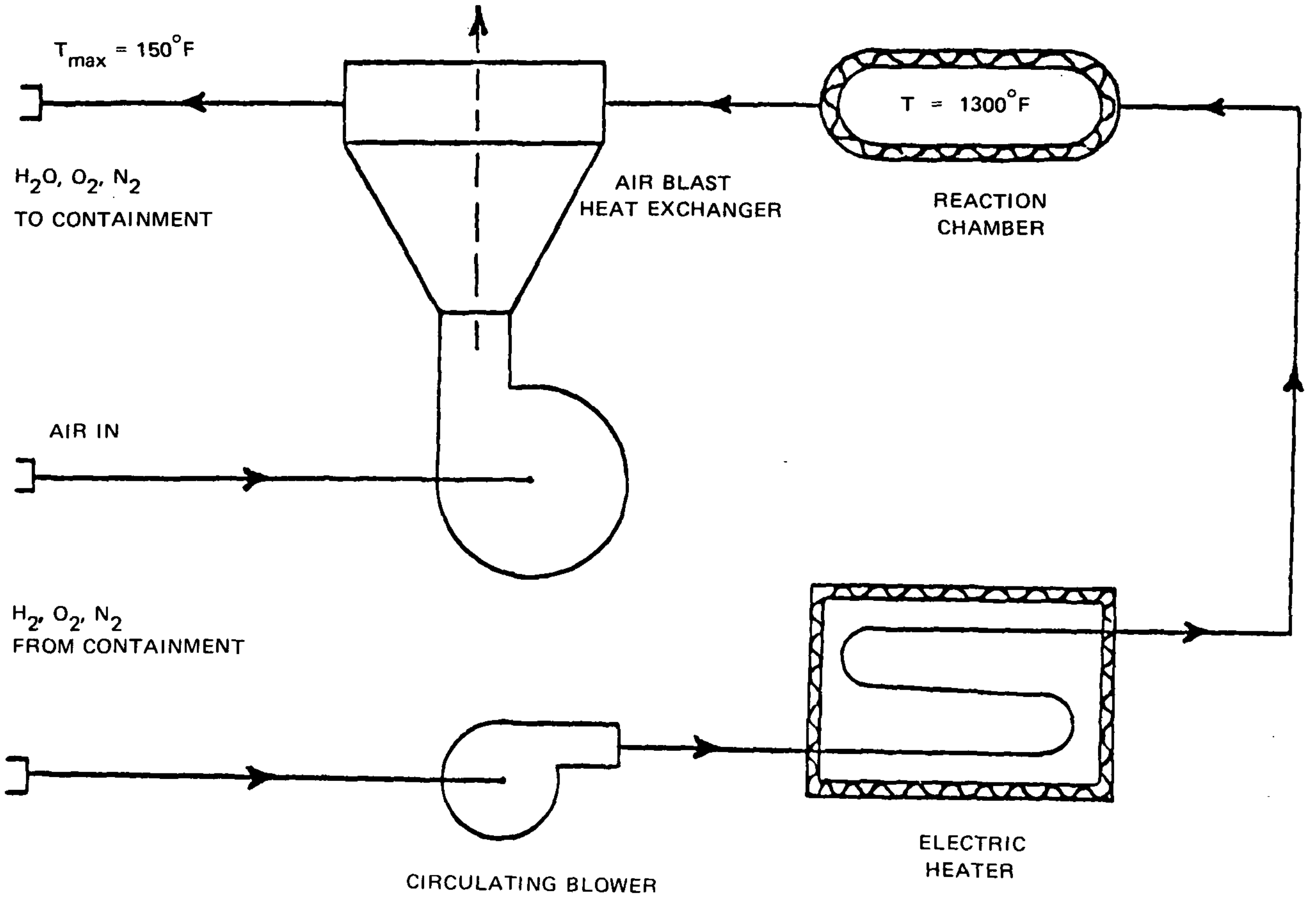

Figure 4-49. Schematic Representation of the Outside-Containment Thermal Recombiner

36-inch containment penetrations for the normal Containment Purge System by tapping 4-inch lines off the purge lines outside the containment building between the building and outer containment isolation valves. Operation of the hydrogen recombiners required opening of the inboard 36-inch containment isolation valve in both a Containment Purge System inlet and outlet line. With this design, once the hydrogen recombiner is put into operation, containment integrity is vulnerable to a single active failure. Thus, a spurious or inadvertent opening of one of the 36-inch outboard containment isolation valves would result in venting the containment to the environment.

As a result, a proposed amendment to 10CFR50 was prepared.[4-5] The purpose of this amendment is to provide assurance that facilities with hookups for external recombiners or post-accident purge systems that are susceptible to single failures make design modifications to correct this situation. Systems designed to meet these proposed requirements would not provide through-line leakage paths between the containment atmosphere and the environment and would eliminate the possibility of violating containment integrity through a single active failure during hydrogen recombiner or purge system operation.

4.9.1.2 Capabilities. Hydrogen recombiners can, in general, be used from the onset of an accident in which severe core damage has resulted. Although they are considered capable of handling the hydrogen resulting from a DBA-LOCA, they appear to be ineffective for significant hydrogen generation rates. A typical recombiner, for example, has a capacity of 100 SCFM[4-39]. To deal with a 75 percent metal-water reaction, as proposed for 10CFR50, an inordinate number of recombiners would be required.

4.9.1.3 Positive and Negative Aspects. Tables 4-7 through 4-9 present the positive and negative aspects of the various types of flame recombiners, thermal recombiners, and catalytic recombiners.

TABLE 4-7

FLAME RECOMBINER

Positive	Negative
o There is a minimal pressure rise in containment in conjunction with its use o The technology is developed o Inadvertent actuation will not present hazards	o It cannot control a large-scale generation of hydrogen. (Each recombiner is of limited capacity.) o Use is limited to containment atmospheres not within the flammability limits (<4% H_2 or <5% O_2). o Flame recombiners are difficult to start. o It requires supplemental hydrogen and oxygen supplies for reliable ignition and flame control.

TABLE 4-7 (Cont.)

FLAME RECOMBINER

Positive	Negative
	o It could be an ignition source for a flammable mixture in containment.
	o The necessity to use many of these recombiners would lead to high installation and maintenance costs.

TABLE 4-8

THERMAL RECOMBINER

Positive	Negative
o There is a minimal pressure rise in containment in conjunction with its use	o It cannot control a large-scale generation of hydrogen. (Each recombiner is of limited capacity.)
o The technology is developed	o Use is limited to containment atmospheres not within the flammability limits
o Inadvertent actuation would not present hazards	o It could be an ignition source for a flammable mixture in containment.
	o The necessity to use many of these recombiners would lead to high installation and maintenance costs.

TABLE 4-9

CATALYTIC RECOMBINER

Positive	Negative
o Minimal pressure rise in conjunction with use. o Inadvertent actuation would not pose hazards.	o It is susceptible to catalytic poisoning from methyl iodide (CH_3I). o Cost is high. o It cannot control a large-scale generation of hydrogen. o It could provide an ignition source for flammable mixtures in containment. o Use is limited to containment atmospheres not within the flammability limits (<4% H_2 or < 5% O_2).

4.9.2 Deliberate Ignition of Hydrogen

4.9.2.1 Method. Another method of controlling liberated hydrogen within LWR containments is deliberate ignition. The philosophy behind this type of mitigation scheme is very simple: keep the hydrogen concentration below levels that would challenge the integrity of the containment. At the present time, however, this method has only limited application. The only plants that currently employ deliberate ignition are three PWRs with ice condenser containments and one BWR with a Mark III containment; another is planning to use deliberate ignition.

A typical Mark III BWR containment contains approximately 1.5 million cubic feet of free air volume. If one assumes a metal-water reaction similar to the one believed to have occurred at TMI-2, the resultant deflagration (or possible detonation) in a containment of this volume might challenge the containment integrity. Since the PWR ice condenser containment free air volume and design pressure (about 15 psig) are similar to those of the Mark III containment, the same type of concern exists for it. Hence, for these containment designs, the deliberate ignition concept has become an attractive scheme to mitigate the consequences of possible metal-water reactions that could take place during a LOCA.

One reason for the limited applicability of deliberate ignition is that in most PWRs incorporating large dry containments it has been calculated that the containment hydrogen concentration following a degraded core accident probably would not threaten containment integrity (the issue of equipment survivability for these plants is not yet resolved). For BWR Mark I and II primary containments, the volume is so small that the hydrogen problem can be readily handled by inerting the entire drywell atmosphere with nitrogen during operation.

BWRs with Mark III containments have substantially larger drywells and, in addition, have communication between the suppression pool and the outer containment (reactor building). This design has the distinct advantage of having a much greater volume for steam expansion and gas dilution during a LOCA.

Those PWRs that employ ice condensers for pressure suppression in containment are unique in that they have significantly smaller containments than other PWRS. If a degraded-core condition (in which a major portion of the fuel cladding reacted with steam) was reached at one of these facilities, containment integrity could be challenged if no mitigation systems were employed. The volume of the ice condenser containment may not be sufficient to contain the resultant deflagration (or detonation). Deliberate ignition is a method that has been chosen for plants of this type. Most PWRs do not utilize deliberate ignition because their extremely large volumes (relative to the amount of zirconium in the core) are probably sufficient to keep the hydrogen concentration below values that would challenge containment integrity. Note that most large dry PWR containments may have a sufficient volume to handle the hydrogen production from the oxidation of 100% of the zirconium in the core. Large dry PWRs may have a problem if there were a high baseline pressure due to steam before a burn. This might occur in accidents where the containment cooling systems have failed. If it should become necessary to provide an extra margin of safety, these containments could be retrofitted with additional systems for hydrogen control. In such a case, deliberate ignition might be a likely candidate for use in non-ice condenser PWR containments. Figures 4-3 and 4-5 showed simplified representations of containments in which deliberate ignition is employed.

Although deliberate ignition is used in different types of containments, the philosophy of operation of the system is always the same. The most important consideration when developing a deliberate ignition scheme is to plan the burns in such a way that the resultant pressure will not approach the failure pressure of the containment.

Igniters should not be placed next to key safety equipment such as power supplies or electrical cable trays. In addition, they may not be as effective when placed below solid ceilings because they may not ignite a significant quantity of gas until the downward propagation limit of 9% hydrogen concentration is reached, as discussed in Chapter 2. A conservative estimate of pressure rises from a hydrogen deflagration can be made by assuming an adiabatic (no heat transfer) and isochoric (constant volume) process. Refer back to Figs. 2-10 to 2-13 for such estimates of possible pressure rises.

Notice that significantly different overpressure values could be obtained depending on the completeness of the burn. Hydrogen burns in LWRs can be incomplete, with the degree of combustion efficiency dependent on many factors, such as containment size and strength of ignition source. Burns are likely to be nearly complete for hydrogen concentrations above 8%, while below about 8% the glowplug igniters become less reliable. Note, however, that there may be the possibility of higher hydrogen concentrations if the containment is temporarily steam inerted.

In ice condenser containments, the upper and lower compartments are separated by paths running through the ice condensers and recirculation fans. Hydrogen burns in the upper and lower compartments have significantly different characteristics. Burns occurring in the lower compartment can expand into the upper compartment and, in the process, transfer large quantities of heat by cooling and condensation in the ice condensers. This, in addition to the large volume available for expansion in the upper compartment, greatly reduces the pressure and temperature rises associated with the burns. For ignitions in the upper compartment, however, pressure and temperature reductions result only from heat transfer to the walls (and cooling sprays, if they have been preactivated) and minimal expansion through the recirculation fans. Hence, the assumptions of adiabatic and isochoric combustion yield results that should be fairly accurate for fast global burns in the upper compartment and overly conservative for burns in the lower compartment. It is therefore preferable to initiate deliberate ignitions in the lower compartment of PWR ice condenser containments.*

Referring again to Figs. 2-10 to 2-13, it can be seen that the failure pressure of an ice condenser containment (about 45 psig for Sequoyah) is reached with about an 8% hydrogen concentration in containment -- assuming that deliberate ignition is the sole mitigation scheme. If the generation and release of hydrogen is slow enough, the hydrogen can be consumed gradually in multiple burns, with interim cooling of the atmosphere by heat transfer and water sprays, thus preventing a continuous buildup of pressure. Deliberate ignition is a mitigation scheme that is limited in the amount of hydrogen it can control for a single ignition, and limited in the rate of hydrogen it can control for multiple ignitions with interim cooling.[4-7]

Devices that have been considered for use as igniters are spark plugs and glow plugs. These are both weak igniters and have been found to cause incomplete combustion in large chambers at low hydrogen concentrations. Pyro-fuses could also be used, but since they are usually intended for one-time use they are considered impractical. One concern that has been expressed about the use of spark plugs is the possible radio frequency interference caused by the sparks. For this reason, glow plugs seem to be the most popular type of igniter at present. The glow plugs employed at Grand Gulf are the General Motors AC Division model 7G plugs.[4-14] Sequoyah is planning to install comparable devices manufactured by Tayco.

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* This statement may not be true if the possibility exists for flame acceleration and deflagration-to-detonation transition in the ice condenser.

Igniters may be actuated manually or automatically, and are distributed throughout the containment in such a way that uniform combustion can be achieved. This is done to prevent the formation of isolated pockets with excessive concentrations of hydrogen. It can be seen that the location of the igniters is critical to the proper operation of the system. At present, several igniters are planned for the region around the periphery of the containment at the top of the ice condensers. It is postulated that under certain accident conditions, the lower compartment would be inerted either by high concentrations of steam, or by low concentration of oxygen. The inerted gas mixture would enter the bottom of the ice condensers and emerge as an extremely rich mixture at the top. Hydrogen concentrations is this area could possibly exceed detonable limits, making it possibly a less than ideal location for the placement of igniters. The current state of knowledge does not allow us to say with any certainty whether or not detonations are possible in these geometries. Sandia recommended that these igniters be relocated higher in the upper compartment where hydrogen concentrations will be much lower than at the outlet of the ice condensers.[4-7] Some consultants, however, feel that the current placement of igniters is desirable and safe. This disagreement might arise for igniters placed at the top of the suppression pool in a BWR.

In summary, deliberate ignition can be an effective method of hydrogen control if the hydrogen can be consumed slowly enough so that neither containment integrity nor equipment survival is jeopardized. As we mentioned, this can be accomplished in several ways: by burning lean mixtures; by burning in the lower compartment (in a PWR ice condenser containment); and by burning infrequently enough to prevent pressure and temperature buildup.[4-7] Deliberate hydrogen burns would occur at low enough concentrations to maintain the hydrogen below its detonable limit and to prevent containment overpressure failure. The potential for significant pocketing of hydrogen would be reduced by:

- Utilization of distributed ignition sources
- Simultaneous operation of containment sprays
- Mixing caused by turbulence resulting from localized burns
- Use of air handling fans

Ignition may be initiated by manual control of glow plugs from the control room. (Glow plugs are presently preferred over spark plugs as the source of ignition.) The number and placement of the glow plugs are dependent upon the type of containment.

4.9.2.2 Grand Gulf Nuclear Station. The Grand Gulf Nuclear Station is a BWR-6 employing a Mark III containment. It has a Combustible Gas Control System comprised of two 100%-capacity hydrogen recombiners (based on the DBA-LOCA), a drywell purge subsystem, and a backup containment purge subsystem; this system provides the capability to control the hydrogen that may be generated from a DBA. This system fully meets the current requirements in the Code of Federal Regulations for combustible gas control. However, as a result of the TMI-2 incident, the NRC requested (on October 30, 1980) a description of a program to improve the hydrogen control capability of Grand Gulf. A Hydrogen Ignition System was chosen as the best method of complying with the NRC request. The following discussion concerns this system.[4-14,4-61]

In the event of a severe LOCA resulting in a large generation of hydrogen, hydrogen can be released directly to the BWR containment atmosphere via the safety/relief valves that exhaust to the suppression pool. Therefore, igniter assemblies are located in a ring above the suppression pool as well as at other locations throughout the containment. Hydrogen can also be released directly to the drywell atmosphere via a pipe break in the drywell. Therefore, igniter assemblies will also be located through the drywell.

The Grand Gulf HIS design calls for 90 igniter assemblies located in the drywell and containment, and the use of containment sprays to ease pressure and temperature build-up. No igniters are located between elevations 208 ft-10 in and 262 ft-10 in because of an absence of adequate support members. This configuration should not negatively affect the functioning of the HIS for the following reasons:

- No major structures exist in this region that would promote the formation of hydrogen pockets. (For example, the polar crane is not large enough to allow hydrogen to pocket.)
- The turbulence resulting from localized burns at other elevations and the operation of the containment sprays will promote the movement of any hydrogen in this area to areas supplied with igniters.[4-14]

The igniters are powered from Class 1E power panels that have normal and alternate ac power supply from offsite sources. In the event of a loss of offsite power the igniters would be powered from the emergency diesel generators. In addition, the HIS is designed as a seismic Category I system.

The igniter assemblies will be located in all areas of the containment and drywell so that:

- Assuming only one engineered safety feature (ESF) power distribution panel is funtional following an accident, a maximum distance of 60 feet will exist between operable igniters.
- Assuming both ESF power distribution panels are functional following an accident, a maximum distance of 30 feet will exist between operable igniters.

In addition, for enclosed areas inside containment, two igniter assemblies will be located in each area, with each igniter fed from a separate ESF power distribution panel.

The igniter assemblies will be designed to include the following:

- A welded metallic enclosure that partially encloses the igniter and contains the transformer and associated electrical wiring
- Provisions for access to the interior of the enclosure
- A spray shield to protect the igniter from containment spray
- A copper heat shield, if required, to protect assembly components from high temperatures

- An igniter capable of maintaining a 1700°F surface temperature for a minimum of one week
- A transformer capable of stepping down 120 volts AC power to the voltage necessary to achieve a minimum igniter operating temperature of 1700°F.

As mentioned before, the HIS is manually initiated from the control room. Instrumentation for the HIS consists of two control room handswitches, one for each of the two Class IE power division. Each handswitch energizes the igniters in its respective division.

4.9.2.3 Sequoyah Nuclear Plant. The Sequoyah Nuclear Plant is a PWR ice condenser containment facility that has proposed thermal igniters for its Permanent Hydrogen Mitigation System (PHMS).[4-59,4-62] The Sequoyah PHMS is designed to operate without the use of containment sprays and fogs, in contrast to the Grand Gulf HIS, which is designed to be used in conjunction with containment sprays.

The basic design at Sequoyah includes a total of 64 igniter assemblies in two trains distributed throughout containment, with at least one pair of redundant igniter assemblies in each region. The following system description is excerpted from two reports on the Sequoya Nuclear Plant:[4-59,4-62]

> Following a degraded core accident, any hydrogen which is produced would be released from a break or the pressurizer relief tank into the containment in the lower compartment inside the crane wall. To cover this source region, there will be 22 igniters (equally divided between trains) located high in the lower compartment inside the crane wall. Eight of the igniters will be equally distributed around the interior of the crane wall between ice condenser inlet doors. . . Two igniters will be located at the lower edge of each of the five steam generator and pressurizer enclosures. . . A pair of igniters will be located in the top of the pressurizer enclosure. . . Another pair of igniters will be placed above the reactor vessel in the upper reactor cavity. . .Since there are no potential hydrogen sources in the steam generator enclosures and significant flows into these enclosures are not expected from the rest of the lower compartment, igniters will not be located in the top of these enclosures.
>
> Any hydrogen not burned in the lower compartment would be carried up through the ice condenser and into its upper plenum. Because steam would be removed from the mixture as it passes through the ice bed, thus concentrating the hydrogen, mixtures that were nonflammable in the lower compartment would tend to become flammable in the ice condenser upper plenum. Controlled burning in the upper plenum is preferable because upper plenum burns involve smaller quantities of hydrogen and allow for the expansion of the hot gases into the upper compartment, thereby reducing the peak pressure.
>
> TVA has chosen to take advantage of the beneficial characteristics of combustion in the upper plenum by distributing 16 igniters around it. The igniters are located on the containment shell side of the upper plenum at 16 equally spaced azimuthal locations. To handle any accumulation of

hydrogen in the upper compartment, four igniters will be located in the upper compartment dome. Additional igniters are located at lower elevations in the upper compartment to take advantage of upward flame propogation at lower hydrogen concentrations; specifically, four igniters are located near the top and inside the crane wall, and one is located above each of the two air return fans. The air return fans provide recirculation flow from the upper compartment through the dead-ended volume and back into the lower compartment. To cover the dead-ended region, there will be a pair of igniters in each of the eight rooms through which the recirculation flow passes.

In order to prevent system breakdown, components of a deliberate hydrogen ignition system, whether in a BWR or PWR facility, should:

maintain their functional capability under the full range of main steam line break and post-LOCA temperatures, pressures, humidity, radiation, and chemical sprays present in the containment. These components of the system must survive the effects of multiple hydrogen burns and must be protected from containment spray impingement and flooding. All components of the system outside containment must be qualified to operate in the environment in which they are located.[4-59]

The impact on operations of a thermal igniter system would be minimal. The system poses no threat to personnel since it is not required during normal operation and would normally be deenergized. Inadvertent actuation of the system during any phase of plant operation presents no threat to personnel or equipment. This would prevent reluctance by the operator to activate the system and would enable him to activate it at a point in the accident before hydrogen could be released to the containment. The relatively short warmup time for the thermal igniters following activation would contribute to the high likelihood of their availability.[4-59]

The cost of design and hardware should be moderate for a thermal igniter system since the technology is proven and does not need extensive development. Installation costs should not be excessive if the work is performed during a refueling outage instead of during a special forced outage.[4-59]

4.9.2.4 Capabilities. The glowplug hydrogen igniter system is promising in that it can burn hydrogen as it is produced from the onset of a severe accident in which significant core damage has occurred. It can be energized upon receipt of an ECCS signal or some other suitable input (from hydrogen detectors, for example). Since the system would burn the hydrogen at or near the lower combustible limit, the formation of detonable concentrations of hydrogen would, in all probability, be prevented. An added advantage of burning the hydrogen in this manner is that the oxygen in the containment air is also being consumed, thereby reducing the probability that a combustible mixture exists as time progresses.

The glowplugs used in this system should be durable and reliable. Hence, long-term use of these devices can be expected. Naturally, the deliberate ignition system only lends itself to use for a non-inerted type of reactor containment.

4.9.2.5 Positive and Negative Aspects. Table 4-10 outlines the positive and negative aspects of the deliberate ignition system.

Table 4-10

DELIBERATE IGNITION

Positive	Negative
o Deliberate ignition distributes the energy addition to containment over a period of time, which allows the pressure and temperature changes inside containment to be less severe.	o It may require additional containment penetrations for electrical connections.
o It may control a large-scale generation of hydrogen.	o Each ignition will increase containment pressure and temperature.
o The system is no threat to personnel since it is not required during normal operation, and inadvertent actuation would not present a threat.	o Burns may damage equipment in containment.
o It has a relatively short warmup time.	
o Maintenance would be minimal.	
o The cost is moderate.	
o The technology is already developed.	
o Minimal space is required inside containment.	

4.9.3 Combination of Water Fog or Spray with Deliberate Ignition

4.9.3.1 Method. Deliberate ignition removes hydrogen through a series of controlled burns. The effectiveness of deliberate ignition is limited primarily by containment pressure considerations. The frequency at which burns can be tolerated is limited by the rate at which the containment atmosphere cools. Water fogs or sprays can serve as a pressure and temperature suppressant. This method involves the supension of a large mass of liquid water, in the form of droplets, in the containment atmosphere. The drops act as a large thermal capacitance, greatly reducing the temperature rise that otherwise would occur as a result of hydrogen combustion or steam release from the reactor vessel. For these reasons, there may be advantages to using deliberate ignition and water fogging together. Figures 2-28 and 2-29 and Table 4-11 show how the addition of a fog increases the hydrogen concentration required to attain given pressures. The values in Table 4-11 were calculated for the Sequoyah Nuclear Plant and are for a 0.05% water concentration. Although this concentration is difficult to achieve, the values indicate the general trend of increased hydrogen concentration necessary to produce a given pressure.

Table 4-11

HYDROGEN CONCENTRATION REQUIRED TO ATTAIN GIVEN PRESSURES

Pressure psig	Complete Combustion	Incomplete Combustion	0.05% Water Droplets
31	5.5	6-9	13.5
45	8.2	8-9	15.7

In order for fogging to reduce the pressure and temperature from a hydrogen burn effectively, the kinetics of drop vaporization must be taken into account. There are three major characteristics of a fog that must be considered. The first, and most important, is water content. The use of any fog, regardless of water content, is beneficial. However, as shown in Chapter 2, water densities between 0.01 and 0.05 volume percent are needed to produce significant reductions in the pressure and temperature. In most cases, especially when considering loss rate, water content is the most critical parameter of the fog.

The second characteristic is droplet size. In order for a fog to perform correctly in the presence of hydrogen combustion, it must be produced and maintained with the droplets of optimum size -- a size that is bounded both above and below. If the droplets are too large, they will not vaporize fast enough, and an initial pressure overshot could occur before equilibrium is achieved as the droplets vaporize. The overshoot could last long enough to increase the static load on the containment structure. If the droplets are too small, they vaporize inside the flame front, thereby inhibiting, or even quenching, the flame. A droplet size (radius) typical of containment spray systems is about 200-300 microns; it is estimated that the optimum droplet size for an effective water fogging system is in the neighborhood of 10-200 microns. Small droplets also tend to remain supended in the containment atmosphere longer than larger drops. The production of fog with an appropriate droplet size is technically possible and can be accomplised with air blast nozzles. With these, a very low pressure drop is developed across the spray nozzles, resulting in a high resistance to clogging. The atomization is accomplished by a high speed, compressed air jet.

The final characteristic, and one that is closely related to droplet size and density, is droplet spacing. Close spacing may quench the flame while droplets placed farther apart may not provide adequate thermal capacitance. Proper droplet sizing will automatically eliminate the problem of spacing for the densities of interest. If the fog is made such that the great majority of droplets are larger than 5 microns, it is not expected that droplet vaporization or droplet spacing will significantly affect the flame structure; hence they should not influence flammability limits.

Although the high-volume production of small water drops is possible, maintaining a stable, high-density fog could be extremely difficult if there are very large settling losses. Estimates of loss rates vary over a considerable range of values. Large estimates of loss rates may require such high injection rates that water fogging would be impractical. For this reason, it is necessary to determine expected loss rates more accurately. This will invlove studying the mechanisms of droplet interaction in greater detail.

A rigorous discussion of droplet interaction mechanisms is beyond the scope of this manual. However, there is one particular phenomenon that is extremely important and that is the critical factor in determining the loss rate. This phenomenon is know as gravitational coagulation. It results from the fact that nozzles do not produce monodispersed (single droplet size) sprays, but polydispersed sprays covering a range of drop sizes. As the fog settles, larger drops (with higher terminal velocities) will overtake, collide with, and coalesce with smaller ones. This process increases the mean droplet size and, therefore, the rate of water loss, as well as the injection rate required to maintain a particular water concentration. Several variables have been tested to determine their effect on water loss, including: injection rate, log-standard deviation of drop size, drop spacing, and drop size. Although optimum values were found for these variables, it was determined that, when considering coagulation, none of them greatly affected the water content beyond an initial transient. Coagulation clearly dominated the dynamic behavior of the fog.

In addition to its capability for limiting pressure and temperature rises, it has been suggested that suspended water (from either sprays or fogs) can also suppress detonation and shock waves. The droplets act to dissipate energy from these waves, both by mechanical action of the droplet drag and by the thermal action of evaporation in cooling the gas. Again, however, there is considerable lack of knowledge on the subject.

A combination of fogging and ignition appears to be very attractive with few potential problems other than those experienced by conventional spray systems. The economics of such a system have not been adequately evaluated. Inadvertent operation of a spray or fog system may affect electrical equipment; however, safety systems are expected to operate in the presence of sprays.[4-39, 4-59] Another possible undesirable consequence of inadvertent operation of the fogging system would be containment depressurization. Although analysis of the effect of this negative pressure is still required, it is expected that it can be avoided through pressure relief modification.

The presence of a fog should not interfere with operation of the igniters. If the droplets are of the proper size, they will not alter the flame structure or the flammability limits. A fog may also provide the added advantage of creating turbulence that may enhance the effectiveness of the igniters (it would increase flame speed).[4-59] (Increasing the flame speed could also have a negative effect since there would be less time for heat transfer to occur.) Since a fogging system would provide all of the protection now provided by spray systems, it could serve as a complete replacement for the current system. However, if it is determined that simultaneous operation of sprays and fogs is required, the integrated effects should be analyzed. Computer calculations by Sandia National Laboratories have shown that, although the spray does not significantly alter the water content, it does have a stabilizing effect on the overall fog density.[4-7]

The combination fogging/ignition system should be appropriate for use in any plant that presently employs deliberate ignition alone. However, different concerns do exist for different types of containments. Ice condenser and Mark III containments are substantially smaller that those of large dry PWRs, but have a similar or greater potential for hydrogen production. Therefore, ice condenser and Mark III containments are much more susceptible to overpressure.

