Roles of nuclear fuel cycle technologies on geological disposal:

Resilience in management of spent nuclear fuel by development of technology and social agreement

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Contents

- Final disposal, difficult to realize
- Couplings observed in waste management
- Multifaceted performance assessment
- Relation between technology development and social discussions
- Closing thoughts

Final disposal, difficult to realize

- Canada 1998 (Failure in getting public approval for concept)
  - M.V. Ramana, *Energy Policy*, **61**(2013) 196–206
- USA 2009 (Political decision-making)
  - J. Ahn, ATOMOZ, November 2011.
  - C. Singer, *Energy Policy*, **61**(2013) 1521–1528
- Japan 2012 (Science Council's recommendation)
  - J. Ahn, *Kagaku (Science)*, Iwanami, October, 2013
- South Korea 2013 (Deadlocked in US-ROK 123 agreement negotiation)
  - J. Ahn, To be published

Why?

- Lack of reversibility in siting process = Decide-Announce-Defend (DAD) approach
  - Reversibility results from:
    - Adaptive, staged approach
    - Feedback loop between social discussions and technology development
- Dilemma between convergence and sustainable use of nuclear power
  - "Footprint" issue

For ROK, once-through scheme did not work, because …

- The only parameters that affect the attribute of the materials to be disposed of are time and location.
  - to wait for decay and cooling
  - to site facilities
- This absence of flexibility made the public agreement difficult.
  - only a limited number of stakeholders would agree with the prefixed option.
  - room for adjusting the system to meet the public's wide range of desire and preference is very small.

"Footprint" issue

Dilemma between Convergence and Sustainability

- Spent fuel continues to accumulate as long as nuclear power is utilized.
  - Radioactivity will <u>not</u> reach a steady state as long as nuclear power is generated, and will last much longer than the use of nuclear energy.
- Therefore, repository footprint expands accordingly.
  - <u>(perception issue)</u> The public would not consider this as a solution, but rather consider that the problem continues to grow bigger.
  - <u>(substantive safety issue)</u> With an increasing radioactivity inventory and footprint of a geological repository, potential risk of the geological disposal also increases.

US has many (too many?) options.

- Large territory
- Wide variety in geological conditions
- Wide variety in technological options
- No international constraints as the largest and first weapons country
- Active interactions among law makers, policy makers, regulators, and academia
- BUT,
  - Interactions have been confrontational, sometimes hostile,
  - Because of its own nonproliferation policy, direct disposal has been the only option, and
  - Local residents were not properly involved in decision-making process for YMR siting.

BRC Recommendations (2012)

1. A new, consent-based approach to siting future nuclear waste management facilities.
2. A new organization dedicated solely to implementing the waste management program and empowered with the authority and resources to succeed.
3. Access to the funds nuclear utility ratepayers are providing for the purpose of nuclear waste management.
4. Prompt efforts to develop one or more geologic disposal facilities.
5. Prompt efforts to develop one or more consolidated storage facilities.
6. Prompt efforts to prepare for the eventual large-scale transport of spent nuclear fuel and high-level waste to consolidated storage and disposal facilities when such facilities become available.
7. Support for continued U.S. innovation in nuclear energy technology and for workforce development.
8. Active U.S. leadership in international efforts to address safety, waste management, non-proliferation, and security concerns.

- Final disposal, difficult to realize
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Couplings observed in spent fuel management

- Short term (fuel cycle) vs. Long term (disposal)
  - Short term ➔ Long term
    - Overall long-term *performance* is dependent on short-term options.
  - Long term ➔ Short term
    - Without a plan for repository siting, implementation of short-term options is difficult due to lack of public trust and confidence.
- Domestic vs. International
  - Domestic ➔ International
    - Failure in consuming recovered fissile materials may cause international skepticism.
  - International ➔ Domestic
    - International and bilateral treaties define framework for fuel-cycle options.
      - E.g., US-Japan 123 agreement negotiation by 2018

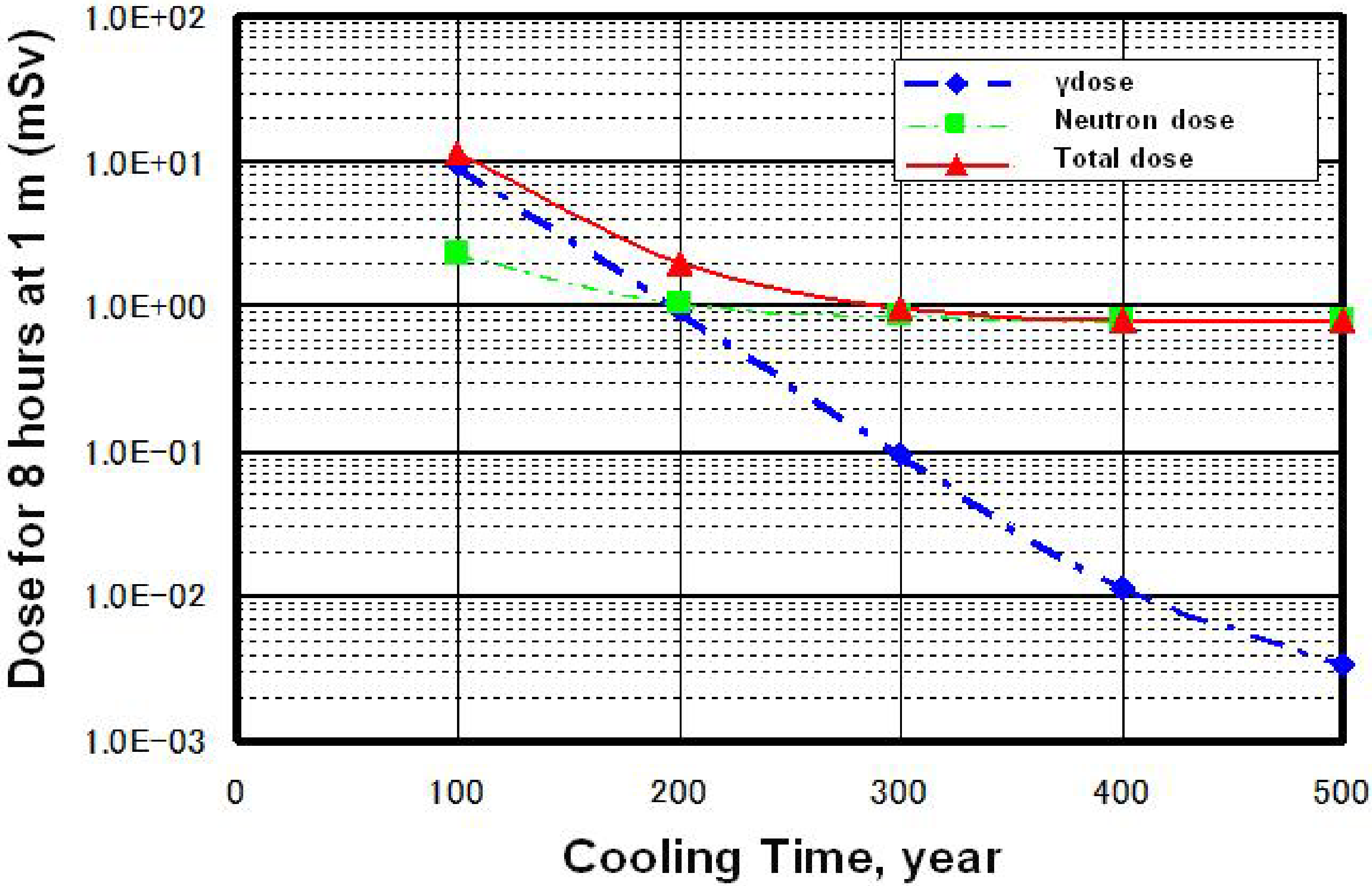
Effects of Fuel Cycle on Disposal

- Effects of Storage
- Effects of Separation
- Effects of Sequestration (Waste form)
- Effects of Transmutation

