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차세대원자로 소형냉각재상실사고시의 DVI ECCS 성능실험을 위한 예비 실험 조건

Preliminary Test Conditions for KNGR SBLOCA DVI ECCS Performance Test

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제 출 문

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이 보고서를 1998년도 차세대원자로 기술개발과제중 계통안전해석분야의 기술보고서로 제출합니다..

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요 약 문

차세대 원자로에 채택될 4 트레인 DVI 안전주입은 안전주입수가 8.5" DVI 노즐을 통하여 원자로용기 내 Downcomer로 직접 주입됨으로 인하여 LOCA시 하향 유로에서의 ECC mixing 및 bypass 등의 열 수력 현상이 기존의 저온관 주입과는 매우 다르게 예측되므로 비상노심냉각수의 실질적인 주입 현상을 파악하고, 저온관 주입을 기본으로 개발된 해석 코드의 개선을 위한 열 수력 자료 생산을 위해서는 차세대원자로를 모의한 열 수력 실증실험이 수행되어야 하고 이를 위한 성능해석이 필요하다.

차세대원자로에 채택하고자하는 DVI 주입방식의 소형냉각재상실사고에 대한 CEFLASH-4AS/REM 해석결과를 검토하여, 당 사고시의 사고 시나리오 및 주요 열수력 현상을 파악하고 도출하였다. 이 코드에 의한 계산 결과 노심 수위를 포함한 계통의 과도상태 거동은 Downcomer 모델링에 많은 영향을 받는 것으로 나타났다. 따라서, 제한된 실험경비 및 시간 내에서 Downcomer에서의 열 수력학적 특성을 적절히 살펴보기 위해서는 이 영역에 초점을 둔 개별효과 실험을 수행하는 것이 효과적인 것으로 판단되며 이를 반영한 예비실험장치를 제시하였다. 제시된 실험 장치에 대한 초기 및 경계조건을 CEFLASH-4AS/REM 해석결과를 바탕으로 작성하였으며, 이는 예비실험요건서의 입력으로 사용될것이고 실험 수행 팀과의 긴밀한 협의를 통하여 최종 실험요건서가 작성될 것이다.

SUMMARY

The Korean Next Generation Reactor (KNGR) adopts 4-train Direct Vessel Injection (DVI) configuration and injects the safety injection water directly into the downcomer through the 8.5" DVI nozzle. Thus, the thermal hydraulic phenomena such as ECC mixing and bypass are expected to be quitely different from those observed in the cold leg injection. In order to investigate the realistic injection phenomena and modify the analysis code developed in the basis of cold leg injection, thermal hydraulic test with the performance evaluation is required.

Preliminarily, the sequence of events and major thermal hydraulic phenomena during the small break LOCA for KNGR are identified from the analysis results calculated by the CEFLASH-4AS/REM. Is is shown from the analysis results that the major transient behaviors including the core mixture level are largely affected by the downcomer modeling. Therefore, to investigate the proper thermal hydraulic phenomena occurring in the downcomer with a limited budget and time, the separate effects test focusing on this region is considered to be effective and the conceptual test facility based on this is recommended. For this test facility the test initial and boundary conditions are developed using the CEFLASH-4AS/REM analysis results that will be used as input for the preliminary test requirements. The final test requirements will be developed through the further detailed discussions with the test performance group.

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1. Test Objectives

The objectives of the test facility are (1) to study the thermal hydraulic phenomena primarily in the downcomer region of the reactor vessel, but also in the core with respect to mixture level predictions, during direct vessel injection (DVI) line and cold leg breaks, (2) to generate thermal hydraulic data for CEFLASH-4AS/REM modification and development, and (3) to evaluate the performance of the ECCS with respect to the optimum elevation of DVI nozzles.

A conceptual schematic of the test facility is illustrated in Figure 1.1. This separate effects test facility focuses on the downcomer region above the cold-leg elevation and includes the necessary auxiliary equipment to simulate the various conditions that may occur in the downcomer during a DVI line and cold leg break. The test facility would allow the identification of the type of three dimensional, steam/water flow regimes that characterize the downcomer and show if (1) steam venting from one or more cold-legs and (2) the potential for SI fluid bypass to the break will take place. This test would provide sufficient information to either (1) adjust CEFLASH-4AS/REM to account for realistic, three dimensional effects in one or more downcomer nodes or (2) verify the results of a more sophisticated downcomer model (e.g., TRAC, FLUENT, etc.).

Other objectives of the test facility include predicting the core mixture level during a DVI line or cold leg break and core reflooding which occurs when the SITs discharge. The separate effects test illustrated in Figure 1.1 will provide the necessary information to deduce this behavior with additional calculations using data measured from the tests. The test facility will be capable of testing DVI line breaks at several elevations to obtain data that would indicate the optimum DVI line elevation with respect to the minimum core mixture level.

The test facility illustrated in Figure 1.1 consists of a reactor vessel annulus mockup fabricated from two concentric vessels or pipes.

Penetrations are provided to install cold leg, hot leg and DVI nozzles. The hot leg nozzles are included to complete the full representation of the annulus geometry and are not used to pass any flow. A heater (or boiler) provides the necessary energy to heat and pressurize the water in the mockup to the initial test conditions and to provide additional steam during depressruization to simulate steam generation by decay heat and flashing. A pressurizer is included to control the test system pressure and a pump to initially circulate the water during heatup. Safety injection through the DVI nozzles is simulated by a pressurized water storage tank whose pressure is controlled by a nitrogen blanket. Valves in various locations throughout the system control the flow of water or steam to simulate the test conditions and to control the operation of the facility.

