# 경쟁노형 피동안전계통 열수력 현안

이정익

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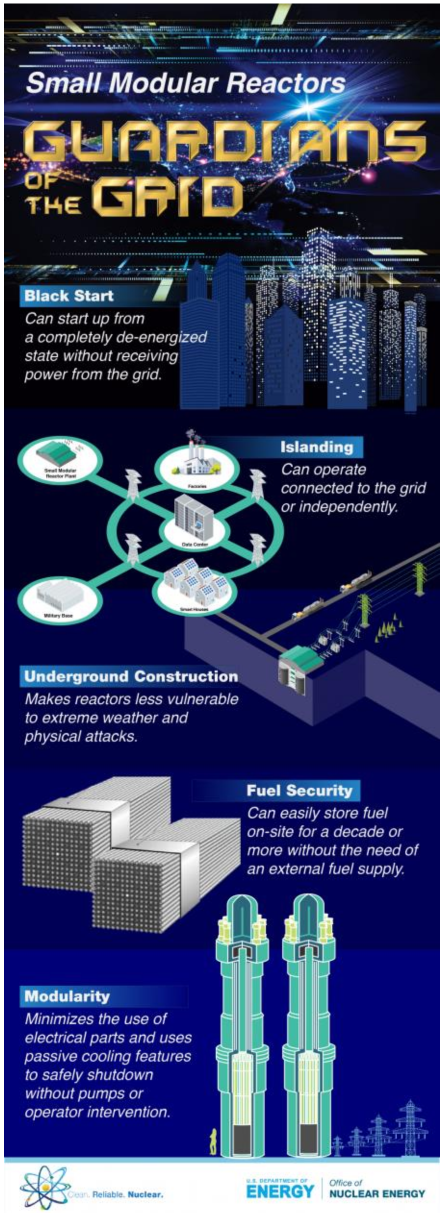
# SMR의 필요성




**노후 석탄화력발전 교체**
- 석탄의 15%, 천연가스의 5%를 소형원자로 대체할 경우
- 연간 90조원 잠재 수요 발생

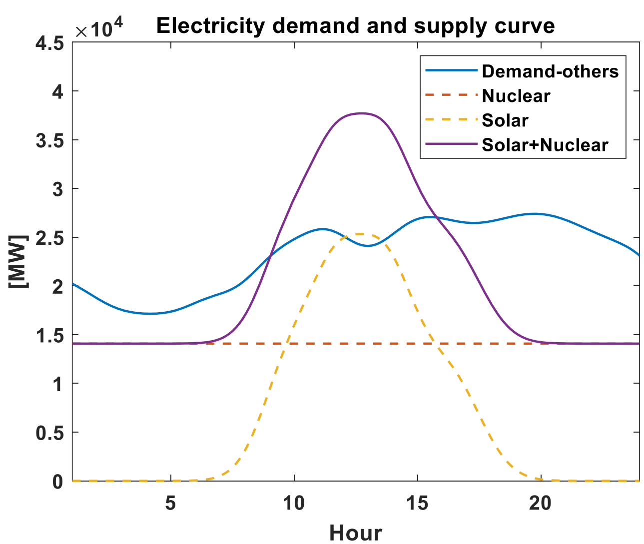
**중공업에 쓰이는 고온증기**
- 화석연료 대신 5% 정도 소형원자로 대체할 경우
- 연간 10.8조원 잠재 수요 발생

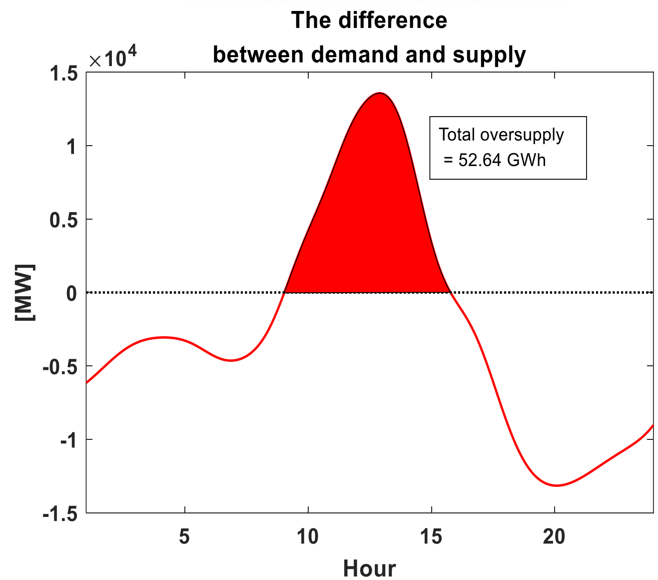
**해수 담수**
- 2020-2024년 동안 해수담수 규모는 16GWe 규모
- 연간 9조원 잠재 수요 발생

**수소생산**
- 2023년 수소생산 시장의 5%를 원자력 발전소로 대체할 경우
- 연간 12조원 잠재 수요 발생

**광산지역**
- 30년부터 디젤의 61%를 소형원자로로 대체할 경우
- 연간 3.15조원 잠재 수요 발생

**도서 및 오지 지역**
- 7만개 이상의 지역사회가 디젤로 전력 생산
- 연간 27조원 잠재 수요 발생



# 혁신형 SMR

**SMR 개념**

SMR(Small Modular Reactor, 소형모듈원자로)은 원자로 모듈의 공장 생산이 가능한 전기 출력 300MWe 미만의 원자로를 의미

## SMR 특징

**안전성**
소형원자로인 특성을 살려 원자로계통을 단순하고 피동안전성이 뛰어난 원자로로 실험함으로써 대형원전 대비 안전성 크게 향상

**경제성**
SMR은 규모가 작아서 발전단가는 상승하지만, 건설비용 절감 및 건설기간의 단축으로 초기비용이 크게 감소

**유연성**
소규모 전력망을 위한 발전원 외에 다양한 산업적 활용이 가능

계통단순화·일체형 원자로에 의한 안전성 제고, 초기 투자비용 부담 경감, 발전 외에 다양한 산업분야에서의 유연성 측면에서 대형원전 대비 다양한 장점을 보유


자료: 혁신형SMR 기획공청회 자료

# 혁신형 SMR

| | |
|---|---|
| 전략 목표 | 혁신형 SMR 글로벌 경쟁력 강화를 통한 2030년대 수출 달성 |

**성과 목표**

안전성·경제성·유연성이 확보된 혁신형 SMR 핵심기술 개발 및 2028년 시장경쟁력 있는 표준설계 및 기술 검증

| 세계 최고 수준의 안전성 검증 | 경쟁 예상 노형 및 대형원전 대비 경쟁력 있는 경제성 확보 | 세계 최고 수준의 부하추종 능력 확보 |
|---|---|---|
| 노심손상빈도 : 1.0e-9/M·Y | 건설단가 = $4,000/kw<br>발전단가 = $65/kwh | 출력변화율 5%/min |

**추진전략**

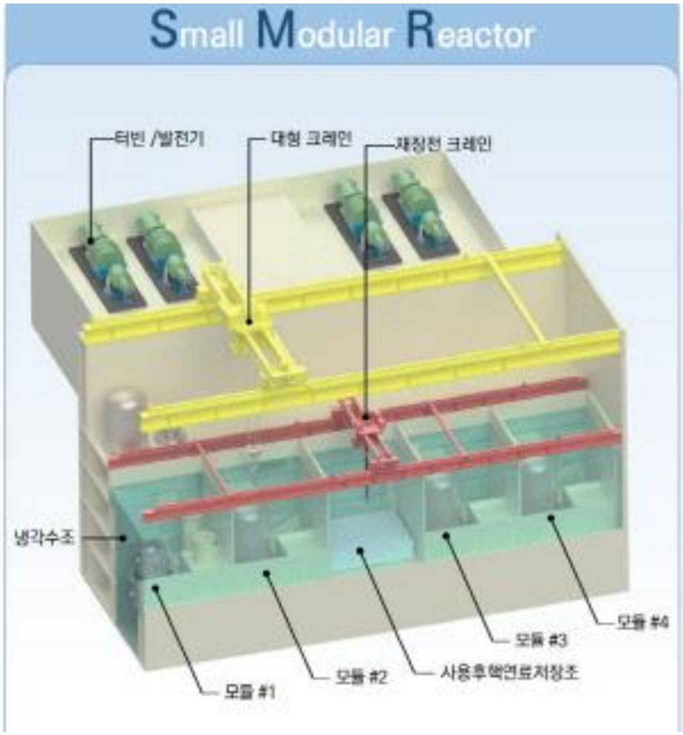
| | |
|---|---|
| 기술력경쟁력 제고 | 안전성·경제성·유연성 확보를 위한 핵심기술 개발 |
| 사회적 수용성 제고 | 인허가 이슈 조기 발굴 및 선제적 대응 |
| 국가 역량 결집 | 구조화된 국내 원자력산업 특성을 고려한 역량 결집 |

