Resilience in management of spent nuclear fuel: Development of technology and social agreement

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Contents

- Prologue
- Status quo for spent fuel management
- Technological options available
- Multifaceted performance assessment
- Closing thoughts

Japan's complex situation after Fukushima Daiichi Accident

- Huge social cost for decontamination and recovery
  - Incomplete understanding and implementation of "defense in depth"
  - Too narrow and limited inclusion about types of "damages" in a severe accident
- Legacy materials and non-proliferation
  - Pu stockpile and spent fuel management
  - Substantial changes in objective and necessity for nuclear fuel cycle
- Tight energy demand & supply
  - Drainage of national wealth

Aftermath of Fukushima (1)

Huge social cost

- No direct public fatality by the accident,
- But, unquantifiable damage to people's daily lives
  - Radioactive contamination (soil, sea, food chains…)
  - Evacuation (still >80,000 people cannot come back home)
- Huge cost for
  - Decontamination of the environment (20 – 300 Billion USD), and
  - Decommissioning of the Fukushim Daiichi site (>20 Billion USD)

Defense in depth

Levels of defence in depth	Objective	Essential means
Level 1	Prevention of abnormal operation and failures	Conservative design and high quality in construction and operation
Level 2	Control of abnormal operation and detection of failures	Control, limiting and protection systems and other surveillance features
Level 3	Control of accidents within the design basis	Engineered safety features and accident procedures
Level 4	Control of severe plant conditions, including prevention of accident progression and mitigation of the consequences of severe accidents	Complementary measures and accident management
Level 5	Mitigation of radiological consequences of significant releases of radioactive materials	Off-site emergency response

- Often misunderstood and confused with multi-barrier concept,
- Lacks deep scientific basis for radionuclides behavior in the environment and impacts on human health,
- Considers only radiological consequences, i.e., cancer fatality.

Aftermath of Fukushima (2)
Legacy materials and nonproliferation

- Plutonium stockpile
  - If nuclear is phased out, this remains.
  - Potential international issue.
- Spent fuel and reprocessing
  - If reprocessing is abandoned,
    - Aomori demands to return spent fuel back to origins.
  - It is not clear why reprocessing needs to be continued.

Japan's Spent Fuel Balance (02/2013)

Stored at JNFL (Rokkasho)	3,350 MT
Stored at NPPs	14,170 MT
Overseas reprocessing	7,100 MT
Tokai reprocessing	1,020 MT
TOTAL	25,640 MT

Vitrified HLW	8,120 canisters
Pu	73 MT
RepU	7,950 MT

Legacy materials waiting for disposal

- Direct disposal of used fuel:
  - 17,520 MT
  - $ 26.3 Billion (2.63兆円)
  - Subject to IAEA Safeguard inspection
- HLW disposal
  - 8,120 canisters
  - $ 6.9 Billion (0.69兆円)
  - IAEA Safeguard inspection likely to be terminated due to low Pu content
- Pu disposition
  - 73 MT
- RepU disposition
  - 7,950 MT
  - Subject to IAEA Safeguard inspection
- Depleted uranium (DU)
  - Approximately 7 times more mass than fuels (25,640 x 7 = 180,000 MT)
  - Subject to IAEA Safeguard inspection
- Mill Tailings

Aftermath of Fukushima (3)
Vulnerability of energy supply

- All operable reactors are currently out of service.
- Very successful energy saving efforts in summer (2011 - 2013), but …
- More fossil fuel consumption
  - Costing extra 4 trillion yen (50 Billion USD) a year
  - Emitting extra 175 Million ton CO_2 a year

Increase in Imports of Fossil Fuels

Natural gas import (Trillion Yen)

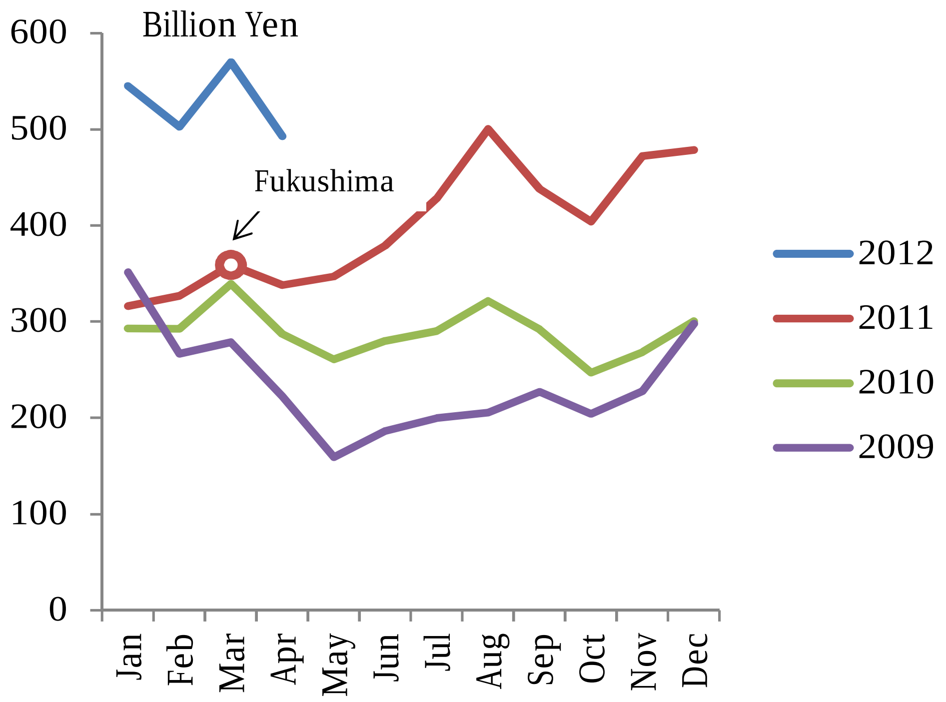
FY2009：2.9　FY2010：3.5　FY2011：5.4 About 2 trillion yen increase

