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Current Status and Review of Spent Fuel Management in HANARO Research Reactor

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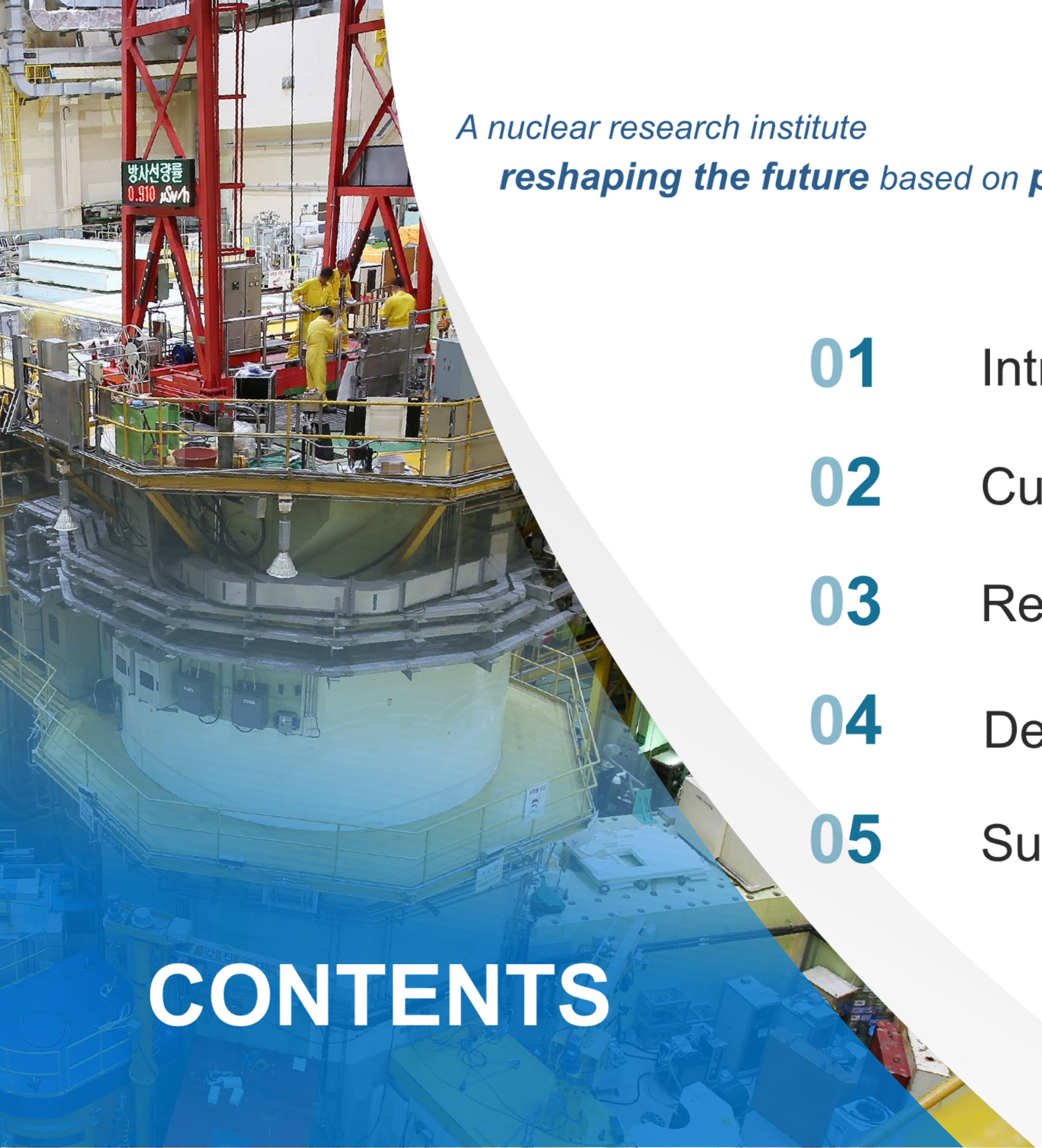

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01 Introduction of HANARO

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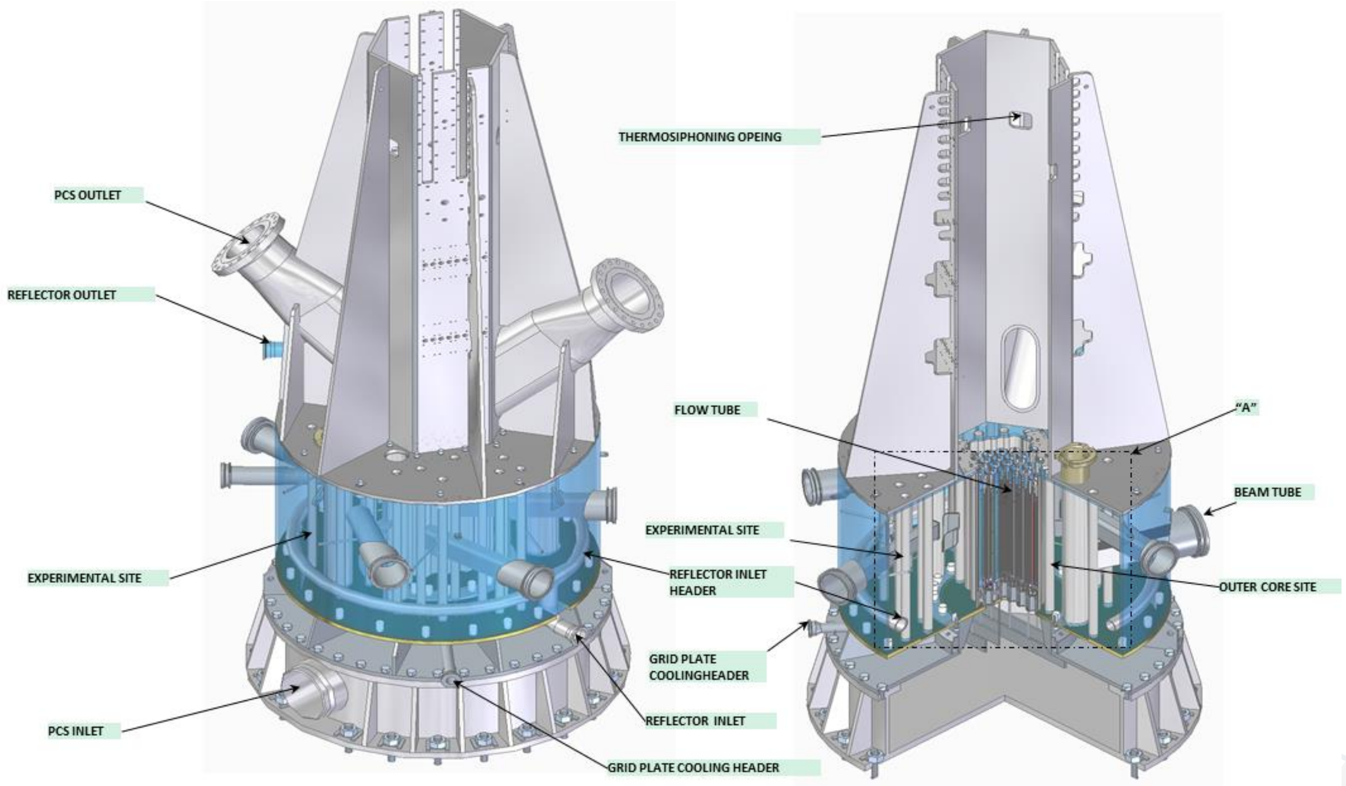
HANANRO: High-flux Advanced Neutron Application ReactOr

Reactor Type	Open-tank-in-pool
Power	30 MWth
Fuel	LEU(19.75 w/o 235 U, U_3Si-Al Meat, Al clad)
Coolant	H_2O
Moderator	H_2O/D_2O
Reflector	D_2O
Absorber	Hafnium
Core Cooling	Upward Forced Convection Flow + Bypass Flow
Reactor Building	Confinement
Max. Thermal Flux	4~5x10^{14} n/cm^2s
Holes & tubes	7 horizontal ports & 36 vertical holes
Operation Cycle	28/14 days operation/maintenance 8 cycles/yr (~200 days/yr)



01 Introduction of HANARO

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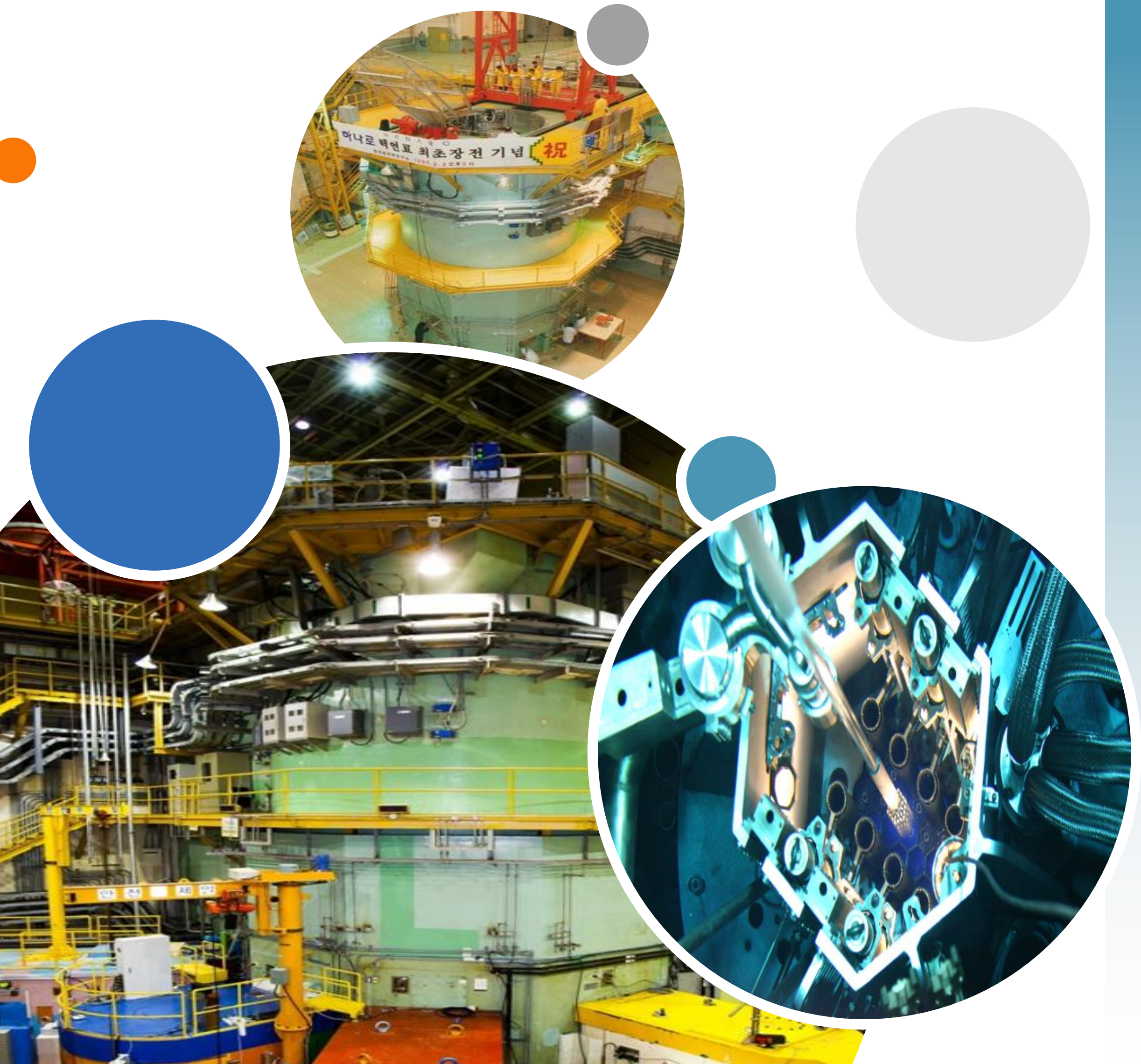