Effects of storage

- Cooling → Improvement of repository safety
  - Reduction of repository footprint
  - Retardation of Engineered-Barrier degradation
  - Reduction of uncertainty in repository performance
- Reduction of radioactivity and radiotoxicity (i.e., source terms)
  - Reduction of adverse consequences in severe accidents
- Increase of proliferation potential

Protection by radiation



Dose for 8 hours at 1 m location from the spent fuel package for the Yucca Mountain Repository

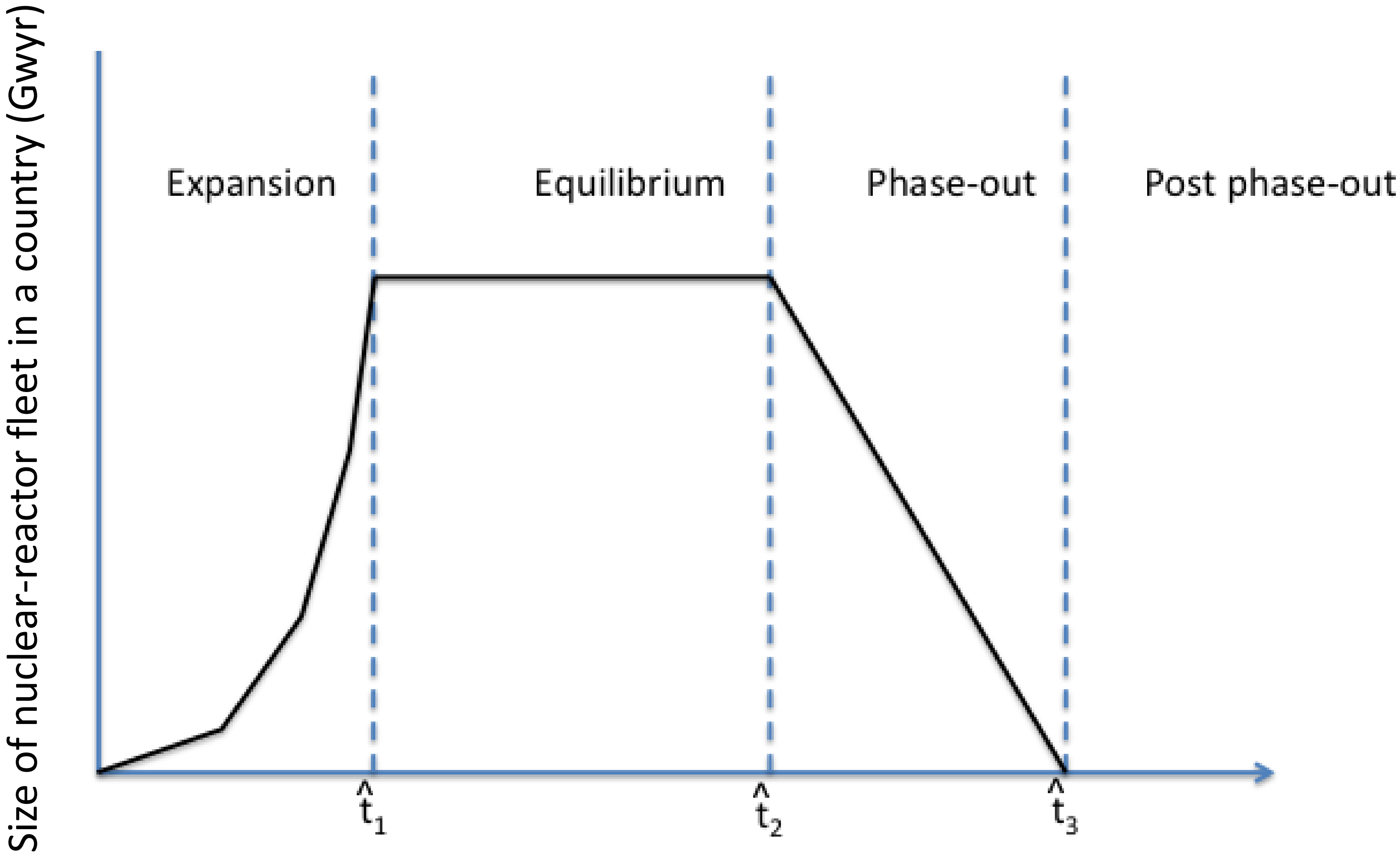
Effects of separation

- High heat radionuclides (HHR) (Sr-90 and Cs-137)
  - with short half-lives (about 30 years) and
  - small masses (approximately 4 kg/metric ton of initial heavy metal (MTIHM)).
- Low-heat radionuclides (LHR)
  - with long half lives and
  - significant masses

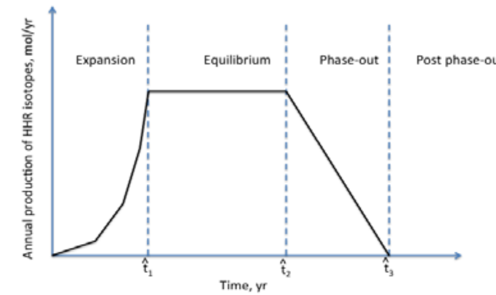
Time, years	Spent fuel	HHRs (Cs and Sr)	LHRs			
			U and Pu	Minor actinides	Others	Structure
10	1,443	1,024	185	113	64	48
20	1,096	755	211	90	22	13
50	658	373	228	55	2	0.3
100	356	115	201	39	0.1	0.05
1,000	63	~0	54	9	0.02	0.02

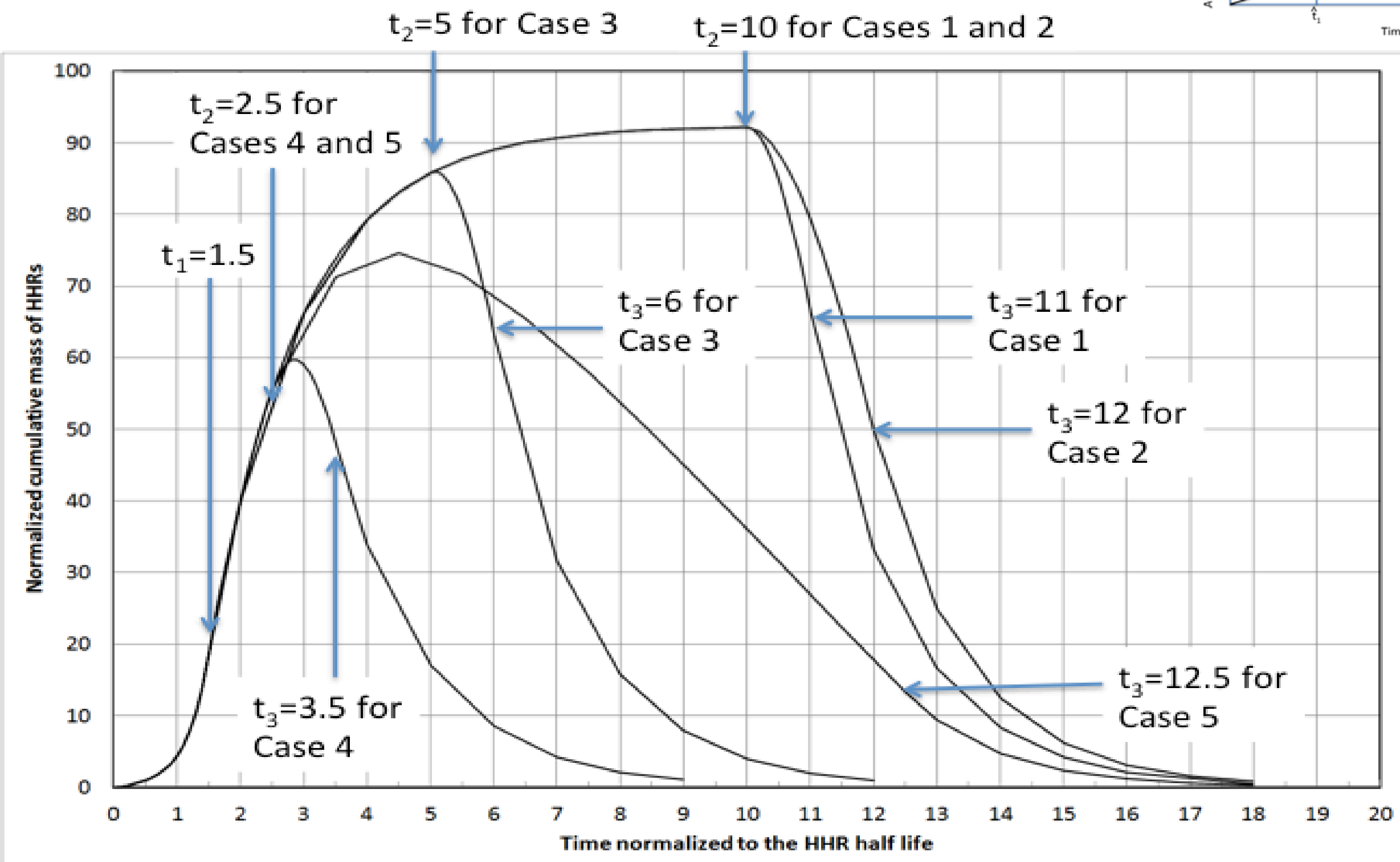
Forsberg CW. Rethinking high-level waste disposal: separate disposal of high-heat radionuclides (^{90}Sr and ^{137}Cs). Nuclear Technology. 2000 Aug; 131(2): 252-268.

