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Development of Quantitative Indicators for the Graded Regulation of Research Reactors with Various Criteria

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Need & Objective

- **Current Regulation**
  - HANARO : **30 MWth**
  - AGN-201K : **10 Wth**

  → 30^6 difference in thermal power

  - Same "Research Reactor" regulatory category
- **Recommendation**
  - 2024 IAEA IRRS
- **Limitation of PSA-based Approach**
  - Limited component-failure and accident-sequence data for low-power research reactors
- **Need for Alternative Screening Indicators**
  - Quantifiable deterministic indicators based on design characteristics and accident analyses

→ **Development of a quantitative grading framework reflecting facility-specific risk**

» Previous Study : Thermal Power Based Graded Regulation

J. Hur, M. J. Kim, and H. J. Park, A Study on the Safety Regulatory Framework Analysis and Graded Regulation for Zero Power Research Reactors in South Korea, KNS Autumn Meeting, 2025.

- **Previous Study (2025)**
  - Thermal Power-based subdivision of research reactors

100W (Thermal power boundary)	
≤ 100 W Zero-Power Reactors	> 100W Low/Medium-Power Reactors

- **Proposed Regulatory Improvements**
  - Combined construction permit & operating license
  - PSR exemption
  - Simplified licensing documentation

→ **Current Study : Extending graded regulation beyond thermal power using several indicators**

IAEA SSG-22 Graded Approach Factors

- **Reactor Power**
- **Potential source term**
- **Amount and enrichment of fissile and fissionable material**
- Spent fuel elements, high pressure systems, heating systems and the storage of flammable materials
- Type of fuel elements
- Type and the mass of moderator, reflector and **coolant**
- Amount of reactivity that can be introduced and its rate of introduction, reactivity control, and inherent and additional safety feature
- Quality of confinement structure
- Utilization of the reactor
- Site characteristics
- Proximity to population

Selected Quantitative Indicators

- **Thermal Power**
  - Stable design parameter
  - Reflects overall scale of radioactive inventory
- **Radiological Consequence**
  - Maximum Offsite Individual TEDE
- **Fissile Material**
  - U-235 loading & enrichment
- **Core Cooling System**
  - Forced cooling during operation
  - Forced cooling after shutdown
  - Heat sink requirement

Remaining Factors → Qualitative Expert Evaluation

Quantitative Screening Approach from 10 CFR Part 57

- **Proposed 10 CFR Part 57**
  - Low-Risk Reactor Eligibility
    - ✓ Maximum culmulative dose in unrestricted area under MHA/MCA : 10 mSv TEDE
    - ✓ Total Th/U/Pu inventory per reactor : 10MTHM

Key Concepts Adopted

- **Two key elements**
  - Utilizing the maximum dose in the unrestricted area derived from global criteria as a common quantitative metric for potential radiological consequences.
  - Rationale of establishing threshold values for fissile material inventory based on case studies of multiple reactors.

Study Scope & Reactor Database

- **Study Scope**
  - 15 Facilities
    - ✓ Domestic & international research and test reactors
    - ✓ Research Reactor, Test Reactor, Critical Assembly, Educational/zero power reactor

- **Data Sources**
  - Safety Analysis Reports (SAR)
  - Licensing Documents
  - Published Literature
    - ✓ **Four** Quantitative Indicators
    - ✓ Thermal power, Radiological consequence, Fissile material, Core cooling system

» Thermal Power & Radiological Consequence

Reactor	Country	Thermal Power (P_{th})	Max. offsite TEDE (mSv)
HANARO	Rep. of Korea	30MW	52.72
AGN-201K		10W	<0.0032
KJRR		15MW	44.74
FRM-II	Germany	20MW	6.5
JRTR	Jordan	5MW	50
NBSR	United States	20MW	0.067
MURR (LEU)		12MW	0.0858
MNRC TRIGA		2MW	0.0056
OSTR		1.1MW	0.19
Dow TRIGA		0.3MW	0.067
GHARR-1	Ghana	0.03MW	0.0262
KUCA	Japan	100W	0.00019
UTR-KINKI		1W	0.023
JMTR		50MW	2.78
HTTR		30MW	1.7

Dose values are based on non-harmonized accident and evaluation conditions and are used for order-of-magnitude comparison only.