The other type of containment requiring special consideration is that which is operated at subatmospheric pressure. The effects of negative pressure due to inadvertent operation are of particular importance here, and require substantial investigation. Operation of the fogging system in place of, or in conjunction with, the Containment Depressurization System (CSD) is also of importance. The CDS consists of quench spray and recirculation spray subsystems. These subsystems are used after a LOCA of main steam line break (MSLB) to remove heat from the containment structure and restore a negative pressure. The interaction of these subsystems with water fogs, or their replacement by it, must also be studied in much greater detail.

In summary, the utilization of water fogging in conjunction with deliberate ignition is potentially an extremely useful hydrogen mitigation scheme. If it is found to be feasible, it will allow the combustion of relatively high concentrations of hydrogen at a fairly rapid rate with no challenge to containment integrity.

Production of an adequate water fog appears possible; however, maintaining sufficient water content in the fog could be extremely difficult. Further investigation is being conducted to determine the actual rate of water loss that can be expected and the effects of electrically-charged droplets. The feasibility of using water fogging as a means of protecting containment integrity is dependent upon the results of these investigations. If loss rates are found to be so high that the required injection rate cannot be reasonably maintained, then fogging will have no useful application. If, however, loss rates are found to be moderate enough to be made up by reasonable injection rates, water fogging could be a valuable aid in ensuring containment integrity during hydrogen combustion.[4-7]

4.9.3.2 Positive and Negative Aspects. Table 4-12 lists the positive and negative aspects for deliberate ignition used in conjunction with a water fog.

Table 4-12

DELIBERATE IGNITION WITH A WATER FOG

Positive	Negative
o Deliberate ignition distributes the energy addition to containment over a period of time, which allows the pressure and temperature changes inside containment to be gradual.	o It requires additional containment penetrations for electrical connections.
	o It is an active system requiring power to pump water to maintain the fog.

Positive

- It will control a large-scale generation of hydrogen.
- The system is not a threat to personnel since it is not required during normal operation, and inadvertent actuation would not present a threat.
- It has a relatively short warmup time.
- Maintenance would be minimal.
- It will condense steam, reducing containment steam pressure during A LOCA.
- It may prevent detonations. This issue is not yet resolved.
- It could effectively remove fission products and aerosols from the containment atmosphere.
- It will reduce the pressure and temperature increase of the combustion caused by deliberate ignition alone.

Negative

- If the loss rate of drops is as high as predicted by some aerosol codes, then the water rate required may be impractically high.
- The technology is not fully developed.
- Burns may damage equipment in containment.

4.9.4 Short-and Long-Term Venting Capabilities

4.9.4.1 Methods. It is important to be able to provide paths for venting hydrogen from both the RCS and the containment structure to prevent or control hydrogen combustion. Facilities must provide fail-safe methods of venting hydrogen from unwanted systems, and treatment or recycling procedures to handle vented hydrogen. This section discusses venting capabilities of both a short-term (removal of hydrogen from primary systems to a secondary holding area before treatment) and long-term (venting of hydrogen to permanenent treatment) nature. Short-term venting is discussed for high-point vents on the reactor vessel, pressurizer, and pressurizer relief tank (PRT). Long-term venting is discussed for the volume control tank, PRT, and Containment Purge System for PWRs; and Containment Atmosphere Dilution (CAD) System for BWRs. In addition, filtered venting is described. The high-point vents proposed for PWRs by NUREG-0737 were discussed in detail earlier in this chapter. This section will summarize the main characteristics of the Reactor Vessel Head Vent System (RVHVS).

In the event a metal-water reaction occurs, there is a possibility that hydrogen could collect in the reactor vessel head. In a PWR a bubble could bind the reactor coolant flow, prohibiting flow into the RCS hot leg. As a result of the TMI accident, the NRC proposed that a Reactor Vessel Head Vent System (RVHVS) be installed in PWR facilities;[4-12] BWRs, on the other hand, have been built with a remote-manual reactor head vent system constant vent.

During operation of a BWR, there is a constant vent open at the top of the reactor vessel head that taps into the main steam line. In this way, any stagnant steam or noncondensables at the top of the reactor vessel are vented to the main steam line. The noncondensables are then removed from the main condenser and vented to the Off-Gas System. This RVHVS would be capable of handling hydrogen generated by a cladding-steam reaction.

Presently there is no way to vent noncondensable gases from the reactor vessel head of a PWR. A typical system to meet the NRC requirement that PWRs incorporate a RVHVS is shown in Figure 4-50. This system would allow noncondensables from both the reactor and pressurizer vessel heads to be vented to either the PRT or containment. The system consists of two parallel flow paths, with solenoid valves that fail closed. The system would be manually operated from the control room.

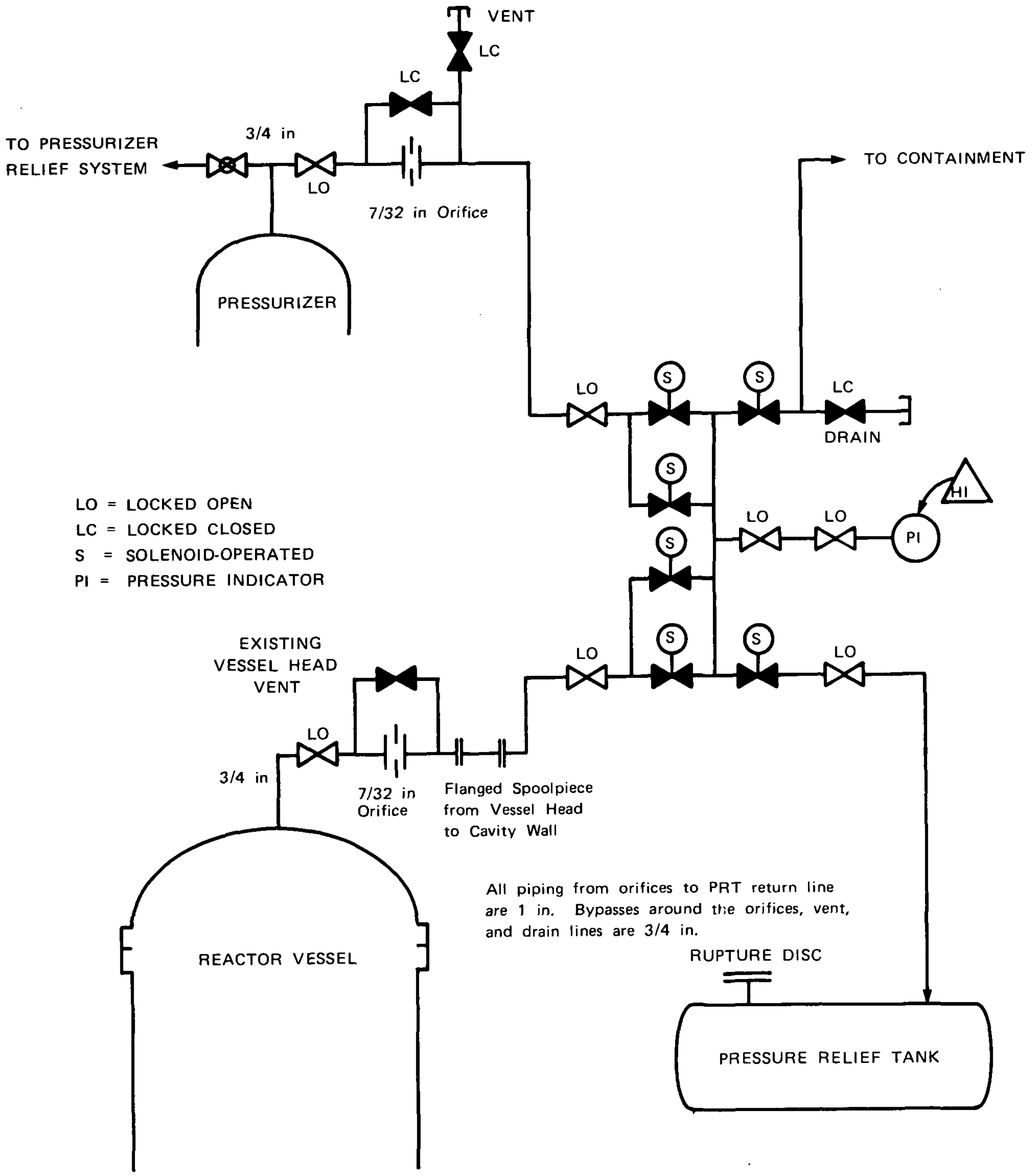
A detailed system description was presented earlier in this chapter. The main characteristics of the proposed PWR RVHVS are:

- It provides the operator with the ability to remove noncondensable gases from the reactor vessel head through parallel flow paths, vented to either the pressurizer relief tank or the containment atmosphere.
- Solenoid-operated valves in the parallel flow paths are remotely operated from the control room, fail closed, and are powered by different vital power supplies.
- The new system attaches to the manual head vent, used during RCS filling, which already exists on most PWRs.
- The system piping is sized and orifice-controlled so that a break could not cause a significant loss of coolant.

It should be emphasized that the RVHVS is not designed to be used as the primary means to mitigate an inadequate core cooling event. The RVHVS should be used only to vent gases from the PWR reactor vessel head once the RCS has stabilized and the situation has been diagnosed.

Once hydrogen has been vented to the PRT or to containment atmosphere, it must be handled properly. The PRT will vent to the waste disposal system, or to the containment atmosphere through a rupture disc. Hydrogen in the containment atmosphere is handled by one of the mitigation techniques discussed earlier in Chapter 2.

There is also the possibility of hydrogen build-up in the pressurizer of a PWR system. The consequences of the presence of hydrogen and other noncondensable gases in the pressurizer were discussed in Chapter 3. The pressurizer will vent to the PRT, which will then vent noncondensables for long term treatment in the waste processing system. If the pressurizer could not vent to the PRT (e.g., due to the pipe break or stuck valve), relief valves venting to containment are also located on the pressurizer vessel head. Any hydrogen venting from the pressurizer would be short term because hydrogen cannot be allowed to build up either in the PRT or in containment. If the PRT could not vent to the waste processing system, short-term venting would occur through the rupture disc on the PRT.



LO = LOCKED OPEN
LC = LOCKED CLOSED
S = SOLENOID-OPERATED
PI = PRESSURE INDICATOR

All piping from orifices to PRT return line are 1 in. Bypasses around the orifices, vent, and drain lines are 3/4 in.

Figure 4-50. Reactor Coolant System Gas Vent (PWR)

In the volume control tank (VCT) of the Chemical and Volume Control System (CVCS) of a PWR, a small amount of hydrogen is dissolved in the coolant to control the radiolytic decomposition of water. If there is a hydrogen buildup in the VCT, as detected by the sampling system, the gas can be vented to the waste processing system for long-term treatment.

The purpose of long-term treatment of the containment atmosphere is to remove hydrogen before it reaches a flammable level. Two ways available to perform this in a PWR are controlled recombination with oxygen in a recombiner (discussed in Chapter 3), and containment purge. The Containment Purge System* is used periodically. It operates by exhausting contaminated air out of containment through a filtered venting system that exhausts to the atmosphere. Containment pressure is kept below atmospheric pressure to prevent leakage of contaminated air to the environment. If the containment pressure rises to a preset level, the purge system will actuate and remove air from containment until the pressure is reduced. The major problem associated with containment purge is the large volume of air inside the containment structure. A typical PWR containment volume is about 2 x 10^6 ft^3. This much air requires very large air handling units. It should be emphasized that a containment cannot be vented quickly enough to mitigate a hydrogen burn.

how much

In a Mark I or II BWR facility, the post-LOCA atmosphere is controlled manually by the CAD System. This system utilizes nitrogen inerting to keep oxygen concentration below five volume percent (hydrogen is not combustible in mixtures containing less than five volume percent oxygen). The system is redundantly piped to both the drywell and suppression pool. Effluent gases from the drywell or suppression pool are treated by the Stand-by Gas Treatment System (SBGTS). Vented gases from the SBGTS are safely released to the atmosphere after decontamination.

Filtered venting of contaminated containment air to the atmosphere takes place through several stages of filters. After passing through a prefilter that takes out large particles, the contaminated air enters a HEPA (high efficiency particulate air) filter. This filter removes all particles down to 0.3 microns (0.01 mils);[4-55] the filtrate then passes to an activated charcoal absorption filter. This filter is cooled to prevent spontaneous combustion of the charcoal. The exhaust gases then pass through another HEPA filter (to remove charcoal particles), before being mixed with outside air and exhausted to the atmosphere.

With the exception of PWR reactor vessel head vents, systems in containment are provided with adequate hydrogen-venting capabilities. As a result of the TMI-2 incident, the NRC has recently required that a RVHVS be designed and fitted to PWRs. Once hydrogen has been vented out of the RCS, or other areas, it receives long-term treatment for eventual release to the atmosphere by the Containment Purge System and filtered venting in PWRs, or by the CAD System and filtered venting in BWRs. These venting procedures, along with the mitigation schemes discussed earlier, provide adequate hydrogen control even for severe conditions.

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*Different systems are present in different plants, and also the terminology varies.

4.9.4.2 Venting Times and Capabilities. In general, venting is not performed immediately at the onset of an accident: It tends to be performed only after the size of the noncondensable gas void in the reactor vessel or RCS has been determined.[4-39]

Further, the degree or amount of venting to containment is predicated upon the other systems that are available to deal with hydrogen once it is released to the containment. Although, theoretically, venting can be used over the long term, in order to do this, the hydrogen either must be burned or removed from the containment volume if it reaches or exceeds the flammability limit of about 4.1%.

4.9.4.3 Positive and Negative Aspects. Table 4-13 lists the positive and negative aspects of purging or venting.

Table 4-13

PURGING OR VENTING

Positive	Negative
o It does not generally require additional equipment or systems.	o It cannot control a large-scale generation of hydrogen.
	o It cannot control a large pressure rise.
	o Possible increased fission product release

4.9.5 Halon Combustion Suppressant System

4.9.5.1 Halon as a Flame-Quenching Agent. Another method of controlling liberated hydrogen that has received considerable attention is Halon inerting. Halon is a general term used to identify any of several halogenated hydrocarbons comprising a group of gaseous fire-extinguishing agents. Among these, Halon 1301 (Bromotrifluoromethane, CF_3Br) exhibits good flame quenching capabilities. Currently, Halon 1301 is the most popular halon in this country for total space flooding systems, including possible systems for use in containments. The physical properties of Halon 1301 are listed in Table 4-14.[4-56]

Table 4-14

PHYSICAL PROPERTIES OF HALON 1301 (BROMOTRIFLUOROMETHANE)[4-54]

Chemical Formula	CF_3Br
Molecular Weight	149
Boiling Point	-72°F
Freezing Point	-270°F
Critical Temperature	152.6°F
Critical Pressure	575 psia

Critical Density	46.5 lbs/ft^3
Heat of Vaporization	35.5 Btu/lb @ 70°F
Surface Tension of Liquid	9.7 dynes/cm @ 0°F 4.5 dynes/cm @ 70°F
Density: Liquid	82.2 lbs/ft^3 @ 120°F 98.0 lbs/ft^3 @ 70°F
Saturated Vapor	16.2 lbs/ft^3 @ 120°F 7.4 lbs/ft^3 @ 70°F
Heat Capacity	0.257 Btu/lb-°F @ 120°F 0.205 Btu/lb-°F @ 70°F 0.176 Btu/lb-°F @ 0°F
Vapor Pressure	400.4 psia @ 120°F 213.7 psia @ 70°F 71.2 psia @ 0°F
Thermal Conductivity	0.025 Btu ft/h-°F-ft^2 @ 70°F
Solubility in Water	100 ppm at 15 psia and 120°F 300 ppm at 15 psia and 70°F

The extinguishing mechanism of the halogenated agents is not clearly understood. However, it undoubtedly involves a chemical reaction that interferes with the combustion process. Halon 1301 acts by removing the active chemical species involved in the flame chain reactions (a process known as "chain breaking"). While all the halogens are active in this way, bromine, which is contained in Halon 1301, is much more effective than either chlorine or fluorine.[4-57]

A number of possible mechanisms by which bromine inhibits combustion have been proposed. Many research endeavors seem to indicate that in the heat of a fire, the halogenated hydrocarbons decompose with ease into free radicals of the particular halogen involved, and that these free radicals, through a counterattack of their own, eliminate hydroxyl free radicals as follows:

- Bromotrifluoromethane (Halon 1301) will break down to give up a bromine atom:

  $$CF_3Br + Heat \longrightarrow \overset{0}{CF_3} + Br^0$$

- The Br atom can then react with an organic molecule, e.g.:

  $$CH_4 + Br \longrightarrow CH_3 + HBr$$

- One possible mechanism for this operation assumes the removal of H atoms and the formulation of H_2 molecules as follows:

  $$H + HBr \longrightarrow H_2 + Br$$

- Another proposed mechanism involves a reaction with OH radicals:

  $$OH + HBr \longrightarrow Br + H_2O$$

- In this way, chain carriers are removed from the system while the inhibiting HBr is continuously generated. The net results of this process might typically be:

$$CH_4 + OH \longrightarrow CH_3 + H_2O$$

In the above process, it is postulated that the halogen first dehydrogenates methane (CH_4) (as an example), forming a free CH_3 radical (that will be further attacked by more bromine) and hydrobromic acid (HBr). The acid reacts with the hydroxyl free radical forming water and releasing bromine for further use in dehydrogenating CH_4, CH_3, CH_2, and CH groups. A true counter-attack is launched at the "heart" of the flame, resulting in its rapid extinguishment.

A key feature of Halon, then, is that it acts by chemically interrupting the combustion process, whereas regular inerting materials (such as nitrogen and carbon dioxide) work by simply diluting the oxygen concentration below the flammable limits and by providing a thermal heat sink.[4-58] For this reason, inerting can be achieved with significantly smaller amounts of Halon than of other materials. The concept behind Halon suppressing is to chemically inert the containment atmosphere at some time after a serious accident begins and before significant quantities of hydrogen are generated. The Halon would be stored in liquid form in several storage vessels near containment and discharged, either automatically or manually, into containment. Upon introduction into containment, the liquid Halon will depressurize and immediately turn into a gas, thereby inerting the containment atmosphere and preventing any hydrogen combustion.[4-54] The properties of Halon have been studied extensively, and it has been determined that this type of system would provide full safety; any concerns about the feasibility of the system involve economic (i.e., system recovery after a LOCA), rather than safety, consequences.

4.9.5.2 <u>Halon Post-LOCA Hydrogen Suppressant System</u>. Many operational advantages are associated with the simplicity of the Halon 1301 system: It possesses few moving parts, minimal power requirements, high reliability, relative economy, storage convenience, ease of periodic testing, and, once activated, requires little further attention. A Halon injection system typically will consist of several Halon tanks valved independently to two manifolds. Each tank has an associated tank of nitrogen gas to keep the Halon highly pressurized (600 psig). Inside the containment, the piping branches to the upper and lower compartments where the Halon is introduced into the atmosphere by an array of spray nozzles from each manifold pipe. To ensure that the Halon is injected as a liquid, the pressure at the discharge nozzle should exceed the vapor pressure (434 psig at 130°F). A simplified diagram of a Halon injection system proposed for the Sequoyah Nuclear Power Plant is shown in Figure 4-51.[4-56]

The storage vessel, piping, and valve configuration (Figure 4-52) are based on the principle that the system must function properly even if three independent malfunctions occur. In the event of a LOCA, the Halon system could be activated manually or automatically; the current requirement is for total delivery within 1000 seconds. The hydrogen and Halon concentrations would be continuously monitored during the post-LOCA period.

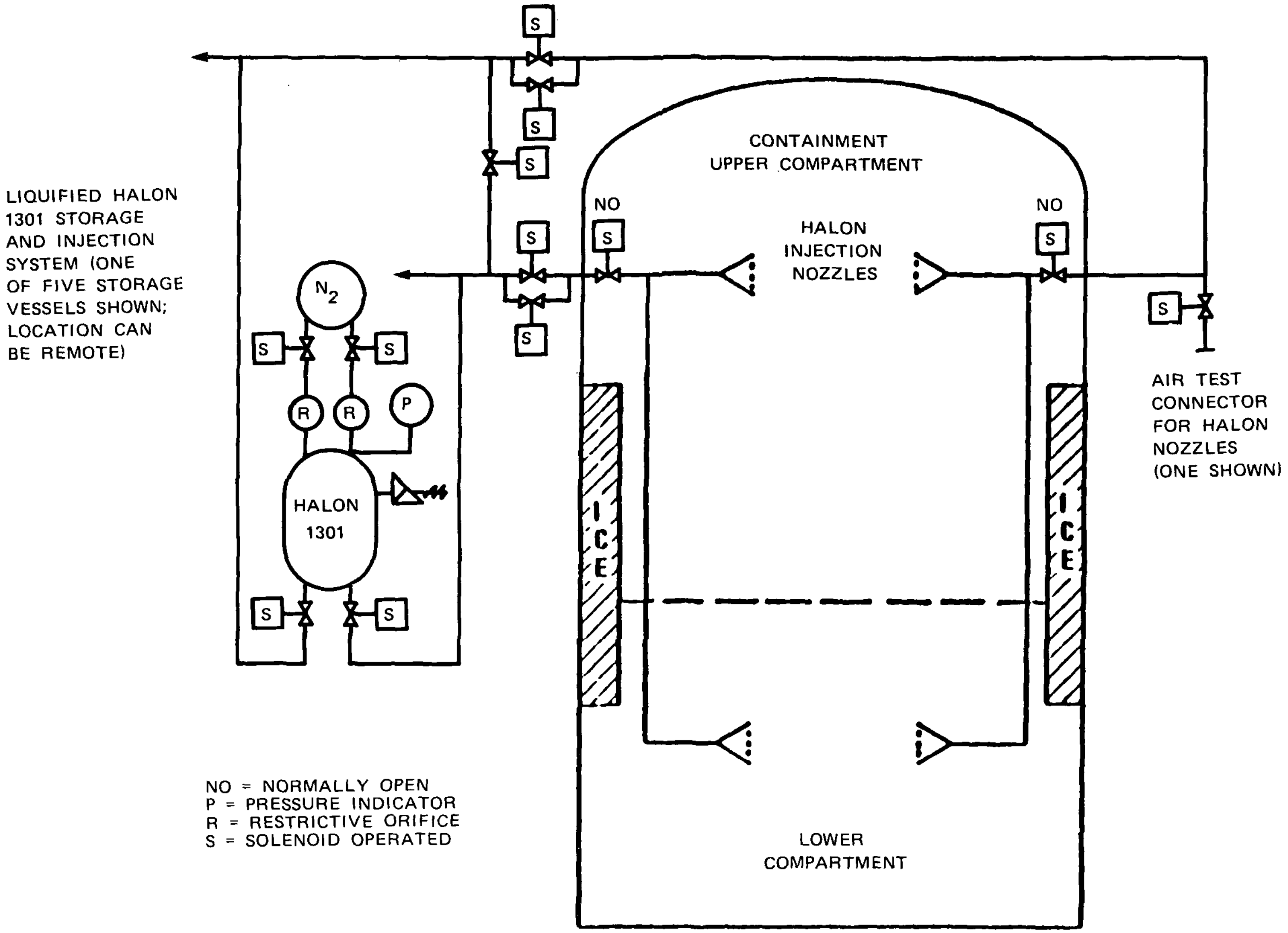

Figure 4-51. Conceptual Diagram of Halon 1301 Post-LOCA Hydrogen Suppression System for Ice Condenser

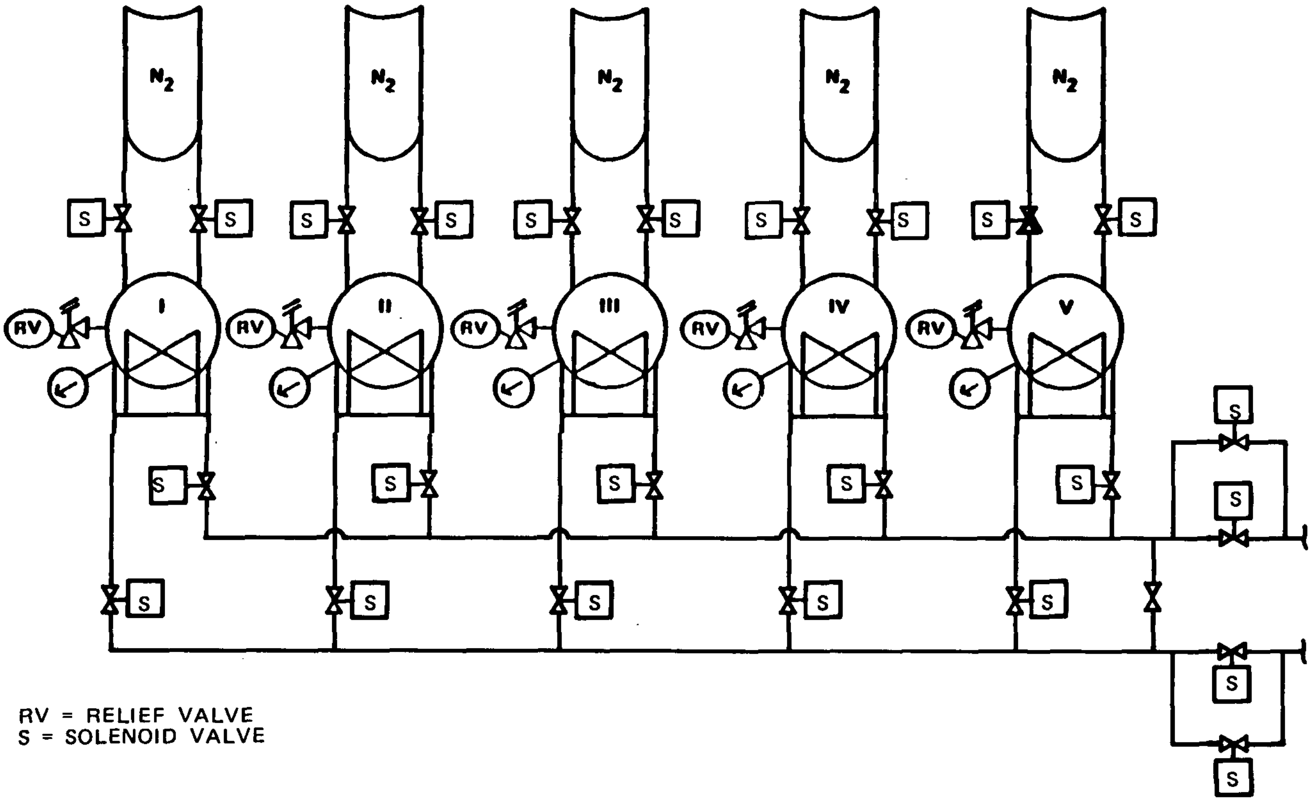

Figure 4-52. Diagram of Valving and Piping for Five Halon Storage Vessels

Despite all the positive aspects, there are some potential problems with the proposed Halon injection system. The primary concern is with the corrosion that could be caused in metallic containment components by prolonged exposure to Halon at elevated temperatures without adequate control procedures. If clean-up does not occur within a few months of a LOCA and no attempt is made at corrosion control, the potential exists for many problems, including general corrosion and stress corrosion cracking, as well as extensive crevice, pitting, and galvanic corrosion. However, there are methods to lessen the problem of corrosion. These include:

- Addition of bromides (e.g., NaBr, KBr, LiBr) to prevent Halon decomposition, or the addition of hydroxide (e.g., NaOH, KOH, LiOH) to increase pH. Either of these should mitigate general corrosion and reduce the potential for stress corrosion cracking.
- Addition of inhibitors to prevent localized corrosion. Chromates, nitrates, borates, silicates, and zinc have been shown to be effective.
- Addition of sacrificial zinc or magnesium that could potentially eliminate both pH depression and localized corrosion problems. Nonmetals are not expected to be significantly affected by the presence of Halon.[4-56]

Another problem of considerable magnitude is that Halon concentrations below that required to inert the containment atmosphere could be detrimental. Very low concentrations (2-4 volume percent) can actually decrease the minimum ignition energy. Furthermore, if combustion occurs in the presence of noninerting quantities of Halon, the Halon will thermally decompose into very corrosive halogens or halogen acids, which could adversely affect the plant and safety systems. The pressure rise caused by the addition of Halon should also be taken into account when analyzing a suppressant system. (For the Sequoyah plant, it was estimated that inerting the atmosphere with Halon 1301 would increase the containment pressure about 9 psig.[4-7])

In June of 1981, TVA issued a report concerning the selection of a permanent hydrogen mitigation scheme for Sequoyah. This report considered several different systems, including Halon injection. It should be noted that TVA came to less optimistic conclusions concerning the modes of corrosion mitigation than did McHale (Ref. 4-56). In explaining why the Halon injection option was rejected, the report states that uncertainty about the radiolytic decomposition of Halon and subsequent metal corrosion, uncertainty concerning suitable post-accident water chemistry control, its toxicity at the concentrations required, and difficulty in finding room for and installing five Halon tanks and their associated components made it impossible for TVA to resolve the issue consistent with the January 31, 1982, license conditions.[4-54] Despite the problems associated with Halon inerting, it is widely employed in industry as a fire suppressant and its use in nuclear applications promises to become more widespread.