Country's nuclear utilization



Convergence of HHR





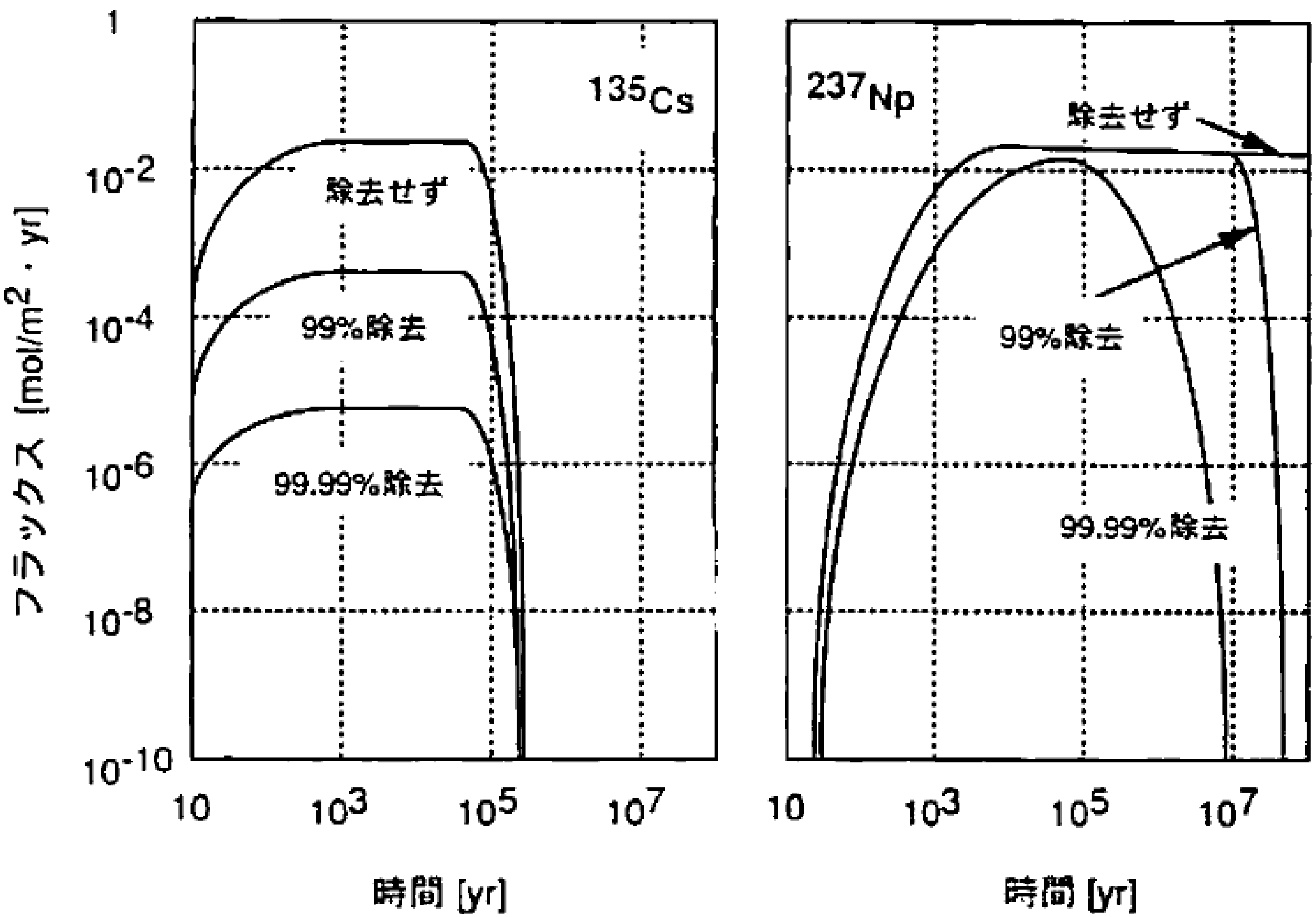
LHR

- Uranium:
  - occupies majority (~ 95%) of the mass;
  - is hardly soluble and immobile in a reducing environment in groundwater.
- Plutonium, and minor actinides (TRU):
  - are fissionable materials, for which stringent control for safeguard and safety are required;
  - are highly radiotoxic due to alpha emission;
  - are hardly soluble particularly in a reducing environment;
- Long-lived fission products, such as I-129, Se-79, and Tc-99, and Cs-135:
  - are relatively mobile in geological formations, i.e., high solubility and weak sorption retardation with rock during hydrological transport by groundwater