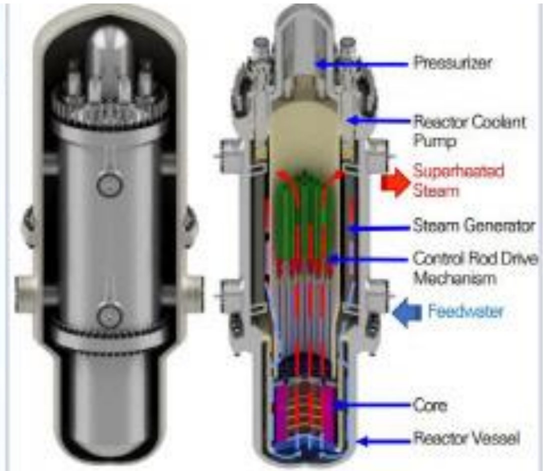
**핵심기술**

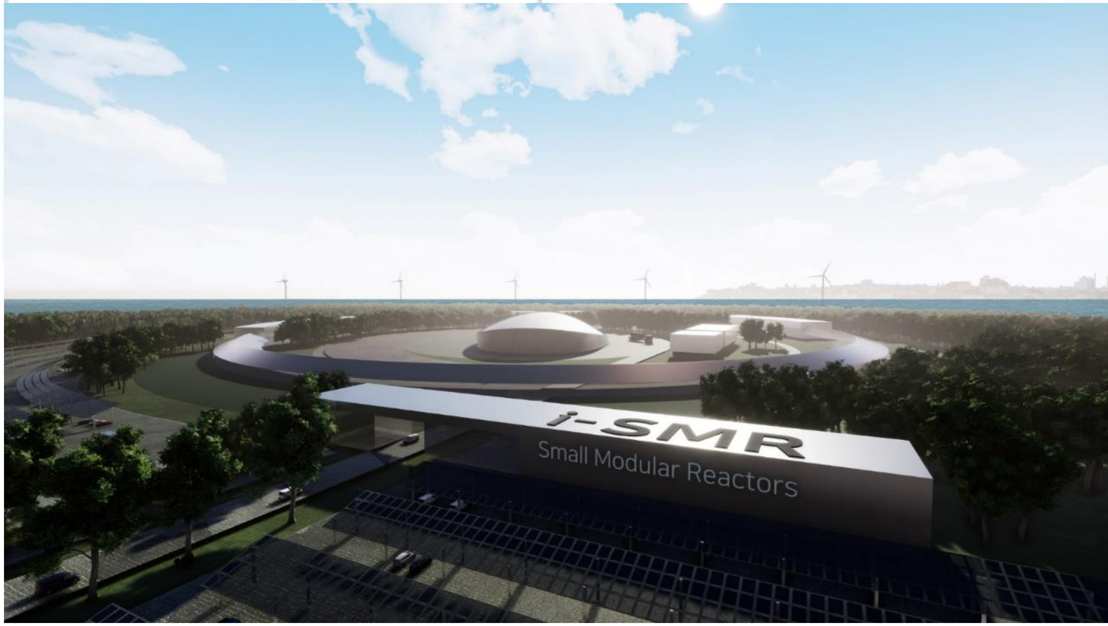
- 무한냉각
- 내장형 CEDM
- 혁신 핵연료
- 자율운전/디지털트윈
- 모듈화
- 재생에너지 연계
- 무붕산 운전
- 혁신 제조기술
- 통합형 제어실

자료: 혁신형SMR 기획공청회 자료

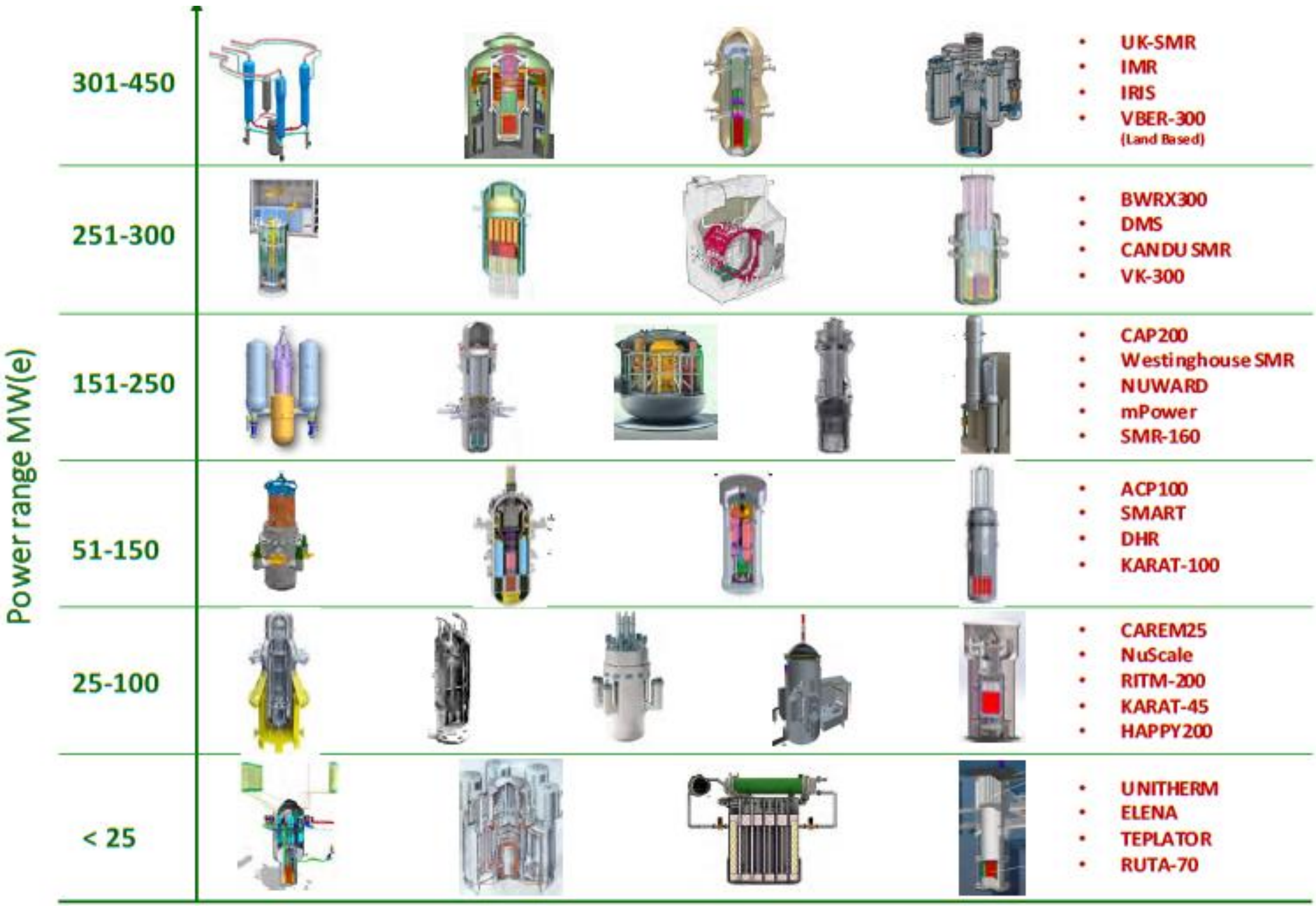
# 혁신형 SMR


Small Modular Reactor
터빈 /발전기
대형 크레인
재장전 크레인
냉각수조
모듈 #1
모듈 #2
사용후핵연료저장조
모듈 #3
모듈 #4


Pressurizer
Reactor Coolant Pump
Superheated Steam
Steam Generator
Control Rod Drive Mechanism
Feedwater
Core
Reactor Vessel


i-SMR
Small Modular Reactors

# 경쟁노형




Land-based water-cooled reactors

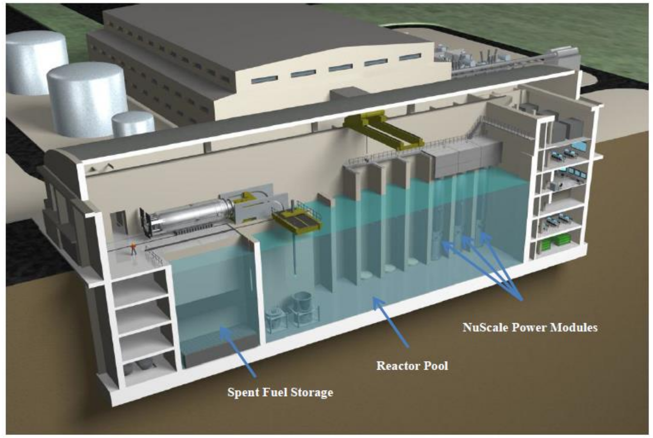
자료: IAEA SMR 보고서 (2020)

