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Possible Containment Failure Mechanisms in Severe Core Meltdown Accidents

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중대 노심사고시 격납용기 손상유형에 대한 고찰

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Abstract

The severe core meltdown accident, which is not included as a design basis accident, has high consequence and low probability of occurrence and turns out to be a major risk factor in the overall risk assessment. The physical mechanisms of containment failure in core meltdown accidents are identified as steam explosion, debris bed coolability, hydrogen burning, steam spike and core-concrete interaction. The state of technology review is made for each subtopic about the previous and current researches for better understanding of the phenomenon.

요　　약

중대 노심사고는 아직 Design Basis Accident에 포함되지 않고 있으나, 극히 적은 사고 확률을 가지는 반면 사고 후 영향이 큼으로해서 원자력발전소의 전반적 위험 평가에 중요한 요인중의 하나가 되고 있다. 중대 노심사고시 격납용기 손상에 관련된 물리현상들은 Steam Explosion, Debris Bed Coolability, Hydrogen Burning, Steam Spike와 Core-Concrete Interaction등이며, 각각의 현상에 대한 좀 더 나은 이해를 위해 현재 이루어지고 있는 연구들에 대한 개략적 설명을 시도 하였다.

I. Introduction

During the past few decades there has been a lot of argument about the safety issue of nuclear power plants. The regulatory procedures were initially based on the concept of Maximum Credible Accident (MCA)[2] which relies on engineering judgement to designate credible accidents and designs the safety system to work against the most serious credible accident. The MCA approach was improved to result in the design basis accident concept which is similar to the MCA, but more systematic in its application. The DBA concept identifies low frequency, high consequence accidents to be designed against, e. g., loss of coolant accidents, reactivity accidents and steamline breaks. Although core meltdown accidents have not been considered on the design basis yet, the probabilistic approach in the Reactor Safety Study (WASH-1400)[1] shows that they are major risk factors to the public, although extremely unprobable, and cannot be excluded at all from the safety concerns.

Three barriers to radioactivity release of fission products are fuel rods, primary system and finally containment. The TMI-2 accident showed that containment integrity is the ultimate crucial concern under any accident situation. The containments of all PWR type reactors in Korea are of large dry containment type. The design pressure is about 70~75 psia and the volume is about 2.0×10^6 ft^3. They usually have a prestressed concrete structure of 3.75 ft thickness with a steel liner on the inside. Under a normal condition they are maintained at the atmospheric pressure and the design leakage rate is~0.1 v/o per day at the waximum design pressure.

The major limiting aspects of core meltdown accidents are

1) In-vessel and ex-vessel steam explosions,
2) In-vessel and ex-vessel debris bed coolability,
3) Hydrogen generation, distribution and combustion,
4) In-vessel and ex-vessel steam spike and direct heating,
5) Core-concrete interaction.

As a result of these phenomena, containment failure can occur to result in fission products release to the environment. Most of fission products in the containment are thought to be released in the form of aerosols. Possible containment failure modes can be categorized into

1) A catastrophic breach of the containment wall due to steam explosions, hydrogen burning or steam spike,
2) Inadequate isolation of containment openings and penetrations, and
3) Basemat meltthrough by core-concrete interaction.

Currently active researches have been going on in the U.S. to understand the physical mechanisms of these accidents progression and reevaluate their importance from a regulatory viewpoint. Since most of the reactors in operation and under construction in Korea are from the U.S., the authors consider it necessary to pick up their knowledge, review the point whether the severe core meltdown accidents should be incorporated into the DBA's, and set up regulatory safeguards to prepare for their occurrence. The purpose of this paper is to review their physical mechanisms and importance to overall risk assessment of PWR type nuclear power plants.

2. Severe Core Meltdown Accident Progression[2,5]

As the coolant boils off in the core, the fuel rods get uncovered and begin to heat up oxidizing zircaloy claddings. Since oxidized claddings are more brittle, they deform and burst easily and fall downward to form early debris. As the fuel temperature further increases, binary and ternary (U-ZR-O) melts form and large scale blockage may occur due to downward relocation. The melt grows radially and slumps downward either forming a debris bed on the core bottom or causing a steam explosion as it interacts with the liquid coolant. If the steam explosion is energetic enough to push the overlying liquid coolant layer like a piston, the kinetic energy of the slug may rupture the pressure vessel generating a missile, which may again rupture the containment wall by its kinetic energy. Otherwise the molten core may settle down as a debris bed or a molten corium layer and breach the vessel by its thermal energy. Then the core material will get ejected down to the cavity and various cavity phenomena will follow.

There are two possible accident scenarios at this point, one for a high primary system pressure and the other for a low primary system pressure according to whether the primary system has depressurized to the containment pressure level at the time of vessel breach. In the high pressure scenario the core material will blow down to the cavity with choking at the breached vessel hole and sweep out everything in the cavity to the containment through the instrumentation pipeway. In the low pressure scenario the molten corium will fall down to the cavity by gravitation as a coherent slug. Since the cavity is likely to contain some liquid coolant from emergency core cooling safety features, the molten corium may either settle down as a debris bed or cause a steam explosion in the cavity. In any case a debris bed of various particle sizes may form and get heated up by the decay energy of fission products. If the debris bed is coolable by overlying coolant, the accident progression will be ceased at that point. Otherwise the fuel debris will remelt inducing core-concrete interaction. As a mode of containment failure, cavity bottom structures may fail and release radioactive materials to the earth.

