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Experimental Investigation on the Vapor Explosions with Water/R22

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Water / R22 폭발실험수행을 통한 증기폭발에 관한 연구

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Abstract

Experimental studies have been performed to investigate vapor explosion phenamena which may threaten the containment integrity during severe accidents in nuclear power plants. In this study, experimental equipment is constructed for vapor explosion experiments, and the vapor explosion experiments were conducted using water/R22. During the experiments, water/R22 interaction phenomena were observed using the high speed camera, and the explosion pressure and released mechanical energy were measured with presure transducer and presssure relief tube. And the effects of some important parameters-hot liquid temperature, hot liquid injection velocity, hot liquid injection velocity, hot liquid injection time, and cold liquid depth-were investigated on the vapor explosion. Also, the experiment with grid was conducted to study reactor-vessel-lower-structure effect on fuel/coolant interaction. Water/R22 explosion conversion ratios were measured between 0.5~1.6%.

요 약

원자력발전소 중대사고시 용융된 노심과 잔류냉각수가 증기폭발을 일으켜 원자로 격납용기의 건전성을 위협할 수있다. 본 연구에서는 증기폭발을 모사할 수 있는 실험장치를 제작하고, 물과 프레온을 사용하여 증기폭발실험을 수행하였다. 이때 고속카메라를 사용하여 폭발현상을 관측하였고, 동압측정기와 압력분출관을 이용하여 생성되는 폭발압력과 기계적인 에너지를 계측하였다. 이를 토대로 증기폭발의 중요인자들(물의 온도, 물의 주입속도, 물의 주입 시간, 그리고 냉매의 깊이)에 대한 민감도 분석을 수행하였다. 그리고, 압력용기 바닥의 구조물이 용융/냉각재의 반응에 미치는 영향을 살펴보기위하여 실험용기 내부에 그리드를 설치하여 폭발실험을 실시하였다. 물/프레온의 폭발실험에서 계측된 기계적에너지를 이용한 에너지효율은 0.5~1.6%인 것으로 계산되었다.

1. Introduction

The term "Vapor Explosion" refers to a phenomenon in which the molten fuel rapidly fragments and transfers its energy to the coolant resulting in shock wave and possible mechanical damage[1]. If such event occurs during severe accidents in a nuclear power plant, the integrity of reactor and/or containment may be highly threatened [2, 3]. Thus, many analytical and experimental works have been performed to understand the explosion phenomena and predict the amount of mechanical energy produced. However, due to the complexity of the phenomena and the paucity of large-scaled experimental data, few questions are so far cleared and, moreover, even complex mechanism are not satisfactory to precisely describe the whole process in spite of their great efforts.

In this study, experimental investigations have been performed using hot water(70°C~97°C)/R22(saturated at atmospheric pressure) in a rectangular vessel of 30×30×40cm to investigate the effects of some important parameters on the vapor explosion. The hot water is injected onto the liquid freon. The parameters studied in this experiments are cold liquid depth, hot liquid mass and temperature, injection velocity and existence of grid in the lower plenum. The explosion pressure and mechanical energy released are measured with piezo-electric type pressure transducers installed at the vessel wall and slug velocity measurement equipment, respectively.

2. Review of Water/Freon Experiments

Numerous experiments have been performed to understand the mechanisms of vapor explosion and energy generation with various simulant materials[4, 5]. Among them, a water/freon pair has been frequently used in studying the fundamental mechanism due to its visuality, and proper thermal property for explosion[5].

Enger[6] and Holt[7] conducted experimental studies with various liquid pairs including water and R22. Both groups found that each liquid pair would explode only when the hot liquid temperature fell within a certain range; Enger observed explosions between 47°C an 82°C and Holt reported explosions with 25°C water and R22 subcooled to-160°C. Since the reported explosive temperature ranges lay above the homogeneous nucleation temperature(Thn) of varous liquids, Nakanishi[8] and Katz[9] proposed that vapor explosions could occur above Thn. However, pointing out that the explosive temperature range extended below Thn of R22(54°C) and that initial contact temperature between the two liquids was below the homogeneous nucleation for almost explosive temperature ranges, the homogeneous nucleation would not be the sufficient condition for the explosions[9].