Oil import (Trillion Yen)

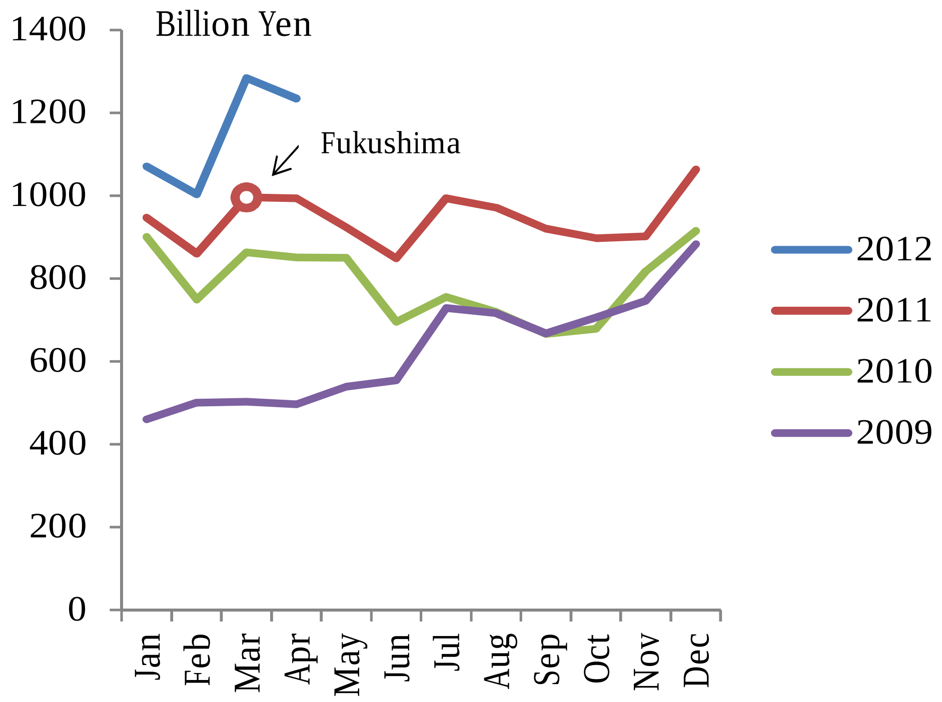
FY2009：8.5　FY2010：9.7　FY2011：11.8 About 2 trillion yen increase

Total 4 trillion yen increase!