1985 JAN	Start of HANARO Project
1989 JAN	Start of HANARO Construction
1993 AUG	Installation of HANARO Reactor Structure
1995 FEB	Fuel Loading and Achievement of Initial Criticality
1996 JAN	15 MW Power Operation
2004 NOV	30 MW (Design Power) Power Operation started
2005 MAR	First Loading of HANARO Fuel Made by KAERI
2006 APR	Start of Cold Neutron Laboratory Construction (Completed in May 2008)
2008 MAY	Start of Cold Neutron Source System Installation
2009 SEP 3	First Generation of Cold Neutron
2010 NOV	Inauguration of Cold Neutron Research Facility
2015-2017	Planned Long-term Shutdown for Reinforcement of Reactor Building Wall
2019 DEC	Re-operation started

Introduction of HANARO

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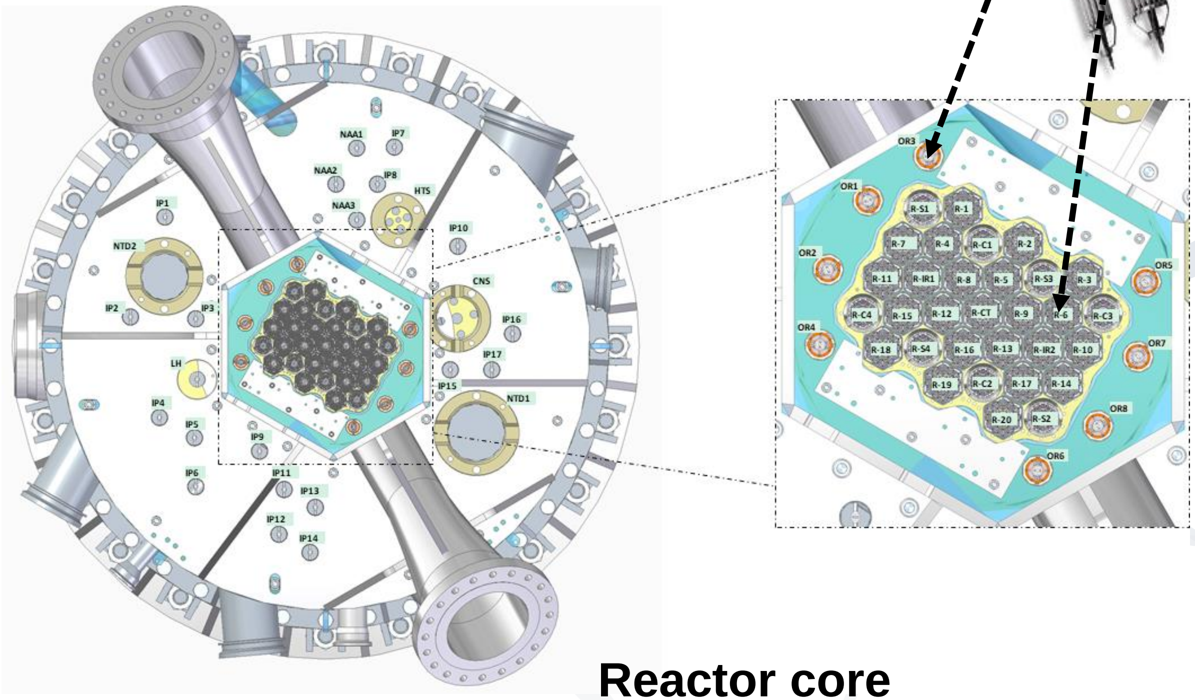
Reactor Core and Fuels

Fuel meat	U_3Si dispersion fuel (LEU 19.75 w/o) in Al matrix
Material	61.4 wt.% U_3Si - 38.6wt.% Al
Theoretical density	5.4 g/cc
U-density	3.15 g-U/cc
Diameter of fuel meat	6.35 mm, 5.49 mm
Length of fuel meat	700 mm
Cladding	Co-extruded Al 1060 with 8 fins
Fuel assembly	Hexagonal(36 el.) Circular(18 el.)

Fuel Rod

Fuel Assembly



Reactor core

Introduction of HANARO

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Hexagonal FA (36-rods)

Shape	Hexagonal
Length (mm)	961
Number of Element • standard core element • reduced core element	36 18 18
Mass of Bundle (g)	6784
Mass of fuel meat (g)	3719
Mass of uranium (g)	2169
Mass of U-235 (g)	428
Initial linear fissile content (g U-235 /cm) • standard core element • reduced core element	 3.55 2.64
Element pitch (mm) (nominal)	12
Element spacing (center to center) - at end plate (mm) (nominal)	 12.0
Pitch circle diameters (reference) - inner row (mm) - intermediated row (mm) (two diameters) - outer row (mm) (two diameters)	 24.0 41.57 and 48.0 63.50 and 71.6
End plate - thickness (mm) - dimensions across flats (mm)	 8 73.8 (nominal)
Central Rod - material - diameter - outer - flat to flat (mm) - length (mm)	 Zircaloy-4 8.0 (nominal) 6.05 (nominal) 894.6

Circular FA (18-rods)

Shape	Cylindrical
Length (mm)	961
Number of Element	18
Mass of Bundle (g)	3848
Mass of fuel meat (g)	2131
Mass of uranium (g)	1244
Mass of U-235 (g)	246
Initial linear fissile content (g U-235 /cm) • standard core element	 3.55
Element pitch (mm) (nominal)	12
Element spacing - at end plate (mm)	 12
Pitch circle diameters (reference) - inner row (mm) - outer row (mm) (two diameters)	 24.0 47.18
End plate - thickness (mm) - outer diameter (mm)	 8.0 59.4 (nominal)
Central Rod - material - diameter - outer - flat to flat (mm) - length (mm)	 Zircaloy-4 8.0 (nominal) 6.05 (nominal) 894.6

01 Introduction of HANARO

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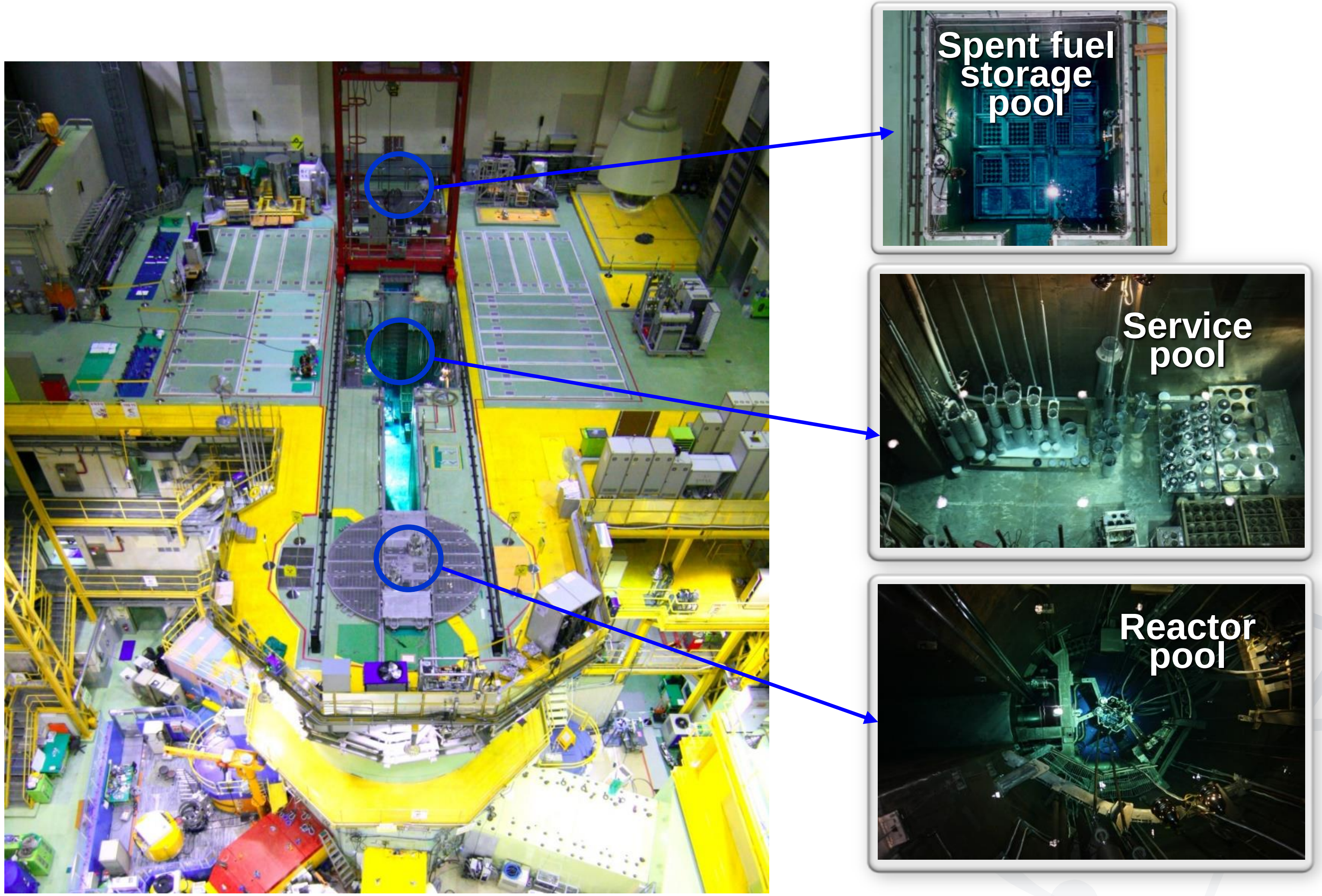
Reactor Pools



Current Status and Review of SF Management in HANARO

02

Current Status of HANARO Spent Fuel Management

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02 Current Status of HANARO SF Management

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What Makes HANARO Fuel Exotic(non-standard) in SF Management?