Effects of waste forms/canisters

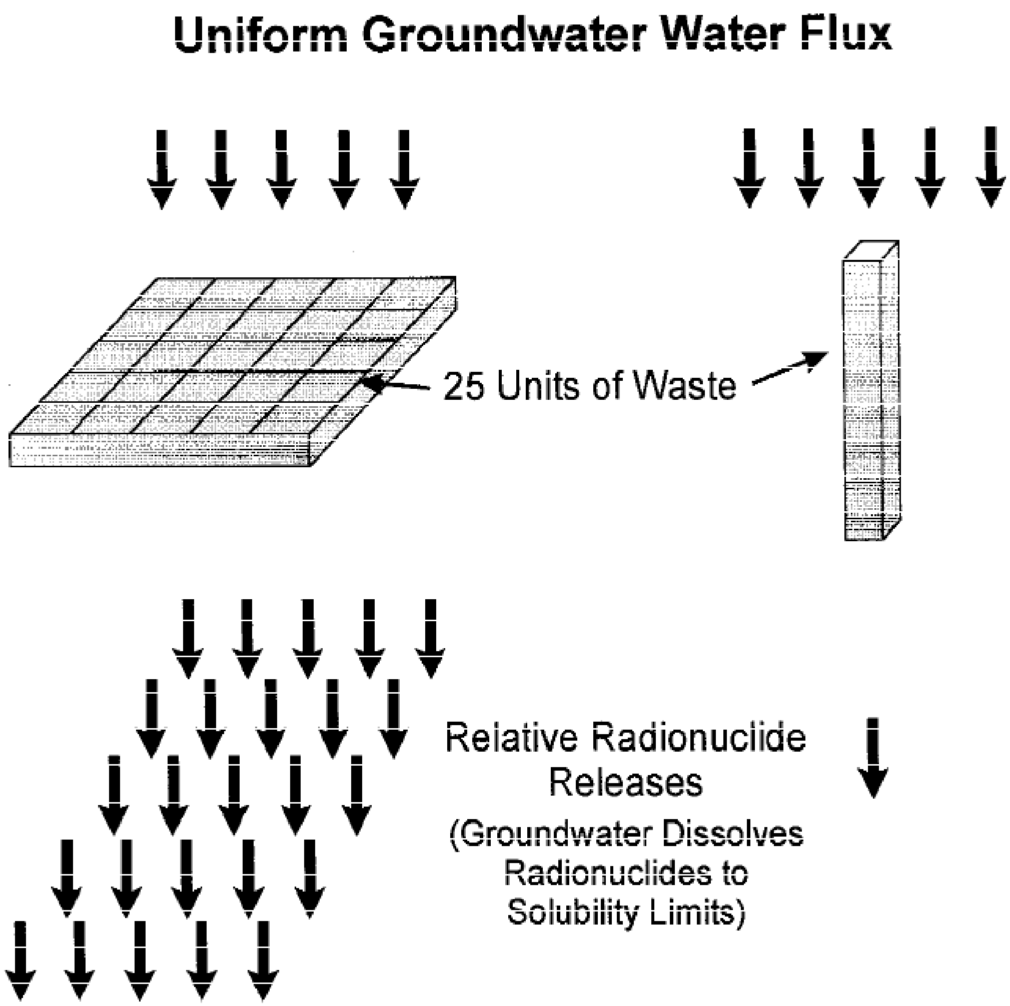
- Radionuclide loadings in waste form ➔ Determines the number of canisters and footprint
  - Heat emission
  - Proliferation resistance
  - Radionuclide release rates
- Dissolution rates of waste form
  - Radionuclide release rates
  - Alteration of near-field environment
- Choice of backfill/buffer materials

Effects of Transmutation

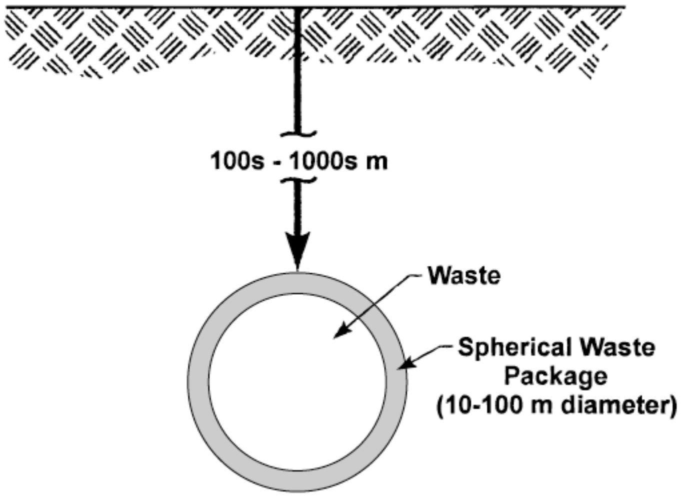


中山、安、放射性廃棄物研究 (1996) ２（１＆２）27 - 34

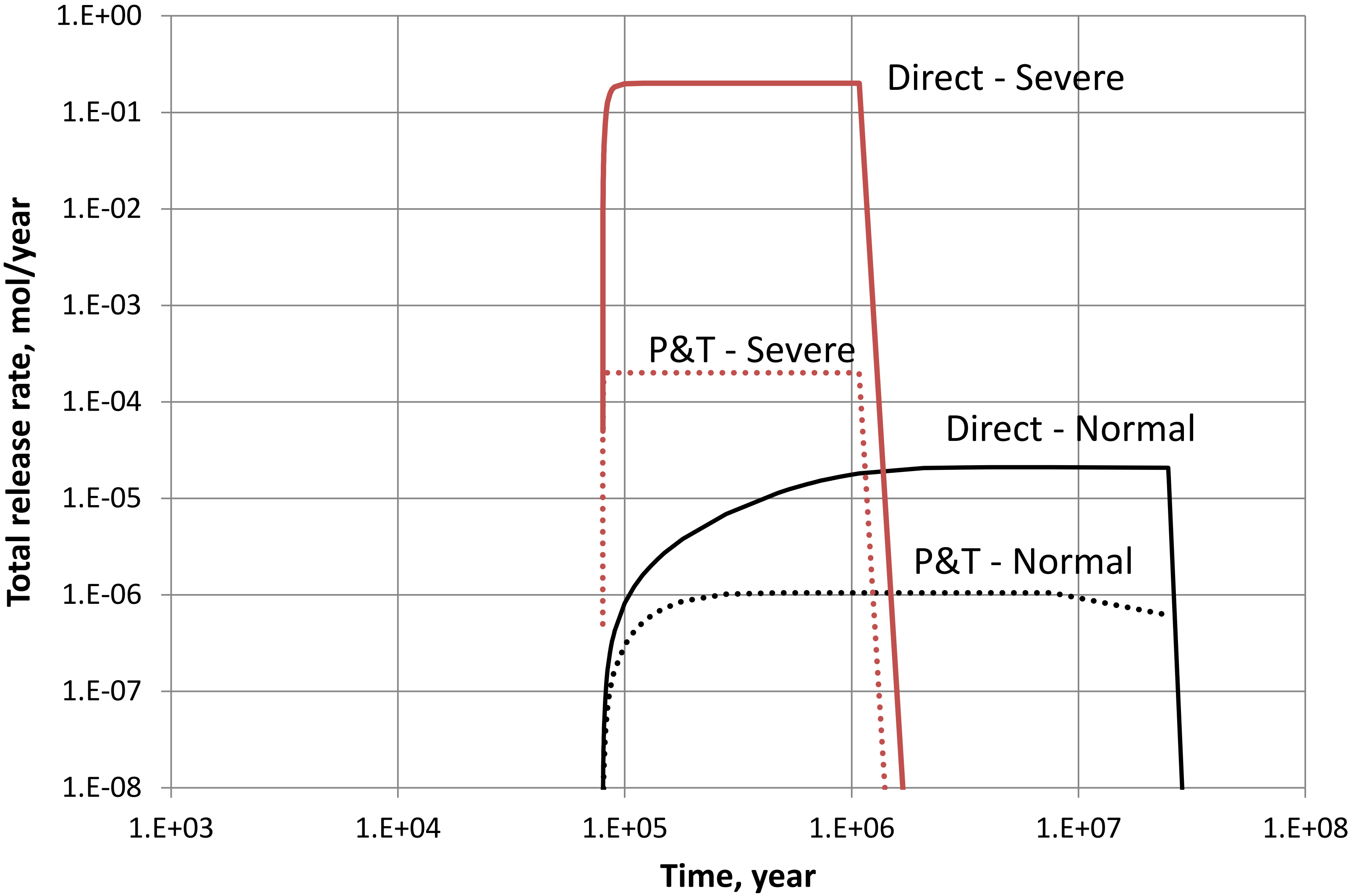
With solubility limited mechanism, repository performance is controlled by S/V ratio.



With no heat emission, a big sphere gives the best performance.



Comparison



Direct - Severe
P&T - Severe
Direct - Normal
P&T - Normal
1.E+00
1.E-01
1.E-02
1.E-03
1.E-04
1.E-05
1.E-06
1.E-07
1.E-08
1.E+03
1.E+04
1.E+05
1.E+06
1.E+07
1.E+08
Time, year
Total release rate, mol/year

- Final disposal, difficult to realize
- Couplings observed in waste management
- Multifaceted performance assessment
  - Taking Japanese case as an example
- Relation between technology development and social discussions
- Closing thoughts

Conventional vs. Multifaceted performance assessment

- Conventional PA is done to confirm that a certain system comprises with regulatory guidelines.
- Multifaceted PA is done to compare performance of multiple options from multiple viewpoints.