4.9.5.3 Halon Injection Times and Capabilities. Theoretically, Halon can be introduced into the containment volume at any time. If it is mixed at a sufficient concentration in containment, it can be very effective in preventing hydrogen deflagrations or detonations.* However, continual release of hydrogen and Halon into the containment will increase containment pressure. For some containments, the design pressure can be reached (or exceeded) if the hydrogen generated by a 75% zircaloy-steam reaction in the core were to be released to the containment.

Over the long term, Halon seems to exhibit some additional negative qualities. These include:

- Extended exposure to Halon concentrations of about 20% may be hazardous to humans.
- If Halon compounds are exposed to temperatures above 900°F, they decompose to halogenic acids and carbonyl halides, which are extremely toxic.
- Halon and its decomposition products are also very corrosive and could cause potential degradation to safety systems.

4.9.5.4 Positive and Negative Aspects. Table 4-15 lists the positive and negative aspects for a Halon suppressant system.

Table 4-15

HALON 1301 POST-INERTING

Positive	Negative
o The technology is developed, including large-volume ($10^6 ft^3$) systems.	o If Halon were to decompose, it would cause acidic corrosion, severe stress corrosion, crevice and galvanic corrosion, and pitting
o Without decomposition, a H_2:air:Halon:steam mixture should be stable for a long time.	o Inadvertent actuation would be hazardous to personnel in containment, as well as expensive.
o The system can be designed to be electrically passive.	o Halon is expensive.
o Halon can be stored conveniently as a pressurized liquid.	o The operator may be hesitant to use the system because of hazard and expense.
o It will control a large-scale generation of hydrogen.	o Addition of Halon will increase containment pressure.
o Halon decomposition, and subsequent metal corrosion, may by avoided by the addition of NaBr, KBr, or LiBr.	o The Halon concentration must remain above the required inert

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*Reference 4-39 states that this concentration is about 20%. Sandia National Laboratories personnel state that 28-30% is more accurate.

Positive	Negative
o Mininal space is required in containment.	level at all times or else it could aid a combustion.
	o It could be impractical for large PWR containments and BWR Mark III containments because of the large amount of system equipment required.

4.9.6 Post-Accident Inerting with Carbon Dioxide

4.9.6.1 Method. It is impossible for a gas, most notably carbon dioxide (CO_2), to be injected into the post-accident containment atmosphere in sufficient quantities to inert against a potential hydrogen combustion. Such a system would be very similar to the Halon post-inerting system previously described. Two primary differences, however, distinguish the systems. First, carbon dioxide is noncorrosive, thus eliminating the need for the extensive corrosion-inhibiting mechanisms necessary with Halon injection systems. Second, because a carbon dioxide inerts by simply increasing the mixture heat capacity (acting as a thermal sink) instead of by chemically preventing combustion, a much greater amount (on the order of 55%) of carbon dioxide is required to inert the containment atmosphere. The addition of this greater volume of gas would result in a higher containment pressure. This latter difference is the major drawback associated with the carbon dioxide post-inerting concept. Some people feel that other hydrogen mitigation methods can adequately control combustion without producing the excessive pressures that would result from post-inerting with carbon dioxide.[4-54]

4.9.6.2 Positive and Negative Aspects. Table 4-16 lists the positive and negative aspects of post-accident inerting with carbon dioxide.

Table 4-16

CARBON DIOXIDE POST-INERTING

Positive	Negative
o Carbon dioxide will not cause corrosion.	o The amount of carbon dioxide necessary to suppress combustion may cause containment overpressure.
o It will control a large-scale generation of hydrogen.	o Cost is an important consideration
o The technology is developed.	o It is untried for the large PWR and BWR Mark III containments.
o Carbon dioxide can be conveniently stored as a pressurized liquid.	o The operator may be reluctant to use system.
o Minimal space is required in containment.	

4.9.7 Pre-Inerting, Partial Pre-Inerting, and Post-Accident Inerting with Nitrogen

4.9.7.1 Methods. Pre-inerting is a hydrogen mitigation scheme that has been employed in BWR containments since their inception. The concept is simply to inert the containment atmosphere with nitrogen during operation, thereby eliminating the possibility of hydrogen combustion following a LOCA. This method of control is particularly suited for use in early-model (Mark I and II) BWR containments because of their smaller volumes. PWRs and later generation BWRs have not used inerting for two main reasons: First, larger containments must be accessible during operation, and accessibility is facilitated by having a breathable atmosphere in containment. Second, the containments are so large that maintaining a nitrogen atmosphere during normal operation is difficult and expensive. For these reasons, the pre-inerting of large containment structures has been considered impractical and thus, has not been employed.

There is, however, a variation of this scheme that has been considered for use in large containments. It involves the partial pre-inerting, with nitrogen, of the containment atmosphere during operation to about 14-15% oxygen. The normal oxygen content of air is about 21%, so this represents a gaseous mixture that is roughly 70% air and 30% added nitrogen. An atmosphere with this composition is breathable and, therefore, would allow access to containment during operation. It also possesses several other advantages. If partial pre-inerting is used in a situation where post-inerting is also employed, it provides a significant "head start" in case of an accident. The lower oxygen concentration also promotes slower and weaker combustion of hydrogen, which makes partial pre-inerting a likely candidate for use in conjunction with deliberate ignition. Note, however, that partial preinerting has never been employed, nor is it currently proposed for use in any reactor containment.

A nitrogen post-inerting system has not been proposed for use in any plant at the time of this writing. It appears that the inert nitrogen gas injection could cause a significant increase in containment pressure. Although this technique is feasible, determining when the gas should be injected is a problem as it is with any post-inerting scheme.

4.9.7.2 <u>Positive and Negative Aspects</u>. Tables 4-17 through 4-19 list the positive and negative aspects of nitrogen pre-inerting, partial pre-inerting, and post-inerting, respectively.

Table 4-17

NITROGEN PRE-INERTING

Positive	Negative
o It will control a large-scale generation of hydrogen. o The technology is developed. o Minimal space is required inside containment. o Nitrogen can be conveniently stored as a pressurized liquid. o Nitrogen will not cause corrosion.	o Is impractical for the large PWR and BWR Mark III containments. o Maintenance in containment is considerably more difficult if the containment is nitrogen inerted during normal operations.

Positive	Negative
o Nitrogen inerting is already in use in most BWR Mark I and II containments.	

Table 4-18

NITROGEN PARTIAL PRE-INERTING

Positive	Negative
o The atmosphere would be breathable, thus allowing containment entry during normal operation.	o It has never been employed in reactor plant containments, therefore only theoretical data are available.
o It provides a "head start" on hydrogen control if an accident occurs.	o Requires additional system to control or mitigate H_2 combustion.
o May be of use in conjunction with deliberate ignition.	
o May be of use in large containments.	

Table 4-19

NITROGEN POST-INERTING

Positive	Negative
o Containment atmosphere would be breathable during normal operation, thus facilitating entry.	o It would require some finite period of time to inert the containment atmosphere following an accident.
o Relatively inexpensive, since nitrogen would only be used following an accident.	o Overpressurization

4.9.8 Oxygen Removal By a Gas-Turbine

4.9.8.1 Theory of Operation. A gas-turbine combustor system is another proposed method for rendering a mixture of air and hydrogen nomflammable following a degraded reactor core accident. This system would rapidly inert the containment by reducing the oxygen level following a degraded core accident before hydrogen could be released. Such a system would involve one or more turbines, fuel supply lines, and monitoring instrumentation and controls. It would require an

> additional forced-air induction system with fans and associated ductwork. It should also include its own supplemental cooling to avoid impacting the containment heat removal capability. Using a representative fuel such as methane [the reaction would be]4-54
>
> $$CH_4 + 2O_2 \longrightarrow CO_2 + 2H_2O$$

Such a system was proposed for one PWR facility*

> Estimates were made of some of the combustion parameters. In order to reduce the containment oxygen concentration from the original 20 percent to the required level of 5 percent (conservatively neglecting the addition of CO_2), [about] two tons of methane would be required and 82 million [Btu] would be generated. To inert the containment within 30 minutes, an average airflow of 54,000 scfm would be required.
>
> The 82 million [Btu] heat load would be comparable to the heat load from combustion of the amount of hydrogen generated by a 75-percent metal-water reaction (1500 lbm H_2)4-54

A gas-turbine combustor system is shown schematically in Figure 4-53 such a system is discussed in Ref. 4-59 and 4-60; the following description is from Ref. 4-59:

> A duct leads from a containment penetration to an inlet isolation valve. During operation, the air flows through this valve and enters a separator where entrained water is removed. The air then flows through ducting to the inlet of a gas-turbine/ generator system. Approximately 30% of the incoming oxygen is burned in the gas turbine and the exhaust is ducted to a desuperheater-type spray tower where it is quenched and cooled by a water spray system. The exhaust then enters a second separator where entrained water is removed. The cooling water is returned to a large holding tank for recycling through the heat exchanger. Two pumps are used to cycle the water through the heat exchanger system. The cooled exhaust gas leaves the separator and is ducted to a return penetration in the containment.4-59
>
> For the gas turbine system to inert the containment by the time hydrogen could be released, it must be initiated in time to perform its function. The previous estimate of 30 minutes to deplete the oxygen

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* Tennessee Valley Authority's Sequoyah Nuclear Power Plant.

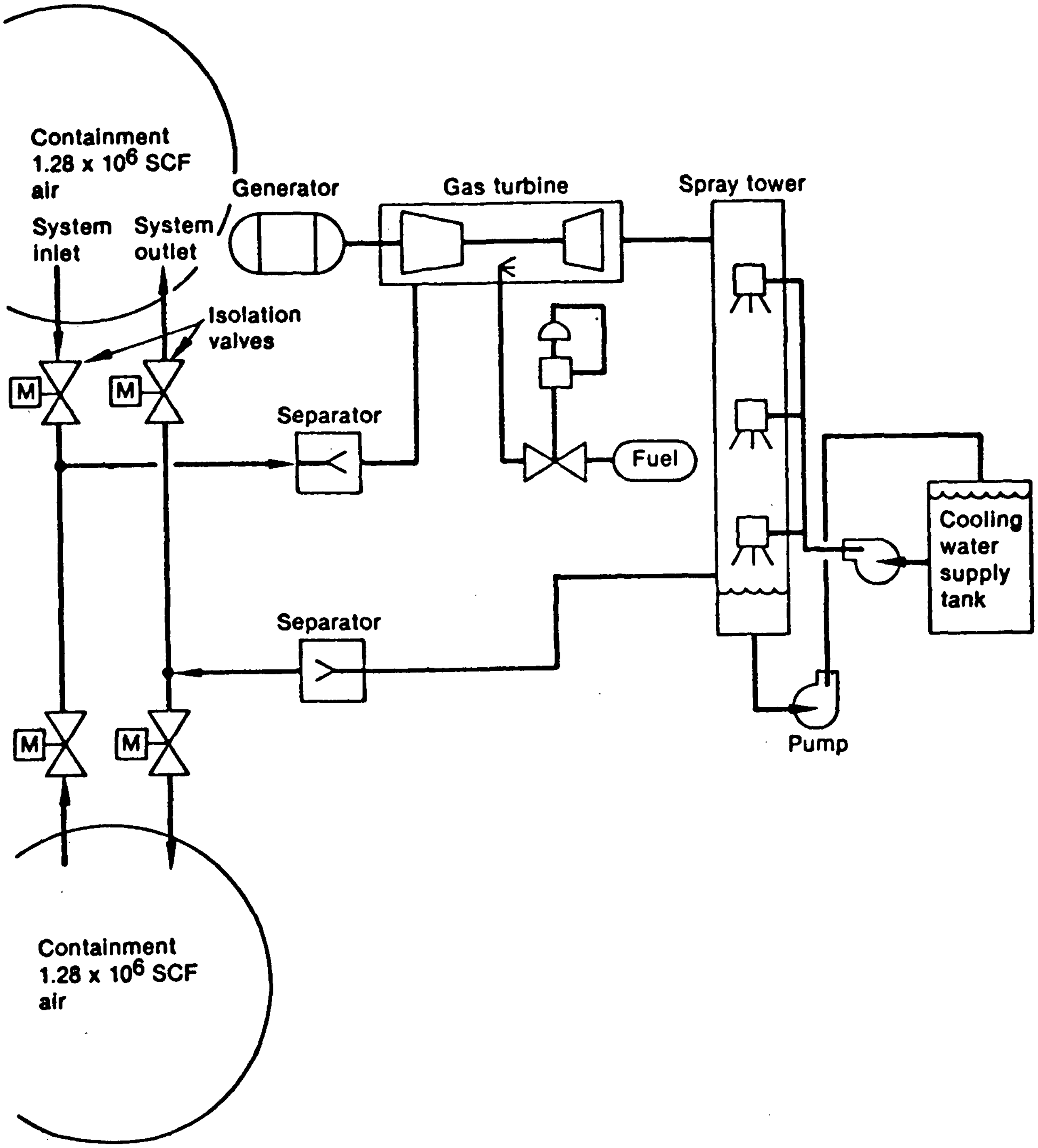

Figure 4-53. Gas Turbine Combuster System Schematic

is probably a reasonable minimum time. It would be difficult, for all scenarios, for the operator to determine that the event was serious enough to warrant initiating the gas turbine that far in advance of hydrogen release into the containment. [For an ice-condenser containment,] the operator would naturally be reluctant to activate a system that would impose such a heat load, cause ice melting, and force a plant shutdown for several months until he was absolutely sure it was necessary.[4-54]

4.9.8.2 Positive and Negative Aspects. Table 4-20 lists the positive and negative aspects of the gas-turbine combustor system.

Table 4-20

GAS TURBINE COMBUSTOR SYSTEM (FOR OXYGEN REMOVAL)

Positive	Negative
o One turbine can serve two units o Gas turbine is located outside containment. o Heat rejection is outside containment; the gas is returned inside containment. o It does not compromise the existing containment.	o Gas turbines can leak air at their mating flanges. A separate containment boundary would be required for this system. o Decreasing oxygen concentration during use would require the fuel supply to be reduced during system operation. o Installation of a gas-turbine combustor system has significant impact on existing plant systems and features. o Operator judgement is required for its actuation. o Potentially severe heat loads, fire, and missile hazards are additional drawbacks of this system.

4.9.9 Summary of Control System Positive and Negative Aspects

There are many possible ways of mitigating hydrogen generation in containments. Table 4-21 gives an overview by summarizing the advantages and disadvantages of the schemes discussed in previous sections.

Not all of the schemes presented are practical for all containment types. For example, it is possible to inert the large PWR and BWR Mark III containments. However, to do so would require large amounts of inerting gas, and also would require entering personnel to wear protective and respiratory apparatus, thus making inerting impractical. It is possible to inert the drywells, of BWR Mark I and II containments because of their small volumes and because entry into a Mark I or II containment during operation would rarely, if ever, occur.

The notes accompanying Table 4-21 should be reviewed for a more complete understanding of the table.

Notes for Table 4-21

1. N.A. = Not applicable.

2. Inerting may be practical only for the smaller BWR Mark I and II containments.

3. Halon has a tendency to decompose, which causes severe corrosion problems. However, if bromides are added to the Halon, the decomposition is prevented, thereby minimizing corrosion.

4. Most containments already include some type of hydrogen recombiner system designed to handle small rates of hydrogen generation.

5. Deliberate ignition with a water fog or spray will increase containment pressure and temperature less than deliberate ignition alone.

6. Carbon dioxide, Halon, and nitrogen may be stored as liquids under pressure.

7. Large-scale hydrogen generation would result from a severely degraded core condition in which a metal-water reaction occurred.

8. This is true for some, but not all, cases.

9. N_2 partial pre-inerting, which is not shown in the table, has many of the same operational features as N_2 pre-inerting and would be used in conjunction with one of the other mitigation systems.

Table 4-21

POSITIVE AND NEGATIVE ASPECTS OF HYDROGEN MITIGATION SCHEMES

Positive	Deliberate Ignition	Deliberate Ignition & Water Fogs	CO_2 Post-Inerting[2]	Halon Post-Inerting[2,3]	N_2 Pre-Inerting[2]	N_2 Post-Inerting[2]	Flame Recombiners[4]	Thermal Recombiners[4]	Catalytic Recombiners[4]	Purging or Venting	O_2 Removal by Gas Turbines
Suppresses or prevents deflagration			X	X	X	X	X	X	X	X	X
Suppresses or prevents detonation	X	X	X	X	X	X	X	X	X	X	X
Reduces pressure and temperature increase of combustion	X	X[5]	N.A.[1]	N.A.[1]	N.A.[1]	N.A.[1]	N.A.[1]	N.A.[1]	N.A.[1]	N.A.[1]	N.A.[1]
Controls large-scale hydrogen generation[7]	X	X	X	X	X	X					X
Minimal pressure rise in containment by use (Independent of H_2 burns)					X		X	X	X	X	X
Minimal danger associated with inadvertent actuation	X	X			N.A.[1]		?	?	?	X	?
Removes fission products and aerosols from containment atmosphere		X								X	

Table 4-21 (Cont'd)

POSITIVE AND NEGATIVE ASPECTS OF HYDROGEN MITIGATION SCHEMES

Negative	Deliberate Ignition	Deliberate Ignition & Water Fogs	CO_2 Post-Inerting[2]	Halon Post-Inerting[2,3]	N_2 Pre-Inerting[2]	N_2 Post-Inerting[2]	Flame Recombiners[4]	Thermal Recombiners[4]	Catalytic Recombiners[4]	Purging or Venting	O_2 Removal by Gas Turbines
Handles only small-scale hydrogen generation							X	X	X	X	
High risk of corrosion after use		?		X[3]							
Increase containment pressure with use	X	X	X	X		X					
High Maintenance		?	?	?	?	?	?	?	?		?
Hard to start							X				X
Requires considerable room in containment							?	?	?		X
Requires considerable pumping power (expensive to operate)		X									
May require new containment penetrations to install	?	X	?	?	?	?				X	X
Use may damage equipment inside containment	X	X		X[3]							
Technology not fully developed		X									X

Table 4-21 (Cont'd)

POSITIVE AND NEGATIVE ASPECTS OF HYDROGEN MITIGATION SCHEMES

Positive	Deliberate Ignition	Deliberate Ignition & Water Fogs	CO_2 Post-Inerting^{2}	Halon Post-Inerting^{2,3}	N_2 Pre-Inerting^{2}	N_2 Post-Inerting^{2}	Flame Recombiners^{4}	Thermal Recombiners^{4}	Catalytic Recombiners^{4}	Purging or Venting	O_2 Removal by Gas Turbines
Does not require new containment penetrations to install	?		?	?	?	?	X	X	X		
Minimal space requirements in containment	X	X	X	X	X	X				X	
Low maintenance	X	?	?	?	?	?	?	?	?	?	?
Minimal corrosion of containment equipment	X	?	X	3	X	X	X	X	X	X	X
Electricity passive			?	X	?	?				?	
Fast, easy startup	X	X	X	X	N.A.[1]	X		X	X	X	
Technology already developed	X		X	X	X	X	X	X	X	X	

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Appendix I

THE THREE MILE ISLAND UNIT 2 ACCIDENT SCENARIO*

On March 28, 1979, at approximately 4 am, the Three Mile Island Unit 2 (TMI-2) experienced a loss of normal feedwater to its steam generators (henceforth OTSGs-once-through steam generators). The plant had been operating at 97% of full power, as shown in Figure I-1. A resin block had developed in a condensate polisher unit's transfer line; since the polisher outlet is operated within 50 psig of the net positive suction head (NPSH) for the condensate booster pumps, both of these pumps tripped by closure of the condensate polisher outlet valves. The net result was that two condensate pumps tripped, both feedwater pumps tripped, and then the main turbine tripped. (Figure I-2 is a schematic of the TMI-2 plant showing the placement of these components.) The turbine trip resulted in the pressure in the Reactor Coolant System (RCS) rising sharply causing a reactor trip on high pressurizer pressure. During the RCS pressure rise, the pressurizer's electromatic relief valve (also called a power-operated relief valve, or PORV) opened (and remained stuck in that position). The reactor trip caused the RCS pressure to drop briefly; however, at approximately 30 seconds into the event the OTSG water level was low enough to automatically open the emergency feedwater control valves. The block valves between the control valves and the OTSGs were closed; RCS conditions were as shown in Figure I-3. The block valves were opened about 8 minutes later when it was noticed that a control board tag had been obscuring the indication that these valves were closed. This event did not, however, have a significant impact on the outcome of the TMI-2 incident. As stated in the Rogovin Report:

> We have concluded, however, that the 8-minute delay in restoring emergency flow did not directly affect the outcome of the accident - though it did serve to divert the attention of the operators, who patently needed no more distractions at this point.[I-2]

The report of the Nuclear Safety Analysis Center generally concurs with the above comments.[I-1]

As the cool feedwater entered the dry OTSGs, the hot leg temperatures dropped. RCS pressure, however, continued to drop, since the PORV remained open. Figure I-4 also shows the rising pressurizer level. A control board indicating light signalled that the PORV was closed; in fact, it merely indicated that the solenoid was actuated. The PORV itself was actually open.

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*The details of the accident at Three Mile Island are still being evaluated, and will continue to be evaluated for some time. The information presented here represents most of the current thinking as of the summer of 1982. Additional information not received in time for incorporation into this report, may be found in Ref. I-4.

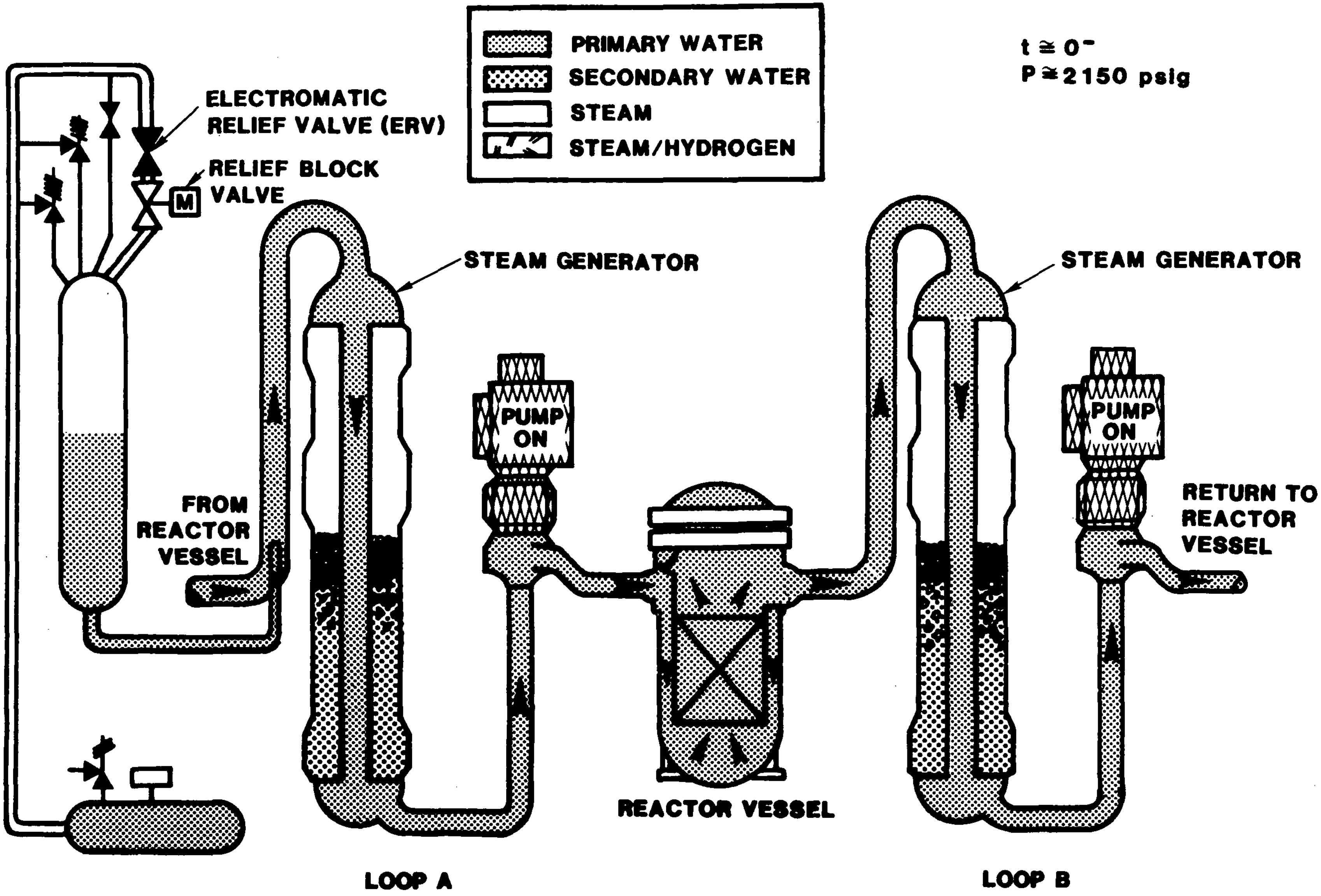

Figure I-1. TMI-2 Scenario: Initial Conditions - System Steady at 97% Power Operating Conditions

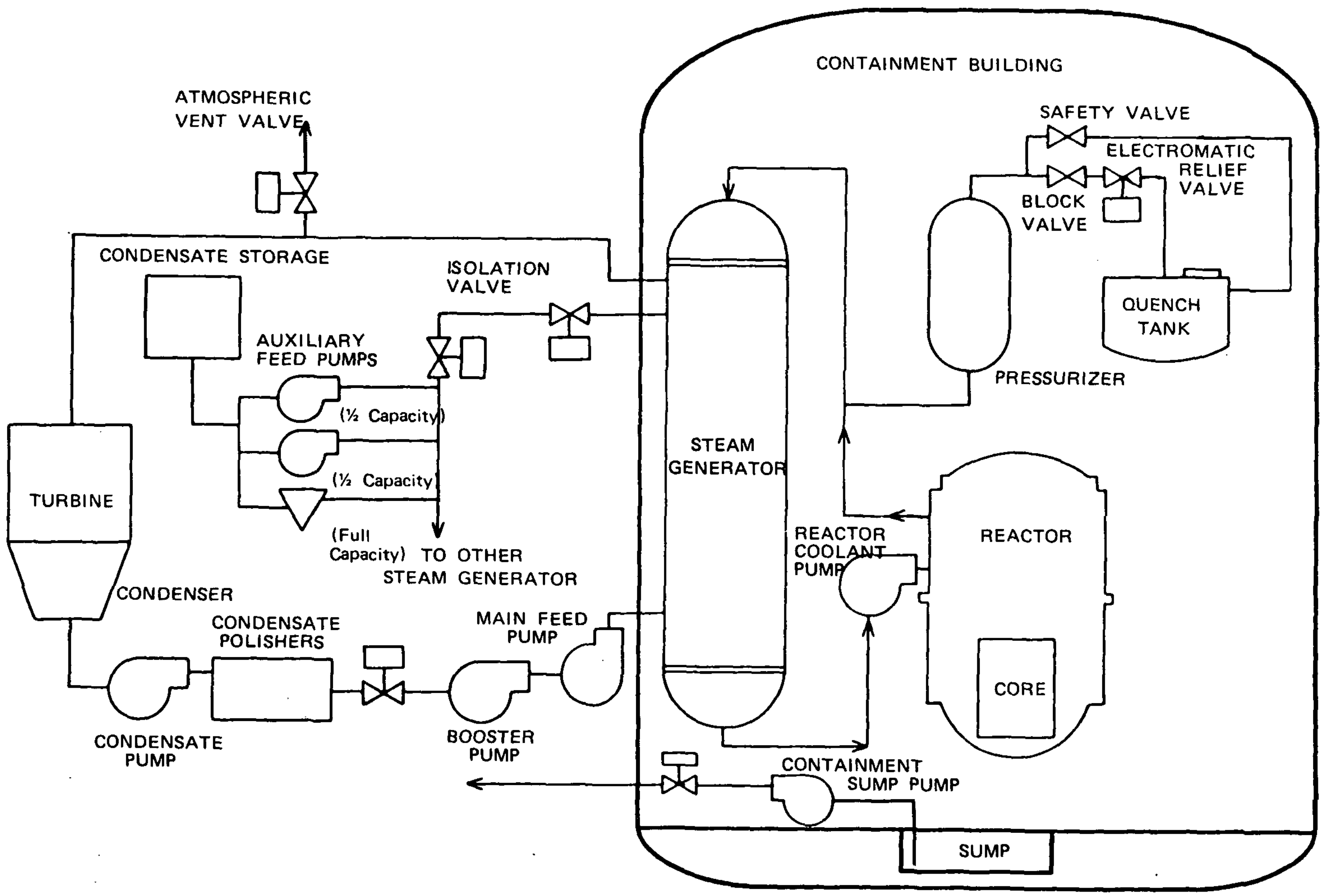

Figure I-2. Three Mile Island Unit 2 Plant Arrangment

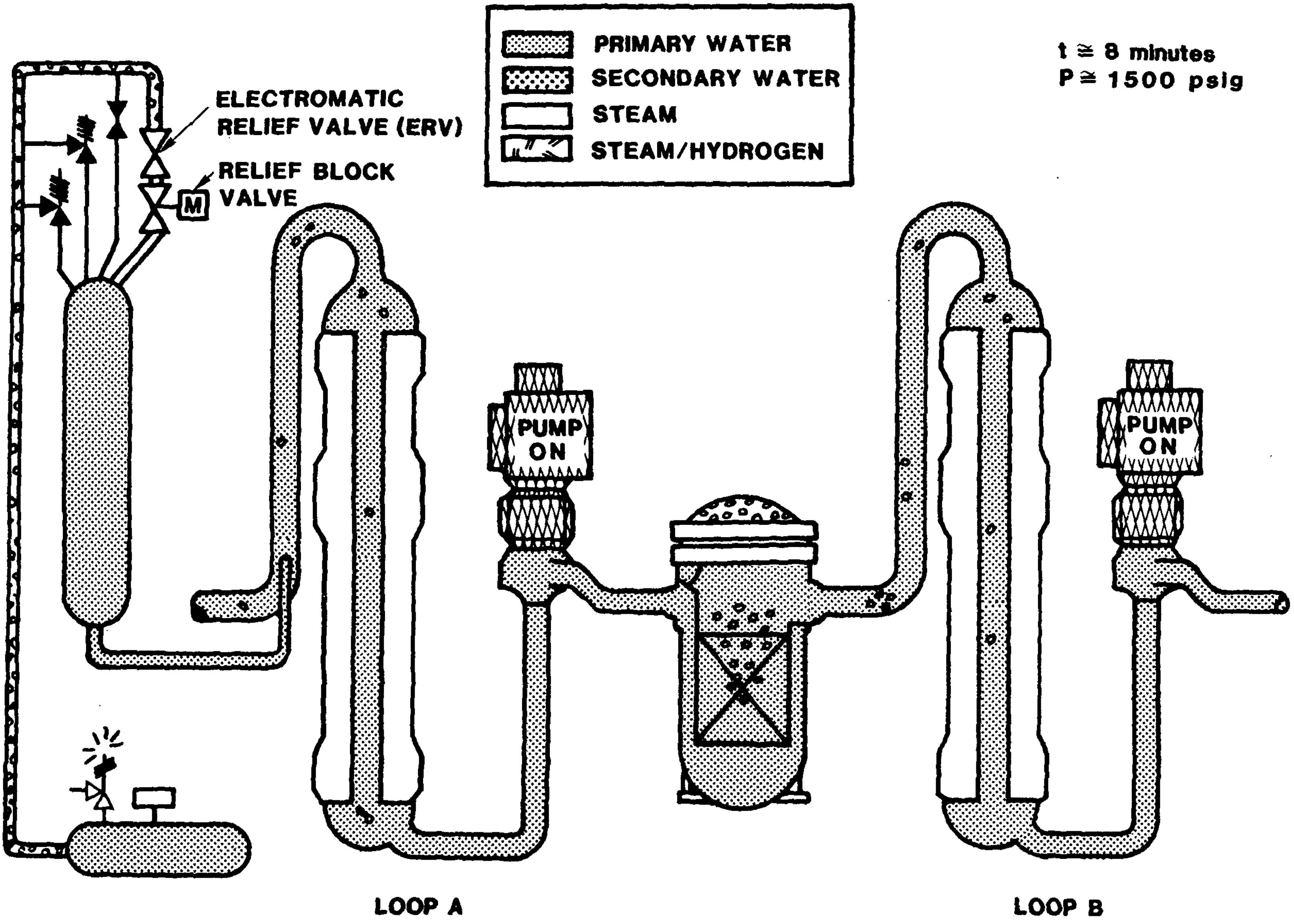

Figure I-3. TMI-2 Scenario: System Nearly Liquid Solid. Liquid Expanding with Increasing Temperatures.