# 경쟁노형

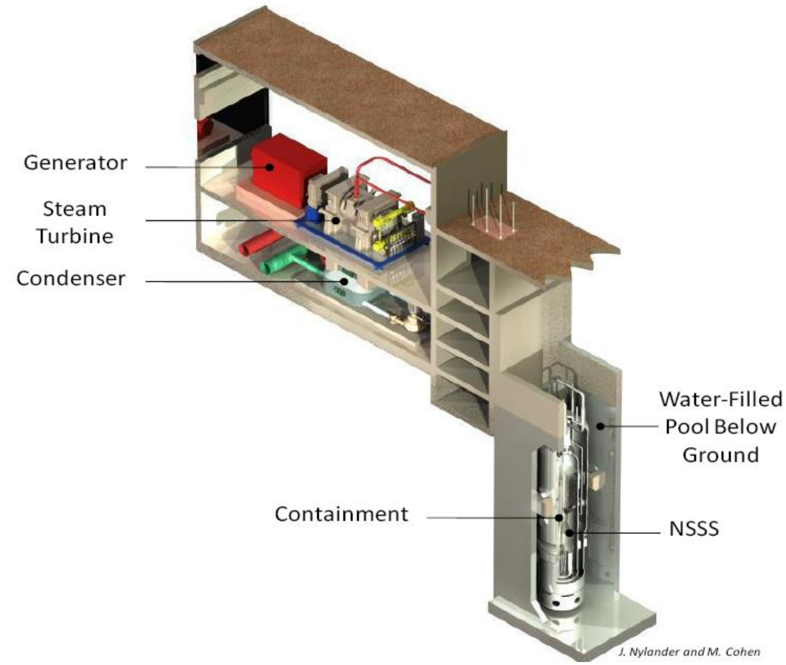
| | CAREM | ACP100 | CANDU SMR | NUWARD | SMART | UK-SMR | NuScale | BWRX-300 |
|---|---|---|---|---|---|---|---|---|
| Country of Origin | Argentina | China | Canada | France | Republic of Korea & Saudia Arabia | United Kingdom | United States of America | United States or Americ and Japan |
| Design organization(s) | CNEA | CNNC/NPIC | Candu Energy | EDF | KAERI, K.A.CARE | Rolls Royce, Plc. | NuScale Power, Inc. | GE Hitachi & Hitachi GE Nuclear Energy |
| Reactor Type / Primary Circulation | Integral PWR / Natural Circulation | Integral PWR / Forced Circulation | PHWR with / Calandria | Integral PWR / Forced Circulation | Integral PWR / Forced Circulation | 3-loop PWR / Forced Circulation | Integral PWR / Natural Circulation | Boiling Water Reactor / Natural Circulation |
| Fuel type/assembly array | $UO_2$ pellet / hexagonal | $UO_2$ pellet / 17x17 square | 37-element fuel bundle | $UO_2$ pellet / 17x17 square | $UO_2$ pellet / 17x17 square | $UO_2$ pellet / 17x17 square | $UO_2$ pellet / 17x17 square | $UO_2$ pellet / 10x10 array |
| Number of fuel assembly | 61 | 57 | 2064 bundles | 76 | 57 | 121 | 37 | 240 |
| Coolant | Light water | Light water | Heavy water | Light water | Light water | Light water | Light water | Light water |
| Moderator | Light water | Light water | Heavy water | Light water | Light water | Light water | Light water | Light water |
| Thermal output, MW(t) | 100 | 385 | 960 | 2 x 540 | 365 | 1276 | 200 | 870 |
| Electrical output, MW(e) | 30 | 125 | 300 | 2 x 170 | 107 | 443 | 60 (gross) | 270-290 |
| Core inlet temp., °C | 284 | 286.5 | - | 380 | 296 | 296 | 265 | 270 |
| Core outlet temp., °C | 326 | 319.5 | 310 | 307 | 322 | 327 | 321 | 287 |
| Enrichment, % | 3.1 | < 4.95 | Natural uranium, not enriched | < 5 | < 5 | 4.95 (max) | < 4.95 | 3.40 (avg) / 4.95 (max) |
| Fuel cycle, months | 24 | 24 | Online refuelling | 24 | 30 | 18 – 24 | 24 | 12 – 24 |
| Reactivity control | Control rods | Control rods + $Gd_2O_3$ solid burnable | Zone controllers + adjusters | Control rods + $Gd_2O_3$ solid burnable | Control rods + Soluble boron | Control rods + $Gd_2O_3$ solid burnable | Control rods + Soluble boron | Rods, Solid Burnable Absorber ($B_4C$, Hf, $Gd_2O_3$) |
| Reactor Vessel's height/diameter, (m) | 11 / 3.2 | 10 / 3.35 | N/A - Calandria | 13 / 4 | 18.5 / 6.5 | 11.3 / 4.5 | 17.7 / 2.7 | 26 / 4 |
| Design status | Under construction as Prototype | Detailed Design for construction | Conceptual | Conceptual | Licensed / Standard design approval | Conceptual, Pre-Licensing in the UK | Under design certification review | Pre-Licensing in UK, Canada, and the United States |

자료: IAEA SMR 보고서 (2020)

# NuScale Overview








## Development Milestones

| | |
|---|---|
| 2003 | First Integral test facility operational |
| 2007 | NuScale Power was formed |
| 2008 | US NRC design certification pre-application started |
| 2012 | Twelve-reactor simulated control room was commissioned |
| 2016 (2nd half) | NuScale to submit design certification application to the NRC |
| 2020 | NuScale design certification target |
| 2023 | NuScale commercial operation target |

# NuScale DC

## NuScale SMR receives US design certification approval

01 September 2020

Share

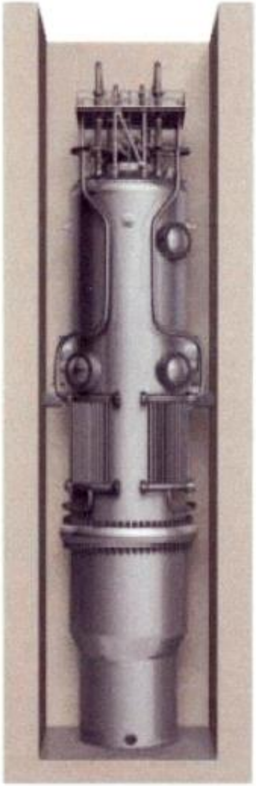
**The US Nuclear Regulatory Commission (NRC) has issued a final safety evaluation report (FSER) for NuScale's small modular reactor. This is the first-ever FSER to be issued by the NRC for an SMR, and represents the completion of the technical review and approval of the design.**

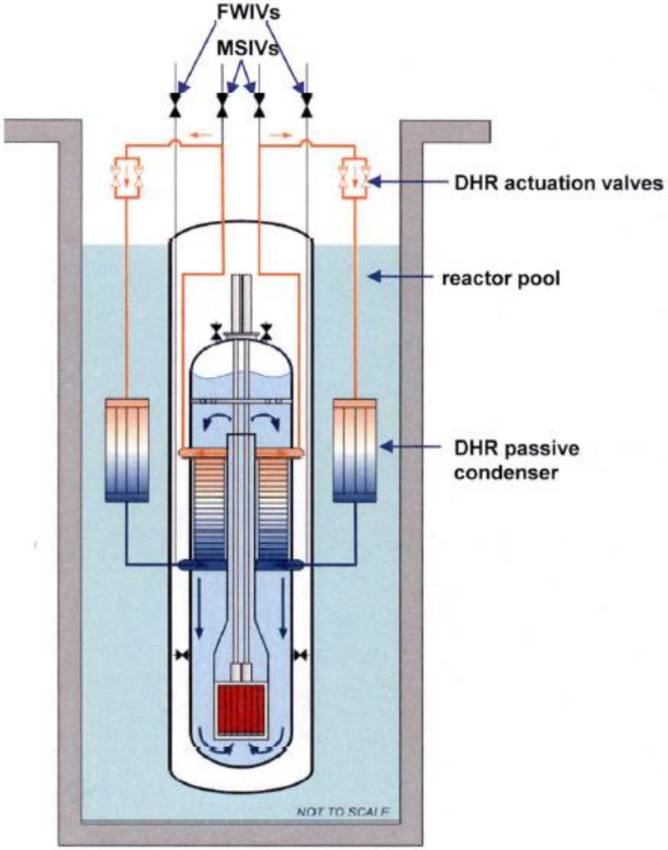
*How a NuScale SMR plant could look (Image: NuScale)*

# NuScale Safety (DHR)

## Decay Heat Removal System

- Main steam and main feedwater isolated
- Decay heat removal (DHR) valves opened
- Decay heat passively removed via the steam generators and DHR heat condensers to the reactor pool
- DHR system is composed of two independent single failure proof trains (1 of 2 trains needed)