Amount and Enrichment of Fissile Material

Reactor	U-235	Enrichment (wt%)
HANARO	11.64kg	19.75 (LEU)
AGN-201K	690g	19.5 (LEU)
KJRR	13.84kg	19.75 (LEU)
FRM-II	7.53kg	93.0 (HEU)
JRTR	7kg	19.75 (LEU)
NBSR	10.5kg	93.0 (HEU)
MURR (LEU)	12.05kg	19.75 (LEU)
MNRC TRIGA	2.8 ~15.1kg	<20.0 (LEU)
OSTR	13.6kg	19.75 (LEU)
Dow TRIGA	2.8kg	19.9 (LEU)
GHARR-1	1.355kg	13.0 (LEU)
KUCA	1~10kg	19.75 (LEU)
UTR-KINKI	3.07kg	19.75 (LEU)
JMTR	9.63kg	19.75 (LEU)
HTTR	53.1kg	6.0 (LEU)

MURR, KUCA and UTR-KINKI are currently being converted to LEU.

» Core Cooling System

Reactor	Forced cooling during operation	Forced cooling following shutdown	Heat Sink
HANARO	O	O	O
AGN-201K	X	X	X
KJRR	O	X	O
FRM-II	O	O	O
JRTR	O	X	O
NBSR	O	O	O
MURR (LEU)	O	X	O
MNRC TRIGA	X	X	O
OSTR	X	X	O
Dow TRIGA	X	X	O
GHARR-1	X	X	O
KUCA	X	X	X
UTR-KINKI	X	X	X
JMTR	O	O	O
HTTR	-	-	-

HTTR could not be classified because it is a helium cooled.

» Grading by Thermal Power

Grade	Thermal Power	Reactors
1	$P_{th} \geq 10$ MW	HANARO, JMTR, HTTR, NBSR, FRM-II, KJRR, MURR
2	$1 \text{ MW} \leq P_{th} \leq 10 \text{ MW}$	JRTR, MNRC TRIGA, OSTR
3	$100 \text{ W} < P_{th} < 1 \text{ MW}$	Dow TRIGA, GHARR-1
4	$P_{th} \leq 100$ W	KUCA, **AGN-201K**, UTR-KINKI

