

TROI

An Investigation on the Influence of Water Depth and Melt Composition on a Steam Explosion in the TROI Experiments

150

TROI 가 가 zirconia
 80 : 20 , 10 ~ 20kg . UO₂ ZrO₂ 70 : 30
 67cm . 가 130cm . 5 130cm
 steam spike 가 가 67cm 2
 5.43kg . 가 67cm zirconia ~
 5.5MPa , 500kN .
 가 , zirconia
 가 (FARO 2%)

Abstract

In the recent TROI experiments, steam explosion experiments have been performed using corium melt of two different compositions and zirconia melt. The compositions (UO₂ : ZrO₂) of the corium were 70 : 30 and 80 : 20 in weight percent and the mass of the corium was 10 ~ 20kg. The water depth was 130cm and 67cm for the experiments. In case of the interaction between the corium melt and water pool of 130cm in depth, no steam explosion occurred. With a 67cm deep water pool, steam spikes were observed with corium melt of two different compositions. In the interaction between the zirconia melt(~5.43kg) and the 67cm deep water pool, an explosive steam explosion occurred accompanying pressure waves of 5.5MPa and a dynamic load greater than 500kN. It is thought that a steam explosion would not be triggered in a deep water pool since the melt could be cooled down and then solidified before the contact between the melt and the vessel bottom due to the long traveling through water. As varying the composition of the melt, the explosivity of zirconia is found to be much higher than that of corium. The hydrogen gas which was commonly believed to suppress a steam explosion was negligibly generated (less than 2% of the FARO experiment), irrelevantly to the occurrence of a steam explosion.

1.

가 ,
 가 .
 [1], [2, 3, 4], [5, 6, 7], [8, 9, 10] [11].
 ANL ZREX [4] JRC-Ispra FARO/KROTOS [5, 6, 7] zirconia TROI
 zirconia 가 [12, 13, 14, 15].
 TROI

2. TROI

TROI 1 , , ,
 212°C 20
 (>3000K) 가 가
 water jacket
 가 가 가 150kW, 50kHz ..
 가
 , 가 가 , ,
 가 가 1 가 2
 (IRCON 1500~3500°C)
 (grey-body condition) 가
 K-type 가
 (Piezoelectric pressure transducer, PCB Piezotronics Inc., Model 112A, maximum range: 60MPa 20MPa)가
 (Druck Co., Model PMP4060, maximum range: 3.5MPa, Rosemount model 1511: 2.0MPa)가
 VXI system(Agilent Technology)
 가 CCD
 Phantom V4.0 512×512 pixel 1000 frames/sec
 CCD
 가 (zirconia)
 가 가
 Zr 가 Zr 가 ,
 zirconia 가
 가 가 가 가 가 가

가 plug
 puncher
 triggering

3. TROI

zirconia TROI-19 TROI-26 8
 . TROI-19 UO₂ ZrO₂ 80 : 20 ~ 20kg
 130cm . TROI-20 UO₂ : ZrO₂ = 70 : 30
 TROI-19 . TROI-21 80 : 20
 10kg 130cm
 . TROI-22 TROI-23 TROI-21 . TROI-24 ~ TROI-26
 67cm . TROI-24
 zirconia , TROI-25 70 : 30 , TROI-26
 80 : 20 . TROI-19 TROI-26
 2 3

3.1. TROI-19

TROI-19 36.3kg UO₂ ZrO₂ (80:20)
 21.1kg , 130cm
 UO₂ , 2 IRCON
 3200K 가
 가 3200K
 3 void 가
 가 4 , 51K
 가 가 가
 가 2 5
 (0.71mm
) (7%) . 0.526g FARO [5]
 . FARO 157kg 300g 가
 , FARO 1.3%

3.2. TROI-20

TROI-20 30kg UO₂ ZrO₂ (70:30)
 19.7 kg , 130cm

가 . 6 IRCON 2 가 .
 3200K 가 가 .
 7

TROI 70 : 30 67cm
 [14, 15], 가 (8
) , 180K 가 .
 2 9
 2 ~ 4.75mm (48%) , (0.71mm) 9%

3.3. TROI-21 ~ TROI-23

TROI-21 ~ TROI-23 가 TROI-23
 . TROI-21 22 2
 TROI-18 17kg 80 : 20 (UO₂ : ZrO₂) 10.4kg ,
 130cm . 3600K
 10
 가 11
 , 80 : 20 TROI
 가 (67cm) [15], 가
 , 105K 가 . 12 3
 13 . 0.288g FARO 1.4% (8%),

3.4. TROI-24

TROI-24
 9.5kg zirconia 5.43kg , 67cm
 14
 3600K .
 data 15 data 5.5MPa 16
 data 500kN . zirconia 가
 17 ,
 가 21K . 18 ,
 35K 가 . ,

가
 3 19 (0.71mm) 12%
 , 6.35mm (52%)
 zirconia

3.5. TROI-25

TROI-25 15.0kg
 70 : 30 (UO₂ : ZrO₂) 9.005kg , 67cm
 20
 3500K 21 ,
 가 steam spike 가
 data steam spike , 25kN
 steam spike 가 22 23
 24 , 90K 가
 3 25 steam spike
 15%
 (20%) (10%) [14, 15].

