Steam Explosion Experiments in the "Test for Real cOrium Interaction with water (TROI)" Program

I. K. Park, Y. J. Chang, Y. S. Shin, C. H. Kim, B. T. Min, S. W. Hong, J. H. Song and H. D. Kim
Korea Atomic Energy Research Institute, Taejon, Republic of Korea

ABSTRACT

Korea Atomic Energy Research Institute (KAERI) launched an intermediate scale steam explosion experiment named "Test for Real cOrium Interaction with water (TROI)" using reactor material to investigate the effect of material composition, multi-dimensional melt/water interaction, and hydrogen generation. In the first series of tests using several kg of ZrO_2 where the melt/water interaction were made in the water pool at 30 ~ 95 °C, either a quenching or a spontaneous steam explosions was observed. The morphology of debris and pressure wave profiles show that there were mild local steam explosions. The melt water interactions were monitored by video cameras. The ZrO_2/Water interaction tests will continue until early 2001, in parallel with the improvements of the design of test facility. The test using UO_2 will be followed.

INTRODUCTION

The experimental research on fuel coolant interaction(FCI) has been performed during the last few decades. It was carried out in a wide range covering analytical work on single drop fragmentation[1], test on mixing[2], intermediate scale experiments with simulant material on FCI energetics in the FITS[3], ALPHA[4] and experiments using prototypic materials, such as FARO[5,6], KROTOS[7,8] , and COTELS[9]. The previous work greatly contributed to the agreement that the alpha-mode failure is not likely to occur in the absence of the external trigger and can be considered resolved from the risk perspective as discussed at the Steam Explosion Review Group (SERG-2) workshop in 1995, and the Specialist Meeting in Tokai, in 1997. But, there still remain FCI issues of safety concern to be resolved for PWRs. The first one is the structural loading to the PWR cavity with a deep water pool. The concern is of possible damage to the cavity walls, RPV (Reactor Pressure Vessel) supports and to containment penetrations. The second one is the structural loading of the lower head due to water-onto-melt steam explosions in the new plant designs adopting in-vessel retention (IVR) strategy. Steam explosions could potentially lead to a rapid failure of the RPV weakened by molten pool in the lower head. The RPV failure mode has an influence on melt ejection and spreading, and possibly an impact on coolability and on the operation of a core-retention device.

We note that the experimental data of the prototypic material was not sufficient to resolve a few uncertainties. The past prototypic experiments have some limitation such as material component, pouring diameter, and hydrogen effect. (1) Material properties: Most of the experts agree that the physical properties of the binary oxide melt seem to have a significant effect on the steam explosion triggerability and explosivity. The state of knowledge of the relevant material properties is still rather poor. (2) Hydrogen effect: The role of hydrogen augmentation or suppression in the FCI need also be investigated further, as the excessive hydrogen generation w as observed in the FARO/KROTOS experiments using prototypic melts. (3) Large pouring diameter: The past FCI work have usually conducted with the small size pouring diameter and the fuel/water mixing zone has very limited one-dimensionally geometry. It is clearly known in small scale experiments that the poured amount should have an effect on the violence of the steam explosion[10]. But, its effect is still not clear in the medium or large scale experiments.

KAERI (Korea Atomic Energy Research Institute) launched an experimental FCI research program named as "Test for Real cOrium Interaction with water (TROI)" under governmental long-term nuclear R&D plan since 1997. The object of the research is to resolve the generic safety issue of ex-vessel steam explosion for Korean Next Generation Reactor(KNGR) and to propose an appropriate severe accident management(SAM) strategy. It would also contribute to the understanding of the effect of the material property on the conversion efficiency of steam explosion, which is the essential and high-priority research topic for the FCI community. This paper describes the TROI test facilities, measurement system, the cold crucible, and results of five ZrO_2/Water tests.

The TROI TEST FACILITIES

A schematic diagram of the TROI test facilities is shown in Fig. 1. The test facilities consist of a pressure vessel including the upper and lower vessel, a sliding valve, and a test section inside the pressure vessel. The upper vessel contains crucible and melt release assembly. A slide valve located between the lower and upper vessel is used to isolate the upper and lower vessel.