In the accident sequence, the containment may by overpressurized beyond the design pressure level either by steam generation or by direct heating effect of swept out fuel particles. The direct heating effect may occur if the thermal energy of airborne fuel debris is used directly to heat the gas component causing a large thermal nonequilibrium between the gas and liquid component in the containment.

Various hydrogen sources have also been identified in the severe core meltdown sequences, such as metal-water reaction, coreconcrete interaction, radiolysis of liquid coolant and corrosion of various metallic elements. The generated hydrogen gas gets distributed in the containment air by convection and molecular and turbulent diffusion mechanisms. If the hydrogen gas concentration is above a certain level, it can explode and endanger the containment integrity.

3. Steam Explosion[3,4)

A steam or vapor explosion is a phenomenon of steam production at a rate which exceeds the rate at which the surrounding media can either acoustically or inertially relieve and accmmodate the rapid steam formation. Such explosive interactions have been encountered for decades in metal foundries as well as in the pulp and paper industries. In addition to such non-nuclear experiences, destructive steam explosions have been observed in the BORAX and SPERT test reactors as well as in the SL-1 experimental, boiling water reactor. The SL-1 accident seems to have been initiated by the withdrawal of a control rod which led to a power excursion causing the fuel elements and aluminum claddings to melt. The resulting explosion caused the reactor vessel to fail with peak pressure estimated to have reached 700 bar. Therefore there is no doubt that a steam explosion could potentially occur in a commercial LWR in severe core meltdown accidents.

In the Reactor Safety Study (WASH-1400)[1) steam explosions were considered as a potential containment failure mechanism due to the in-vessel steam explosion which might rupture the pressure vessel and propel the fragments against the containment wall. The probability of such an occurrence was set at 1 in 100 core meltdown accidents with the guidance for numerical values provided by a parametric model. It was assumed that the molten core was assumed to collect on the grid plate and fail this plate castastrophically releasing the corium into the liquid coolant in parametrically varied times of 1 msec to 3.2

sec. The molten corium was assumed to instantaneously fragment and disperse uniformly throughout the coolant into parametrically varied sizes of 400 microns to 10cm in diameter. The resulting energy transfer form the melt is evaluated by considering conduction within the molten debris and the conduction, convection and radiation heat transfer off the particle surfaces. This energy transfer is completed in a few tens of milliseconds. The assumed configuration of an expanding mixture with an overlying inertial layer is illustrated in Fig. 1, the instantaneous mixing, interaction zone, slug displacement and impact are characterized in Fig. 2 and the calculated results for a 400 microns particle diameter are given in Fig. 3. As illustrated in Fig. 3, containment failure results from the slug impact and not from the shock pressure of the exploding mixture.

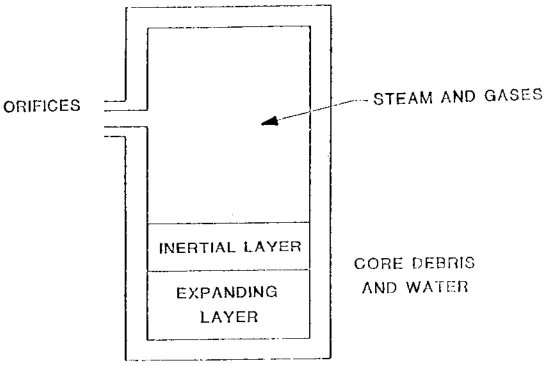
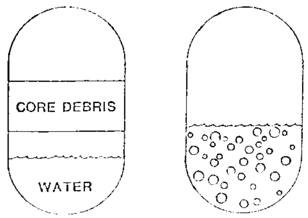
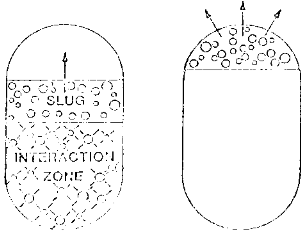


Fig. 1. Model Geometry Used in WASH-1400 Steam Explosion Analyses.



A) INITIAL SEPARATED CONFIGURATION B) CATASTROPHIC FAILURE AND INSTANTANEOUS MIXING



C) SUSTAINED ENERGY TRANSFER AND SLUG ACCELERATION D) SLUG IMPACT

Fig. 2. Behavior Modeled in WASH-1400.