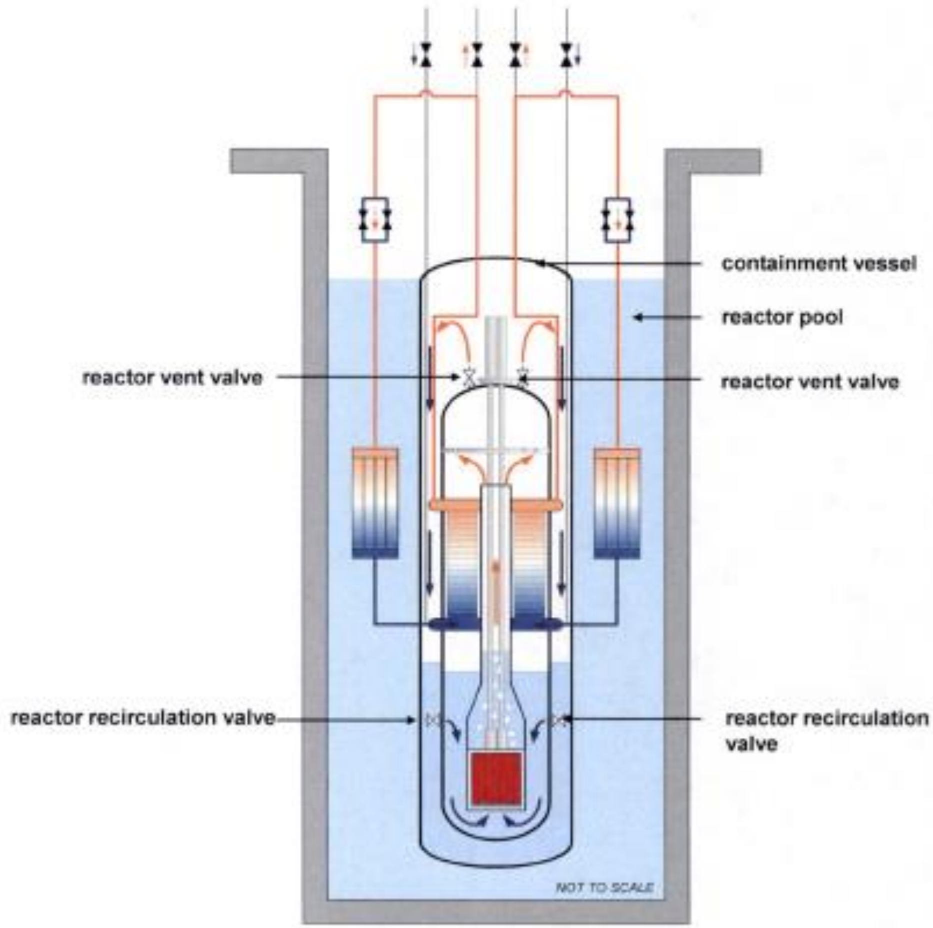




# NuScale Safety (ECCS)

## Emergency Core Cooling System

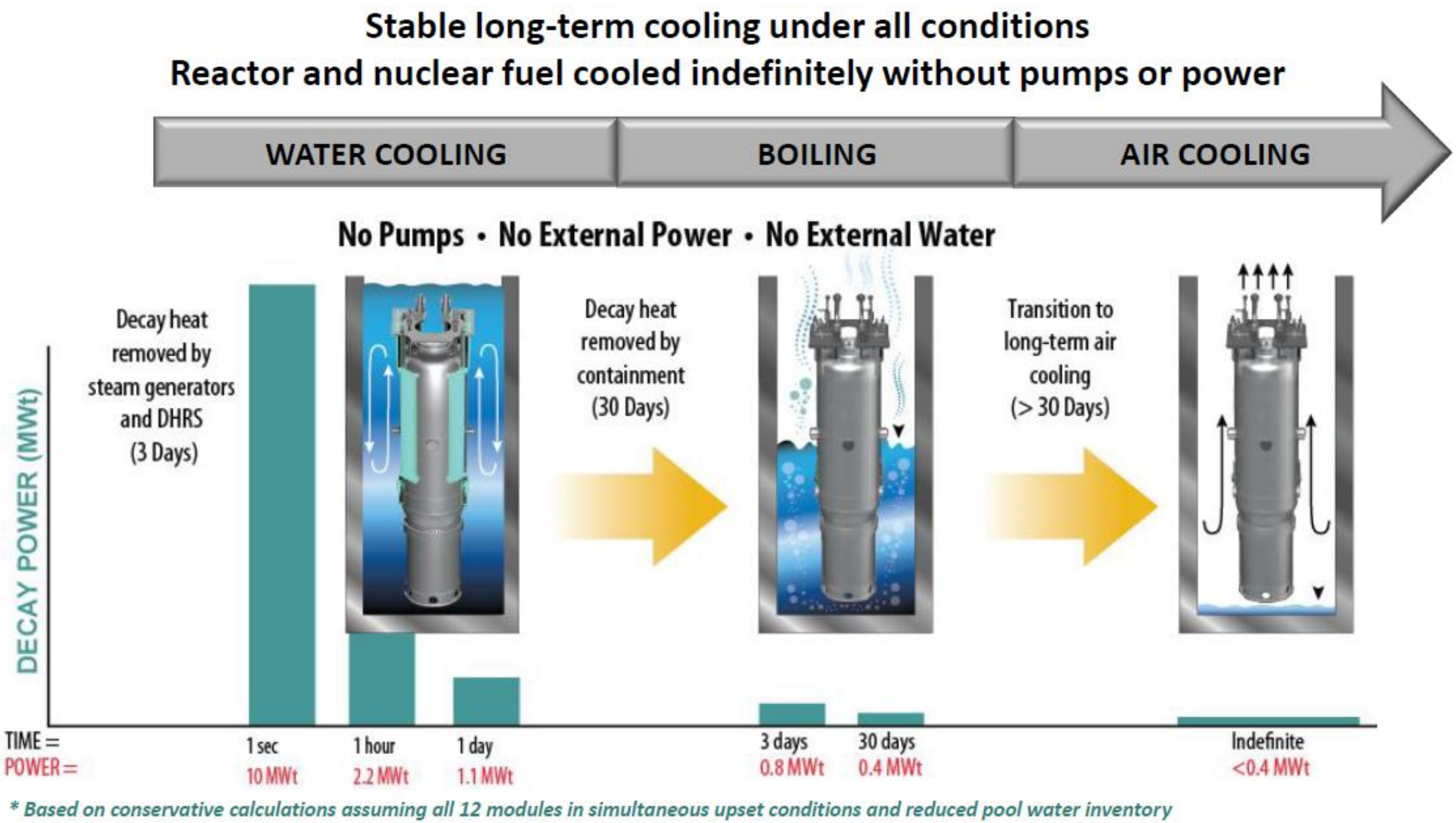
- Main steam and main feedwater isolated
- Reactor vent valves and reactor recirculation valves open on safety signal
- Decay heat removed
  - condensing steam on inside surface of containment vessel
  - convection and conduction through liquid and both vessel walls



# NuScale Safety

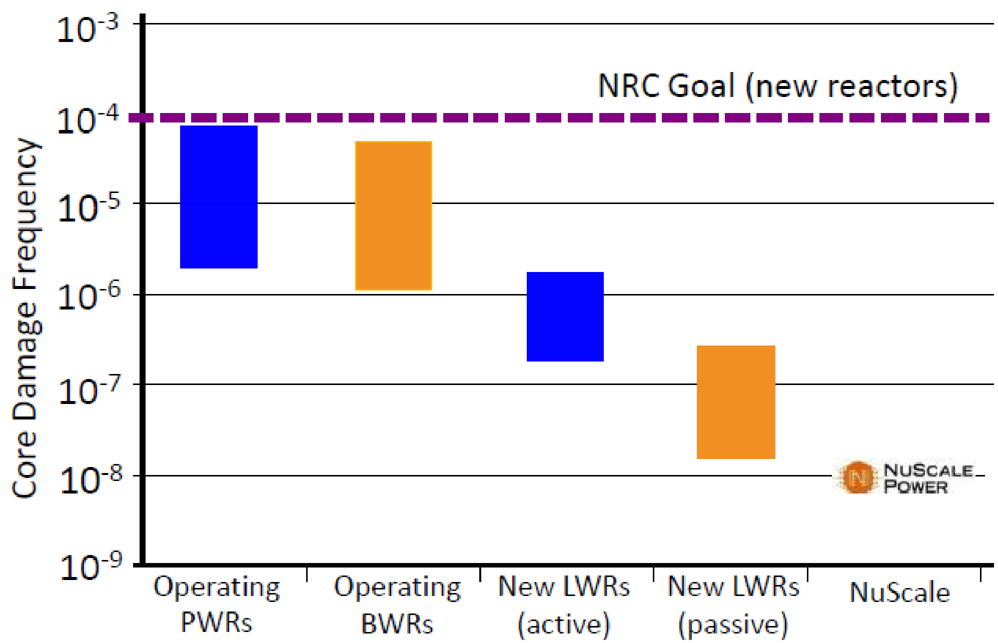
- NuScale design has achieved the “Triple Crown” for nuclear plant safety. The plant can safely shut-down and self-cool, indefinitely, with:
    - **No Operator Action**
    - **No AC or DC Power**
    - **No Additional Water**
- Safety valves align in their safest configuration on loss of all plant power
- Details of the Alternate System Fail-safe concept were presented to the NRC in December 2012