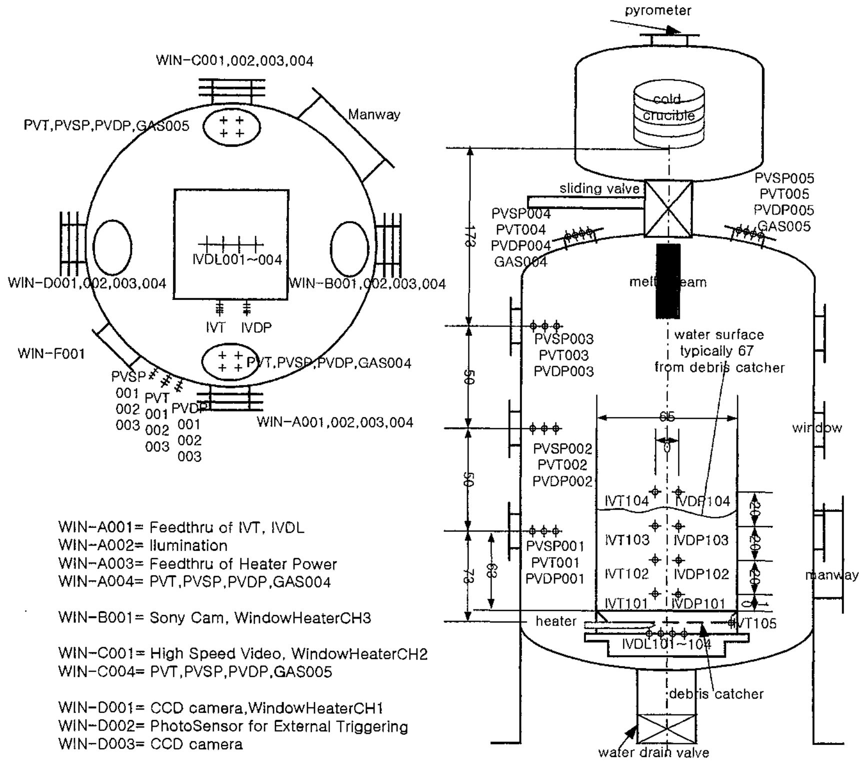

Fig. 1 TROI Facilities Configuration and Measurement Location(unit=cm)

Pressure Vessel and Test Section

The pressure vessel was designed to endure the static and dynamic load caused by a postulated steam explosion. The design pressure was determined to be 2 MPa, which was obtained by multiplying the safety factor of three to the conservative equilibrium pressure determined from the instantaneous mixing of 25 kg of corium with water. The dynamic impulse was determined from the TNT equivalent method, where the explosive energy was based on the conservative conversion efficiency of 3%, which was observed in the FCI experiments using Alumina/Water system[3]. The dynamic pressure was assumed to be in the triangular shape with duration of 3 ms. The integrity of the pressure vessel due to steam explosion load was demonstrated by an analysis using ANSYS computer code [11]. As the results of recent experiments [7,8] indicate that the corium is much resistant to the steam explosion than Alumina, the procedure used in the analysis of the structural loading provides proper safety margin.

In TROI tests, the various types of test section could be adapted because the pressure vessel has a role of pressure boundary. The test section of TROI tests was designed to easily visualize the fuel/water interaction. The transparent (1cm thick polycarbonate) plates were attached at the four side of 1450x65x65 cm rectangle. The lower part and the frame were made of stainless steel. The debris catcher, 15kW water heater, and thermocouple were adapted at the lower part. The one side was used for mounting thermocouple and piezo-electric pressure sensor and other walls were used for visualization.

Crucible and Melt Release Assembly

The cold crucible and release assembly consists of a crucible made of copper tubes, a plug at the bottom, and a puncher. The melt is typically contained in a cold crucible with a palisade-like wall consisting of water-cooled copper tubes. The sintered layer, which is naturally formed along the inner surface of cold crucible, plays a crucial role in retaining the molten material without direct contact. Inductive skull melting of oxides is basically a direct inductive heating of an electrically conducting melt by an alternating electromagnetic field. After the plug is removed for melt delivery, the conical-shaped puncher punches the crust formed at the bottom of melt to initiate the melt discharge. The theory and results of melting experiments using cold crucible used in this facility is described in detail in Hong et. al.[12] .

Measurements System

Table 2 and Fig. 1 show the measurement configuration. An optical two-color pyrometer (Korea-Chino co., resolution : 2℃, 1100~3100℃) measured the melt temperature in the furnace. The pyrometer views the melt pool through a hole formed in the upper crust of the melt. The hole in the upper crust is formed at the initial charging of the powder. The hole is maintained naturally during the melting process. A number of K-type thermocouples measure temperatures in the test section, pressure vessel atmospheric space, and in the inlet and exit cooling line of the induction coil.