Multifaceted PA

- <u>In the first round</u>, "cost" comparison should not be the primary viewpoint.
  - Remember Muskie Act 1970.
  - How to frame the problem?
- Once the public understands and shares what the society would like to achieve, cost will become the primary issue, but can be solved by technological development and breakthrough.
  - Cf. Discussion after Fukushima Daiichi accident in Japan is misaddressed because cost comparison seems to be the most decisive factor.

Issues that Japan faces
-- Short and Mid-term ranges --

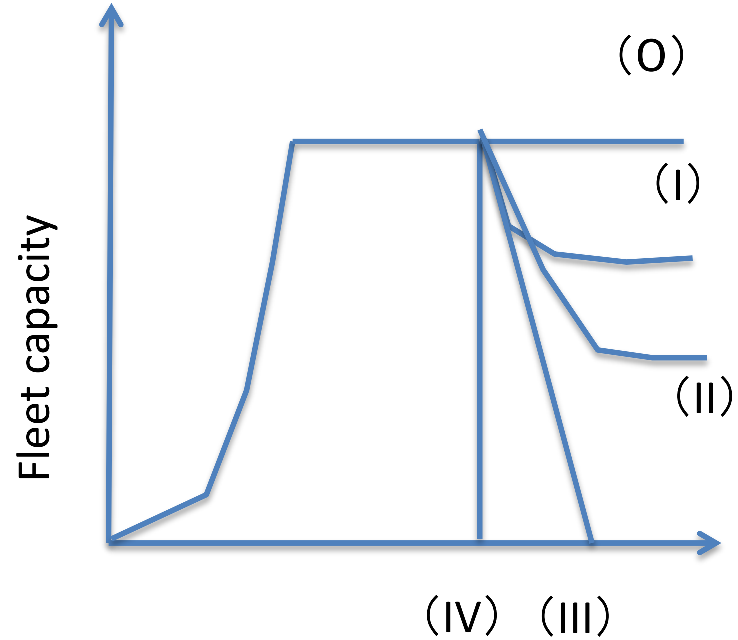
- National wealth is draining out.
  - Import of fossil fuels
    - Additional 4 trillion yen/year
    - Additional 175 million ton CO_2 emission /year
  - Huge investment could become irrecoverable.
    - Nuclear power plants,
    - Rokkasho reprocessing plant
- International competitiveness and influence are being lost.
- Pu stockpile can complicate US-Japan bilateral relation.

Issues that Japan faces
-- Long-term range --

- Risk to be imposed on future generations is heavily dependent on options taken in short and mid-term ranges.
  - Amount and contents to be disposed of become substantially different.
  - Technologies available in future will be different, or maybe decreased.
- Options for mitigating global warming issues will be limited.

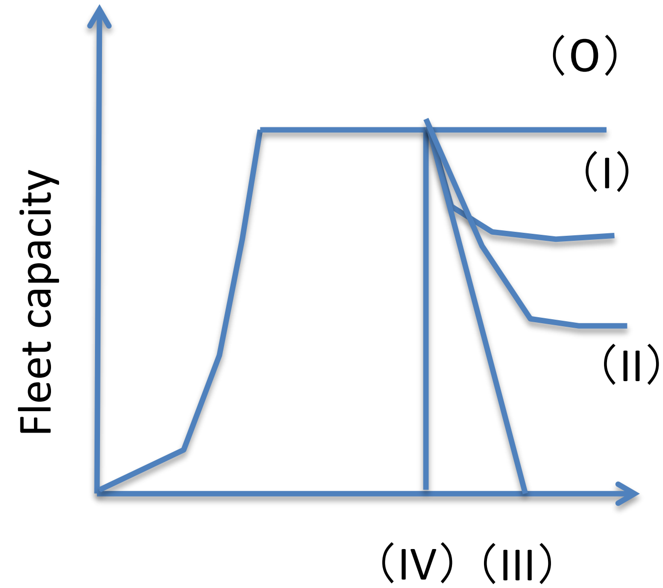
Options

- Option（0）: Full-fledged fuel cycle
  - Maintain the same fleet capacity (e.g., 50 LWRs equivalent; includes FBRs)
  - PUREX (U, Pu recovered)
  - Recovery of TRU for transmutation
  - Disposal: HLW vitrified waste（legacy + future）
- Option（IV）: Phase out immediately
  - Disposal: HLW vitrified waste（legacy）, Pu stockpile, Spent fuel including MOX, Recovered U

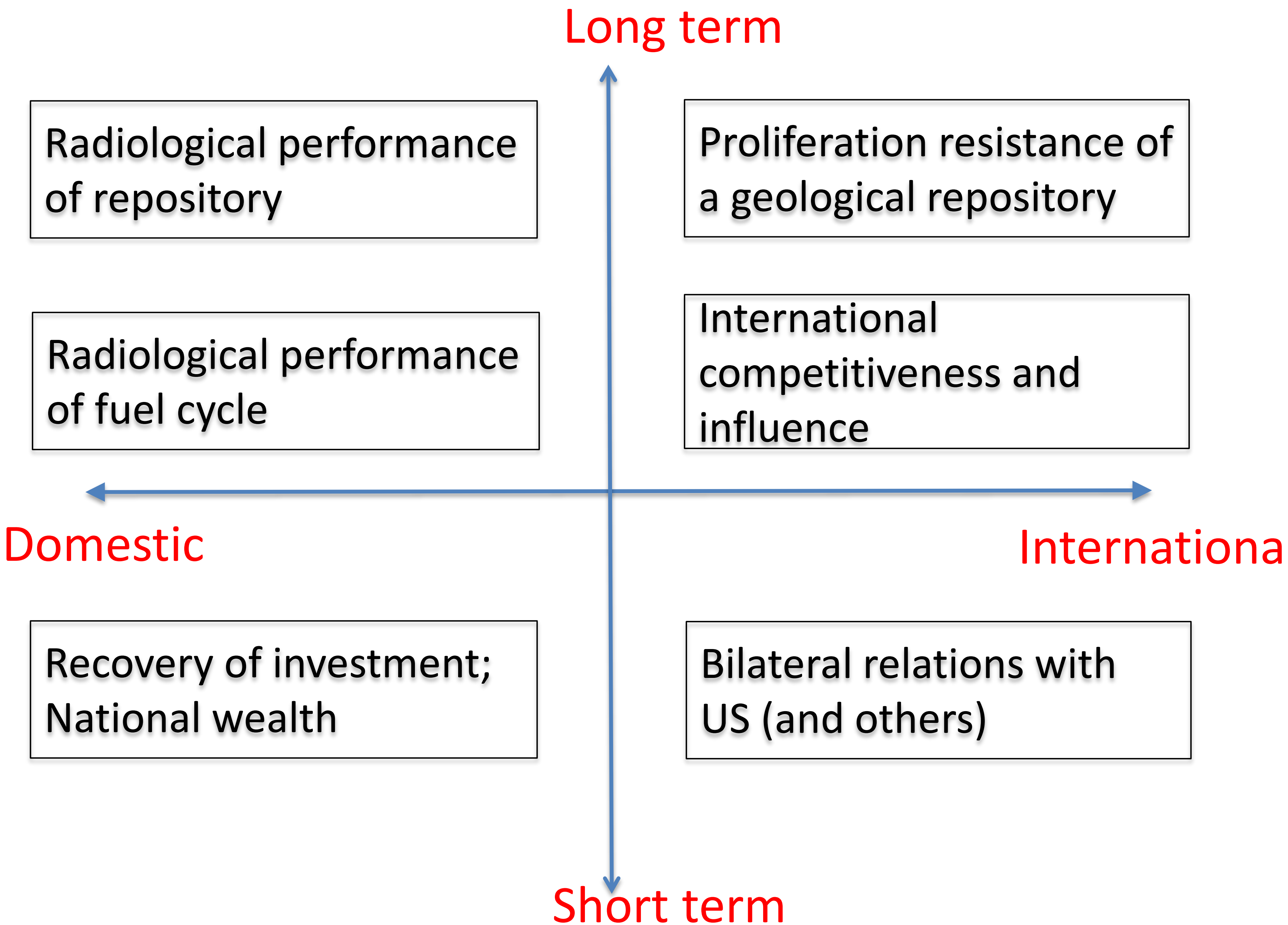


Options

- Option（I）
  - Fleet capacity that can be accommodated by Rokkasho capacity
  - Old reactors replaced as needed
  - PUREX (U, Pu recovered)
  - MOX
  - Disposal：HLW vitrified waste （legacy + future）, MOX SF, Recovered U
- Option（II）
  - Fleet capacity that can be accommodated by Rokkasho capacity
  - No LWR replacement; HTGR
  - PUREX (U, Pu recovered)
  - TRISO
  - Disposal：HLW vitrified waste （legacy）, TRISO, Recovered U



