국내외 중대사고 로드맵 개발 현황 및 전망

송진호, 한국 원자력연구원

원자력 학회 추계학술대회, 2015, 10. 28

중대사고 현상규명 및 대처체계 구축 로드맵 특별위원회 워크샵

Highly Populated NPPs in East Asia

Kori site:
3 M people within 30 km

On average 1 out of 10 people in Korea lives within 30 km

중대사고 국내외 환경 변화

- **가동 원전 (PWR, PHWR) 중대사고 대처 능력 향상**
  - 국제안전협약 방사성물질 방출 제한 구체화,
  - 국내 외 중대사고 관리전략 법제화
  - 인구 밀집 지역의 다수호기 및 장기 가동 원전의 대중 수용성 확보

- **SMART 원자로 수출**: 한-사우디 협력, 2018 예비 검토, 이후 시범 건설
  중대사고 해석 기술 국산화 필요

- **미래원전: SFR 중대사고 쟁점:** 2018 실증로 표준설계, 2022 건설 허가
  - 소듐/격납건물 내 방사성 물질 거동, 냉각성능 확보/재임계 방지

- **아시아 지역 리더쉽 유지:**
  국제 수준 원천기술 (독자 코드, 실증실험) 개발 요구됨

일본 신 안전법: 정량적 안전 목표 설정, 세슘의 양으로..., 가동 원전도 적용

Safety Goals

- **The now-defunct Nuclear Safety Commission did not make final decision on safety goals that is aimed to achieve through regulation, different from other foreign countries.**
- **The NRA held discussions and finally agreed on the safety goals in April 2013.**

(i) The discussions were based on the results of the deliberation(*) by the Special Committee on Safety Goals of the now-defunct Nuclear Safety Commission.

* Core damage frequency: approximately 10^{-4}/year
Containment failure frequency: approximately 10^{-5}/year ,etc.

(ii) Incorporating the impact of environmental contamination by radioactive materials, **the frequency of an accident that causes discharging Cs-137 over 100TBq should be reduced to not exceed one in a million reactor years** (excluding accidents by terrorist attacks, etc.)

(iii) Safety goals should be **applied to all power reactors without exception**.

(iv) Safety goals are paramount **in the NRA's administration of nuclear regulations**

(v) The NRA is dedicated to continuous discussions on strengthening safety goals **in the nuclear industry**.

25

Taken from "Enforcement of the New Regulatory Requirements for Commercial Nuclear Power Reactors", July 8, 2013, Nuclear Regulation Authority

NUGENIA/SARNET SARP

- Objective of NUGENIA/SARNET SARP (Severe Accident Research Priority) group
  - Continue the work done in the SARNET network (FP6 and FP7 projects from 2004 to 2013) in the NUGENIA Technical Area 2 “Severe Accidents” that has integrated the SARNET network
  - Sustain efficiency and relevance of severe accident research in the EU
- Methods
  - Identify the remaining safety issues and evaluate the most recent experimental results
    - SARNET2 FP7 results, OECD projects
    - Results related to accident at Fukushima
  - Analyse R&D progress and results from Level 2 PSA studies
  - Re-assess ranking of issues and eventually re-orient priorities

W. Klein-Heßling, M. Sonnenkalb, D. Jaquemain, B. Clément, E. Raimond, H. Dimmelmeier, G. Azarian, G. Ducros, C. Journeau, L. E. Herranz Puebla, A. Schumm, A. Miassoedov, I. Kljenak, G. Pascal, S. Bechta, S. Güntay, M. K. Koch, I. Ivanov, A. Auvinen, I. Lindholm, The NUGENIA/SARNET Severe Accident Research Priorities, Plinus 2 Seminar, 2014, Marseille

NUGENIA/SARNET SARP

The European Severe Accident PIRTs

PIRTs SUMMARY

DOMAINS / PHENOMENA	IDENTIFIED	SAFETY IMPORTANT	LACK OF KNOWLEDGE
In-Vessel	162	44	24
Ex-Vessel	149	48	28
Dynamic Loading	461	71	26
Long Term Loading	116	36	10
Fission Products	128	30	18
	916	229	106

106
phenomena are important for safety and present an important lack of knowledge.

D. Magallon, A. Mailliat, J.-M. Seiler, K. Atkhen, H. Sj¨ovall, S. Dickinson, J. Jakab, L. Meyer, M. Buerger, K. Trambauer, L. Fickert, B. Raj Sehgal, Z. Hozer, J. Bagues, F. Martin-Fuentes, R. Zeyen, A. Annunziato, M. El-Shanawany, S. Guentay, C. Tinkler, B. Turland, L.E. Herranz Puebla, European expert network for the reduction of uncertainties in severe accident safety issues (EURSAFE), Nuclear Engineering and Design 235 (2005) 309–346

NUGENIA/SARNET SARP

Basic Classification of Phenomena

1. Phenomena during in-vessel accident progression
2. Phenomena that could lead to early containment (or reactor building) failure
3. Phenomena that could lead to late containment failure
4. Phenomena of release and transport of fission products
5. Phenomena in spent fuel pool storages
6. New topics related to severe accidents

See complete list of research priorities at *http://www.sar-net.eu/sites/default/files/Paper%20SARP.pdf*