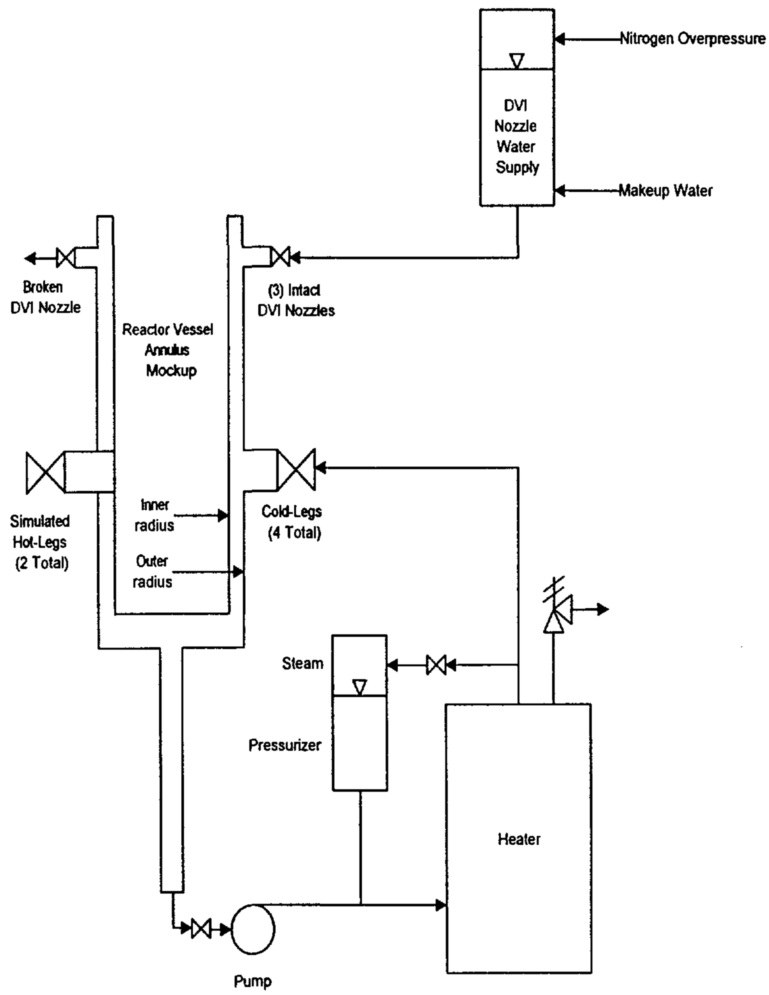

Figure 1.1 Separate effects test facility concept.

2. Background

1. The Korean Next Generation Reactor (KNGR) design adopts 4-train Direct Vessel Injection (DVI) configuration for SIS.

2. The thermal hydraulic test is required
   - to identify the injection phenomena during DVI line break
   - to develop a proper RV downcomer model for analysis of DVI line break
   - to evaluate ECCS performance depending on DVI nozzle elevation

3. The schematic drawing of KNGR reactor vessel with DVI nozzle is shown in Figure 2.1.

4. The KNGR SIS design is based on System 80⁺.
   - 2 Electrically separated divisions
   - 4 Mechanically separated hydraulic trains
   - 1 HPSIP & 1 SIT in each train
   - DVI : 8.5″ ID(10″ OD) nozzle
   - LBB issue is resolved by 10 OD pipe
   - PTS issue is resolved by changing the angle & elevation between DVI nozzle and cold leg nozzle and by increasing Copper content in RV material

5. The previous DVI tests for the ECC bypass and vent valve effects during the LBLOCA in cold leg performed at CCTF, UPTF (International 2D/3D program, [4]) showed that :
   - Definite multi-dimensional effect in downcomer region
   - Larger amount of ECC water is bypassed through the break till EOB than in CLI
   - Large amount of ECC water is penetrated into the lower plenum till EOB 40 - 50% of ECC water is bypassed through the break during the

reflood period

6. Since the test results may be significantly influenced by the geometric configuration of DVI, the test results of UPTF and CCTF can not be directly applied to KNGR. Thus, the test is required using the test facility simulating the KNGR DVI configuration.

7. The KNGR design should meet the following requirements related with SBLOCA.
   - 10 CFR 50.46 acceptance criteria should be met for up to double ended guillotine (DEG) of DVI line (8.5″ ID, 0.4 ft^2)
   - EPRI URD requirement : no fuel damage (no core uncovery) up to 6″ (0.2 ft^2) break using best estimate analysis

The CEFLASH-4AS/REM simulations documented in [1] and [2] show differences in the results between the cold-leg and DVI line break simulations, particularly those beginning with breaks larger than 0.2 ft^2 as illustrated in Figure 2.2 taken from [1]. The results in [1] show that for breaks smaller than 0.2 ft^2 the cold-leg and DVI line breaks produce similar results with regard to the minimum core mixture level reached during the transients. However, for breaks larger than 0.2 ft^2 the results for the cold-leg and DVI line breaks diverge significantly. For breaks larger than 0.2 ft^2 the cold-leg break simulations predict an increasing minimum core mixture level with increasing break size while the DVI line break simulations show a decreasing minimum core mixture level. Core uncovery is predicted to occur with DVI line breaks beginning at 0.2 ft^2. The largest breaks analyzed were 0.55 ft^2 for cold-leg breaks and 0.4 ft^2 for DVI line breaks.

Figures 31-42 for cold leg breaks and Figures 69-82 for DVI line breaks in [1] show that the two simulations proceed as expected and give nearly the same system responses until about 180 seconds into the transient when the steam discharge through the break is regularized.

After that, for the cold-leg breaks, steam exits the break thereby depressurizing the system and allowing the SITs to discharge their inventory. In contrast, for the DVI line breaks, a two-phase mixture exits the break. This increases the rate at which mass is lost from the system, it reduces the rate at which the system depressurizes and delays the time at which the SITs discharge. These effects are primarily responsible for the lower, minimum core mixture levels observed in the DVI line break simulations.

The two-phase flow out the DVI line during DVI line breaks is due to the limitations of the single, lumped node representation of the downcomer in CEFLASH-4AS/REM. For DVI line breaks the steam in the cold-legs is forced to pass through a continuous liquid phase in the downcomer node at a rate governed by the phase separation model used in lumped nodes for all steam flow rates. Actual flooding or entrainment, or the consideration of changing flow patterns due to varying steam velocities, are not explicitly modeled in the node. In addition, the three dimensional, asymmetric flow pattern distribution expected to occur in the downcomer region above the cold-legs cannot be predicted by a single, lumped node representation. It was concluded that the phase separation model together with the other limitations inherent in the single, lumped node representation does not provide a sufficiently accurate prediction of the flow in the downcomer.

Additional insights into the conditions calculated by CEFLASH-4AS/REM and those expected from a consideration of the flow patterns expected to prevail are given in [8]. Temporary recommendations to adjust CEFLASH-4AS/REM to simulate more realistic flow patterns are also recommended in [8] and [9]. References [8] and [9] describe a DVI SBLOCA analysis using an earlier version of CEFLASH-4AS (version 88030D). This analysis addressed the potential model bias discussed above by significantly increasing the steam separation multiplier in the downcomer node. The references also provide an engineering rational for this increase in the steam separation multiplier. With this increased steam separation multiplier, the break quality for the DVI line break increased significantly and the results of the analysis showed no core uncovery for a 10 inch DVI line break as can be seen from Figure 1 in [8].

The simulation results documented in [2] involve two, sectionalized node representations of the downcomer with cross-flow between the nodes. Parametrics were performed with different K-factors characterizing the cross-flow. This modification to the original single, lumped downcomer node model [1] produced only marginal improvements in the minimum core level during the transient. Clearly, additional modifications to the model are required, perhaps those discussed in [8]. Also, analysis using a more sophisticated three dimensional downcomer model (*e.g.*, TRAC, FLUENT, etc.) could potentially show a more beneficial response of the upper downcomer.