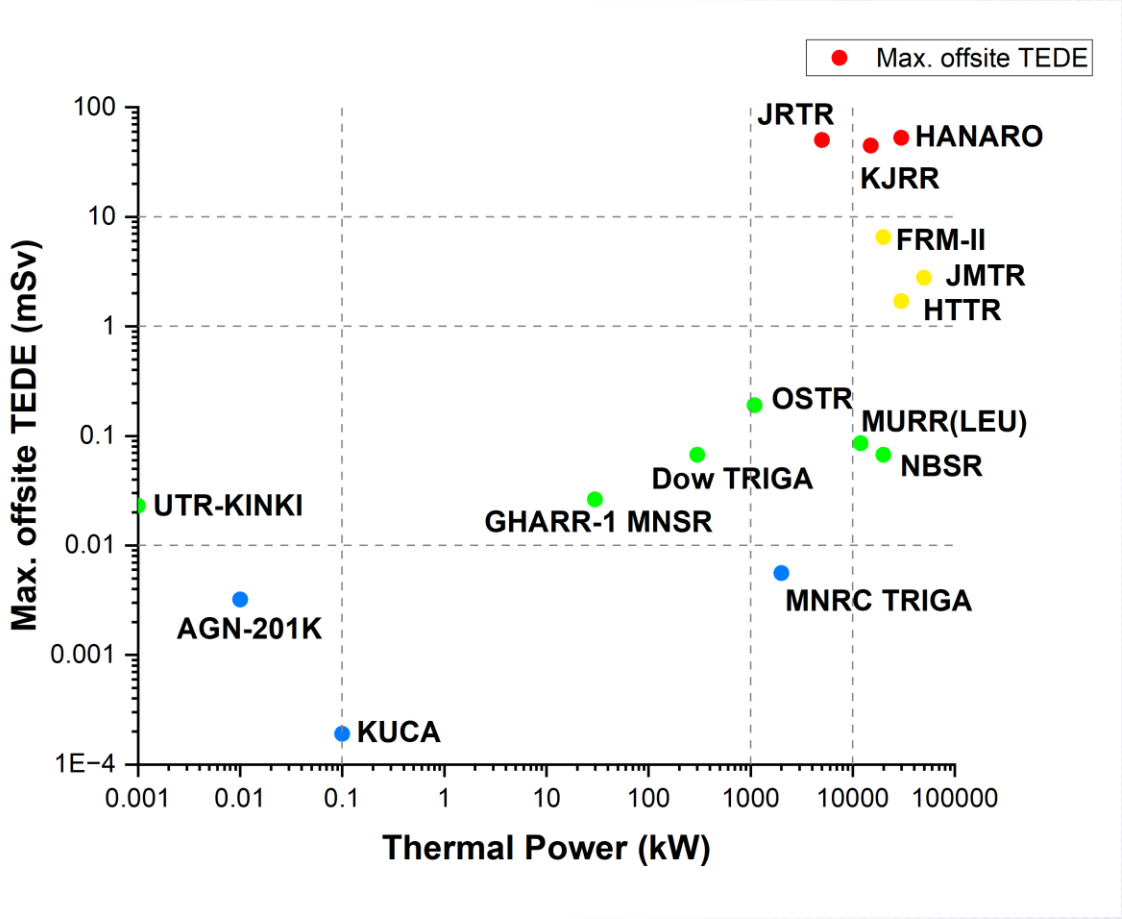
- **Basis for Grade Boundaries**
  - **10MW** : Japanese research reactor classification — Nuclear Safety Commission of Japan, Safety Design Review Guidelines for Water-Cooled Research Reactor Facilities, 1991 (revised 2001).
  - **1MW** : study-defined screening value
  - **100W** : Preceding domestic graded-regulation study — Hur et al., KNS Autumn Meeting, 2025. / NRC NUREGG-0849

Grading by Radiological Consequence

- **Grading Criteria**
  - **10 mSv**
    - ✓ Non-power reactor consequence
    - ✓ Part 57 screening

    10 CFR 50.34(a)(1)(i)
  - **1 mSv**
    - ✓ Public dose limit 10 CFR 20.1301(a)(1)
  - **0.01 mSv**
    - ✓ Exemption / clearance level

    NSSC Notice No. 2025-11, Art. 2(3)



→ **The selected thresholds align with both existing regulatory criteria and observed distribution of reactor data.**

Grading by Radiological Consequence

Grade	Max. offsite TEDE	Reactors
1	≥ 10 mSv	JRTR, HANARO, KJRR
2	> 1 mSv	HTTR, FRM-II, JMTR
3	> 0.01 mSv	OSTR, NBSR, Dow TRIGA, UTR-KINKI, MURR(LEU), GHARR-1
4	≤ 0.01 mSv	**AGN-201K**, MNRC TRIGA, KUCA

- High thermal power does not always imply high radiological consequence.
- Radiological consequence should be retained as an independent grading axis.

Proposed Grading Scheme for Research Reactors

» Grading by Amount and Enrichment of Fissile Material

Grade	Amount and Enrichment	Reactors
1	HEU	NBSR, FRM-II
2	LEU (≥ 10kg)	OSTR, MNRC TRIGA, MURR (LEU), HTTR, HANARO, KJRR
3	LEU (5~10kg)	JRTR, KUCA, JMTR
4	LEU (≤ 5kg)	**AGN-201K**, Dow TRIGA, GHARR-1, UTR-KINKI

- **Basis for Grade Boundaries**
  - HEU/LEU : IAEA SSG-22
  - **10 kg** : IAEA INFCIRC/225 Category II threshold
  - **5 kg** : study-defined subdivision to improve grading discrimination