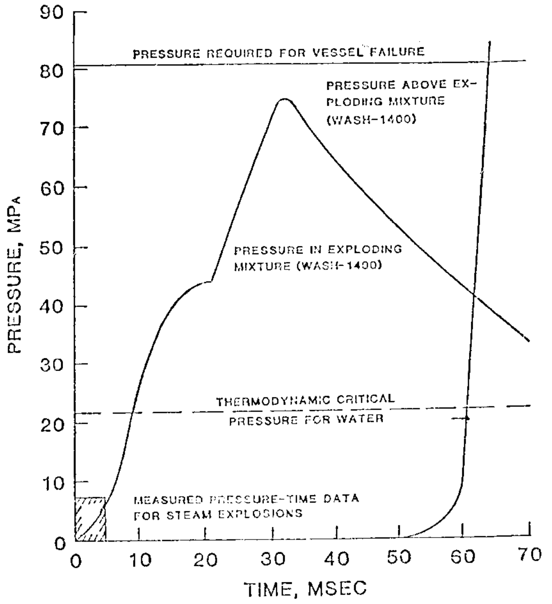


Fig. 3. Comparison of Predicted Pressure-time Behavior from WASH-1400(400⊿m particle size) and Available Experimental Results for Steam Explosions.

Since the Reactor Safety Study in 1975, steam explosion has been a controversial issue among the nuclear safety people and many experiments have been performed for better understanding of the phenomenon. The configurations of most experiments were in a shock tube geometry, a small scale and a large scale experiment. In a small scale experiment, steam explosion is induced for a single droplet of fuel or coolant in abundance of the other, while a large amount of fuel and coolant is intermixed in varying ratios in a large scale experiment. Although there is no consensus about its physical mechanism yet, it has been agreed that the assumptions in the RSS were overly conservative. For example reduction of the likelihood of a steam explosion at a higher ambient pressure was not taken into consideration. The existence of a coherent liquid slug is also doubtful due to the internal structures and high void fraction by film boiling around fuel particles. Therefore a much higher conversion ratio of the thermal energy into mechanical energy was used in the RSS than the representative experimental data.

A steam explosion occurs through a few distinct steps which are mixing, triggering and expansion stages. Each stage is shortly described as

1) An initial quiescent stage in which two fluids coarsely intermix by interpenetration maintaining film boiling,

2) A small disturbance or a trigger is applied to induce a local interaction, and

3) A coherent propagation throughout the interaction zone.

In the mixing stage, the molten corium fragments into particles of adequate sizes as it falls down through the liquid coolant. A uniformly intermixed fuel and coolant is a necessary condition for a maximum conversion ratio of the steam explosion. The limit of this fragmentation is determined by flooding of fuel particles by upward steam flow. Triggering is an external perturbation, usually a pressure pulse, to initiate a local interaction. Since the basis of a steam explosion is the increase of the heat transfer area by fine fragmentation in a very short time scale, the exact initiation mechanism by triggering is of crucial interest. There is a group of people who think that the role of triggering is to supply the energy required for the fine fragmentation. Another possibility is that the energy source for fragmentation may be the thermal energy of molten corium itself. Presently there are many proposed theories about this fragmentation mechanism, i.e., shell solidification11), coolant entrapment12), spontaneous nucleation16), acoustic cavitation14), vapor film collapse15) and relative velocity induced fragmentation13), with no consensus among these theories. In the expansion phase the explosion propagates through the interaction zone resulting in fine fragmentation of fuel particles behind the propagation front. Two proposed models for the expansion phase are the spontaneous nucleation model7) and the detonation model9). The spontaneous nucleation model suggests that a large scale explosion cannot occur unless the contact temperature between the fuel and coolant exceeds the spontaneous nucleation tempeature of the coolannt. This is based on the fact that the molten corium surface in its liquid state is free from nucleation sites unlike a solid state surface. This will allow the coolant to be superheated to the spontaneous nucleation temperature and an explosive steam generation will follow by internally generated nucleation sites. The detonation model is based on the classical theory of detonation and proposes that the steam explosion is sustained by a shock wave passing through the coarse mixture of molten corium and coolant. The shock front collapses vapor films and fragments the corium leaving fine scale fuel particles in intimate contact and rapid heat transfer with the coolant. The fragmentation mechanism in the detonation model was attributed to the steep pressure gradient at the shock front which induces Rayleigh-Taylor instability at the fuel-coolant interface.

Since no mechanistic model has ever been developed due to the complicated features of steam explosion, most experimental and analytical efforts were concentrated on a parametric model8). The relevant parameters are ambient pressure, coolant temperature, fuel temperature, fuel composition, coolant composition and fuel viscosity, etc10). Among these, the parameters of practical interest are the fuel temperature, coolant temperature and ambient pressure. As the coolant temperature is lowered below the saturation point increasing the coolant subcooling, it always gets easier to initiate a steam explosion. As the fuel temperature increases above the melting point or above the minimum temperature that guarantees film boiling, it always gets more difficult to initiate a steam explosion. The ambient pressure affects both the coolant subcooling and the density ratio of liquid and vapor coolant. At a higher density ratio, it gets more difficult to initiate a steam explosion and the explosion will not be energetic enough if one occurs.