Large scale dropping experiments were conducted at ANL using water and R22 as well as other simulants. The first ANL experiment by Henry et al. [10] showed that the lowest limit(threshold) for energetic explosions was as that which produced an instantaneous contact temperature equal to the homogeneous nucleation temperature of R22(54°C). Also, Anderson and Armstrong at ANL showed that the peak pressure increased linearly with dwell times. And later, based on the available experimental data reported prior to 1977, Fauske and Henry proposed that vapor explosions were impossible unless the initial interface temperature between the two interacting liquids was above the spontaneous nucleation temperature[11].

The spontaneous nucleation is an extension of the concept of homogeneous nucleation to include surface nucleation effects. In addition to the lower limit for the steam explosions, they have hypothesized the existence of effective upper temperature limits where stable film boiling prevented contact between the two liquids. Thus, Fauske and Henry suggested that explosions may occur when the interface temperature is between the spontaneous nucleation temperature and critical temperature.

However, this criterion has been criticized as a necessary condition for a large steam explosion because the contact temperature of molten corium/water in the light water reactor would exceed the critical temperature of water.

Recently, stratified explosion experiments with an external trigger were conducted using the water/R12 pair[12]. They measured shock propagating speed (90m/s), peak pressure(0.6 MPa) and explosion work of 2500 J. There have been hundreds of experiments on vapor explosions for many purposes; there are still left further work despite such enormous what are still left further work despite such enormous efforts in the pasts. Morever, in experiments using corium or metallic simulants, the systematic sensitivity study was very limited.

Thus, the purpose of this experiment is to measure the maximum explosion pressure under various conditions and investigate the parametric effects on the explosion process.

3. Experimental Facility

The test facility consists of interaction vessel, water injection chamber, isolation valves, pressure relief tube as shown in Figs. 1 and 2. The rectangular interaction vessel of 30×30×40cm is made of 5mm thick stainless steel. Its inner surface is coated with FRP(Fiberglass Reinforced Plastic) and the outer surface is covered with the ceramic fiber for thermal insulation. The front face of the vessel has observation glass which is made of 3cm thick acrilic. The cylindrical water injection chamber of 30cm diameter and 60cm long has a 1kW electric heating rod for heating the water and is pressurized by N_2 gas to control the water injection velocity.

The isolation valve(solenoid valve) on the guiding pipe of 2.5cm inner diameter between the interaction vessel and water injection chamber controls the injection time. The pressure relief tube, through which the explosion pressure is released and the slug velocity is measured, is a stainless steel tube of 10cm diameter and 100cm height. The slug cuts off the enamel wires(0.1mm diameter) equipped inside the tube at the interval of 5cm and then, the electric circuit connected with the wire converts the break signal to voltage drop signal. The slug mass is 1.5 and 7kg.

A piezo-electric type pressure transducer-PCB 102 A05 SN3 152, its power unit is PCB Model 482A-is used for the explosion pressure measurement. A data acquisition system is composed of A/D con-

