연구용 원자로 기술 개발 및 수출 현황

2023. 5. 17., 제주국제컨벤션센터

한국원자력학회 원자로시스템기술연구부회

수출용신형연구로 개발 및 검증

(Development and Validation of KiJang Research Reactor)

한국원자력연구원

수출용신형연구로실증사업단

김성훈

CONTENTS

01 Introduction

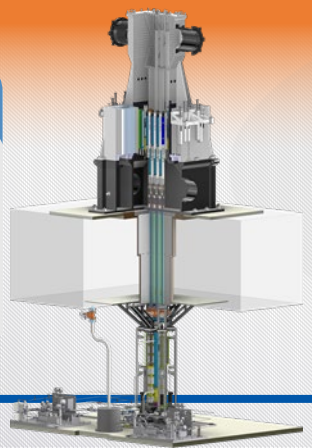
Research Reactors in Korea

	KRR-1	KRR-2	AGN-201	HANARO	KJRR
Location	Seoul (KAERI)	Seoul (KAERI)	Suwon (Kyunghee Univ.)	Daejeon (KAERI)	Busan
Critical	1962. 3. 19	1972. 5. 10	1982. 12. 3	1995. 2. 8	2019.5 (CP)
Status	Decommissioned	Decommissioned	Operating	Operating	Under Construction
Power (th)	250kW	2 MW	10W	30 MW	15 MW
Supplier	GA	GA	AGN	KAERI/AECL	KAERI
Utilization	· Basic research · Education/ Training · RI production	· Basic research · Application of Beam & NAA · Education/ Training · RI production	· Education · Physics experiment	· Neutron beam · RI/NTD · Nuclear material · Training	· RI production · NTD · Export model

01 Introduction

사업명	수출용신형연구로 개발 및 실증
사업기간	2012년 4월 ~ 2027년 4월(15년)
위치	부산광역시 기장군 방사선의·과학산업단지 내
규모	부지: 130,495 m^2 , 연면적: 31,132 m^2(지하4층, 지상3층) 연구로 1기, 동위원소 생산시설 및 중성자조사시설 등 구축
사업비	7,428억원: 7,028억원(국비), 400억원(지방비), 21년기준

원자로 특성 및 조건



기능 요건

방사성동위원소
생산 및 연구,
중성자조사 서비스

성능 요건

- 열 출력 : 15 MWt (열 중성자속 : 3x10^{14} n/cm^2. s 이상)
- 핵연료 : 저농축 우라늄 U-Mo 판형핵연료(농축도: 20% 미만)
- Fission Moly 표적: 저농축 우라늄(LEU)

01 Introduction

전략 목표

- **의료 및 산업용 방사성동위원소의 국내공급 안정화와 수출촉진**
  암 진단용 몰리브덴 등 동위원소, 전력반도체 소재
- **연구용원자로 최신핵심기술 개발 및 실증을 통해 연구로 수출 경쟁력 강화**
  (최신핵심기술)U-Mo 판형핵연료 제조 및 실증, 하부설치 제어봉구동장치 등

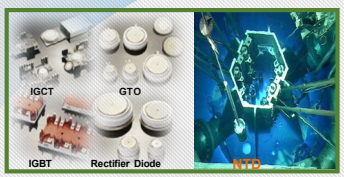
15MWt 수출용신형연구로 개발 및 실증

수출용 신형연구로

의료 및 산업용 방사성동위원소 생산시설 구축

세계 최초 저농축 U-Mo 판형핵연료 실증

중성자도핑 전력반도체 소재 생산시설 구축



동위원소 국내 공급 및 수출
- 국민 의료 복지 및 국제사회 기여
- 고부가 가치 의료 및 관련산업 활성화

연구로 수출경쟁력 강화
- 방글라데시 등 잠재 수요국에 대한 연구로 수출 시장 선점
- 저농축 고성능 핵연료 공급

중성자도핑 서비스 제공
- 반도체 산업 분야의 규모 확대

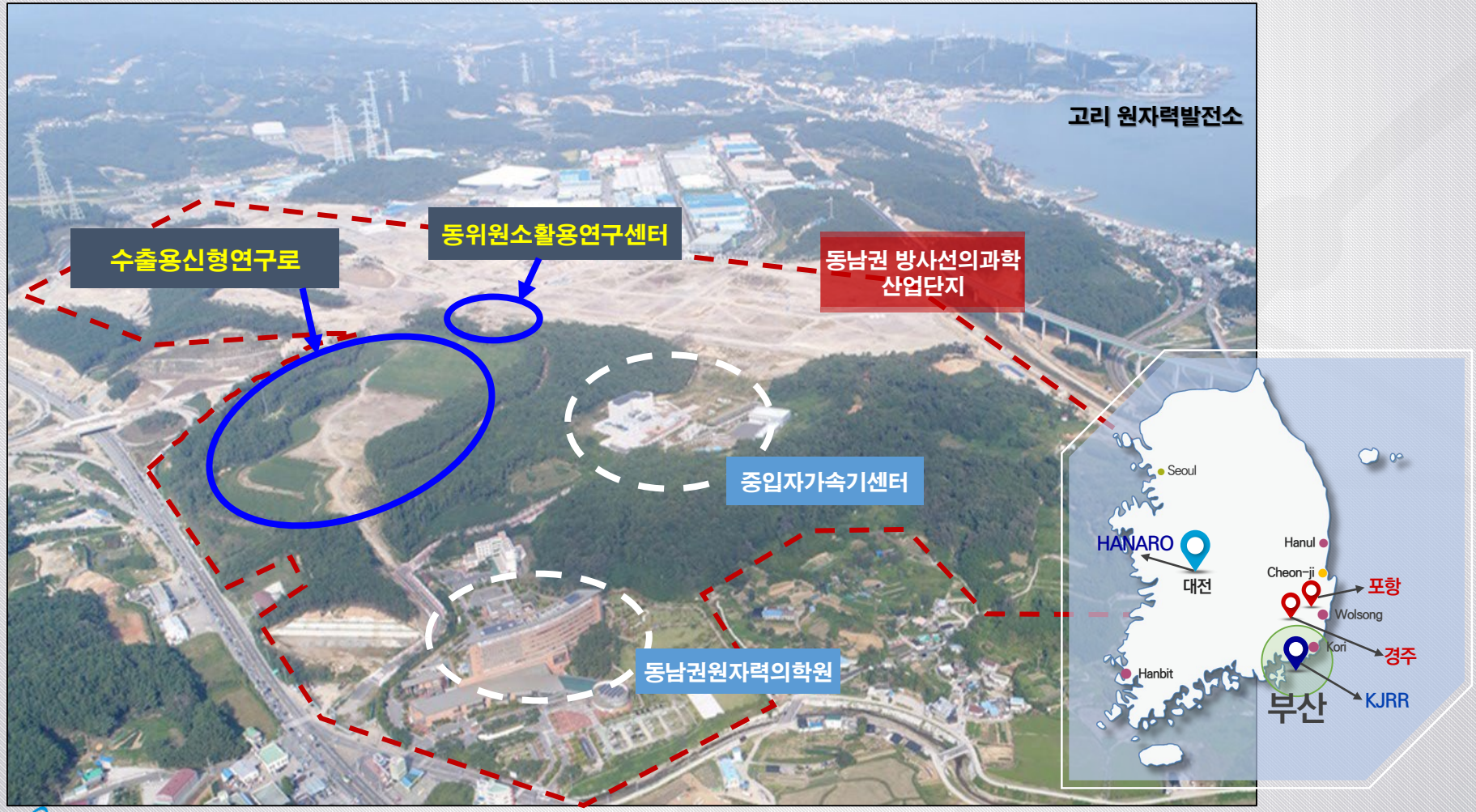
01 Introduction

KJRR Design Specification

Parameter	Value
Power	15 MW
Reactor Type	Open-tank-in-pool type
Max. thermal neutron flux	> 3×10^{14} (n/cm^{2}s)
Annual operation	~ 300 days
Fuel	Plate type, U-7Mo (19.75% enriched)
F-Mo Target	UAlx plate type (LEU, 2.6 g/cc)
Reflector	Be and Al
Coolant and Cooling method	H_2O, downward forced convection flow
Decay heat cooling	SRHRS and natural circulation by flap valves
Reactor building	Confinement