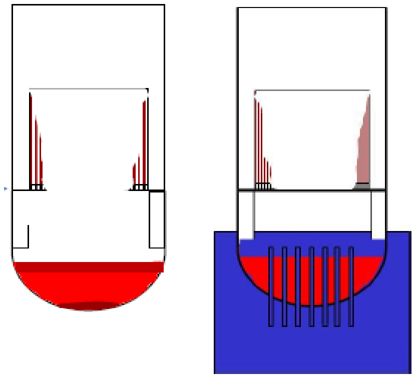
W. Klein-Heßling, M. Sonnenkalb, D. Jaquemain, B. Clément, E. Raimond, H. Dimmelmeier, G. Azarian, G. Ducros, C. Journeau, L. E. Herranz Puebla, A. Schumm, A. Miassoedov, I. Kljenak, G. Pascal, S. Bechta, S. Güntay, M. K. Koch, I. Ivanov, A. Auvinen, I. Lindholm, The NUGENIA/SARNET Severe Accident Research Priorities, Plinus 2 Seminar, 2014, Marseille

Phenomena during in-vessel accident progression

Corium behaviour in lower head/ RPV cooling

No.	Topic	Explanation	Previous Status	Revised Status
1,4	Corium behaviour in lower head	Improve predictability of corium behaviour and the thermal loading on RPV lower head to assess RPV integrity. BWR: Consideration of specific BWR boundary conditions	M	H
1,5	Integrity of RPV due to external vessel cooling	Improve database for critical heat flux and external cooling conditions to evaluate and design AM strategies of external vessel cooling for in-vessel melt retention.	M	H

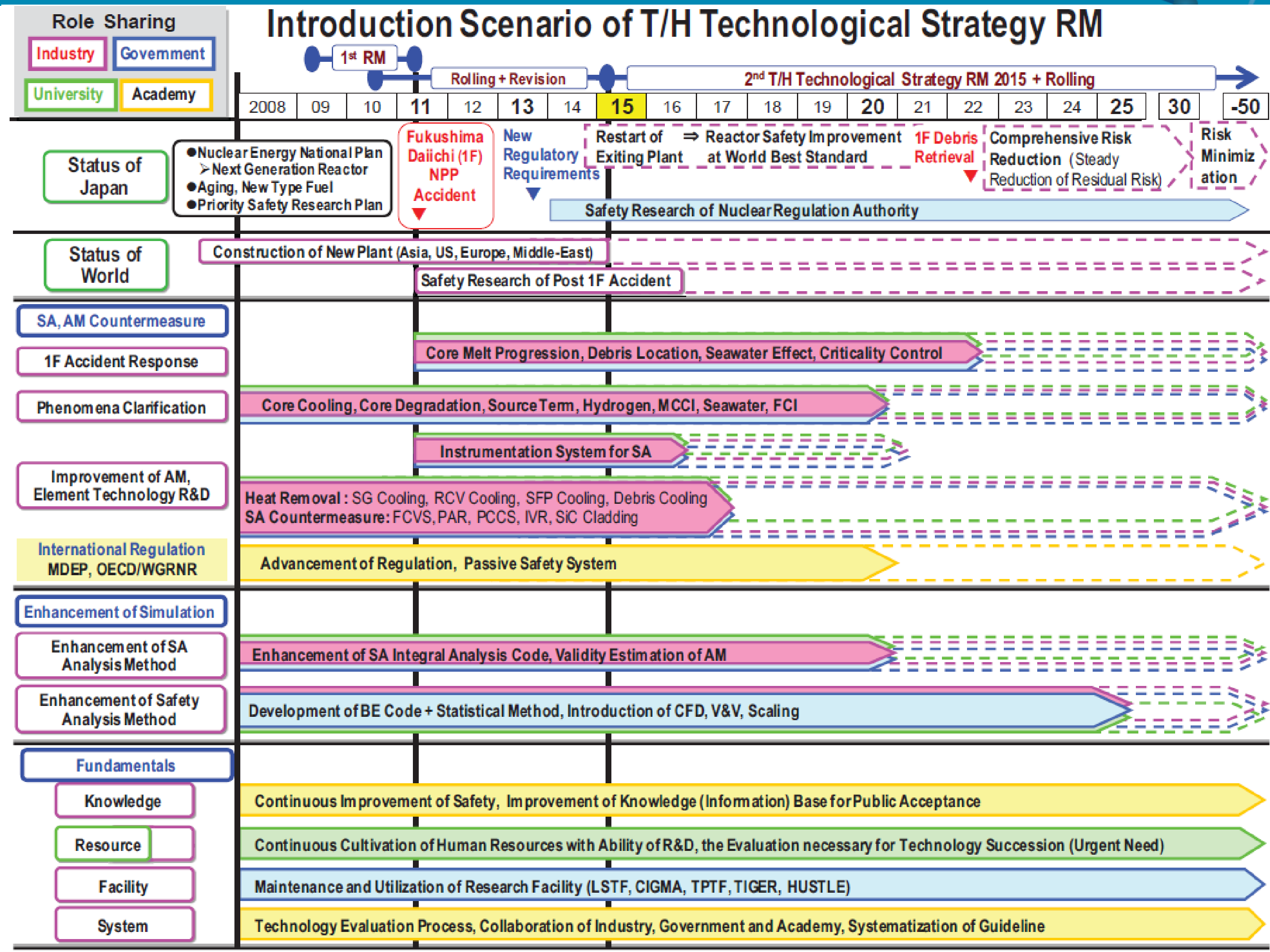
- Special point for BWRs because of the control rod guide tubes
- Main Topics of interest:
  - Heat flux to metal layer in layered melt & 3-layer configuration
  - Thickness of metallic layer
  - Use of additives, “dirty” water, pressure dependence, hot spots