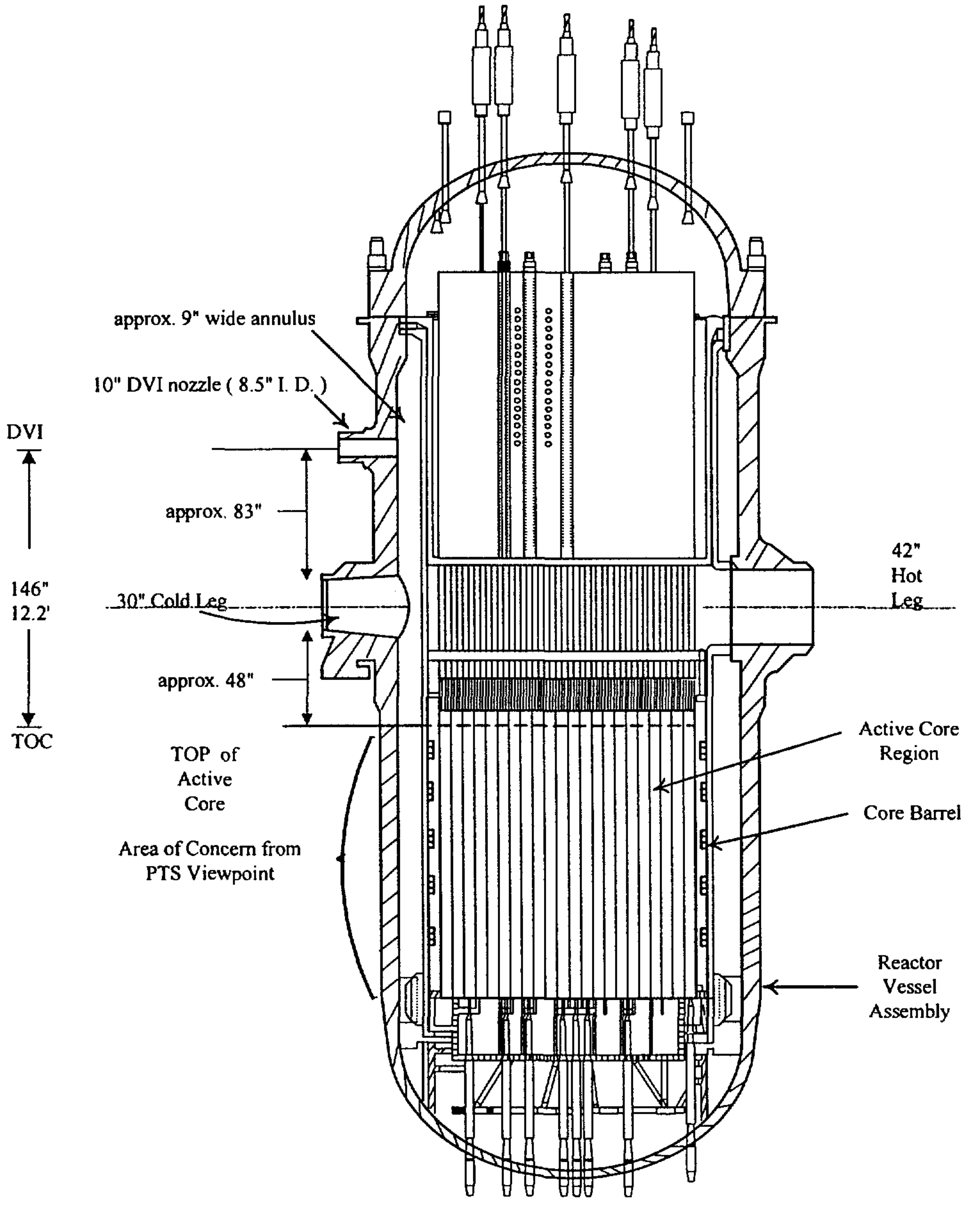

Figure 2.1 KNGR Reactor Vessel with DVI Nozzles

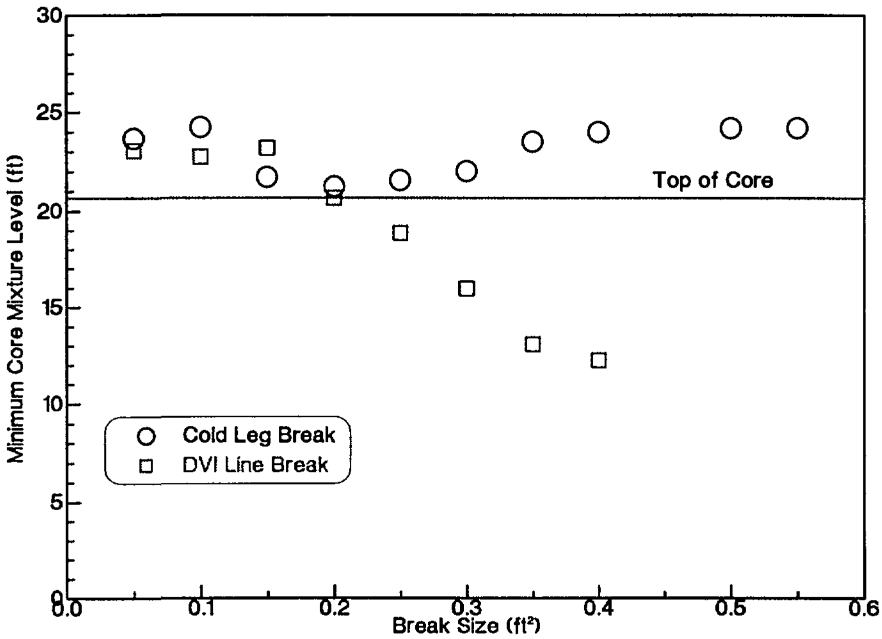

Figure 2.2 Summary of SBLOCA cases performed in [1].