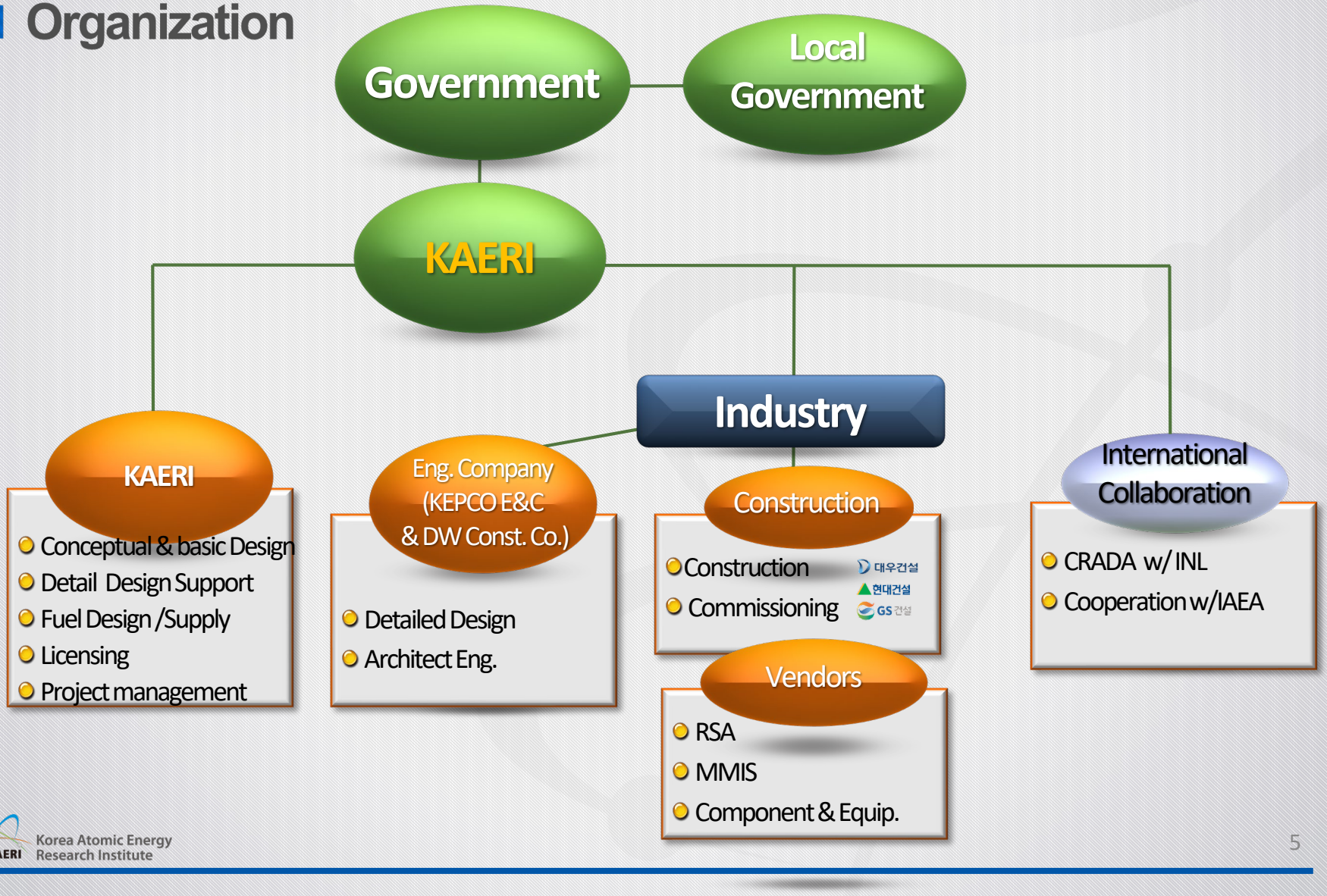
01 Introduction

Construction Site



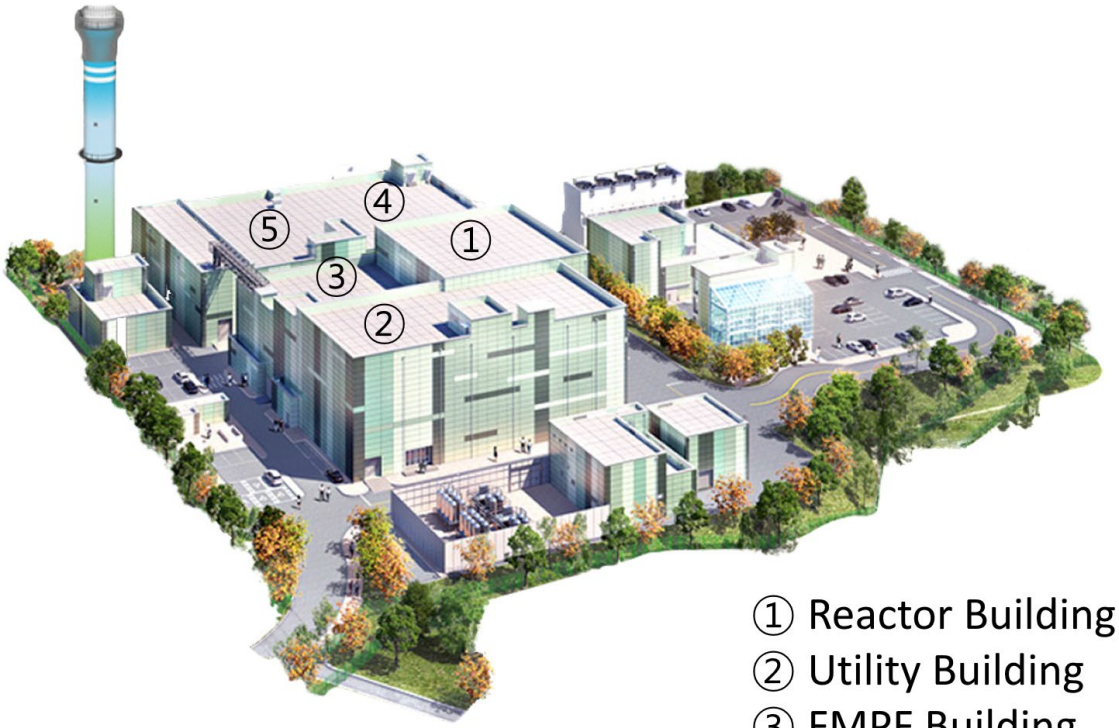
01 Introduction

Organization



01 Introduction

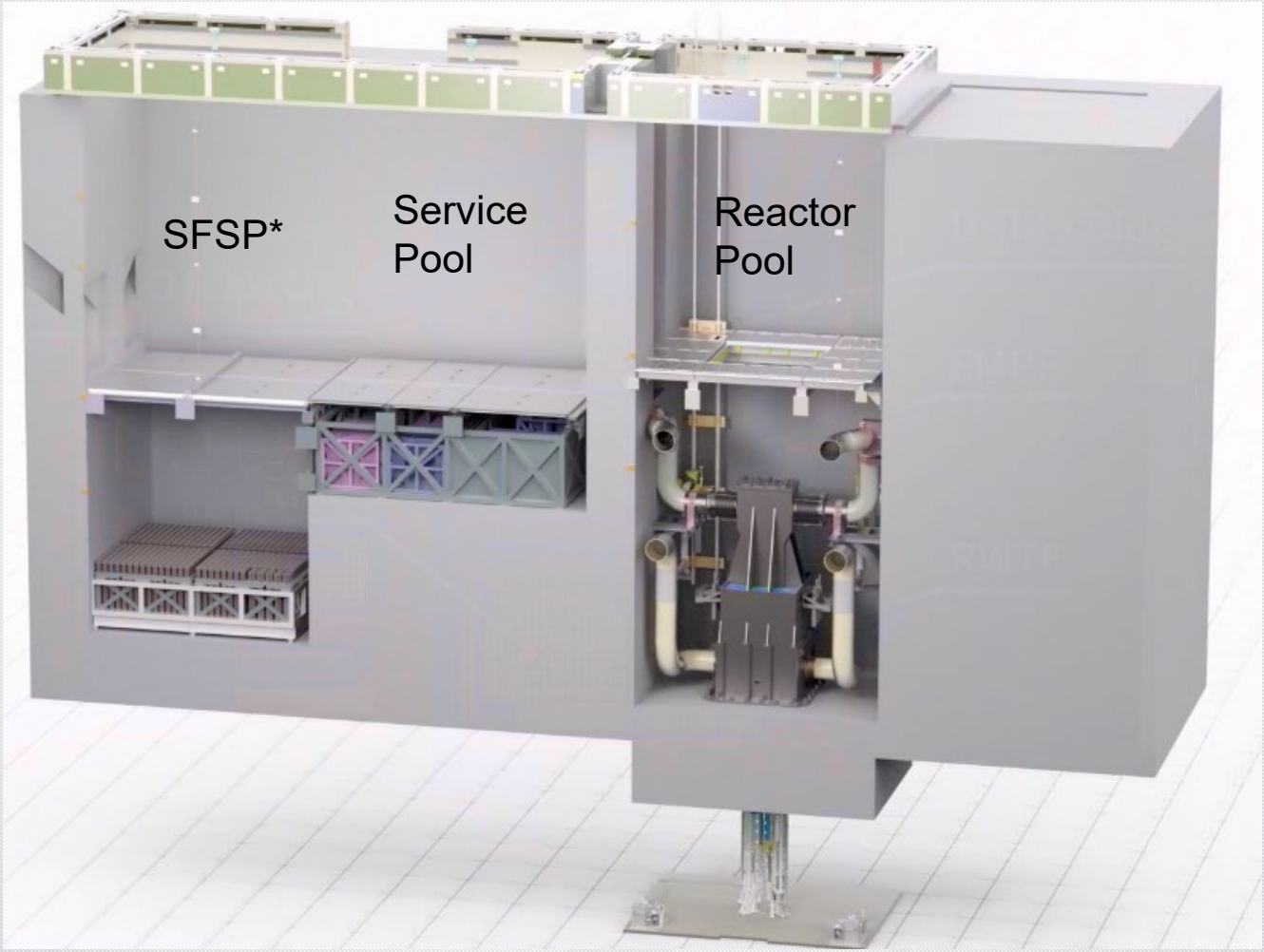
Bird's Eye View of the KJRR



① Reactor Building
② Utility Building
③ FMPF Building
④ RIPF Building
⑤ RWTF Building

02 Characteristics of KJRR

Reactor Pool Arrangement

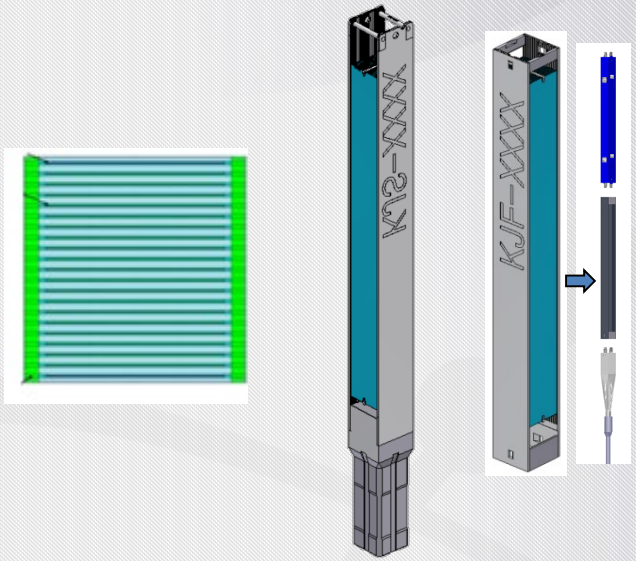


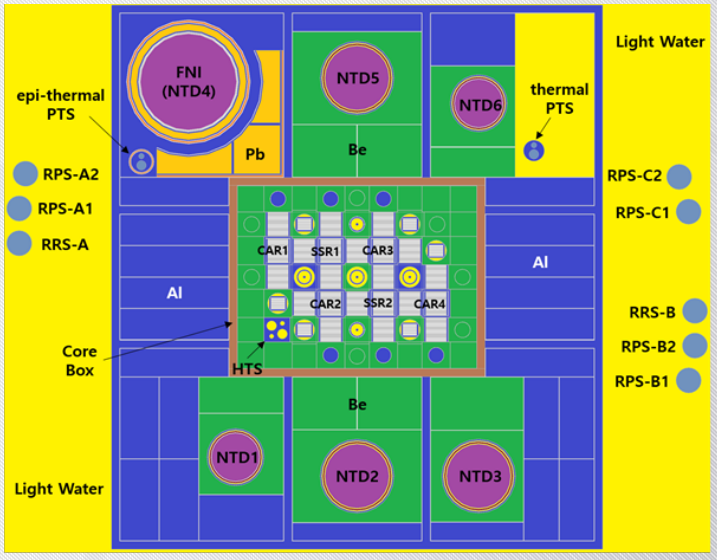