Piezoelectric pressure transducers(PCB piezotronics inc., model 112A, maximum pressure 69 MPa, or 6.9Mpa, r ise time 2 μs, and resonant frequency 250 kHz) are mounted on the wall of the test section and on the wall of the pressure vessel for measuring dynamic pressures during the melt water interaction. The static pressure transducer (Druck Co., model pmp4060, maximum pressure 35 bar, response time 1KHz) measures the transient pressure inside the test vessel and containment chamber. V XI system (800kHz sampling/channel, 1kHz/channel) by Agilent Technology is used for the data acquisition. The transient data are acquired at two different frequencies of 100 Hz and 50 kHz by one control program.

The high-speed digital video imaging system (Phantom V 4.0, 512x512 pixels at 1000 pps) captures the pictures of explosive fuel coolant interaction. CCD camera at 4 locations (two at the lower vessel, two at the upper vessel) monitors the sequence of the events for the experiments. Two out of four CCD cameras are connected to the video system for recording. Gas samples are taken for chromatographic analysis using a gas sampling system consisting of sample cylinders with manual valves at the inlet and outlet of cylinders.

Table 1. Measurements Position and Sensor Description

Parameter	Sensing location	Sensor description
Coolant temperature	IVT101~IVT104	1mm, Thermocouple
Dynamic pressure in the coolant	IVDP101, IVDP103	PCB model 112A <60MPa
Atmosphere temperature in the pressure vessel	PVT001~PVT003	1.6mm, Thermocouple
Transient pressure in the pressure vessel	PVSP002, PVSP003	Druck model PMP4060 <35bar
Dynamic pressure in the pressure vessel	PVDP001, PVDP002	PCB model 112A <20MPa
FCI phenomena visualization	13 windows available	30pps videos and 1000pps video

TROI-ZrO_2 TEST PROCEDURE

1) Heat up the water in the test section. 2) Start melting of ZrO_2 by turning on the power of RF generator while the slide gate valve is closed. 3) Monitor the melting process and the temperature of the melts. 4) Vent the containment chamber to maintain the atmospheric pressure. 5) Open the slide gate valve. 6) Turn off the power to the RF generator. 7) Open the plug, activate puncher, and Close the slide gate valve. This procedure was automated with appropriate time delay. Complete data acquisition

RESULTS AND DISCUSSTION

In three tests out of the five TROI-ZrO_2 tests, the mild spontaneous steam explosions occurred. That results are very interesting in comparison to those of past UO_2-ZrO_2/Water system [5~8], which did not lead to any spontaneous explosion. In the case of non-explosive TROI-ZrO_2 tests, the quite different breakup behaviors from those of the UO_2-ZrO_2/Water system were observed, which will be discussed below.

Table 2. Initial Condition and Results for TROI-ZrO_2 Tests(SS=Steam Spike, SE=Steam Explosion)

	TROI test number	Unit	1	2	3	4	5
Melt	Composition UO_2/ ZrO_2/Zr	[w/o]	0/99/1	0/99/1	0/99/1	0/99/1	0/98/2
	Temperature	[K]	>3327	-	3200	3200	3900
	Charged mass	[kg]	8.01	8.4	7.8	7.2	6.4
	Initiator mass	[kg]	0.1	0.1	0.1	0.1	0.1
	Released mass	[kg]	5	5.5	4.88	4.2	2.9
	Initial jet diameter	[m]	0.037	0.052	0.060	0.028	0.038
	Free fall in gas	[m]	2.5	2.5	2.5	2.5	2.5
Test Section	Water mass	[kg]	283	283	283	283	283
	Height	[m]	0.67	0.67	0.67	0.67	0.67
	Cross section	[mxm]	0.65x0.65	0.65x0.65	0.65x0.65	0.65x0.65	0.65x0.65
	Initial temperature	[K]	365	365	323	292	337
	Subcooling	[K]	5	8	50	81	36
Pressure Vessel	Initial pressure(air)	[MPa]	0.1	0.1	0.1	0.1	0.1
	Free volume	[m3]	8.032	8.032	8.032	8.032	8.032
Results	Maximum PV pressurization	[MPa]	0.02	0.008	0.01	0.03	0.035
	Maximum PV heat-up	[K]	15	20	25	37	40
	Maximum water heat-up	[K]	4	10	10	-	-
	Steam explosion		SS	NO	NO	SE	SE
	Dynamic pressure peak	[MPa]	1	-	-	2.1(3peaks)	0.9(2peaks)
Debris	Total amount	[kg]	2.2	5.5	4.88	4.256	3.02
	Crust(>50mm)	[kg]	0.98	2.54	2.56	1.36	0.62
	Crust(10-20mm)	[kg]	-	-	-	0.76	0.58
	Particle(10-20mm)	[kg]	0.2	2	1.12	0.18	0.04
	Particle-dominated(2-5mm)	[kg]	0.67	0.67	0.77	1.116	0.74
	Particle(2-710 m)	[kg]	0.15	0.25	0.35	0.54	0.54
	Fine particle(<710 m)	[kg]	0.04	0.04	0.08	0.26	0.5