3. Thermal Hydraulic Phenomena during DVI Line Break

o Typical DVI line break for a break area less than 0.5 ft^2 in pressure boundary.

o DVI line ID ; 8.5 " (0.4 ft^2)

o Event description of DVI line SBLOCA

- Rapid RCS coolant discharge and depressurization upon break opening
- Void generation from core upper plenum region by flashing due to depressurization
- SIAS, Reactor trip signal, RCP trip signal occur
- Turbine trip simultaneous with reactor trip causes the rapid increase of secondary pressure due to the MSSV opening pressure
- Core power decreases to decay heat level shortly after reactor trip
- Primary pressure decreases near to the secondary pressure and forms pressure plateau
- HPSI flow is delivered to the downcomer through three 8.5" DVI nozzles
- RCP starts coastdown with RCP trip signal
- Due to the loss of RCP head, water in the hot side U-tube and hot leg region drain to RV and the two-phase natural circulation path is broken
- Steam generated by flashing and boiling in core passes through the hot side U-tube and condenses
- Condensed water drains to RV and condenses the steam from the

core again : reflux condensation heat transfer mode

- The steam not condensed in the hot side U-tube passes through the cold side U-tube and RCP discharge leg and is collected in the loop seal
- The continuous steam buildup in loop seal causes pressure increase
- Loop seal clearing occurs when the steam pressure overcomes the hydraulic head in loop seal
- Direct steam venting path to the break is formed only when the steam pressure overcomes the hydraulic head in the downcomer from cold leg to the broken DVI nozzle
- When the energy removal through the break is less than the decay heat energy, the remaining energy should be removed by steam generator. i.e, primary heat is transferred to the secondary side by maintaining the primary temperature slightly above the secondary temperature
- Since the pressure is determined from temperature, RCS pressure is maintained slightly above the secondary pressure and shows pressure plateau
- Pressure plateau is continued until the break is uncovered and the steam starts to discharge
- From this time on, RCS pressure decreases below the secondary pressure and the secondary side plays the role of heat source superheating the steam generated from the core
- RCS pressure is rapidly decreased by the steam discharge through the DVI line
- When the RCS pressure decreases below the SIT gas pressure, large amount of SI water is injected to the downcomer
- When the SI water delivered to the core exceeds the break flow

core mixture level increases, core heatup stops, fuel cladding temperature decreases and the transient is terminated.

However, since the elevation of DVI nozzle is about 83″ higher than the cold leg, the thermal hydraulic phenomena during the DVI line break is expected to show a different behavior from those observed during the cold leg break. Thus, the more realistic thermal hydraulic phenomena during the DVI line break should be identified by performing a test, which will be used as a basis for model improvement of analysis code.

The sequences of events for representative breaks in cold leg and DVI line obtained from CEFLASH-4AS/REM analysis [1] are shown in Table 3.1

Table 3.1a Sequence of Events for Representative Cold Leg Breaks

Events	Break Cases		
	$0.05\ ft^2$	$0.2\ ft^2$	$0.55\ ft^2$
Break initiates	0.0	0.0	0.0
Reactor trips	35.12	12.72	9.51
RCPs trip	35.12	12.72	9.51
MSSVs open	42.32	18.87	15.70
HPSIs start	74.10	51.62	48.35
Hot leg drains	~ 750	130	not clearly seen
Loop seal clearing occurs	1080	210	109
Steam discharge occurs	900	172	36 (flashing) 84
Core uncovery occurs	N/A	N/A	N/A
Minimum core * mixture level is reached at, sec	23.668 ft at 886.1 sec	21.245 ft at 168.0 sec	24.212 ft at 67.8 sec
SITs start	N/A	558.7	170.7
End of simulation	3000	1000	300

Note : *) Top of core level = 20.67 ft

Table 3.1b Sequence of Events for Representative DVI Line Breaks

Events	Break Cases		
	0.05 ft^2	0.2 ft^2	0.4 ft^2
Break initiates	0.0	0.0	0.0
Reactor trips	35.32	12.72	10.61
RCPs trip	35.32	12.72	10.61
MSSVs open	42.32	18.78	16.0
HPSIs start	74.31	51.58	49.51
Hot leg drains	~ 1600	125	76
Loop seal clearing occurs	not cleared	230	216
Steam discharge occurs	2940	185	92
Core uncovery occurs	N/A	404.8	86.6
Fuel heatup starts	N/A	no heatup	135
Minimum core * mixture level is reached at, sec	23.046 ft at 2939.5sec	20.659 ft at 405.3 sec	12.236 ft at 212.6 sec
SITs start	N/A	440.6	209.9
End of simulation	5000	1000	500

Note : *) Top of core level = 20.67 ft

4. Phenomena Identification of DVI line SBLOCA

Since the different thermal hydraulic behavior between the cold leg break and DVI line break is expected to occur in the downcomer and core region, phenomena identification for DVI line break is considered only for this region. The other PIRTs (Phenomena Identification Ranking Tables) are described in [3].

The major three event phases of DVI line SBLOCA are as follows :

- Blowdown Phase
- Natural Circulation Phase
- Loss of Natural Circulation and Recovery

The thermal hydraulic phenomena expected to occur in downcomer and core region during each phase of DVI line SBLOCA : See Table 4.1. The expected Phenomena for DVI line break are :

- High speed jet impingement of SI water
- Injected SI water is entrained to the steam from the loop and bypassed to break
- Thermal hydraulic phenomena in downcomer such as water entrainment, axial and radial flow distribution, coolant mixing, and ECC bypass are expected to occur quite differently from CLI.
- Slower RCS depressurization due to the difficulty of steam venting
- More severe core level depression than in cold leg break

Table 4.1 DVI SBLOCA Identification of Phenomena

Phase	Component	Subcomponent	Phenomena
Blowdown	Vessel	Downcomer	Jet Impingement & Jet Breakup
			Entrainment
			ECC Bypass
			Counter Current Flow Limit
			Downcomer Flow Distribution
		Core	Core Level Depression
Natural Circulation	Vessel	Downcomer	Jet Impingement & Jet Breakup
			Entrainment
			Downcomer Hydraulics
Loss of Natural Circulation	Vessel	Downcomer	Jet Impingement & Jet Breakup
			Entrainment
			Downcomer Hydraulics

5. Test Matrix

The test matrix has two primary objectives. The first is to confirm the CEFLASH-4AS/REM DVI line break simulation results. Several small cold-leg and DVI line breaks will be conducted while principally measuring break flow rate and static quality. However, many other variables will also be measured during the test. The basis for this objective can be explained using Figures in [1]. For the 0.2 ft^2 break shown in Figures 25 and 28 (cold-leg breaks) and Figures 61 and 64 (DVI line breaks) it can be seen that the cold-leg break quality is 1.0 (all steam) shortly after the core mixture level reaches its minimum for that simulation while the DVI line break quality is much lower (two-phase flow) during the time the core mixture level reaches its minimum for that simulation. Similarly, for the 0.55 ft^2 cold-leg break (Figures 37 and 40) the break quality shortly after the minimum core mixture level is reached is again 1.0 while the 0.4 ft^2 DVI line break (Figures 75 and 78) is again much lower during the time the core mixture level reaches its minimum. Therefore the objective of the test matrix is to determine if the DVI line break quality is actually two-phase or if it is more like the cold-leg break flow. If it is shown, as expected, that the DVI line break flow is all, or mostly, steam then adjustments to CEFLASH-4AS/REM can be made to allow more steam venting during the DVI line break thereby increasing the predicted minimum core mixture level. The additional measured data from the test will indicate the mechanism responsible for the increased steam venting (*e.g.*, the absence of local flooding in the region between the broken DVI line and the nearest cold-leg nozzles or steam by-passing from the cold-legs to the broken DVI line, or both).