* Spent Fuel Storage Pool

02 Characteristics of KJRR

Reactor Core and Fuel Assembly

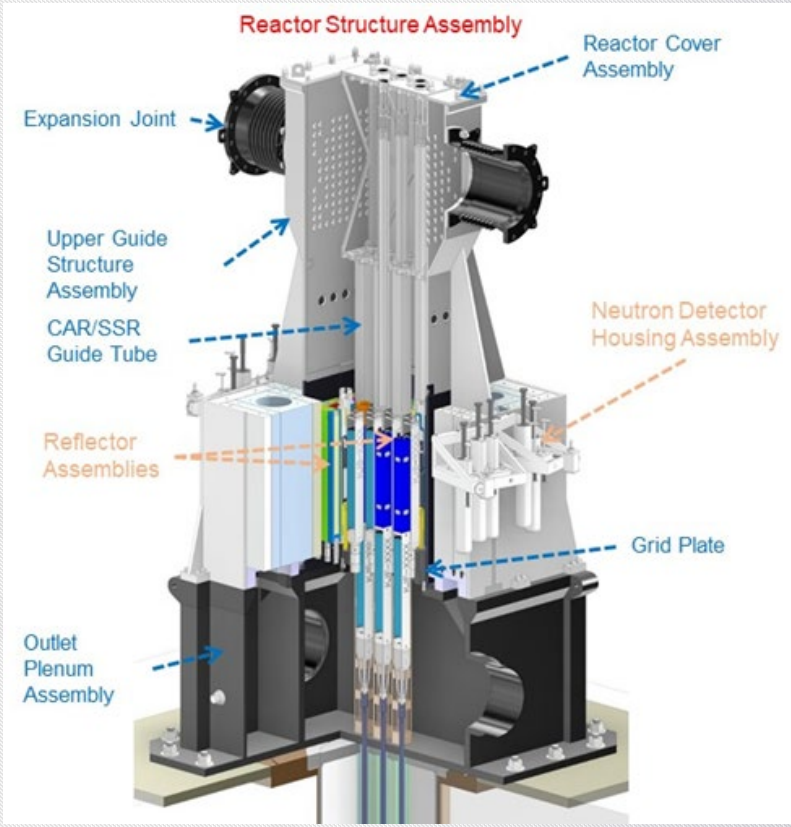
- **Fuel**
  - Plate type (Typical RR fuel)
  - 21 plates & 22 flow channels
  - Fuel meat (U-7Mo)
    - 8.0 gU/cm^3 (17 inner plates)
    - 6.5 gU/cm^3 (4 outer plates)
  - Follower fuel assembly (FFA)
  - Fission Mo target : U-Alx
- **Core**
  - 7x9 lattice
  - SFA (16) + FFA (6)
  - Fission Mo target (6)
  - 3 flux traps, 9 IRs with on-power loading