FCI Visualization

The five 30pps videos and one 1000pps video were used for visualizing FCI phenomena and melt release. The exposure time was set with very short time and/or the neutral density filter was needed because melt was very bright. Fig. 2 shows that the mixture is nearly 20cm wide body. We focus on taking the picture of the mixing phenomena .The recording speed, exposure time, and recording time were 500pps, 0.8ms, and 8sec respectively. Thus, the whole picture became very bright when the explosion occurred.

Melt Temperature

During melting process, the melt temperature was measured using the two-color pyrometer. When the melt temperature was out of the upper range of the pyrometer., it can be extrapolated by using Eqn (1).

$$\frac{1}{S} = \frac{1}{T} + K\ln(\gamma) \tag{1}$$

where, S ,T ,K , and γ are the real melt temperature, the measured temperature, the characteristic constant of pyrometer, and the emissivity of the pyrometer to be set, respectively. K was evaluated from the black body system with 1000~2000 K temperature range and the value of K is 3.4106E-4. With this extrapolation, the measured melt temperature was close to 3900K for the TROI-5 test.

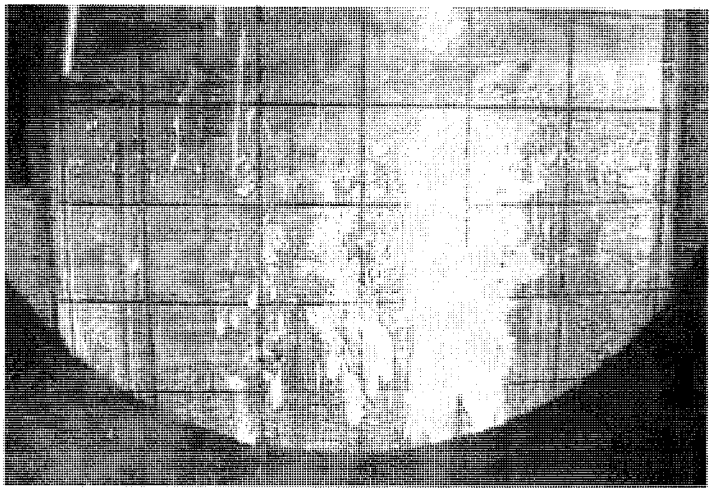

Fig. 2 The High Speed Photo Image of the ZrO_2/Water Mixing Behaviors

Dynamic Pressure

Fig. 3 shows the measured dynamic pressure wave profiles. The dynamic pressures were measured at the test section and the violent sound could be heard outside pressure vessel in TROI-1, 4, 5 tests. The measured peak pressure at TROI-5 was less than the TROI-1, 4 tests, but its pressure wave width was larger than those. The explosion sound and the mechanical damage of the test section were most severe at TROI-5. It implies that the explosion work was not proportional to the peak pressure, but dependent upon the width of the pressure wave. The pressure wave at TROI-1 has a peak without width, the sound was very weak, and there was no damage in the test section. There exist two pressure peaks in TROI-5 test. The first peak is due to explosion and the second peak is reflected pressure wave. The pressure wave speed can be obtained as around 300m/s considering test section width and the time delay between two pressure peaks. It must be noted that the measured explosion pressure might be reduced due to the destruction of the interaction vessel wall.