- Rod-type fuel in research reactor (vs. Plate-type)
- LEU fuel (19.75 w/o, but relatively high compared to commercial NPP)
- ?

Comparison of decay heat of SF: Research Reactor vs. Commercial NPP

Decay Heat	HANARO SF (100 GWD/MTU)	PWR SF (45 GWD/MTU)	CANDU SF (7.5 GWD/MTU)
W/MTU	3.29E+03	1.62E+03	2.25E+02
vs. PWR SF	2.03	-	-
vs. CANDU SF	14.62	-	-

02 Current Status of HANARO SF Management

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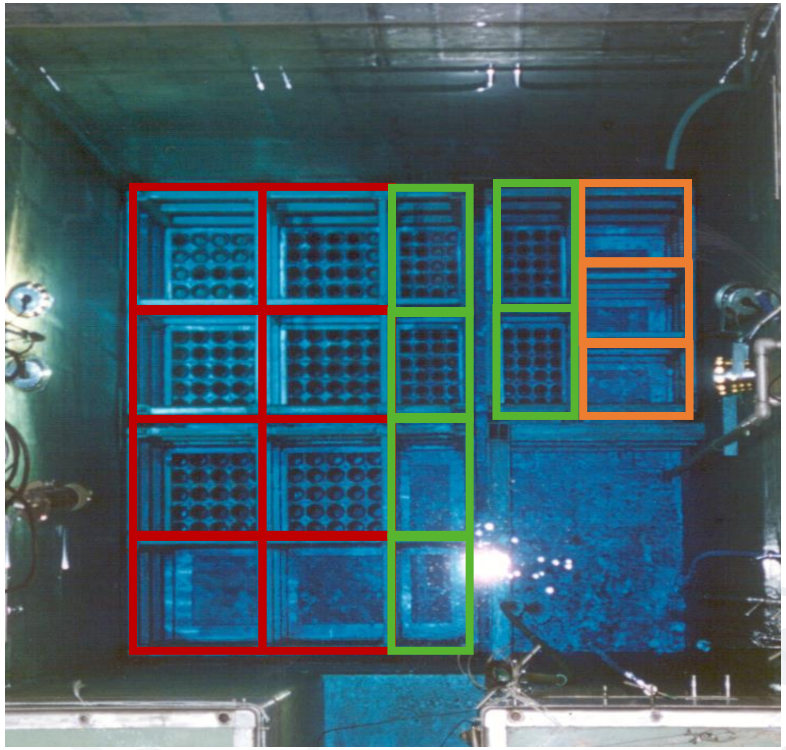
Configuration of SF Storage

- 3 storage racks placed inside the HANARO SF storage pool
- Each rack designed to stack Fuel Storage Modules in three layers
  - Hexagonal FA (36-rods) storage module (5×5)
  - Circular FA (18-rods) storage module (6×4)
  - TRIGA fuel storage module



02 Current Status of HANARO SF Management

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Capacity of SF Storage

- Hex. FA (36-rods) / Cir. FA (18-rods) storage modules can store 600 / 432 bundles
- TRIGA fuel storage module is empty (returned to the US)

	Hex. FA (36-rods)	Cir. FA (18-rods)	TRIGA
# of FA per storage module	25 (5 x 5)	24 (6 x 4)	–
# of storage module	24 (8 x 3 layers)	18 (6 x 3 layers)	
Total capacity (bundles)	600	432	
Dimensions of storage module (WxDxH, mm)	800×780×1126	800×490×1126	690×506×1126
FA pitch (mm, minimum)	150	120	–
Cell tube dimension (Outer diameter/Thickness, mm)	101.7 / 3.0	73.0 / 3.0	

02 Current Status of HANARO SF Management

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Expected Saturation Time of the SF Storage Pool

- HANARO is expected to operate for **6 to 8 cycles per year**
- 5 bundles of SF (**3 Hex. FA + 2 Cir. FA**) are generated for each cycle
- The estimated saturation time is approximately between 2035 and 2039

1 cycle = 28 / 14 days operation / maintenance

Fuel Assembly Type	Storage Capacity and Current (2025) Inventory			Expected Full Year	
	Capacity [ea]	Inventory [ea]	Storage Usage [%]	Practical Scenario* [year]	Max. Operation Scenario** [year]
Hex. FA (36-rods)	600	344	57.3%	2039	2035
Cir. FA (18-rods)	432	202	46.8%	2044	2039
Total	1032 (1839 kg-U)	502 (917 kg-U)	48.6%		

* Operation of 6 cycles (24 weeks) per year

** Operation of 8 cycles (32 weeks) per year

Review of Previously Proposed Solutions

03

Review of Previously Proposed Solutions

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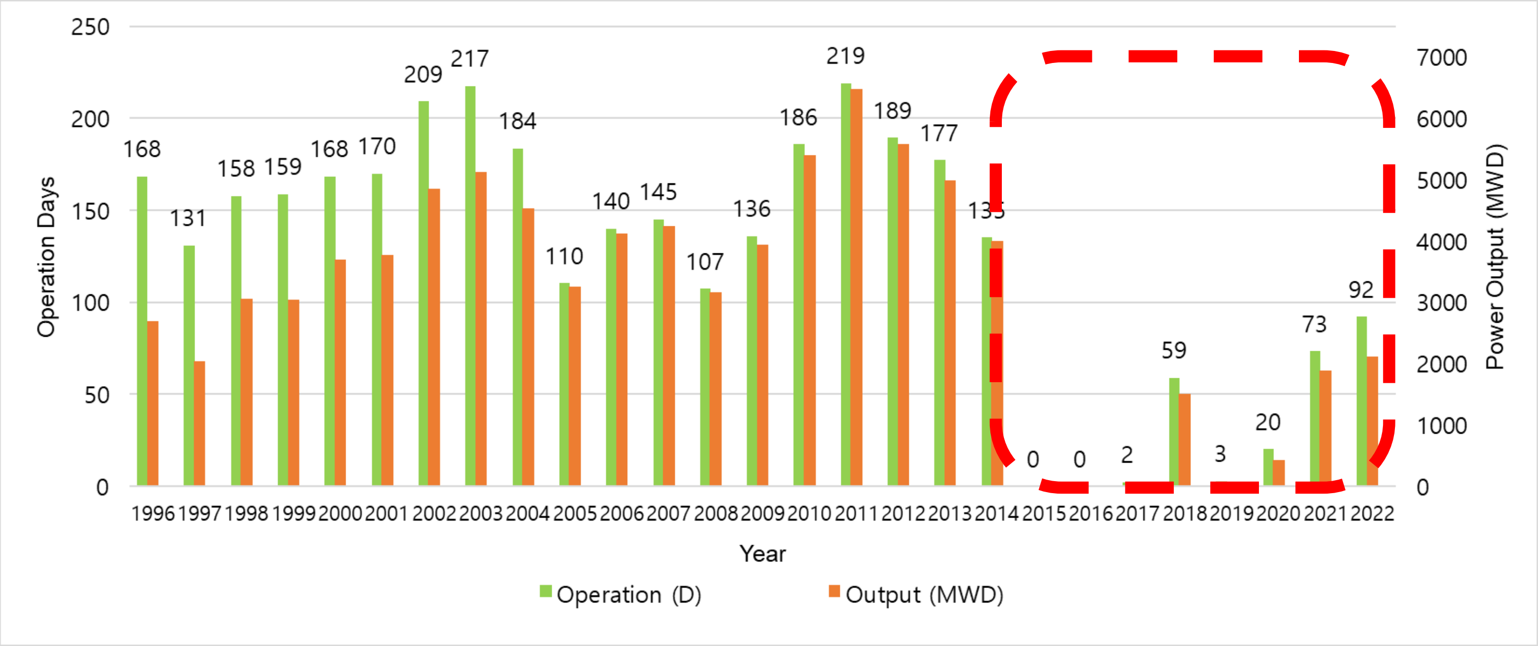
Backgrounds

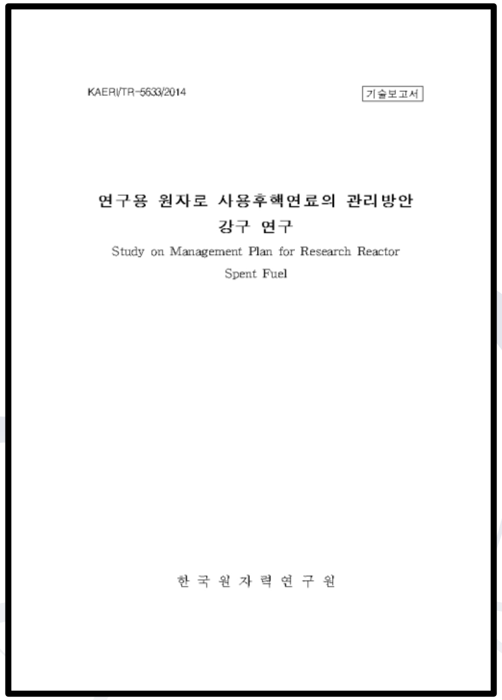
- A study on this issue (SF storage full) was already conducted **in 2014**
  - The storage-full was expected to be reached in **2022 at that time**
- However, due to seismic reinforcement project and changes in the regulatory environment, HANARO operation did not **return to normal for a long time (2015 ~ 2024)**



03 Review of Previously Proposed Solutions

Backgrounds

- Recently, as HANARO's operating rate has improved → expected full at 2035 ~ 2039
  - Now, we should **study again the previously proposed solutions**
- In the previous study, three options were considered:
  - Conversion to compact storage module(rack)
  - Dry cask storage
  - US return program for SF with US-origin uranium