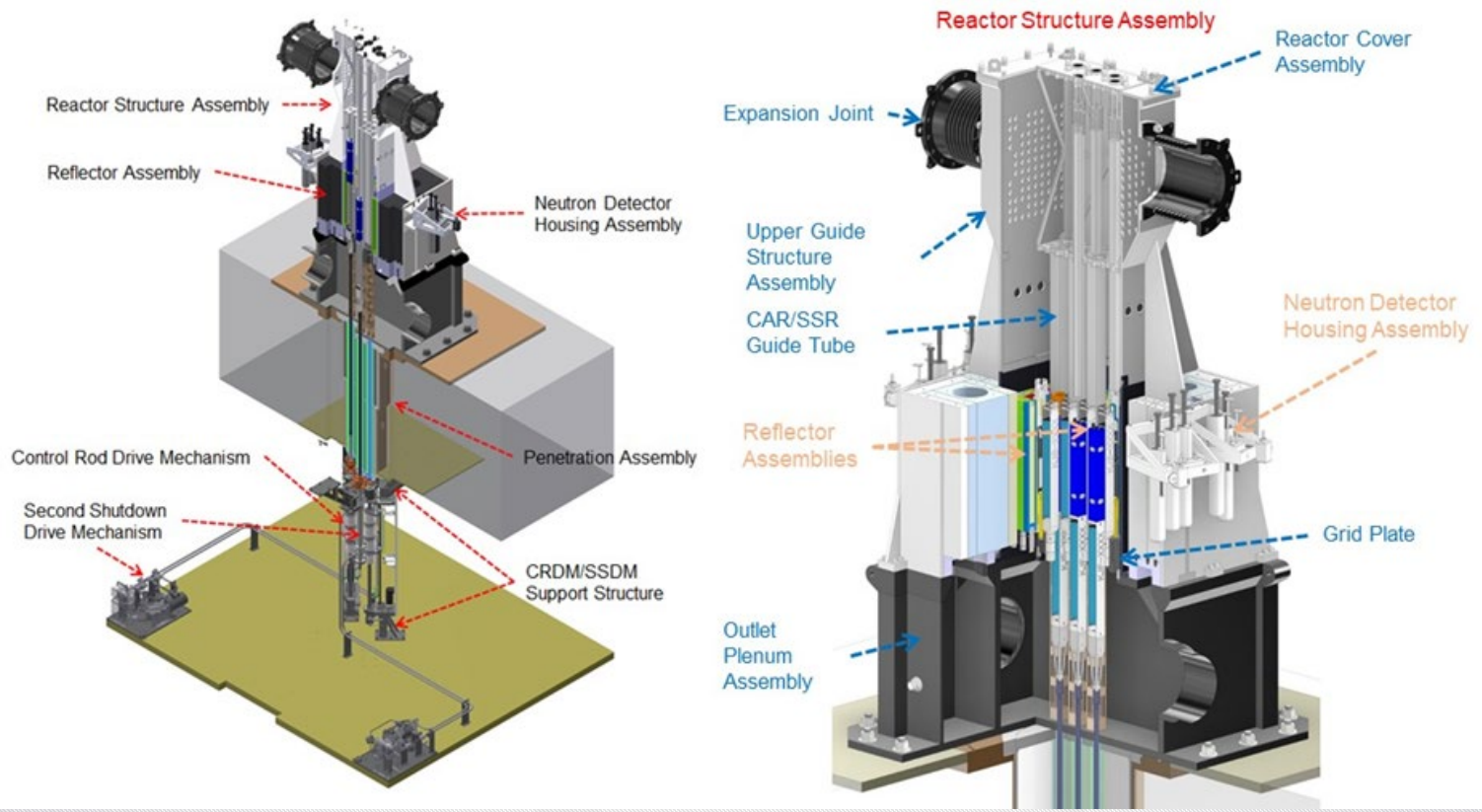


Reactor Structure Assembly

- **Rx structure assembly (RSA)**
  - Flow path
  - Support the structures
- **Fuel assemblies**
- **Reflectors**
- **Reactivity control unit**
  - 4 CRDMs
  - 2 SSDMs
  - Different driving mechanisms (by stepping motor & hydraulic pump)



Reactor Structure Assembly



02 Characteristics of KJRR

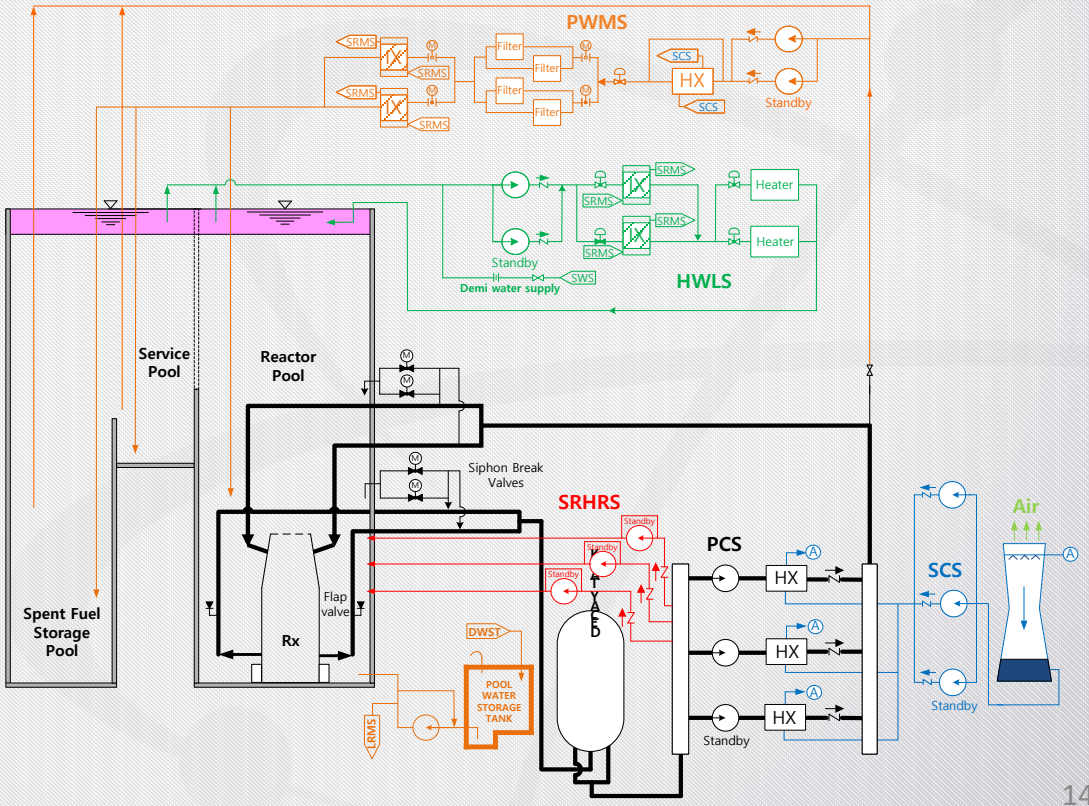
Reactor Cooling and Connected System

Primary Cooling System, Secondary Cooling System,
Pool Water Management System, Hot Water Layer System,
Safety Residual Heat Removal System (SRHRS)