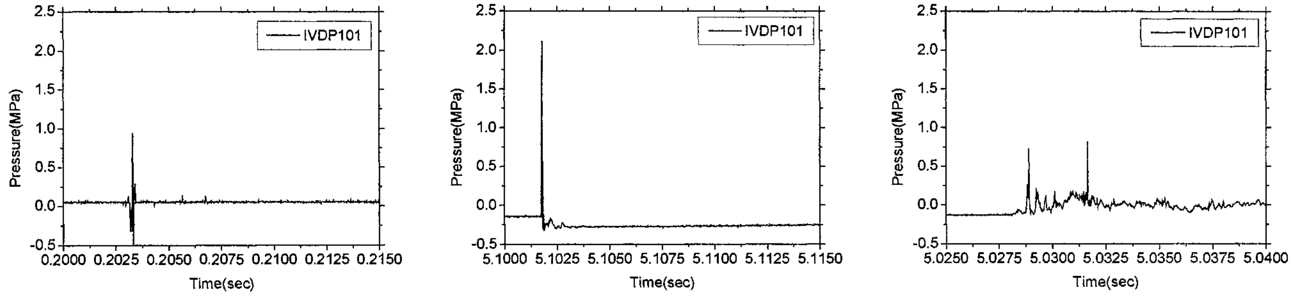

Fig. 3 Measured Dynamic Pressure Profiles at TROI-1, 4, 5 tests

Pressure and Temperature of the Pressure Vessel Atmosphere

Fig. 4 shows that if the FCI is more violent, the rate of the pressure vessel pressurization is larger. The pressure vessel pressurization for TROI-4, 5 tests were much higher than those at TROI-1, 2, 3. The pressure buildup of the pressure vessel seems to be caused by steam generation. Thus, the fine fragmentation due to the explosion increased the heat transfer area between coolant and fuel, and the rates of steaming and pressure buildup were high.

Fig. 5 shows that the pressure vessel atmospheric temperatures had the same trend as the pressure profile. The temperature increases at TROI 4, 5 tests, in which steam explosion occurred, were sharper and larger than those at TROI-1, 2, 3 tests. The temperature increase in the explosive case was above 35K, but the increase in the non-explosive case was below 25K. The very sharp increase in temperature of the pressure vessel atmosphere was measured in TROI-5 test. The temperature profiles of TROI-5 test have two peaks: The first peak is very sharp and the second peak is relatively broader than the first. It is estimated that the first peak was generated by the compression work and the second peak indicated heating by steam generation. That behavior did not occur in TROI-4, in which the interaction was less violent than TROI-5 test.

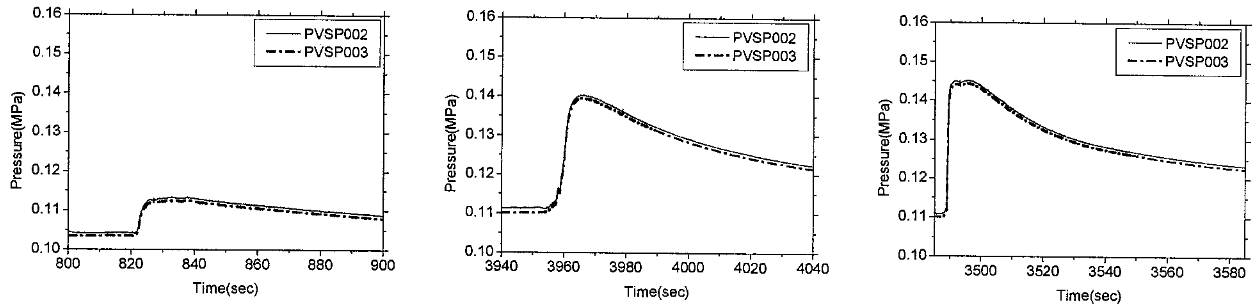

Fig. 4 Transient Pressure Profiles in the Pressure Vessel Atmosphere at TROI- 2, 4, 5 tests

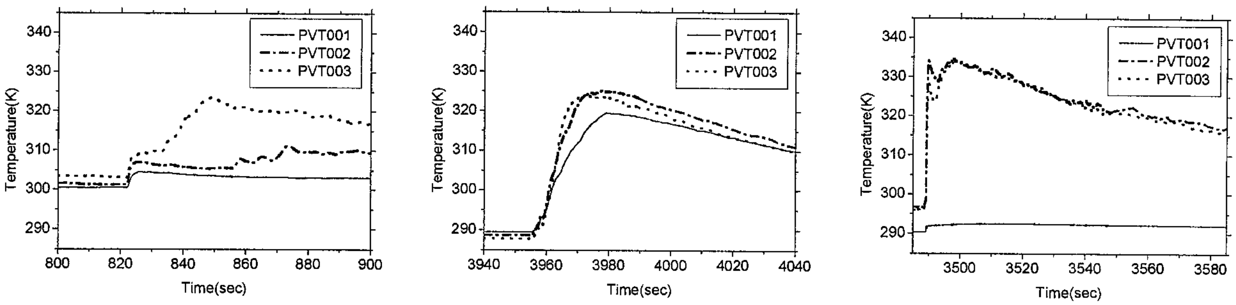

Fig. 5 Transient Temperature Profiles in the Pressure Vessel Atmosphere at TROI 2, 4, 5 tests