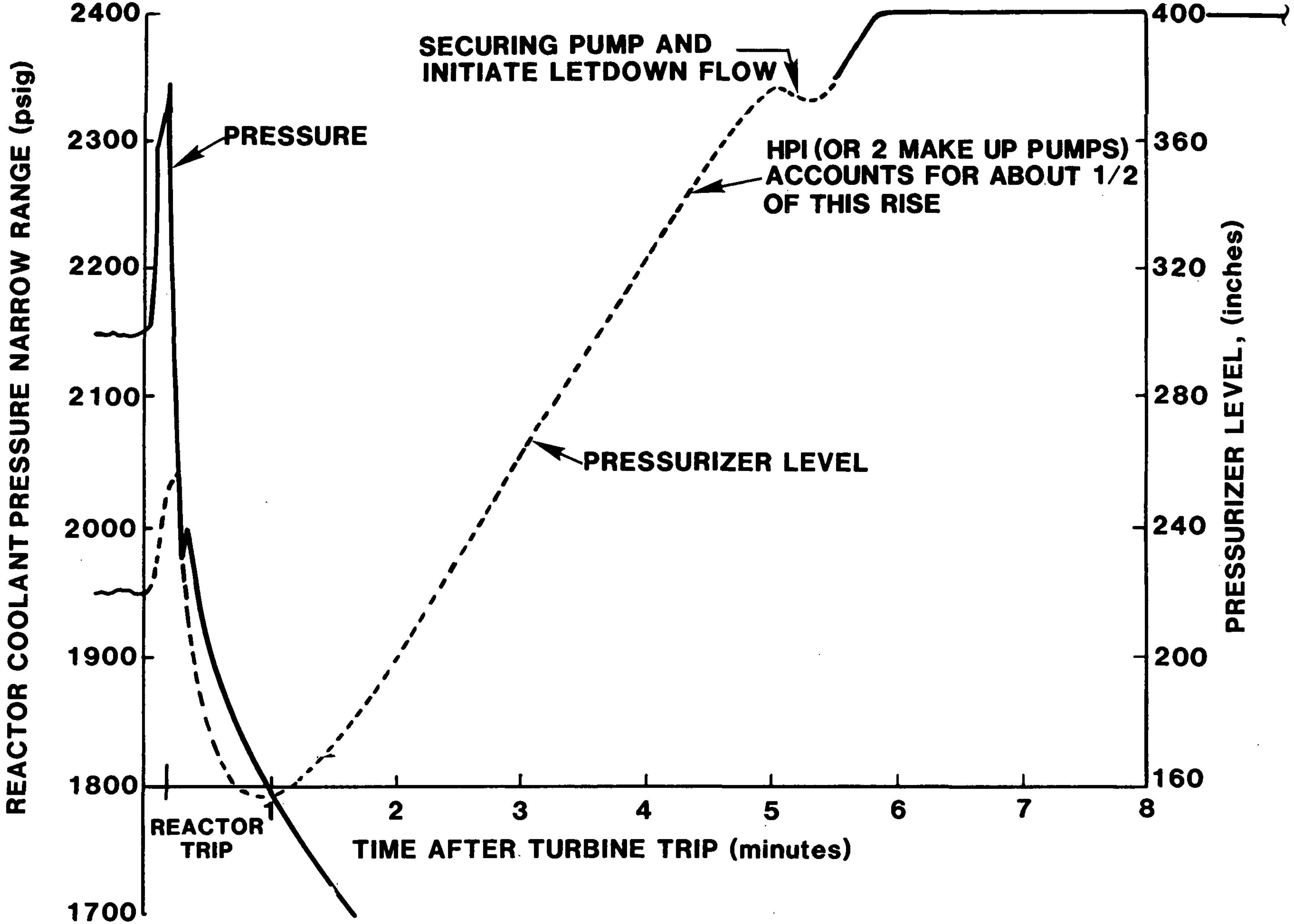

Figure I-4. TMI-2 Scenario: Reactor Coolant Pressure and Pressurizer Level vs. Time

Temperature readings downstream of the PORV were elevated slightly. This had been perceived earlier and attributed to a leak of approximately 6 gpm through one of the pressurizer relief valves. It was not considered plausible from this evidence that the PORV could be open. In fact, the throttling of steam through the open PORV is essentially an isenthalpic process. The rapid expansion of steam will drop the temperature and pressure of the steam to about atmospheric pressure and the corresponding T_{sat}, 212°F. Thus, the downstream temperature is not significantly elevated even if the PORV is stuck open.

At about 3 minutes into the incident the quench tank safety valve lifted. Since the PORV remained open, the rupture disk on the reactor coolant drain tank burst at about 15 minutes into the incident. Reactor coolant, therefore, found its way to the reactor building sump (Figure I-5) to which it continued to flow for about 139 minutes (2.3 hours), until the block valve was closed.

At 2 minutes into the incident, safety injection automatically initiated due to low RCS pressure. However, at about 4.5 minutes, the operator thought the RCS was going solid because the pressurizer level was rising rapidly, as shown previously in Figure I-4. Because of this indication, one high pressure injection pump was turned off, and the other one was throttled back. Full high pressure injection to the RCS was not re-initiated until 3.3 hours into the incident.

Since the high pressure injection rate was reduced, the mass of water leaving the RCS via the stuck-open PORV and the letdown line was greater than the mass entering the RCS through injection. This disparity led to steam voids in the RCS, shown in Figure I-6, which caused the pressurizer level indication to not be a true indication of reactor vessel inventory.

Until 73 minutes into the incident, all four reactor coolant pumps were running. Seventy-three minutes into the incident, the B-loop pumps were shut off because of low pressure, high vibration, and low flow. This resulted in the separation of the water-steam mixture in the B-loop, which greatly reduced flow through the B-loop. The increased steam voids caused by this separation are shown in Figure I-7. (Compare to Figure I-6, which shows the RCS before the B-loop pumps were shut off.) The increased voiding is further evidenced by the abrupt increase in the source range indication, shown in Figure I-8. One hundred minutes into the incident, the A-loop pumps were shut off, resulting in a second increase in the source range indication, indicating further voidings, shown in Figure I-9.

At 139 minutes into the incident, operators closed the pressurizer block valve. Hydrogen generation had already begun from the steam:zirconium reaction, filling the RCS voids with a steam-hydrogen mixture as shown in Figure I-10.

For the next 13 hours, operators <u>attempted</u> to establish a stable cooling mode by:

- o Natural or forced circulation through the RCS using the OTSGs as the heat sink. (This was not very successful because of the many steam/hydrogen voids in the RCS.)
- o High Pressure Injection (Safety Injection) was used intermittently during the first 16 hours of the incident
- o The core flood tanks were used about 8.5 hours into the incident
- o The Decay Heat Removal System which operates at a pressure of 320 psig (They could not get the RCS down below 400 psig during the first 16 hours, therefore the Decay Heat Removal System was not used during this time frame.)

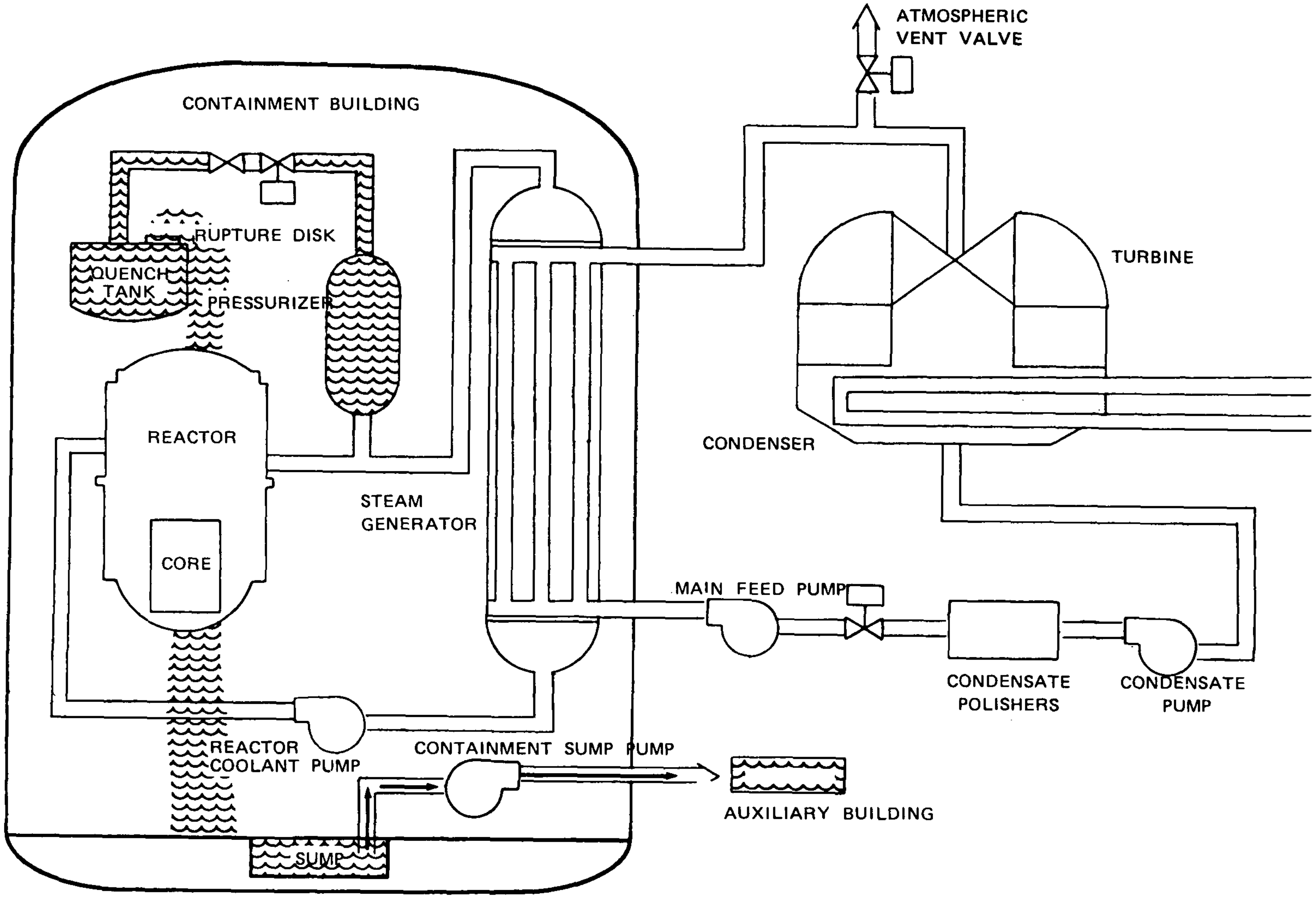

Figure I-5. TMI-2 Scenario: Following Bursting of the Quench Tank Rupture Disk, Water Flowed to the Containment Sump, from which it was Pumped to the Auxiliary Building.

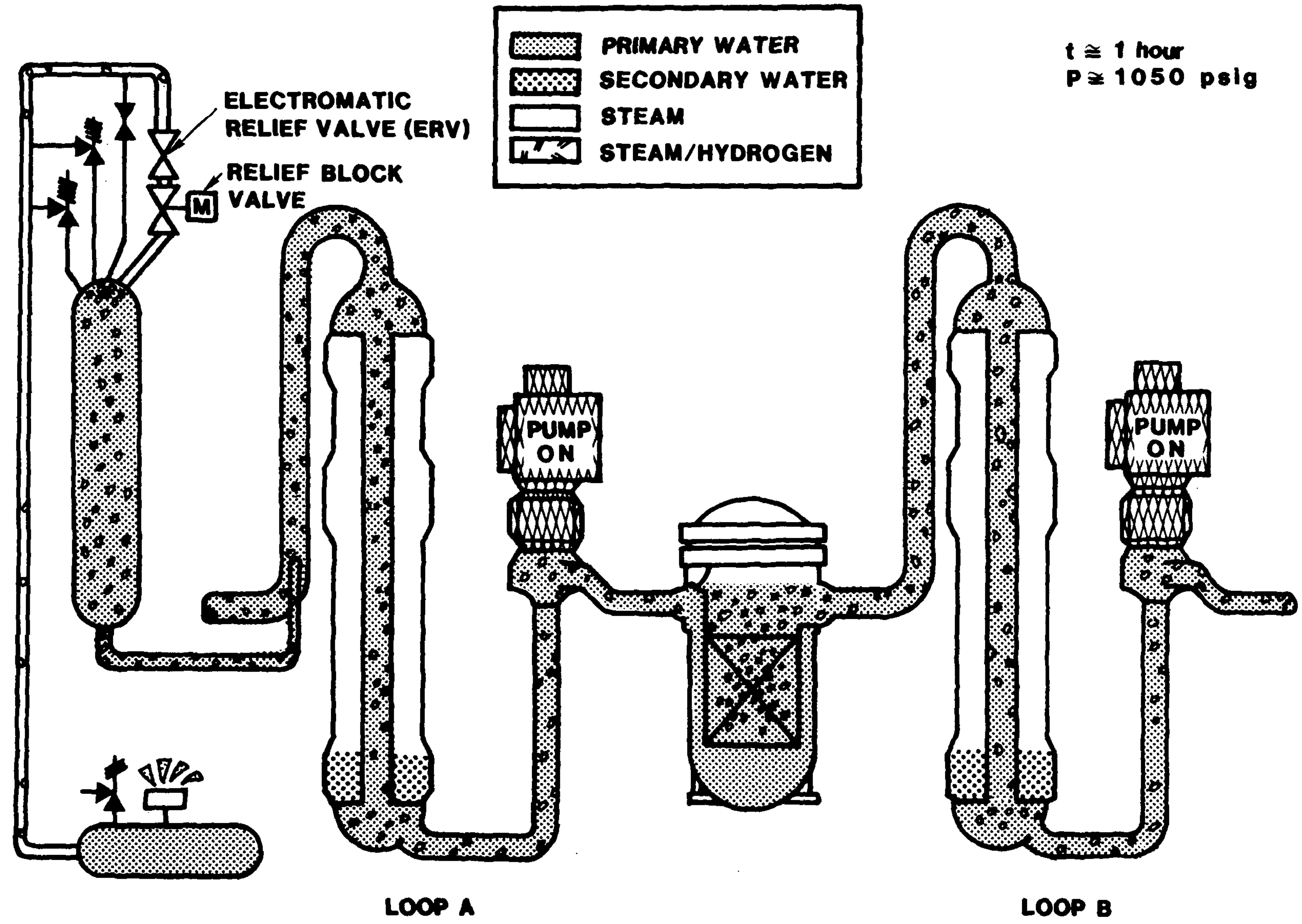

Figure I-6. TMI-2 Scenario: Primary System Pressure and Temperatures Nearly Constant Following Secondary Steam Condition. Primary Voids Increasing.

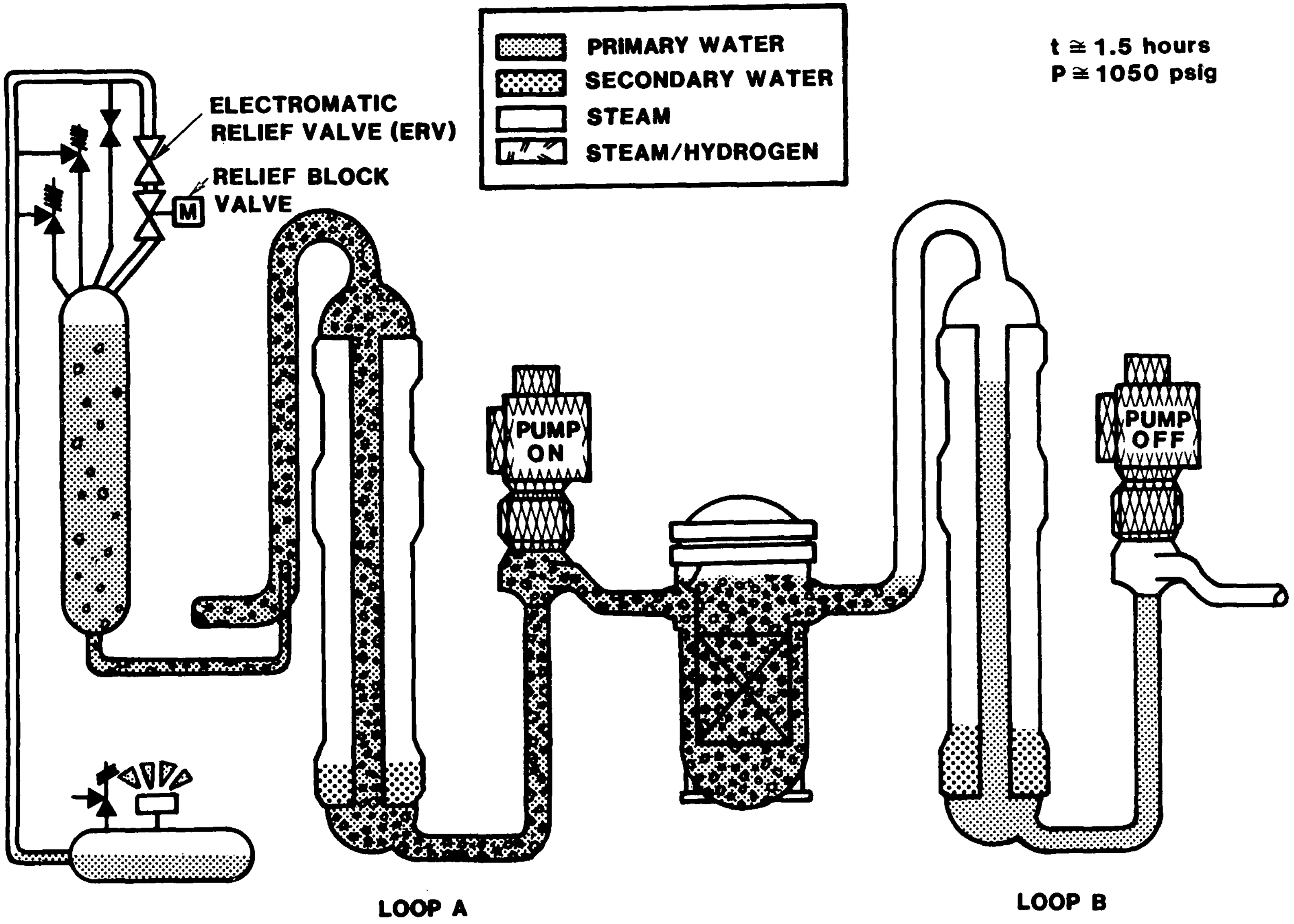

Figure I-7. TMI-2 Scenario: Loop A Pumps Operating. Loop B Stagnant After Shutdown of Loop B Pumps. Primary Voids Increasing.

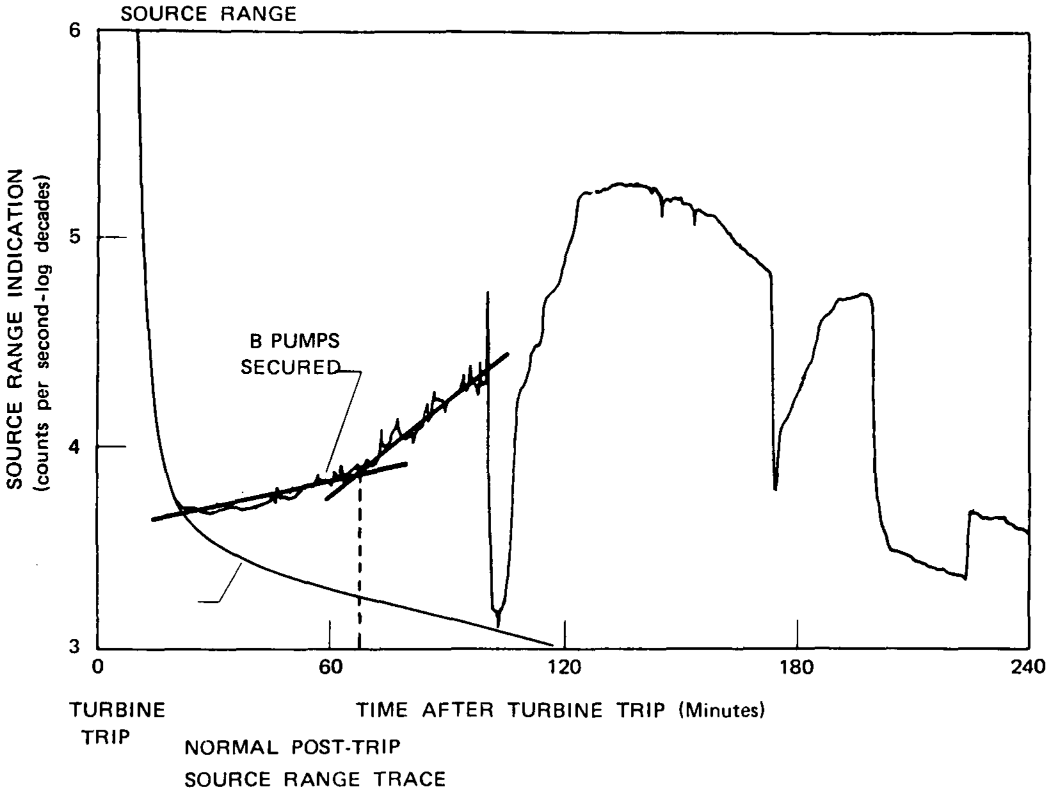

Figure I-8. TMI-2 Scenario: Source Range Indication vs. Time

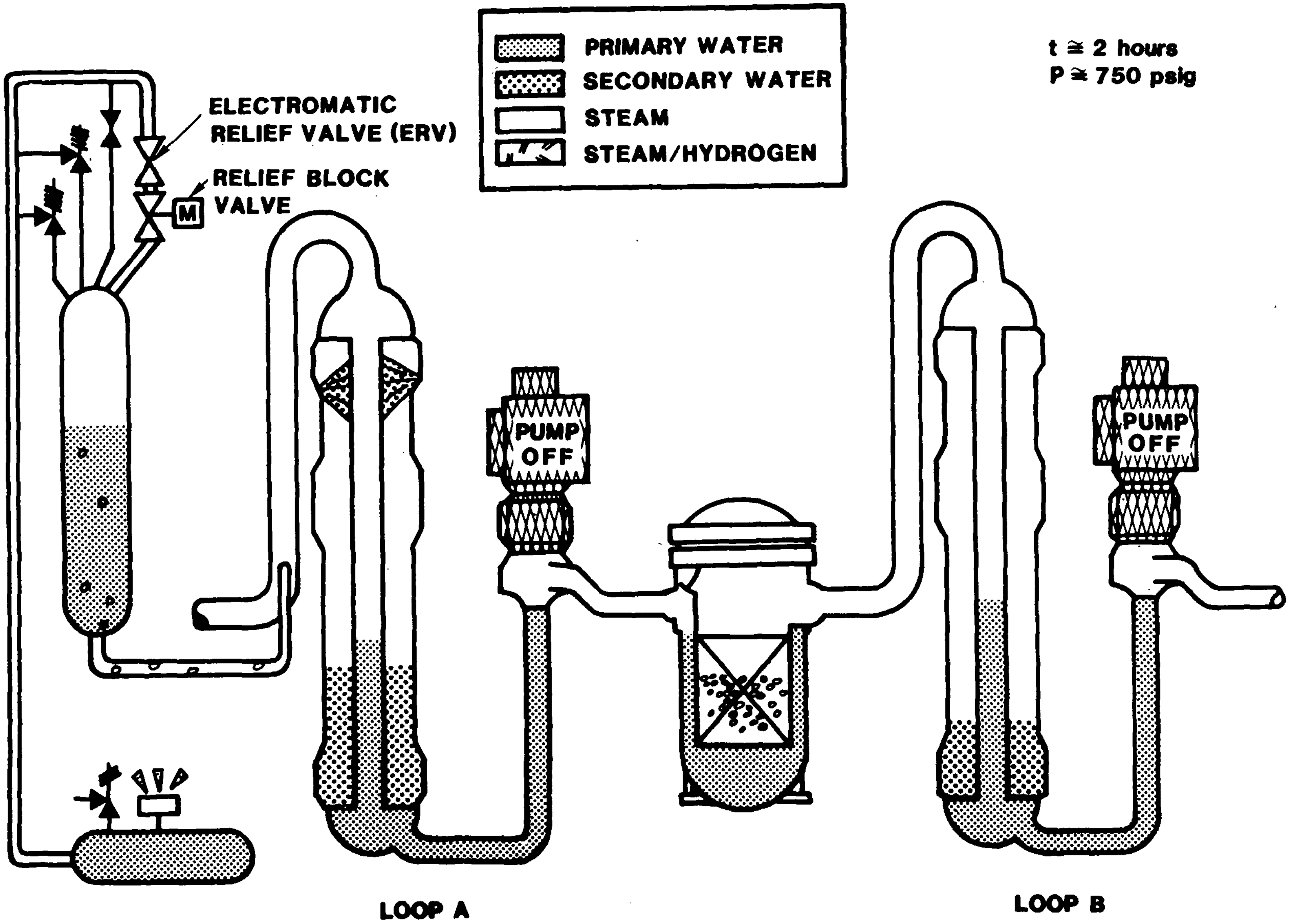

Figure I-9. TMI-2 Scenario: All Pumps Off. Reactor Core Drying Out and Heating Up. Superheated Steam Flowing to Pressurizer and to One Steam Generator and Condensing.