# NuScale Safety (SBO)

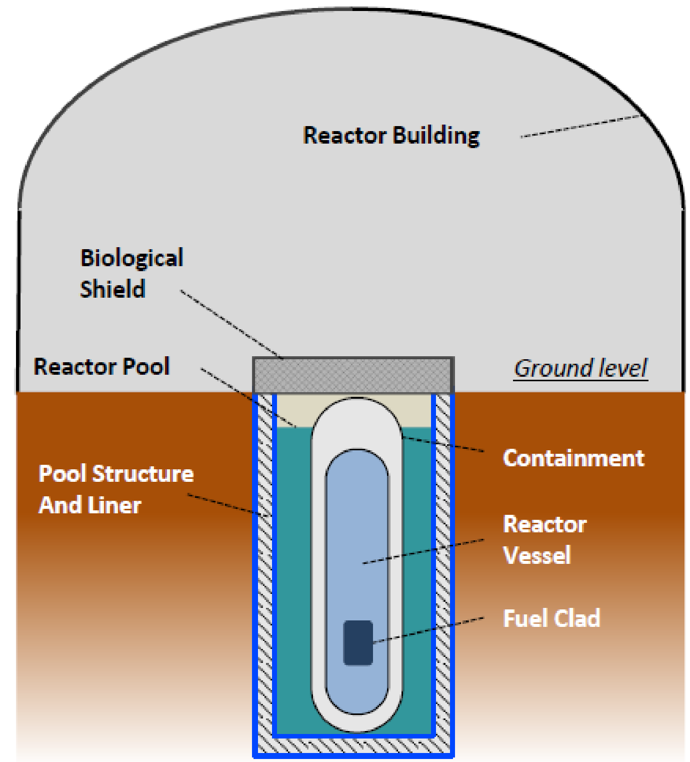


# NuScale Safety (Risk)

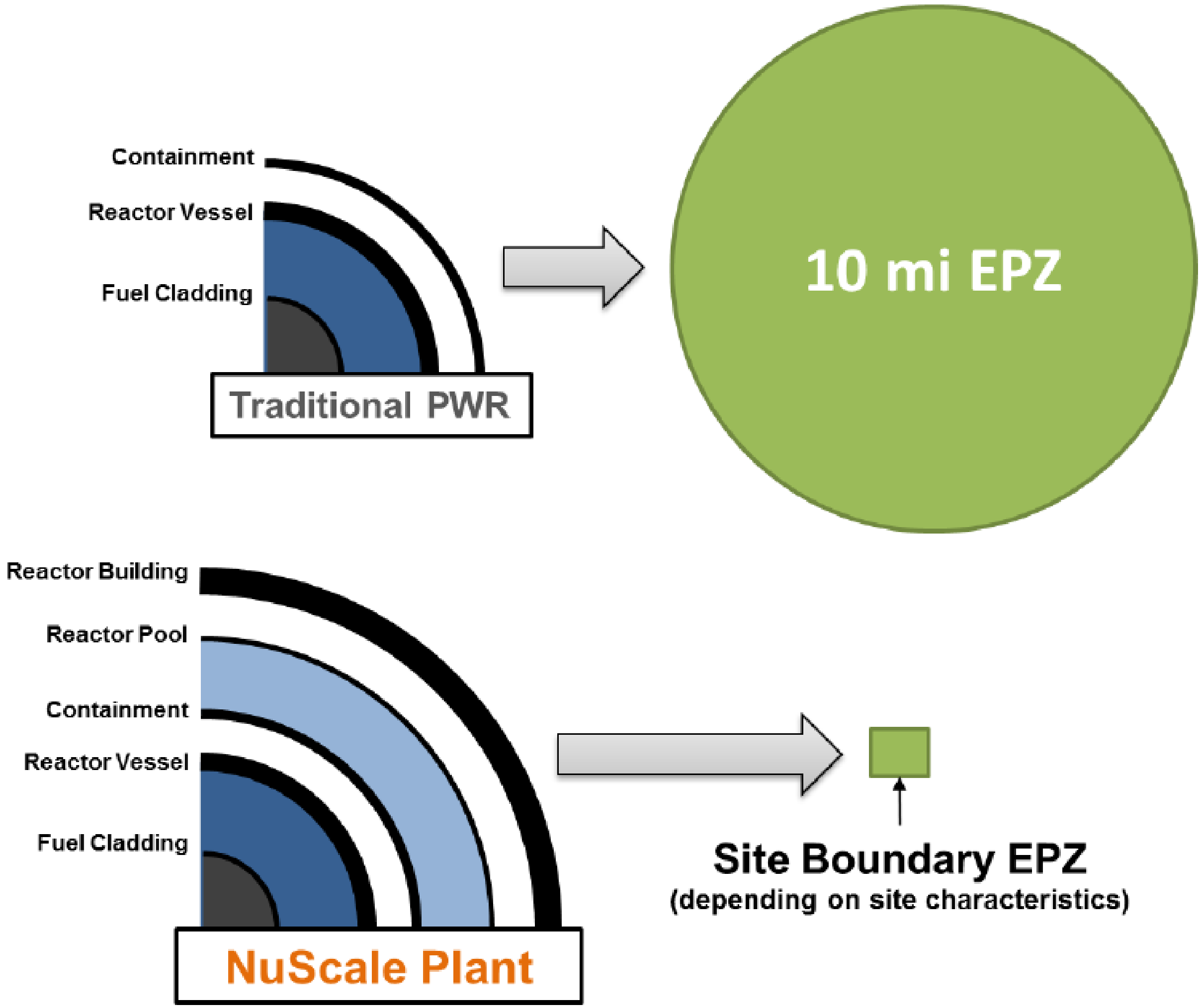
**Risk** = (frequency of failure) X (consequences)




*Probability of core damage due to NuScale reactor equipment failures is* ***1 in 100,000,000 years***



# NuScale EPZ




- *Passive Safety*
- *Additional Fission Product Barriers*
- *Significant Delay in Release of Fission Products*

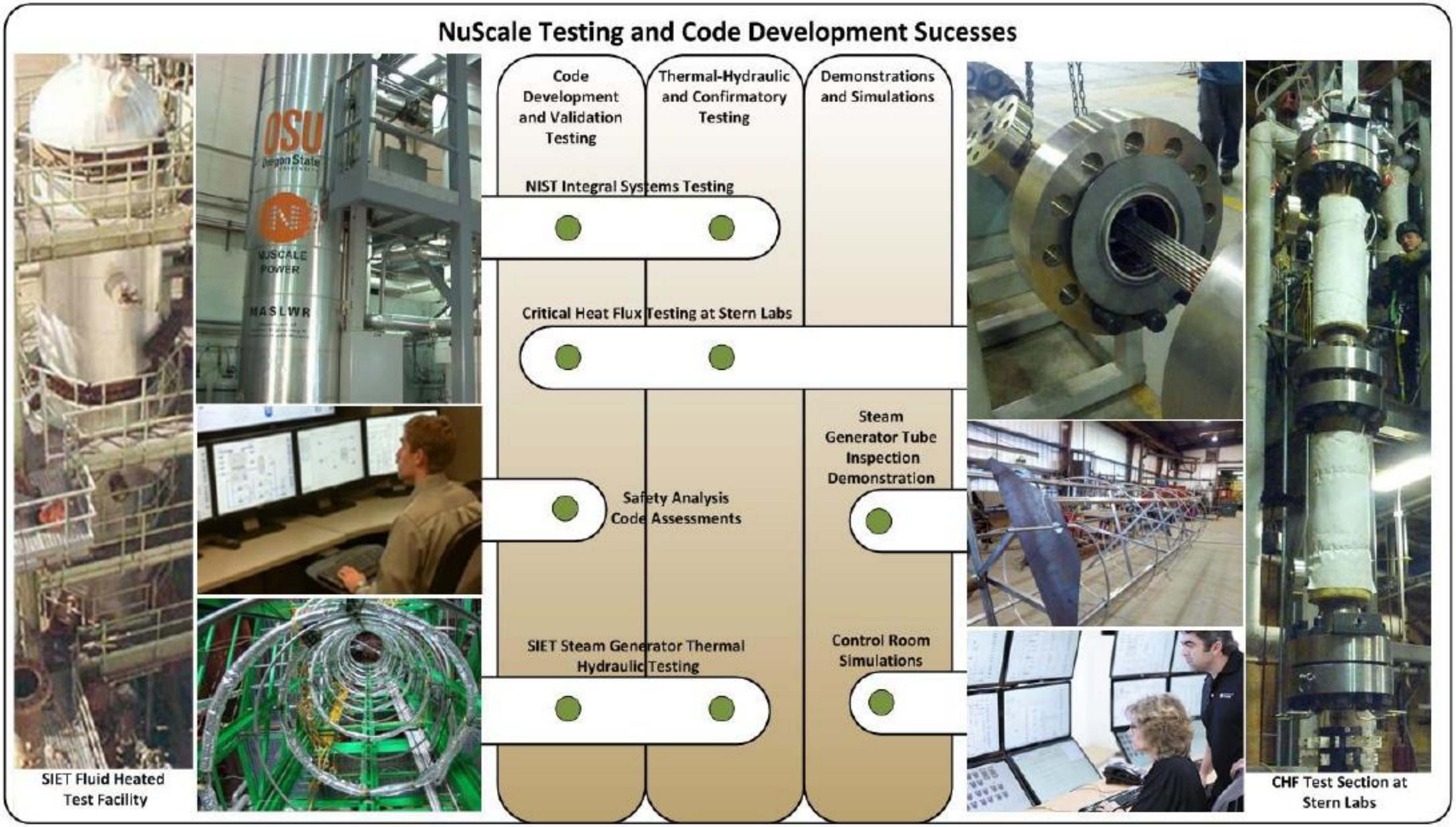
# NuScale Systems

**Systems and Components Needed to Protect the Core:**

- Reactor Pressure Vessel
- Containment Vessel
- Reactor Coolant System
- Decay Heat Removal System
- Emergency Core Cooling System
- Control Rod Drive System
- Containment Isolation System
- Ultimate Heat Sink
- Residual Heat Removal System
- Safety Injection System
- Refueling Water Storage Tank
- Condensate Storage Tank
- Auxiliary Feedwater System
- Emergency Service Water System
- Hydrogen Recombiner or Ignition System
- Containment Spray System
- Reactor Coolant Pumps
- Safety Related Electrical Distribution Systems
- Alternative Off-Site Power
- Emergency Diesel Generators
- Safety Related 1E Battery System
- Anticipated Transient without Scram (ATWS) System