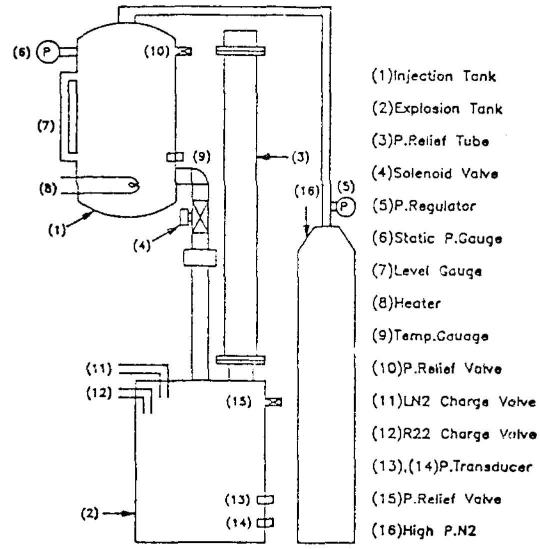


Fig. 1. Diagram of Experimental Facilities

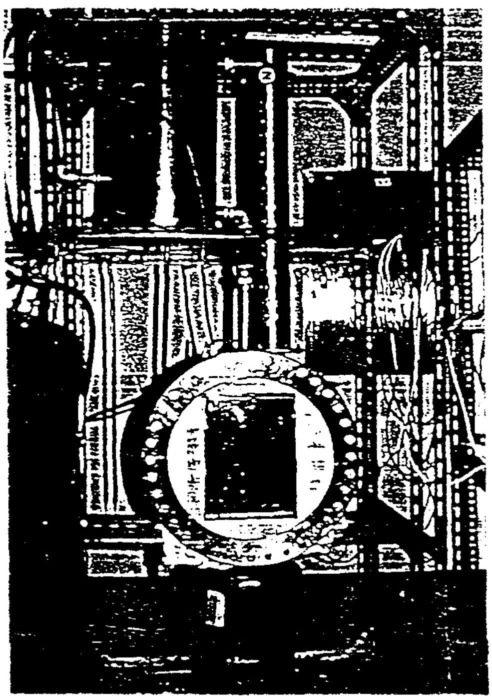
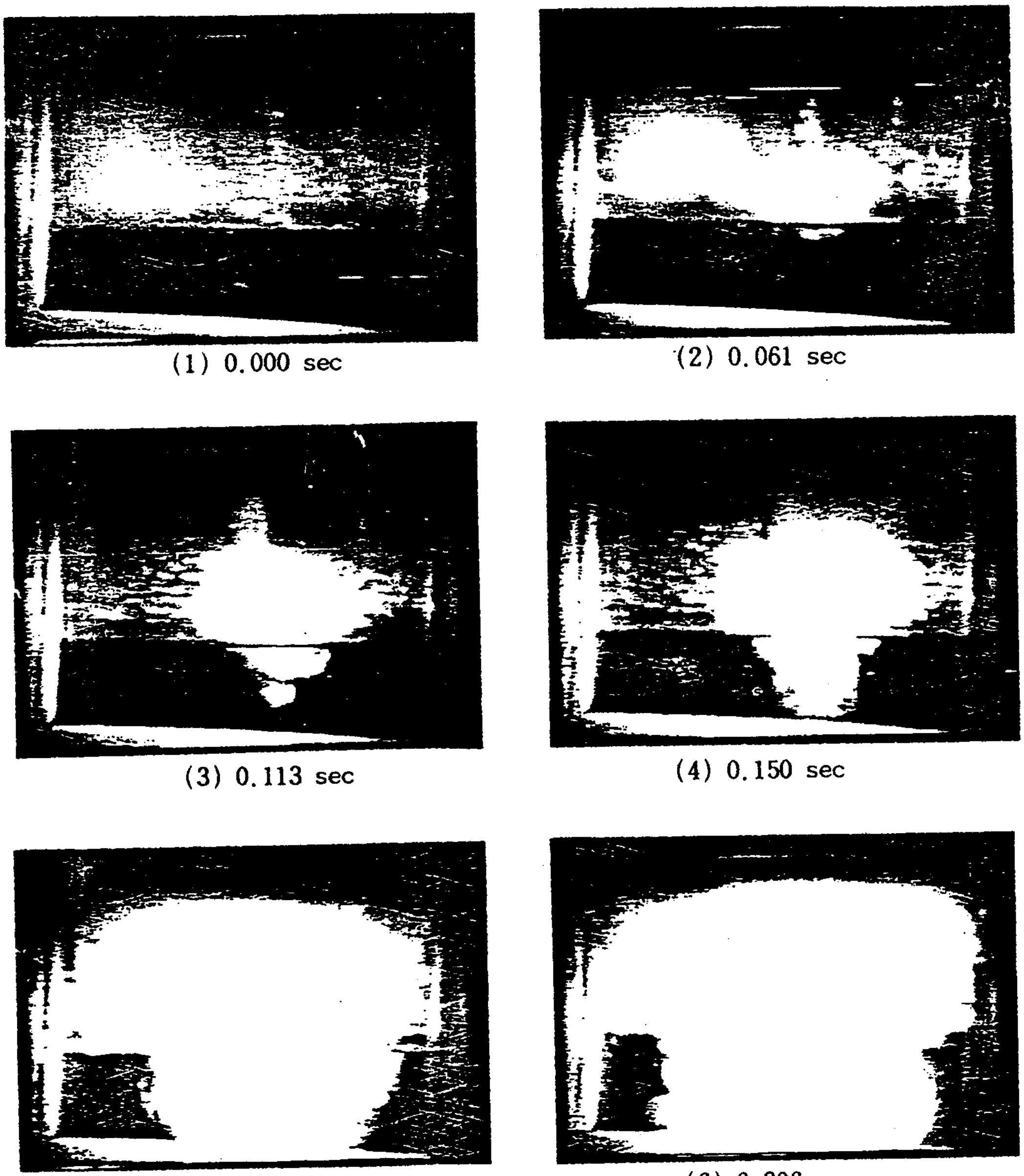