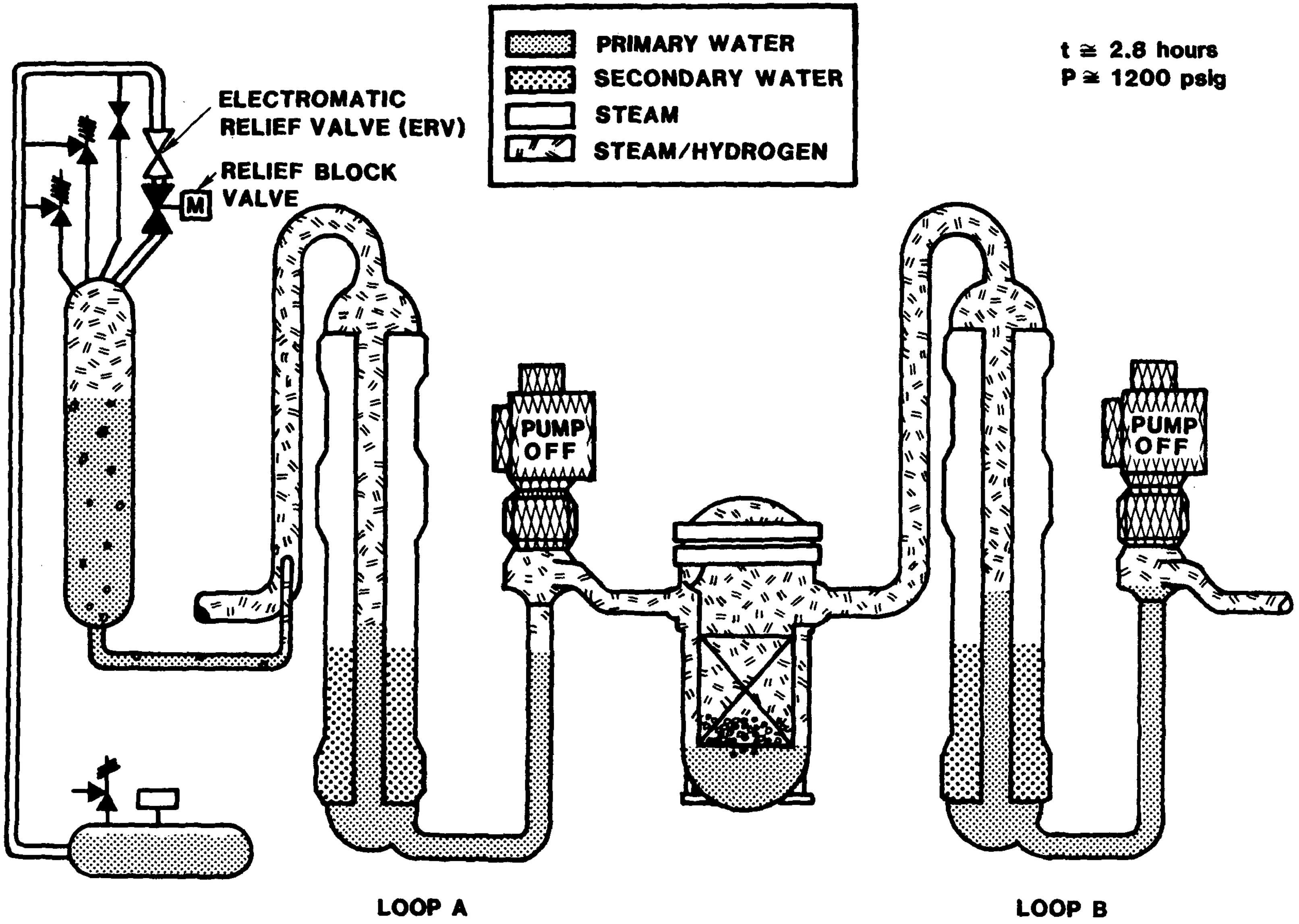

Figure I-10. TMI-2 Scenario: Core Dryout and Heatup Continuing. Hydrogen Generation by Steam Zirconium Reaction in Hotter Regions.

The operators attempted to restart RCP 2B 174 minutes into the incident. Flow was indicated for a few seconds and then dropped to zero. The pump was shut off 19 minutes later. Conditions were then as shown in Figure I-11, with an RCS pressure of about 2050 psig.

At about 192 minutes, the operators opened the pressurizer block valve for about 17.5 minutes, and at 200 minutes, full safety injection was manually initiated. RCS pressure dropped to about 1500 psig by 210 minutes, but radiation levels were increasing. Figure I-12 shows the RCS conditions at 210 minutes (3.5 hours); it shows that the core had been recovered.

The PORV block valve was again opened at about 3.7 hours into the incident; it remained open until about 5.3 hours. During this period, the overall trend in RCS pressure was downward; some pressure increases occurred during high pressure injections. At about 5.3 hours, the PORV block valve was closed and RCS pressure increased. When the pressure was around 2000 psig the valve was cycled to maintain pressure in this vicinity. Figure I-13 shows the approximate RCS conditions at about 6 hours. This situation continued until about 7.5 hours into the incident, when a decision was made to depressurize the RCS conditions at about 6 hours. This situation continued until about 7.5 hours into the incident, when a decision was made to depressurize the RCS by opening the block valve to actuate the Core Flood System. Two makeup pumps (HPI pumps) were running during this entire period.

The operators attempted to depressurize the RCS by using the Core Flood System at approximately 7.6 hours. The pressure reduction was also performed to approach conditions that would allow the decay heat removal pumps to be placed in service. RCS pressure had been reduced to about 1000 psig at about 8 hours into the incident, as shown in Figure I-14. The conditions necessary for actuation of the Decay Heat Removal System were not met. The Core Flood System did actuate at approximately 8.6 hours into the incident when the RCS pressure reached 600 psig.

During this time, hydrogen was being released through the pressurizer into containment. It was about 9 hours, 50 minutes into the incident that a 28 psig pressure spike was recorded in containment (Figure I-15). It was later determined that this spike was the result of a hydrogen deflagration in containment. By 10.5 hours, RCS pressure had been reduced to about 400 psig (Figure I-16), and the pressurizer temperature had reached saturation. High pressure injection was maintained during the entire depressurization procedure.

At 13 hours conditions were as shown in Figure I-17. RCS pressure had increased to 600 psig, the OTSGs were blocked by hydrogen, and the reactor vessel water level had dropped. The RCS pressure never dropped to 320 psig, which is the necessary pressure for Decay Heat Removal System operation to begin. Further, the RCS temperature never dropped to below 250°F, which is the necessary temperature to begin operation of the Decay Heat Removal System.

By 15 hours, RCS pressure had been restored to 2300 psig by high pressure injection. Natural circulation occurred in RCS "A" Loop with OTSG "A" steaming to the condensor; OTSG "B" was isolated at this time. Conditions at 15 hours are shown in Figure I-18. By 16 hours, with RCS pressure at 1300 psig, forced circulation had been reestablished in the A-loop, with the OTSG serving as the heat sink (Figure I-19).

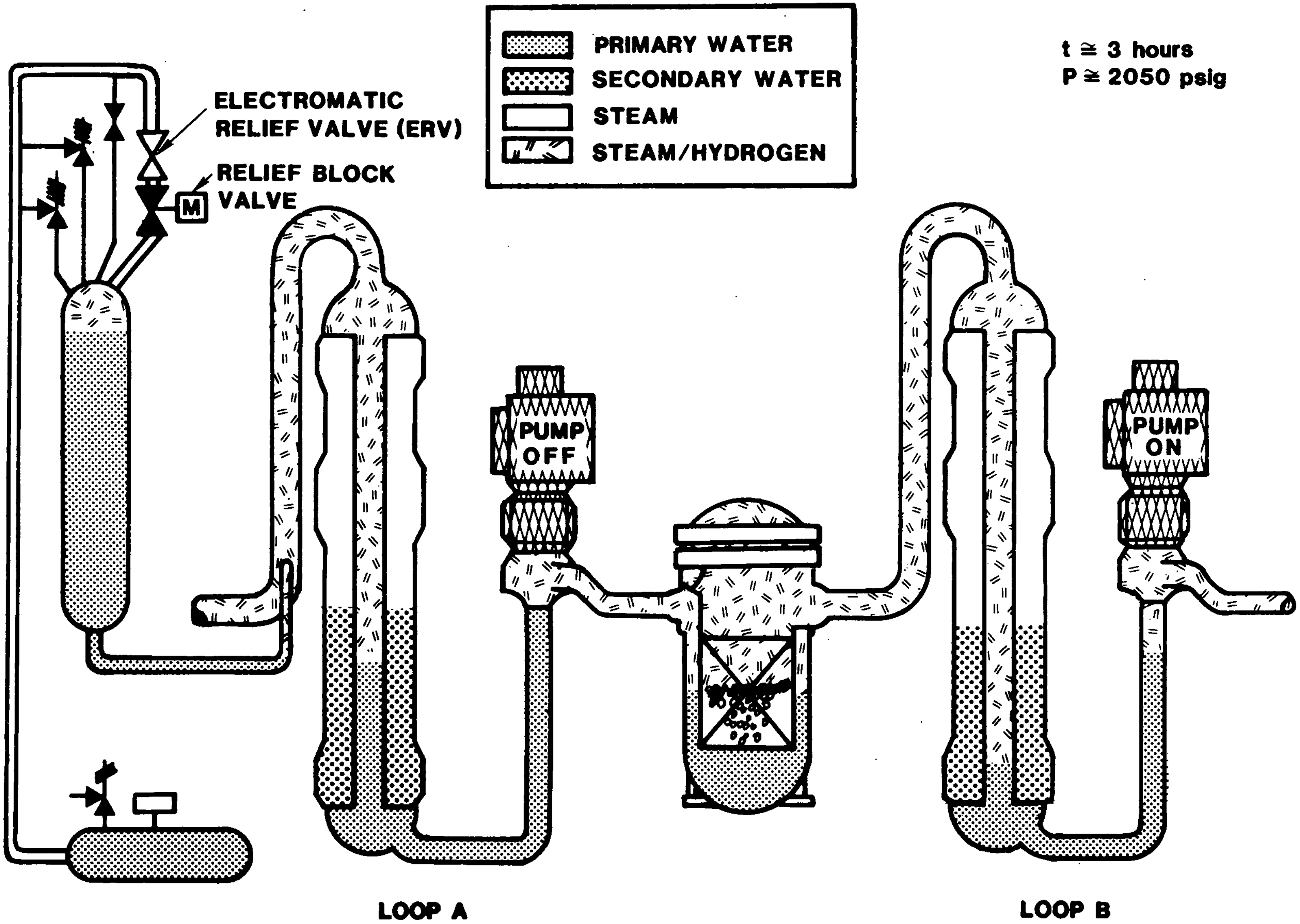

Figure I-11. TMI-2 Scenario: Core Partially Quenched by Fluid During Loop B Pump Start. Heatup Resumes.

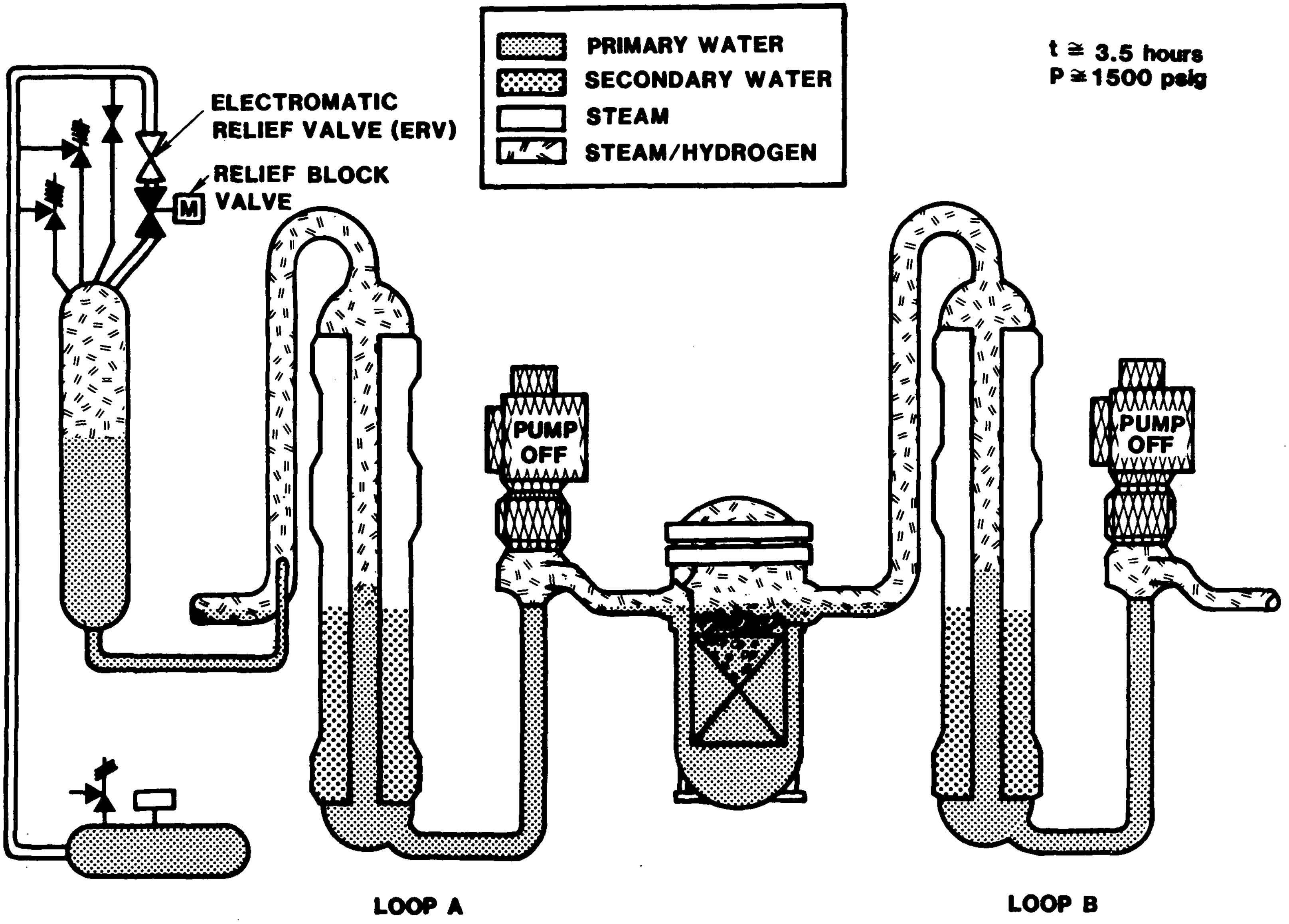

Figure I-12. TMI-2 Reactor Vessel Refilled by Manual Initiation of Safety Injection. Core Temperatures Decreasing.

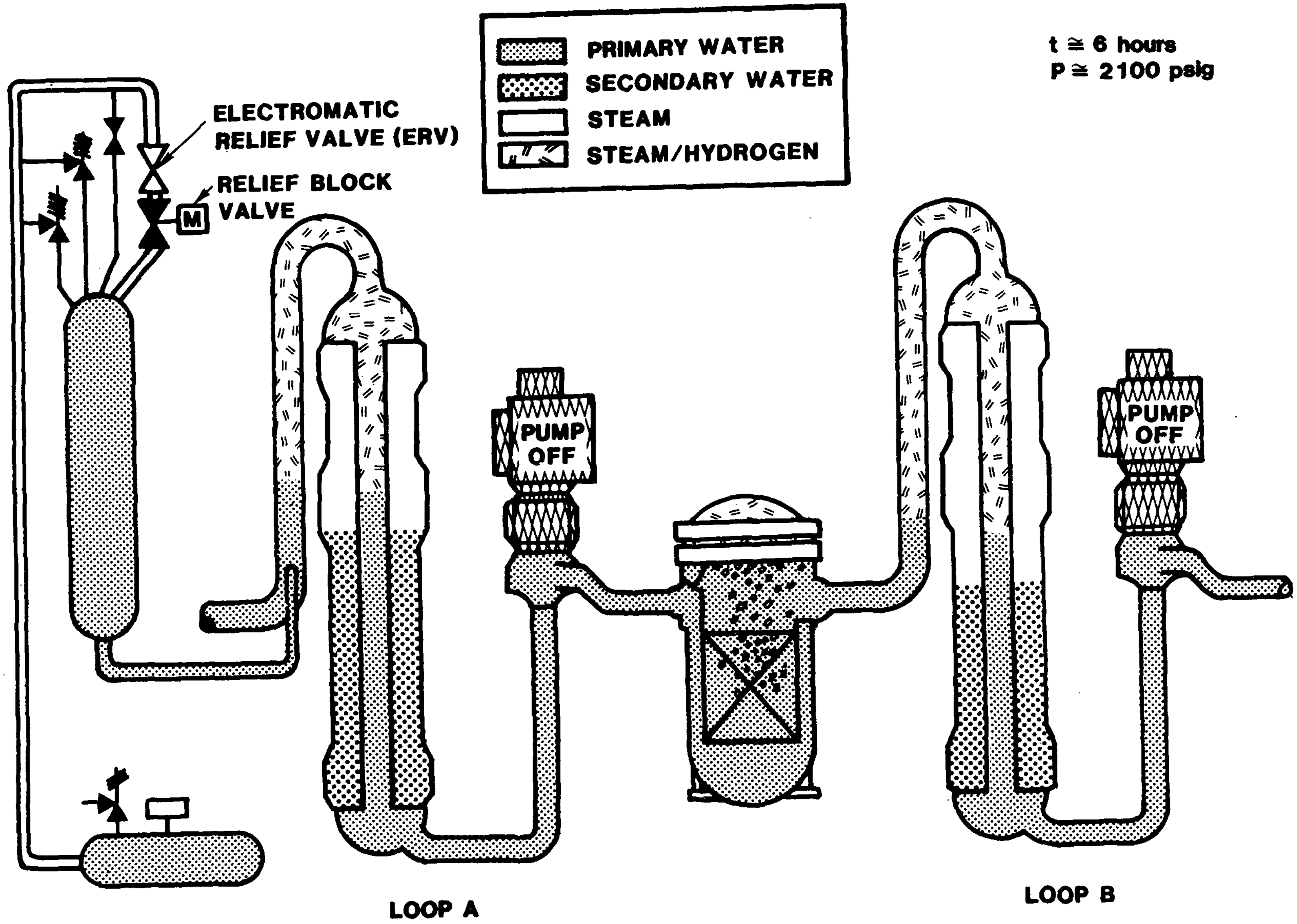

Figure I-13. TMI-2 Scenario: System Pressurized by High Pressure Injection System. Intermittent Liquid Release Through Top of Pressurizer. Heat Removal by Heatup of Injected Water. Heat Steam Generator Heat Transfer Blocked by Hydrogen.

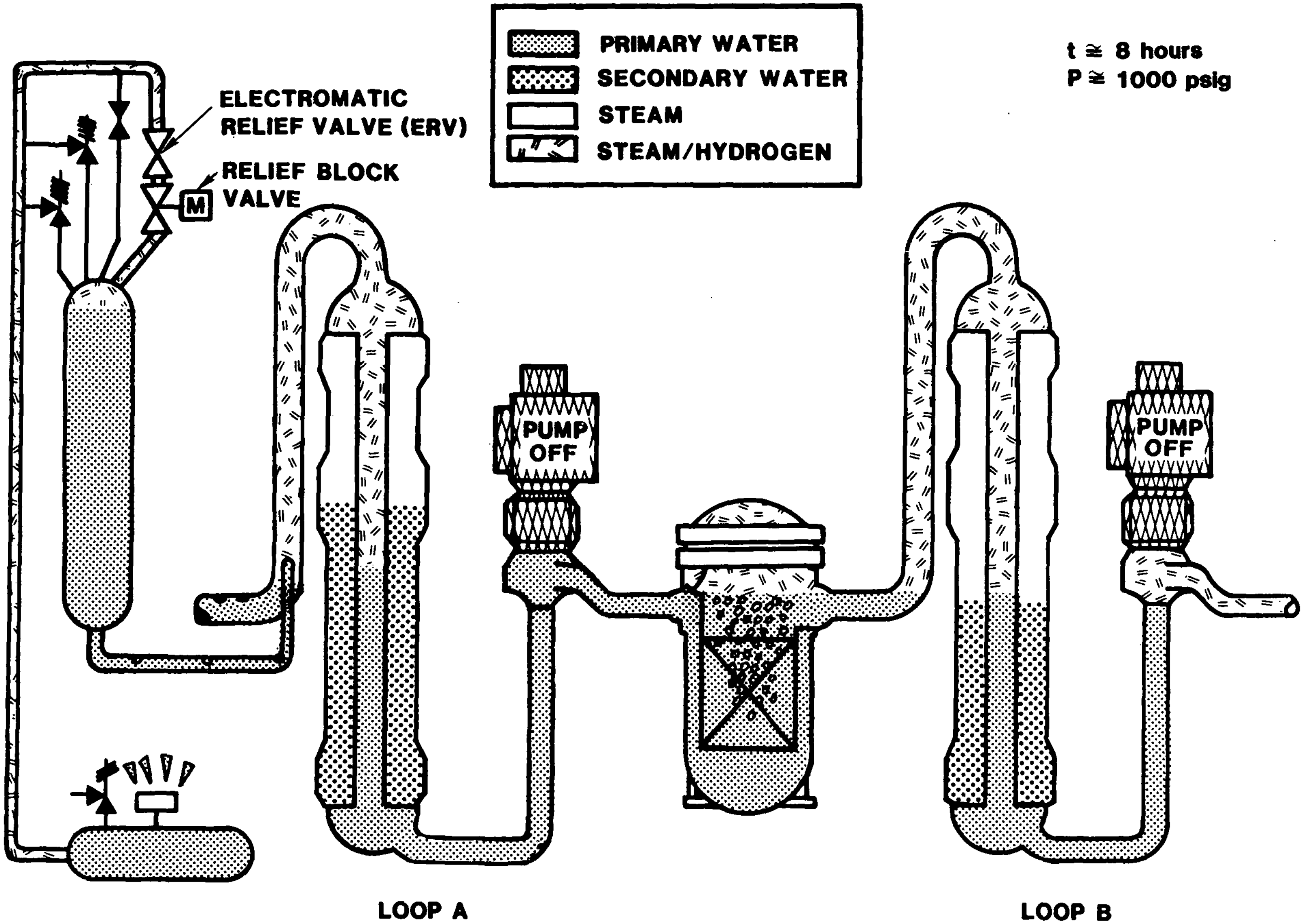

Figure I-14. TMI-2 Scenario: Primary System Depressurizing and Releasing Hydrogen Through the Pressurizer into the Containment.

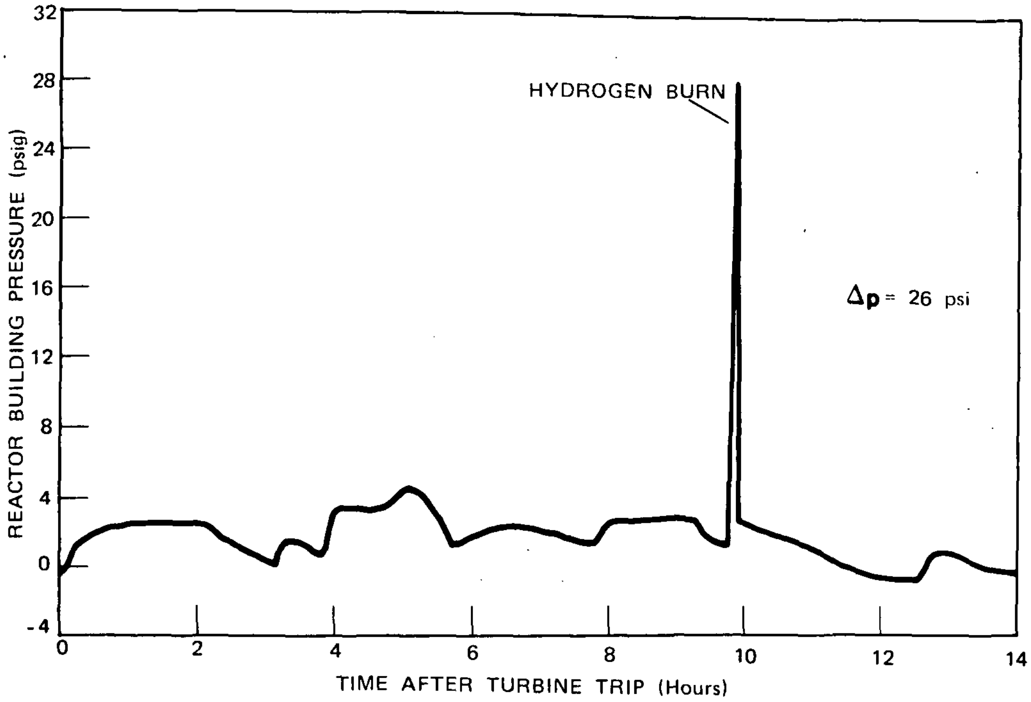

Figure I-15. TMI-2 Scenario: Reactor Building Pressure vs. Time

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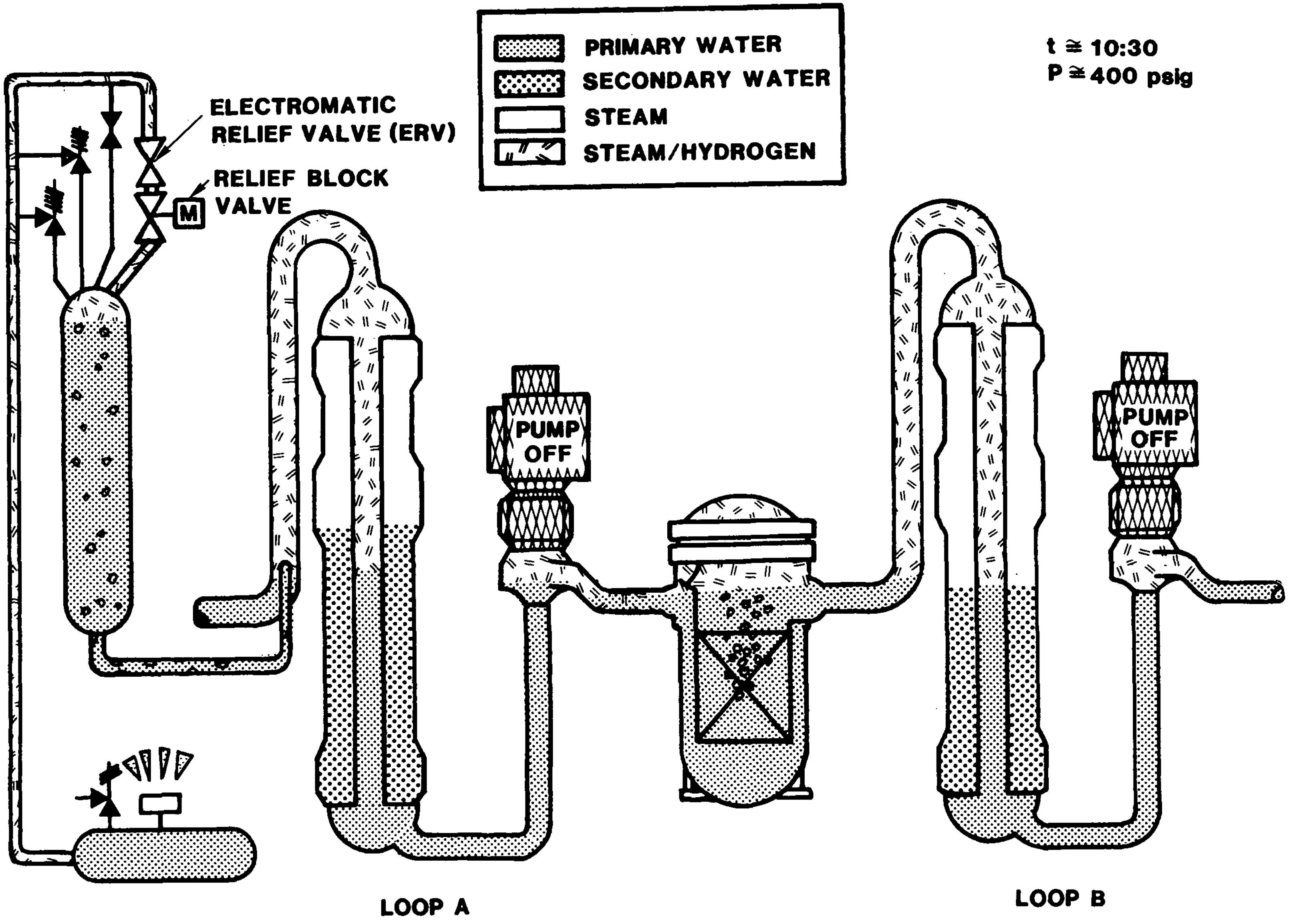


Figure I-16. TMI-2 Primary System Pressure Reaches a Minimum as Pressurizer Temperature Returns to Saturated Condition. Liquid in System Maintained During Depressurization by High Pressure Injection and Core Flood Tanks.