# NuScale Activities for Licensing

- NuScale's testing supports reactor safety code development and validation, reactor design, and technology maturation to reduce first-of-a-kind risk




SIET Fluid Heated Test Facility

CHF Test Section at Stern Labs

# NuScale DC과정 미해결 안전현안

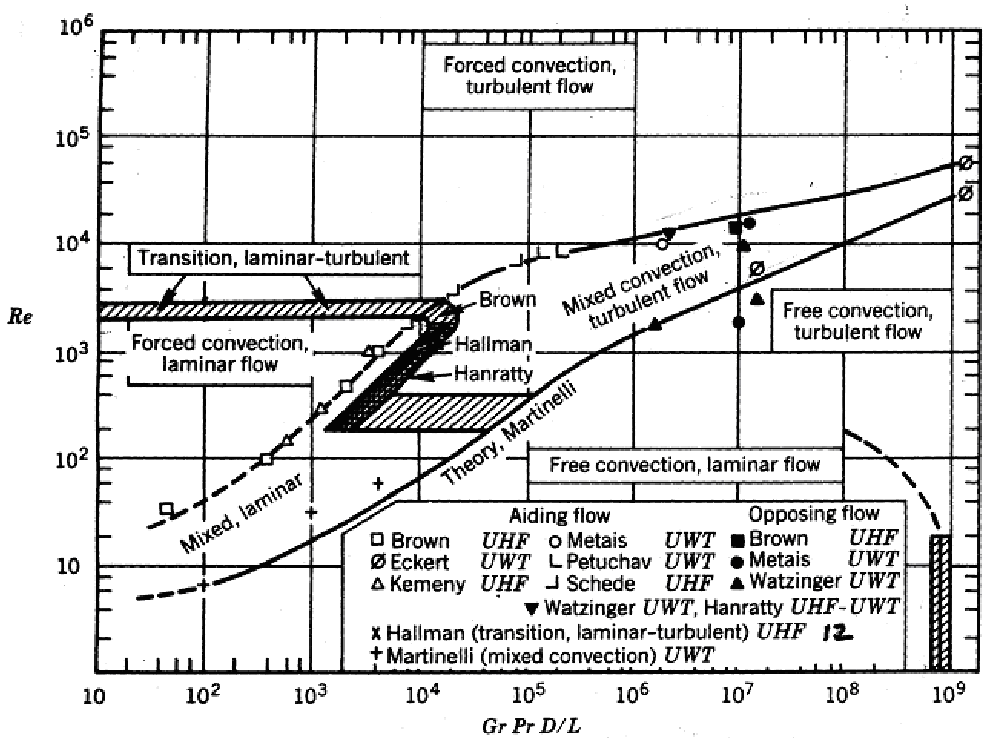
- 방사선차폐 설계(shield wall design)
  - 방사선 Streaming effect 저감 방안 COLA에서 제시
- 연소가스 모니터링에 의한 격납건물 누설
  - 연소가스 모니터링용 배관구경이 비안전등급으로 너무 커서 COLA에서 설계변경 권고
- 증기발생기 관구조 및 누설대비 강건성
  - DWO에 의한 구조건전성 및 성능문제
  - Accelerated wearing

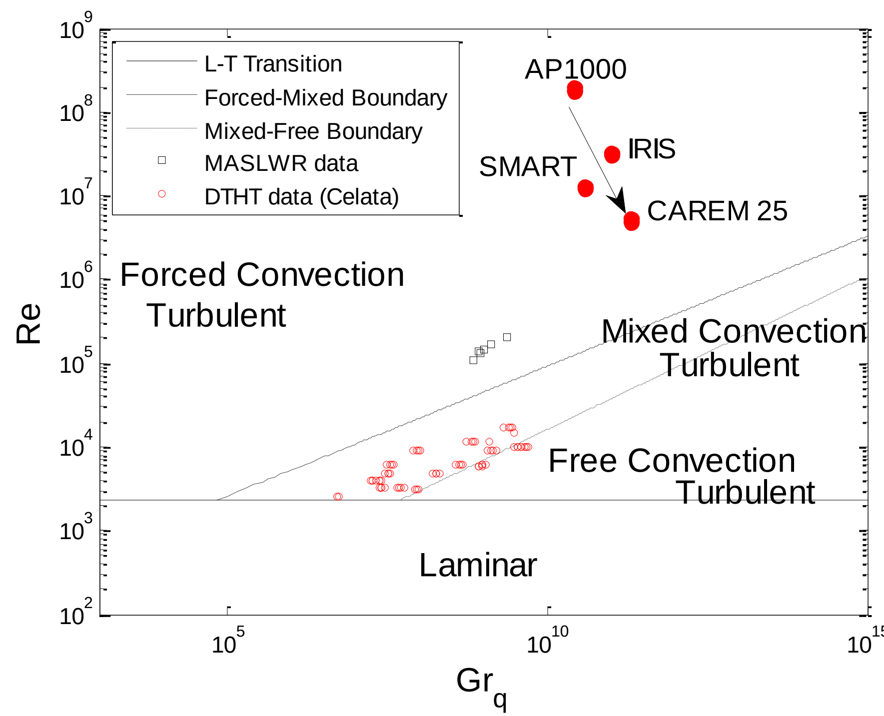
# NuScale DC과정 미해결 안전현안

- ECCS에 사용되는 밸브의 성능
  - 신뢰도 및 장기적 성능평가 필요
- 보론 희석에 따른 양의 반응도 삽입 방지대책
  - 붕산을 이용한 노심반응도 제어로 인해 증발응축과정에서 노심의 붕산희석에 의한 반응도 삽입 문제

# SMR 안전관련 기술현안

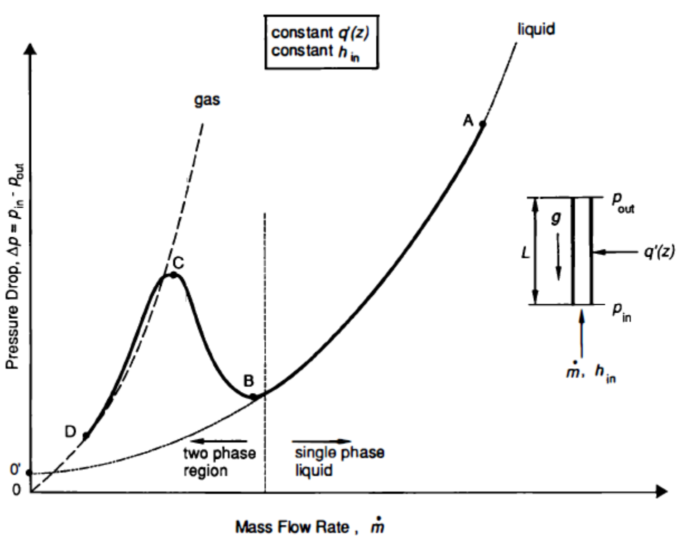
## □ 단상 자연순환 (Mixed Convection)



# SMR 안전관련 기술현안

- □ 이상 자연순환 Instability

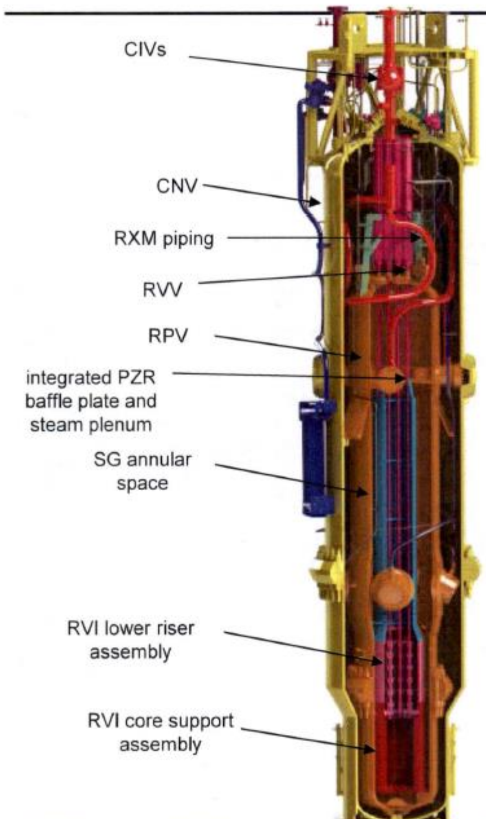



| Class | Type | Mechanism | Characteristics |
|---|---|---|---|
| 1. Static instabilities | | | |
| 1.1. Fundamental (or pure) static instabilities | 1. Flow excursion or Ledinegg instability | $\left.\frac{\partial \Delta p}{\partial G}\right\|_{int} \leqslant \left.\frac{\partial \Delta p}{\partial G}\right\|_{ext}$ | Flow undergoes sudden, large amplitude excursion to a new, stable operating condition |
| | 2. Boiling crisis | Ineffective removal of heat from heated surface | Wall temperature excursion and flow oscillation |
| 1.2. Fundamental relaxation instability | 1. Flow pattern transition instability | Bubbly flow has less void but higher $\Delta P$ than that of annular flow | Cyclic flow pattern transitions and flow rate variations |
| 1.3. Compound relaxation instability | 1. Bumping, geysering, or chugging | Periodic adjustment of metastable condition, usually due to lack of nucleation sites | Period process of super-heat and violent evaporation with possible expulsion and refilling |
| 2. Dynamic instabilities | | | |
| 2.1. Fundamental (or pure) dynamic instabilities | 1. Acoustic oscillations | Resonance of pressure waves | High frequencies (10–100 Hz) related to time required for pressure wave propagation in system |
| | 2. Density wave oscillations | Delay and feedback effects in relationship between flow rate, density, and pressure drop | Low frequencies (1 Hz) related to transit time of a continuity wave |
| 2.2. Compound dynamic instabilities | 1. Thermal oscillations | Interaction of variable heat transfer coefficient with flow dynamics | Occurs in film boiling |
| | 2. BWR instability | Interaction of void reactivity coupling with flow dynamics and heat transfer | Strong only for a small fuel time constant and under low pressures |
| | 3. Parallel channel instability | Interaction among small number of parallel channels | Various modes of flow redistribution |
| 2.3. Compound dynamic instability as secondary phenomena | 1. Pressure drop oscillations | Flow excursion initiates dynamic interaction between channel and compressible volume | Very low frequency periodic process (0.1 Hz) |