3.6. TROI-26

TROI-26 80 : 20 17.0kg
 80 : 20 (UO₂ : ZrO₂) 12.31kg , 67cm
 26
 3300K 27 , 가
 data steam spike , steam spike 가
 , 28 29 15kN
 , 27K 30
 , 85K 가 3 31
 steam spike 13%
 TROI-25
 0.069g (FARO 0.5%)

4.

TROI-19 TROI-26

- (130cm) TROI-19 ~ TROI-23

- zirconia () TROI-24
5.5MP, 500kN zirconia
 - (UO₂ : ZrO₂ = 70 : 30) TROI-25 steam
spike 가
 - (UO₂ : ZrO₂ = 80 : 20) TROI-26
steam spike 가 [13, 14, 15]
80 : 20 70 : 30
 - 가 FARO
2%
- conversion ratio

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10. K. H. BANG and G. D. Jeun, "Minimum Film Boiling Temperatures for Spheres in Dilute Aqueous Polymer Solutions and Implications for the Suppression of Vapor Explosions," *Journal of Korean Nuclear Society*, **27**, No.4, 544-554 (1995).

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12. , “TROI ZrO₂/ FCI ;” (2001).
13. , “ZrO₂ UO₂/ZrO₂ FCI ;” (2001).
14. , “TROI ;” (2002).
15. , “ TROI ;” (2002).

1. Sensor descriptions in the TROI tests

Parameter	Sensing location	Sensor descriptions
Melt temperature	Top window	IRCON pyrometer (1500 ~ 3500°C)
Coolant temperature	IVT101 ~ IVT106	1.0mm dia., K-type thermocouple
Melt velocity	IVT201 ~ IVT208	0.5mm dia., K-type thermocouple
Dynamic pressure in the coolant	IVDP101 ~ IVDP106	PCB model 112A <60MPa
Dynamic load at the test section bottom	IVDL101	PCB model W217B <500kN
Atmosphere temperature in the pressure vessel	PVT001 ~ PVT005	1.0mm dia., K-type thermocouple
Static pressure in the furnace vessel	FVSP001	Rosemount model 1511 < 2.0MPa
Static pressure in the pressure vessel	PVSP002, PVSP003	Druck model PMP4060 <3.5MPa
Dynamic pressure in the pressure vessel	PVDP004, PVDP005	PCB model 112A <20MPa
Gas Sampling for Hydrogen detection	GAS005	Gas sampling bottle
FCI phenomena visualization	13 windows available	30pps videos and 1000pps video