If the test results show that the cold-leg break quality is different from that predicted by CEFLASH-4AS/REM and the DVI line break quality is predominantly two-phase then a reassessment of the CEFLASH-4AS/REM models will be required. The cold-leg break response predicted by CEFLASH-4AS/REM has been compared to integral tests for cases where the ECCS is injected in the cold-leg.

The second objective of the test matrix is to find an optimum elevation for the DVI nozzles which results in the highest minimum core mixture level for a DVI line break. DVI line breaks at several elevations will be conducted with the principal measurements being downcomer flow rate and mixture level. From this data (and other relevant data measured during the tests) the core mixture level will be predicted by calculations.

The tests that will be conducted are listed in Table 5.1.

Table 5.1 Summary of Tests

Test No.	Type of Break	Break Size (ft^2)	Principal Data Measurements
Confirmation of CEFLASH-4AS/REM			
1	DVI Line	0.05	Break mass flow rate, break flow static quality.
2		0.20	
3		0.40	
4	Cold Leg	0.05	
5		0.20	
6		0.40	
Optimization of DVI Elevation			
7	DVI Line	0.40	Same as Test 3 but at an elevation of ? ft.
8		0.40	Same as Test 3 but at an elevation of ? ft.

6. Initial & Boundary Conditions

The initial condition is selected as the time when the RCS pressure plateau ends. The initial conditions and assumptions used for the CEFLASH-4AS/REM analysis and the calculated values of major parameters at the times when the pressure plateau ends and when rapid inner vessel mixture level recovers are given in Table 6.1. The node Diagram of CEFLASH-4AS/REM used for KNGR SBLOCA Analysis is shown in Fig.6.1

Table 6.1a Initial and Boundary Conditions and Assumptions Used For Analysis (0.05 ft^2 DVI Line Break)

PARAMETER	VALUE	
	Initial Time[1] (2940 sec)	End Time[1] (3600 sec)
Core Power, % Nominal Power (3914MWt)	1.54	1.44
DVI water supply tank initial N_2 pressure, psia	1187	
Total DVI Flow (3 DVI nozzles), lbm/s	257	354
DVI Water Temperature, ℉	120	120
DVI Flow Curve	See Table 6.2	See Table 6.2
Inner Vessel Pressure, psia	1187	736
Inner Vessel Mixture/Collapsed Level, ft	23.1/23.1	27.7/27.7
Inner Vessel Fluid Temperature (Avg./Subcooled), ℉	568/568	507/507
Inner Vessel Inlet Flow, lbm/s	696	-26
Downcomer Mixture/Collapsed Level, ft	29.6/29.6	29.7/29.7
Downcomer Fluid Temperature (Avg./Subcooled), ℉	568/322	506/313
Reactor Vessel Liquid Mass, lbm	141390	178990
Downcomer Liquid Mass, lbm	56294	56554
Cold Leg Fluid Temperature, ℉	344	354
Upper Cold Leg Flow (Paths 4/34/28/29), lbm/s	20/20/545/13	92/92/111/96
Lower Cold Leg Flow (Paths 14/33/19/21), lbm/s	-132/-132/420/-15	-154/-154/-135/-154

Table 6.1b Initial and Boundary Conditions and Assumptions Used For Analysis (0.2 ft^2 DVI Line Break)

PARAMETER	VALUE	
	Initial Time[1) (185 sec)	End Time[1) (440.6 sec)
Core Power, % Nominal Power (3914MWt)	3.08	2.56
DVI water supply tank initial N_2 pressure, psia	1189	
Total DVI Flow (3 DVI nozzles), lbm/s	256	376
DVI Water Temperature, ℉	120	120
DVI Flow Curve	See Table 6.2	See Table 6.2
Inner Vessel Pressure, psia	1189	623
Inner Vessel Mixture/Collapsed Level, ft	24.8/21.8	20.9/15.6
Inner Vessel Fluid Temperature (Avg./Subcooled), ℉	569/561	488/483
Inner Vessel Inlet Flow, lbm/s	408	442
Downcomer Mixture/Collapsed Level, ft	29.9/28.6	28.2/17.7
Downcomer Fluid Temperature (Avg./Subcooled), ℉	568/544	487/484
Reactor Vessel Liquid Mass, lbm	154190	91109
Downcomer Liquid Mass, lbm	44410	29490
Cold Leg Fluid Temperature, ℉	568	488
Upper Cold Leg Flow (Paths 4/34/28/29), lbm/s	101/101/38/205	89/89/26/101
Lower Cold Leg Flow (Paths 14/33/19/21), lbm/s	38/381/5.8/26	5.5/5.5/-2.7/2.9

Table 6.1c Initial and Boundary Conditions and Assumptions Used For Analysis (0.4 ft^2 DVI Line Break)

PARAMETER	VALUE	
	Initial Time1) (80 sec)	End Time1) (210 sec)
Core Power, % Nominal Power (3914MWt)	3.77	2.98
DVI water supply tank initial N_2 pressure, psia	1189	
Total DVI Flow (3 DVI nozzles), lbm/s	256	377
DVI Water Temperature, °F	120	120
DVI Flow Curve	See Table 6.2	See Table 6.2
Inner Vessel Pressure, psia	1189	618
Inner Vessel Mixture/Collapsed Level, ft	23.6/19.7	13.1/10.5
Inner Vessel Fluid Temperature (Avg./Subcooled), °F	569/565	487/482
Inner Vessel Inlet Flow, lbm/s	-3621	-86
Downcomer Mixture/Collapsed Level, ft	30.1/29.8	29.6/13.1
Downcomer Fluid Temperature (Avg./Subcooled), °F	568/558	487/485
Reactor Vessel Liquid Mass, lbm	152300	64486
Downcomer Liquid Mass, lbm	45366	21838
Cold Leg Fluid Temperature, °F	568	487
Upper Cold Leg Flow (Paths 4/34/28/29), lbm/s	-105/-83/-83/-81	22/123/122/21
Lower Cold Leg Flow (Paths 14/33/19/21), lbm/s	114/143/121/121	3.5/59/57/10

Table 6.1d Initial and Boundary Conditions and Assumptions Used For Analysis (0.05 ft^2 Cold Leg Break)