W. Ma, NUGENIA TA2.1, Meeting 2014

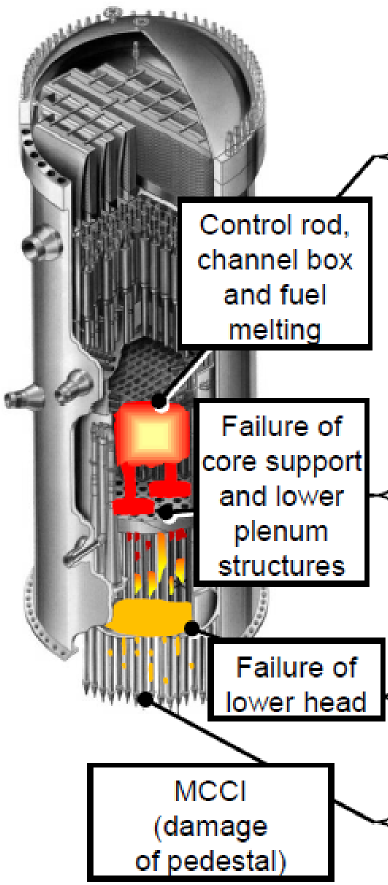
W. Klein-Heßling, M. Sonnenkalb, D. Jaquemain, B. Clément, E. Raimond, H. Dimmelmeier, G. Azarian, G. Ducros, C. Journeau, L. E. Herranz Puebla, A. Schumm, A. Miassoedov, I. Kljenak, G. Pascal, S. Bechta, S. Güntay, M. K. Koch, I. Ivanov, A. Auvinen, I. Lindholm, The NUGENIA/SARNET Severe Accident Research Priorities, Plinus 2 Seminar, 2014, Marseille

New AESJ Thermal-Hydraulics Roadmap



New AESJ Thermal-Hydraulics Roadmap for LWR Safety Improvement and Development after Fukushima Accident, NURETH-16, 2015, Chicago, USA, H. Nakamura, K. Arai, H. Oikawa, T. Fujii, S. Umezawa, Y. Abe, J. Sugimoto, S. Koshizuka and A. Yamaguchi

Post Fukushima Research Initiatives at CLADS



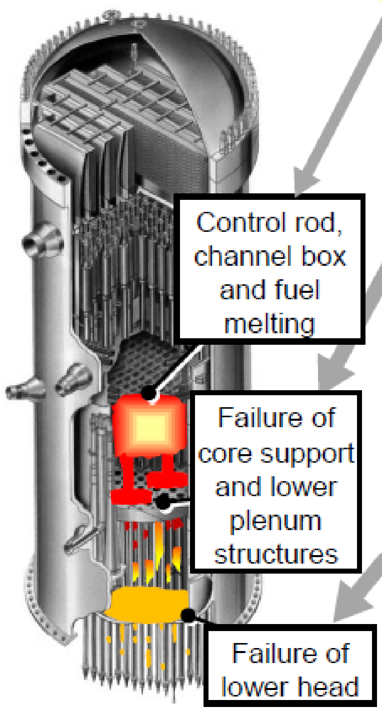
	Existing tests	tests and research needs
Temperature rise and water vapor generation due to decrease of heat removal		
Further temperature increase in fuel rods with lowered water level		Range of associated phenomena
Oxidation of cladding and channel boxes	CORA; PHBUS, LOFT, PBF, DF	
Melting and downward relocation of control blades and channel boxes		
Melting and downward relocation of cladding	XR2	
Downward relocation of metallic melt into lower core-support structure region and lower plenum		
Fuel melting and local blockage formation		
Axial and lateral expansion of molten ceramic pool		
Failure of lower core-support structure and/or downward relocation of molten-core materials through the core-support structure region	Focal point 1	
(rapid cooling by water injection)		
Drain of melt to the lower plenum structures and damage of the structures		
Falling of melt onto the lower head and accumulation there	ORNL (BWR)	
Failure of lower head	LHF, OLHF, FOREVER (PWR)	
Core material relocation onto pedestal	Focal point 2	
Melt concrete reaction	MOCKA, VULCANO, ANL	

Limited knowledge for BWR

Ikken Sato, CLADS (Collaborative Laboratories for Advanced Decommissioning Science), Japan Atomic Energy Agency, STATUS OF SOME JAEA PROGRAMS FOCUSING ON CORE-MATERIAL RELOCATION BEHAVIOR FEATURING BWR DESIGN CONDITIONS

Post Fukushima Research Initiatives at CLADS

- Worldwide specilists' interests will help realization of this program
- Such specialists' remarks will be reflected to the program



Focal point 1 (relocation to lower plenum)

planning

Integral tests (6.1)

Reliable boundary condition

on-going

Separate effect tests (6.2)

Advanced evaluation methods (6.2)

Reliable boundary condition

Focal point 2 (Failure of lower head)

- On-going tests
- Discussion on research needs

on-going

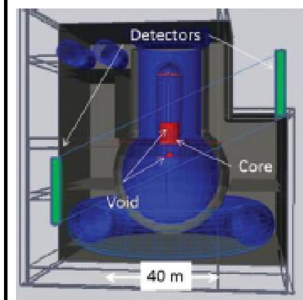
Advanced evaluation methods (7.1)