2. Initial condition & results for the TROI tests (TROI-19 ~ TROI-22)

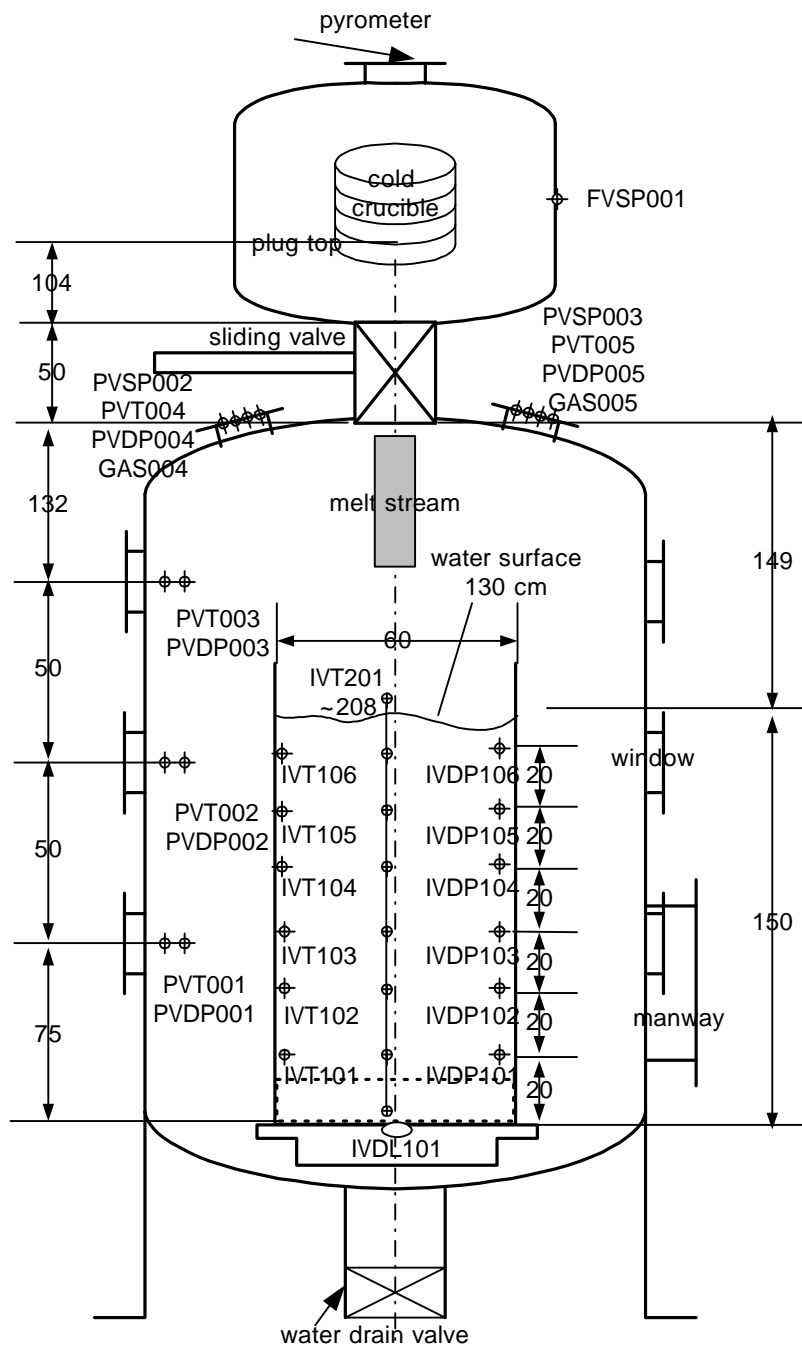
	TROI test number	Unit	19	20	21	22
Melt	Initial Charge Composition UO ₂ / ZrO ₂ /Zr	[w/o]	79/20/1	69/30/1	79/20/1	79/20/1
	Temperature	[K]	3200(?)	3200	3000	2900
	Charged mass	[kg]	36.263	30.0	17.0	17.0
	Initiator mass	[kg]	0.1	0.1	0.1	0.1
	Released mass	[kg]	21.065	19.715	7.320	9.910
	Plug/puncher diameter	[cm]	10.0/6.5	10/6.5	8.0/6.5	8.0/6.5
	Initial jet diameter	[cm]	7.7	-	8.0	7.4
	Free fall in gas	[m]	3.2	3.2	3.2	3.2
	Test Section	Water mass	[kg]	367	367	367
Initial height		[cm]	130	130	130	130
Final height		[cm]	-	-	-	-
Cross section		[m ²]	0.283	0.283	0.283	0.283
Initial temperature		[K]	295	303	298	297
Sub-cooling		[K]	78	70	75	76
Pressure Vessel	Initial pressure(air)	[MPa]	0.118	0.108	0.110	0.110
	Initial temperature	[K]	297	298	296	295
	Free volume	[m ³]	8.032	8.023	8.023	8.023
Results	Maximum PV pressurization	[MPa]	0.035	0.037	0.011	0.025
	Time to reach peak	[sec]	2	2	10	3
	Maximum PV heat-up	[K]	51	180	50	160
	Time to stabilize	[sec]	20	10	10	15
	Maximum water heat-up	[K]	22	30	20	13
	Time to stabilize	[sec]	5	10	15	10
	Steam explosion		NO	NO	NO	NO
	Dynamic pressure peak	[MPa]	-	-	-	-
	Duration	msec	-	-	-	-
	Impulse	kN	-	-	-	-
Duration	msec	-	-	-	-	
Debris	Total	[kg]	21.065	19.715	7.320	9.910
	>6.35mm	[kg]	3.210	1.955	-	-
	4.75mm ~ 6.35mm	[kg]	2.635	2.675	-	-
	2.0mm ~ 4.75mm	[kg]	9.340	9.520	-	-
	1.0mm ~ 2.0mm	[kg]	3.535	2.860	-	-
	0.71mm ~ 1.0mm	[kg]	0.940	0.970	-	-
	0.425mm ~ 0.71mm	[kg]	0.880	0.985	-	-
	<0.425mm	[kg]	0.525	0.750	-	-
H ₂ gas	Before/After the interaction	[ppm]	86/801	Not measured	Not measured	Not measured
	Mass	[g]	0.526	measured	measured	measured
Note			Medium crucible, Water level: 130cm	Medium crucible, Water level: 130cm	Small crucible, Water level: 130cm	Same as TROI-21