ESFs

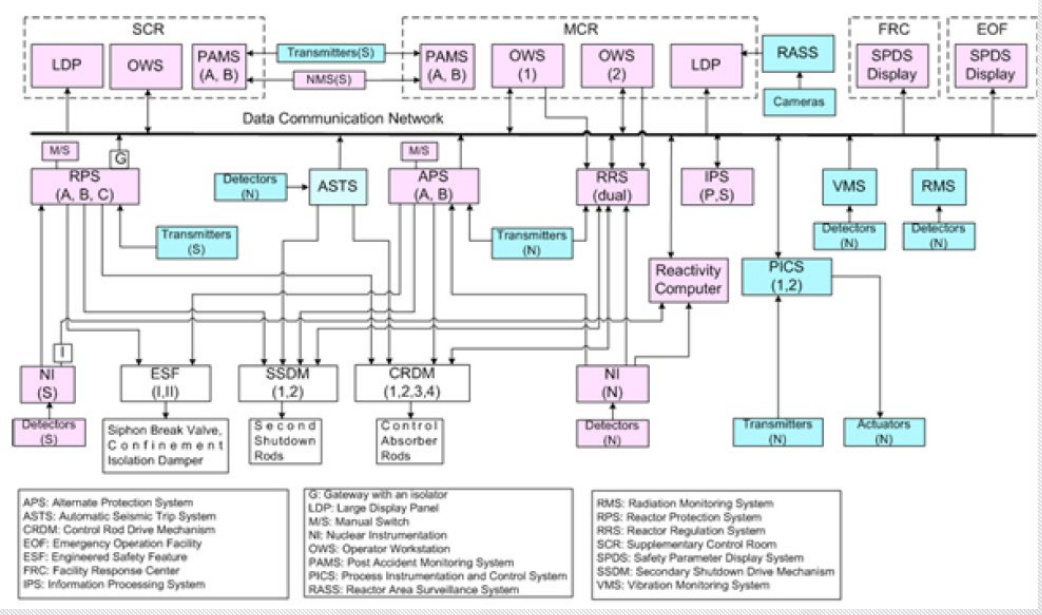
Flap Valves

SRHRS



Instrument & Control System

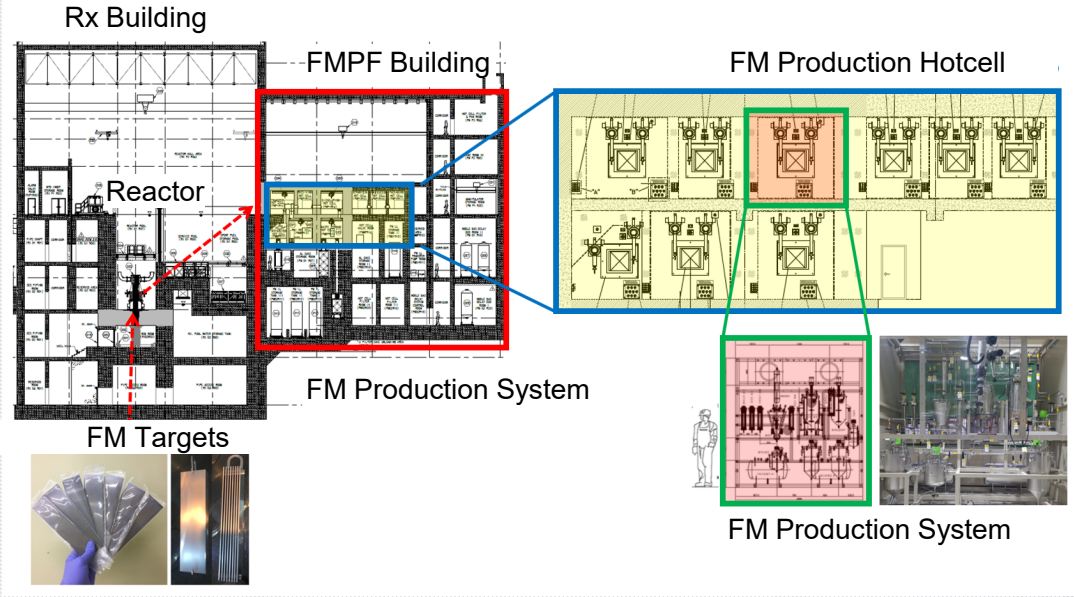
- Control, protection, monitoring functions by the defense-in-depth
- Digital technology to improve operation and maintainability
- Reactor Protection System, Reactor Regulation System, Accident Monitoring System, Alternative Protection System, Automatic Seismic Shutdown System, Radiation Monitoring System, Main Control Room etc.



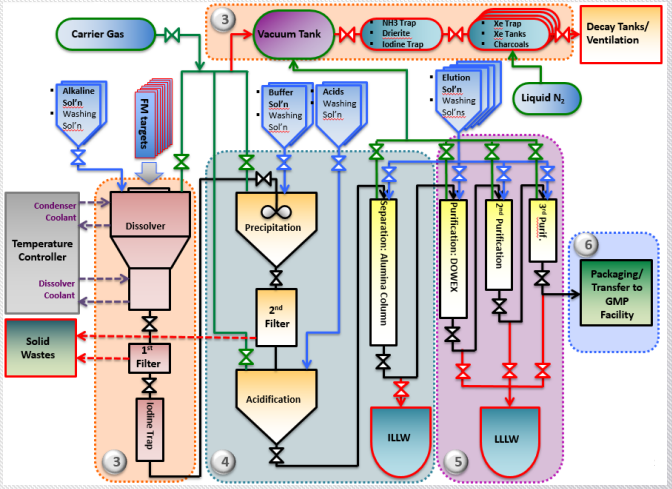
02 Characteristics of KJRR

Fission Moly

- **The FM target :**
  dispersed UAlx particles on an aluminum matrix

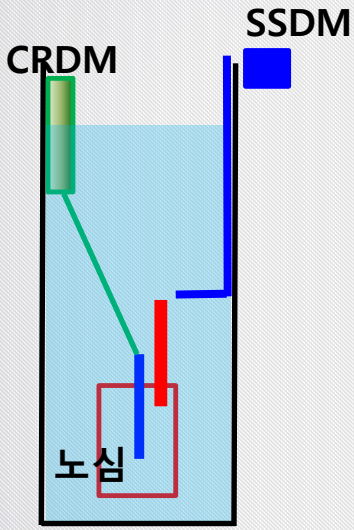


- **Production Mo-99**
  - Irradiated for 1 wk in the core (5% burnout)
  - Transfer elevator : Reactor pool → FMPF
  - Dissolving with an alkaline solution → Mo-99 separation in Hotcells

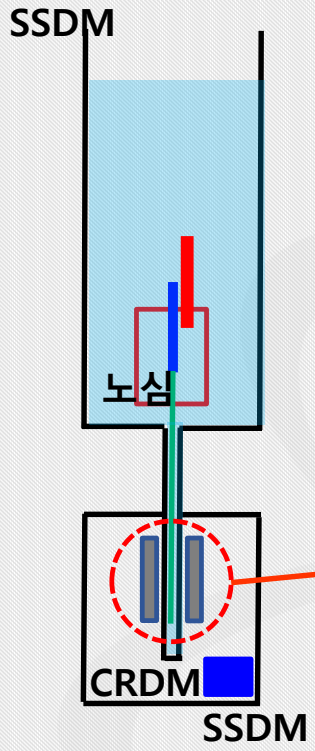


03 CRDM/SSDM

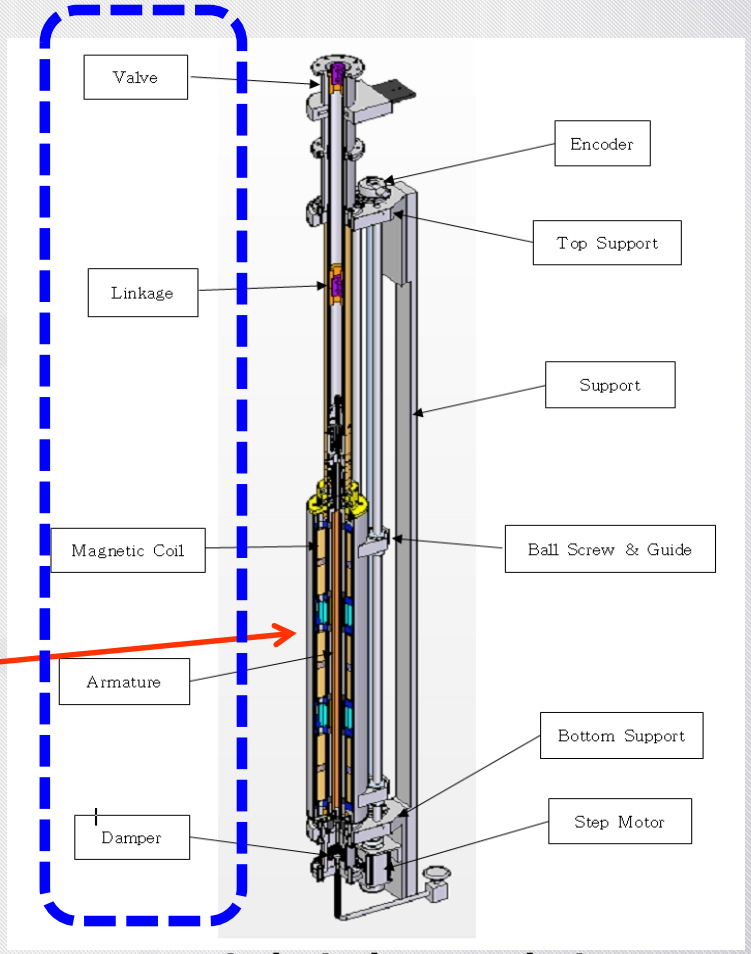
CRDM (Control Rod Drive Mechanism) / SSDM (Second Shutdown Drive Mechanism)



상부설치형
(하나로, JRTR)



하부설치형
(기장로)



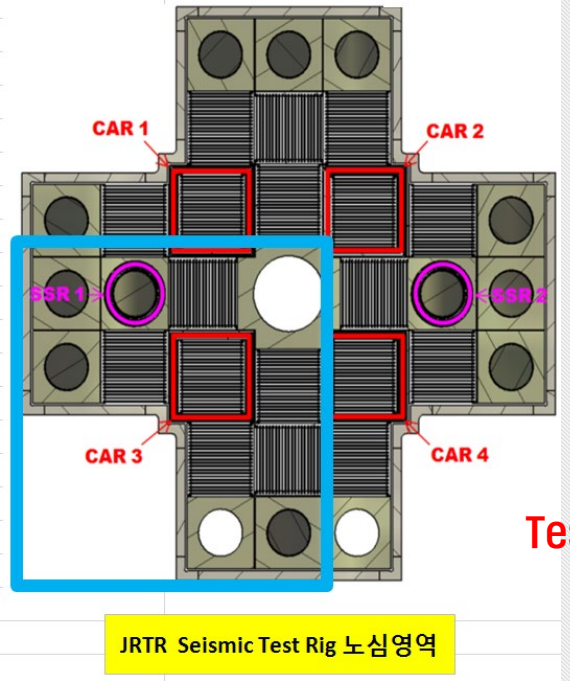
전자기력 구동방식

03 CRDM/SSDM

» 설치위치별 CRDM (제어봉구동장치)