KAERI/TR-5633/2014

기술보고서

연구용 원자로 사용후핵연료의 관리방안 강구 연구

Study on Management Plan for Research Reactor Spent Fuel

한 국 원 자 력 연 구 원

KAERI/TR-2633/2014

Review of Previously Proposed Solutions

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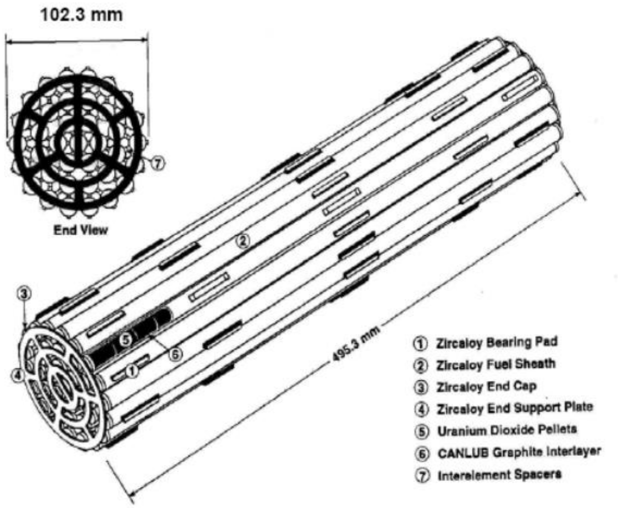
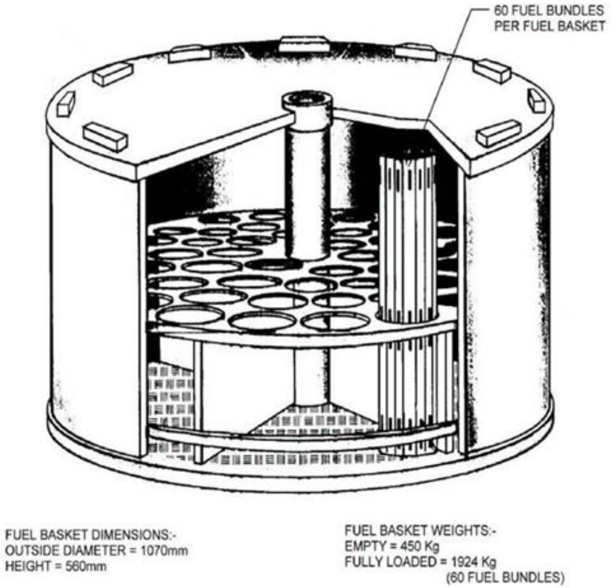
Dry Cask Storage

- The previous study was conducted with reference to the SF storage strategy of Korean **CANDU**-type NPP in Korea

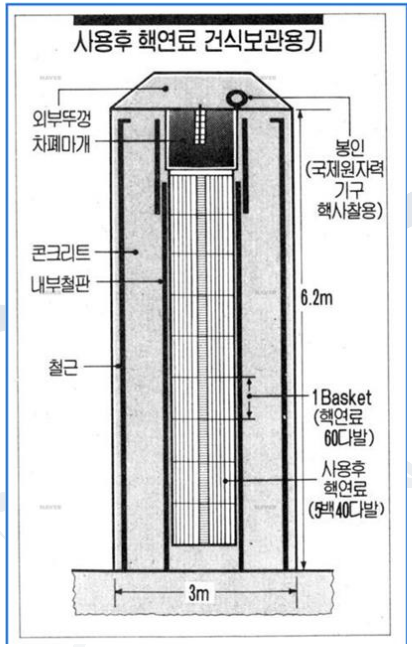
CANDU-type FA



SF basket



Dry cask



Review of Previously Proposed Solutions

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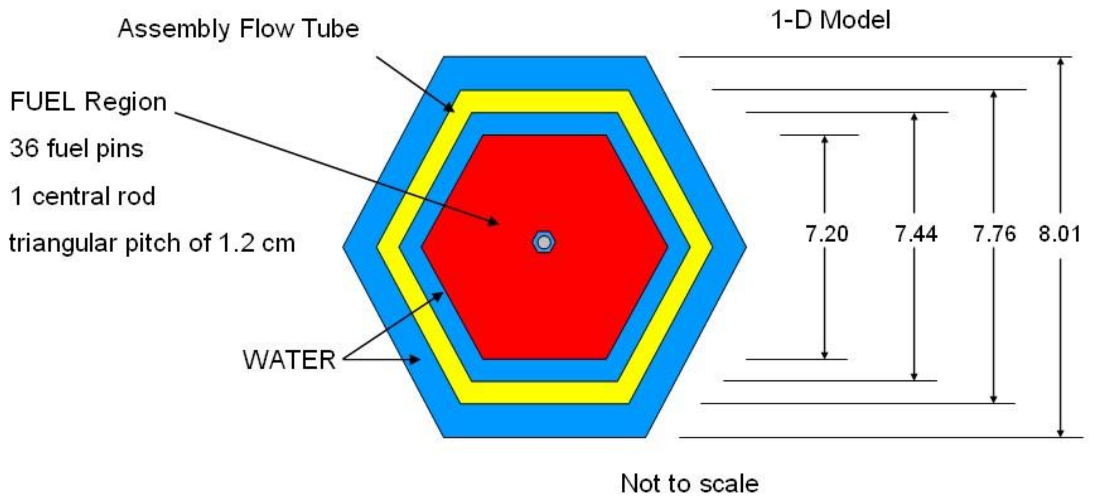
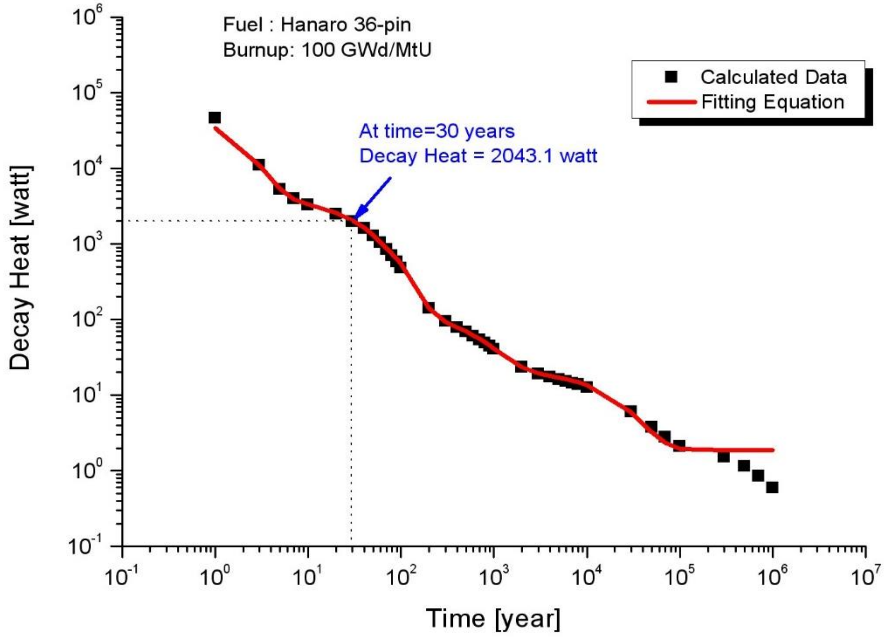
Dry Cask Storage - Decay heat analysis

- Calculation conditions
  - Code: ORIGEN-ARP / SCALE-SAS2
  - Hex. FA (36-rods) with **100 GWD/MTU** discharge burnup
- Maximum 4000 W/MTU after **10 years** of cooling
  - **4000 W/MTU** → **8.7 W per FA** → **0.241 W per rod**





03 Review of Previously Proposed Solutions

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Dry Cask Storage - Preliminary thermal analysis

- Surface temperature of fuel rod
  - 0.241 W per rod → **0.723 W** (conservatively)
  - Natural convection at the surface ($h = 0.59\ k/H\ Ra^{0.25}$, $10^4 < Ra < 10^9$)
  - Approximately **15 °C** higher than ambient air
- Surface temperature of dry cask
  - It seems that cask (diameter 3m, height 6m) can contain **240 FA**
  - Total decay heat inside cask would be **2100 W**
  - Natural convection at the surface ($h = 0.021\ k/H\ Ra^{0.4}$, $10^9 < Ra < 10^{13}$)
  - It is expected to maintain below **45 °C** (about 15 °C higher than ambient air)

Review of Previously Proposed Solutions

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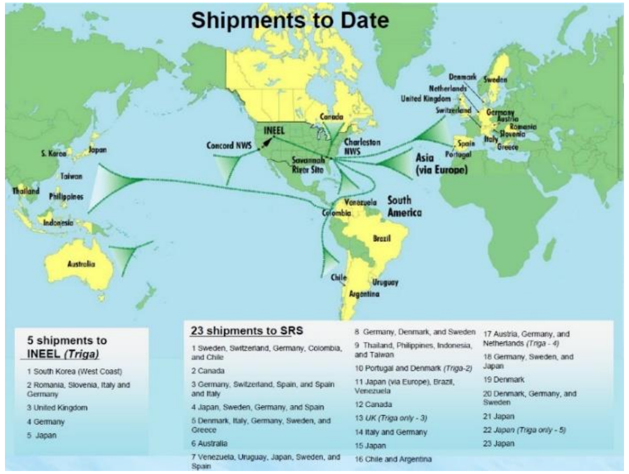
US Return Program(ended)

- FRR SNF AP(Foreign Research Reactor SNF Acceptance Program) of US DOE (1996~2019)
- The previous study refers to the case of Austrian ASTRA reactor
  - Cost of 1,206,240 $ for 54 fuel rods (HEU+LEU)

Target Countries for FRR SNF AP



Transportation Cases (~2004)

Transportation basket (Austria, 2005)

Review of Previously Proposed Solutions

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US Return Program(ended)

- (2016~) **7,500 USD/kgU for LEU** (minimum of 0.2 M USD per case) without cost of shipment
- **In 2014**, it was estimated that total return costs for HANARO SF (including containers, and shipping fees) would be between **15 ~ 25 million USD**
  - 10 million USD for nuclear fuel return
  - 1 million USD for container
  - Others for shipping and associated costs

TABLE 1—SUMMARY OF FEE POLICY

Effective dates	Aluminum based fuel		Training, Research, Isotopes, General Atomics (TRIGA)	
	LEU	HEU	LEU	HEU
Current Rates	$3,750	$4,500	$4,500	$4,500
Date of Publication in **Federal Register**	5,625	4,500	5,625	4,500
January 1, 2014	7,500	6,750	7,500	6,750
January 1, 2016	7,500	9,000	7,500	9,000

The Department of Energy is also implementing a new minimum fee of $200,000 per shipment of any type and amount of eligible fuel to reflect a minimum cost of providing acceptance services.
All rates are "per kg total mass" (not heavy metal mass).
The first phase of the change in the current fee policy takes effect immediately upon publication of this Notice in the **Federal Register**.