* NO : No steam explosion

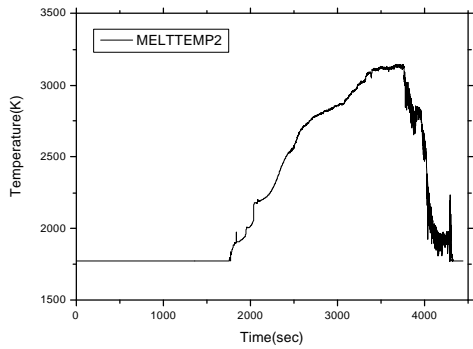
3. Initial condition & results for the TROI tests (TROI-23 ~ TROI-26)

	TROI test number	Unit	23	24	25	26
Melt	Initial Charge Composition UO ₂ / ZrO ₂ /Zr	[w/o]	79/20/1	0/99/1	69/30/1	79/20/1
	Temperature	[K]	3600	3600	3500	3300
	Charged mass	[kg]	17.0	9.5	15.0	17.0
	Initiator mass	[kg]	0.1	0.1	0.1	0.1
	Released mass	[kg]	10.385	5.430	9.005	12.310
	Plug/puncher diameter	[cm]	8.0/6.5	8.0/6.5	8.0/6.5	8.0/6.5
	Initial jet diameter	[cm]	7.4	3.2	8.0	4.5
	Free fall in gas	[m]	3.2	3.8	3.8	3.8
	Test Section	Water mass	[kg]	367	189	189
Initial height		[cm]	130	67	67	67
Final height		[cm]	117	60	64	62
Cross section		[m ²]	0.283	0.283	0.283	0.283
Initial temperature		[K]	293	288	287	283
Sub-cooling		[K]	80	85	86	90
Pressure Vessel	Initial pressure(air)	[MPa]	0.110	0.110	0.110	0.106
	Initial temperature	[K]	296	291	291	288
	Free volume	[m ³]	8.023	8.032	8.023	8.023
Results	Maximum PV pressurization	[MPa]	0.020	0.015	0.021	0.029
	Time to reach peak	[sec]	3	3	3	5
	Maximum PV heat-up	[K]	105	35	90	85
	Time to stabilize	[sec]	10	10	10	25
	Maximum water heat-up	[K]	8	21	22	27
	Time to stabilize	[sec]	5	20	30	35
	Steam explosion		NO	SE	SS	SS
	Dynamic pressure peak	[MPa]	-	5.5	0.2	-
	Duration	msec	-	1.0	1.5	-
	Impulse	kN	-	>500	25	15
Duration	msec	-	7.0	10.0	20.0	
Debris	Total	[kg]	10.385	5.430	9.005	12.310
	>6.35mm	[kg]	1.250	2.805	0.705	1.095
	4.75mm ~ 6.35mm	[kg]	1.505	0.325	1.030	1.720
	2.0mm ~ 4.75mm	[kg]	4.475	0.865	4.135	4.980
	1.0mm ~ 2.0mm	[kg]	1.825	0.595	1.285	2.215
	0.71mm ~ 1.0mm	[kg]	0.500	0.180	0.495	0.720
	0.425mm ~ 0.71mm	[kg]	0.490	0.240	0.655	0.870
	<0.425mm	[kg]	0.285	0.420	0.700	0.710
H ₂ gas	Before/After the interaction	[ppm]	20/438	19/1335	49/14	28/105
	Mass	[g]	0.288	0.877	0.009	0.069
Note			Same as TROI-22	ZrO ₂ 67cm	70:30 67cm	80:20 67cm

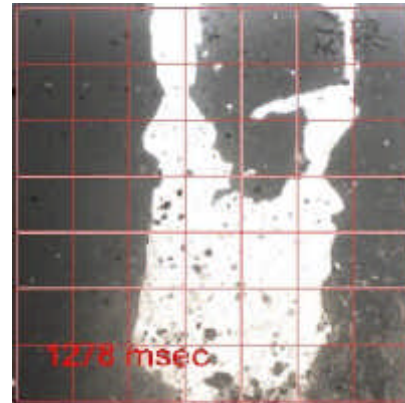
* NO : No steam explosion, SE : Steam explosion, SS : Steam spike