PARAMETER	VALUE	
	Initial Time1) (920 sec)	End Time1) (1500 sec)
Core Power, % Nominal Power (3914MWt)	2.17	1.9
DVI water supply tank initial N_2 pressure, psia	1185	
Total DVI Flow (3 DVI nozzles), lbm/s	342	409
DVI Water Temperature, °F	120	120
DVI Flow Curve	See Table 6.2	See Table 6.2
Inner Vessel Pressure, psia	1185	964
Inner Vessel Mixture/Collapsed Level, ft	25.5/24.5	26.0/25.5
Inner Vessel Fluid Temperature (Avg./Subcooled), °F	568/490	541/452
Inner Vessel Inlet Flow, lbm/s	551	500
Downcomer Mixture/Collapsed Level, ft	20.6/20.6	22.1/22.1
Downcomer Fluid Temperature (Avg./Subcooled), °F	568/408	541/301
Reactor Vessel Liquid Mass, lbm	140430	156120
Downcomer Liquid Mass, lbm	36924	42510
Cold Leg Fluid Temperature, °F	568	541
Upper Cold Leg Flow (Paths 4/34/28/29), lbm/s	-60/-60/-60/8.2	-8.6/-8.6/-7.6/72.3
Lower Cold Leg Flow (Paths 14/33/19/21), lbm/s	98/98/98/6	19/19/19/-259

Table 6.1e Initial and Boundary Conditions and Assumptions Used For Analysis (0.2 ft^2 Cold Leg Break)

PARAMETER	VALUE	
	Initial Time1) (175 sec)	End Time1) (440 sec)
Core Power, % Nominal Power (3914MWt)	3.12	2.56
DVI water supply tank initial N_2 pressure, psia	1189	
Total DVI Flow (3 DVI nozzles), lbm/s	341	478
DVI Water Temperature, ℉	120	120
DVI Flow Curve	See Table 6.2	See Table 6.2
Inner Vessel Pressure, psia	1189	710
Inner Vessel Mixture/Collapsed Level, ft	24.8/21.8	25.8/24.4
Inner Vessel Fluid Temperature (Avg./Subcooled), ℉	569/556	502/409
Inner Vessel Inlet Flow, lbm/s	153	184
Downcomer Mixture/Collapsed Level, ft	25.7/25.5	22.2/22.1
Downcomer Fluid Temperature (Avg./Subcooled), ℉	568/514	502/231
Reactor Vessel Liquid Mass, lbm	145780	154500
Downcomer Liquid Mass, lbm	41316	43931
Cold Leg Fluid Temperature, ℉	568	502
Upper Cold Leg Flow (Paths 4/34/28/29), lbm/s	224/224/90/46	58/58/22/-7
Lower Cold Leg Flow (Paths 14/33/19/21), lbm/s	8/9/-149/-768	-31/-31/-30/-228

Table 6.1f Initial and Boundary Conditions and Assumptions Used For Analysis (0.4 ft^2 Cold Leg Break)

PARAMETER	VALUE	
	Initial Time1) (58 sec)	End Time1) (250 sec)
Core Power, % Nominal Power (3914MWt)	3.77	2.88
DVI water supply tank initial N_2 pressure, psia	1190	
Total DVI Flow (3 DVI nozzles), lbm/s	341	505
DVI Water Temperature, °F	120	120
DVI Flow Curve	See Table 6.2	See Table 6.2
Inner Vessel Pressure, psia	1190	606
Inner Vessel Mixture/Collapsed Level, ft	24.5/21.1	26.0/22.1
Inner Vessel Fluid Temperature (Avg./Subcooled), °F	569/564	485/427
Inner Vessel Inlet Flow, lbm/s	-2467	897
Downcomer Mixture/Collapsed Level, ft	30.3/30.2	17.0/17.0
Downcomer Fluid Temperature (Avg./Subcooled), °F	585/545	485/249
Reactor Vessel Liquid Mass, lbm	159990	127810
Downcomer Liquid Mass, lbm	46861	33472
Cold Leg Fluid Temperature, °F	569	485
Upper Cold Leg Flow (Paths 4/34/28/29), lbm/s	-361/-148/-67/-1363	63/62/35/-162
Lower Cold Leg Flow (Paths 14/33/19/21), lbm/s	107-3.4/62/-1509	63/62/34/-162

Table 6.1g Initial and Boundary Conditions and Assumptions Used For Analysis (0.55 ft^2 DVI Line Break)

PARAMETER	VALUE	
	Initial Time1) (58 sec)	End Time1) (170 sec)
Core Power, % Nominal Power (3914MWt)	4.08	3.13
DVI water supply tank initial N_2 pressure, psia	1186	
Total DVI Flow (3 DVI nozzles), lbm/s	342	500
DVI Water Temperature, °F	120	120
DVI Flow Curve	See Table 6.2	See Table 6.2
Inner Vessel Pressure, psia	1186	626
Inner Vessel Mixture/Collapsed Level, ft	26.1/22.5	25.9/20.0
Inner Vessel Fluid Temperature (Avg./Subcooled), °F	568/566	488/453
Inner Vessel Inlet Flow, lbm/s	-254	1123
Downcomer Mixture/Collapsed Level, ft	28.3/25.1	16.2/16.2
Downcomer Fluid Temperature (Avg./Subcooled), °F	568/561	488/309
Reactor Vessel Liquid Mass, lbm	154980	112410
Downcomer Liquid Mass, lbm	37994	31070
Cold Leg Fluid Temperature, °F	568	488
Upper Cold Leg Flow (Paths 4/34/28/29), lbm/s	241/245/367/-1330	82/82/65/-229
Lower Cold Leg Flow (Paths 14/33/19/21), lbm/s	66/672/760/-1438	82/82/63/-229

Table 6.2 HPSI Flow Curve (1 HPSIP)

RCS Pressure (psia)	Average (gpm)	Maximum (gpm)	Minimum (gpm)
14.7	1106	1232	980
34.7	1104	1232	976
54.7	1098	1224	972
74.7	1094	1224	964
94.7	1090	1220	960
114.7	1086	1216	956
134.7	1082	1212	952
154.7	1072	1204	940
174.7	1068	1201.7	934.2
189.7	1064.4	1200	929
214.7	1056	1192	920
229.7	1051	1184	918
244.7	1048	1180	916
314.7	1029	1152	906
414.7	1004	1116	892
614.7	914	1044	784
814.7	818.7	961.3	676
914.7	769	920	618
1014.7	716	872	560
1214.7	604	776	432
1414.7	477.3	658.7	296
1514.7	373.2	600	146.4
1553.7	330.7	573.5	88
1614.7	266	532	0
1834.7	0	396	0
1964.7	0	192	0
2055	0	0	0