Fig. 2. Photograph of Experimental Facilities

verter(12bit 100kHz) and micro personal computer (20MHz), which has the capability to store 30,000 samples per trigger. The slug velocity signal is sampled with a oscilloscope (Tektronix 2430A, 300MHz). The electrical signal generated from a Z-80 micro-computer(8 bit, 2 MHz) controls the whole equipment including the valve and the data acquisition system.



(1) 0.000 sec
(2) 0.061 sec
(3) 0.113 sec
(4) 0.150 sec
(5) 0.297 sec
(6) 0.306 sec

Fig. 3. Visual Results of Water/R22 Vapor Explosion

4. Experimental Procedure

The experiments are performed under the various conditions of R22 depth(8∼12cm), water temperature(70°C∼97°C) and water injection velocity(2∼4m/sec). Also, the grid effect is investigated with an iron wire net. The experimental procedures are controlled with Z-80 Microcomputer for the systematic experimental prodecure due to the very short period of process. First, the interaction vessel is filled with R22. Then, triggering the highspeed camera, previously heated water pressurized by N_2 gas is injected with opening the isolation valve. After injecting the water, the data acquisition system is triggered at a preset time and collects data.

5. Results and Disscussions

In the beginning of this work, a series of tests using water(80°C) and saturated liquid nitrogen were attempted which did not produce the effective explosion due to Fauske's criterion. That is, the contact and critical temperature of liquid nitrogen are 17 and -147°C, respectively, instead of 55 and 96°C for water/R22. The water/R22 interaction process, potographed with high speed camera(1000fps), is represented as Fig. 3. These are allowed to observe the hot liquid/cold liquid interaction process and to obtain the special data, for example, mixture area, which is the area occupied by R22 vapor before triggering, and hot liquid proceeding velocity through the cold liquid (1m/sec : injection velocity is 2.87m/sec, and R22 depth is 10cm).

One interesting observation for water/R22 is the double explosion for relatively long valve open(over two second), where the second explosion is much larger than the first explosion. This seems to be caused by the fact that the unfragmented water during first explosion may be fully mixed in the whole volume when stirring the liquid R22 and refragmented to produce the second explosion under the confinement of upper ice layer.

Now, the effects of parameters such as R22 depth, water temperature and injection velocity on the explosion pressure are as follows. First, the explosion pressure increases as the temperature of hot liquid increases. However, at higher temperature where the pressure in R22 increase due to the increase of R22 boiling rate and the film boiling is more stable because the contact temperature(66°C at water 93°C) is higher than R22 homogeneous temperature(40°C∼60℃), the explosion pressure drops remarkably as shown in Fig. 4. Above 95°C of the water temperature, the explosion pressure re-increase is thought to be the phenomenon by additional instability generation due to void generation in injected water, but this is not important because the molten corium is not boiling.

The explosion pressure trend versus the cold liquid(R22) depth in Fig. 5 also shows that the increase of R22 depth does not monotonously increase the explosion pressure. When the cold liquid depth is low enough, the mixing time is short and thus the mixture area-this is obtained from the film photographed using high speed camera-is small as shown in Tab. 1. However, when the cold liquid depth is deep enough, the impulse of the injected water is weaker and the ambient pressure is built up due to larger vapor generation before triggering.

Fig. 6, which is the explosion pressure versus the hot liquid(water) injection velocity for three different depths, shows the same results. The explosion press-

Table 1. Measured Explosion Pressure for Three Different Coolant Depth

R22 Depth (cm)	Water Vel. (m/s)	Mixture Area (m^2)	Water Amount (g)	Peak Pressure (MPa)
8.0	2.57	0.0095	414	0.24
10.0	3.26	0.0153	745	0.46
12.0	3.26	0.0226	644	0.26

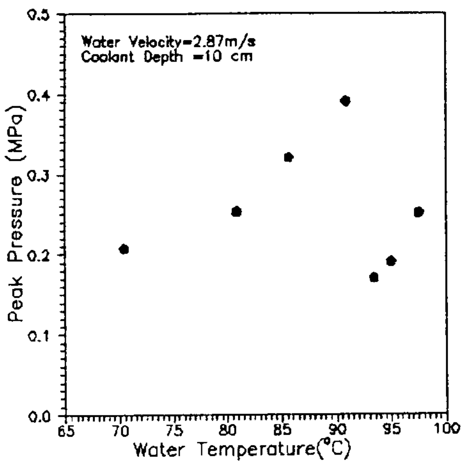


Fig. 4. Explosion Pressure vs. Hot Temp.

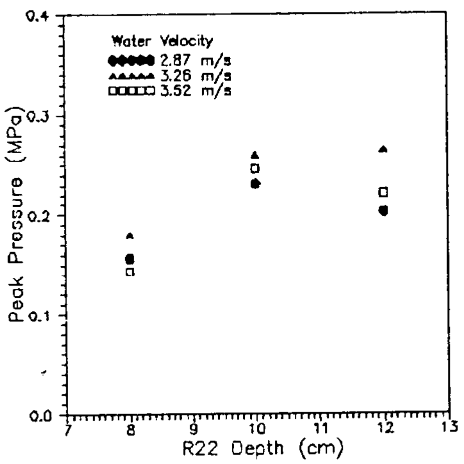


Fig. 5. Explosion Pressure vs. Cold Depth

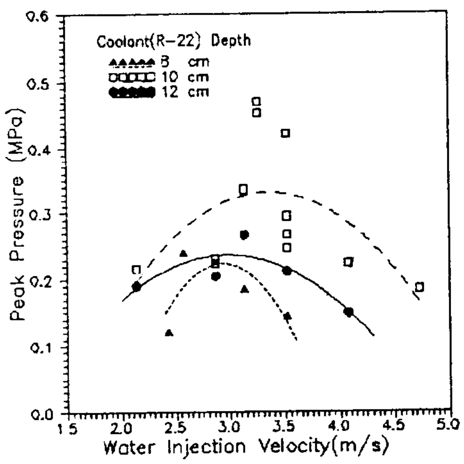


Fig. 6. Explosion Pressure vs. Hot Vel.

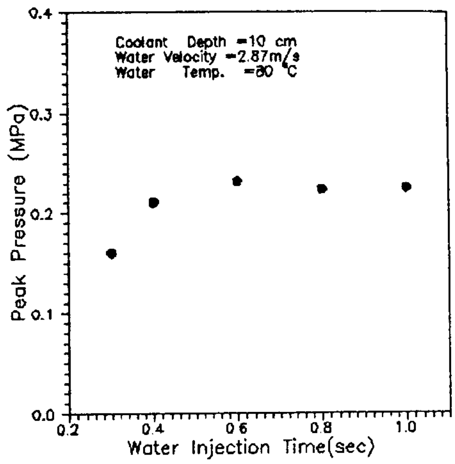


Fig. 7. Explosion Pressure vs. Hot Amount

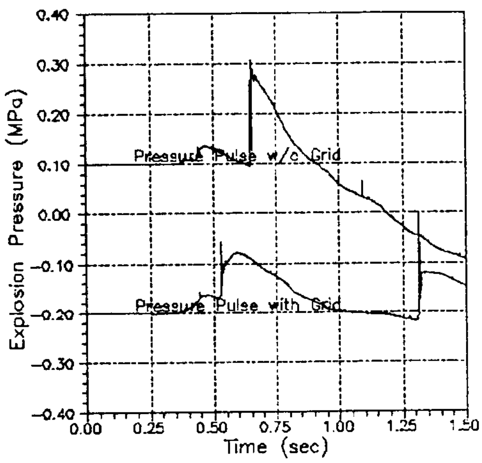


Fig. 8. Grid Effect on Explosion Pressure

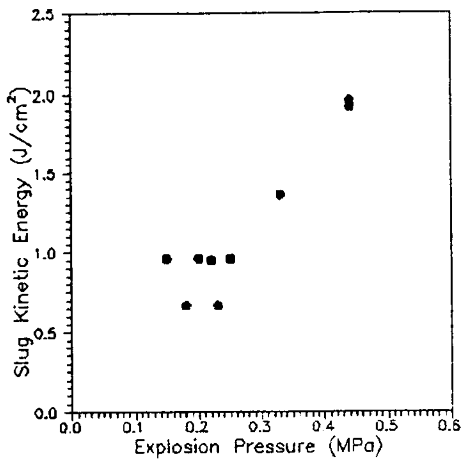


Fig. 9. Slug K.E. vs. Explosion Pressure

ure has a very strong dependency upon the hot liquid velocity. At the low injection velocity, the mixture is not sufficiently developed because the hot liquid is incapable of penetrating into the cold liquid, and at the high injection velocity, the hot liquid penetrate into the cold liquid, bump against the interaction vessel, and the triggering event occurs before the mixture attains full growth. Thus, the explosion pressure increase according to the injection velocity is limited.

Fig. 7 shows that the explosion pressure is not much affected by hot liquid injection time because the triggering time, which are not varied by the injection time, is constant if only hot liquid temperature, hot liquid velocity, and cold liquid depth are constant. The triggering time is about 0.47sec after the isolation valve open when hot liquid temperature, hot liquid velocity, and cold liquid depth are setted to be 80°C, 2.87m/sec, and 10cm as experimental condition showed Fig. 7. Figs. 6 and 7 are the good evidence of a bound of vapor explosion even though increasing the fuel mass.

The grid effect is investigated. In the reactor vessel, the lower support plate seems to affect the molten core behavior and the interaction between molten fuel and coolant. Thus, an iron wire net with 1mm spacing is installed at a location 7cm above the vessel bottom. As shown in Fig. 8, this grid weakens the explosion pressure because the first interaction with grid pressurizes the cold liquid, which is induced by the vapor generation with the hot liquid fragmented, and the impact force at the bottom may be reduced due to break of the column.

Finally, the mechanical energies measured in the pressure relief tube are shown in Fig. 9. The range lies between 0.5 and 2.5J/cm^2, and the injected hot liquid has total thermal energy, which is calcuated from the difference between water and R22 temperature. Then, the conversion ratio obtained by deviding total thermal energy by the total mechanical energy, which multiply mechanical energy per unit area by the interation vessel upper surface, is 0.5~1.6%. The

Table 2. Summary of Assumptions and Mechanistic Calculation Results

Investigator	Conversion Ratio	Melt Mass Participating (Kg)
Bankoff		24,000
Corradini (no mixing) (mixing)	.10−.15 .02−.05	1,000 1,000−10,000
Fauske		Mixing rate is 70 Kg/ms
Theofanous	.15 .15	1,905 6,350
Park	0.005−0.016	0.4−0.8(water/R22)

results are shown in Tab. 2 and compared with those of other works[13].

6. Conclusion

In this study, experiments were conducted using water/R22 to investigate the effects of some important parameters on the vapor explosion. The parametric study in experiments shows that the explosion pressure has the bound for all parameters of the hot liquid mass, temperature, injection velocity and the cold liquid depth. And, the effect of grid in the lower plenum is revealed to weaken the explosion pressure because the first interaction with grid pressurizes the water and the impact force at the bottom may be reduced due to break in the liquid column.

The conversion ratio due to the shock wave of high pressure vapor lies between 0.5 and 1.6%. However, this result is difficult to be compared with that of corium/water interaction because the scaling analysis is difficult. Thus, more large-scaled experiments are further required for best estimate of steam explosion threat during the nuclear power plant severe accident.

References

1. M.L. Corradini, et al., Vapor Explosion in LWR: A Review of Theory and Modeling, Progress in Nuclear Energy, Vol. 22 (1988).
2. M.L. Corradini, D.V. Swenson, R.L. Woodfin and L.E. Voelker, An Analysis of Containment Failure by a Steam Explosion Following a Postulated Core Meltdown in a Light Water Reactor, Nuclear Engineering and Design, 66, pp. 287−298 (1991).
3. B.D. Turland et al., Quantification of the Probability of Containment Failure Caused by an In-vessel Steam Explosion for the Sizewell-B PWR, CSNI-FCI Specialists Meeting, Santa Barbara, CA (1993).
4. S.J. Board and R.W. Hall, Propagation of thermal explosions 1−tin/water experiments, CEGB Report RD/B/N 2350 (1974).
5. R.P. Anderson and D.R. Armstrong, R−22 vapor explosions, ANL Proceeding of ASME Annual Winter Meeting, Atlanta, Geogia (1977).
6. T. Enger and P. Hartman, Rapid phase transformation during LNG spillage on water, Proceeding of the 3rd Conference on Liquefied Natural Gas, Washington, D.C. (Sept. 1972).
7. R.J. Holt and A.H. Muenker, Flameless vapor explosions in LNG/water and other cryogen-hot liquid systems, GRV. 1 GPR. 72 (May 1972).
8. E. Nakanishi and R.C. Reid, Liquid nitrogen gas-water reactions, Chem. Eng. Progress Vol. 67 (12), p. 36, (1971).
9. D.L. Katz and C.M. Sliepdevish, LNG/water explosion: cause and effect, Hydrocarbon Processing, p. 240, (Nov. 1971)
10. R.E. Henry, J.D. Gabor, I.O. Winsch, E.A Erickson, J.J. Heiberger and G.T. Goldfuss, Large scale vapor explosions, Proceeding of the Fast Reactor Safety Meeting, Beverly Hills, Calf., p. 922 (April 1974).
11. H.K. Fauske, On the mechanism of UO_2−Na explosive interactions, Nuclear Science and Engineering 51, 95−101 (1979).
12. K.H. Bang and M.L. Corradini, Vapor explosions in a stratified geometry, Nuclear Science and Engineering 108, 88−108(1991).
13. Steam Explosion Review Group, A Review of the Current Understanding of the Potential for Containment Failure from In-Vessel Steam Explosion, NUREG−1116, pp. 10 (1985).