4. Debris Bed Coolability

For a postulated meltdown accident, core debris collapses into water in the bottom of the vessel and large quantities of hot core bebris could contact water in the reactor cavity. The interaction of the debris with water in the cavity yields a rapid generation of steam which might in turn cause rapid pressurization of the containment building. It is important to accurately analyze the steam generation rates associated with both in-vessel and ex-vessel debris/water interactions so that potential containment failure modes due to these phenomena can be assessed.

Among the many phenomenological processes associated with reactor meltdown, the core debris coolability depends on the interaction of the core debris and water. The water is rapidly heated to its boiling temperature by the sensible heat and decay heat of the hot debris particles. As shown in Fig. 4, the boiling process generates a counter flow of downward moving liquid replacing the upward flowing steam even with a complete inlet blockage. However, the downward moving liquid may not be able to penetrate the bed swiftly enough to offset vaporization if the heat flux is sufficiently large and/or the particles are sufficiently small. Under these conditions, incipient dryout will occur in

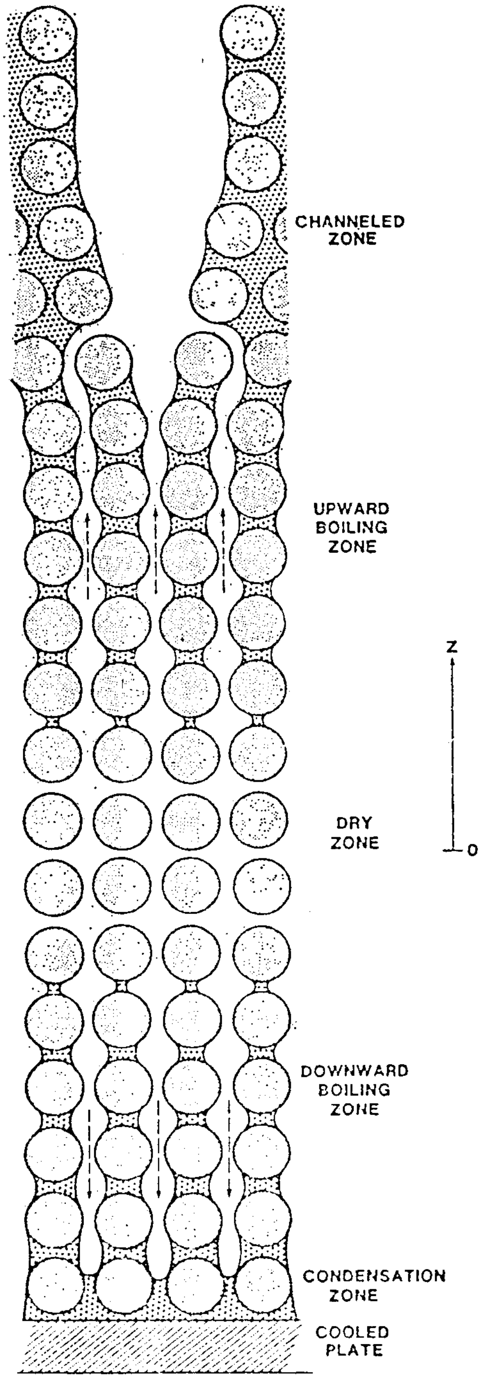


Fig. 4. Downward Boiling in a Bottom-Cooled Bed.

Table 1. Summary of Experimental Conditions on Debris Bed Coolability

	ANL	SNL	UCLA	KFK (GERMAN)	Westinghouse	SNL[1]	Simulated PWR Plant
Coolant	H_2O, Na Acetone Methanol F-113	H_2O, Na Acetone Methanol	H_2O Acetone Methanol	H_2O F-113	H_2O	H_2O	H_2O
Particle	Uo^2, Fe	Uo^2	Fe	Fe	Fe	Fe	Uo^2, Zr
Meterial	Copper		Pb	Bronze			Fe
Particle Size(mm)	0. 2~1. 095	0. 1~1. 0	0. 3569~0. 9	0. 258~15. 88	0. 55~6. 35	3. 4~3. 8	1~50
Bed Height(cm)	5. 5~4. 0	5. 8~15. 8	1. 33~40	2. 0~13	7. 6~28. 8	25	135-220
Porosity	0. 39~0. 536	0. 43~0. 48	0. 38~0. 45	0. 373~0. 473	0. 4	0. 4	0. 4
Pressure (psia)	—	—	0. 3~14. 7	—	—	—	12~3000

1: The Ex-vessel Core Debris/Water/Concrete Interactions by Tarbell

the bed. Considerable research has been performed on the particles bed dryout. Experiments involving different coolants and particles have been performed under various conditions. The conditions of experiments performed at ANL, SANDIA and UCLA and simulated containment conditions are summarized in Table 1. It is seen that the debris bed on the bottom of the reactor vessel and on the cavity is quite different from those studied under laboratory conditions. In a PWR plant, a very deep bed is expected to form for a wide range of particle sizes, and the dryout process may occur under much higher pressure. The particle size is determined by whether there is an energetic or non-energetic fragmentation of the fuel material.