Water Temperature

Fig. 6 show that the coolant temperature increase at TROI-ZrO_2 test was relatively low because the coolant volume was very large compared to the fuel amount and the thermocouple location was far from the mixture. The coolant temperature at TROI-4, 5 tests showed the atmospheric temperature because the test section was broken and empty when the fuel was poured into the coolant. In the first three series TROI-1, 2, 3 tests, the coolant temperature increase was nearly 10K.

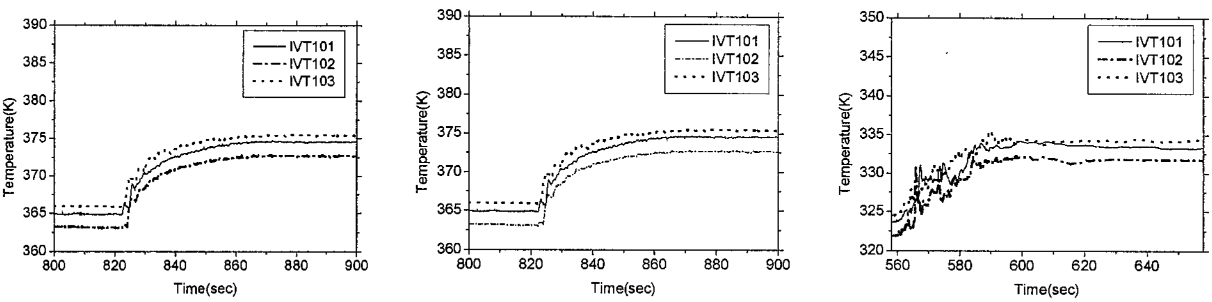

Fig. 6 Transient Temperature Profiles of the Water at TROI 1, 2, 3 tests

Debris Analysis

After all test, the debris were collected and analyzed using meshes at sizes 20mm, 5mm, 2mm, 710 m as shown as Table 2 and Fig. 7. Two kinds of debris were produced during ZrO_2/Water interaction: particles and crust. In TROI-2,3 tests, the amount of large size(5-10cm) crust is about 50% of total poured melt, and the amount of large particle size at 1~2cm is 20% and the other are smaller particles. In TROI-4, 5 tests, the large amount of small size crust and the fine fragments less than 1mm were produced, while the portions of the large particle and large shell shape debris became lower than those at TROI-1, 2, 3 tests. The fine fragments seem to be generated during explosion propagation wave, which breaks the large size particle. And the small size crust produced when expansion wave split the large size crust.

Thus, the primary difference of debris distribution between explosive case and quenching case were in the amount of large particles and fine particles. The fine particles were only discovered in TROI-4, 5, in which FCI was violent. The amount of fine particles at TROI-5 was 0.5kg as much as the double of 0.26kg at TROI-4, while the amount of other size particles were larger at TROI-4 than at TROI-5. Thus, the fine particle mass should be explosive measure together with the explosion pressure wave. The FCI was more explosive, the portion of fine particles was larger and the potion of large particles was smaller. It seems that the large particles generated in mixing process should be participated in the steam explosion and be converted into the fine particles.

When there was no spontaneous explosion, the debris distribution was quite different from that of previous work using UO_2-ZrO_2 melt. This ZrO_2/Water interaction induced a lot of large size particle with 1~2cm diameter, while the primary portion of the particle had the diameter of less than 5mm in the previous UO_2-ZrO_2/Water interaction.