Fee Policy for Return (without cost of shipment)

Design of compact storage module

04

04 Design of compact storage module

Assumptions and Constraints of the New Design

- No modification for FA
- No modification for storage rack (3 layers)
  - Additional layer can cause an issue of mechanical integrity
  - Replacement can cause an issue of handling and disposal of irradiated storage rack
- Utilization of **TRIGA fuel storage (empty now) space**
- **Design requirement*** for
  - Criticality: k_{eff} < 0.90 with considering bias, uncertainty, abnormal condition
  - Shielding: radiation level outside the wall < 12.5 μSv/hr
  - Mechanical integrity: sufficient structural integrity even in the event of an earthquake
  - Cooling: T_{pool} < 40 °C (in case of accident < 50 °C)
  - Purification of SF pool: water quality is at the same level as the reactor pool

* KINS/GE-N10 Vol.2 (2014)

04 Design of compact storage module

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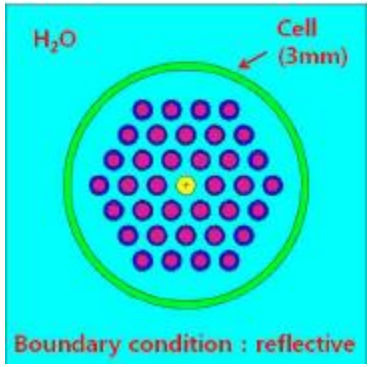
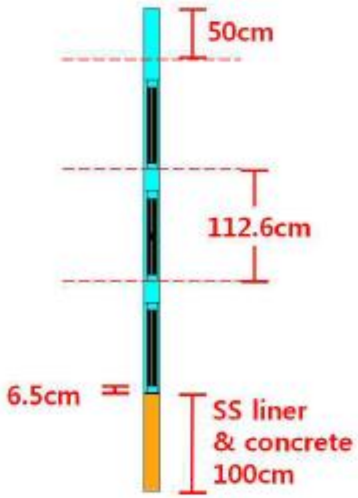
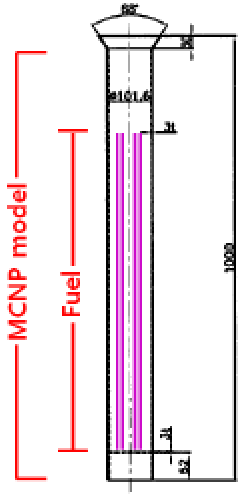
Re-evaluation of the minimum spacing limit between FA

- Minimum spacing between FA were limited as **14/11 cm (Hex./Cir.)** in terms of **criticality safety**
- Previous design calculation was **too conservative** without considering **SS structural material**







MCNP calculation model

04 Design of compact storage module

Re-evaluation of the minimum spacing limit between FA

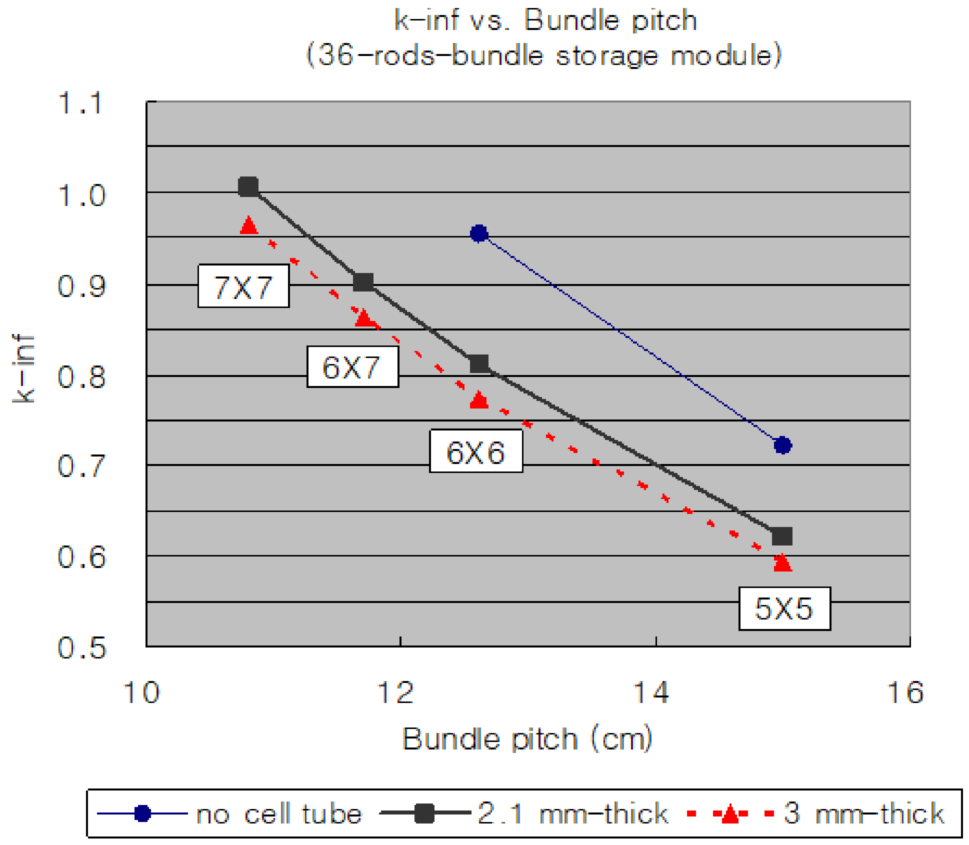
- Safety limit for criticality is **0.90**
  → **0.88** with considering bias, uncertainty, abnormal condition
- Pitch (consideration of SS cell tubes): **14/11 → 13/10 cm (Hex./Cir.)**

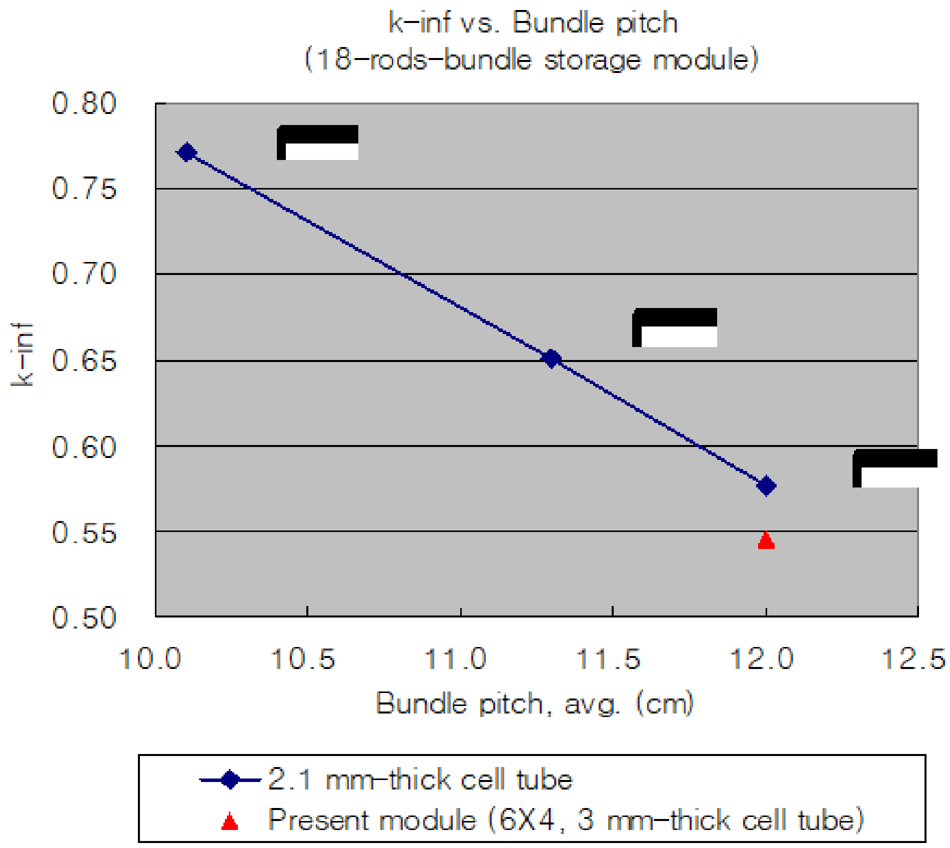
Location	FA per module	Pitch (cm)	Cell tube Thickness (mm)	Criticality	
Hex. FA rack	5×5	15.0×15.0	3.0	0.594	Current
			2.1	0.621	
			No Tube	0.723	
	6×6	12.6×12.6	2.1	0.810	New
	6×7	12.6×10.8	2.1	0.901	
	7×7	10.8×10.8	2.1	1.006	
TRIGA rack	5×4	12.9×12.2	2.1	0.815	New

Location	FA per module	Pitch (cm)	Cell tube Thickness (mm)	Criticality	
Cir. FA rack	6×4	12.6×11.8	3.0	0.545	Current
			2.1	0.576	
	7×4	10.8×11.8	2.1	0.651	
	7×5	10.8× 9.4	2.1	0.771	New
TRIGA rack	6×4	10.8×12.2	2.1	0.634	
	6×5	10.8× 9.7	2.1	0.755	New

04 Design of compact storage module

Re-evaluation of the minimum spacing limit between FA





Design of compact storage module

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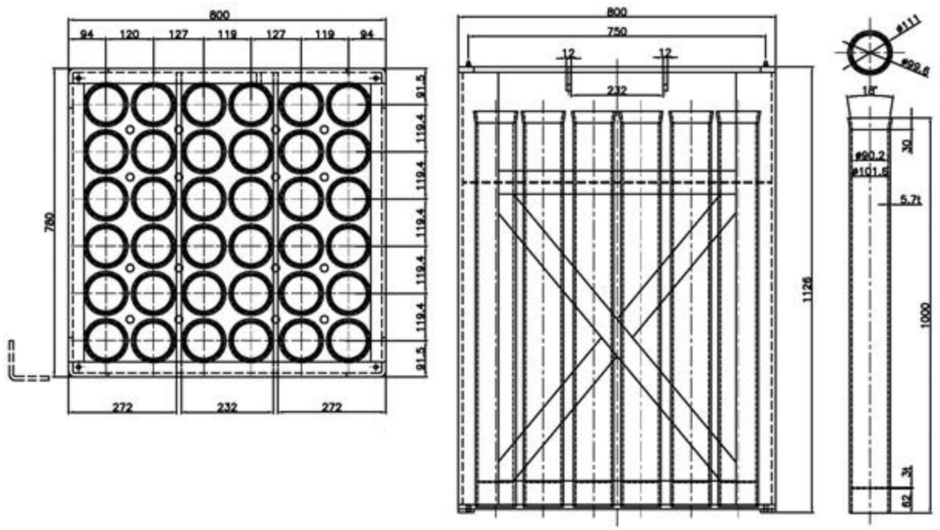
Detailed Design Plan for Compact SF Storage Module