Reliable boundary condition

MCCI

- On-going tests
- Discussion on research needs

Additional site data such as muon measurement and debris sampling



http://sustainablejapan.net/?p=2651

Continued updates in terms of **consistency with reality**

This presentation covers Items in blue

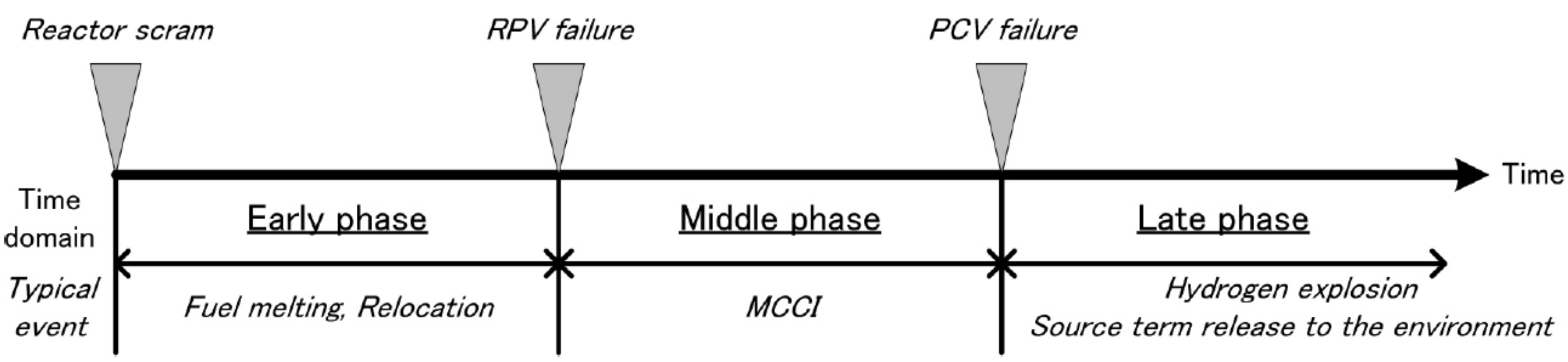
Ikken Sato, CLADS (Collaborative Laboratories for Advanced Decommissioning Science), Japan Atomic Energy Agency, STATUS OF SOME JAEA PROGRAMS FOCUSING ON CORE-MATERIAL RELOCATION BEHAVIOR FEATURING BWR DESIGN CONDITIONS

Source Term PIRT: 일본

AESJ (Atomic Energy Society of Japan)has developed thermal hydraulic PIRT and source term(ST) PIRT based on findings during the Fukushima Daiichi NPPs accident.

These PIRTs aim to explore the debris distribution and the current condition in the NPPs and to extract higher priority from the aspect of the sophistication of the analytical technology to predict the severe accident phenomena

Three Event Phase: Up to 7 days…, Lessons from Fukushima Accident



The magnitude of source term (release fraction of radionuclide into environment, their chemical forms and the release timing) was selected as the FoM.

Shoichi Suehiro, Jun Sugimoto, Akihide Hidaka, Hidetoshi Okada, Shinya Mizokami, Koji Okamoto, Development of the source term PIRT based on findings during Fukushima Daiichi NPPs accident, Nuclear Engineering and Design 286 (2015) 163–174