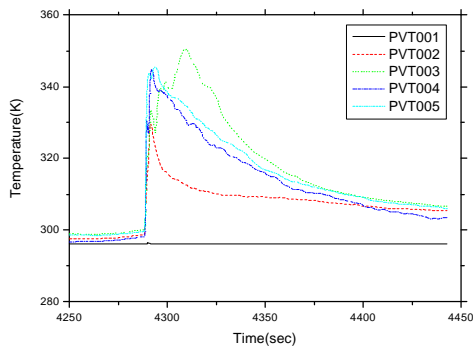
1. Schematic diagram of TROI facility



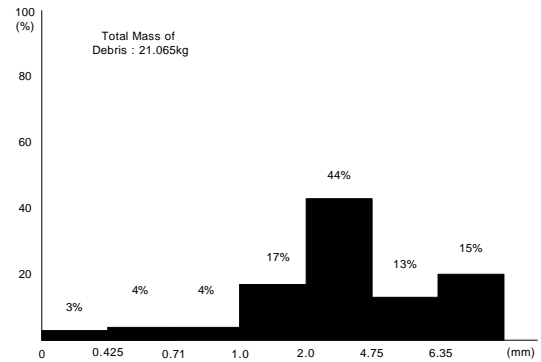
2. Melt temperature in the TROI-19 test



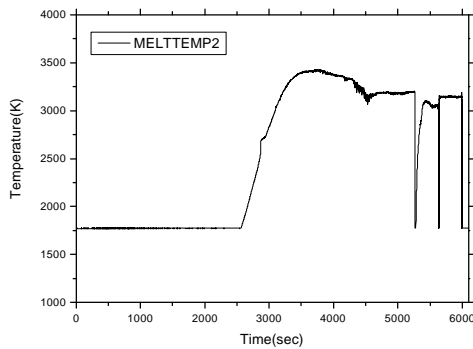
3. Photograph of melt injection in the TROI-19 test



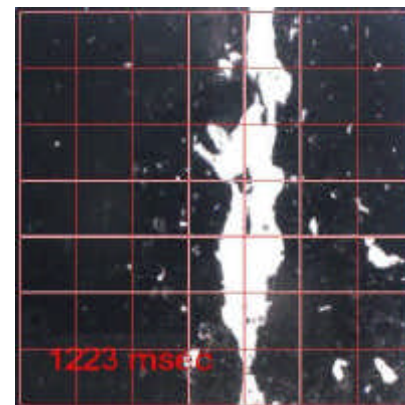
4. Temperatures in the pressure vessel in the TROI-19 test



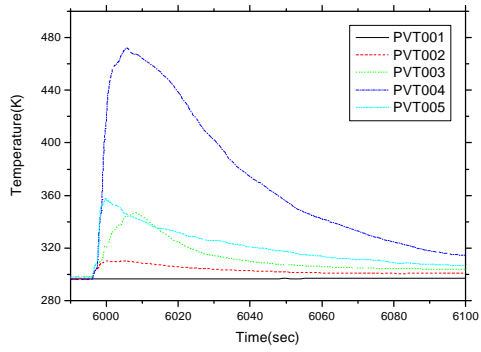
5. Sieved debris distribution in the TROI-19 test



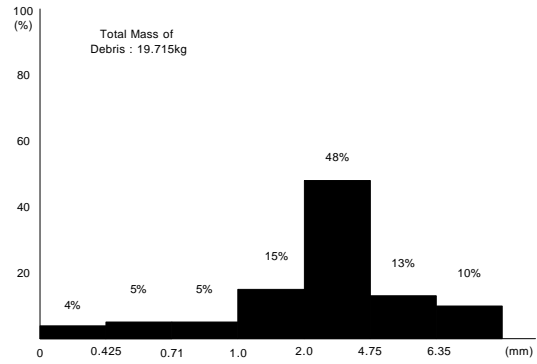
6. Melt temperature in the TROI-20 test



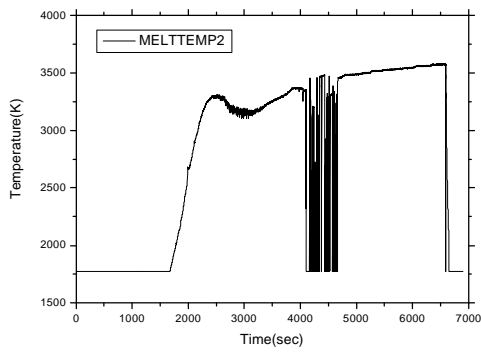
7. Photograph of melt injection in the TROI-20 test