형태	장점	단점	적용사례
상부 설치형	• 제어봉 직접연결방식 - 고정밀도 제어용이 • 100% 국산화 달성 - 2015년 JRTR 설치 • 하나로/JRTR 경험으로 설계 용이 • 제작 경제성 • 운전중 접근성 용이, 보수용이성	• 제어봉 구동장치 연결봉 및 가이드 등 수조 내 구조물 복잡 • 조사공 배치의 제한 • 조사공 활용의 불편	• HANARO • JRTR • FRM2 • TRIGA • 빔이용연구로
하부 설치형	• 수조내부의 간섭 감소, 활용도 증가 • 노심내부 CAR 배열 용이 • 새로운 기술도입 및 다양한 설계기술 확보 기회 • 기술경쟁력 증가 • 100% 국산화 달성 - 2017년 기장연구로시제품 검증	• 자력제어 기술 및 누설방지기술 개발 → 2017년 검증 완료 • 종속핵연료와 제어봉 연결부의 연결부 중성자조사에 의한 잦은 교체 필요 → 설계개선으로 해결 및 검증완료(2017년) • 제작비가 상대적으로 고가	• JRR3M, JMTR • OPAL • CARR • JHR • SAFARI • 기장연구로 • PALLAS

하부설치 CRDM/SSDM Test Rig



Test Rig Core Section

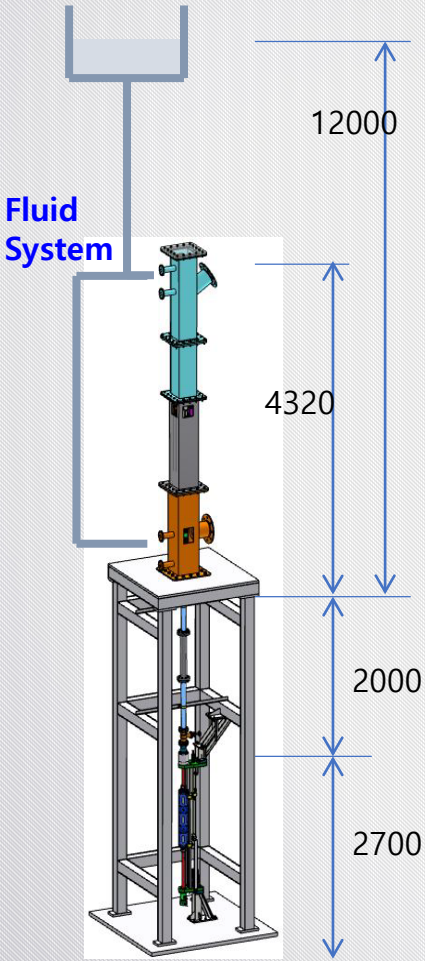
Flow rate: 6 fuel channels + gap flow

Flow rate: 5 fuel channels + gap flow

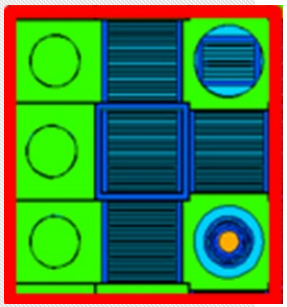
- Test Rig 1: Performance test, Endurance test, 9-channel, (PCS flow: JRTR Test Loop 활용가능)
- Test Rig 2: Seismic Test Rig, 9-channel

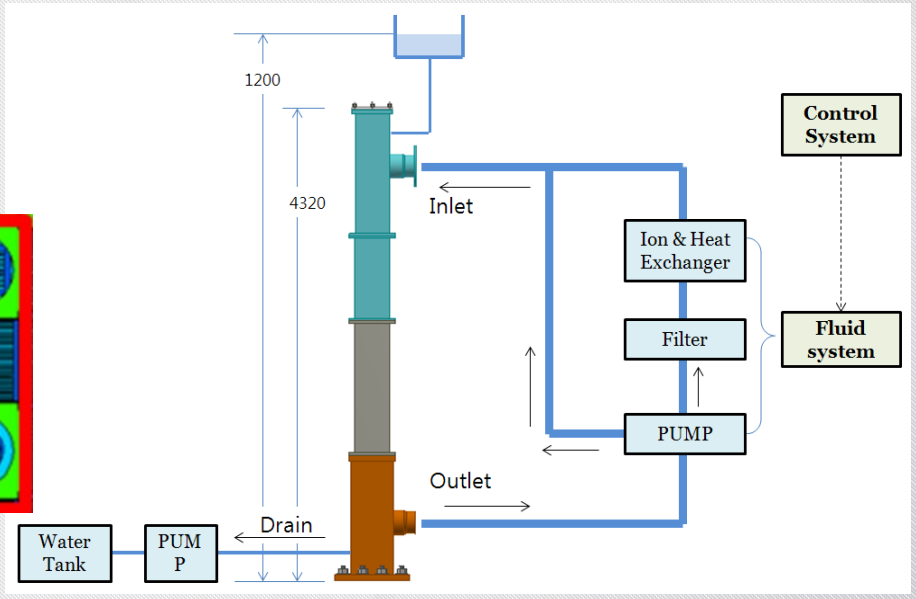
03 CRDM/SSDM

» Test Rig 1 개념- 성능시험/내구성시험용



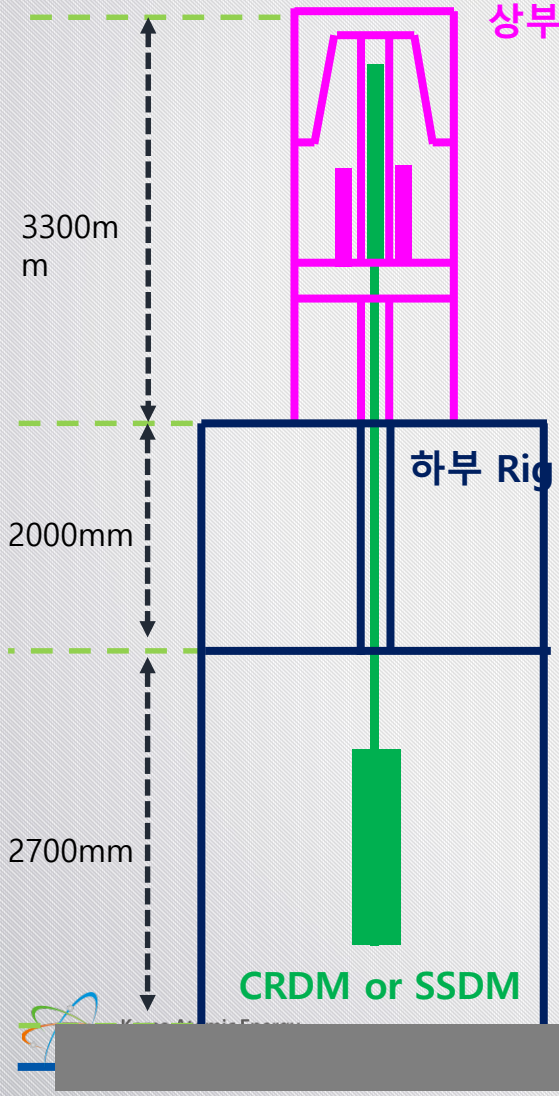
- **Test Rig 1**
  - 기장연구로 9 channel core /유체계통 모사
  - 1 CRDM or 1 SSDM 설치
  - Dummy fuel, beryllium reflector, FM 설치
  - 유량, 압력
  - Plenum 유동형상 모사
  - 전체 높이 약 17m