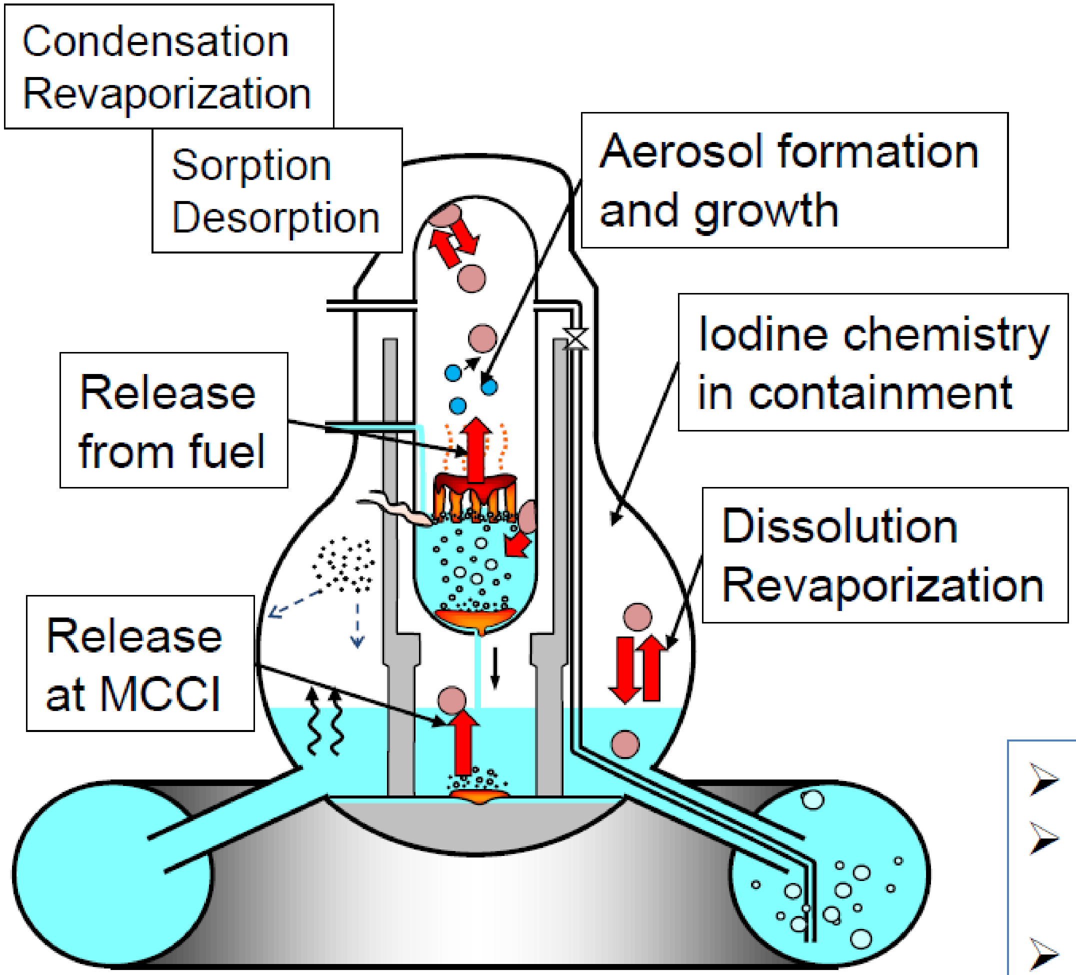
Source Term PIRT: 일본

High ranked phenomena of the source term PIRT.

No.	Phenomena	Phase			SoK
		Early	Middle	Late	
1. In-vessel release					
2106	Pellet form change and radionuclides release at the time of the clad rupture	High			P
2107	Radionuclides release after pellet is exposed to the atmosphere in the core by clad melting	High			U
2108	Radionuclides release from molten fuel	High	High		U
2111	Influence on iodine/cesium chemical form and hydrogen production from molten/re-solidified fuel due to the B_4C control rod existence	High			U
2. Gas/aerosol behavior in RPV, RCS, and Steam line					
2201	Condensation/re-vaporization/adsorption	High	High		K
3. Transport in RPV and PCV					
2301	Leakage via instruments, penetration, etc.	High	High	High	P
2302	Leakage via gasket	High	High	High	P
2303	Leakage by RPV damage		High	High	P
4. Ex-vessel release					
2401	MCCI (concrete erosion)		High	High	P
5. Aerosol behavior in containment					
2501	Scrubbing by steam flow from SRV to S/C	High			K
2502	Scrubbing with the vent from D/W to S/C		High	High	P
2503	Scrubbing due to water injection to the pedestal floor			High	P
2507	Condensation/re-vaporization/adsorption		High		K
2513	Deposition by gravitational settling			High	K

Shoichi Suehiro, Jun Sugimoto, Akihide Hidaka, Hidetoshi Okada, Shinya Mizokami, Koji Okamoto, Development of the source term PIRT based on findings during Fukushima Daiichi NPPs accident, Nuclear Engineering and Design 286 (2015) 163–174

Source Term PIRT



- Thermal-hydraulic condition
- Chemical reaction
- SA progression

- Gas: Kr, Xe
- Volatile: I, Cs, (Ru), Sb,
- Semi/low-volatile: Mo, Rh, Ba, Sr, Ce, (Ru)
- Structural material: B, Fe, Si, Ca, etc.

- Release from fuel
- Transport thorough reactor coolant system
- Transport in the containment

Masahiko OSAKA, Kunihisa NAKAJIMA, Shuhei MIWA, Chikashi SUZUKI, Fidelma Giulia DiLEMMA, Fumihisa NAGASE, Fundamental research on fission product chemistry for accurate evaluation of FP release and transport behavior, 1st Workshop of the OECD/NEA BSAF Project Phase 2, 24 June 2015.

- knowledge gaps given the current state of LWR severe accident research, and augmented by insights from Fukushima. Results from these activities were used as the basis for refining DOE-NE's severe accident Research and Development (R&D) plan.

Table I. Summary of identified gaps with associated importance rankings and recommended R&D to address the gaps [11]

Category	Identified Gap	Importance Ranking	Recommended R&D to Address the Gap:
In-Vessel Behavior	Assembly/core-level degradation	1 [a]	• Re-examine existing tests for any additional insights that could reduce modeling uncertainties • Planning to determine if scaled tests are possible • MAAP/MELCOR evaluations to gain a common understanding of regimes where predictions are consistent and regimes where predictions differ qualitatively and quantitatively • Develop tools to support SAMG enhancements and for staff training.
	Lower head	2 [a,b]	• Scaled tests addressing melt relocation and vessel wall impingement heat transfer
	Vessel failure	4 [a,b]	• Scaled tests addressing vessel lower head failure mechanisms; focus on penetration-type failures
Ex-Vessel Behavior	Wet cavity melt relocation and CCI	5 [a,b]	• Modify existing models based on ongoing prototypic experiments and investigate the effect of water throttling rate on melt spreading and coolability in BWR containments
Containment - Reactor Building Response	H_2 stratification and combustion	7 [a]	• Analysis and possible testing of combustion in vent lines under prototypic conditions (i.e., condensation, air ingress, hot spots, and potential DDT)
	H_2 /CO monitoring	10	• Leverage ongoing international efforts as a basis for developing a H_2-CO containment monitoring system
	Organic seal degradation	12 [a]	• Similar to a process completed by the BWR industry, develop PWR containment seal failure criteria under BDBE conditions based on available information sources
	PAR performance	13	• Evaluate optimal position in containment with existing codes that predict gas distributions • Examine performance with H_2/CO gas mixtures under BDBE environmental conditions
Emergency response equipment performance	RCIC/AFW equipment	3 [a]	• Plan for a facility to determine true BDBE operating envelope for RCIC/AFW systems • Based on stakeholder input, construct the facility and conduct the testing
	BWR SRVs	6 [a]	• Testing to determine BDBE operating envelope (in RCIC/AFW test facility)
	Primary PORVs	11 [a]	• Testing to determine BDBE operating envelope (in RCIC/AFW test facility)
Additional Phenomena	Raw water	8 [a]	• Monitor studies underway in Japan to obtain basic insights into phenomenology. • Develop tools to analyze raw water effects; apply to postulated accident scenarios. • Based on outcome of these activities, formulate additional R&D if uncertainties persist.
	Fission product transport and pool scrubbing	9 [a]	• Leverage existing international facilities to characterize: i) thermodynamics of fission product vapor species at high temperatures with high partial pressures of H_2O and H_2, ii) the effect of radiation ionizing gas within the RCS, and iii) vapor interactions with aerosols and surfaces. • Leverage existing international facilities to address the effect of H_2/H_2O and H_2/CO gas mixtures on pool scrubbing at elevated pressures and saturated conditions.