- Option（III）
  - No replacement of reactors
  - No reprocessing
  - Legacy Pu is made into MOX and used in remaining LWRs
  - Disposal：HLW vitrified waste （legacy）, MOX SF, Spent fuel, Recovered U


Long term
Radiological performance of repository
Proliferation resistance of a geological repository
Radiological performance of fuel cycle
International competitiveness and influence
Domestic
International
Recovery of investment; National wealth
Bilateral relations with US (and others)
Short term

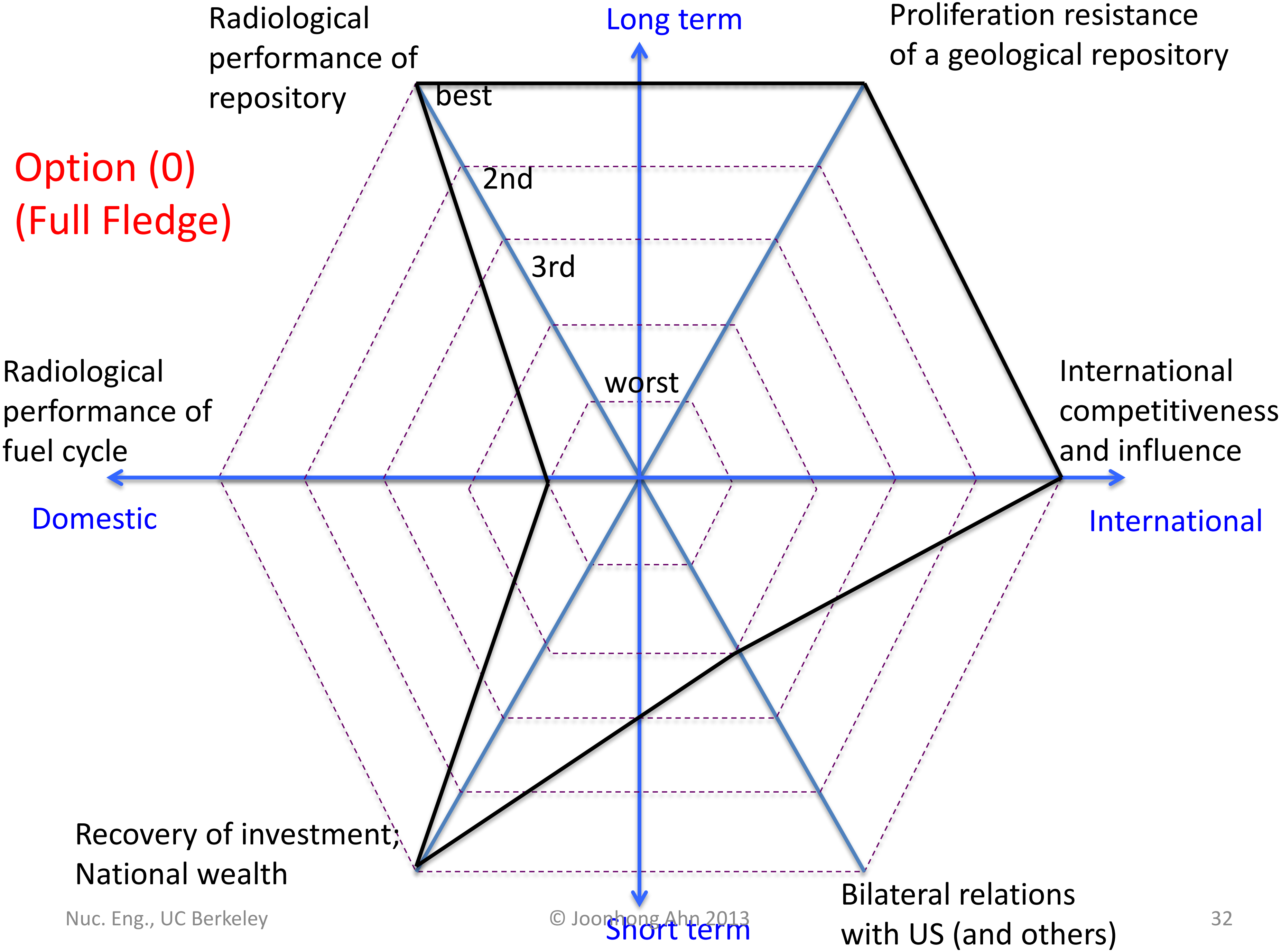
Performance Viewpoints (Domestic)

- Radiological performance of repository
  - difficulty for meeting regulatory requirements;
  - radiological risk resulting from a severe accident.
- Radiological performance of fuel cycle
  - complexity of processes and activities included in respective options, and so
  - amount of regulatory work necessary to maintain normal operation
- Recovery of investment; National wealth
  - Utilization of existing facilities

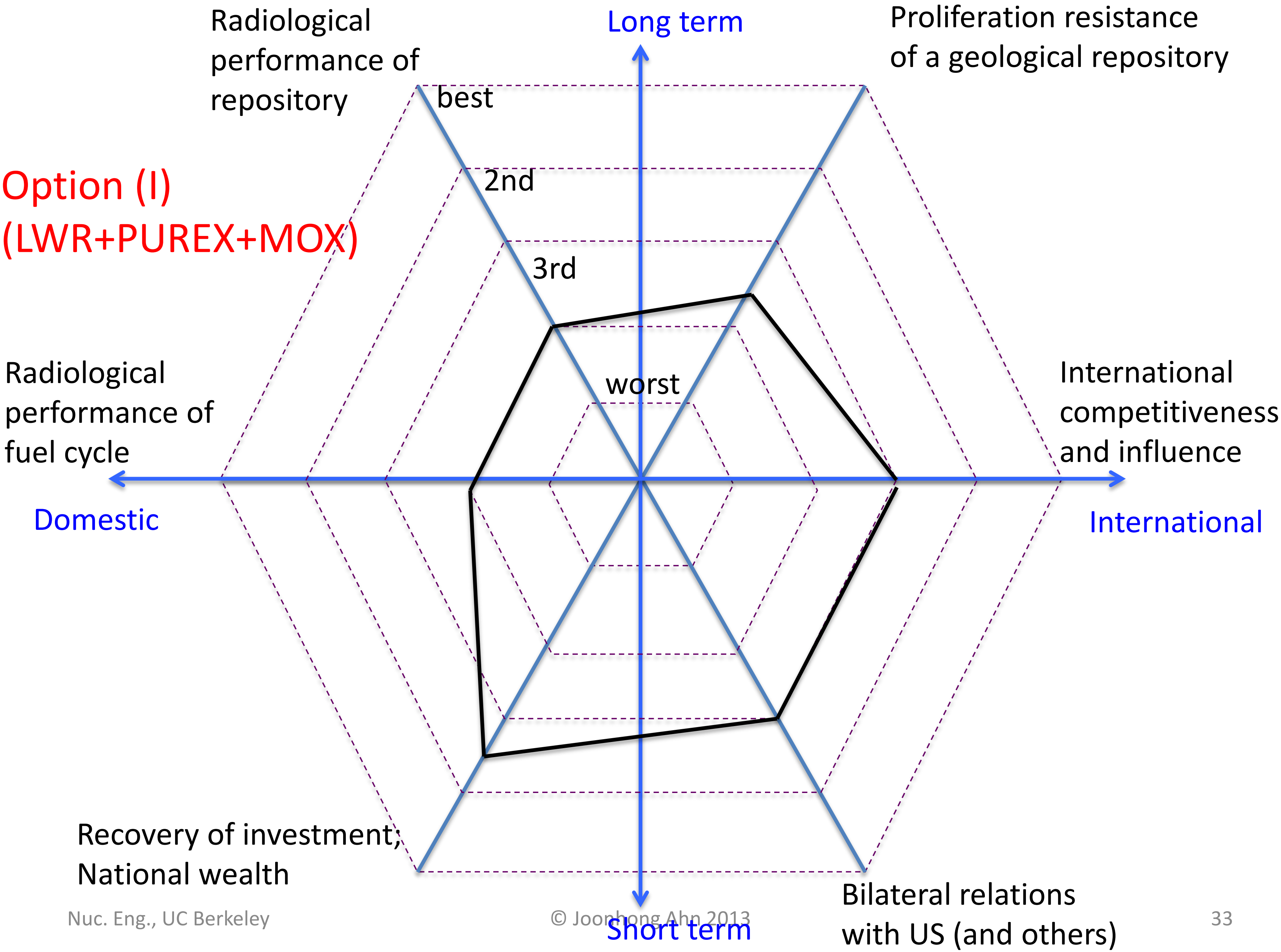
Performance Viewpoints (International)