Many empirical correlations and phenomenological models were developed from these experiments. Several mechanisms have been proposed for the limit of coolability under this counterflow condition. The model proposed by Hardee and Nilson[17] models an annular flow configuration in which the liquid is traveling downward through one region and the vapor is moving upward through a separate zone. Dhir-Catton[18] model, based on their UCLA experiments, have proposed an approach wherein the coolability is determined by the ability to supply water to the bottom of the bed. Ostensen[19] developed a dryout model based upon the Wallis flooding correlation. The flooding model fits large particles and turbulent flow. Shires-Stevens[20] extended the Hardee-Nilson model to include the effect of capillary force. In LMFBR research, caprllary term is predicted by the model to be two to ten times stronger than gravity and thus increase the dryout flux by three to eleven times. Lipinski[21] developed an approach which assumes that liquid is flowing over the surface of each particle as thin film, which can be treated either as laminar or turbulent, and the vapor is flowing upward over the surface of this film, also between the particles.

Of all models considered, it appears that Lipinski model provides better agreement with experiments. Recently the results of debris bed quenching experiments by Ginsberg[22] suggested that the quench rate of the bed is limited by the countercurrent two-phase flow. The steam generation rates observed are bounded by the calculations based upon the Lipinski and Ostensen models. These results imply that the correlations based upon steady state particle bed heat transfer can be used to compute the containment pressurization of the quench mode via particle bed heat transfer with the overlying pool of water. The dryout heat flux of various models is illustrated in Fig. 5 for comparison.

The parameters affecting bed dryout are the particle characteristics (particle size, shape and

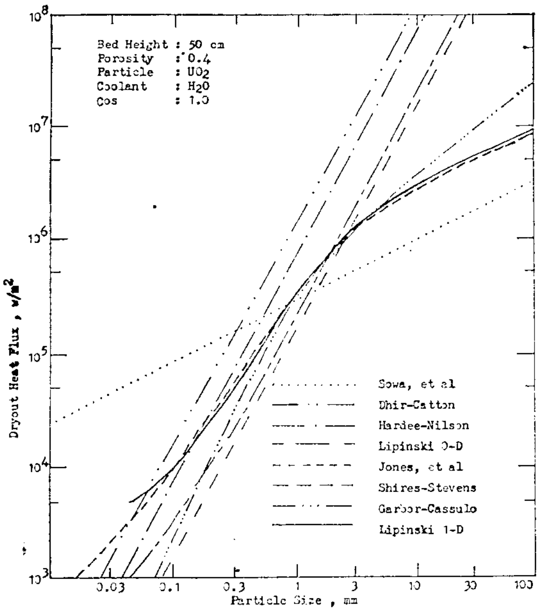


Fig. 5. Dryout Heat Fluxes for Several Debris Bed Models

distribution), bed depth, bed power density, overlying liquid layer depth and subcooling and thermophysical properties of the liquid, etc. For reduction of the uncertainty, the sensitivity study of various dryout models are recommended before application to the reactor systems. It is suggested, from the simple description of core debris coolability, that the quenching time by the dryout model can be reduced from hours to minutes as the pressure was increased from atmospheric to higher values. Since all of the degraded core accident scenarios result in either a pressurized primary system or a pressurized containment, the probability of obtaining a coolable debris bed becomes greater as the pressure increases, provided that there is sufficient water available in the vessel or in the cavity.

5. Hydrogen Generation, Distribution and Combustion[23]

Hydrogen has long been recognized as a safety issue in nuclear power plants. Since the TMI-2 accident, where a fully-contained hydrogen burn occurred in the containment building, hydrogen problem received a great deal of study. The hydrogen problem can be grouped under the three main issues of generation, distribution and combustion.

5.1. Hydrogen Generation

The only significant source of hydrogen under accident conditions is the decomposition of water. The processes by which water can be decomposed to hydrogen are:

- ○ Oxidation of metals (Zr, steel) and UO_2 by high temperature steam
- ○ Radiolytic decomposition of water,
- ○ Corrosion of metals (Zn, Al) by spray solution, and
- ○ Thermal decomposition of water at a high temperature.

The Zirconium-water reaction is believed to be the dominant hydrogen source in the TMI-2 accident, with approximately 50% of the zircaloy cladding in the core reacted. A complete reaction of all the cladding would yield ~900 Kg H_2 in a typical PWR. For postulated severe accidents involving long term core uncovery, complete oxidation of the core zirconium could occur in time periods of 30~60 minutes. Since the steel-water reaction is kinetically slower, hydrogen from this source would be released at times later than for the zirconium reaction. Therefore in core meltdown accidents with subsequent meltthrough of the primary reactor vessel, the steel-water reaction would also be a significant source of hydrogen.

Water can be decomposed into a number of products by absorbing ionizing radiation. The amount of hydrogen gas generation varies with the solution chemistry, the degree of agitation, the concentration of hydrogen accumulated in the solution, and to a lesser extent with thermal conditions. Typically a few percent of H_2 can be added to the containment atmosphere by radiolysis in a fow days times.