[a] Panel consensus was that Fukushima forensics offer best opportunity for insights in these areas.
[b] Panel consensus was that uncertainties in these areas are dominated by uncertainties related to assembly/core-level degradation; thus, the latter should be higher priority.

중대사고 대처에 대한 후쿠시마 교훈

- **자연재해에 의한 중대사고, 다수호기 사고, 운전원에 의한 복구 실패**
- **원자로 파손, 원자로 건물 파손, 대량 방사성 물질 방출, 해양, 대기, 토양 오염**
- **수십 년에 걸리는 복구 과정**
- **Severe Accident Tolerant Passive System and Measurement System** needed

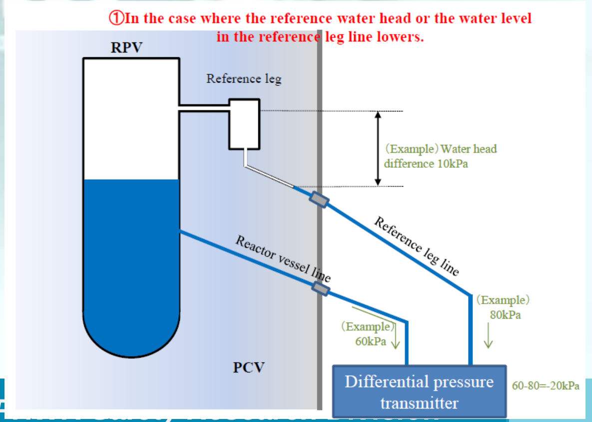
RCS 냉각: Passive safety systems driven by the steam from the RPV, RCIC (Reactor Core Isolation Cooling) and HPCI (High Pressure Core Injection) significantly delayed core damage for Unit 2 and Unit 3, while IC (Isolation Condenser) did not work for Unit 1.

RCS 감압: did not work due to malfunction of SRV and loss of battery

격납 건물 (PCV 배기): did not work due to loss of power. And leakage from the PCV (probably head flange) led to a hydrogen explosion and loss of RB

RCS 주입: delayed and effective injection was less than half due to bypass lines….

Malfunction of Water Level Measurement, no indications in the MCR



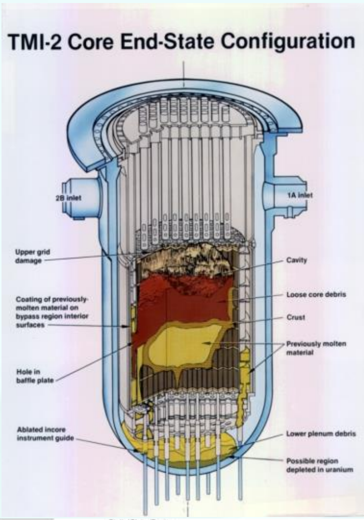
중대사고 현상규명 및 대처체계 구축 로드맵

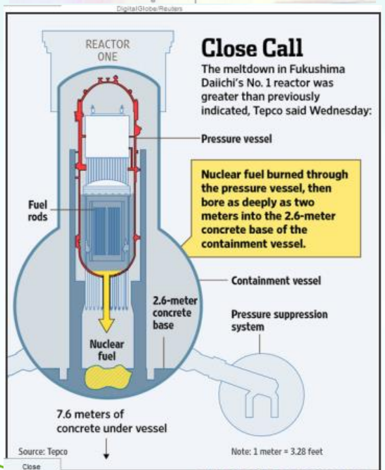
❑ 추진 전략 및 향후 전망

- 활동 목표: 중대사고 현상규명 및 대처 체계 구축을 위한 연구 로드맵 작성
- 활동 기간: 2015. 3 – 2016. 2
- 활동 방안: 일차계통 방호, 격납건물 방호, 사고 방사선원항 거동의 세 분야로 나누어 산학연의 전문가들(안)를 중심으로 활동 중
- 분야별로 정기적인 회의 및 세미나를 개최하여 로드맵을 작성함.
- 추계 원자력 학회에서 초안을 발표 및 의견 청취를 하며, 국내외 전문가 자문을 받아 내년 1월 최종안 학회 이름으로 발표함.
- 미래부, 원자력 안전 위원회, 산업부의 안전 연구 방향 정립에 로드맵이 반영될 수 있도록 각 부처에 적극 건의