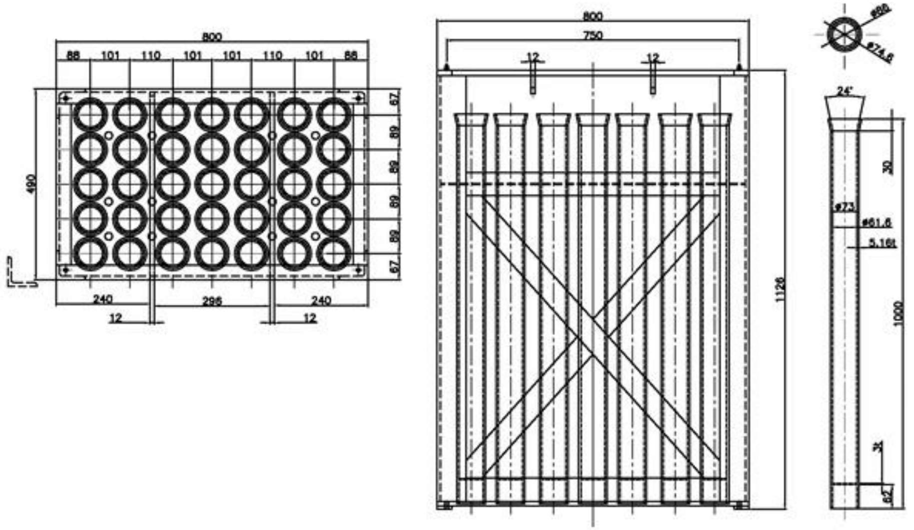
- The biggest difference is the change in the number FAs per storage module:

(5x5) → (6x6)



Hex. FA Storage Module (6x6)

(6x4) → (7x5)



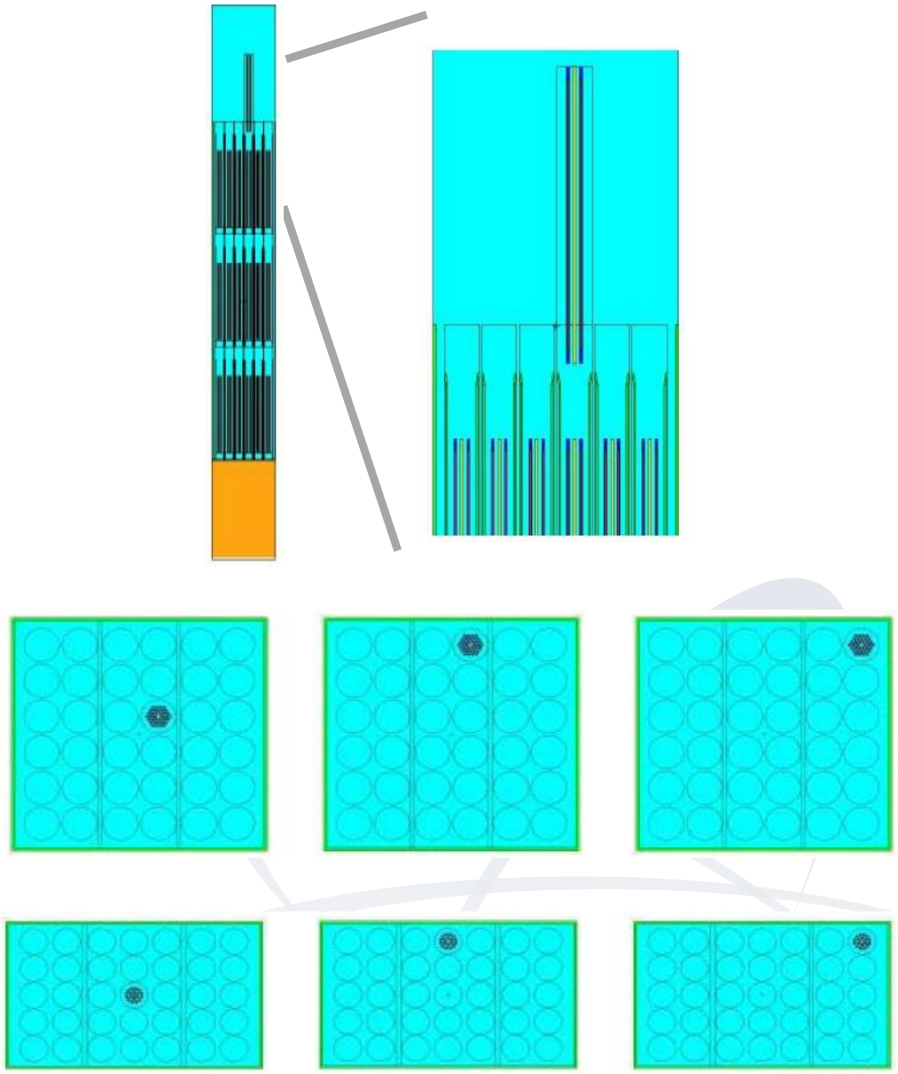
Cir. FA Storage Module (7x5)

04 Design of compact storage module

Criticality Safety

- In case of vertical overload accident

Overload location	Hex. FA Storage (k_{eff})	Cir. FA Storage (k_{eff})
Center	0.70351±0.00010	0.68232±0.00009
Side	0.70353±0.00010	0.68216±0.00009
Corner	0.70348±0.00009	0.68227±0.00011
Ref.	0.70363±0.00011	0.68213±0.00010

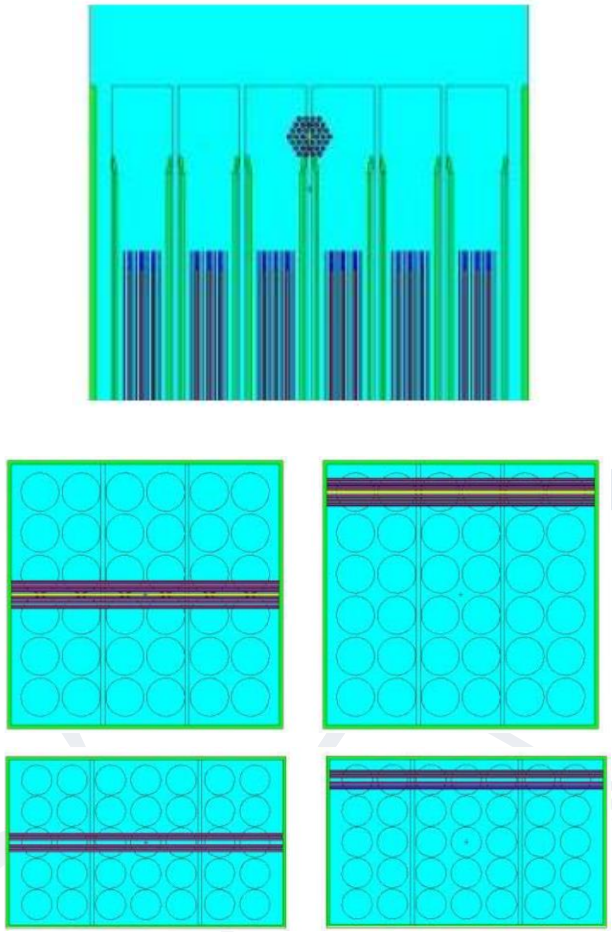


04 Design of compact storage module

Criticality Safety

- In case of horizontal overload accident

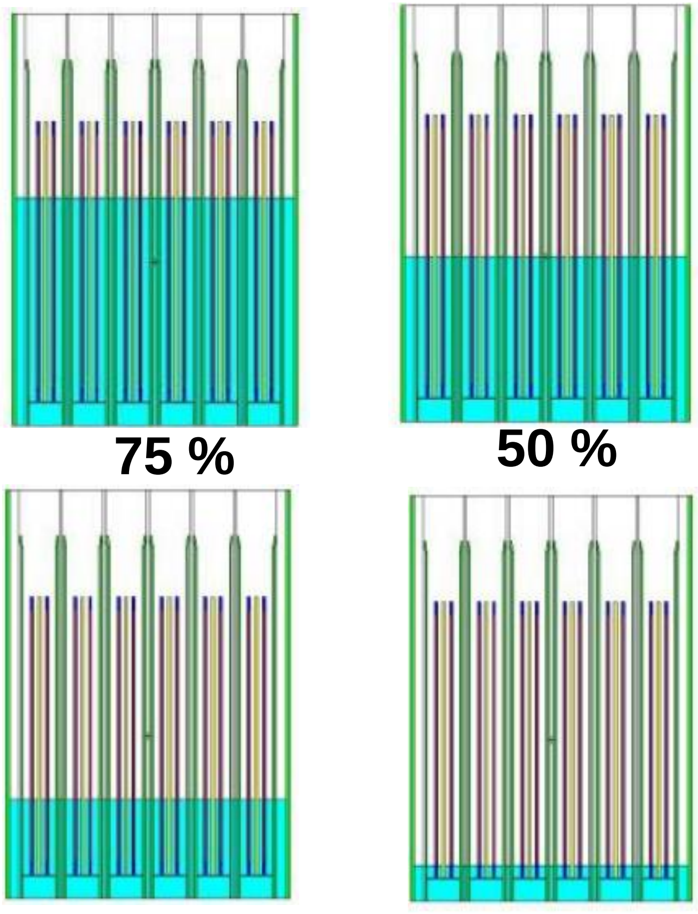
Overload location	Hex. FA Storage (k_{eff})	Cir. FA Storage (k_{eff})
Center	0.70342±0.00010	0.68233±0.00010
Wall	0.70346±0.00010	0.68239±0.00009
Ref.	0.70363±0.00011	0.68213±0.00010