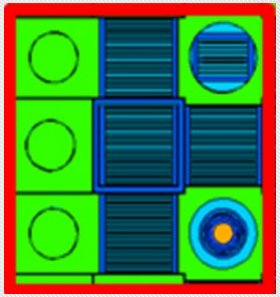
03 CRDM/SSDM

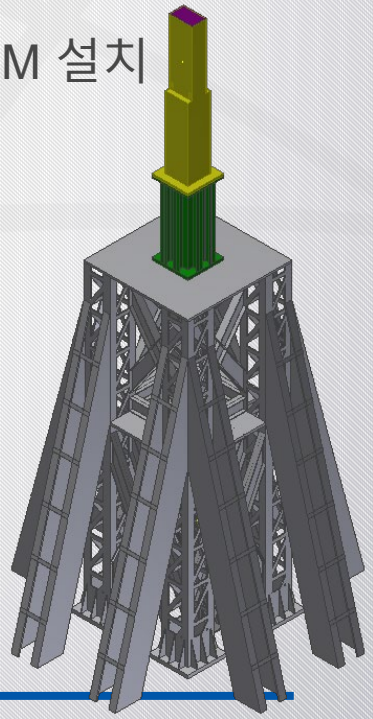
Test Rig 2 개념 - 내진시험용



- **Test Rig 2 : Seismic Test Rig**
  - 기장연구로 9 channel core
  - 고유진동수 : 기장연구로 모사
  - 1 CRDM 또는 1 SSDM 설치
  - Dummy fuel, beryllium reflector, FM 설치
  - 전체 높이 약 8m, 무게 15톤

  → 부산대학교 Shaker 활용





검증시험 결과

- **CRDM 성능/내구성/내진 성능 만족**
  - 기장로 본품과 동일 재료/품질 제작성
  - 제어봉 낙하시간
  - 제어구동 정밀도
  - 내구성
  - 가진중 낙하시간/구동성
  - 기밀성

- **SSDM 성능/내구성/내진 성능 만족**
  - 기장로 본품과 동일 재료/품질 제작성
  - 이차정지봉 낙하시간/인출시간
  - 내구성
  - 가진중 낙하시간/구동성
  - 기밀성

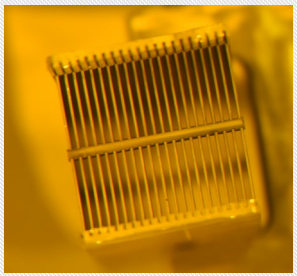
03 U-Mo fuel test for KJRR

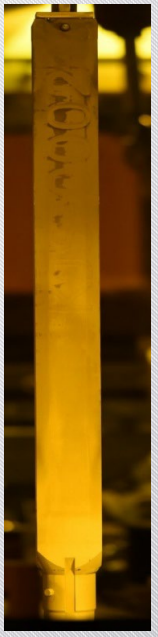
» KJRR-LTA (Lead Test Assembly) irradiation test & PIE (CRADA, DOE)

Irradiation Test	2015.10.26 – 2017.02.23
Achieved Burnup, FA average	70 % U-235 Depletion
Achieved Burnup, Local peak	83.1 % U-235 Depletion
Peak heat flux (W/cm^2)	182
Effective Full Power Day (EFPD)	216.6

After final cycle (ATR 160B Cycle)

- **KJRR-LTA was irradiated without abnormality.**
- **Post-irradiation examination successfully done by HFEF at INL**
  - Non-Destructive examinations (2018.2 ~ 2019.9)
    - Fuel Assembly Visual Examinations
    - Neutron Radiography
    - Disassembly
    - Gamma Scanning
    - Measurement of Plate thickness and oxide thickness
  - Destructive examinations (2019.10 ~ 2022.4)
    - Optical Metallography (OM)
    - Chemical Burnup Analysis
    - Blister Test

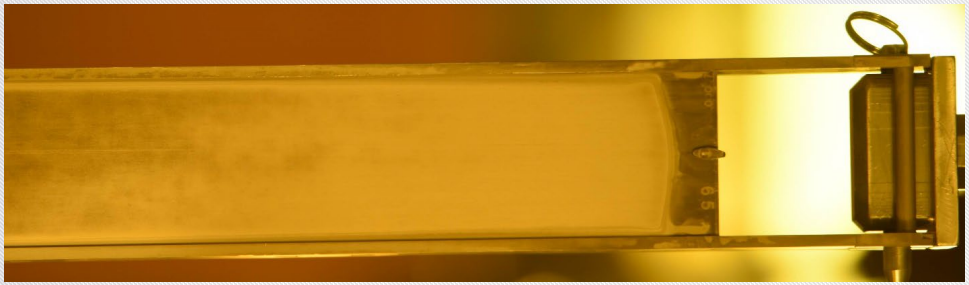




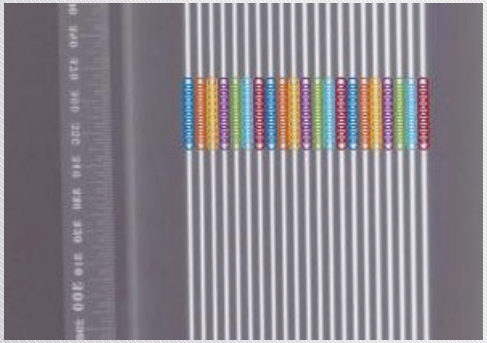
03 U-Mo fuel test for KJRR

» Post-irradiation examination of KJRR-LTA

- No excessive swelling upto BU of about 83 at%U-235
- Non-destructive and destructive PIE results of KJRR-LTA show stable irradiation behavior of U-Mo dispersion fuel for KJRR.



Visual inspection



Neutron radiography
(channel gap analysis)

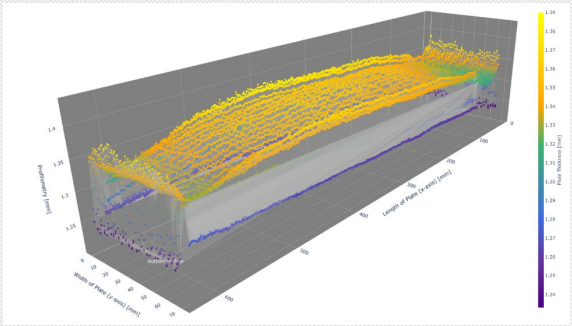
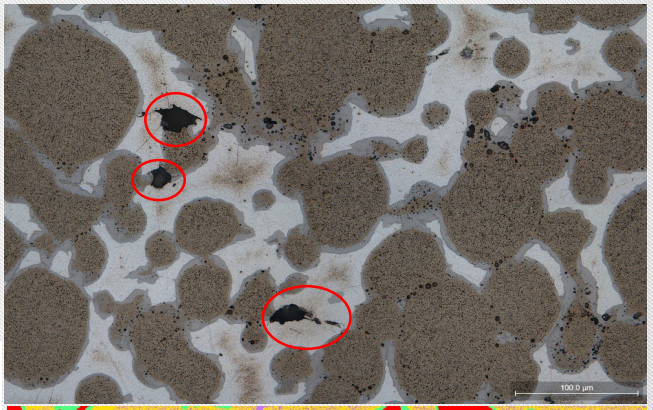
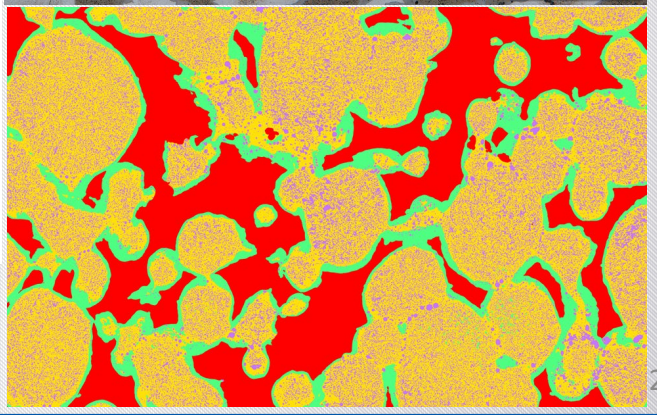


Plate thickness
measurement

Microstructure analysis using optical metallography

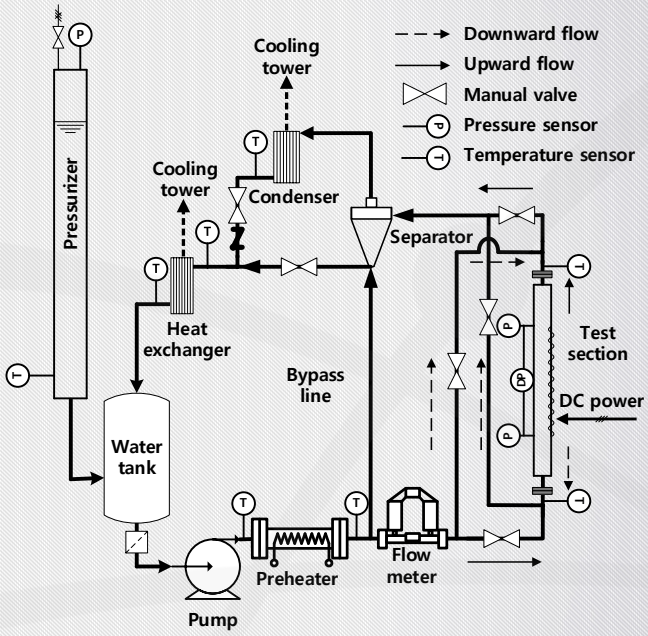




CHF experiments (at PNU Facility)