(1) 일차계통 방호

주요 현상	사고관리전략	피동형 대응설비	개발현황, 기술 쟁점
	원자로 감압 및 대체 충수	중대사고 전용 안전 감압설비 (APR1400, EPR)	중대사고 조건 생존성 후쿠시마 원전 SRV 작동 불량 (전원, 기계적 고장)
		대체펌프, 소방차등..	Discharge head, Mobile DG, Battery
	ERVC	중력 충수 혹은 펌프	- AP1000 -고출력원전 열제거 능력 -노외 증기폭발
	필수기기 가용성	원자로계통 온도, 압력, 수위 계측	UPS, Innovative Technology (power harvesting and/or SA tolerant I&C: 개발 미미)



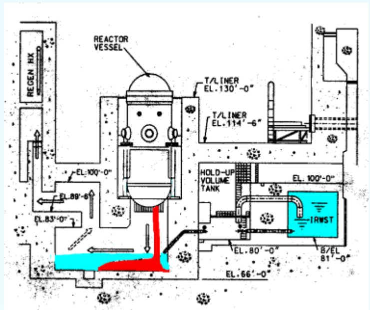


(1) 일차계통 방호: Proposed PIRT

Subject and Issue	Component and Representative Physics	Phenomenon	Phenomena Description	Challenge to the Defence in Depth
RCS Response: In-Vessel Core Degrdation				
Core Degradation	Oxidation and hydrogen production	Oxidation by steam and/or air	Oxidation of Zr cladding by steam will result in a heat up of cladding. Oxidation, brittlement, melting. The oxidation by air is more exothermic than that by steam but without hydrogen generation. Nitriding of zirconium may occur if the oxygen content is exhausted.	CNTMT and RCS
	Fuel Degradation	Cladding-Fuel interaction, Candling	Melted cladding interact with UO2 fuel. There will be eutectic reaction between cladding and UO2 fuel. Candling of melted fuel will occur. They will flow downward along the fuel and can be frozen when they reach coolant.	RCS
	In-core molten pool and/or debris behaviour	Spatial growth of the pool	Without reflooding, the molten pool will continue to grow gradually because of inner heat sources. It consist of debris and molten pool.	RCS

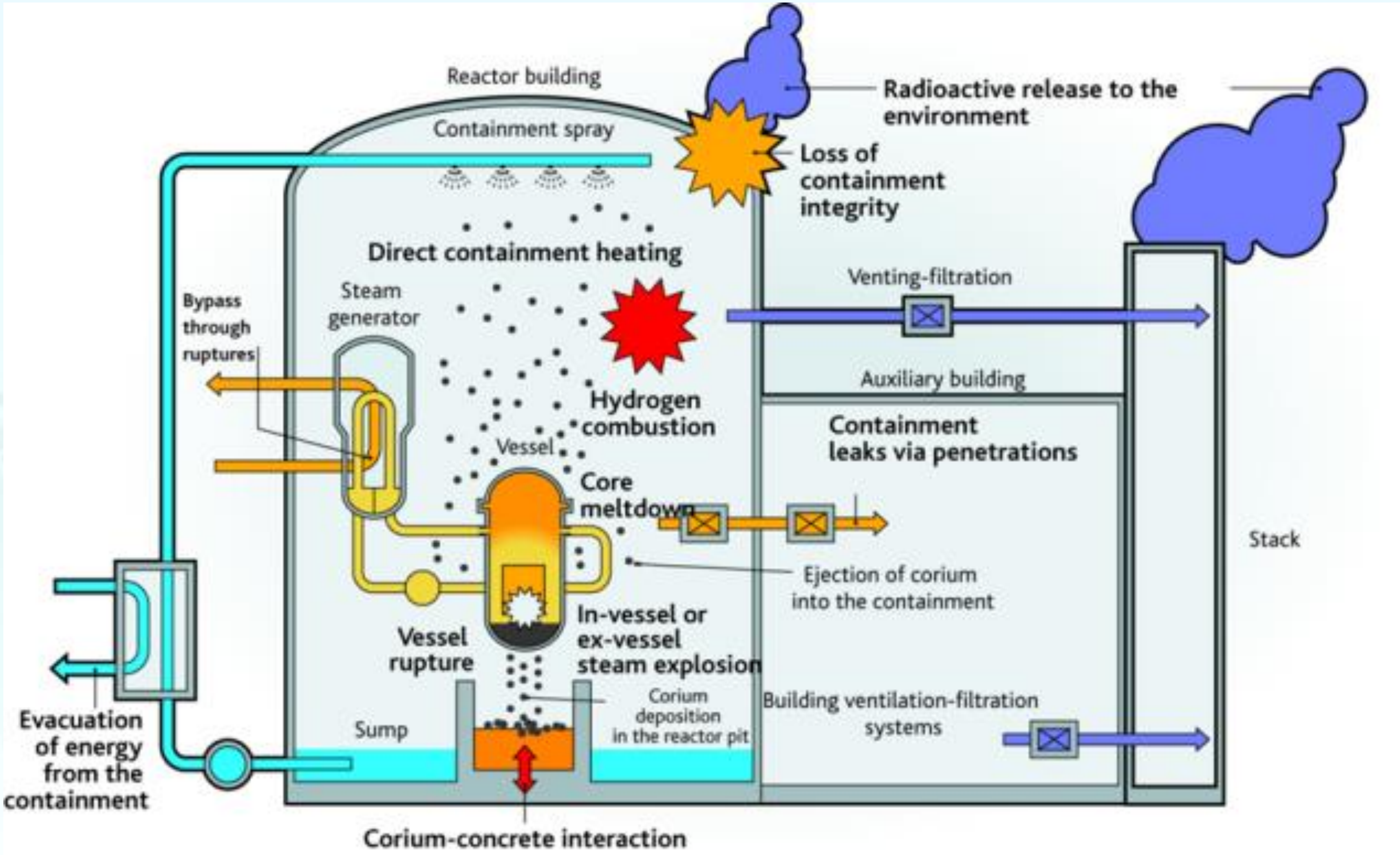
Safety Issue/Resolution	Knowledge Level	SAMG Actions	Mitigation Features	Regulatory Aspects	Further Research Needs	Status of Experimental Program and/or Computer Code
Difference between and current generation of SA anaysis computer code, for example MAAP and MELCOR simulations						
Generic issue for the current fule design			PAR, Igniter for hydrogen removal			See exp. CODEX-RU, MOZART, QUENCH, RUSET Phébus 2K: in discussion exp. at very high temperatures VERCORS expts
Generic to SA		NA	NA			
Generic to SA		NA	NA			Related phenomena will be investigated in the LIVE and KTH facilities, Benchmark to Phébus, ACRR-MP