Natural gas import

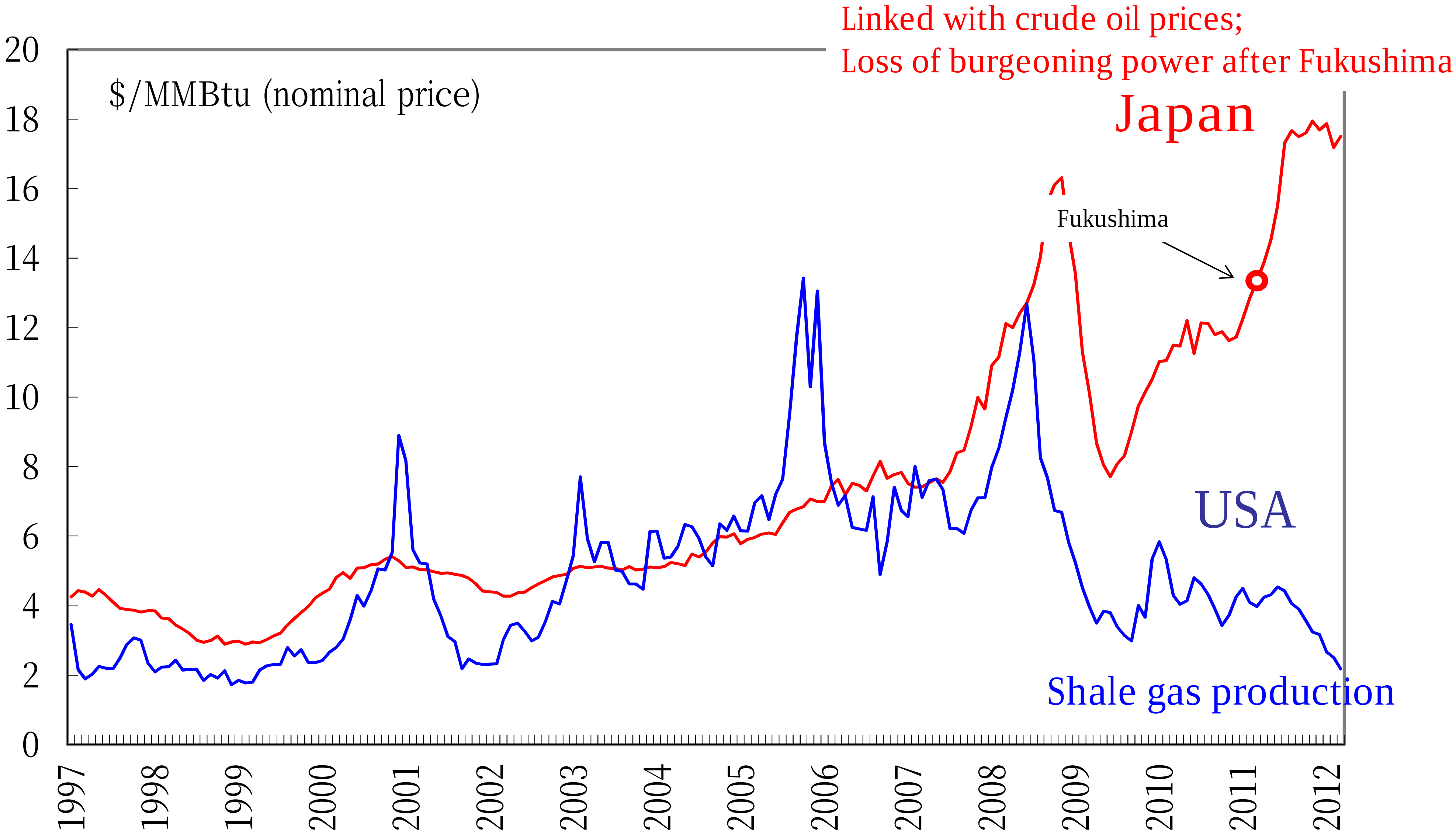


Oil import



Sources: 1) Ministry of Finance: Monthly Trade Report, 2) METI: Monthly Statistics on Resources and Energy

Natural gas prices

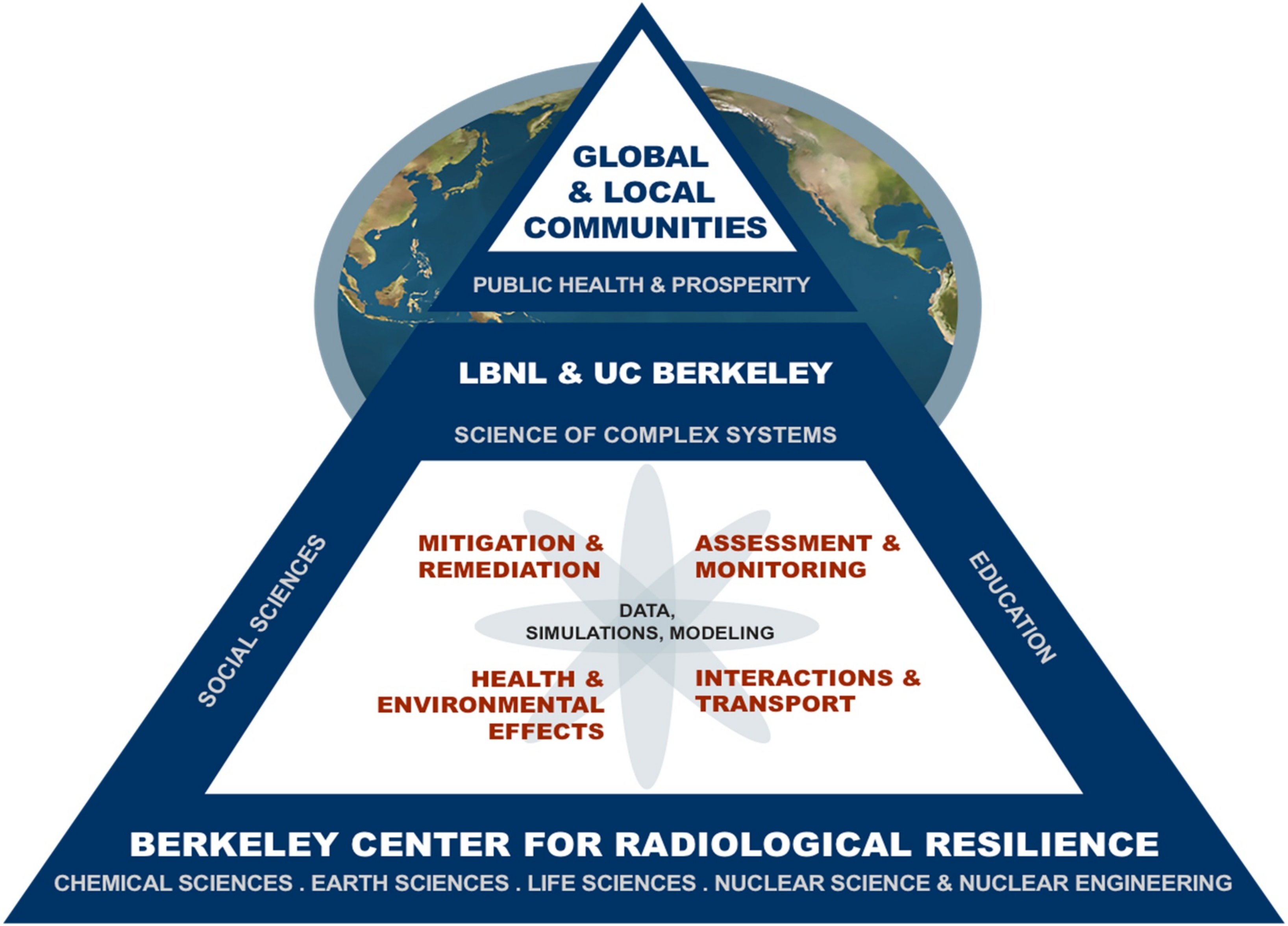


(Sources) EIA/DOE, ministry of Finance: Monthly Trade Report

Securing stable and safe energy supply based on objective risk management.