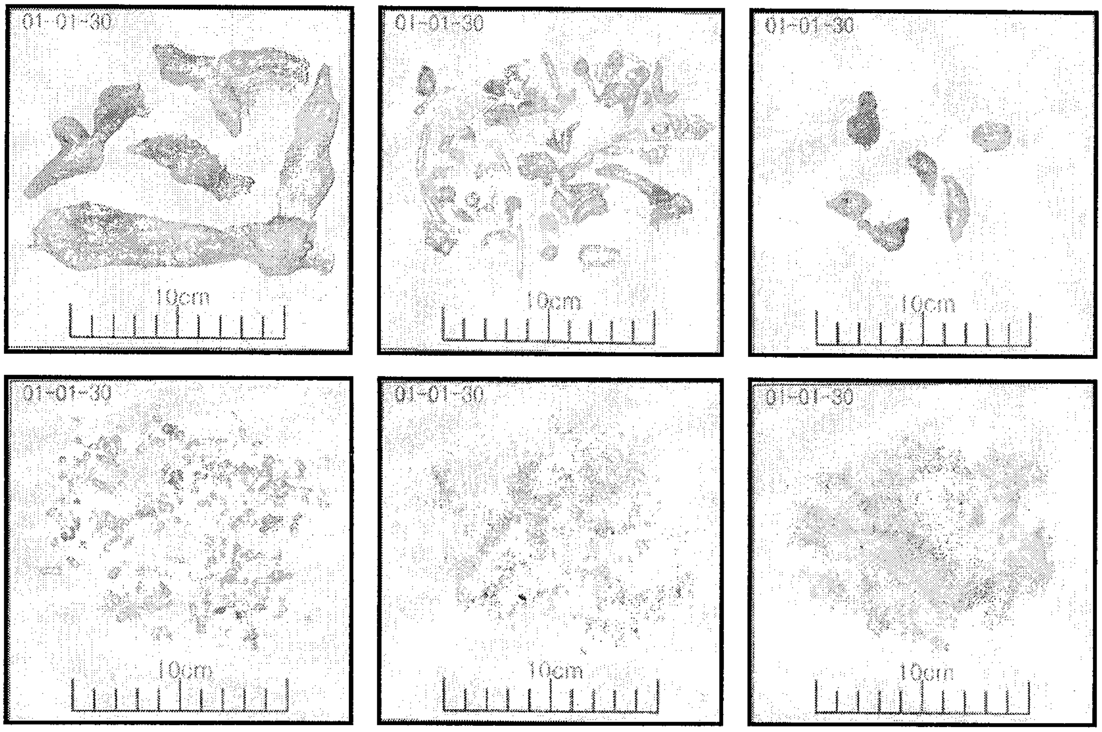

Fig. 7 Debris Configurations (a. Crust 5~10cm, b. Crust 1~2cm, c. Particle 1~2cm, d: Particle-dominated 2~5mm, e. Particle 2~0.710mm, f. Particle <710 m)

Violent FCI vs. Quenching FCI

The violent cases could be distinguished from the quenching cases by the dynamic pressure wave, the exploding sound, the fine fragments, and the sharp pressure and temperature increase. The results of TROI-2 and TROI-5 test, which are chosen as the representative quenching test and steam explosion test, obviously show this difference. In TROI-5 test, the explosion pressure with the peak of 1 MPa and the width of several mili-seconds was measured and the violent exploding sound was heard. The pressure and temperature in the pressure vessel rapidly increased. In TROI-2 test, however, there were no explosion pressure wave and violent sound. Also, the pressure and temperature increase were mild and small.

In TROI-5 test, 0.54kg of the tiny particles with about 2mm diameter and the fine fragments with the diameter below 0.7mm of 0.5kg were collected, while the large particle with 1~2cm diameter was rarely collected. The TROI-2 test shows exactly the reverse behaviors. The small particle and fine fragments was rarely collected and the mass of large particle amounts to 1.12 kg. This trend is consistently observed in the TROI-1, 3, 4 tests.

SUMMARY AND CONCLUSION

Korea Atomic Energy Research Institute (KAERI) has been working on the intermediate scale steam explosion experiments named

"Test for Real cOrium Interaction with water (TROI)" using reactor material to investigate the effect of material composition. The construction of the test facilities for FCI test in a multi-dimensional geometry was completed and the instrumentation and control system was set up and the cold crucible technology was implemented for the melting of UO_2-ZrO_2 mixture. TROI-ZrO_2 tests were performed and relevant transient data are collected. From the results of test it is observed that

(1) The ZrO_2/Water system induced spontaneous steam explosion, even though the subcooling of coolant was not very high. The dynamic pressure, which is considered to occur due to FCI, was measured in three tests among five tests.