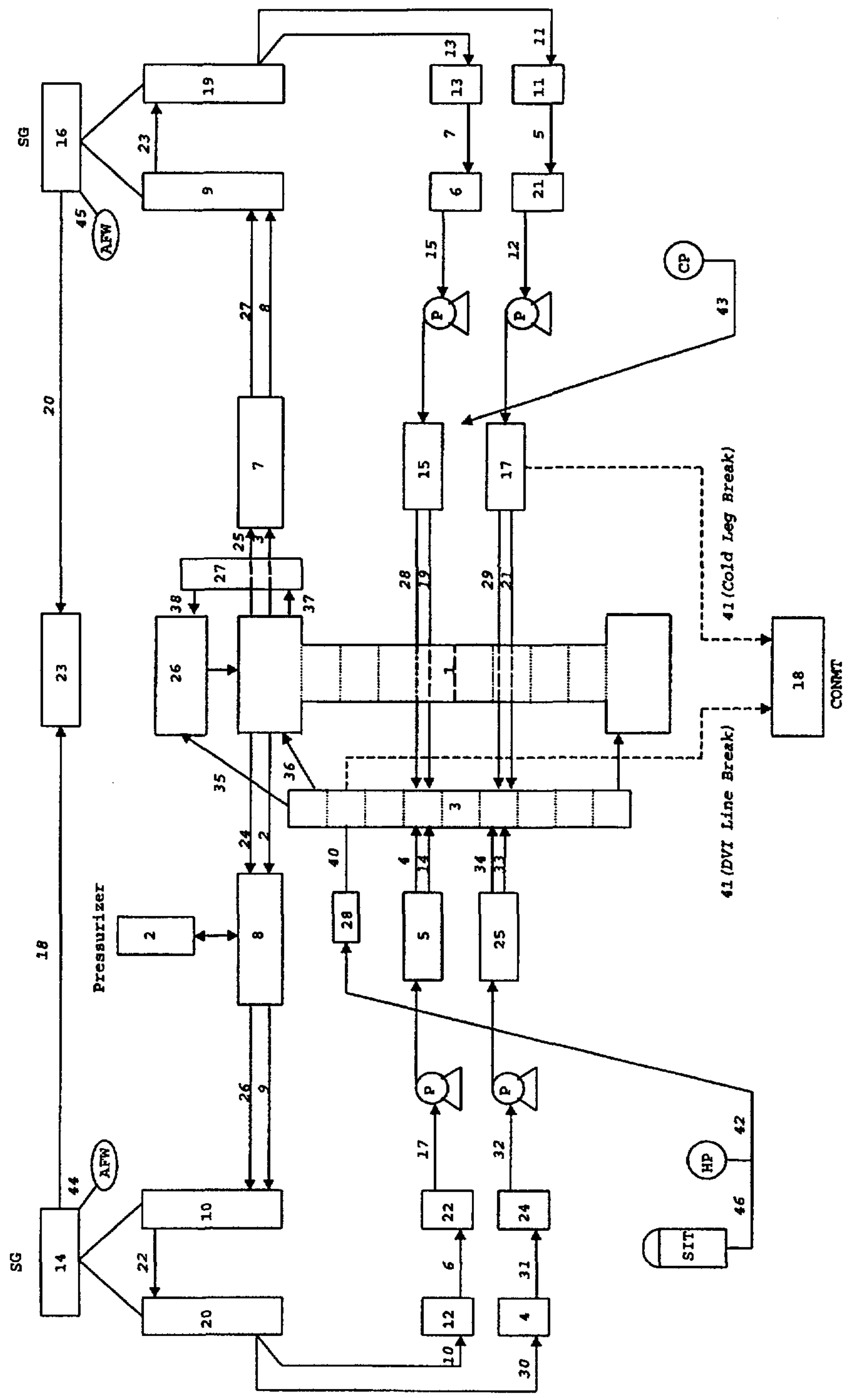

Figure 6.1 Node Diagram of CEFLASH-4AS/REM for KNGR SBLOCA Analysis [1].

7. Measurement Requirement and Data

Measure requirements

- Redundancy on measurements and methodology
- Overlapping instrumentation ranges

7.1 Inner Vessel

Table 7.1 Measurement Ranges for Inner Vessel Variables

Measured Variable	Values		
	Nominal	Minimum	Maximum
Core inlet mass flow rate (lbm/sec)	408	-5000	45203
Inner vessel pressure (psia)	1189	300	2282
Inner vessel fluid temperature (°F)	569	60	650
Inner vessel fluid density (lbm/ft^3)	38.05	0.0	65
Collapsed level (ft)	21.8	0.0	27.813
Mixture level (ft)	24.8	0.0	27.813
Void fraction	0.245	0.0	1.0
Top head pressure (psia)	1186	300	2277.4
Top head void fraction	0.55	0.0	1.0

7.2 Cold Leg

Table 7.2 Measurement Ranges for Cold Leg Variables

Measured Variable	Values		
	Nominal	Minimum	Maximum
Level (ft)	2.5	0.0	2.5
Mass flow rates (lbm/sec)	282	-1250	11514
Steam velocity (ft/sec)	15.1		
Void fraction	0.45	0.0	1.0
Mixture Density (lbm/ft^3)	48.1	0.0	65
Pressure (psia)	1187	300	2334
Temperature (°F)	568	60	650

7.3 Downcomer (4 Symmetric measurements)

Table 7.3 Measurement Ranges for Downcomer Variables

Measured Variable	Values		
	Nominal	Minimum	Maximum
Collapsed liquid level (ft)	28.6	0.0	34.615
Mixture level (ft)	29.9	0.0	34.615
Pressure (psia)	1185	300	2317
Axial temperatures (°F)	575	60	650
2-phase region steam release rates (lbm/sec)	9.45	0	150
Void fraction	0.145	0.0	1.0
Mixture density(lbm/ft^3)	45	0.0	65

7.4 Intact DVI Line

Table 7.4 Measurement Ranges for Intact DVI Line Variables

Measured Variable	Values		
	Nominal	Minimum	Maximum
Safety injection jet velocity (ft/sec)	3.5	0.0	35
Liquid density (lbm/ft^3)	62	0.0	65
Pressure (psia)	1189	300	2316
Temperature (°F)	120	60	120

7.5 Broken DVI Line (Upstream of DVI Break)

Table 7.5 Measurement Ranges for Broken DVI Line Variables

Measured Variable	Values		
	Nominal	Minimum	Maximum
Void fraction	0.145	0.0	1.0
Mass flow rate (lbm/sec)	1602	0.0	7500
Pressure (psia)	1185	14.7	2300
Temperature (F)	568	60	650
Break path quality	0.018	0.0	1.0
Fluid density (lbm/ft^3)	36.2	0.0	65

8. Test Facility Scaling Methodology

The scaling methodology is summarized in Table 8.1. The procedure involves (a) normalizing the governing equations, (b) normalizing the equations defining the initial and boundary conditions, (c) evaluating the dimensionless groups (model coefficients) revealed from the normalization process and neglecting those that are relatively small in the full-size and model systems, (d) considering physical limitations imposed by test facility power requirements and building space, (e) evaluating the limitations necessary to ensure a three dimensional flow field within the scale model downcomer, and, finally, (f) evaluating the impact of a distorted model (rather than a true dynamically similar model) with regard to how the results should be interpreted.