- Risk management is “triage” (prioritization of risks taken)
- For “triage” to be agreed by the society, social trust for decision making processes and technologies must be rebuilt.
- For that,
  - Establishing scientific basis for resilience
    - Right understanding about “defense in depth,” particularly, about the 5th level defense, with
    - Comprehensive understanding about “damages” of a severe accident to be imposed on various stakeholders in the society
  - Establishing a strategy for legacy materials management
    - New motive/objective for nuclear technologies

An initiative for establishing scientific basis for radiological resilience is being launched in Berkeley.



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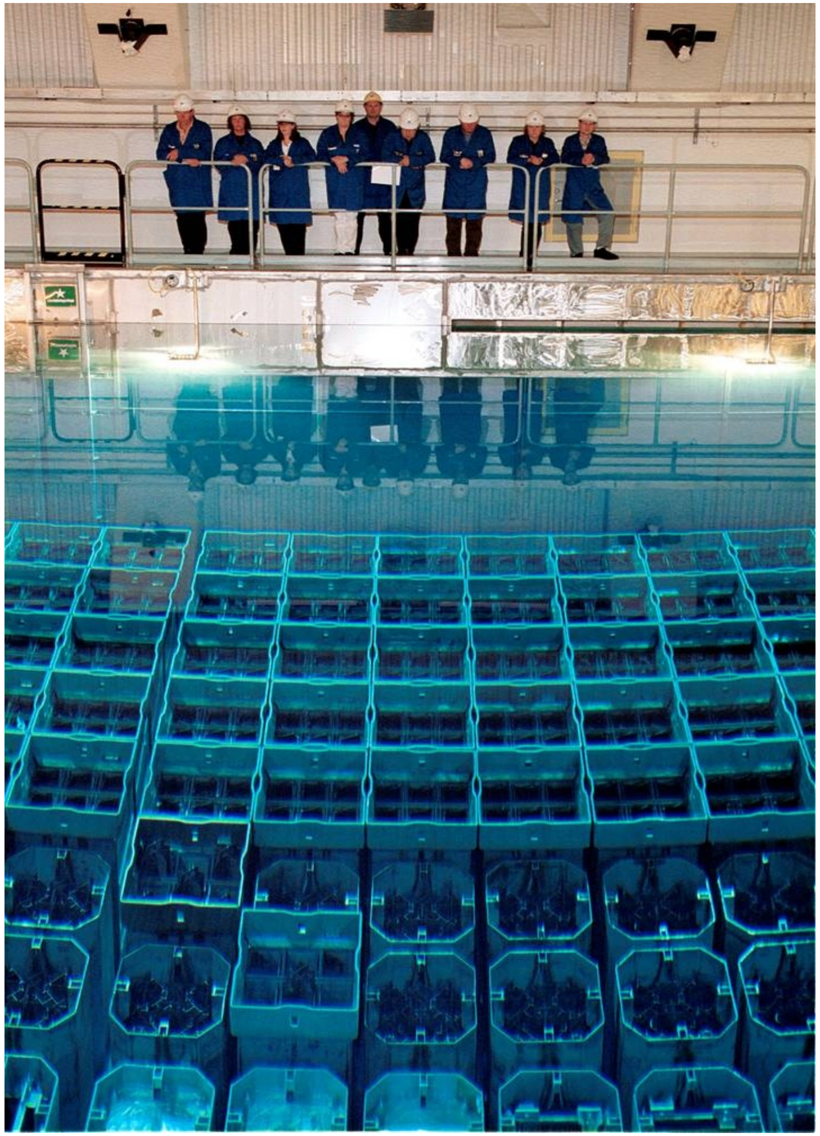
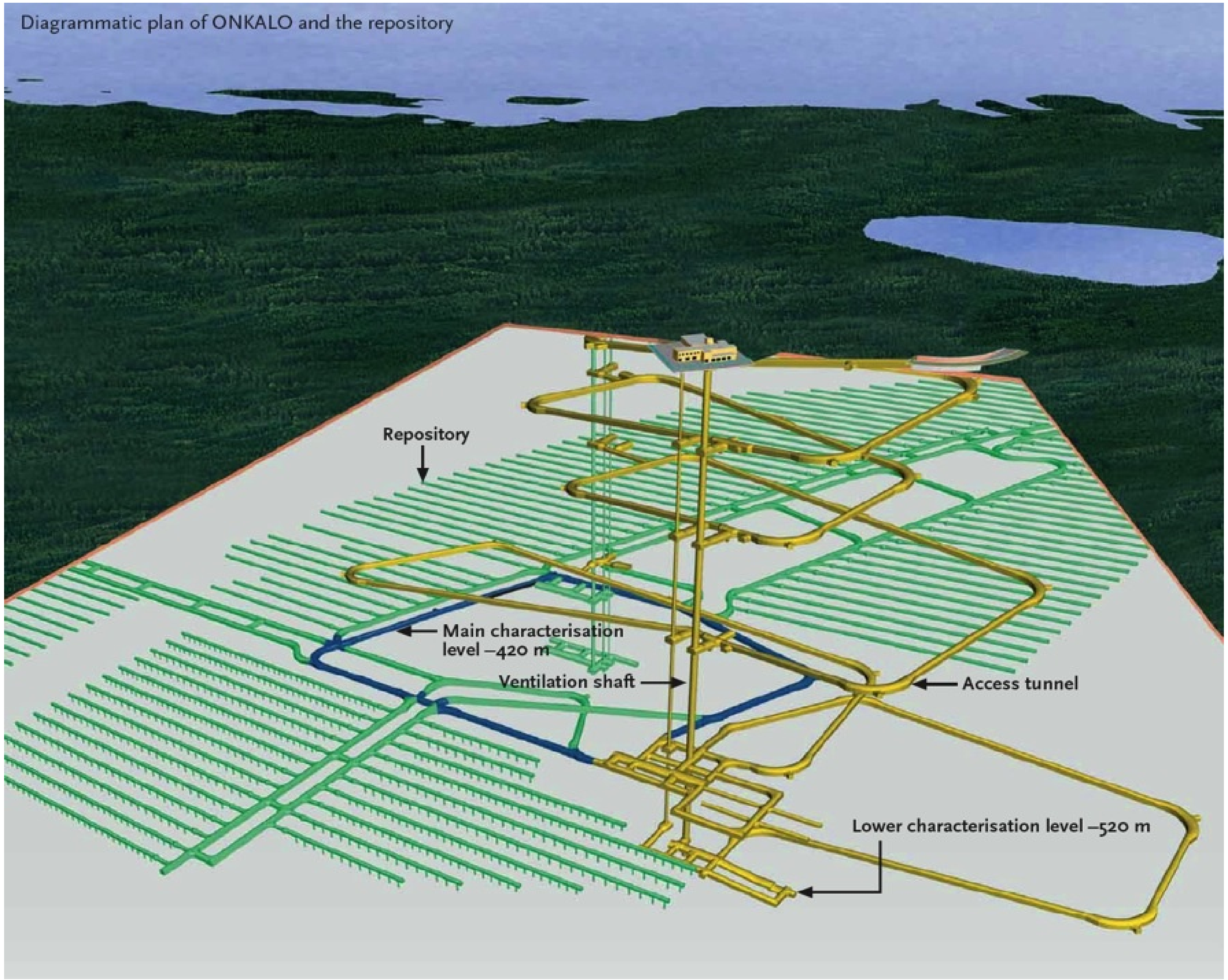
Interim Storage of Spent Fuel