04 Design of compact storage module

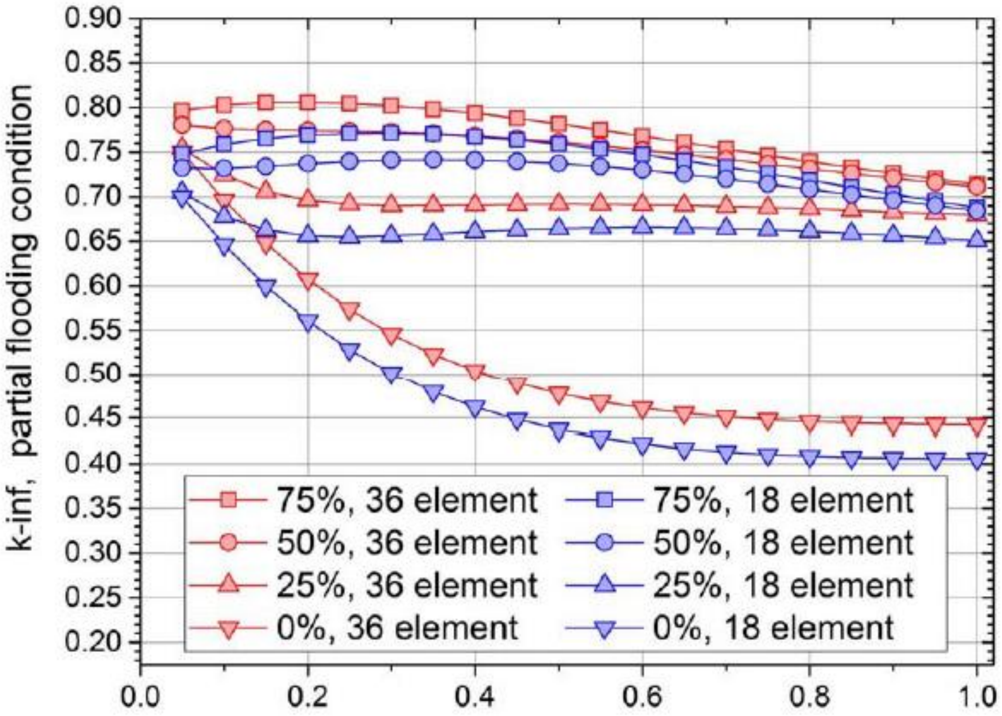
Criticality Safety

- Partial submersion condition (coolant leakage accident)"



75 %   50 %

25 %   0 %

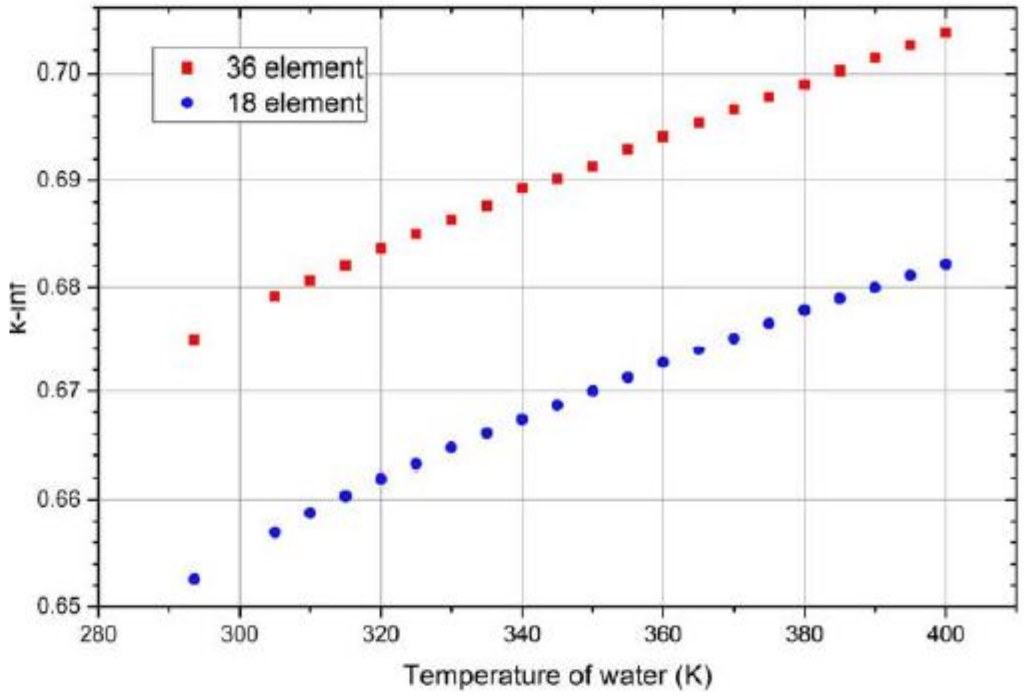


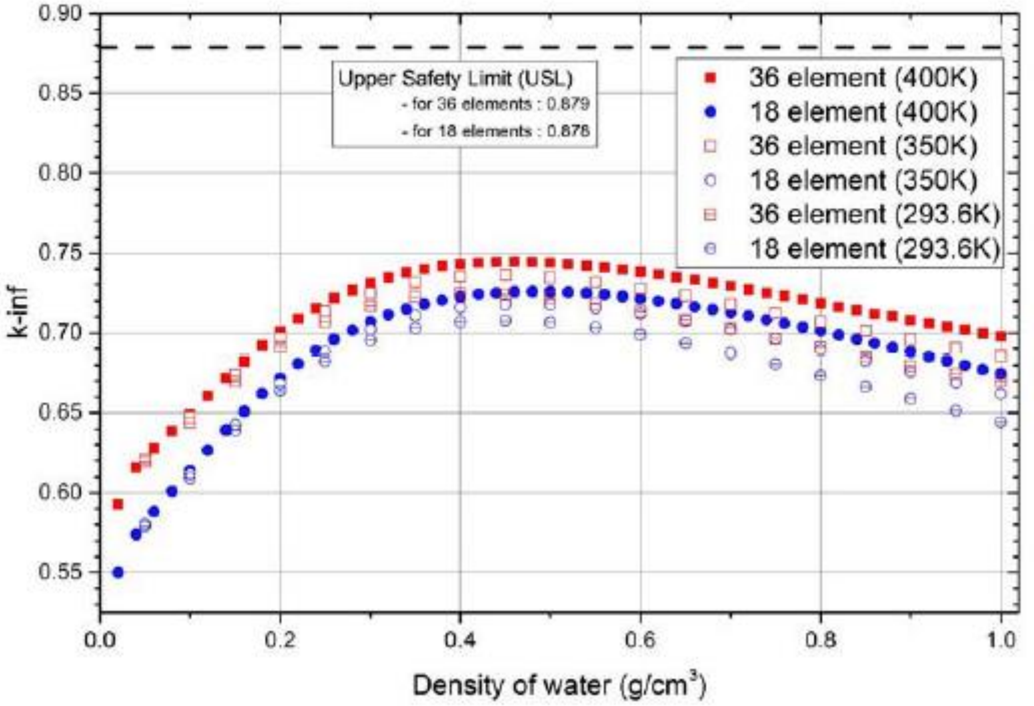
Design of compact storage module

Criticality Safety

Study on the Impact of the S(α, β) Library

- 400 K library is the most conservative





04 Design of compact storage module

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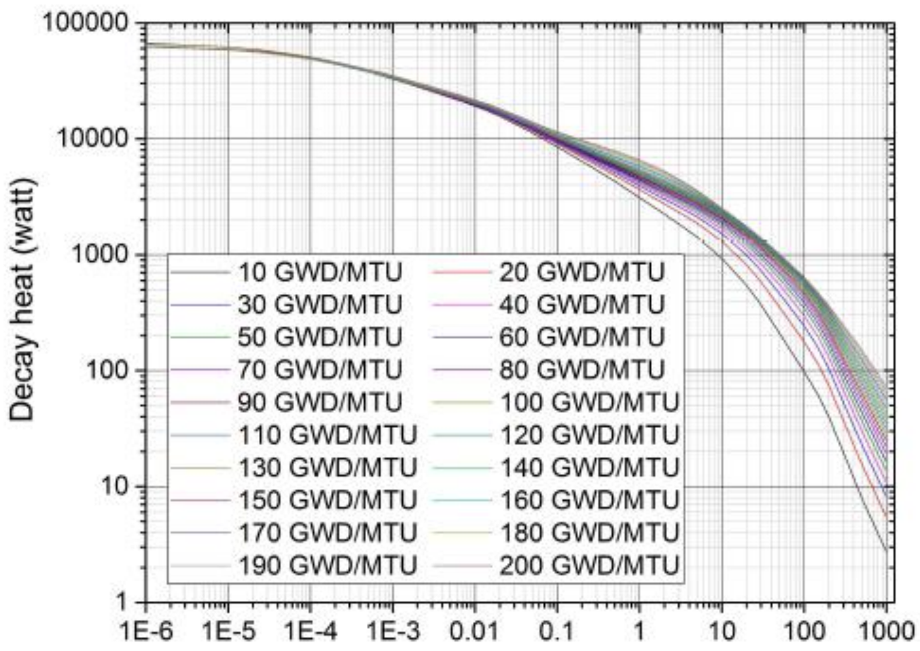
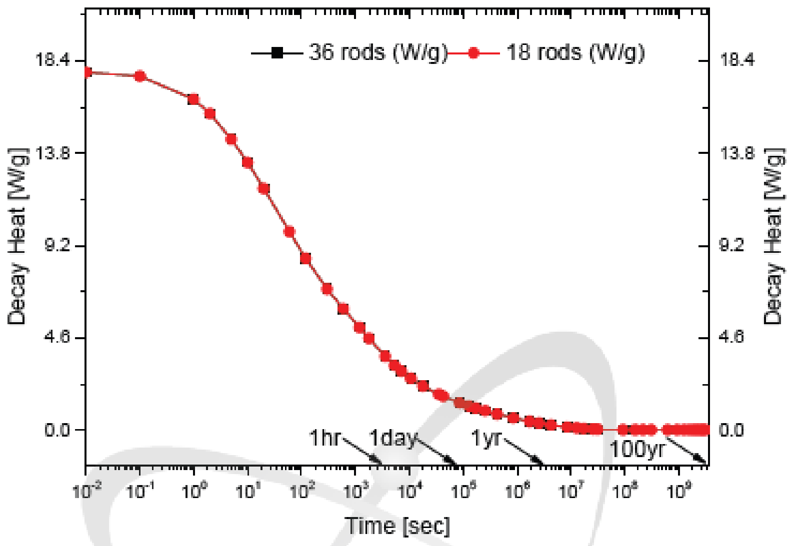
Thermal Safety - decay heat analysis

- Discharge burnup: 90~100 GWD/MTU → **120 GWD/MTU** (for conservatism)
- Total decay heat is 40,150 W (SF storage is full)



Cooling Time (day)	Decay heat (W/g)
0	17.887
1	1.351
3	0.9519
5	0.7956
10	0.5983
30	0.3380



Design of compact storage module

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Thermal Safety

- It is predicted that it will take more than approximately **100 days until coolant boiling**
- In the event of a loss of cooling accident, the coolant temperature can be maintained **below 50°C for more than 100 hours** in HANARO