The differential equations which must be formulated for the downcomer system must be written for two-phase, nonequilibrium, nonhomogeneous and multi-dimensional flow in order to capture all the relevant physics in the scaling laws[1]. In addition, equations for appropriate boundary conditions must be written. Normalization of these equations will give all the relevant nondimensional groups that will define the scaling laws between the full-size system and scale model. Conceptually, dimensional analysis using the Buckingham Pi Theorem can also be used but this approach requires a priori knowledge of which variables are important and does not indicate which effects are negligible. Normalization of the governing equations followed by evaluation of the model coefficients for the full-size and scale model overcomes this difficulty. This procedure is described for single phase systems in [7].

In addition to analytical considerations certain physical considerations may also impose limitations on scaling that must be taken into account. These include the power requirements to operate the test facility, the space available for the test equipment, and the limitations on certain downcomer geometrical attributes to ensure that the flow field

1) The equations for one-dimensional flow are given in [10]

in the scale model is three dimensional. These may include the downcomer width and overall length. As a result, the scale model will be distorted (in the context of not having true geometric and, therefore, dynamic similarity with the full-scale system) and this will impact how test results can be interpreted.

ACKNOWLEDGEMENT

This study was performed under contract with Korea Electric Power Company (KEPCO)

Table 8.1 Scaling Methodology

Analytical Considerations
Normalization of the Governing Equations
Formulate the equations for the conservation of mass, momentum and energy for a two-phase, nonequilibrium, nonhomogeneous system.
Normalize the variables appearing in the governing equations.
Substitute the normalized variables into the governing equations to extract nondimensional groups $?_1$, $?_2$, ..., $?_n$ which will act as model coefficients.
Normalization of the Boundary Conditions
Formulate the equations for the initial and boundary conditions.
Normalize the variables appearing in the equations defining the initial and boundary conditions.
Substitute the normalized variables into the equations defining the initial and boundary conditions to extract nondimensional groups $?_{n+1}$, $?_{n+2}$, ..., $?_{n+m}$ which will act as model coefficients.
Evaluating the Model Coefficients
Determine the boundaries of the system to be modeled.
Estimate the full-size system space interval *L* and response time *?t*.
Estimate the full-size property changes *?* from a known disturbance. Also, list other reference properties which do not appear in derivatives of the describing equations.
Express all model coefficients ($?_i$) algebraically in terms of the given parameter symbols. Then obtain numerical values for the all the *?'s* based on the full-size system.
Neglect all relatively small *?* values and verify that the neglected *?'s* do not become too large to neglect in the scale model.
Physical Considerations
Estimate the power requirements (either in terms of electric power or steam demand) for the test facility and assess the impact these limitations have on scaling.
Estimate minimum downcomer geometry scales necessary to preserve a three dimensional flow field in the scale model and assess the impact this limitation has on scaling.
Estimate the space limitations of the test facility building and take this limitation into account when determining the model size.
Distorted Model Considerations
Assess the impact of a distorted model in terms of how the results from the model are to be interpreted. In particular, consider the impact of maintaining a distorted axial length scale and downcomer width scale (from step 13).

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서 지 정 보 양 식

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KAERI/TR-1236/99			

제목 / 부제	차세대원자로 소형냉각재상실사고시의 DVI ECCS 성능실험을 위한 예비 실험 조건
연구책임자 및 부서명 (AR,TR 등의 경우 주저자)	배규환 (열수력안전연구팀)
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초록 (15-20줄내외)

차세대 원자로에 채택될 4 트레인 DVI 안전주입은 안전주입수가 8.5" DVI 노즐을 통하여 원자로용기 내 Downcomer로 직접 주입됨으로 인하여 LOCA시 하향유로에서의 ECC mixing 및 bypass 등의 열 수력 현상이 기존의 저온관 주입과는 매우 다르게 예측되므로 비상노심냉각수의 실질적인 주입 현상을 파악하고, 저온관 주입을 기본으로 개발된 해석 코드의 개선을 위한 열 수력 자료 생산을 위해서는 차세대원자로를 모의한 열 수력 실증실험이 수행되어야 하고 이를 위한 성능해석이 필요하다.

차세대원자로에 채택하고자하는 DVI 주입방식의 소형냉각재상실사고에 대한 CEFLASH-4AS/REM 해석결과를 검토하여, 당 사고시의 사고 시나리오 및 주요 열수력 현상을 파악하고 도출하였다. 이 코드에 의한 계산 결과 노심 수위를 포함한 계통의 과도상태 거동은 Downcomer 모델링에 많은 영향을 받는 것으로 나타났다. 따라서, 제한된 실험경비 및 시간 내에서 Downcomer에서의 열 수력학적 특성을 적절히 살펴보기 위해서는 이 영역에 초점을 둔 개별효과 실험을 수행하는 것이 효과적인 것으로 판단되며 이를 반영한 예비실험장치를 제시하였다. 제시된 실험 장치에 대한 초기 및 경계조건을 CEFLASH-4AS/REM 해석결과를 바탕으로 작성하였으며, 이는 예비실험요건서의 입력으로 사용될것이고 실험 수행 팀과의 긴밀한 협의를 통하여 최종 실험요건서가 작성될 것이다.

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Abstract (15-20 Line)

The Korean Next Generation Reactor (KNGR) adopts 4-train Direct Vessel Injection (DVI) configuration and injects the safety injection water directly into the downcomer through the 8.5" DVI nozzle. Thus, the thermal hydraulic phenomena such as ECC mixing and bypass are expected to be quitely different from those observed in the cold leg injection. In order to investigate the realistic injection phenomena and modify the analysis code developed in the basis of cold leg injection, thermal hydraulic test with the performance evaluation is required.

Preliminarily, the sequence of events and major thermal hydraulic phenomena during the small break LOCA for KNGR are identified from the analysis results calculated by the CEFLASH-4AS/REM. Is is shown from the analysis results that the major transient behaviors including the core mixture level are largely affected by the downcomer modeling. Therefore, to investigate the proper thermal hydraulic phenomena occurring in the downcomer with a limited budget and time, the separate effects test focusing on this region is considered to be effective and the conceptual test facility based on this is recommended. For this test facility the test initial and boundary conditions are developed using the CEFLASH-4AS/REM analysis results that will be used as input for the preliminary test requirements. The final test requirements will be developed through the further detailed discussions with the test performance group.

Subject Keywords (About 10 words)	Thermal-hydraulic test, SBLOCA, ECCS, ALWR, DVI, ECC bypass, KNGR, Downcomer