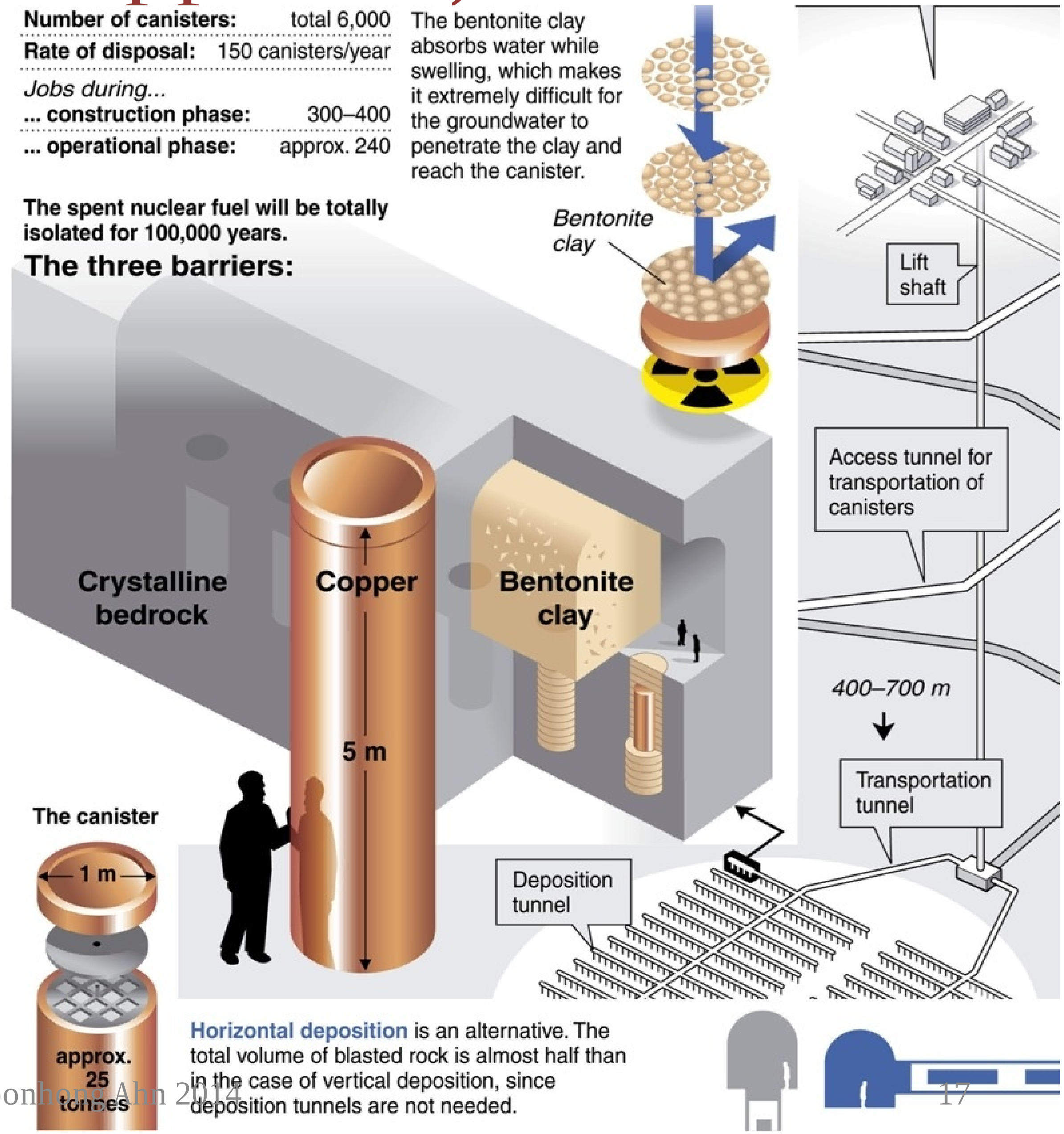


Finland

- Direct disposal of spent fuels
- Site: Olukiluoto (2000), Posiva
- 6,500 ton
- ONKALO facility (2004 – 2011)
- Construction: till 2020
- Disposal (2020-2090)
- Decommissioning (2090 --)