- Proliferation resistance of a geological repository
  – attractiveness as weapons-usable materials.
- International competitiveness and influence
  – Economical, technological, political
- Bilateral relations with US (and others)
  – Pu stockpile

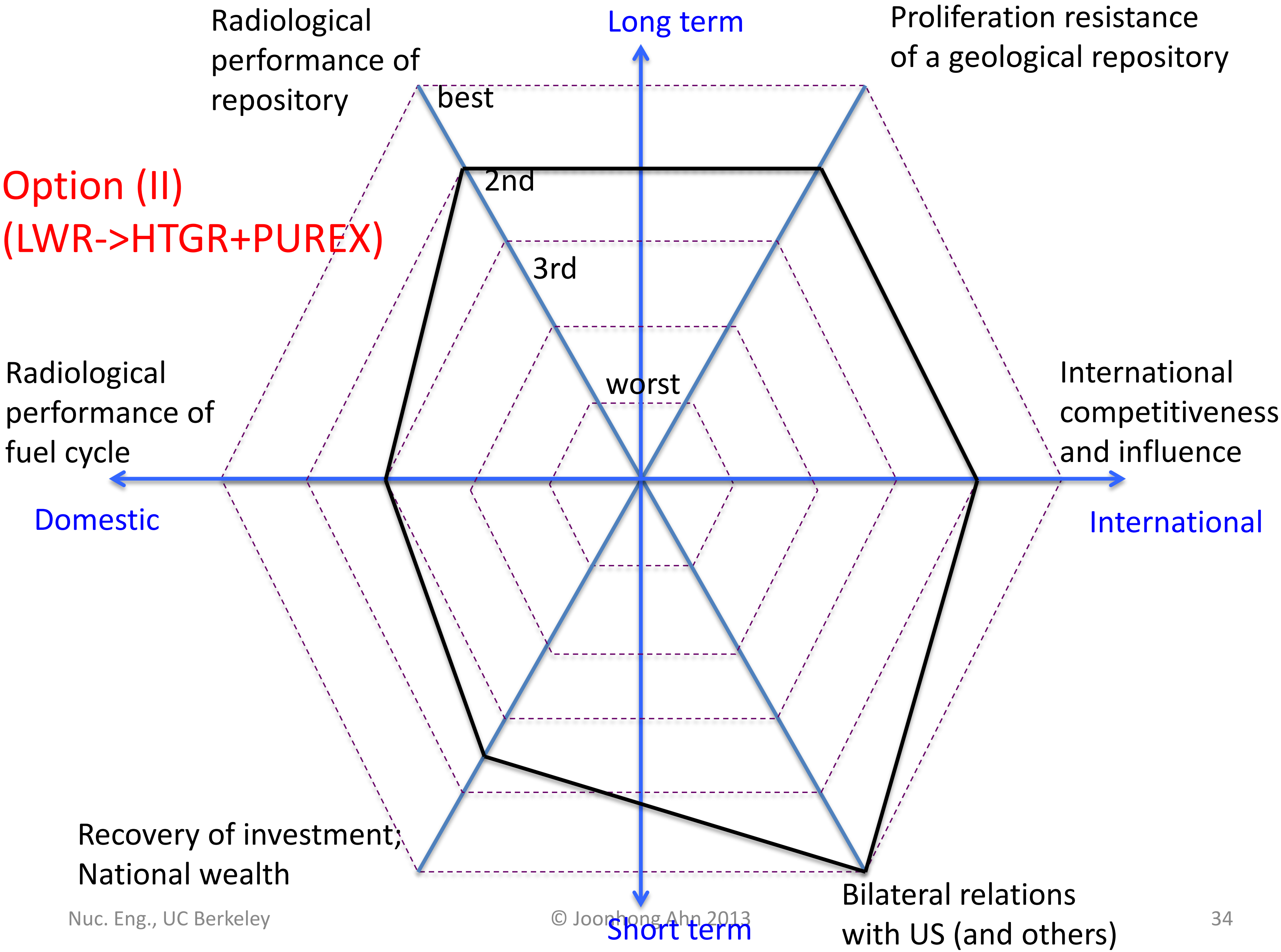
Option (0)
(Full Fledge)