Metals and coatings used in the containment building may be exposed to spray solutions or to steam-air atmosphere during a LOCA. Both aluminum and zinc react with aqueous solutions to produce hydrogen. Calculations indicate that the total consumption of aluminum and zinc could produce a few percent hydrogen in the containment atmosphere in a few days time, which is comparable to radiolysis.

5. 2. Hydrogen Distribution

Under severe accident conditions, hydrogen will enter the containment atmosphere as a buoyant, turbulent jet or plume. The degree to which hydrogen becomes mixed within the containment atmosphere is important because it can affect the design of control methods, such as the placement of igniters.

Several processes are involved to mix the hydrogen and limit the extent of stratification: gas motion due to momentum of the H_2-steam jet, natural convection arising from temperature gradients and nonhomogeneous fluids, and molecular and turbulent diffusion.

The modelling of hydrogen mixing in containment atmosphere has proceeded along two ways. In one of them is the empirical approach where experimental data obtained from scale models are applied to full scale plants using similarity principles. In the other are the numerical solutions to the governing equations of the fluid flow which are mass, momentum and eneray conservation equations[24,25]. The containment air is assumed incompressible with Boussinesque approximation for the buoyancy force. In the Navier-Stokes Equation, the viscosity term is composed of molecular and turbulent contributions which are modelled by the multi-component gas diffusion model and κ-ε model. The diffusion term in the energy conservation equation is also composed of these two contributions. The turbulent Prandtl and Schmidt numbers are usually set equal to one.

5. 3. Hydrogen Combustion

Hydrogen gas mixed with the containment air react with oxygen to form water liberating a substantial amount of energy. The characteristics of hydrogen combustion depend strongly on the hydrogen concentration and other conditions.

A hydrogen mixture is said to be flammable if a localized ignition is able to propagate indefinitely. Flammability limits are affected by a number of parameters. The increase of the gas temperature widens the flammability limit of hydrogen gas concentration. The addition of noncondensible gases narrows the flammability limit. If the mixture contains more than ~50 % of water vapor, no mixture of H_2 and air is flammable. The flammability limit for a mixture of hydrogen-air-steam is shown in Fig. 6. For pressures in the range of post-LOCA atmospheres, flammability limit does not vary significantly with pressure. While turbulence has been shown to affect ignition energy requirements and burning efficiency, the limit of flammability is not significantly affected by turbu-

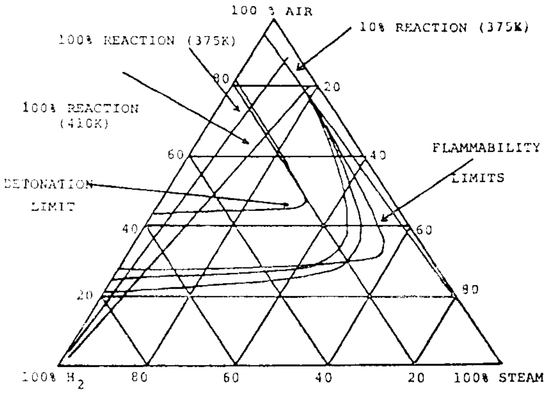


Fig. 6. Flammability and Detonation Limits of Hyrogen-AIR-Steam Mixtures

lence level. Inert particles and drops act as energy sinks and thereby narrow the flammability limit.

Combustible mixtures of hydrogen and air do not burn unless supplied with enough energy to cause spontaneous combustion on a local scale. If combustible hydrogen mixtures are heated to a sufficiently high temperature and held at that temperature for a certain period of time, ignition occurs spontaneously. Hydrogen-air mixtures can also be ignited by sparks of very low energy under optimum conditions.

If a flammable hydrogen mixture were formed in the containment and if ignition occurred, a flame would propagate through the atmosphere, raising the temperature and pressure of the contained gas. Deflagrations are burns that take place relatively slowly. The flame front propagates from its inception point at speeds well below sonic and the entire atmosphere is compressed at more or less the same rate. In a quiescent atmosphere, relatively high hydrogen concetrations (10%~20%) are required before burning is complete, but when the atmosphere is agitated, complete burning can occur at low concentrations (6%~8%). The hydrogen burn observed at TMI-2 was a deflagration equivalent to complete burning of an 8.5% H_2/air mixture which increased the containment pressure to 28 psig.

Detonations are burns that propagate at speeds that are supersonic with respect to the unburned gas. The leading edge of the detonation front is a shock wave, in which the unburned gas is heated to a temperature well above the spontaneous ignition point. The energy of hydrogen /oxygen reaction maintains a high temperaturehigh pressure region behind the shock front, causing the wave to be self-propagating. Detonations are possible only in gases where the chemical reaction is sufficiently rapid and energetic. Composition limits for detonations fall well within the flammability limits as show in.Fig. 6. For H_2-air mixtures at a room temperature, detonations are possible for H_2 concentrations between 18% and 60% hydrogen.