Grading by Core Cooling System Design

Grade	Core Cooling System (forced cooling during operation / after shutdown / heatsink)	Reactors
1	O / O / O	JMTR, HANARO, NBSR, FRM-II
2	O / X / O	KJRR, MURR (LEU), JRTR
3	X / X / O	MNRC TRIGA, OSTR, Dow TRIGA, GHARR-1
4	X / X / X	KUCA, UTR-KINKI, **AGN-201K**

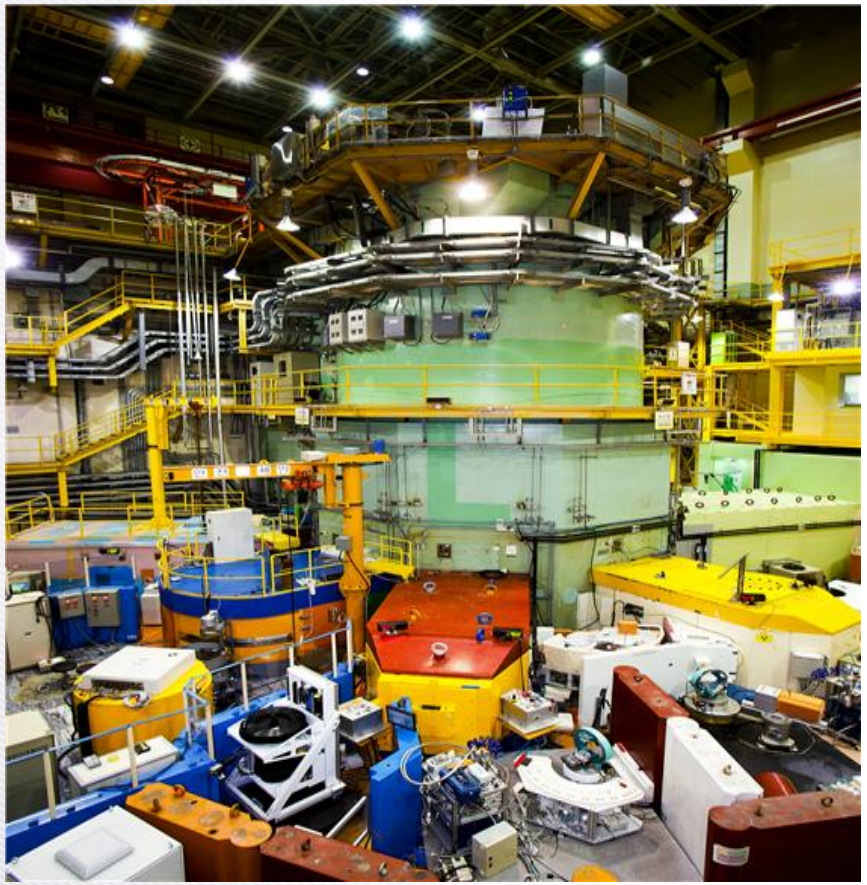
- **Basis for Grade Boundaries**
  - Directly from the classification of preceding domestic study

H. J. Park, J. Hur, and M. J. Kim, “Analysis of the Safety Regulatory for Educational Zero Power Reactors and Proposal of Graded Regulatory Improvements,” MCRPL-TR-005(2025) R0, Kyung Hee University, 2024.

Integrated Grading Results

Reactor	Thermal Power	Radiological consequence	Fissile material	Core cooling system
HANARO	1	1	2	1
AGN-201K	4	4	4	4
KJRR	1	1	2	2
FRM-II	1	2	1	1
JRTR	2	1	3	2
NBSR	1	3	1	1
MURR (LEU)	1	3	2	2
MNRC TRIGA	2	4	2	3
OSTR	2	3	2	3
Dow TRIGA	3	3	4	3
GHARR-1	3	3	4	3
KUCA	4	4	3	4
UTR-KINKI	4	3	4	4
JMTR	1	2	3	1
HTTR	1	2	2	N/A