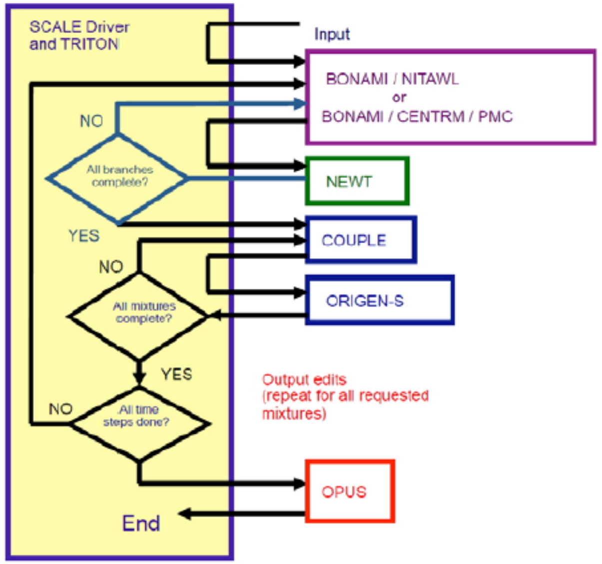
case	Water level up to the top of storage rack	Normal water level
Time to reach 80˚C	–	213.0 h
Time to reach saturation	21.4 h	319.5 h
Boiling allowance time from saturation	20.0 h	2,331 h
Allowable recovery time after loss of cooling	41.4 h (1.6 d)	2,650 h (110.4 d)

Design of compact storage module

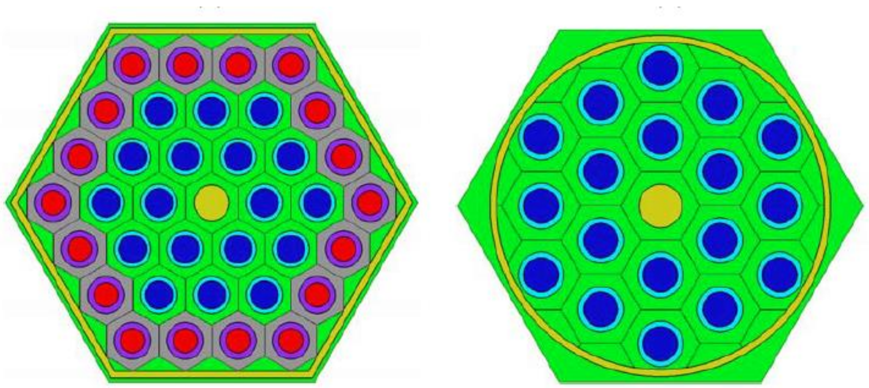
Radiation Shielding Analysis – source term calculation

- TRITON for XS library, ORIGEN-S for source term (included in SCALE 6.2 code system)
- Impurities in fuel (Al in U_3Si-Al)

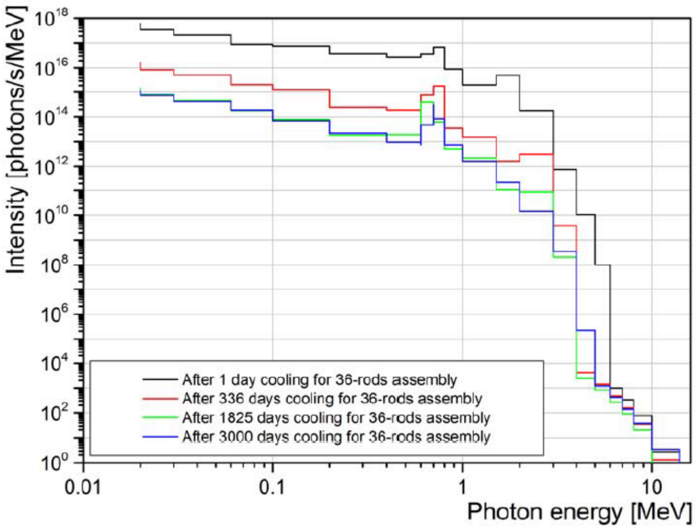
Element	B	Fe	Mn	Cr	Mg	Si
ppm	4	240	80	40	3	20



SCALE system



TRITION model

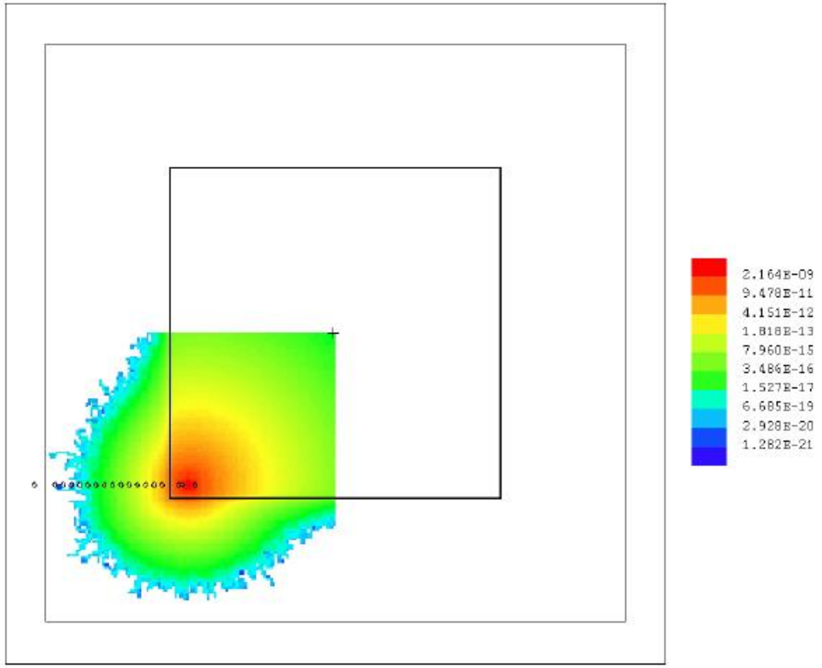


Gamma spectrum of SF (Hex. FA)

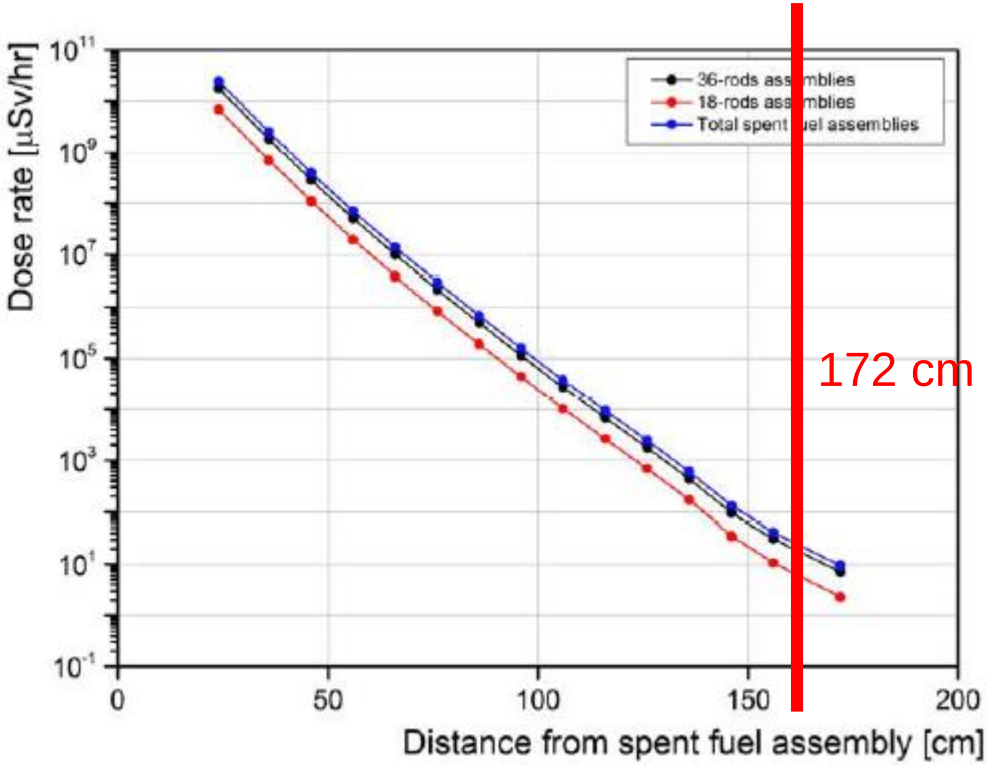
04 Design of compact storage module

Radiation Shielding Analysis – dose

- MCNP 6.1 with DCF from ICRP 74
- New design meets design criteria (radiation level outside the wall < 12.5 μsV/hr).



Dose rate distribution (1-day cooling)



04 Design of compact storage module

Extended Capacity with New Compact Storage Module Design

- The capacity of SF storage can be increased by **60 %**
- Thinner cell tube (but same outer diameter)
  - 71% weight reduction for one cell tube → 3% increase in total → mechanical integrity

Type	Hex. FA (36-rods) Storage Module		Cir. FA (18-rods) Storage Module	
	Current Storage Rack	TRIGA Storage Rack	Current Storage Rack	TRIGA Storage Rack
# of FA per storage module	36 (6x6)	20 (5x4)	35 (7x5)	30 (6x5)
# of storage module	24 (8 x 3 layers)	6 (2 x 3 layers)	18 (6 x 3 layers)	3 (1 x 3 layers)
Storage capacity (bundle)	864	120	630	90
Total	984		720	
Expansion factor	1.64 (=984/600)		1.67 (=720/432)	
Weight ratio for cell tube	1.017 (36/25*0.706)		1.034 (35/24x0.709)	

Design of compact storage module

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Cost and Gain of the New Storage Module

- Total cost(estimated in 2018) for new storage module is about 2.5 million USD considering
  - 5 years of project lead timeline (design, licensing, manufacturing, installation)
  - Manufacturing Hex. FA (36-rods) / Cir. FA (18-rods) storage module **(30 / 21 EA)**
  - Removal and disposal of existing storage module
  - Installation
- With new storage module, the saturation time of SF storage can be extended to **2051~2060**

Fuel Assembly Type	Storage Capacity and Current(2025) Inventory			Expected Full Year	
	Capacity [ea]	Inventory [ea]	Storage Usage [%]	Practical Scenario* [year]	Max. Operation Scenario** [year]
Hex. FA (36-rods)	984	344	35.0%	2060	2051
Cir. FA (18-rods)	720	202	28.1%	2068	2057

05 Summary

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Current Status of SF Management in HANARO

- HANARO is 30 MW open-tank-in-pool type research reactor
- U_3Si dispersion fuel (LEU 19.75 w/o) in Al matrix
- 3 Hex.(36-rods) / 2 Cir.(18-rods) FAs of spent fuel for each cycle (6~8 cyc. per yr)
- Storage full of SF pool is expected to be 2035 ~ 2039

Review of Previously Proposed Solutions

- Previous studies (compact storage module / dry cask / US return program) were reviewed
- In the design of the compact SF storage module, criticality, decay heat, radiation shielding analysis were considered
- With new compact design, the capacity of SF storage can be incread by 60 %

→ the storage full year can be extended to 2051 ~ 2060

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THANK YOU