Hydrogen burns typically begin as deflagrations. If the concentration is within the detonation limits, then a transition from a slow moving flame to a detonation can take place. Studies have shown that turbulence and the interaction of weak shocks play important roles in the transition process, and that the presence of walls or obstacles enhances transition.

A diffusion flame would result if a hydrogen mixture enters the containment atmosphere as a jet or plume and gets ignited. The nature of the flame is affected by the laminar and turbulent diffusion processes that mix the two reactants, hydrogen and oxygen. The flammability limit for a diffusion flameis narrowed because of the impeding influence of diffusional mixing.

Deflagration should be considerd from the viewpoint whether the developed pressure is high enough to fail the containment building and whether the high gas temperature(~100°C) can damage various containment equipments and structures. Detailed evaluation of hydrogen deflagrations in a large dry containment would not fail the containment by overpressure even if all the hydrogen from 100% zirconium-water reaction accumulates in the atmosphere and then undergoes an adiabatic burn. For an ice-condenser containment, 20~35% metal-water reaction can be tolerated.

The controlling parameter of detonation for the conainment integrity is the magnitude of the impulse (defined as the time integral of the applied load) rather than the pressure itself. This is due to the fact that detonation waves are short compared to the natural vibration frequency of containment structures.

6. In-vessel and Ex-vessel Steam Spike and Direct Heating[6),26),27)]

In-vessel and Ex-vessel steam spike (steam generation) could occur when overheated core debris and water come into contact on a global scale. The difference between a steam spike and a steam explosion is the time scale during which the steam is generated. A steam spike involves the vapor generation in a time scale which is considerably longer than the acoustic relaxation time of the system.

The in-vessel and ex-vessel steam generation rates should be assessed for three characteristic configurations. The first is the thermal interaction between molten debris and water, the second is quenching of a solidified but overheated debris bed, and the third is the dispersal of core material into the containment after vessel failure. The first and second configuration have already been discussed in the previous sections on steam explosion and debris bed cooling. The last configuration is applicable only for vessel failure at a high primary system pressure or a steam explosion in the cavity.

For accident scenarios with molten debris pouring in a confined water space, the quenching process is determined by the debris fragmentation during the interaction process. Without fine fragmentation, quenching would be limited to the rate at which energy could be transferred to the debris-water interface, i.e. the conduction rate limited within the fragments. However for fine fragmented debris with extensive interfacial area, the energy removal limitation would occur within the coolant. The maximum steaming rate would be flooding limit that allows water to penetrate downward to maintain the quenching process. Application of this fragmentation model to the material quantities and configurations in the lower vessel plenum predicts large particle sizes (centimeters to tens of centimeters). This means that the molten fuel would pour into the lower plenum with relatively little area available for contact with water.

For severe core meltdown accidents by large break LOCAs, the primary system would be depressurized to the containment pressure level and molten debris would be discharged by gravitation. The quenching process would occur over time intervals ranging from tens of seconds to tens of minutes. For the accidents with an elevated primary system pressure, the gaseous blowdown through the vessel breach could disperse the core debris from the reactor cavity/instrumentation tunnel region into the containment. Dispersal of the overheated debris could cause a rapid quenching of the core material and a steam spike in the containment. The sweepout fraction of the molten debris is a crucial parameter determining the steam spike pressure because the retained portion in the cavity has a longer time scale of quenching and is likely to lose its energy to the structural materials. A typical transient case with steam spike is analyzed the MARCH code with its result in Fig. 7, where the containment pressure history is given as the core meltdown proceeds. At around 5 hours after the accident initiation, a steam spike is shown to occur with a sharp increase of the containment pressure. After the peak the pressure gradually decreases due to heat loss by condensation and increases again by core-concrete interaction.

The containment overpressurization might occur by generation of steam and other noncondensible gases with the thermal energy of molten core material. Another possibility is to increase the gas temperature directly through the thermal energy of the airborne core debris, resulting in a large temperature nonequilibrium between liquid and gas components[26)]. The