# SMR 안전관련 기술현안

## □ 고신뢰도 밸브 개발

### NuScale Power Module




CIV = containment isolation valve

CNV = containment vessel

PZR = pressurizer

RPV = reactor pressure vessel

RRV = reactor recirculation valve

RVI = reactor vessel internals

RVV = reactor vent valve

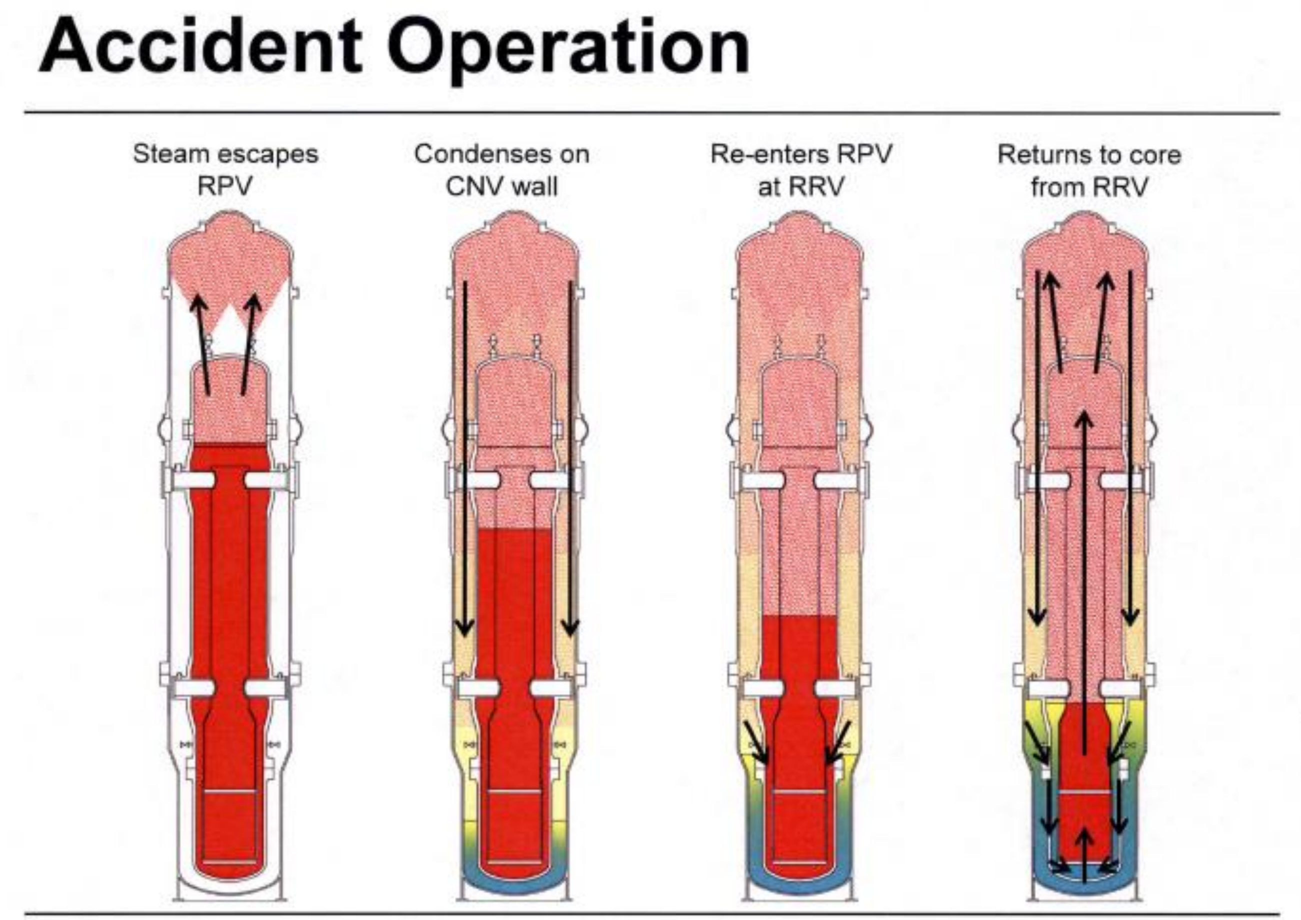
RXM = reactor module

SG = steam generator

| Parameter | Numerical Value |
|---|---|
| CNV height; OD max./min. | 75.8 ft and 15/11.2 ft |
| RPV height and OD | 58 ft. and 10 ft. |
| Module weight (metal) | 762 tons |
| RPV weight (metal) | 343 tons (w/o fuel) |