HANARO



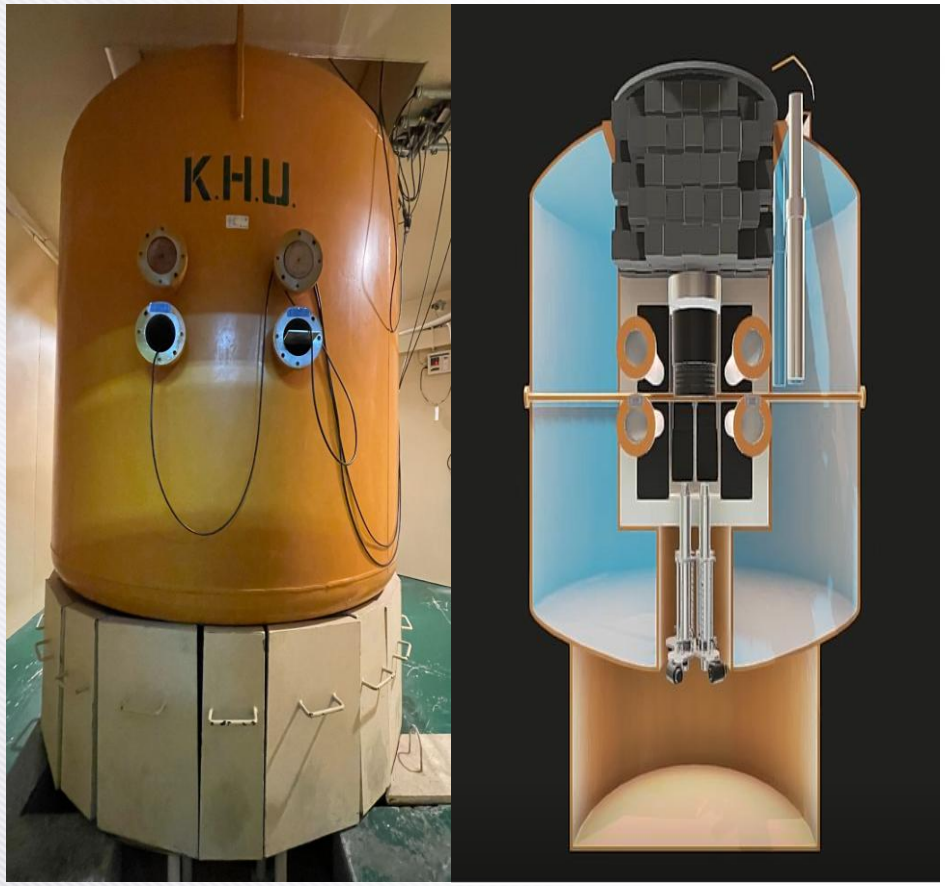
Indicator	Value	Grade
Thermal Power	30 MW	**1**
Radiological consequence	52.72 mSv	**1**
Fissile material	LEU / 11.64 kg	**2**
Core Cooling System	O / O / O	**1**

KJRR



Indicator	Value	Grade
Thermal Power	15 MW	**1**
Radiological consequence	44.74 mSv	**1**
Fissile material	LEU / 13.84 kg	**2**
Core Cooling System	O / X / O	**2**

AGN-201K



Indicator	Value	Grade
Thermal Power	10W	**4**
Radiological consequence	<0.0032 mSv	**4**
Fissile material	LEU / 690 g	**4**
Core Cooling System	X / X / X	**4**

Key Findings

Reactor	Grade Range	Assessment
HANARO	Grade 1-2	Very high risk research reactor
KJRR	Grade 1-2	Very high risk research reactor
AGN-201K	**Grade 4**	Very low risk research reactor

- **Divergence among indicators**
  - Most reactors receive different grades across the four indicators.
  - No single quantitative indicator can adequately represent all relevant risk characteristics.

Proposed Framework for Graded Regulation

- Quantitative indicators establish a range for the overall grade.
- **Expert qualitative evaluation** of the remaining SSG-22 factors determines the final grade.
  - Reducing variability in regulatory grading through quantitative criteria and expert judgement.



Future work

- **Development of a Qualitative Evaluation Framework**
  - Establish systematic expert evaluation procedures for the remaining SSG-22 factors
- **Integrating results**
  - Combine quantitative result and qualitative result

Thank You