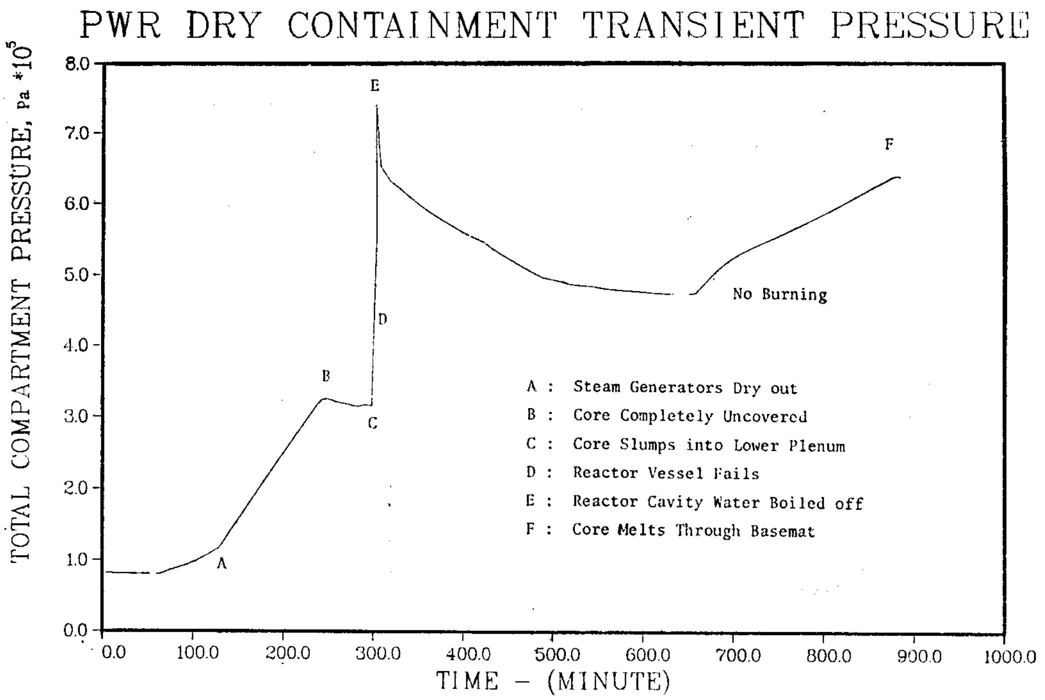


Fig. 7. Containment Pressure versus Time for A Typical Transient Case with Steam Spike

airborne debris particles have the diameter of a few hundred microns and the time scale of heat transfer is a few seconds. The chemical reaction of zirconium and steel with oxygen might be an additional source of energy. Although airborne debris contain sufficient thermal and chemical energy to fail the containment, it is still an open question how much fraction of the total energy will be used for the direct heating effect.

7. Core-Concrete Interaction

Interaction between molten core material and concrete occurs following a postulated core meltdown accident in LWR. Of particular interest is the impact of melt/concrete interaction on two important modes of breaching the containment-overpressurization and leakage due to the generation of heat, steam and noncondensible gases, and penetration of the concrete basemat. The interaction of molten core materials with concrete reactor cavity and support structures has been identified as an important part of the accident sequence. Radioactivity may be released to the earth beneath the reactor building as a result of penetration of the core materials through the concrete basemat. It is necessary to identify the major phenomena characteristic of a core-concrete interaction and to understand the associated physical and chemical processes.

Carbiener[28] assumed that the mechanism for erosion of concrete by molten core materials was rapid spallation of the first 1/2m of concrete. They estimated that core materials would penetrate the concrete basemat in approximately 18 hours. During decomposition and erosion of the concrete, noncondensible gases and water vapor would be released. Some analytical models[23],[30] based on experimental results have been applied to the computer codes, such as INTER, WECHSL, CORCON, etc. For melt/concrete interaction analytical approach of con-

Table 2. Summary of Typical Melt/Concrete Experiments

		Experimental Observations
Melt Behavior	Stratification Agitation Surface Crust Formation Precipitation	Two distinct melt layers-Metallic and oxide layer Gas induced forced convection Surface of the oxide melt Only metal
Concrete Thermal Behavior	Melting Decomposition	Melting temp.-1100~1400°C Based on kinetics, dependent on both temperature and heating rate
Gas Production	CO_2 and H_2O CO and H_2 Gas Ignition	Determined to be dependent on heat transfer in concrete Chemical Reaction Diffusional limit applied
General Thermal Penetration	Spallation Erosion Rate Directional Dependence Heat Disposition	Not significant, 3~5mm of top surface layer Depend on heat flux and melt temp. Horizontal/downward Depend on gas generation rate
Concrete Cracking	Cracking	Thermally induced tensile stress were found to cause extensive cracking

crete behavior is introduced in a simple one-dimensional, steady-state ablation mode. This is coupled to a two-dimensional, axisymmetric shape change procedure which defines a new cavity at each time step. Many features are so complex that an empirical description derived from experiments is used.

Over the past several years, small and large scale experiments on melt/concrete interaction were conducted at Sandia[31),32)]. Their experiments indicated that the concrete penetration was dependent upon the ability of the melt to impart its heat to concrete. Gas generation by thermal decomposition of the concrete takes place below the melt/concrete interface such that the gas composition does not reflect the composition of the eroding concrete. Upward heat transfer was observed as a significant heat loss from the melt. The results observed from experiments are illustrated in Table 2. The experiment by Muir[33)] showed that the incident heat flux was reduced by radiative and convective heat transfer processes.

8. Summary

The containment failure mechanisms in severe core meltdown accidents are reviewed as a state of technology report. Although the limited space does not allow a detailed discussion of each subtopic, this review identifies the relevant issues of importance which should receive attention from a regulatory viewpoint. The aerosol behavior and early degradation mechanism of fuel rods are also relavant topics, which are not considered here. The probabilistic approach for the risk assessment shows that the high consequence of these class 9 accidents dominates the extremely small probability of their occurrence. Therefore, it seems to be necessary to consider the severe core meltdown accidents in one way or the other for the safety of nuclear power plants.

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