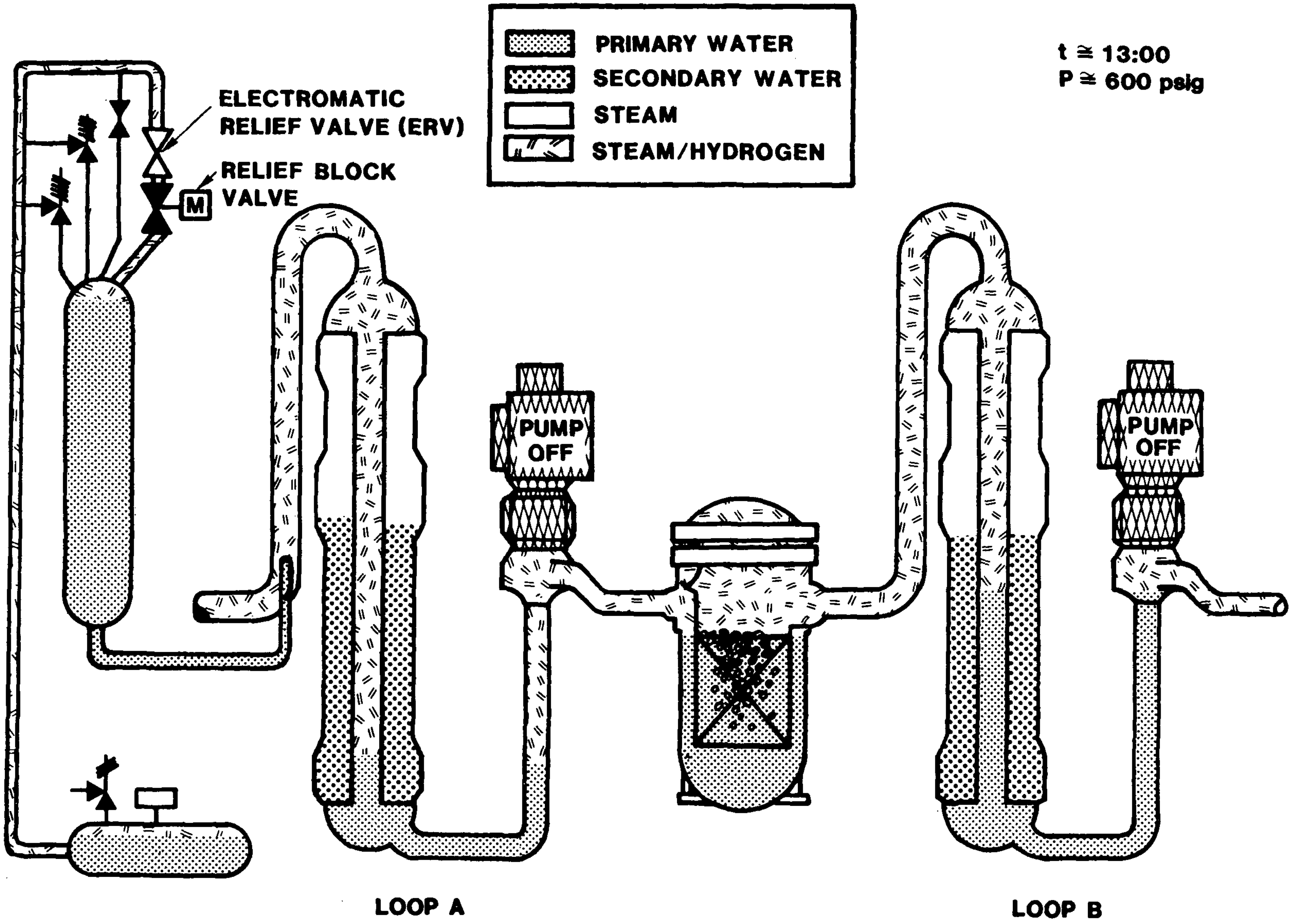


Figure I-17. TMI-2 Scenario: Steam Generators Blocked by Hydrogen. Reactor Vessel Level Decreasing. Primary System Pressure Increasing. Minimal Make-up Flow.

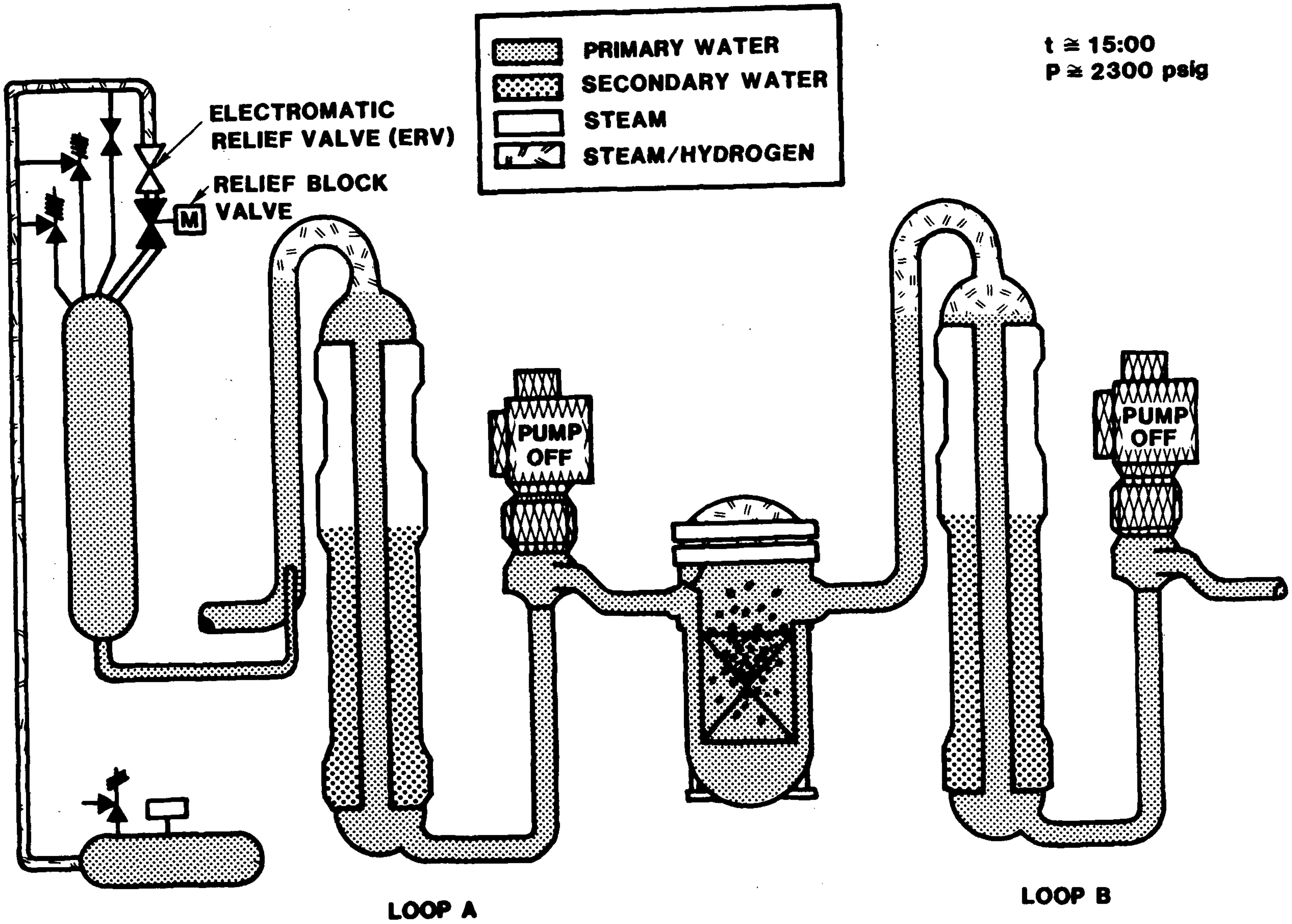


Figure I-18. TMI-2 Scenario. System Repressurized by High Pressure Injection. Natural Circulation to Steam Genrators Blocked by Hydrogen.

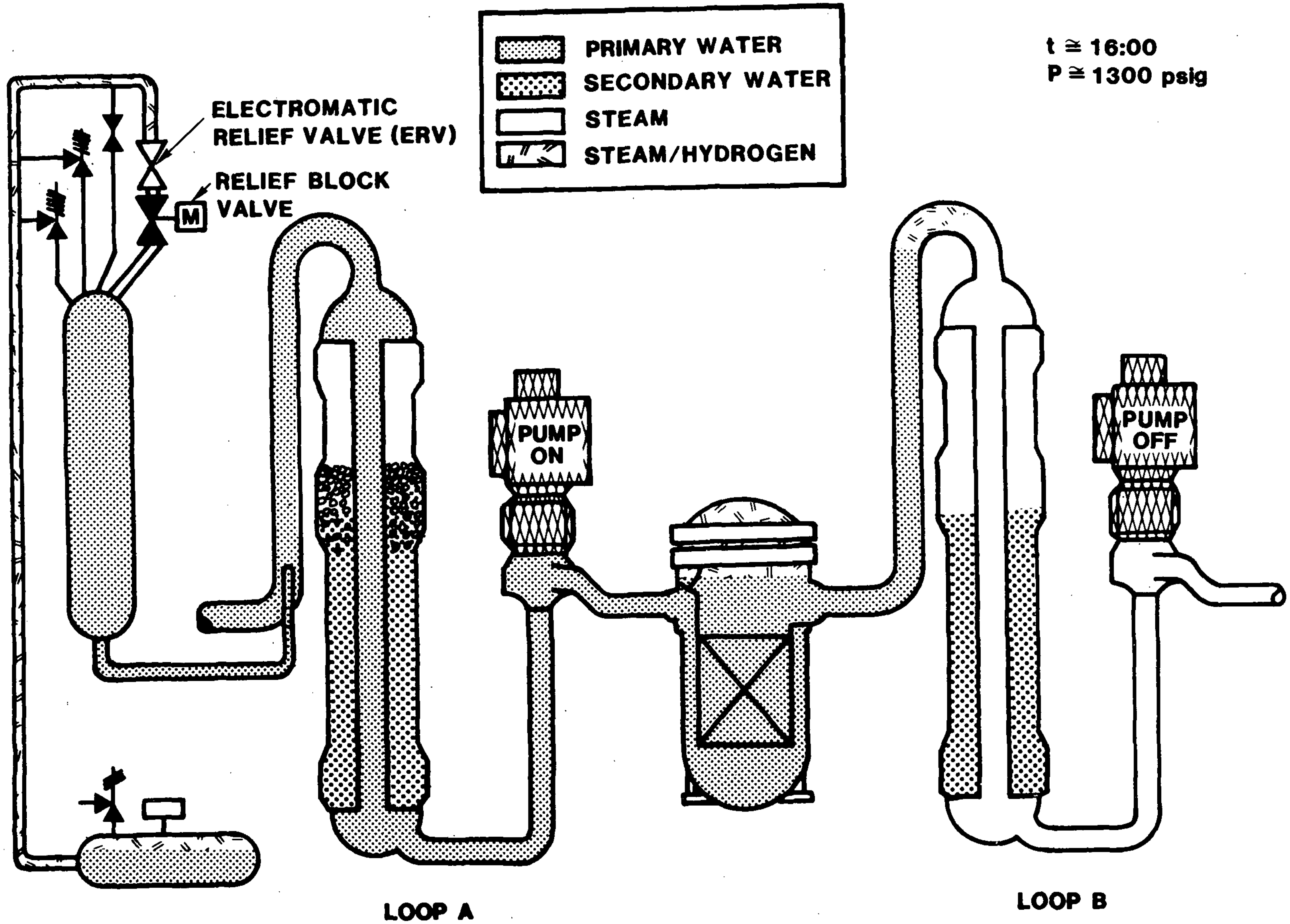


Figure I-19. TMI-2 Scenario: Forced Circulation Reestablished in Loop A with Heat Removal Via Loop A Steam Generator

The reactor coolant that escaped into the TMI-2 containment through the blown rupture disk in the reactor coolant draft tank released both hydrogen and radioactive fission products into the building, as shown in Figure I-20. The TMI-2 facility incorporated two containment sump pumps with automatic start features which pumped water in the containment sump to the Auxiliary Building Miscellaneous Waste Holdup Tank. The sump pumps started operating automatically because of an increasing sump level in the Reactor Building. This radioactive RCS water was then pumped to the miscellaneous waste holdup tank in the Auxiliary Building. The transfer line from this tank is lined up to the Auxiliary Building sump tank which, unfortunately, had a blown rupture disk. Hence, the holdup tank was filled and the water was transferred to the Auxiliary Building sump tank. This RCS water was added to that water which was initially in the sump (mainly from packing leakage from pumps that supply river water, for cooling purposes, to the Reactor Building). This, then, was the path for radioactive fission products initially released to the Auxiliary Building from the Reactor Building at approximately 38 minutes into the incident.

Shortly after 6:30 am (2.5 hours into the incident) radiation readings up to about 1 Roentgen/hour (up from an initial 5 milli-Roentgens/hour) were received in the area of the makeup tank in the Auxiliary Building. By 7:24 am, the radiation monitor on the Auxiliary Building vent stack went off-scale; and the Reactor Building dome monitor had an indicated radiation level of 8 REN/hour; therefore at this time, the Manager-Generation Station Nuclear declared a General Emergency. It was at this point that the public was notified about the incident at TMI-2.

As previously discussed, the majority of the hydrogen was produced between about 1.5 hours and 3.5 hours into the incident. Temperature data from the core exit thermocouples disclosed that sections of the core had temperatures sufficiently high to liberate hydrogen by means of the zircaloy-steam reaction.

At 9 hours and 50 minutes into the incident a hydrogen deflagration took place in the containment. Although it is not known exactly what initiated the hydrogen ignition, one point is clear: A 28 psi pressure spike occurred in containment. This spike was sensed by several types of instrumentation. Figure I-15 showed the pressure pulse in containment as it appeared on a trend recorder in the TMI-2 control room. Note that pressure increased to 28 psig. The pressure rise and subsequent pressure drop took place over about a 200 second time-frame.

Concurrent with this pressure rise was a simultaneous temperature increase on most of the temperature monitors in the containment, as shown in Figure I-21. It should be emphasized that the temperature data were taken once every 6 minutes by RTDs having a slow response time in air (or the order of about 500 seconds). Therefore, the smooth curves shown here are somewhat misleading with regard to the actual Reactor Building temperatures; these curves only show general trends.

Further, the OTSGs experienced an indicated pressure decrease at the same time. The OTSGs have pressure sensors that are referenced to the containment atmosphere pressure. If the containment pressure changes, this will, in turn, affect the OTSG pressure. Both OTSGs experienced approximately a 24 psid pressure drop at the same time that containment pressure increased as shown in Figure I-22.

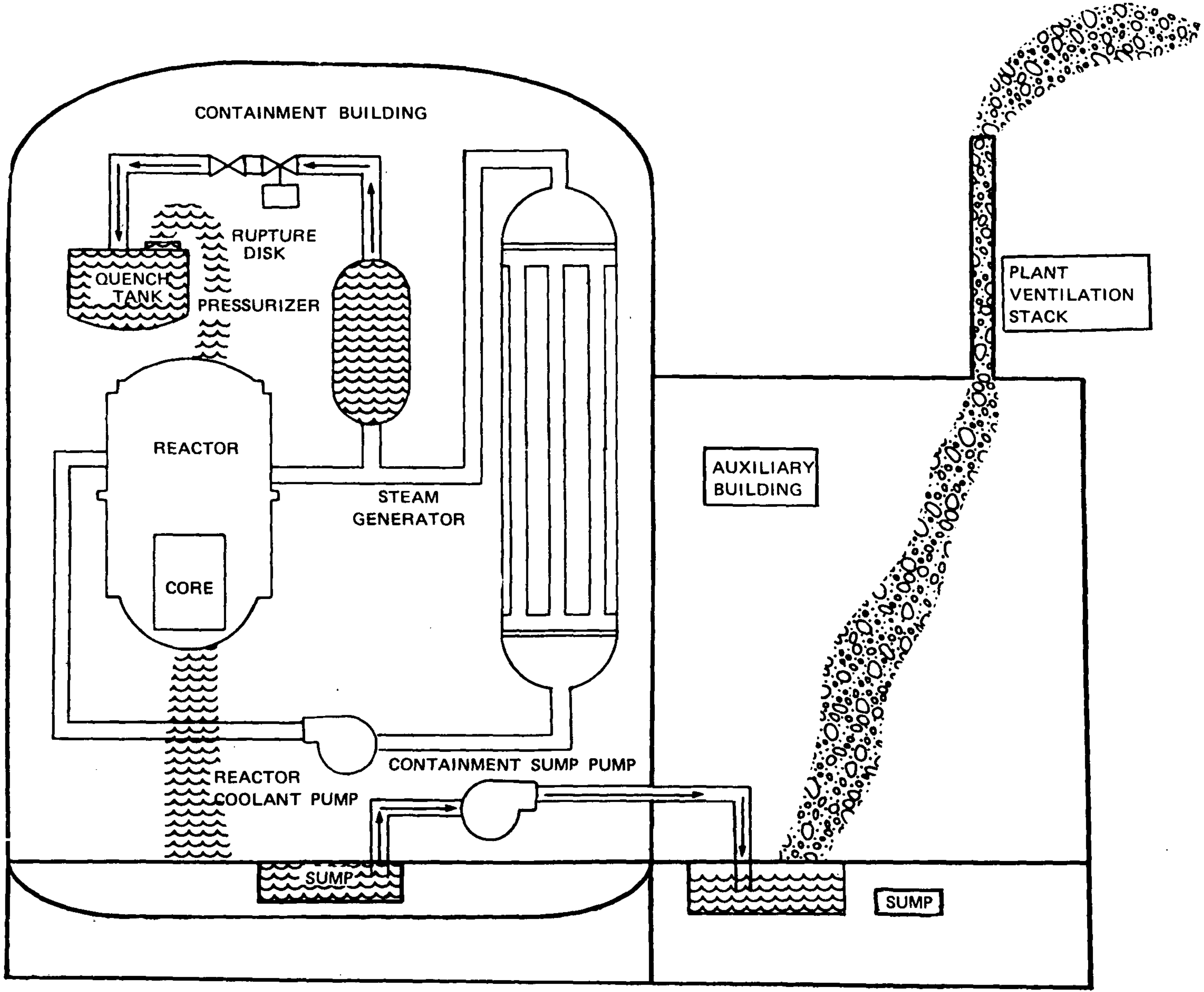


Figure I-20. TMI-2 Scenario: Radioactive RCS Water Pumped from Containment to the Auxiliary Building

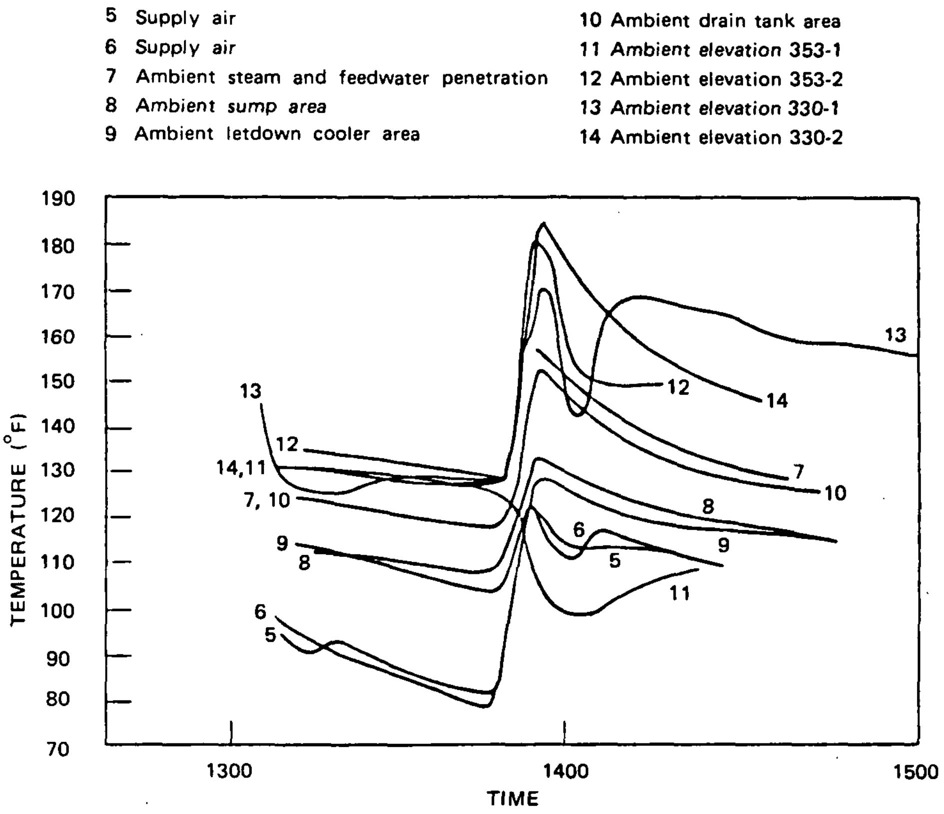


Figure I-21. TMI-2 Scenario: Reactor Building Temperatures During Hydrogen Ignition.

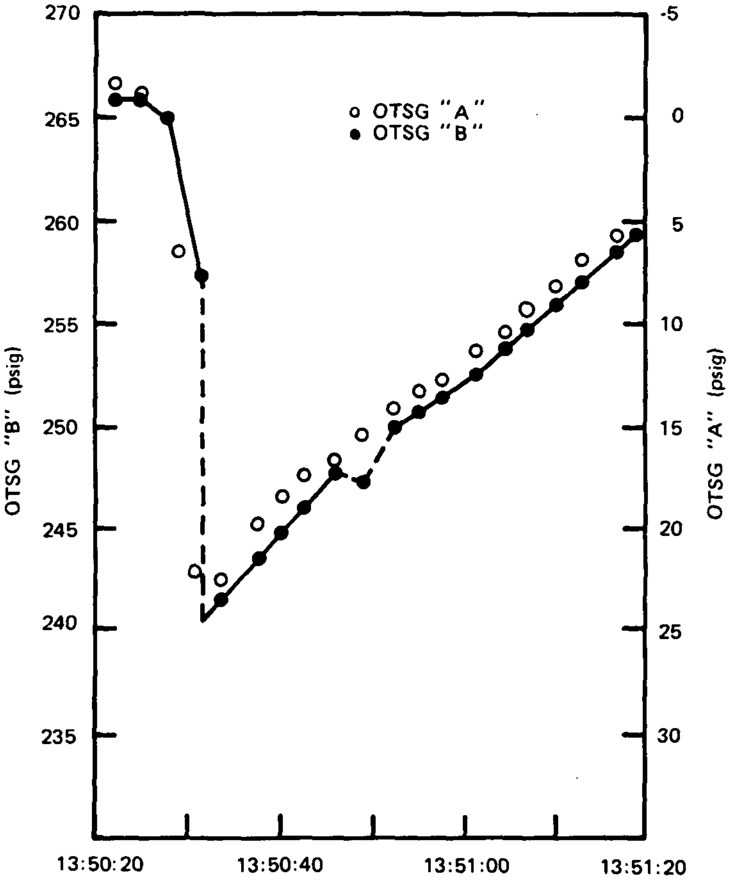


Figure I-22. TMI-2 Scenario: Effect Hydrogen Ignition on Measured Steam Pressures

It has been postulated that the average hydrogen concentration in the TMI-2 containment was approximately 8% when the deflagration took place. From Figure I-23, it can be seen that for this concentration, combustion might have been fairly complete.

By applying an understanding of the source range detector response to void formation, basic thermal-hydraulic principles, and the established sequence of events, it is possible to develop an interpretation of the source-range recording, shown in Figure I-28. The relevant features of the recording are designated by letters and are referenced in the commentary that follows:

A For the first 20 minutes, source-range instrument behavior was consistent with a normal post-trip decay rate of about one-third decade per minute.

B After approximately 20 to 30 minutes, the source count rate should be decreasing through the 600-700 counts per second (cps) range. Instead, the curve leveled out at about 50000 cps due to the buildup of voids (steam bubbles) in the downcomer and core regions. This is consistent with the fact that pressure had reached saturation (approximately 6 minutes after turbine trip), and net outflow through the open electromatic relief valve continued to empty the system. Void formation is also consistent because of the reduced pumping head produced by two-phase flow conditions (not shown).

C Continued loss of coolant from the primary system [leads to increased voiding] and increased detector count rates. The recording began to exhibit noise, and phase separation characteristic of "slug flow." This phenomenon increased with time.

D At 73-74 minutes the B reactor pumps were secured by the operator.

E At 100 minutes the A reactor coolant pumps were secured. This caused a flow transient and separation of voids to the upper regions of the system. Voids rising to the top and coolant fill from the hot legs produced a "solid" water condition seen at the detector. The detector count rate abruptly dropped.

F The minimum count rate is suggestive of the fact that the downcomer water level was at or near the top of the active core level.

G Continued release of fluid out of the relief valve began to boil off inventory from the core and downcomer area. Makeup flow, assumed to be in the neighborhood of 140 gallons per minute, was not sufficient to maintain downcomer water level. The core mixture came within better view of the detector as water levels dropped; the count rate increased.

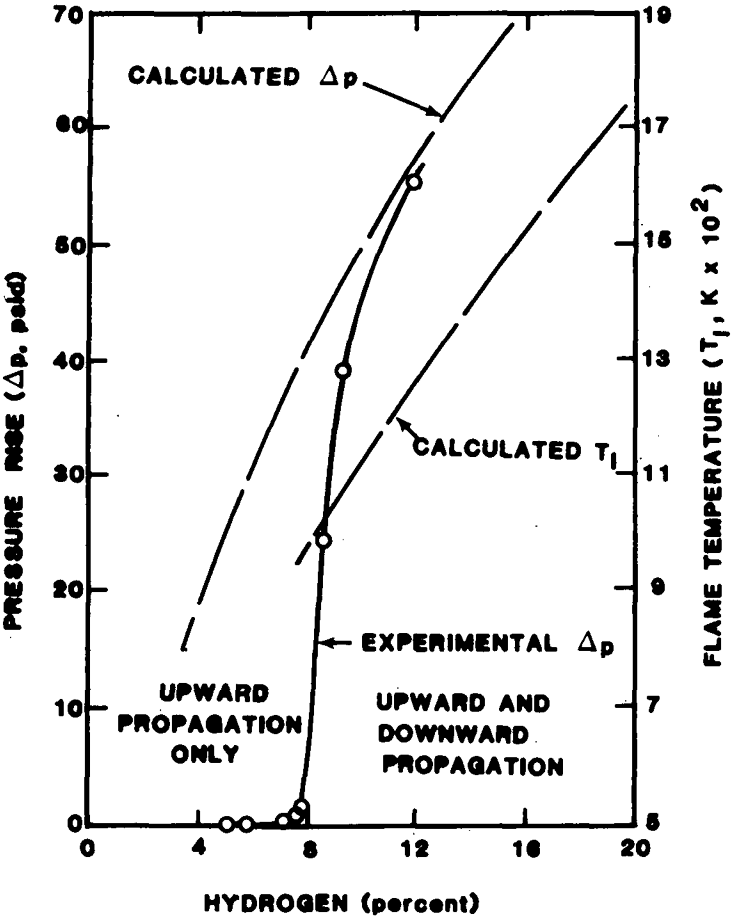


Figure I-23. TMI-2 Scenario: Pressure Rises Resulting from Ignition of Hydrogen in Air in 12 Foot Diameter Sphere at 18°C.

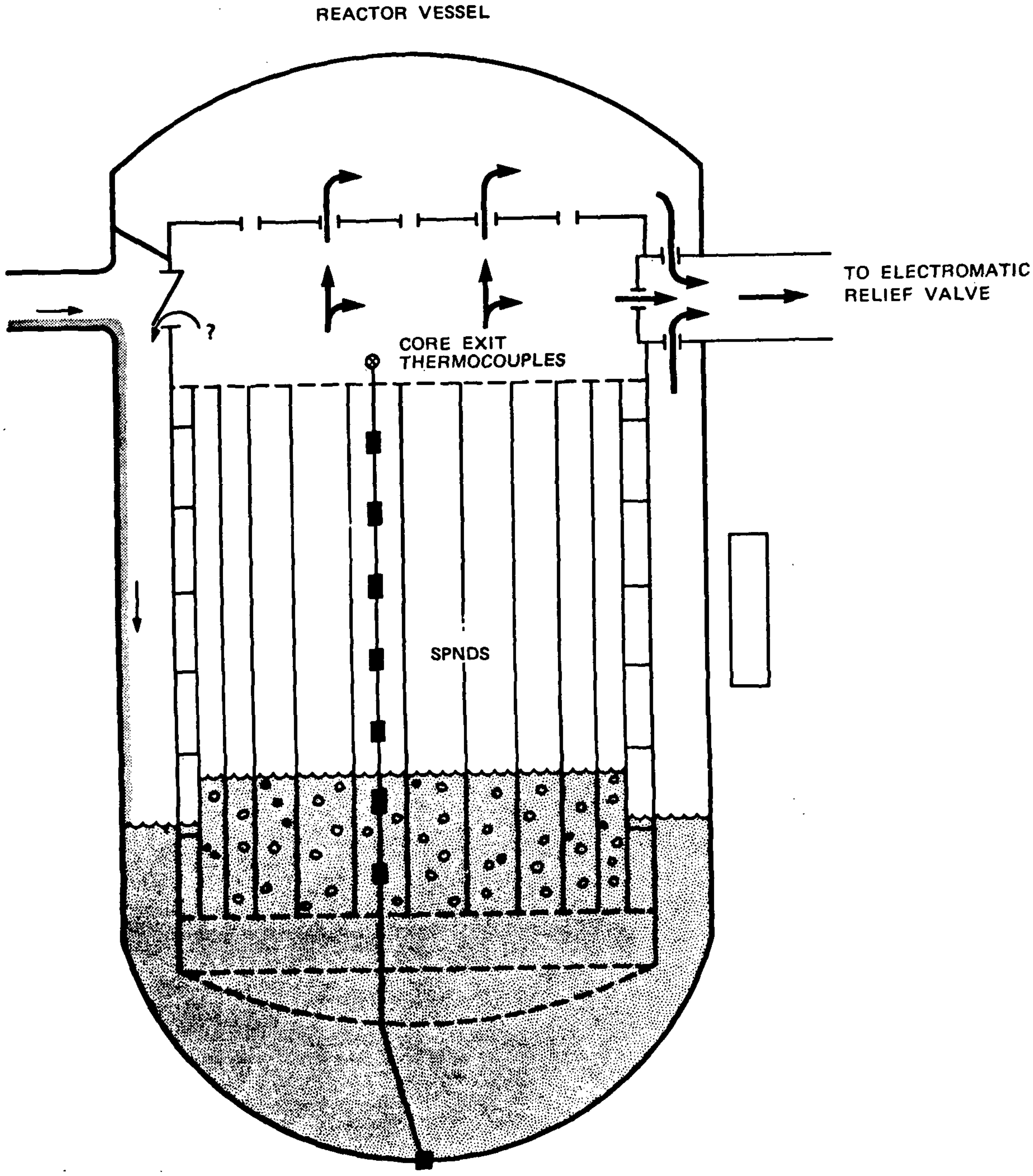


Figure I-24. TMI-2 Scenario: Core Water Level--Time Approximately 135-142 Minutes after Turbine Trip.

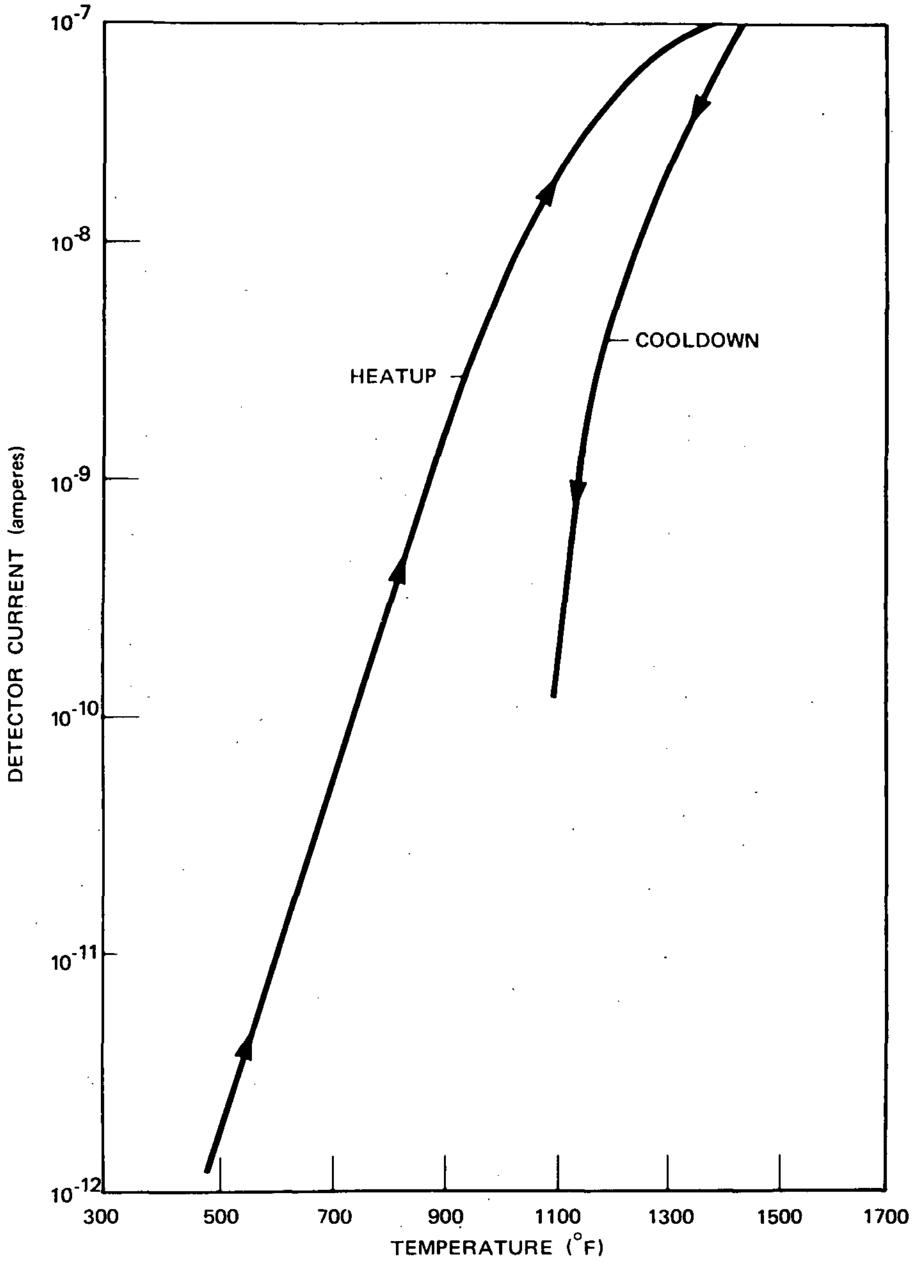
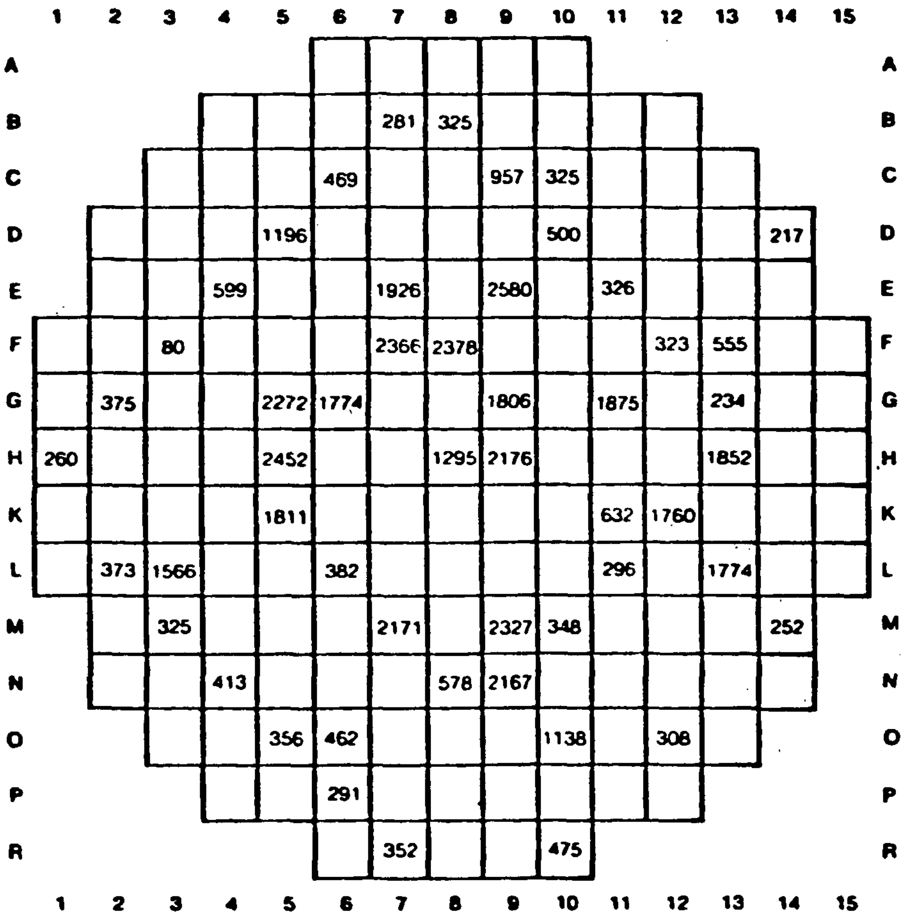


Figure I-25. Approximate Thermionic Response of a Self-Powered Neutron Detector (Typical)



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	
A																A
B							281	325								B
C						469			957	325						C
D					1196					500				217		D
E				599			1926		2580		326					E
F			80				2366	2378				323	555			F
G		375			2272	1774			1806		1875		234			G
H	260				2452			1295	2176				1852			H
K					1811						632	1760				K
L		373	1566			382					296		1774			L
M			325				2171		2327	348				252		M
N				413				578	2167							N
O					356	462				1138		308				O
P						291										P
R							352			475						R
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	

Figure I-26. TMI-2 Scenario: Map of Core Exit Temperature (9°F), 240-300 Minutes.

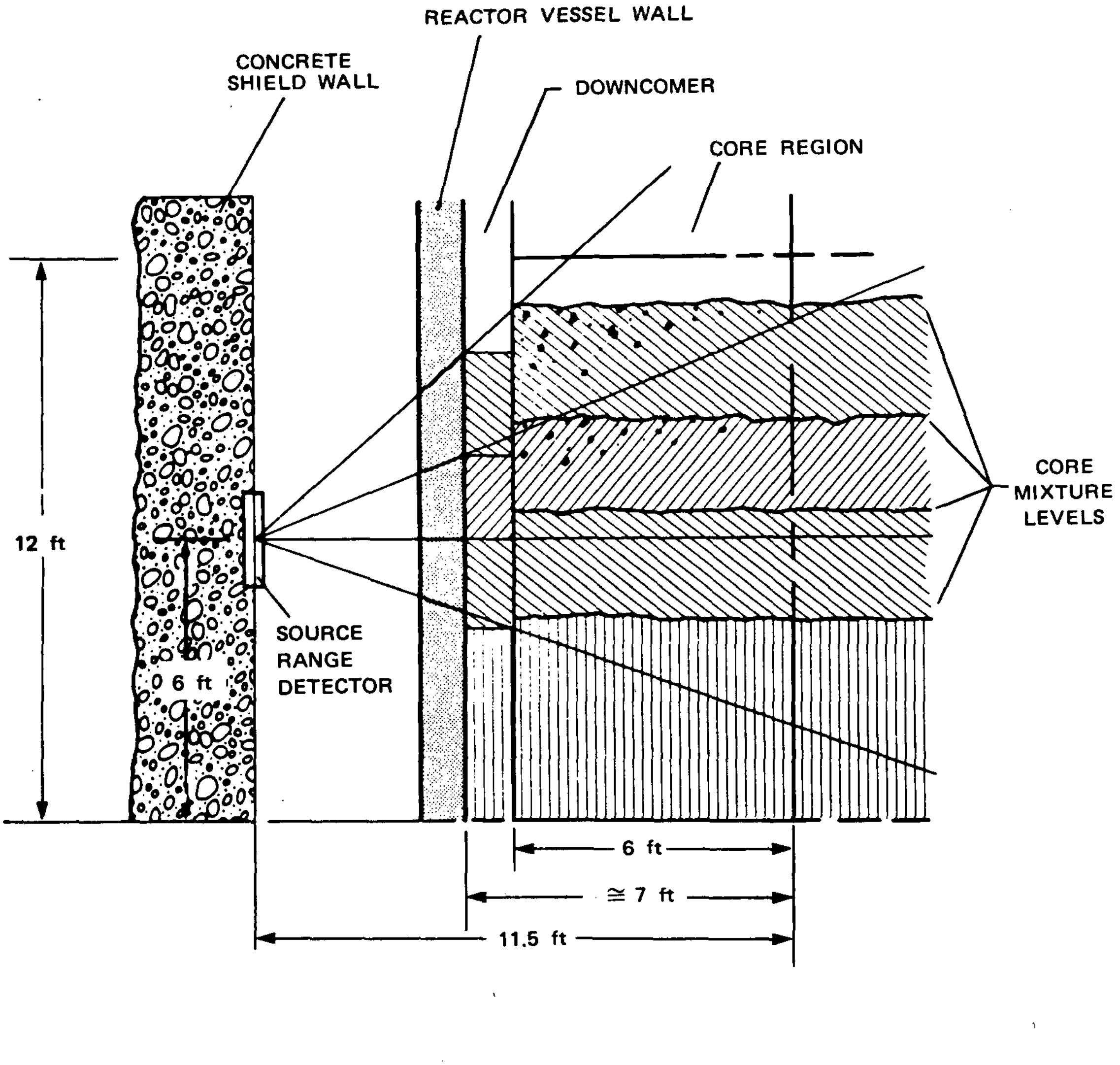


Figure I-27. TMI-2 Scenario: Source Range Neutron Detector Field of View vs. Core Mixture Level.

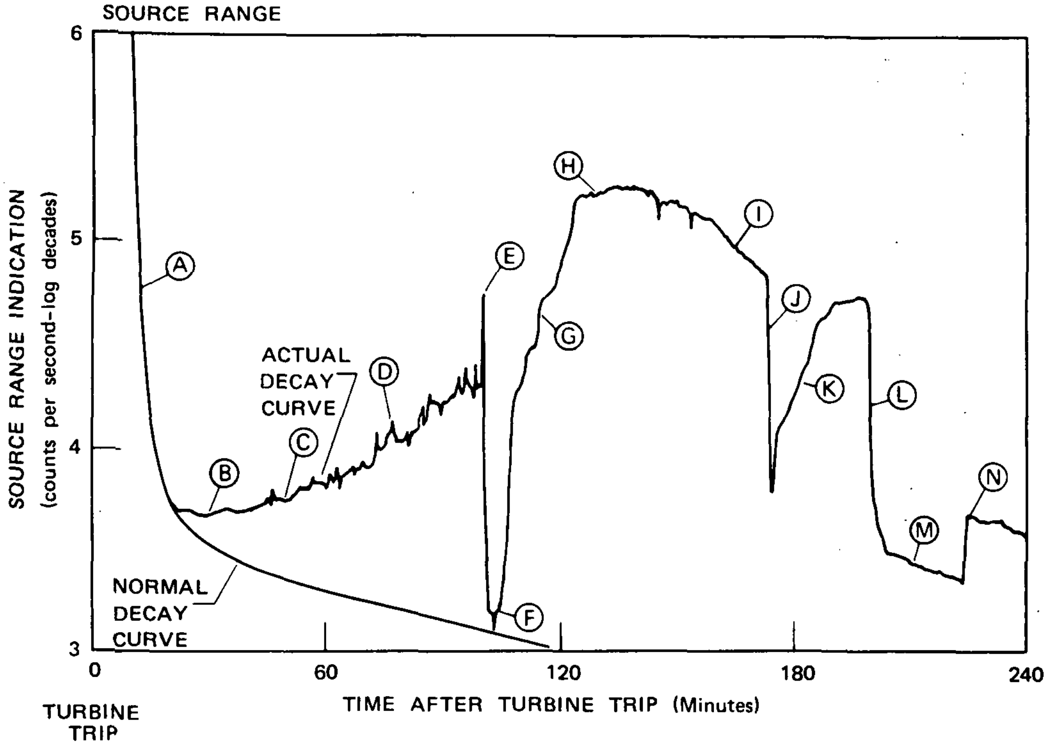


Figure I-28. TMI-2 Scenario: Source Range Trace During the Incident.

H The signal level continued to increase but at a slower rate as shielding variations began to be counterbalanced by the loss of neutron source (i.e., [H_2O]* being removed from the core region). In this period, also, the rate of uncovery is believed to have slowed somewhat as core boil-off tended to equilibrium with a relatively unchanging make-up flow rate.

I Over this period the count rate was decreasing as the loss of neutron source and reduced neutron multiplication became predominant. The turnaround in detector count rate can be interpreted [as due to either] core refill or continued recovery. However, the weight of evidence from make-up flow estimates and other core instrumentation suggests that the decreasing count rate was in response to continued core uncovery.

J The operator started reactor coolant pump 2B, sending a slug of cold water into the downcomer and essentially filling it.

K Loop flow data indicate that the pump worked effectively for a very brief period. This is corroborated by the abrupt turnaround in the source range detector trace, as flow ceased and excess downcomer fluid moved into the core and was boiled off; equilibrium levels were re-established.

L High pressure injection flow was initiated at 200 minutes, 8 minutes after the electromatic relief block valve was opened by the operator. Coolant passed into the downcomer, filling it. Detector count rates dropped sharply.

M Continued addition of high pressure injection flow began to quench the core. It is conjectured that the coolant first re-wetted the outer region of the core, bypassing the hot center.

N Water entering the core eventually led to an unstable thermal-hydraulic condition. It is speculated that major portions of the core may have been suddenly quenched with a resulting large amount of coolant flashing to steam, accompanied by possible core and fuel rearrangement. The jump in detector counts may be due to the displacement of fuel and/or sustained voiding of peripheral fuel regions.[I-3]

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* Reference I-3 says "UO_2" vice "H_2O", but this appears to be an error.

REFERENCES

I-1. Nuclear Safety Analysis Center, "Analysis of Three Mile Island - Unit 2 Accident," NSAC-8--1, NSAC-1 Revised Mar. 1980, Electric Power Research Institute, Palo Alto, Calif.

I-2. Three Mile Island - A Report to the Commissioners and the Public, by Mitchell Rogovin and George T. Frampton, Jr., Volume I., 1980.

I-3. Analysis of Three Mile Island - Unit 2 Accident. NSAC-1 Revised March 1980, Chapter CI-Core Instrumentation and Analysis of Coolant Level, pp 10-13.

I-4. H. W. Schutz and P. K. Nagata, "Estimated Temperatures of Organic Materials in the TMI-2 Reactor Building During Hydrogen Burn." GEND-INF-023 (December, 1982.

Appendix II

REACTOR COOLANT SYSTEM GASEOUS VOID DETECTION AND SIZING

Introduction

During the TMI accident, a gas bubble composed of hydrogen and steam was present in the reactor coolant system (RCS). Calculations of the size of the bubble varied, depending upon the assumptions used in the calculations. In this appendix, we present a method for calculating bubble size that should be valid for most situations encountered in PWRs. This method is taken from Ref. II-1, and the reader should consult this reference for a more thorough treatment of the problem.

Problem Formulation

We assume that the bubble is a mixture of hydrogen and water vapor, and that Dalton's law is obeyed. The density of water vapor in the bubble is assumed to be the saturation density $\rho_{v(sat)}(T)$. The total mass of water in the RCS (exclusive of pressurizer) is given by:

$$M_w^{RCS} = (V^{RCS} - V^B) \cdot \rho_\ell(P^{RCS}, T^{RCS}) + V^B \cdot \rho_{v(sat)}(T^{RCS}) \qquad \text{(II-1)}$$

where

M = mass
V = volume
P = pressure
T = temperature
ρ = density
Subscripts ℓ = liquid
v = vapor
w = water
Superscripts RCS = Reactor Coolant System
B = bubble

If Eq. II-1 is evaluated for two (P,T) states and the results subtracted, one finds:

$$(\rho_\ell - \rho_v)_2^{RCS} V_2^B - (\rho_\ell - \rho_v)_1^{RCS} V_1^B = (V\rho_\ell - M_w)_2^{RCS} - (V\rho_\ell - M_w)_1^{RCS} \qquad \text{(II-2)}$$

With the general notation (f is any quantity)

$$\bar{f} \equiv (f_1 + f_2)/2 \qquad \text{(II-3)}$$

$$\Delta f \equiv f_2 - f_1 \qquad \text{(II-4)}$$

Equation II-2 becomes

$$(\overline{\rho}_\ell - \overline{\rho}_v)\,\Delta V^B + \overline{V}^B\,(\rho_\ell - \rho_v)^{RCS} = \overline{V}^{RCS}\Delta\rho_\ell{}^{RCS} + \rho_\ell{}^{RCS}\,\Delta V^{RCS} - \Delta M_w{}^{RCS} \qquad \text{(II-5)}$$

We can make the following assumptions, as discussed in Ref. II-1:

$$V^{RCS} \approx \text{constant}(\Delta V^{RCS} \approx 0.)$$

$$\rho_v \ll \rho_\ell$$

$$\overline{V}^B \ll \overline{V}^{RCS}$$

Equation II-5 then reduces to:

$$\Delta V^B \approx (V^{RCS}\Delta\rho_\ell{}^{RCS} - \Delta M_w{}^{RCS})/\overline{\rho}_\ell{}^{RCS} \qquad \text{(II-6)}$$

The mass increase in the RCS is simply the net mass introduced from any makeup tanks and the pressurizer, reduced by the net leakage. Because the pressure and temperature in a makeup tank change very slowly, the change in its density may be neglected, but this is not the case for the pressurizer. The resulting expression is:

$$\Delta M_w{}^{RCS} \approx -\,(\rho_\ell A\Delta L)^{MUT} - \Delta(\rho_\ell V_\ell + \rho_v V_v)^{PZR} - \Delta M_w{}^{Leak} \qquad \text{(II-7)}$$

Here

$$V_\ell{}^{PZR} = [A(L + L_o)]^{PZR} \qquad \text{(II-8)}$$

$$V_v{}^{PZR} = V^{PZR} - V_\ell{}^{PZR} \qquad \text{(II-9)}$$

where

A = cross-sectional area
L = level
L_o = effective height of hemispherical section of the pressurizer at the bottom.
$\Delta M_w{}^{Leak}$ = unknown leakage term

Superscripts
MUT = Makeup Tank
PZR = Pressurizer

The hydrogen content of the bubble is:

$$N_H^B = P_H V^B/RT \qquad \text{(II-10)}$$

where

N_H^B = moles of hydrogen in bubble

$P_H = P - P_{sat}(T)$ = partial pressure of hydrogen

R = gas constant

From Chapter 2, Eq. 2-14 can be used to determine the amount of hydrogen in solution

$$X_{H_2} = P_H/H(T) \qquad \text{(2-14)}$$

X_{H_2} = mole fraction of hydrogen

$H(T)$ = Henry's Law Constant

We can rewrite Eq. 2-14 as follows:

$$X_{H_2} = \frac{n_{H_2}^{\ell}}{n_{H_2}^{\ell} + n_{H_2O}^{\ell}} = \frac{P_H}{H(T)} \qquad \text{(II-11)}$$

where

$n_{H_2}^{\ell}$ = molar density of hydrogen in solution

$n_{H_2O}^{\ell}$ = molar density of water solution

Because $n_{H_2} \ll n_{H_2O}$ we can write

$$\frac{n_{H_2}^{\ell}}{n_{H_2}^{\ell} + n_{H_2O}^{\ell}} \approx \frac{n_{H_2}^{\ell}}{n_{H_2O}^{\ell}} \approx \frac{P_H}{H(T)} \qquad \text{(II-12)}$$

or

$$n_{H_2}\ell = n_{H_2}\ell_O \ \frac{P_H}{H(T)} \qquad \text{(II-13)}$$

If we define S(T) as

$$S(T) \equiv \frac{n_{H_2}\ell_O}{H(T)} \qquad \text{(II-14)}$$

then

$$n_{H_2} = S(T)P_H \qquad \text{(II-15)}$$

The total number of moles of hydrogen in the RCS is now given by:

$$N_H^{RCS} = N_H^B + S(T)P_H\ (V^{RCS} - V^B) \qquad \text{(II-16)}$$

assuming that a bubble is present. If N_H^B is eliminated from Eq. II-16 by using Eq. II-10, and we solve for V^B, the result is

$$V^B = \max\left[\frac{n_H^{RCS}\ RT}{(1 - SRT)P_H} - \frac{SRTV^{RCS}}{1 - SRT}\ ,\quad 0\right] \qquad \text{(II-17)}$$

where

$$SRT = SP_H/(P_H/RT) \qquad \text{(III-18)}$$

Equation II-17 explicitly includes the possibility that all hydrogen is in solution with no bubble present.

If measurements are made at two pressures, but nearly equal temperatures so that changes in S and T may be neglected, we can solve Eq. II-17 for N_H^{RCS} and show*

$$N_H^{RCS} = \frac{1 - SRT}{RT}\max\left[-P_{H_2}P_{H_1}\frac{\Delta V^B}{\Delta P_H}\ ,\ P_{H_{min}}\left(|\Delta V^B| + \frac{SRT}{1 - SRT}V^{RCS}\right)\right] \qquad \text{(II-19)}$$

where the Δ notation for Eq. II-4 has been used, and $P_{H_{min}}$ is the lesser of P_{H_1} and P_{H_2}. ΔV^B is calculated using Eq. II-6. Once the hydrogen content of the

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*We assume that N_H^{RCS} is constant during the measurement. A changing hydrogen content could be included with minor changes.

system has been calculated from Eq. II-19, Eq. II-17 may be used to calculate the size of the bubble at any given pressure. Consider the following three cases.

Case 1: Bubble present in both states 1 and 2

In this case, the first term in brackets in Eq. II-19 is larger and the bubble size in either state is given by

$$V_i^B = \frac{P_{Hj}\,\Delta V^B}{\Delta P_H} - \frac{SRT}{1 - SRT}\,V^{RCS} \tag{II-20}$$

where the subscript i refers to the state at which you are calculating the bubble volume, and the subscript j refers to the other state.

Case 2: Bubble present only at the lower pressure

In this case, the second term in brackets in Eq. II-19 is larger and the bubble size in the ith state is given by

$$V_i^B = \text{Max}\left[\frac{P_{Hmin}}{P_{Hi}}\,|\Delta V^B| + \left(\frac{P_{Hmin} - P_{Hi}}{P_{Hi}}\right)\frac{SRT}{1-SRT}\,V^{RCS} \quad , \quad 0\right] \tag{II-21}$$

When $P_{Hi} = P_{Hmin}$, Eq. II-21 reduces to

$$V_i^B = |\Delta V^B| \tag{II-22}$$

and when $P_{Hi} \neq P_{Hmin}$, Eq. II-21 becomes

$$V_i^B \approx 0 \tag{II-23}$$

Case 3: No bubble present in either state

In this case, the second term in brackets of Eq. II-19 will yield an upper bound on the amount of hydrogen present based upon the lower pressure

$$\left.N_H^{RCS}\right)\max = P_{Hmin}\,S\,V^{RCS} \tag{II-24}$$

Equations II-6 and II-17 should yield results near zero for this case.

The formulations presented above are discussed in detail in Ref. II-1 and results are presented for the case of TMI. While it is important to understand the assumptions in these calculations, the results should be good for most regions of practical interest. These calculations include the effects of hydrogen solubility and the differences in water densities in the makeup tank, the pressurizer and the RCS. These effects have been neglected in other formulations, but can significantly impact the results.

References for Appendix II

II-1. M. Rogovin and G. T. Frampton, Jr., "Three Mile Island, A Report to the Commissioners and to the Public," Nuclear Regulatory Commission, Vol. II, Appendix II.9.

Appendix III

REACTOR VESSEL HEAD VENT
VENTING TIME PERIOD

Introduction

Once a Reactor Coolant System gaseous void has been detected and an approximation made of its size (as described in Appendix II), a calculation of the allowable venting time period can be made. The guideline which follows was excerpted from one prepared by the Donald C. Cook Plant, which is operated by the Indiana and Michigan Power Company. The following information includes a discussion of the basis for the venting time period calculation plus a general guideline for determining the venting time period itself.[III-1]

Basis

During a core uncovery event, the potential exists for a significant amount of hydrogen to be generated in the core. This hydrogen could be trapped in the reactor vessel head and released to the containment atmosphere during the venting operation. The containment hydrogen concentration is limited to less than four volume percent to prevent a potential combustible mixture with oxygen, therefore, the amount of hydrogen that can be vented to the containment is restricted. A maximum allowable time period for venting can be determined based on limiting the containment hydrogen concentration.

1. The total containment volume in cubic feet is determined first, and then converted to standard temperature and pressure conditions. Note that the pressure term for the conversion is only applicable to subatmospheric containments and can be deleted for the other plants.
2. The containment hydrogen concentration is then determined in volume percent units. This value can be found by direct sampling or by hydrogen monitors. Sufficient time should be allowed for the air circulation equipment to mix the containment atmosphere prior to sampling in order to determine a representative concentration. The <u>NOTE</u> identifies to the operations and engineering personnel that containment hydrogen concentration will be insignificant if there has been no leakage from the RCS to containment. In such a case, the operator may assume the hydrogen concentration to be 0 volume percent.
3. The maximum volume of hydrogen that can be vented and still limit the containment hydrogen concentration to less than three volume percent is calculated. This ensures that the hydrogen concentration will remain less than the flammable lower limit of 4%.

REACTOR VESSEL HEAD VENT GUIDELINE FOR THE VENTING TIME PERIOD

1. Convert the gaseous containment free-volume to gaseous containment volume at standard temperature and pressure conditions.

   Containment Volume @ STP = (Actual containment volume (ft^3) x

   $$\left(\frac{\text{Containment Pressure**}}{\text{14.7 psia}}\right) \times \left(\frac{492°\text{R}}{\text{Containment Temperature*}}\right)$$

   =_______________ft^3***

   * Temperature in degrees Rankine (°R=°F + 460°).

   ** If containment pressure has increased above 14.7 psia, for conservatism use 14.7 psig as the pressure.

   *** Assuming no humidity correction in containment.

2. Determine the containment hydrogen concentration in volume percent units. <u>NOTE</u>: The containment hydrogen concentration will be insignificant if there has been no leakage from the RCS to the containment.

3. Calculate the maximum hydrogen volume that can be vented to the containment that will result in a containment hydrogen concentration of less than or equal to three volume percent.

   Maximum H_2 Volume =

   $\frac{1}{100}$ [(3.0% Containment H_2 Concentration -% H_2 Concentration measured in Step 2 x (Containment Volume @ STP)]

   = __________ft^3

4. From Figure III-1 (RCS Pressure vs. H_2 Flow Rate) determine the allowable venting period that will limit the containment hydrogen concentration to three volume percent.

$$\text{Venting Period} = \frac{\text{Maximum } H_2 \text{ Vented (from Step 3)}}{H_2 \text{ Flow Rate}}$$

= ____________min

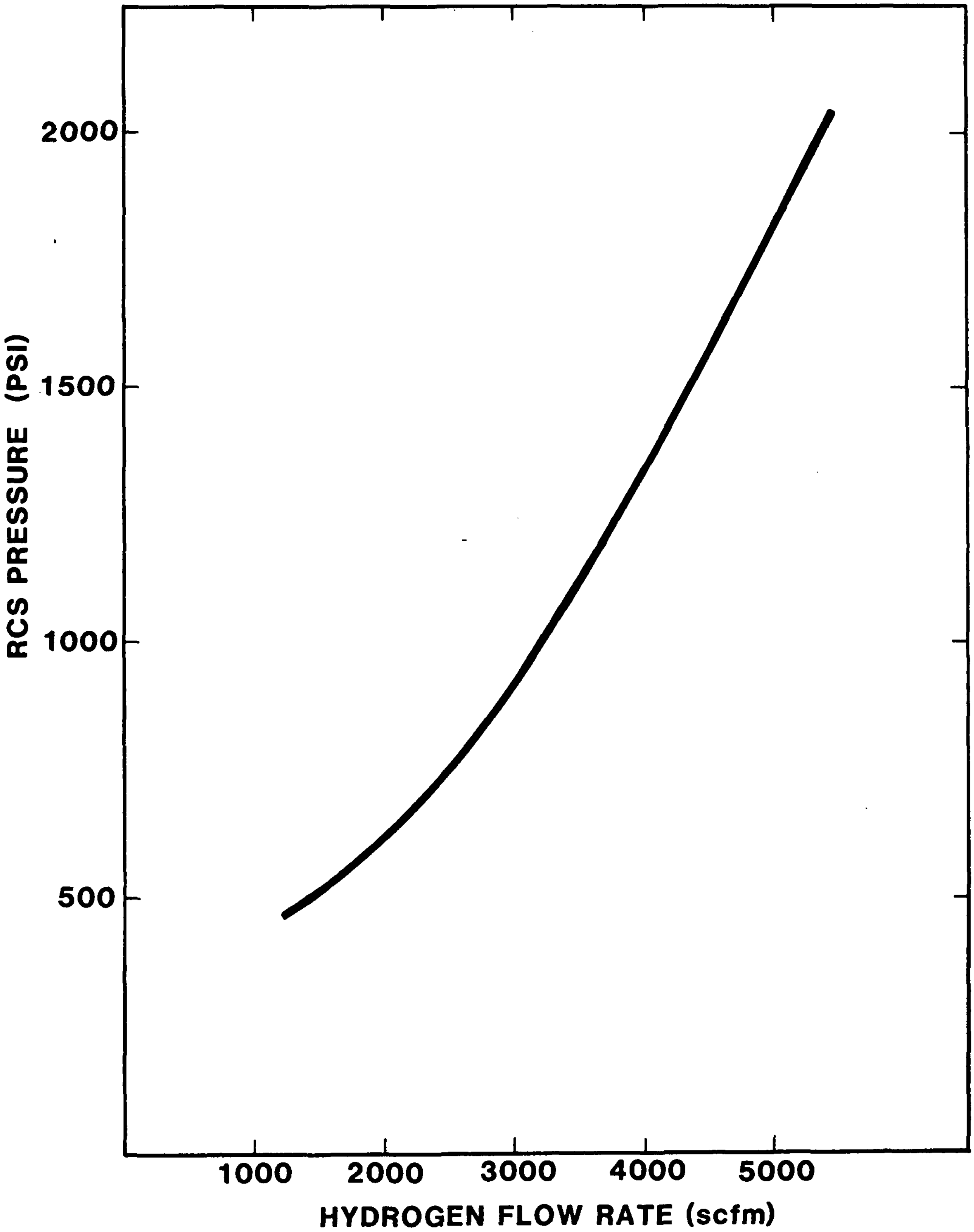

Figure III-1. Reactor Coolant System Pressure vs. Hydrogen Flow Rate.

REFERENCES

III-1. Donald C. Cook Plant, "Background Information for Reactor Vessel Head Vent Operation," rev. 0, Feb. 1981, Indiana and Michigan Electric Co., New York.

LIST OF ABBREVIATIONS

APSR: Axial power shaping rod
B&W: Babcock and Wilcox Company
BWR: Boiling water reactor
CAD: Containment Atmosphere Dilution System
CAS: Containment air sample
CCW: Component Cooling Water System
CDS: Containment Depressurization System
CE: Combustion Engineering, Inc.
CRDM: Control Rod Drive Mechanism
CVCS: Chemical and Volume Control System
DBA: Design basis accident
DDT: Deflagration-to-detonation transition
ECCS: Emergency Core Cooling System
EPRI: Electric Power Research Institute
ESF: Engineered safety feature
GE: General Electric Company
HEPA filter: High efficiency particulate air filter
HIS: Hydrogen Ignition System
HPCS: High Pressure Core Spray
HRSS: High Radiation Sampling System
HUT: Holdup tank
ICC: Inadequate Core Cooling
LOCA: Loss-of-coolant accident
LPCI: Low Pressure Core Injection
LPCS: Low pressure core spray
LRW: Liquid radwaste collection tank
LWR: Light-water cooled reactor
MIDS: Movable Incore Detection System
MSIV: Main steam isolation valve
MSLB: Main steam line break
OGS: Off-Gas System
OTSG: Once-through steam generator
PHMS: Permanent Hydrogen Mitigation System
PORV: Power-operated relief valve
PRA: Probabilistic risk assessment
PRT: Pressurizer relief tank
PWR: Pressurized water reactor
PZR: Pressurizer
RCIC: Reactor Core Isolation Cooling (System)
RCS: Reactor Coolant System
RCP: Reactor coolant pump
RCVS: Reactor Coolant Vent System
RHR: Residual Heat Removal (System)
RTD: Resistance temperature detector
RVHVS: Reactor Vessel Head Vent System
RWP: Radiation Work Permit
SBGTS: Standby Gas Treatment System
SCBA: Self-contained breathing apparatus
SCFM: Standard cubic feet per minute
SI: Safety Injection (System)
SJAE: Steam jet air ejector
SMM: Subcooling margin monitors

SNL: Sandia National Laboratories
TIP: Traversing Incore Probe (System)
VCT: Volume control tank
WDS: Waste Disposal System

GLOSSARY

Acid day tank: Small sulfuric acid batch tank in the Condensate Demineralizer Regeneration System in BWRs. Receives acid from holding tank and feeds it to metering pumps.

Adsorber: A surface used for adsorption.

Adsorption: A type of adhesion which takes place at the surface of a solid or liquid in contact with another medium, resulting in an accumulation of molecules from that medium in the vicinity of the surface.

Annunciator: An illuminated indication, which is electrically controlled in the control room, that denotes a particular plant condition. Annunciators generally have an audible indication as well as a visual one.

Auxiliary Coolant Systems: In a PWR, the Auxiliary Coolant Systems consist of the Residual Heat Removal System (RHR), which removes decay heat generated in the reactor core after shutdown; the Spent Fuel Storage and Cooling System which removes decay heat from the spent fuel storage pool; the Containment Cooling System which is an air cooling system and a direct water spray into the structure, both 100% capacity; the Closed-loop Cooling System which is an intermediate heat exchanging loop between other Auxiliary Coolant Systems and the environment; and the Service Water System, the final heat sink for all heat loads (ocean, river, or cooling tower) except the primary loop.

In a BWR, there are the Residual Heat Removal System; the Spent Fuel Cooling System; the Closed-loop Cooling System; the Service Water System; the Reactor Core Isolation Cooling System (RCIC), a standby core cooling system used when the reactor is isolated from the turbine due to closure of the main steam isolation valve, throttle valve, or stop valve (it is not used for accidents); the High-Pressure Core Spray System (HPCS), designed to make up water lost in any break or rupture; and Low-Pressure Core Spray System (LPCS), a backup to the LPIC mode of the RHR system.

Binary Fission: The most common form of nuclear fission in a nuclear reactor, which results in two fission products. Approximately 1 fission event in 12,000 is a ternary fission event (3 fission products), otherwise fission is generally binary fission.

Burning Velocity (Laminar): Velocity of a flame in a Lagrangian sense (i.e., relative to the flowing gases) at a steady burner.

Catalyst: A substance that accelerates or retards the rate of a chemical reaction, which itself undergoes no permanent chemical change, and which may be recovered when the reaction is completed.

Catalytic Poisoning: The process whereby a substance within a hydrogen recombiner unit itself inhibits the activity of the catalyst. Catalytic poisoning has not presented a problem in thermal recombiners.

Charging System: The system that introduces "new" feedwater into the RCS, from the VCT (or make-up tank) in a PWR, and from the condensate storage tank in a BWR.

Chemical and Volume Control System (CVCS): The system that maintains a proper volume and boric acid concentration in a PWR RCS. Boric acid is added by pumping a concentrated solution into the PZR. The pressure in the RCS may be lowered by spraying water from the VCT into the vapor space of the PZR. RCS water is removed for demineralizing and filtering through the letdown line from the RCS cold leg. Coolant may be added to the RCS cold leg from the VCT through the charging line. The functions of the CVCS may be summarized as follows:

1) Fills RCS.
2) Provides a source of high pressure water to perform cold hydrostatic testing of the RCS.
3) Maintains the water level in the pressurizer when the RCS is hot.
4) Reduces the concentration of corrosion and fission products in the reactor coolant.
5) Adjusts the boric acid concentration of the reactor coolant for chemical shim control.
6) Provides high pressure seal water for the reactor coolant pumps.

Cold Leg: In a PWR, the RCS from the exit of the steam generator to the reactor vessel; in a BWR, the Reactor Coolant System from the feedwater containment penetration to the reactor vessel.

Combustible Gas Control System: The system in BWRs that monitors, records, and indicates the presence of combustible gases throughout the nuclear plant.

Combustion: A rapid chemical reaction (in this text, between hydrogen and oxygen), accompanied by the evolution of light and a rapid production of heat.

Condensate Demineralizer Regeneration System: Used to regenerate condensate demineralizers (periodically). The system consists of two large holding tanks, one for sulfuric acid and one for sodium hydroxide, day tanks, metering pumps, and a water addition line. Used in BWR facilities.

Containment Depressurization System (CDS): The water spray cooling system used to relieve pressure and temperature buildup in containment, and to restore a negative pressure after a LOCA or MSLB.

Containment Purge and Exhaust System: The system in PWR plants that takes a suction on the containment atmosphere and releases it to the environment after treatment for radiation and suspended particles.

Core Plate: One of two plates (either upper or lower) that provide support and orientation for the fuel assemblies and also help to guide the flow entering and exiting the reactor core.

Corrosion: The wearing away of metals due to chemical or electrolytic reactions. There are several types of corrosion, including:

Crevice Corrosion - Corrosive degradation of metal parts at the crevices left at rolled joints or from other forming procedures; common in stainless steel heat exchangers in contact with dissolved corrosives.
Galvanic Corrosion - Electrochemical corrosion associated with the current in a galvanic cell, caused by dissimilar metals in an electrolyte because of the difference in potential (emf) of the two metals.

CRUD: Corrosion products suspended in the RCS. CRUD tends to settle out in areas of low water velocity causing difficulty in repair and maintenance. An acronym for "Chalk River Unidentified Deposits," from the Chalk River Reactor Facility in Canada, where it was first encountered.

Deflagration: A combustion wave that is traveling at a speed that is subsonic relative to the unburned gas.

Detonation: A combustion wave that is traveling at a speed that is supersonic relative to the unburned gas.

Drywell: The primary containment structure in a BWR system. The drywell houses the reactor and recirculating loop. It provides containment in the event of a LOCA or MSLB. Pressure built up during an accident is vented to the pressure suppression chamber. The containment is either of the "inverted light-bulb and torus" design, with the drywell being the "inverted light-bulb" and the pressure suppression chamber being the "torus"; or the "over and under" design, with the pressure suppression chamber located under the drywell.

Electrolyte: A substance that when in solution with water conducts electricity.

Emergency Core Cooling System (ECCS): Systems running in parallel, each with 100% capacity, that will provide emergency coolant to the reactor core in the event of a LOCA. In a BWR, there are two methods for ECC. The first has high and low pressure water spraying directly onto the core through separate spargers. The second method consists of steam blow-off to the pressure suppression pool followed by RHR system operation when the pressure drops. In a PWR the ECCS typically has three ranges of coolant injection into the RCS during an accident condition:

- High Head Injection - Via the charging pumps
- Medium Head Injection - Via the Safety Injection Pumps (see Safety Injection System)
- Low Head Injection - Via the Residual Heat Removal (RHR) pumps (see Residual Heat Removal System)

Enthalpy: The sum of a substance's internal energy and the product of its pressure and volume. Expressed in Btu/lb_m.

Excore Nuclear Instrumentation System (NIS): The system that monitors the nuclear fission process from outside the reactor at a PWR facility. The Excore NIS generally consists of source, intermediate, and power range channels.

Fission Chambers: Part of the Incore Nuclear Instrumentation System for all BWRs and some PWRs. The chambers can be movable or permanently installed. The fission chambers respond to incore radiation: the response will change drastically if the core becomes uncovered, as might occur during an inadequate cooling condition.

Fission Products: Radioactive products of the fission process in a nuclear reactor. These products generally do not enter the RCS, except in the case of a cladding rupture, thus their presence is indicative of a cladding rupture, which, in turn, could indicate that hydrogen generation has occurred. A list of fission products is given in Chapter 4. Fission products can be differentiated from activation products by standard counting laboratory techniques.

Flame Arrester: A device used to isolate a combustion in a BWR Off-Gas System. It operates by removing the heat from the flame and by providing water-gas contact. In addition to limiting flame front propagation, the flame arrester will provide additional humidity to the off-gas and will limit the effects of pressure fluctuations. This helps further limit the catalyst and combustion potential.

Flame Speed: Velocity of a flame in the laboratory (Eulerian) coordinate system. The laminar flame speed is the vector sum of the burning velocity and the gas velocity. Turbulence will effectively increase the flame speed by increasing the flame surface area and enhancing mixing.

Flammable: Capable of being ignited and propagating a flame.

Fog: A very fine spray.

Gas Chromatography: A method used to determine the constituents of a gas. This procedure is used in PWR plants to determine gaseous constituents in containment during normal operations, and as a backup hydrogen determination method after an accident.

Glow Plug: The preferred of two methods to provide intentional hydrogen ignition. An element of the plug is heated to and maintained at a temperature above that necessary for combustion.

Halogen: Any element of the halogen family: fluorine, chlorine, bromine, iodine, and astatine. Gases containing halogens are used in fire extinguishing and fire-suppression systems. Halogen inerting or suppressing has been proposed for controlling hydrogen in both PWR and BWR containments.

Hard Bubble Phenomenon: A condition that, generally, can be caused by overuse of the pressurizer spray in PWR systems. A "hard bubble" occurs when the vapor space in the pressurizer is filled with noncondensable vapor, mostly hydrogen, which makes the pressurizer behave as if it were filled with water. This places constraints on the use of the pressurizer to control pressure in the RCS.

High Radiation Sampling System (HRSS): Samples the gaseous constituents in containment during routine operations and in a post-accident mode.

Holdup Tank (HUT): Part of the CVCS in a PWR plant. It is used to hold letdown from the RCS before demineralizing and filtering when it is necessary to reprocess RCS water.

Hot Leg: In a PWR, the RCS from the reactor vessel, past the pressurizer to the entrance of the steam generator; in a BWR, the Reactor Coolant System from the reactor vessel to the penetration exiting containment.

Hydrogen Analyzing System: The system in a BWR that monitors and records the hydrogen concentration in the drywell and the secondary containment following a LOCA. Part of the Combustible Gas Control System.

Hydrogen Igniter System (HIS): The system used to intentionally burn hydrogen in the containment structure before the hydrogen concentration reaches dangerous levels. Generally, it utilizes glow plugs.

Ice Condenser: A containment system for PWRs in which, during an accident, steam is directed through the ice condensers to a containment compartment separate from all energy sources. The ice cools and condenses the steam, decreasing its volume, therefore allowing the containment structure to be smaller. The ice used contains boron, to poison the reaction, and sodium (in the form of caustic soda), to remove radioactive iodine.

Ignition: The process of starting a fuel mixture burning, or the means for such a process.

Inadequate Core Cooling (ICC): A condition which may occur during an RCS failure which results in a heat build-up in the core. Emergency cooling is provided by the ECCS. Although no official definition of inadequate core cooling has been widely publicized, the NRC provided a definition of ICC in correspondence to utilities owning reactors designed by Babcock and Wilcox. This definition is:

> The staff considers the core to be in a state of inadequate core cooling whenever the two phase froth level falls below the top of the core and the core heatup is well in excess of conditions that have been predicted for calculated small break scenarios for which some core uncovery with successful recovery from the accident have been predicted. Possible indicators of such a condition are core exit super heat temperature and/or the rate of coolant loss or level drop prior to core uncovery and the extent and duration of uncovery.*

Incore Nuclear Instrumentation System: The system which monitors the nuclear fission process from inside the reactor, consisting of fission chambers and thermocouples in PWRs.

Inerting: A mixture is inert if a flame cannot propagate through it. A mixture may be inert due to a lack of hydrogen or oxygen or due to an excess of a diluent gas such as steam.

Ion Exchange: A method of demineralizing PWR primary coolant and adsorption of positive or negative ions on a synthetic resin, where they are replaced with either H^+ or OH^- ions.

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* "NRC Staff Evaluation of Babcock and Wilcox Position Regarding Additional Instrumentation for Detection of Inadequate Core Cooling for B&W Reactors," Enclosed in NRC letters to owners of B&W reactors, September 24, 1980.

Isenthalpic Process: A process in which the enthalpy of a substance is constant throughout the process. (A throttling process, for example, is an isenthalpic process.)

Isotopes: Chemically identical variations of a single element with different atomic weights. That is, atoms of the same element having different numbers of neutrons within their respective nuclei.

Letdown: Reactor coolant removed from the RCS cold leg by means of the letdown line of the CVCS. It is reduced in pressure and temperature and sent to the VCT, the boron recovery subsystem of CVCS, or the Waste Disposal System.

Makeup Tank: Provides a surge volume of water for makeup (or charging) pumps in B&W PWR facilities. Equivalent to the volume control tank (VCT) in a Westinghouse or CE facility.

Nitrogen Inerting System: Used in Mark I and II BWRs in the primary containment (or drywell) to ensure that the primary containment in conjunction with the ECCS will withstand the effects of metal-water reactions subsequent to the postulated design basis LOCA.

Off-Gas System (OGS): The system for handling noncondensable radioactive wastes before releasing them to the atmosphere. The system consists mainly of condensers, to remove any condensable wastes, gas decay tanks, where the radioactive gases are held until radiation levels have dropped to acceptable levels, and ventilation fans, which mix the off-gas with the atmosphere in the exhaust stack. BWR OGSs run continuously, while PWR OGSs run on a batch basis.

Partial Preinerting: Maintaining of a depleted (but breathable) oxygen atmosphere in containment. Oxygen concentrations of 13-17 % would be required. This method would be used in conjunction with deliberate ignition or post-inerting.

Partial Pressure: The partial pressure of a gas in a mixture is equal to the pressure which the gas would exert if it occupied the same volume alone at the same temperature.

pH: A convenient method of expressing the acidity or alkalinity of solutions. The pH is the base 10 logarithm of the reciprocal of the concentration of hydrogen ions in an aqueous solution.

Photolysis: The decomposition or dissociation of a molecule as the result of the adsorption of light.

Polaron: A free electron in an aqueous solution.

Post-inerting: The injection of a gas into or the removal of oxygen from the post-accident containment atmosphere to protect against hydrogen combustion.

Power Operated Relief Valve (PORV): Valves placed on tanks, operated either electrically, hydraulically, or pneumatically, to relieve a pressure buildup inside a tank. The relief valves are set to open before the self-actuating safety valves in the tank.

Pre-inerting: The inerting of containment during normal operation to prevent hydrogen combustion following a LOCA. Used extensively in Mark I and II BWR containments. Partial pre-inerting has been proposed for BWR Mark III and PWR containments.

Pressurizer (PZR): The pressurizer vessel which serves to control the pressure in a PWR's primary loop. The PZR is partially filled with a surge of water, and partially with steam, and possibly other gases. If the pressure rises, water from the VCT is sprayed into the steam space, where some of the steam is condensed, thereby, decreasing the pressure.

Pressurizer Relief Tank (PRT): A tank that receives effluent from the RCS from a pressure increase. If the pressure in the primary loop of a PWR becomes so high that water sprayed into the vapor space of the PZR will not reduce it sufficiently, relief valves open and gas is vented to the PRT. The PRT is partially filled with quench water, which condenses the incoming steam. The non-condensable vapors are then vented to the OGS.

Pressurizer Vent System: A system that allows venting of the PZR steam space. If the pressure on the primary loop of a PWR becomes so high that water sprayed into the vapor space of the PZR will not reduce it sufficiently, relief valves open and gas is vented to the PRT. If the relief valves are stuck closed, there are self-actuating safety valves, set at a higher pressure, which will vent directly to containment.

Process Radiation Monitoring System: The system designed to monitor radiation levels of certain liquid and gaseous processes throughout the plant to assist in controlling the release of radioactive wastes and provide for personnel safety. The subsystems in the Process Radiation Monitoring System are:

1. Main Steam Line Radiation Monitoring System - Detects the release of fission products into the main steam line, primarily as the result of a major fuel failure.
2. Off-Gas Radiation Monitoring System - Monitors, radiation in the Off-Gas System (see Off-Gas System).
3. Flux Tilt Radiation Monitoring System - An expanded scale device used to help locate ruptured or failed fuel elements.
4. Off-Gas Vent Pipe Radiation Monitoring System - Used to permanently record the gross gamma radiation discharged from the OGS to the environment (see Off-Gas System).
5. Process Liquid Radiation Monitoring System - Monitors radiation in the Service Water System discharge, RHR, Closed Cooling System, and Radwaste System effluent.
6. Building Ventilation Radiation Monitoring System - Monitors radiation in the reactor building.

Radiolysis: The decomposition of water caused by exposure to radiation. Also called radiolytic decomposition.

Reactor Coolant Drain Tank: A tank in containment which collects drainage from RCP seal leak-off, reactor vessel flange seal leak-off, the reactor coolant drain header, and accumulator drains.

Reactor Protection System: The system that, when it receives a trip (or SCRAM) signal, causes the shutdown of the reactor and possible initiation of any emergency cooling systems that may be required.

Recombiner: A device in the OGS of a BWR that through a catalytic reaction, recombines hydrogen and oxygen to form water.

Residual Heat Removal System (RHR): In a PWR, a system that provides the capability for removing decay heat from the reactor core following a plant shutdown. This system also provides low-pressure injection water as part of the ECCS. In a BWR, the LPCI System incorporates a residual heat removal subsystem to provide LPCI in the event of a LOCA.

Resistance Temperature Detector (RTD): A temperature measuring device in which the sensing element is a resistor, usually platinum in nuclear plants, whose resistance is an accurately known function of temperature. Also known as resistance thermometer and resistance pyrometer.

Safety Injection System (SI): Provides high pressure coolant injection into the Reactor Coolant System (and, sometimes, the reactor vessel directly) to help maintain adequate reactor core cooling. It is part of the Emergency Core Cooling System.

Spray: A water system used to relieve pressure and temperature buildup by steam release in the containment structure. Mean drop radius is 200-300 microns.

Spark Plug: One of two methods to provide intentional hydrogen ignition. Not the preferred method because the sparks could cause radio frequency interference at a nuclear power station.

Steam Jet Air Ejectors (SJAEs): Remove noncondensable gases from the main condenser and vent them to the Off-Gas System.

Subcooling Margin Monitor (SMM): Used in PWRs to monitor the margin to saturation of the reactor vessel and RCS. The SMM receives temperature inputs from the core exit thermocouples, and hot and cold leg RTDs, and a pressure input from the pressurizer. With the pressure and highest temperature, the SMM determines and indicates the margin to saturation in the reactor vessel and RCS. The water in the RCS must be kept at or below saturation to prevent steam from forming in the RCS.

Suppression Pool: A pool of water in the wetwell of a BWR containment which is designed to condense steam. It vents to the wetwell during the "blowdown" following a LOCA. By condensing the steam, the pressure inside containment is greatly reduced in an accident.

Ternary Fission: One form of nuclear fission which results in three fission products, one of which is sometimes hydrogen in the form of tritium. Ternary fission occurs approximately once in every 12,000 fission events in the reactor.

Thermocouple: A temperature measuring device consisting mainly of two dissimilar metals joined together at their ends. When the two junctions are exposed to a temperature difference (one junction at a known reference temperature, the other at the temperature to be measured), a thermoelectric voltage proportional to the temperature difference develops. This voltage can be measured, and from it the unknown temperature at the junction can be determined.

Thermowell: A small protrusion into a pipe in which a resistance temperature detector (RTD) can be installed.

Traversing Incore Probe (TIP): A vertically traveling fission chamber in a BWR reactor core, used to measure the neutron flux along the length of the active core. A similar system is used in many pressurized water reactors. In the PWR the same type of system is referred to as either a Movable Incore Detection System (MIDS) or an Incore Flux Mapping System.

Volume Control Tank (VCT): A tank that provides a surge volume of water for makeup (or charging) pumps in Westinghouse and CE PWR plants. Equivalent to the makeup tank in B&W plants.

Vital Power Supply: Redundant power supplies to all systems required for safe plant operation and shutdown.

Waste Disposal System (WDS): Consists of OGS (see Off-Gas System) and liquid and solid waste systems. The OGS prepares gases to be exhausted to the atmosphere. Liquid wastes are held in holdup tanks until they can be classified as "clean" (pure water) or "dirty" (chemical wastes), after which they are drummed, demineralized, and recycled in the plant, or discharged from the plant. Solids wastes are compressed and drummed, and sent to government burial grounds.

Wetwell: The volume of a BWR containment that holds the suppression pool. The wetwell in a BWR Mark I contaimment is the "torus" in the "inverted lightbulb and torus"; the wetwell in a BWR Mark II contaimment is located under the drywell; and the wetwell in a Mark III containment is located outside the drywell.

Zircaloy: An alloy consisting of approximately 98% zirconium that is used in the fabrication of fuel assemblies (or fuel bundles) for light-water power reactor facilities.

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16. ABSTRACT *(200 words or less)*

A manual concerning the behavior of hydrogen in light water reactors has been prepared. Both normal operations and accident situations are addressed. Topics considered include hydrogen generation, transport and mixing, detection, and combustion, and mitigation. Basic physical and chemical phenomena are described, and plant-specific examples are provided where appropriate. A wide variety of readers, including operators, designers, and NRC staff, will find parts of this manual useful. Different sections are written at different levels, according to the most likely audience. The manual is not intended to provide specific plant procedures, but rather, to provide general guidance that may assist in the development of such procuedures.

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