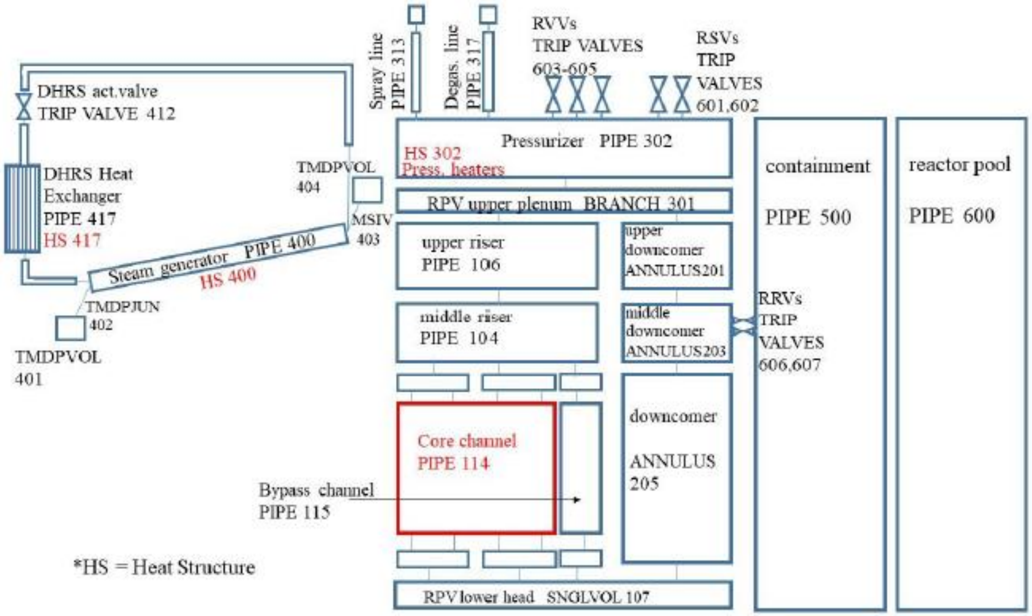
# SMR 안전관련 기술현안

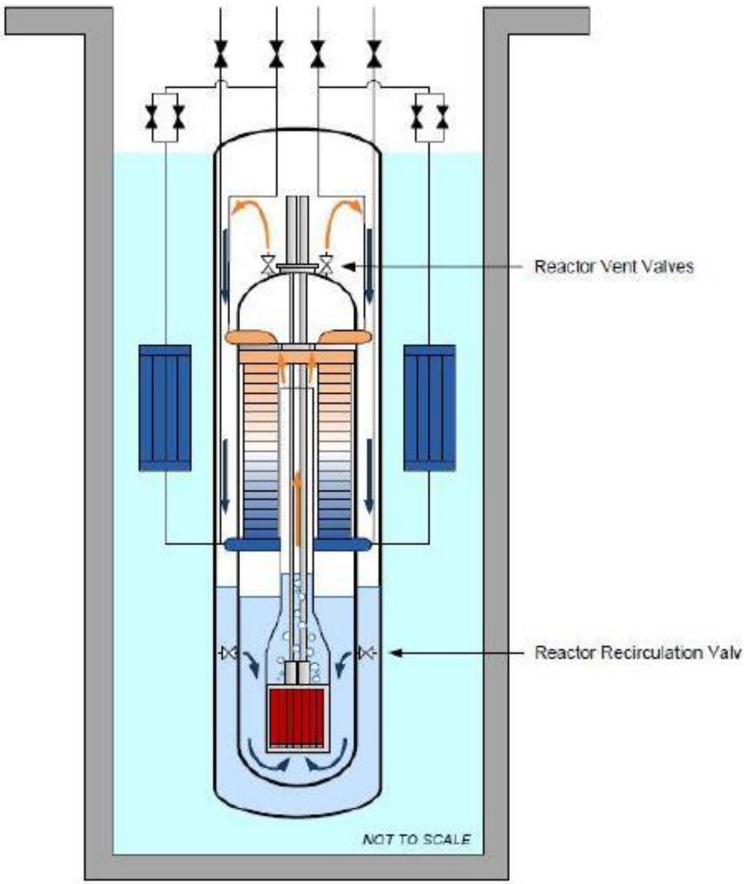
## □ 고신뢰도 밸브 개발

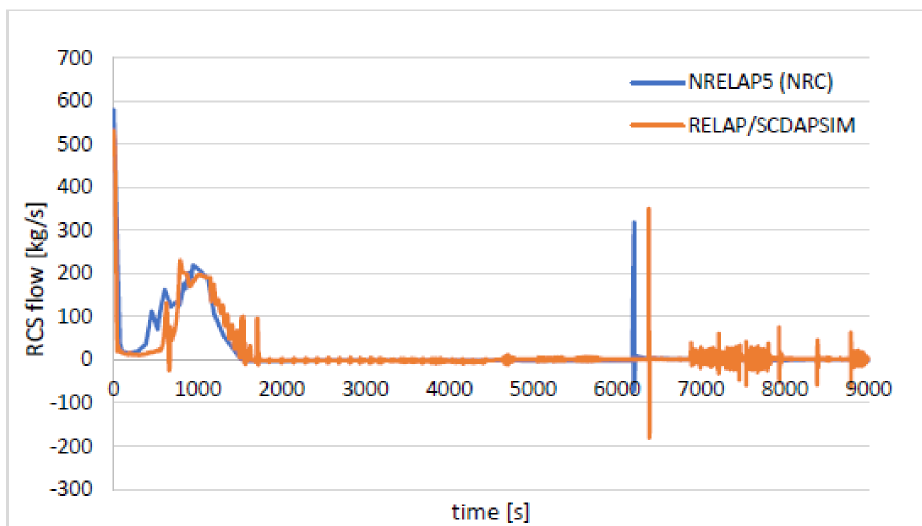


# SMR 안전관련 기술현안

## □ 안전해석 (LOCA)

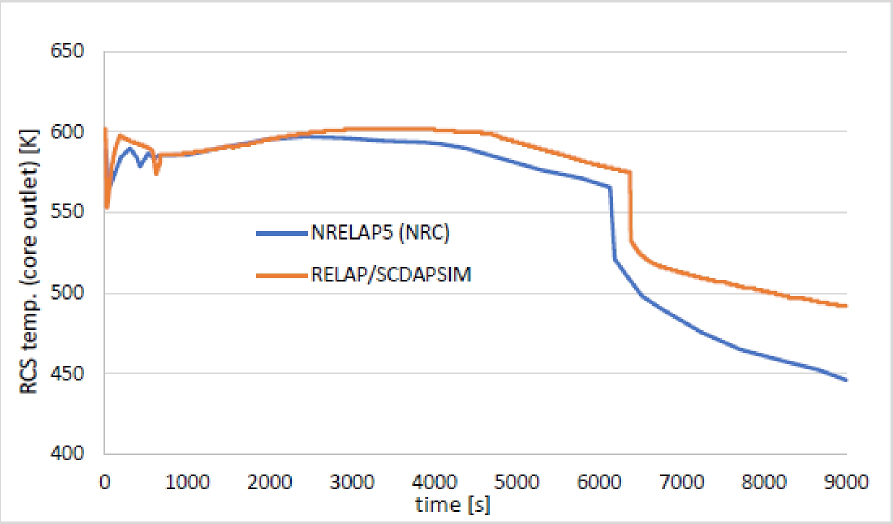


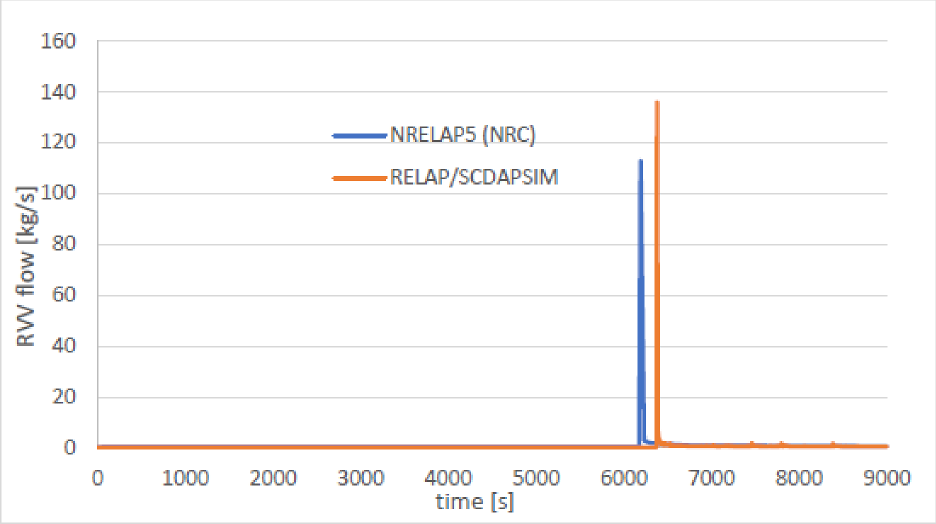



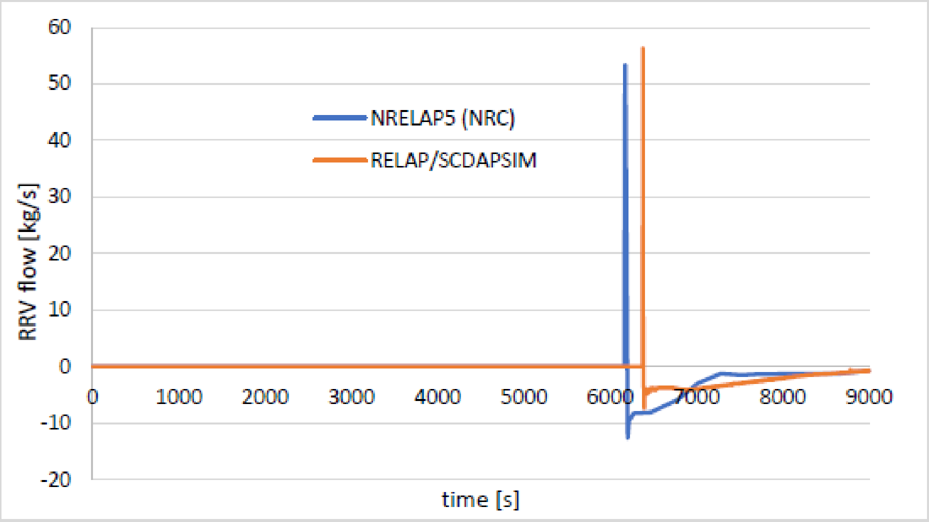



# SMR 안전관련 기술현안

## □ 안전해석 (LOCA)



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## □ 운전원 감소 가능 증명

### ▫ 현재 대형원전 규제요건

**Minimum Requirements[1] Per Shift for On-Site Staffing of Nuclear Power Units by Operators and Senior Operators Licensed Under 10 CFR Part 55**

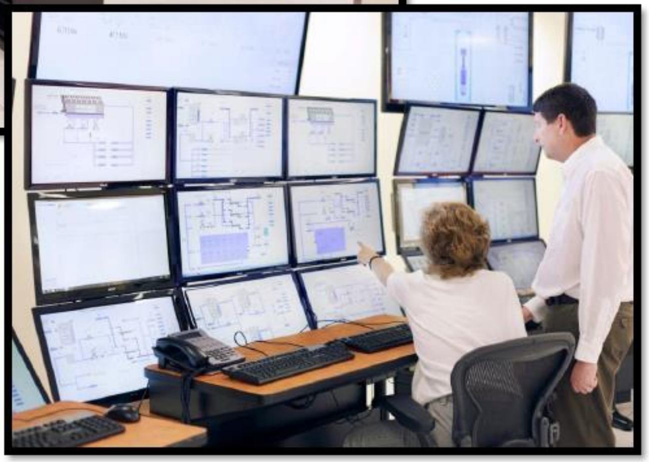
| Number of nuclear power units operating[2] | Position | One Unit | Two units | | Three units | |
|---|---|---|---|---|---|---|
| | | One control room | One control room | Two control rooms | Two control rooms | Three control rooms |
| None | Senior Operator | 1 | 1 | 1 | 1 | 1 |
| | Operator | 1 | 2 | 2 | 3 | 3 |
| One | Senior Operator | 2 | 2 | 2 | 2 | 2 |
| | Operator | 2 | 3 | 3 | 4 | 4 |
| Two | Senior Operator | – | 2 | 3 | 3[3] | 3 |
| | Operator | – | 3 | 4 | 5[3] | 5 |
| Three | Senior Operator | – | -- | – | 3 | 4 |
| | Operator | – | -- | – | 5 | 6 |

# SMR 안전관련 기술현안

## □ 운전원 감소 가능 증명

- NRC Review of HFE Program and site visit Jan.'13

- Simulator used for HFE and operational program development



# 감사합니다!