Spent Nuclear Fuel repository (Swedish approach)



Waste Isolation Pilot Plant　(USA)

New Mexico
過去の核兵器製造などの過程で発生した廃棄物のための処分場

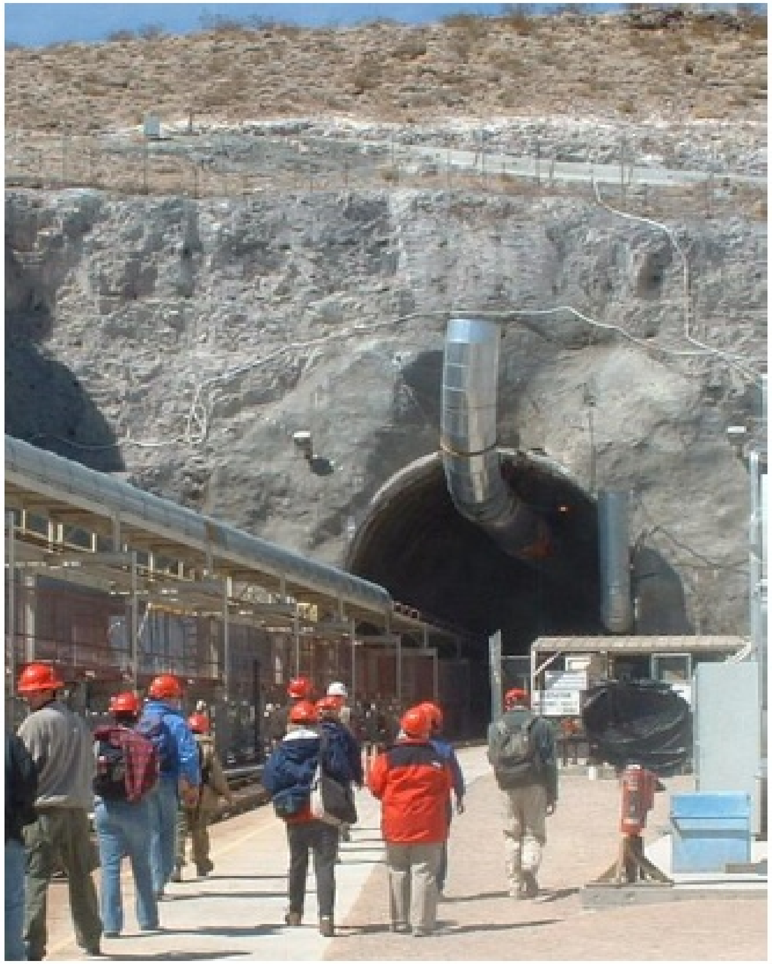
Basic concept of geological disposal system

- Geological disposal consisting of the waste form, the engineered barriers, and the natural barriers can limit the release of radioactivity into the biosphere below sufficiently low level.
- With stability in a geological time scale, long-term robustness and safety of the system can be reasonably expected without human actions after final closure.
- Thus, cost estimate can be made within a scope of finite time.

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（日本原子力学会誌）, November 2011.
  - Clifford Singer, *Energy Policy*, 61(2013) 1521–1528
- Japan 2012 (Science Council's recommendation)
  - J. Ahn, *Kagaku*（科学）, Iwanami岩波書店, October, 2013
- South Korea 2013 (Deadlocked in US-ROK 123 agreement negotiation)
  - J. Ahn, To be published

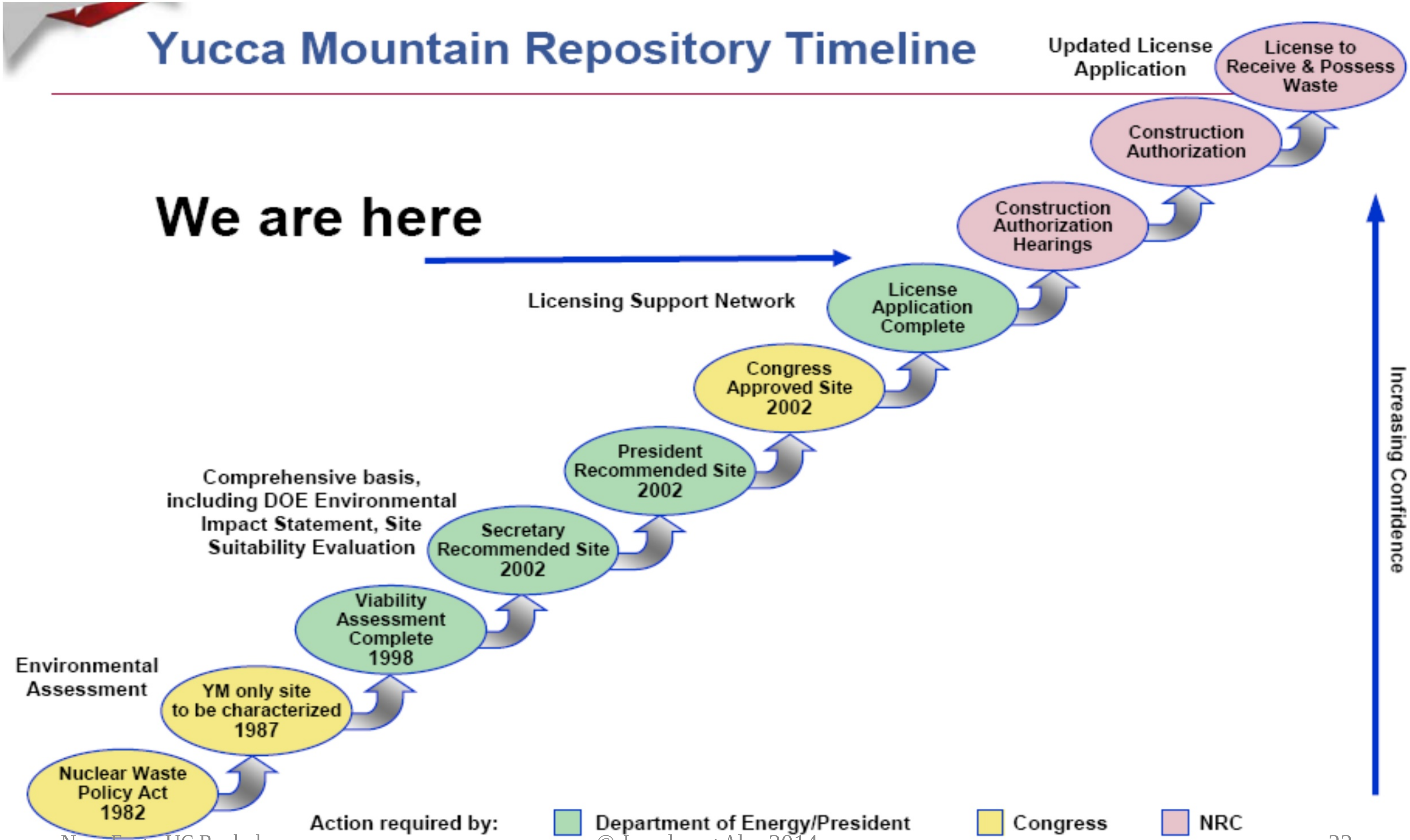
Yucca Mountain



Entrance to Exploratory Studies Tunnel

View of tunnel showing carbon steel support structure and railroad tracks

Miles stones as of 2008



License Application by DOE, submitted to NRC

Department of Energy
Washington, DC 20585

QA: N/A
Project No. WM-00011

June 3, 2008

HAND DELIVERY

ATTN: Document Control Desk
Michael F. Weber, Director
Office of Nuclear Material Safety and
Safeguards
U.S. Nuclear Regulatory Commission
EBB-2B2
11545 Rockville Pike
Rockville, MD 20852-2738

YUCCA MOUNTAIN REPOSITORY LICENSE APPLICATION (LA) FOR CONSTRUCTION AUTHORIZATION

Dear Mr. Weber:

Pursuant to Section 114(d) of the Nuclear Waste Policy Act, as amended, and 10 C.F.R. Part 63, and in accordance with 10 C.F.R. § 2.101, the U.S. Department of Energy (DOE) hereby submits the unclassified part of its Yucca Mountain Repository LA (Enclosure 1) to the U.S. Nuclear Regulatory Commission (NRC). The DOE initially seeks construction authorization pursuant to 10 C.F.R. § 63.31 for a high-level radioactive waste repository at a geologic repository operations area at Yucca Mountain in Nye County in the state of Nevada. To the extent that portions of the LA are based upon the NRC's proposed revisions to 10 C.F.R. Part 63 (70 Fed. Reg. 53,313), the DOE will provide a revision to the LA as the NRC or DOE determine to be necessary. DOE anticipates providing the NRC with an update to the LA prior to requesting a "Receive and Possess" license pursuant to 10 C.F.R. § 63.24.

DOE prepared the LA in accordance with the requirements set forth in 10 C.F.R. § 63.21, "Content of Application," and the guidance contained in the "Yucca Mountain Review Plan," NUREG-1804, Revision 2, Final Report (July 2003) (YMRP). DOE is submitting the LA to the NRC, in both paper and electronic format (i.e., DVD), three (3) copies of the unclassified LA for the Director of the Office of Nuclear Material Safety and Safeguards, as required by 10 C.F.R. § 63.22(a), and an additional thirty-one (31) copies of the LA, as required by 10 C.F.R. § 63.22(b).

NMSS 25

Printed with soy ink on recycled paper

Senator Harry Reid

NRC Chair Gregory Jaczko

Energy Secretary Steven Chu

人が20秒で死亡 150万ミリシーベルト 10万年かけ低減

核のごみ 地層処分ムリ

（会長・大西隆東大大学院教授）が解決の糸口を探るため二年前に議論を開始。だが今月上旬に出した結論は、地下深くに埋める現行の処分方針では安全性の確保も受け入れ先を見つけるのも難しく、方針転換が必要との内容で、一から考え直すことを提起した。近く報告書をまとめるが、将来に負の遺産をつけ回す原発の最大の問題点があらためて浮かんだ。（榊原智康）

毎時一五〇〇シーベルト（一五〇万ミリシーベルト）と人がわずか二十秒で死に至る放射線を放つ高レベル放射性廃棄物は、処分がやっかいだ。国は二〇〇〇年に関連法を制定し、廃棄物をガラスで固め、地下三百メートル以上の地層に埋める「地層処分」方式を採用した。しかし、処分場の受け入れ先はまったくめどが立っていない。

何とか打開策を見いだそうとした原子力委は一〇年、学術会議に知恵を出してもらうよう頼んだ。

「研究者の国会」とも呼ばれる日本学術会議は、人文、社会、自然科学などの研究団体から選ばれた会員でつくる。今回の「核のごみ」問題では、原子力工学や地質学、歴史、社会、経済などさまざまな分野の研究者で検討委を組織し、議論を続けてきた。

日本学術会議でも解決見えず

核のごみの放射線レベルが十分に下がるまでには約十万年という想像もできないような時間がかかる。

日本はもともと地震や火山活動が活発なことに加え、議論を始めた後、東日本大震災が発生し地殻変動も活発化している。

検討委は、そんな現実の中で、十万年間安全だと説明しても住民の理解は得られないとみて、地層処分からの方針転換を議論。五十～数百年にわたって暫定的に貯蔵し、その間に抜本的な解決策を探る、と先送りの案も浮上した。

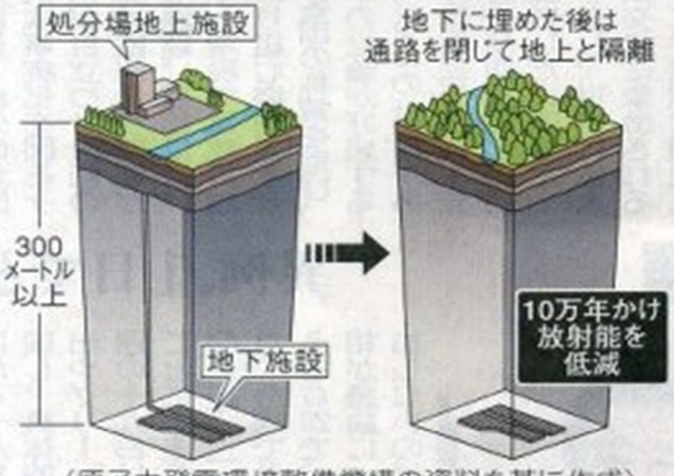
「将来世代にごみを送り続けるのは現代人のエゴだ」「未来の人類の知恵にすがらなければ、最終的な決定ができないとわれわれの限界を認めなければならない」

今月七日の検討委でもさまざまな意見が出た。結局、一致したのは、地層処分では住民理解は進まず、行き詰まりは解消されない－ということだった。

検討委は八月下旬にも報告書をまとめ、原子力委に提出する予定。検討委員長の今田高俊東京工業大教授（社会システム論）は「脱原発を進めても核のごみ問題の議論は避けられない。われわれの検討結果が、国民的な議論を呼び起こすことを期待している」と話している。

めどが立たない 核のごみ処分

現行の地層処分のイメージ



（原子力発電環境整備機構の資料を基に作成）

Hurdles for Geological Disposal

- The issue has been boiled down to "how to develop/reach public agreement."
- Distrust and skepticism against the organization and the process.
  - Aversion to authoritarian "Decide-Announce-Defend" approach

Emerging conceptual issues on geological disposal

- Particularly in Japan after Fukushima, the concept of geological disposal itself seems not supported by the public or by the academic community outside of nuclear engineering.
- Natural Barrier or Environmental contamination
  - If radioactivity is released from the engineered barriers, it is already failure of the disposal system.
  - Success of WIPP
- Severe scenarios
  - Geological, hydro-geological, and geochemical
  - "Unknown unknowns" (Alison Macfarlane)
    - Geology is retrodictive, not predictive.

Why difficult for public agreement?

- Lack of <u>reversibility</u> in siting process
  - Adaptive, staged approach
  - Feedback loop between social discussions and technology development
- Dilemma between <u>convergence</u> and sustainable use of nuclear power
  - “Footprint” issue
- Coupling between
  - long-term and near-term issues
  - Domestic and international issues

US has many (too many?) potential options,

- Wide variety in geological conditions
- Large territory
- Wide variety in technological options
- No international constraints as a weapons country
- Active interactions among law makers, policy makers, regulators, and academia
- BUT,
  - Interactions have been confrontational, sometimes hostile,
  - its own nonproliferation policy allows US to consider only direct disposal, 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.

“Footprint” issue
Conflict between Convergence and Sustainability

- Spent fuel continues to accumulate as long as nuclear power is utilized.
  - Radioactivity will not reach a steady state as long as nuclear power is generated.
  - Its hazard potential will last much longer than the use of nuclear energy.
- Therefore, the repository footprint expands accordingly.
  - <u>(perception issue)</u> The public would not consider this as a solution, but rather considers 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.

Coupled issues in SF management

- Short term ➔ Long term
  - Overall *performance* of the whole scheme 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 ➔ International
  - Failure in consuming recovered fissile materials may cause international skepticism.
- International ➔ Domestic
  - International and bilateral treaties define framework for fuel-cycle options.

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.

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Requirements for advanced options

- An inherently safe reactor
  - Its safety depends not on the intervention of humans or of electromechanical devices but instead depends on immutable and well-understood laws of physics and chemistry. (A. M. Weinberg and Irving Spiewak, *Science*, 1984)
- An economically competitive reactor
  - Low capital cost (small or medium sized reactor?)
  - High burn up
  - High thermal efficiency (less waste; less cost?)
- Robust forms of fuel for safety and safeguard
  - During irradiation,
  - interim storage and
  - final disposal
- Simple fuel cycle for higher proliferation resistance and less cost
- Smooth transition from the current fuel cycle and LWRs fleet
- Flexible and timely inventory control for fissile materials
  - Avoid unnecessary build-up of weapons-usable materials
- Higher level of safety and safeguardability for geological disposal.
  - Severe scenarios (unknown unknowns)

Advanced options

- Thermal neutron systems
  - High-Temperature Gas-Cooled Reactor (HTGR)
- Fast neutron systems
  - Fission reactors (SFR, IFR, ...)
  - