UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D. C. 20555

February 22, 1980

POLICY SESSION ITEM

SECY-80-107

MEMORANDUM FOR: The Commissioners

THRU: W. Dircks, Acting Executive Director for Operations

FROM: H. Denton, Director, Office of Nuclear Reactor Regulation

SUBJECT: PROPOSED INTERIM HYDROGEN CONTROL REQUIREMENTS FOR SMALL CONTAINMENTS

Purpose: To establish the technical basis for interim hydrogen control requirements for small containments

Discussion: The accident at Three Mile Island, Unit 2 (TMI-2) involved a large amount of metal-water reaction in the core with resulting hydrogen generation well in excess of the amounts specified in 10 CFR 50.44 of the Commission's regulations. A rulemaking proceeding on the subject of degraded cores and hydrogen management is under consideration by the Commission. This proceeding was suggested in Item II.B.8 of the "NRC Action Plans Developed as a Result of the TMI-2 Accident," Draft 2, NUREG-0660, January 23, 1980.

Based on our review of the TMI-2 experience, we have found that certain interim hydrogen control requirements for small containments are needed. This interim action would require the inerting of all Mark I and Mark II containments for boiling water reactor plants.

The enclosed technical discussion provides the bases for: 1) the proposed interim action; and 2) continued operation and licensing of nuclear power plants pending the rulemaking proceeding.

The proposed interim rule requiring inerting of the Mark I and Mark II containments, and including other measures to protect against degraded core conditions that need to be implemented in the near term, is in preparation and will be sent to the Commission soon.

Contact: W. R. Butler, NRR (X27783)

<u>Coordination</u>: The Offices of Standards Development and Inspection and Enforcement concur in the proposed action. The Office of the Executive Legal Director has no legal objection.

<u>Sunshine Act</u>: Recommend consideration at an open meeting.

<u>Scheduling</u>: For early consideration.

Roger J Mattson

Harold R. Denton, Director
Office of Nuclear Reactor Regulation

2/22/80

Enclosures:
Technical Discussion

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TECHNICAL DISCUSSION

1.0 INTRODUCTION

The present design basis for post-accident hydrogen management, as embodied in 10 CFR §50.44 and Regulatory Guide 1.7, "Control of Combustible Gas Concentrations in Containment Following a Loss-of-Coolant Accident," is the provision of systems to deal with the hydrogen that would be released as a result of metal-water reaction amounting to between one and five percent of the fuel cladding in the reactor core.

The TMI-2 accident involved metal-water reaction in the range of 30 to 50 percent. Thus, the need for reexamining the NRC's requirements regarding post-accident hydrogen management is clearly indicated by the TMI-2 experience. Consequently, the staff has proposed that rulemaking proceedings be held to develop revised criteria for hydrogen management and other aspects of a degraded core which take into account the TMI-2 experience. Pending the completion of these proceedings, 10 CFR §50.44 should be revised to require inerting of all Mark I and Mark II containments.

The objective of this paper is to provide the technical bases for the staff's conclusion that: 1) all Mark I and Mark II containments should be required to be inerted; and 2) continued operation and licensing of other nuclear plants can be permitted pending completion of the rulemaking proceeding.

In Section 2.0 of this discussion, the concentration of hydrogen inside a containment, as a function of the amount of metal-water reaction, is provided for each class of containment designs. The regions where hydrogen combustion and detonation can occur are identified.

In Section 3.0, the containment pressure response as a function of the amount of metal-water reaction is addressed for each class of containment. Both the partial pressure from the resultant hydrogen concentrations and the metal-water reaction energy are considered in this discussion.

In Section 4.0, containment failure pressure is discussed in terms of the design pressure.

The various mitigation measures are addressed in Section 5.0. These measures include: 1) containment inerting to prevent hydrogen combustion and detonation; 2) use of halon systems; 3) use of a filtered-vent system; 4) hydrogen combustion systems; and 5) other methods.

In Section 6.0, the technical bases for continued operation and licensing of nuclear plants are addressed.

The views of the ACRS are given in Section 7.0 and the staff's conclusions in Section 8.0.

2.0 HYDROGEN CONCENTRATIONS

Following a loss-of-coolant accident, hydrogen gas can be generated by metal-water reactions, radiolysis of coolant, corrosion of zinc-based paints and radiation damage to organic paint. The TMI-2 experience indicates that our licensing requirements dealing with hydrogen gas from metal-water reactions need to be reexamined.

We have calculated the concentration of hydrogen inside a containment for each class of containments, as a function of the amount of metal-water reaction. The results are shown in Figure 1. To comply with the provisions of Regulatory Guide 1.7, the total hydrogen concentration in the containment must be less than four percent when metal-water reactions of less than five percent are postulated.

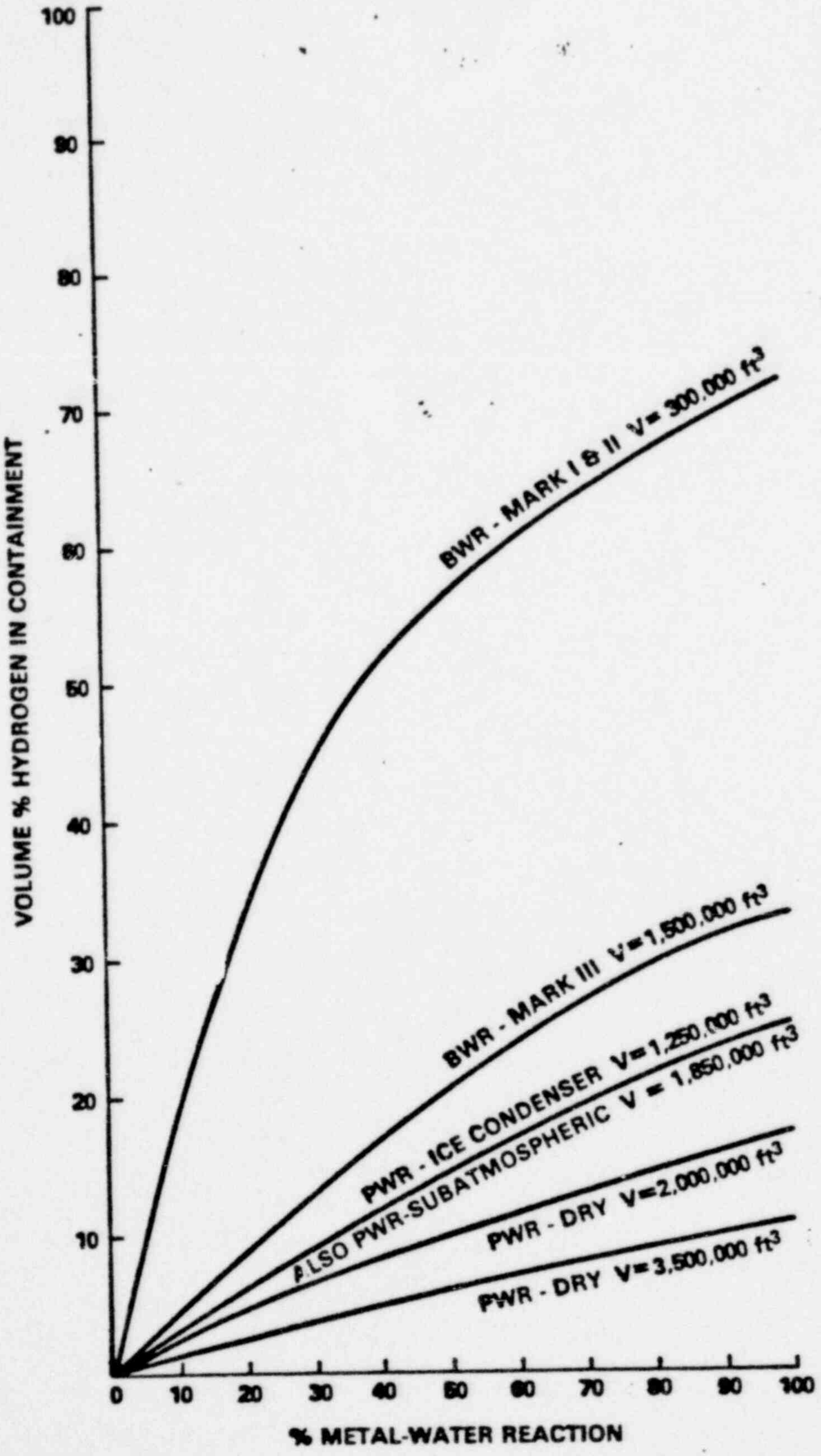
The combustion and detonation characteristics for hydrogen are depicted in Figure 2. Note that hydrogen in steam-free air can be expected to burn at concentrations of from four to eighteen percent and detonate above eighteen percent.

It is evident from Figures 1 and 2 that a TMI-2 type of event involving a 30 to 50 percent metal-water reaction will definitely lead to a combustible mixture and possibly even to a detonable mixture of hydrogen in the non-inerted Mark I and Mark II containments. This situation is primarily the result of the very small (300,000 cubic feet) net free volume inside these containments and the fact that boiling water reactors (BWRs) typically have twice the amount of zirconium cladding that pressurized water reactors (PWRs) have. A comparison of typical containment volumes and design pressures for each class of containments is shown in Figure 3.

For a given fraction of metal-water reaction The corresponding hydrogen concentrations in a Mark III containment, in an ice condenser containment, and in a subatmospheric containment are substantially less than those for the Mark I and Mark II containments. Nevertheless, they are well within the range of hydrogen combustion for metal-water reactions in the 30 - 50

FIGURE 1

VOLUME % HYDROGEN IN CONTAINMENT VS % METAL-WATER REACTION



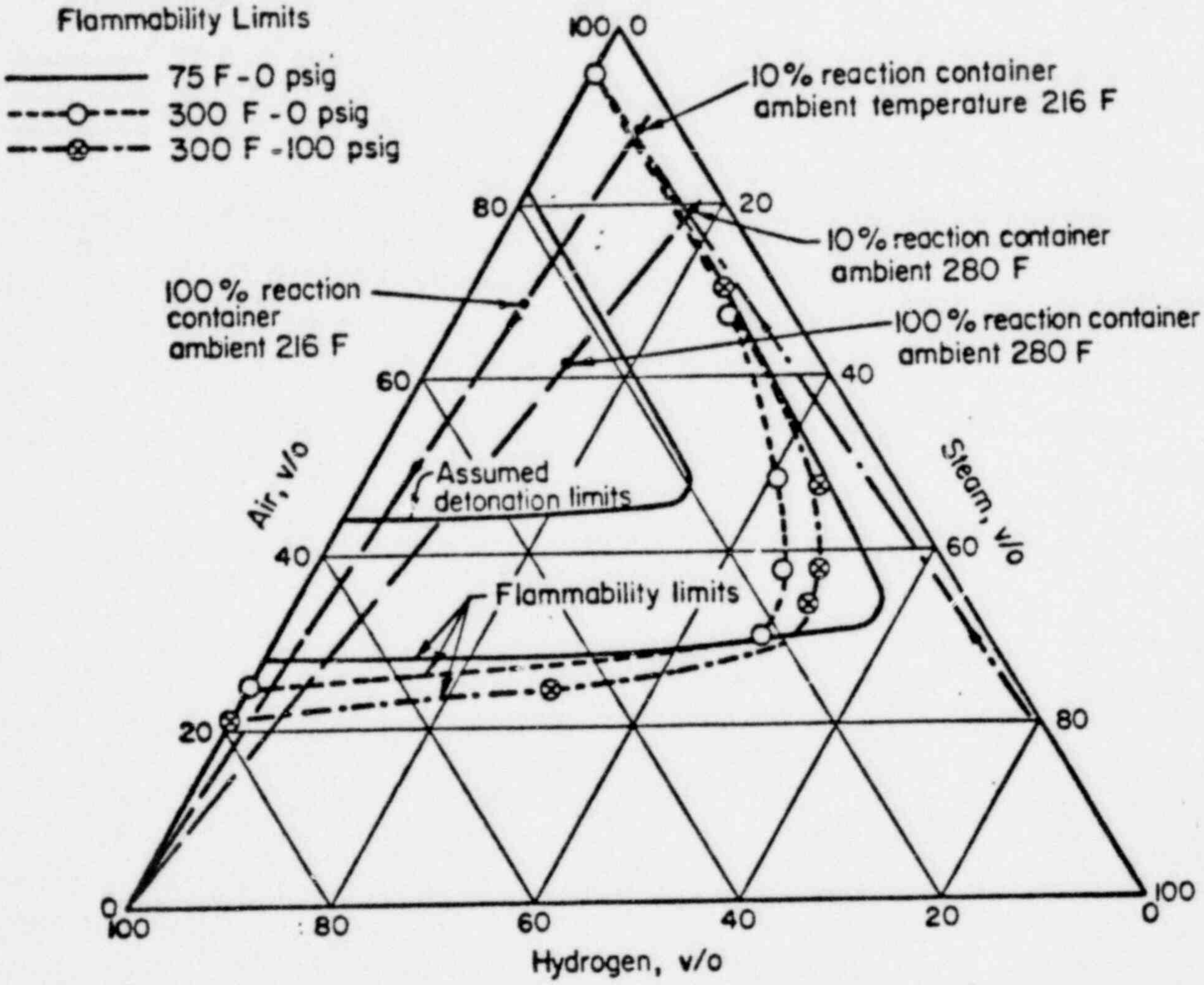
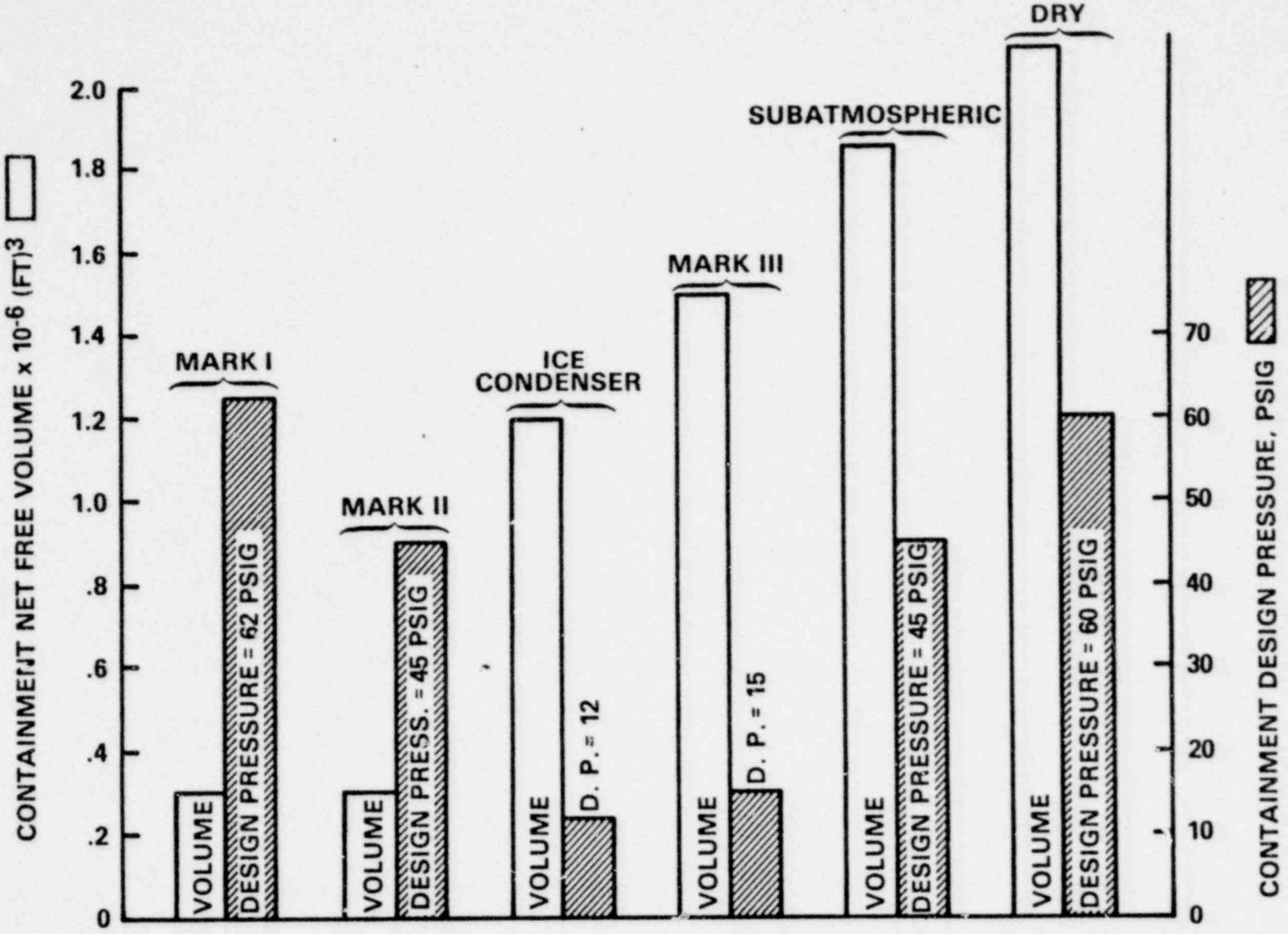


FIGURE 2. FLAMMABILITY LIMITS OF HYDROGEN-AIR-STEAM MIXTURES

FIGURE 3

COMPARISON OF CONTAINMENT
VOLUMES AND DESIGN PRESSURES
(TYPICAL 1200 MWe PLANTS)



percent range. It should be noted that: 1) the first domestic Mark III containment plant is not scheduled for fuel loading until about August 1981; 2) fuel loading for the first domestic Mark II plant is scheduled for July 1980 and; 3) there are two operating ice condenser plants and four operating plants with subatmospheric containments. As will be discussed later, the non-inerted ice condenser and Mark III containments can tolerate between 20 and 25 percent metal-water reaction without exceeding the estimated failure pressure of the containment. The design pressure of subatmospheric containments is more than three times that of ice condenser containments and therefore can tolerate a greater amount of metal-water reaction.

The dry containments have uniformly distributed hydrogen concentrations below 10 percent for the situation described above; i.e., 30 to 50 percent metal-water reaction. Moreover, their design pressures are usually in the range of 45 to 60 psig. Therefore, even if the hydrogen were to burn, the resulting pressure inside containment is not likely to fail the containment. This was the experience at TMI-2 on March 28, 1979.

3.0 CONTAINMENT PRESSURE RESPONSE

If substantial amounts of metal-water reaction were to occur following onset of a loss-of-coolant accident (LOCA) there would be substantial increases in the containment pressure response. The principal contributors to this pressure increase are: 1) the addition of substantial amounts of hydrogen (non-condensible) gas to the containment; 2) the increased energy release to the containment due to the exothermic reaction (oxidation) of Zircaloy with water; and 3) as appropriate, the energy release associated with the combustion of the hydrogen gas, except that this latter condition need not be considered for inerted containments.

We have completed a preliminary analysis of each class of containments to estimate the peak pressures that might be expected from an event involving up to 100 percent metal-water reaction followed by a postulated successful reflood of the core. The matters that need to be considered in this analysis are: 1) the rate of metal-water reaction; 2) the energy storage and removal rates; and 3) the resultant accident pressures vs. design pressures.

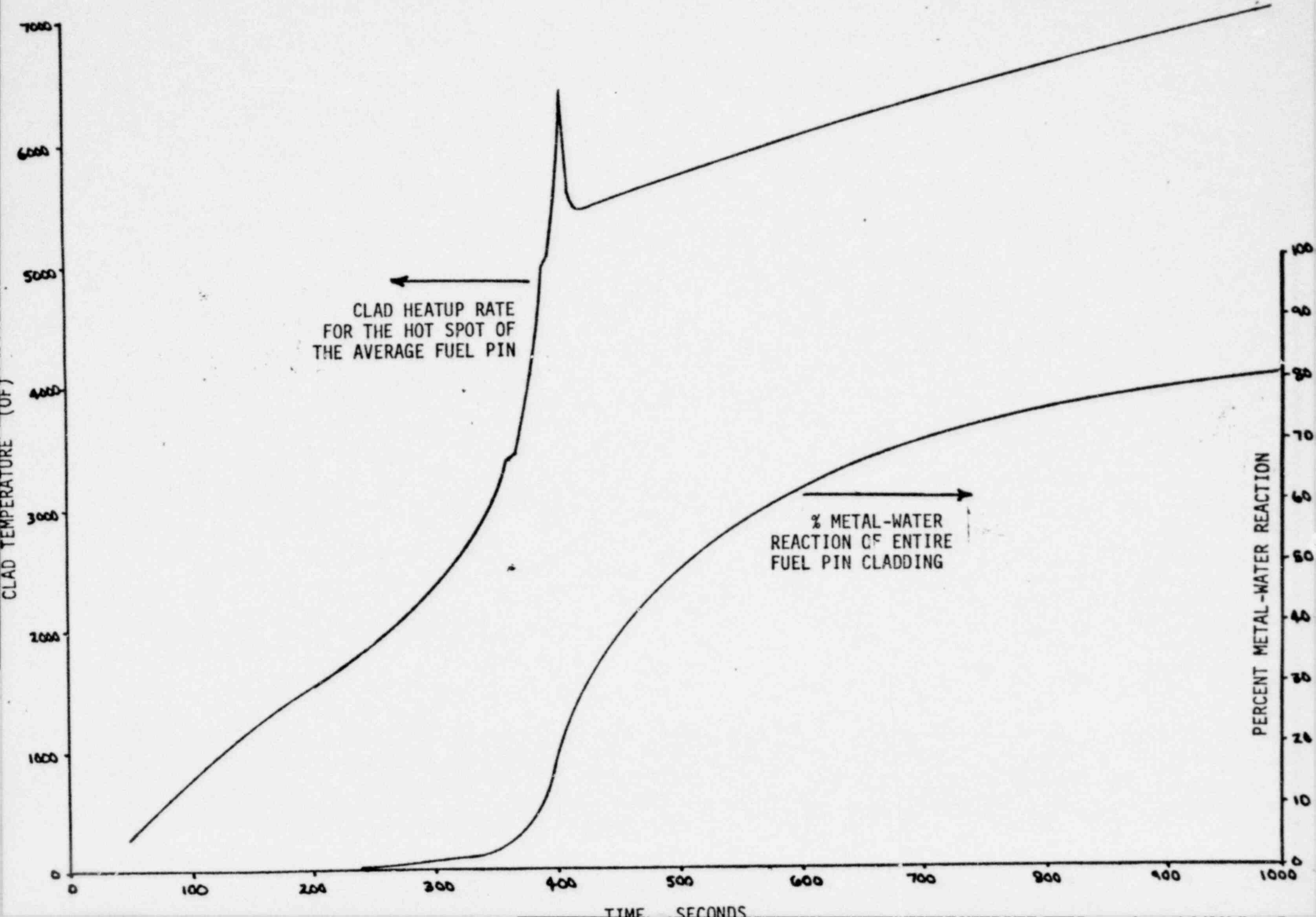
3.1 Rate of Metal-Water Reaction

The rate and extent of metal-water reaction and associated hydrogen production depends strongly upon the course of events assumed for the accident and upon the effectiveness of the emergency core cooling systems (ECCS). For this analysis we assumed a temporary but total failure of ECCS immediately after blowdown. This timing assumption is conservative because the fission product heat rate will be at its maximum level. Although we have assumed the total though temporary failure of the ECCS, we have allowed for an unlimited amount of steam in the core in order to obtain the maximum zirconium-steam reaction rate.

The maximum rate of metal-water reaction is needed so that assessments can be made of the effectiveness of pressure mitigating systems such as the containment heat removal system and the filtered-vent system.

Once the core has been uncovered, the fuel clad will heat up rapidly. Figure 4 shows a plot of fuel clad temperature versus time as calculated with the staff's TOODEE2 computer code. This plot is for the hot spot of the average fuel pin. It is assumed in this analysis that sufficient core cooling exists until 48 seconds after the accident.

FIGURE 4 FUEL CLAD TEMPERATURE RESPONSE



This corresponds to the termination of accumulator water delivery following blowdown of the primary system. At decay heat rates associated with full power operation, the water remaining in the core would be rapidly boiled off or entrained out of the core during the blowdown. At this time, it is assumed that all of the stored energy in the fuel is removed and adiabatic heatup begins.

Figure 4 show the cladding heatup rate for the hot spot of the average fuel pin. It also shows the percent of cladding in the entire fuel pin (not the hot spot) that has reacted with steam. Approximately 80 percent of the fuel pin's cladding has reacted within 15 minutes of the accident.

Not shown on Figure 4 is the percentage of clad at the hot spot that has reacted with steam. The cladding hot spot reaches its melting point of 3400 F at 370 seconds. At this time, approximately 15 percent of the cladding at the hot spot has reacted. It takes an additional ten seconds for the cladding to melt at this spot. When the melting is complete, about 20 percent of the hot spot cladding has reacted. After an additional 36 seconds, the hot spot cladding has reached 6500 F and has completely reacted.

It should be noted that this calculation assumes that the structural integrity of the core and fuel pin has been maintained. Slumping of the clad has not been assumed. It is, however, expected that slumping of the clad would not reduce the reaction rate, unless the clad slumped into a pool of water thus quenching the reaction. Another assumption was that sufficient steam would be available to promote the reaction. At higher temperatures, steam availability would tend to limit the rate of reaction. It is estimated that the times discussed above would be at least doubled if steam limitation were considered.

The exothermic oxidation heat of reaction is 2800 BTU/lbm of zirconium. A typical PWR has 50,000 lbm of zirconium, and the typical BWR has 90,000 lbm of zirconium. If these amounts of zirconium were to react with steam or water, the resulting heat addition would be of 140×10^6 BTU and 250×10^6 BTU, respectively. The capacities of the active heat removal systems are discussed in the next section.

Therefore, mitigating systems must be able to accommodate the noncondensible hydrogen gas along with the associated reaction energy assuming their generation to be complete in about ten minutes.

3.2 Energy Storage and Removal Rates

Each of the five containment types has its own characteristic active and passive heat removal systems. By passive heat sinks, we mean the massive amount of water in the suppression pool of the BWR containment and the 2.5 million pounds of ice in the ice condenser containment. The active heat removal systems include the fan coolers and containment spray systems in PWRs and the RHR systems in BWRs. The passive heat sinks accommodate the short term (one hour) energy release in the event of a LOCA. The active heat removal systems are sized to acccommodate the fission product decay heat rates in the longer term; i.e., about an hour following onset of the LOCA.

In the event of a LOCA, the short term energy release from the primary reactor system amounts to about 400 million BTU. The subsequent fission product heat generation rate amounts to a maximum of about 200 million BTU per hour and falls off at a slow rate with time.

The exothermic reaction energies associated with 100 percent metal-water reaction are 140 million BTU and 250 million BTU in a PWR and a BWR, respectively. If the associated amounts of hydrogen were to burn, the corresponding energy releases are 117 million BTU ad 205 million BTU, respectively.

In Section 3.1 of this discussion we find that oxidation of the Zircaloy cladding can be complete in periods of from five to ten minutes. Moreover, the combustion process can be complete in much shorter periods of time.

It is evident, therefore, that only the design margins in the passive heat sinks would be available to mitigate the pressure increases caused by the hydrogen mass, the exothermic reaction energy and the hydrogen combustion energy resulting from metal-water reactions; that is, the amount of energy that can be removed by the containment's active heat removal system in periods as short as ten minutes is on the order of $30\text{x}10^6$ BTU. This is not significant relative to the amounts of energy associated with either hydrogen generation or combustion.

However, the containment's active heat removal systems can contribute significantly for that set of degraded LOCA scenarios where excessive core heat-up occurs long after onset of the LOCA; i.e., about 10 hours later. In these situations the energy storage capacity in the passive heat sinks will have been restored. Our analyses in the next section take no credit for availability of the slow acting active heat removal systems, though credit is taken for the effect of the energy transfer capability for such systems as the containment spray system, which transfers containment atmosphere energy to the water in the containment sump.

There are also substantial margins between the containment design pressure and the containment failure pressure. This matter is addressed in Section 4.0 of this discussion. In our view, it is appropriate to take credit for these substantial margins during the period between now and the time of the rulemaking proceeding.

3.3 Degraded-Accident Pressures vs. Design Pressures

The current designs of containments for light water reactors are based on the assumption of successful operation of the engineered safety features in the event of a LOCA. In this section, we consider the conquences of a major degradation of the ECCS resulting in substantial metal-water reaction in the reactor core. The accident sequence is assumed to be turned around by a successful reflood of the core, and thus avoiding any need for considering core-melt scenarios.

In our analysis model, we assumed that the core was uncovered immediately after blowdown and remained uncovered until the entire core approached 3400 F, the melting point for Zircaloy. We have examined the containment pressure response to various metal-water reaction percentages up to 100 percent of the Zircaloy cladding for each class of containments. Both the design pressure and estimated failure pressure are used in our assessment of containment capability.

3.3.1 Mark I Containment

If 100 percent of the cladding in a BWR/Mark I containment system were to oxidize (metal-water reaction), the non-condensibles in the containment would be increased by a factor of 3.8. This becomes the dominating pressure determining feature and severely limits the pressure mitigating capability of the containment heat removal systems.

Solution of the energy balance equations indicates that the post-LOCA peak pressure will be 88 psig. This peak pressure includes the effect of: 1) the non-condensible hydrogen gas from a 100 percent metal-water reaction; 2) the energy produced in oxidizing this amount of cladding and 3) the mass and energy release associated with the postulated design basis LOCA. It does not include any energy contribution from the burning or detonation of hydrogen.

The above result means that the peak pressure in an inerted Mark I containment, which experiences a degraded LOCA involving as much as 100 percent metal-water reaction, would be no more than 88/62 or 1.42 times the design pressure. In Section 4.0, we discuss the basis for our view that failure pressures for these containments is expected to be more than twice the design pressure.

We have performed another calculation to determine the amount of metal-water reaction that can be tolerated in a non-inerted Mark I containment assuming that the resulting hydrogen is burned, without having the resulting peak pressure exceed twice the design pressure. The resulting amount of metal-water reaction is about nine percent of the Zircaloy cladding.

Examination of the hydrogen concentration curve for Mark I containments in Figure 1 shows that a detonable mixture can be expected for metal-water reaction amounts that exceed 10 percent. Since the consequences of detonations can be rather severe and are not readily predictable, we conclude that situations that can lead to the creation of detonable mixtures should be avoided.

We conclude that substantial improvement in hydrogen management capability in the Mark I containment system can and should be achieved by requiring the inerting of the containments.

3.3.2 Mark II Containment

The design parameters of the Mark II containment with respect to hydrogen management capability are essentially the same as those for the Mark I containment. The only substantive difference is that the design pressure is typically 45 psig compared with the 62 psig for Mark I containments.

Considering the peak pressure identified in the previous section, the ratio of peak pressure to design pressure in the Mark II containment will be 88/45 or 1.96. We find that our conclusions for the Mark I containment also apply to the Mark II containment.

3.3.3 Ice Condenser Containment

In an ice condenser containment, the maximum amount of metal-water reaction that can occur without exceeding the containment failure pressure is 25 percent. This assumes a failure pressure of 36 psig, (See related discussion in Section 4.0), combustion of the hydrogen gas and availability of only one of the two trains of containment spray systems for a spray flow rate of 3400 gallons per minute. A 15 percent metal-water reaction would lead to a peak containment pressure equal to the design pressure of 12 psig.

If the ice condenser containment were inerted so that hydrogen combustion need not be considered, essentially all of the Zircaloy cladding could react without exceeding the estimated containment failure pressure of 36 psig. Inerting the ice condenser would substantially increase the amount of metal-water reaction that can be tolerated without exceeding the containment's estimated failure pressure. However, an inerted ice condenser containment will lead to restrictions on access to the containment for performing important maintenance functions. Therefore in view of the feasibility question discussed in Section 5.1 of this discussion and the fact that about 25 percent metal-water reaction can be tolerated even with burning, we conclude that, pending the rulemaking proceeding, additional mitigation systems are not required for ice condenser containments.

3.3.4 Mark III Containment

The design pressure of the Mark III containment is 15 psig. The noninerted Mark III containment can accommodate the burning of the hydrogen produced by between 16 and 19 percent metal-water reaction without exceeding its design pressure. This amount will increase to between 22 and 25 percent if we considered the containment failure pressure to be twice its design value or 30 psig. Therefore, since the first domestic

Mark III containment plant will not be operational until about August 1981 and since as much as 22 to 25 percent metal-water reaction can be tolerated without containment failure, we conclude that, pending the rule-making proceeding, additional mitigation systems are not required for the Mark III containments.

3.3.5 Subatmospheric Containment

The design pressure of the subatmospheric containment is 45 psig. For the non-inerted case, between 51 and 64 percent metal-water reaction can occur without exceeding the design pressure. Moreover, at twice the design pressure, essentially all of the Zircaloy cladding can be allowed to react.

The addition of non-condensibles to the containment will make it more difficult for the containment heat removal systems to return the containment to subatmospheric conditions. Assuming 100 percent metal-water reaction, about 400,000 standard cubic feet (SCF) of hydrogen gas will be added to the containment, which before the accident contained about 1,250,000 SCF of air. Since the containment volume is 1,850,000 cubic feet, we can expect the containment pressure to eventually reachieve subatmospheric conditions. It should be noted that much of the hydrogen gas will combine with oxygen to form water and thus mitigate this concern. Analysis of this effect and of the associated dose consequences will be performed in conjunction with Item II.B.8 of the Task Action Plan.

3.3.6 Dry Containment

The dry containment is the least impacted by these considerations. It has the largest volume and matches the highest design pressure of all the containment designs.

For the non-inerted case, about 70 percent metal-water reaction can occur without exceeding the design pressure of 60 psig. Complete reaction of all the Zircaloy cladding will result in a containment pressure that is well within our estimated failure pressure of twice the design pressure.

3.4 Mixing of the Containment Atmosphere

The analyses performed to estimate the effects of hydrogen burning in containment buildings were performed with the assumption that the containment atmosphere consisted of a homogeneous mixture of air, hydrogen and steam. Burning or detonation of local pockets of higher than average hydrogen concentration was not considered. We assumed that adequate mixing would be assured in the large, open dry containment building (including the subatmospheric containment) by the operation of redundant Emergency Safety Features (ESF)(i.e., containment spray systems and containment fan cooler systems), which would promote vigorous mixing of the atmosphere in the containment building. In addition, depending upon the severity of the accident (i.e., its effect upon containment atmosphere temperature and pressure), non-ESF ventilation systems may also be used to aid in the mixing of the containment atmosphere, as was the case at TMI-2.

In the ice condenser containment design, there is a high degree of compartmentalization within the containment. Because of the compartmentalized containment, the ice condenser containment design includes redundant ESF systems to promote post-accident mixing of the containment atmosphere. These systems (the Return Air Fan system and the Hydrogen Skimmer system) have been designed to expressly provide a capability to assure post-accident mixing of the containment atmosphere and to prevent any "pocketing" of hydrogen in containment subcompartments. With both trains of the redundant system operating, the entire containment atmosphere will be circulated through the fans approximately every 15 minutes. With only one train operating, this "cycle time" is increased to about 30 minutes.

3.5 Temperature Effects of Hydrogen Burning

In performing the calculations to estimate the effects of hydrogen burning in containment buildings, we assumed that all the heat of combustion went directly to heating the containment atmosphere. In reality, much of the energy would be lost directly to the massive structures (walls, supports, etc.) by radiant heat transfer. Our very conservative analyses yielded containment atmosphere temperatures up to about 2500 F for the burning of large amounts of hydrogen. This energy would be removed from the atmosphere by containment spray and fan cooler systems. Rough calculations indicate that the thermal transient caused by hydrogen burning would be terminated by sprays and fan coolers in a few minutes (on the order of 5 minutes). Thus, the characteristics of the expected transient would be a rise to a peak temperature in a few seconds and a subsequent return to normal temperature in a few minutes.

Components located in the containment whose continuing function is essential to safety would be subjected to this thermal transient. Examples are, instrument sensors and transmitters, instrumentation and power cabling, valves and their operators, electric motors for fans, pumps and valves.

During the thermal transient expected for hydrogen burning, heat transfer to these components would be governed by natural convection and would, therefore, be limited to the order of a few BTU/ft^2-hr-F with an average driving temperature on the order of a few hundred degrees Farenheit. This would result in an average heat flux to the components that is on the order of a 1000 BTU/ft^2-hr for the few minutes of duration for the transient.

In performing thermal analyses for the same type of components subjected to the environment of Main Steam Line Break (MSLB) accidents, we find that these components are subjected to heat transfer that is dominated by condensation. For these MSLB accident analyses, the average heat flux of the component is also on the order of 1000 BTU/ft^2-hr for a few minutes' duration. In these analyses, the thermal capacity of the components is judged to be high enough that for these short exposure times the equipment temperatures are not expected to exceed the values used in equipment qualification tests for the LOCA conditions. Therefore, it appears reasonable to assume that the same satisfactory results would be expected if the components were analyzed for the thermal transient conditions expected for the assumed hydrogen burning in the containment. This was demonstrated by the continued successful operation of essentially all systems and components of TMI-2 following the containment hydrogen fire.

4.0 Containment Structural Response

The mass and energy releases associated with large amounts of metal-water reaction are not considered in arriving at design pressures for containment buildings. If considered, the resultant accident pressure will exceed the design pressure. The object of this section is to develop estimates of the safety margins between design pressure and failure pressure so that judgments can be made as to the interim licensing requirements pending the rulemaking proceeding.

The containment buildings are designed by use of load combination equations which involve conservative assumptions to ensure that the as-built structure maintains an adequate margin of safety. Upon completion of construction and before plant operation, utilities are required to pressurize the containment structure to 115% of design pressure to demonstrate the structural integrity of the containment. The leak testing requirements of Appendix J, 10 CFR Part 50 provide that the containment shall be periodically pressurized to demonstrate leaktight integrity for periods up to 24 hours. Therefore, it can be expected that the primary containment building would withstand short term pressure transients that significantly exceed the containment design pressure.

The exact margin of safety that exists for a given containment is difficult to quantify. An unspecified margin of safety exists between the containment design pressure and the minimum specified yield stress. Significant amounts of leakage are not expected until the stress in the steel containment and in the liner plate of the reinforced concrete containment reaches yield stress. This leakage will tend to relieve the pressure until equilibrium is reached, i.e., leakage will eventually equal blowdown in the containment.

Another unspecified margin of safety exists between the minimum specified yield strength and the ultimate strength of the steel used in containments. If the ultimate strength of containment is reached, catastrophic failure may be postulated. However, it is highly probable that leakage failure will begin to occur before the ultimate strength is reached. Therefore, any failure can be postulated to occur in a gradual and ductile manner.

Considering the uncertainties discussed above, an examination of the best estimate yield stress was performed for two free standing steel containments, the Sequoyah plant in Hamilton County, Tennessee and the McGuire plant in Mecklenburg County, North Carolina. The major assumptions used in the computation for both types of containment was the existence of a uniform static internal pressure loading. Although other containments may have different factors, the difference is not expected to be substantial. Therefore, some extrapolation of the results to other plants may be appropriate.

The result of the best estimate yield stress for Sequoyah is 36 psig with an uncertainty range between 32 psig and 48 psig. Since the design pressure of Sequoyah is 12 psig, this approximates a margin of safety of about three times design pressure for free standing steel containments.

The result of the best estimate yield stress for McGuire is 47 psig with an uncertainty range of between 42 psig and 63 psig. Since the design pressure of McGuire is 15 psig, a safety margin of about three times design pressure can also be assumed.

The ice condenser containments for the currently operating D. C. Cook, Units 1 and 2 are different from those for Sequoyah and McGuire in that they are steel-lined reinforced concrete structures. Although we have not performed a structural analysis of these containments, it is our judgment that their failure pressures are at least as high as those for the Sequoyah units.

We conclude, therefore, that significant amounts of leakage would not occur for internal containment pressures of less than twice containment design and that any failure of containment will occur in a gradual and ductile manner.

Conventional dry PWR containments and the BWR Mark I and II containments typically have design pressures ranging from 40 to 60 psig. Therefore, these containments should be expected to withstand internal pressures ranging from 80 to 120 psig, respectively.

The typical design pressure for the BWR Mark III containment is 15 psig, thus allowing an expected margin of safety of up to 30 psig.

Ice condenser containments have the lowest design pressures of 12 to 15 psig. Our best estimate analyses indicate that these containments will not fail at peak containment pressures below 36 and 47 psig, respectively.

5.0 MITIGATION MEASURES

There are a number of mitigation measures which can permit the accommodation of substantial amounts of hydrogen without a consequential failure of containment integrity. These measures include: 1) inerting of the containment; 2) use of halon suppression systems; 3) use of filtered-vent systems; 4) use of hydrogen combustion systems, and 5) other methods such as the use of chemical catalysts and gas turbines. Each of these measures is discussed below in terms of its potential for effectively managing the consequences of substantial amounts of metal-water reaction.

5.1 Inerting

Boiling water reactors with Mark I containments have been operating quite successfully with inerted containments. Equipment maintenance and operational flexibility are hampered to some extent because accessibility into the containment is reduced when the containments are inerted. For this reason, the Vermont Yankee and Hatch 2 licensees proposed, and following a staff finding of compliance with 10 CFR § 50.44 were subsequently authorized, to operate their plants without inerting the containments. An ALAB decision was involved with respect to this issue in the Vermont Yankee case, <u>Vermont Yankee Nuclear Power Corp</u>., Vermont Yankee Nuclear Power Station, 8 AEC 425 (1974).

If all Mark I containments were inerted, then the effects of combustion and detonation need not be considered. Our analyses have shown that if 100 percent of the Zircaloy cladding were oxidized following a LOCA, the resultant hydrogen concentration and peak containment pressure would be about 70 percent and 85 psig, respectively. Although the design pressure for Mark I containments is 62 psig, failure pressure is estimated to be about 124 psig.

We conclude, therefore, that inerting of Mark I containments leads to substantial improvement in their ability to accommodate large amounts of metal-water reaction. Accordingly, the inerting of all Mark I containments should be made a licensing requirement.

The hydrogen concentrations and associated containment pressure responses in a Mark II containment are essentially the same as those for the Mark I containments. However, the design pressure for the Mark II containments is lower than that for the Mark I containment and is typically 45 psig. Nevertheless, a failure pressure above two or three times the design pressure would be between 90 and 135 psig, which is well above the 85 psig pressure associated with 100 percent metal-water reaction without combustion. It is, therefore, our view that all Mark II containments, none of which are yet licensed to operate should be inerted like the Mark I containments.

The uniformly distributed hydrogen concentrations in an ice condenser containment for 50% metal-water reaction will be about 15%. The associated pressure is well above the design pressure and is estimated to be about 90 psig. This high pressure is caused by the assumed burning of the hydrogen gas when it exceeds the flammability limits. Inerting of an ice condenser containment would provide a capability to accommodate about 90 percent metal-water reaction. Preliminary calculations predicted the associated maximum containment pressure to be equal to the maximum structural capability of 36 psig. However, the frequency of containment entry for safety-related maintenance functions (especially for the ice chests) is such that inerting of the ice condenser containments may be impractical. Certain maintenance functions in the ice chests may not be safe for the maintenance personnel unless the area is de-inerted. The air-changes associated with each inert/de-inert cycle would probably involve excessive ice-loss making inerting of the ice condenser impractical. If access to the containment were restricted because of inerting, there would be come penalties in equipment reliability. The above matters warrant and will be given further consideration in conjunction with our Action Plan Item II.B.8.

It is our view, therefore, that although some gain in safety might be achieved by inerting, operational and equipment reliability considerations argue against inerting. Further studies are needed on the effectiveness question concerning high containment pressures and on the practicality issue. Other mitigating measures such as the use of halon systems and filtered-vent systems may be found to be more appropriate. These measures are discussed later.

The Mark III containments have higher concentrations of hydrogen than ice condenser containments for the same fraction of metal-water reaction. This is caused by the larger inventory (about twice) of Zircaloy in the BWR core relative to the PWR core. Inerting of the Mark III containment does not involve the severe practicality question relative to maintenance functions in the ice chests of ice condenser containments. Nevertheless, much more equipment is located inside the Mark III containment than in the Mark I or Mark II containments. Since the first domestic Mark III plant is not scheduled for fuel loading until about August 1981, any decision on inerting of the Mark III containment can await the results of more detailed impact/benefit evaluations.

The hydrogen concentrations in subatmospheric containments are comparable to those in ice condenser containments. This results from the fact that, although the volume is larger, the mass of air inside containment is about the same as that in an ice condenser containment, since the containment is operated at a lower pressure. Further analyses are needed to determine the amount of metal-water reaction that can take place without exceeding the estimated failure pressures for the subatmospheric containments. These analyses will be performed in conjunction with Action

Plan Item II.B.8. It is our view that since the design pressure for subatmospheric containments is more than three times that for ice condenser containments, no interim action is needed relative to improved capability for hydrogen management.

The hydrogen concentration and associated pressure consequences in large dry containments are more favorable than those for the Mark III containments and ice condenser containments. While the hydrogen concentrations can exceed the lower flammability limit of four percent for metal-water reactions above 40%, these containments can accommodate a fair amount of hydrogen combustion as demonstrated by the TMI-2 experience. It is our view, therefore, that mitigative measures such as inerting for these containments can and should be deferred pending rulemaking proceedings on this subject.

5.2 Use of Halon Suppressants

If Halon gas were mixed with the containment atmosphere, neither combustion nor detonation of the hydrogen gas can occur. Halon is a chemical compound in which a halogen (fluorine, chlorine, bromine and iodine) atom is added to a hydrocarbon molecule. Chemical formulas for some Halon compounds include $CBrF_3$ and $CBrClF_2$.

The required concentration of Halon in the containment atmosphere is about 20 percent. Although the compound is chemically inert, it may be hazardous to humans for extended exposure at concentrations of about 20 percent. Moreover, if the compounds are exposed to temperatures above 900 F they decompose to form halogen acids and some amounts of carbonyl halides, which are extremely toxic.

The costs associated with use of these systems is primarily in the cost of the compounds themselves. We estimate the expense per plant to be in the range of two to five million dollars.

Halon suppression systems would probably be useful as part of a hydrogen management system in an ice condenser plant. When a substantial core damage but no core melt situation (a degraded LOCA) is known to exist, the Halon system can be actuated before any major release of hydrogen into the containment. The large volume, return-air fans will assure effective mixing of both the Halon and hydrogen gases with the atmosphere.

Although the Halon system can prevent combustion and detonation of hydrogen gas inside an ice condenser containment, it might not prevent overpressurization of the containment due to the addition of substantial amounts of non-condensible hydrogen gas and Halon. The filtered-vent system discussed in the next section may be appropriate for controlling the associated pressure build-up.

The Halon suppression system appears to be an excellent candidate for preventing the combustion and detonation of hydrogen gas in the event of a degraded LOCA. However, its success in dealing with large amounts of metal-water reaction requires the use of a companion filtered-vent system. Both systems have a fair number of potential problems that require thorough analyses.

5.3 Filtered-Vent Systems

Filtered-vent systems have been studied in the recent past in terms of their ability to prevent failure of the containment due to overpressurization. For severely degraded accident situations, the filtered-vent system would be effective in minimizing off-site damage by retaining most of the fission products inside the intact containment and releasing to the environment only that amount of fission products that cannot be held up in its filter system.

Practically-sized filtered-vent systems cannot accommodate the rapid pressurization associated with any major combustion or detonation of hydrogen gas inside a containment. However, if a Halon system were used to prevent the combustion or detonation of the hydrogen gas, the filtered-vent system need only accommodate the pressurization rate associated with the rate of generation of hydrogen gas. Our analysis of the oxidation rate across the thickness of the Zircaloy clad indicates that about ten minutes are required for complete oxidation. These rates of hydrogen production can be readily accommodated by a vent pipe that is no larger than 10 to 15 inches in diameter.

5.4 Hydrogen Combustion Systems

Hydrogen combustion systems involve the intentional and slow burning of the hydrogen as it is released into the containment. Such a system would: 1) burn small amounts of the hydrogen gas at a time as it is released into the containment so that detonable mixtures do not develop and so that the associated reaction energy can be effectively transferred to the water in the containment sump and then to the ultimate heat sink; and 2) combine non-condensible hydrogen and oxygen gases so as to reduce the pressurization of the containment.

Another potential application of the hydrogen combustion system is to prevent the development of detonable mixtures in steam-air-hydrogen atmospheres. Steam from the blowdown process during a LOCA will serve as a diluent to reduce the concentration of any hydrogen gas and as a suppressant making the hydrogen gas less flammable.

As the containment spray system condenses the steam, the hydrogen concentration and flammability will increase. The combustion system could prevent the developmment of detonable mixtures by the timely burning of the hydrogen gas.

5.5 Other Methods

Other methods such as the use of chemical catalysts and gas turbines have been suggested as means for accommodating large releases of hydrogen in containments. Moreover, combining the controlled combustion system with the filtered-vent system may also prove effective for some containment designs.

A substantial amount of additional staff work and licensee and applicant work is needed to assess the merits of these other systems. Their assessment will be made a part of our longer term action (Action Plan Item II.B.8) on systems for improving the capability for hydrogen management.

6.0 BASES FOR CONTINUED OPERATION AND LICENSING

The only interim action prepared by the staff with respect to the capability for hydrogen management is the inerting of the Mark I and Mark II containments for BWRs. It is our view that if this action is taken continued operation and licensing is justified pending completion of the rulemaking proceeding on degraded cores and hydrogen management. The bases for this view for each class of containments are summarized below.

6.1 Mark I and Mark II Containments

Metal-water reactions in the range of 30 to 50% can produce hydrogen concentrations in Mark I and Mark II containments that are well within the range for rapid combustion and detonation. Inerting these containments as proposed will eliminate the concern relative to combustion and detonation. The peak containment pressures, considering the effect of the non-condensible hydrogen gas and the associated exothermic reaction energy, will approach twice the design pressure for the worst case assumption of an uncooled core immediately following a reactor shutdown. In our judgment, Mark I and Mark II containments can withstand without failure, a slowly applied pressure that is as much as two or three times the design pressure. Accordingly, pending the rulemaking proceeding on hydrogen management, we find that continued operation and licensing of Mark I and Mark II containment plants is justified if they are inerted.

6.2 Ice Condenser Containments

Metal-water reactions in the range of 30 to 50% in ice condenser containment plants can produce hydrogen concentrations in the range of 9 to 15%. At these concentrations, detonation is not expected.

Moreover, combustion will be inhibited for steam concentrations above 70%, which is also expected in the event of a LOCA. However, operation of the containment spray system and/or the effects of passive heat sinks will condense the steam and produce mixtures that are combustible.

Assuming that there is combustion of hydrogen gas and considering the effect of the non-condensible hydrogen gas and the energy associated with its formation, the estimated amount of metal-water reaction needed to achieve the containment design pressure and failure pressure are 15% and 25%, respectively. The design pressures for ice condenser plants are between 12 and 15 psig and the corresponding failure pressures are estimated to be between 36 and 47 psig.

The "Short Term Lessons Learned" from the TMI-2 accident have been implemented at all operating plants and will be implemented at all the other plants before issuance of the operating licenses. This action will reduce the likelihood of occurrence of accidents that could lead to substantial amounts of metal-water reaction.

We have considered inerting as a mitigative measure for ice condensers. We find that although it might improve the hydrogen management capability, certain important maintenance functions will be restricted.

Therefore, since the likelihood of degraded LOCAs have been made more remote by implementation of the "Short Term Lessons Learned" and since substantial amounts of metal-water reaction can be tolerated without jeopardizing containment integrity, we conclude on balance that, pending the rulemaking proceeding, continued operation and licensing of nuclear plants with ice condenser containments is justified.

6.3 Mark III Containment

If 30 to 50 percent of the Zircaloy cladding were to oxidize in a Mark III containment system, the resultant uniform concentration of hydrogen gas would be between about 13 and 21 percent. To avoid detonation and combustion for the non-inerted containment, the steam concentrations would have to be greater than about 55% and 70%, respectively.

If it is assumed that the hydrogen gas does not burn, the resulting containment pressure will be between 15 and 20 psig, respectively, for the assumed 30 and 50 percent metal-water fractions. In arriving at these containment pressures, the non-condensible hydrogen gas and its associated energy of formation are assumed to enter the containment along with the other LOCA mass and energy sources.

If it is assumed that the hydrogen gas does burn, the Mark II containment can accommodate the burning of the hydrogen produced by about 17 percent metal-water reaction without exceeding its design pressure and about 23 percent metal-water reaction without exceding twice the design pressure. The design pressure for the Mark III containments is 15 psig. While analyses have not been performed to determine their failure pressures, we believe that it would be at least twice the design pressure (30 psig). This view is based on the analysis that was performed for the ice condenser plant discussed in Section 6.2.

The currently scheduled fuel load date for the first domestic plant using a Mark III containment, the Grand Gulf Nuclear Plant, Unit 1, is August 1981. It is our view that, pending the rulemaking proceeding, additional mitigation systems are not needed for the Mark III containment.

6.4 Subatmospheric Containments

If as much as 50 to 65 percent of the Zircaloy cladding were to react with steam or water in a subatmospheric containment plant, the resulting containment pressure would be less than its design pressure. Essentially all of the cladding would have to be oxidized for the resulting containment pressure to exceed its estimated failure pressure.

As indicated in the discussion for ice condenser plants in Section 6.3, the "Short Term Lessons Learned" from the TMI-2 accident have been implemented at all operating plants and will be implemented at all the other plants before issuance of the operating licenses. This action will reduce the likelihood of occurrence of accidents that could lead to substantial amounts of metal-water reaction.

Therefore, since the likelihood of degraded LOCAs have been made more remote by implementation of the "Short Term Lessons Learned" and since substantial amounts of metal-water reaction can be tolerated without jeopardizing containment integrity, we conclude that, pending the rulemaking proceeding, continued operation and licensing of nuclear plants with subatmospheric containments is justified.

6.5 Dry Containments

The dry containments have about two million or more cubic feet of net free volume. Assuming 30 to 50 percent metal-water reaction in the core, the resulting uniformly mixed concentration of hydrogen in the containment will range from six to ten percent. This is well below the concentrations for detonation and even below the limits for combustion if there were more than 50 percent steam in the containment atmosphere.

The design pressures for these large containments range from 50 to 60 psig. Although analyses have not been performed to determine their failure pressures, we believe that such analyses would show that the failure pressures would be at least twice the design pressures. This view is based on the analysis performed for the ice condenser plants as discussed in Section 4.0.

If the substantial amount of metal-water reaction were to occur following onset of the large LOCA and while the containment is still near its peak pressure, the pressure increase caused by the non-condensible hydrogen gas and its associated exothermic formation energy will be substantially less than the failure pressure. If the metal-water reaction were to occur well after onset of the large LOCA, when the containment heat removal systems have been able to condense most of the steam and also reduce containment pressure, then a substantial margin exists for accommodating the hydrogen generated by the metal-water reaction.

As indicated in the discussion for ice condenser plants in Section 6.3, the "Short-term Lessons Learned" from the TMI-2 accident have been implemented at all operating plants and will be implemented at all the other plants before issuance of the operating licenses. This action will reduce the likelihood of occurrence of accidents that could lead to substantial amounts of metal-water reaction.

Accordingly, pending the rulemaking proceeding on hydrogen generation, we find that continued operation and licensing of nuclear plants with dry containments is acceptable.

7.0 ACRS Views

The ACRS views on this subject are described in Item 10, Design Features for Core-Damage and Core-Melt Accidents, of its "Report on TMI-2 Lessons Learned Task Force Final Report," dated December 13, 1979. The ACRS stated that:

"The ACRS supports this recommendation. However, the Committee believes that the recommendation should be augmented to require concurrent design studies by each licensee of possible hydrogen control and filtered venting systems which have the potential for mitigation of accidents involving large scale core damage or core melting, including an estimate of the cost, the possible schedule, and the potential for reduction in risk.

"The ACRS agrees with the recommendation made by the Lessons Learned Task Force in NUREG-0578 that the Mark I and Mark II BWR containments should be inerted while further studies are made of other possible containment modifications in accordance with the general recommendations in this category. The ACRS also recommends that special attention be given to making a timely decision on possible interim measures for ice-condenser containments."

We believe the course of action we plan is responsive to the recommendations of the ACRS.

8.0 CONCLUSION

The "Short-Term Lessons Learned" from the TMI-2 accident have been implemented at all operating reactors and will be implemented at all plants under construction before operating licenses for them are issued. This action makes the likelihood of accidents involving substantial amounts of metal-water reaction smaller than was the case before the TMI-2 accident.

A rulemaking proceeding on design features to mitigate the consequences of degraded core and core melt accidents is under consideration. Pending this rulemaking proceeding, we conclude that: 1) all Mark I containments that are not now inerted and all Mark II containments should be required to be inerted; 2) no interim requirements are required at this time for improvement in hydrogen management capability at nuclear power plants with other types of containment designs; and 3) subject to implementation of Item 1, above, continued operation and licensing of nuclear power plants is justified.