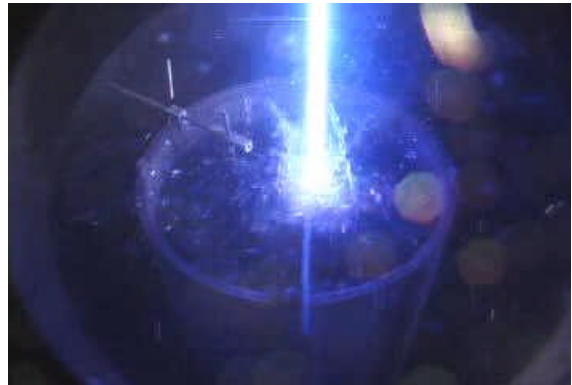
8. Temperatures in the pressure vessel in the TROI-20 test



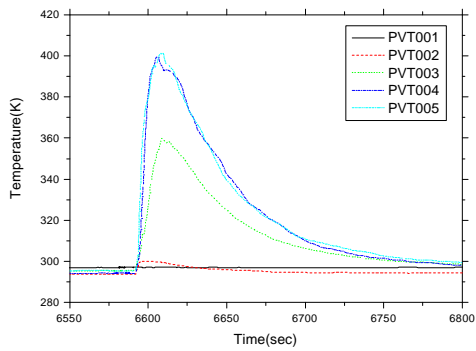
9. Sieved debris distribution in the TROI-20 test



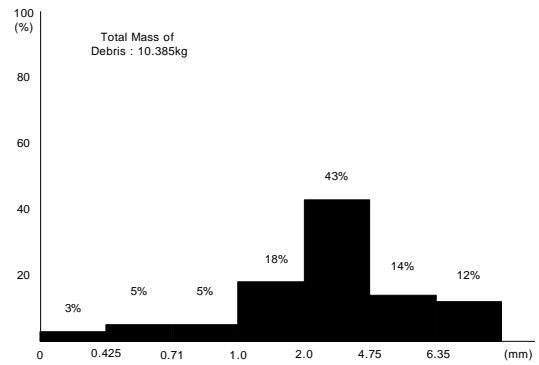
10. Melt temperature in the TROI-23 test



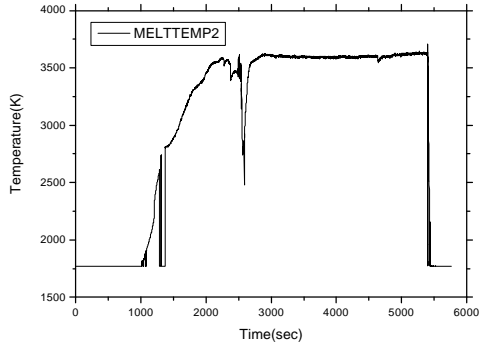
11. Photograph of melt injection in the TROI-23 test



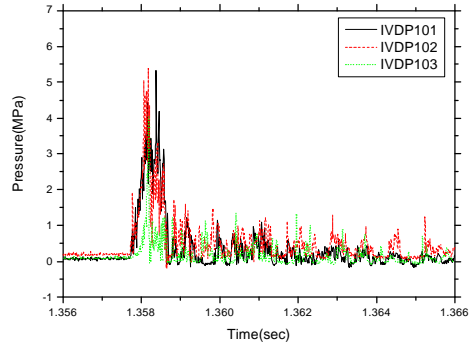
12. Temperatures in the pressure vessel in the TROI-23 test



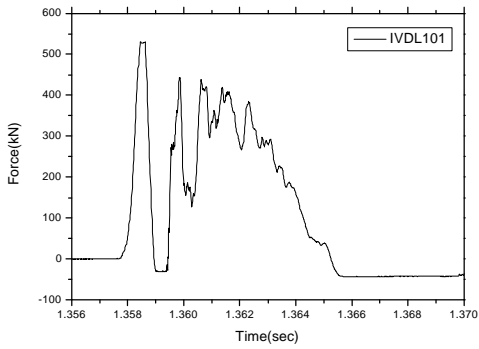
13. Sieved debris distribution in the TROI-23 test



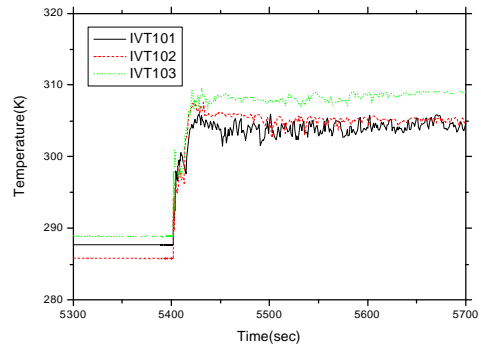
14. Melt temperature in the TROI-24 test