(2) 격납건물 방호



사고관리전략	피동형 대응설비	개발현황, 기술 쟁점
원자로격실 침수	Cavity Flooding System or alternate water source with pump	Water source, power supply to the pump Top flooding may be not enough to quench the ex-vessel corium
수소 제어	PARs and Igniters	중대사고조건 성능 확보
격납건물 냉각	PCCS Water/Air Cooling	AP1000 등
노외노심용융물 냉각 격납건물 배기	Core Catcher, Filtered Containment Venting	중대사고 조건 성능확보, 장기 운전 72 시간
필수기기 가용성	격납 건물 압력, 수소 농도, 원자로 격실 수위, 원자로 파손 여부	UPS, Innovative Technology (power harvesting and/or SA tolerant I&C)

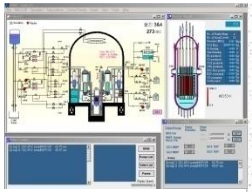
(3) 사고 방사선원항 거동



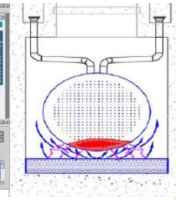
T. Albiol, Thought-provoking » Presentation: Mitigation of Source Term, First NUGENIA-SARNET Workshop on Source Term Paving the Way for Future Source Term Research, Marseille (France), April 1-2, 2015

중대사고 연구 개발 경과

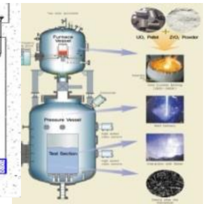
MIDAS



ISAAC



TROI



구체적인 연구 성과

중대사고연구기반구축

1997-2002

중대사고실증실험 및 평가기술개발 (~24억/년)

SONATA
– 용융물 실험 장치

국내 원전 중대 사고 관리 전략

2003-2007

중대사고관리최적방안수립 및 중대사고대처설비개발 (~28억/년)

MIDAS/ISAAC
– 경수로 및 중수로 중대사고 해석 코드 개발

TROI (실제 핵연료 물질 이용 증기폭발실험)

수소 연소 소염망 개발

미·일 중심,
중대사고연구 약화
국내연구 소강상태

2007-2011

대과제 없어짐
-격납건물 수소 및 핵분열 생성물거동평가 기술 개발 (~5억/년)
-노심용융물 위해도 실증 실험 및 쟁점해결기술개발 (~15억/년)

중대사고 핵심쟁점 연구
실제 용융물 이용 실험 기술 심화
COSMOS, HERMES
OECD/SERENA – 국내 최초 국제 공동연구

2012-2016

중대사고대처기술 개발

후쿠시마 사고 이후
실제적이고 효과적인
중대사고 대처기술개발

중대사고연구 국제선도

원천기술수준까지 심화

SMART 중대사고 해석
수출 원전 중대사고 대처 설비 개발: VESTA
중대사고 종합 해석 코드 개발

중대사고 연구 방향 (2015 ~)

- **중대사고 분야 연구는 공익성이 중요:**
  - 일반인의 건강과 재산 보호, - 기술의 개방성 (국제 협력 활발, 기술 제공 장벽 작은 편)
- **방사성물질 대량방출 배제 달성으로 원자로 안전성 향상, 국민 건강 및 재산 보호**
  – 해석 도구, 대처 방안 및 대처 설비, 사고 관리 전략 분야 원천 기술 확보: 기반 기술
  – 원자로 안전에 대한 대 국민 신뢰도 향상, 원자력 안전 위원회 및 안전 기술원 지원
- **동북아 지역 중대사고 연구 및 대처 기술 개발 리더쉽 확보**
  - 국제 수준의 실제 핵연료 물질 이용 중대사고 실증 실험 지속 추진 (TROI, VESTA)
  - 수소제어 기술, 방사성 에어로졸 이송 평가 및 제염 기술 확보 위한 노력 강화

TROI : OECD/SERENA Steam Explosion

VESTA: Corium-Structure Interaction Experiment

LIFE (**L**aboratory for **I**nnovative Mitigation of Threats from **F**ission Products and **E**xplosions)

방사성물질 대량방출 억제 기술 개발: 수소제어, 방사성 에어로졸 이송 및 제염 성능

Protect People, Safe and Economic Nuclear Power