- Experiment Facility
  - Test section
    - Heater Width : 20, 30, 40, 62 mm
    - Channel gap : 2.35, 2.7 mm
    - Channel length : 600 mm
  - Design Pressure : 1.2 MPa
  - Max. Electric Power : 640 kW (75 V, 8000 A)

매개변수	측정 장치	측정 오차
질량유량	Micromotion CMF100	0.05%~0.25% of Reading (20:1) (100:1)
유체 온도	TC (Watlow)	0.5K
압력	Rosemount 3051S	0.11% of FS
전력	YOKOGAWA WT330 & Shunt 0.2% grade	0.25% of FS



CHF experiment facility of PNU

CHF experiments (at PNU Facility)

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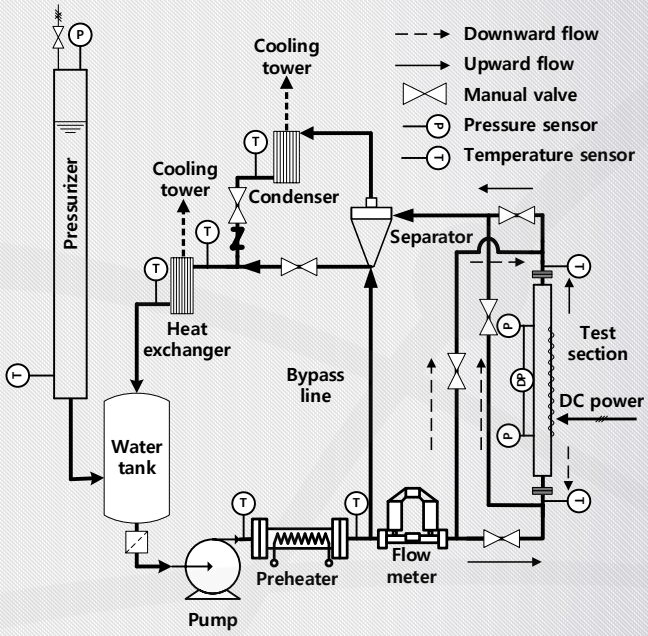


CHF experiment facility of PNU

03 CHF Experiments

New Experimental Facilities : T-REX (at KAERI)

Parameters	Single Channel test	Fuel Assembly test
Mass flow rate	Max. ~2 kg/s	Max. ~30 kg/s
Channel velocity	Max. 12 m/s (single-phase flow)	
Flow direction	Up / Down	
Pressure	Max. 10 bar	
Electric Power	Max. 45V, 18,000A	
Heat flux	Max. 7.0 MW/m^2 (uniform)	
Purpose	High flux CHF test for a rectangular channel	Hydraulic test for a fuel assembly

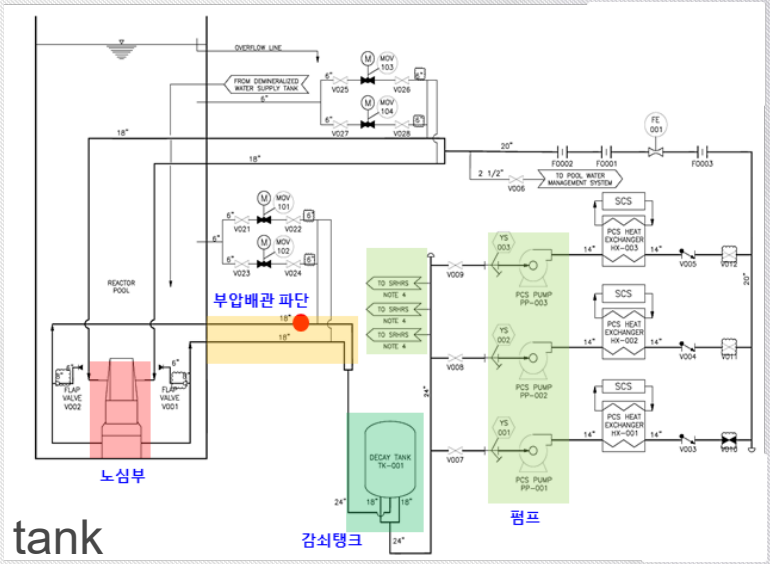
Test Loop and Cooling System

Electric Power Supply System

03 Decay Tank Stratification Verification Test

Test Overview

- Negative pressure induced by high core pressure drop in the open pool type reactor
- Air ingress due to negative pressure pipe breakage accident



Test Objectives

- Verification of air-water stratification in decay tank
- Check for air outflow to decay tank outlet
- Check for PCS and SRHRS pump damage and head reduction by air inflow

Test parameter	Mass Flow rate and Pressure	Break size (inch)			
contents	65 kPa @ 565 kg/s	0.5	2.0	6.0	8.0
	35 kPa @ 634 kg/s				

03 Decay Tank Stratification Verification Test

Test Facility

- Full-scale test facility (level, size of pipe and decay tank)
- Composition of same flow condition, such as flow rate and pressure, with KJRR
- Implementation of core pressure drop using orifices
- Measurement of air inflow due to pipe breakage

Pump inlet VW

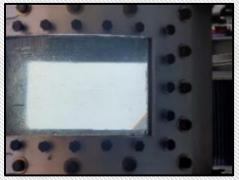
Pump

Aux. Pump

Separator

Test Facility

Negative pressure pipe



Decay tank inlet VW

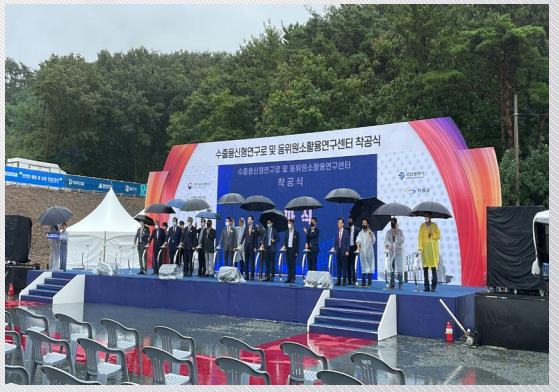
Decay tank

04 사업추진 경과 및 향후 계획

건설공사 추진 경과

- 2022. 3. 30. 건설공사관리용역 선정
- 2022. 3. 31 사용전검사 1단계 신청 (원안위)
- 2022. 4. 1 현장사무소 개소
- 2022. 4.8. 건설공사 시공사 선정
- 2022. 4.15. 건설공사 착공계 및 현장업무 착수
- 2022. 5. 2. 공사착수 기초굴착
- 2022. 7. 11. 산업단지 부분준공 완료
- 2022. 7. 16. 시험발파 (KINS입회)
- 2022. 8. 8. 콘크리트시험실 신축공사 착수
- 2022. 8. 31. 착공식 개최
- 2022. 9. 1. 현장사무실 이전
- 2022. 9. 17. 굴착토사 부지외부 사토 착수

22.3 22.4 22.5 22.7 22.8 22.9



04 사업추진 경과 및 향후 계획

첫 콘크리트 타설식 (2023.04.28)

05 결론

- 기장로의 목표
  - 의료용/산업용 방사성동위원소의 국내공급 안정화와 수출촉진
  - 연구용원자로 최신핵심기술 개발 및 실증을 통해 연구로 수출 경쟁력 강화
- 사업계획적절성재검토 및 총사업비 조정이후 사업단을 정상화하고 건설공사관리용역을 선정하고 건설공사 시공사를 선정하였음. 주요 기자재도 순차적으로 계약되고 제작을 진행 중임
- 기장연구로를 위해 하부설치형 CRDM/SSDM의 개발 및 검증, 핵연료 검증, CHF 실험, 감쇠탱크 성층화 실험 등이 수행되었음
- 설계/인허가/시공/시운전 등에 만전을 기해 2027년 운영허가 획득하는 목표를 달성하겠음

수출용신형연구로,
의료복지와 수출산업에 기여하는 국민행복 연구로

KAERI 한국원자력연구원
Korea Atomic Energy Research Institute