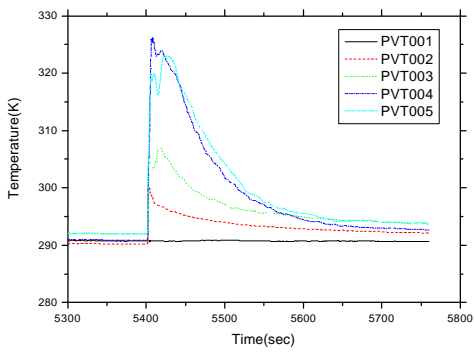
15. Dynamic pressures in the TROI-24 test



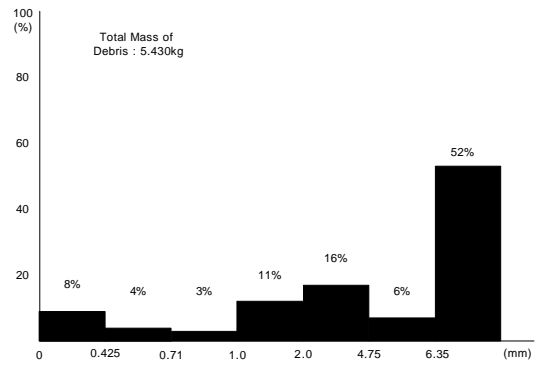
16. Dynamic load in the TROI-24 test



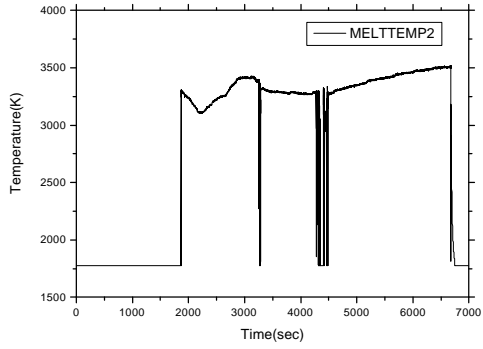
17. Water temperatures in the interaction vessel in the TROI-24 test



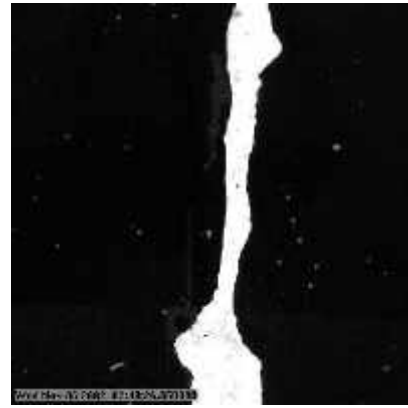
18. Temperatures in the pressure vessel in the TROI-24 test



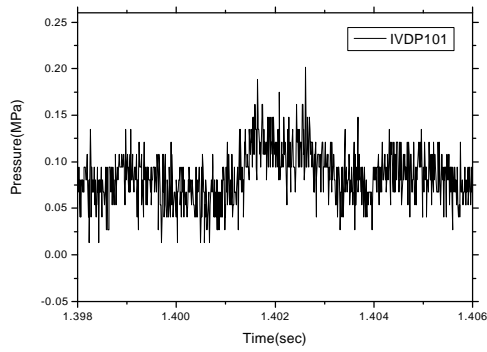
19. Sieved debris distribution in the TROI-24 test



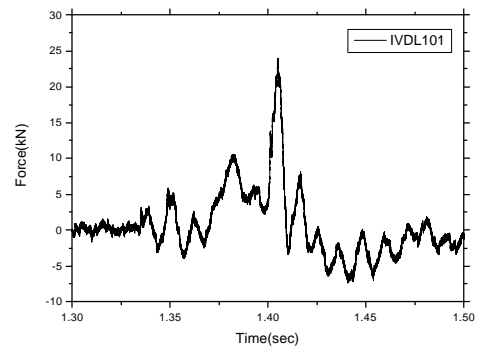
20. Melt temperature in the TROI-25 test



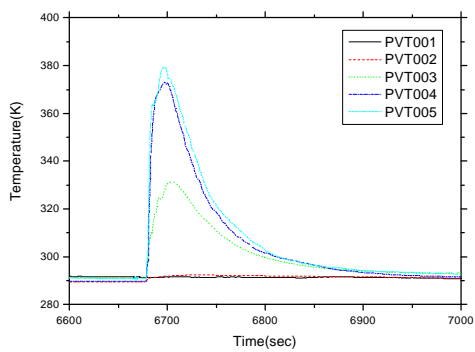
21. Photograph of melt injection in the TROI-25 test