(2) The energetic steam explosion is able to be identified by the measured dynamic pressure, the explosive sound, the mechanical damage of test section, the atmospheric pressure and temperature increase profile, and collected debris distribution.

(3) The debris analysis implied that the breakup phenomena might be quite different from that of previous work using UO_2-ZrO_2 melt.

ACKNOWLEDGEMENT

Present research is supported by the long-term nuclear R&D plan of the Ministry of Science and Technology in Republic of Korea. Mr. Hwang had an effort for preparing these experiments.

REFERENCES

1. X. Chen, R. Luo, W. W. Yuen, T. G. Theofanous, "Experimental simulation of microinteractions in large scale explosions", *Proc. of final program of CSNI specialist meeting on fuel coolant interactions*, pp. 364-390, JAERI-Tokai, Japan, 1997.
2. M. K. Denham, A. P. Taylor, and D. F. Fletcher, "Experiments on the mixing of molten Uranium dioxide with water and initial comparisons with Chymes code calculations", *Proc. of NURETH-5*, Vol. IV, Utah, SA, 1992.
3. D. E. Mitchell, M. L. Corradini, W. W. Tarbell, *Intermediate scale steam explosion phenomena: Experiments and analysis*, SAND81-0124, SNL,1981.
4. N. Yamano, Y. Maruyama, T. Kudo, A. Hidaka, J. Sugimoto, "Pehnomenological studies on melt-coolant interactions in the ALPHA program", *Nuclear Engineering and Design*, Vol. 155, 1995, pp.369-389.
5. D. Magallon, I. Huhtiniemi, and H. Hohmann, "Lessens learnt from FARO/TERMOS corium melt quenching experiments", *Proc. of final program of CSNI specialist meeting on fuel coolant interactions*, JAERI-Tokai, Japan, May 19-21, 1997.
6. D. Magallon and I. Huhtiniemi, "Corium melt quenching tests at low pressure and subcooling water in FARO", Proc. of NURETH-9, San-Francisco, California, U.S.A. October 1999.
7. I Huhtiniemi, D. Magallon, and H. Hohmann, "Results of recent KROTOS FCI tests: Alumina vs. Corium Melts", Proc. of final program of CSNI specialist meeting on *fuel coolant interactions*, JAERI-Tokai, Japan, May 19-21, 1997.
8. Huhtiniemi and D. Magallon, "Insight into Steam Explosions with Corium Melts in KROTOS", *Proc. of NURETH-9*, San-Francisco, California, U.S.A. October 1999.
9. M. Kato, H. Nagasaka, Y. Vasilyev, A. Kolodesshnikov, and V. Zhdanov, "Fuel coolant interaction tests under ex-vessel conditions", *Proc. of the OECD workshop on ex-vessel debris coolabilitty*, pp. 293-300, Karlsruhe, November 1999.
10. M. L. Corradini , "A Review of Experiments for Accident Analysis", *Nuclear Safety*, Vol. 32, No. 3, July-September, 1991.
11. C. R. Cho, J. H. Song, H. D. Kim, "An Assessment of the Integrity of the TROI Vessel under the Steam Explosion Loads", *Proc. of Korean Nuclear Society Meeting*, Fall, 2000.
12. S. W. Hong, B. T. Min, J. H. Song, H. D. Kim, J. K. Choi, "A Study on the Melting and Release of Refractory Materials using Induction Skull Melting", *Proc. of NTHAS2*, Fukuoka, 2000.

Steam Explosion Experiments in the "Test for Real cOrium Interaction with water (TROI)" Program

I. K. Park, Y. J. Chang, Y. S. Shin, C. H. Kim, B. T. Min, S. W. Hong, J. H. Song and H. D. Kim
Korea Atomic Energy Research Institute, Taejon, Republic of Korea

ABSTRACT

Korea Atomic Energy Research Institute (KAERI) launched an intermediate scale steam explosion experiment named "Test for Real cOrium Interaction with water (TROI)" using reactor material to investigate the effect of material composition, multi-dimensional melt/water interaction, and hydrogen generation. In the first series of tests using several kg of ZrO_2 where the melt/water interaction were made in the water pool at 30 ~ 95 °C, either a quenching or a spontaneous steam explosions was observed. The morphology of debris and pressure wave profiles show that there were mild local steam explosions. The melt water interactions were monitored by video cameras. The ZrO_2/Water interaction tests will continue until early 2001, in parallel with the improvements of the design of test facility. The test using UO_2 will be followed.