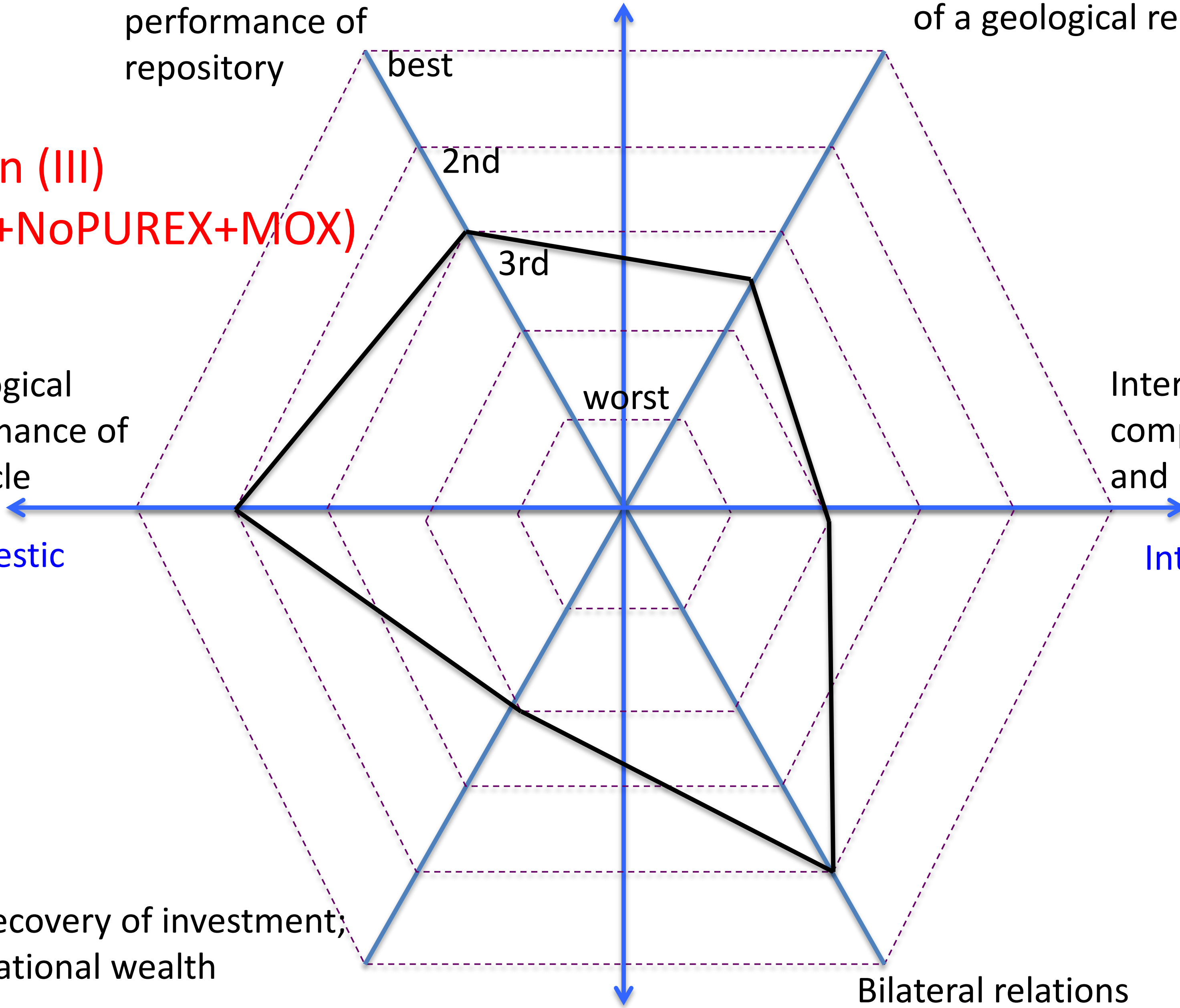
Option (I)
(LWR+PUREX+MOX)



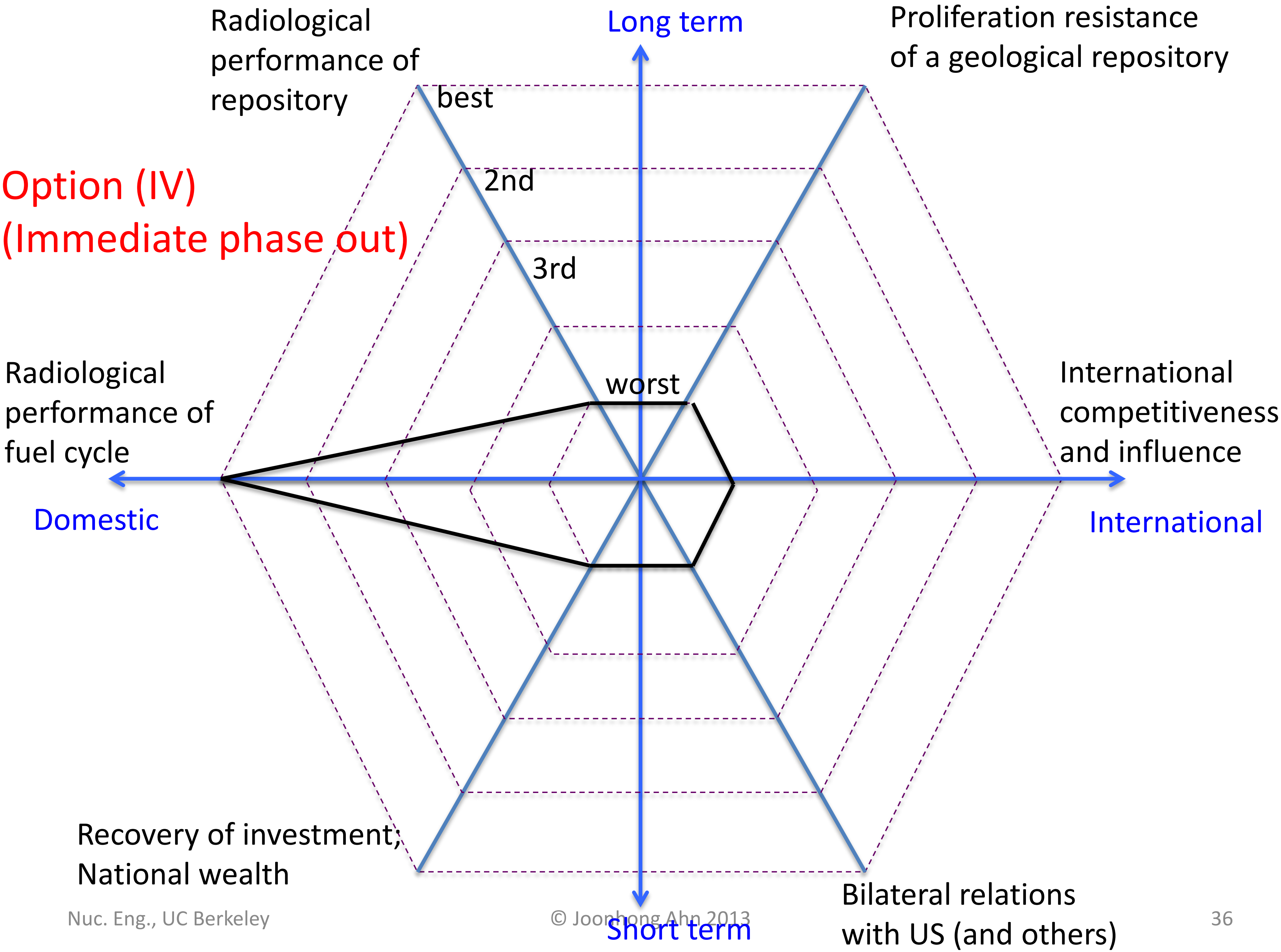
Option (II) (LWR->HTGR+PUREX)



Option (III) (LWR+NoPUREX+MOX)



Option (IV)
(Immediate phase out)



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Aftermath of Fukushima -- Discussions for "better" systems --

- More robust reactors
- Capable operator
- Competent and independent regulatory system
- Energy security/independence
- Accident mitigation & damage minimization
  - Which part of the society has actually been damaged?

Resilient nuclear technology

- Resilience of a reactor
  - Advanced reactors and fuels (inherently safe reactors)
  - Back-fit of existing reactors
- Resilience of a fleet of reactors/fuel cycles
  - Replacement of old reactors with new reactors
  - Spent fuel/high-level waste treatment and disposal
- Resilience of energy portfolio
  - Flexibility of adjusting (increase or decrease) share of nuclear power, depending on situations/needs
- Resilience of society
  - Public-participatory system for decision making,
  - Complicated stakeholders

Where should public participation be implemented?

- Selection of viewpoints for multifaceted assessment
  - Different stakeholders would have different priorities, and thus consider different sets of viewpoints more important or crucial.
  - However, including too many viewpoints would not make assessment useful for grasping trade-off relations embedded in the current issue.
  - This leads to an idea of establishing a committee with participation of various stakeholders for the purpose of selecting a relatively small number of viewpoints for multifaceted assessment.
- Evaluation/ranking with respect to each viewpoint
  - While this has been done historically by judgment of technical experts, evaluation can and should also be done by public participation.
  - Multiple sets of results for different population could be obtained and compared.

Closing thoughts

- Nuclear fuel cycle technology plays crucial roles in augmenting technological options.
- BUT,
- Technological development should be carried under the guidance of, and to serve for, public-participatory, reversible and adaptive decision making, which is essential for social resilience.
- For such decision-making process, multifaceted performance assessment for technological options plays an important role.
  - Performance metrics, based on in-depth analysis of issues that the society faces, and the goal that the society agrees.
  - PA should be conducted not only by experts but also by lay people.
  - Metrics, goals, and assessment should be done iteratively.