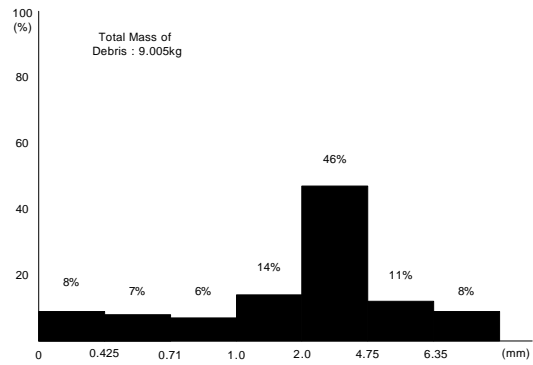
22. Dynamic pressures in the TROI-25 test



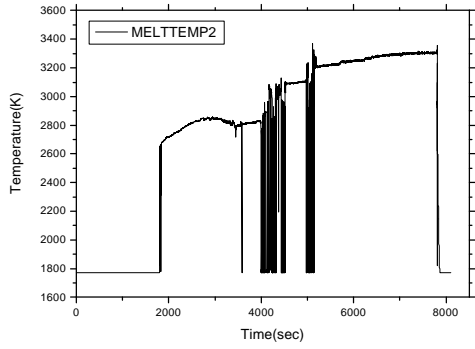
23. Dynamic load in the TROI-25 test



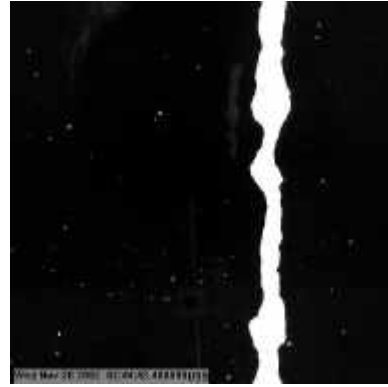
24. Temperatures in the pressure vessel in the TROI-25 test



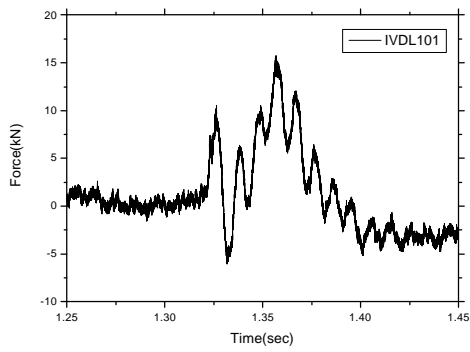
25. Sieved debris distribution in the TROI-25 test



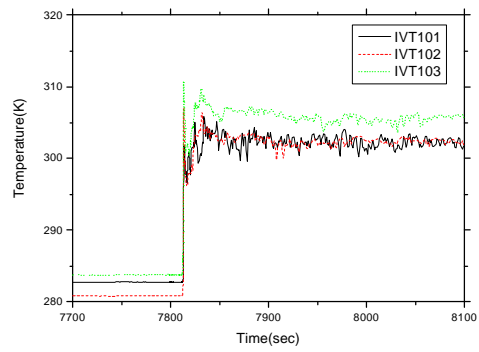
26. Melt temperature in the TROI-26 test



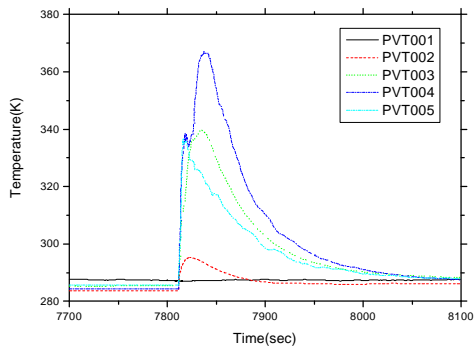
27. Photograph of melt injection in the TROI-26 test



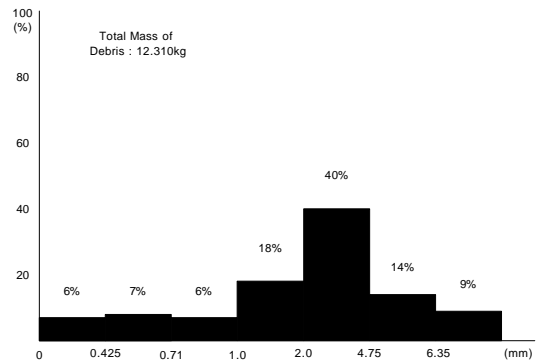
28. Dynamic load in the TROI-26 test



29. Water temperatures in the interaction vessel in the TROI-26 test



30. Temperatures in the pressure vessel in the TROI-26 test



31. Sieved debris distribution in the TROI-26 test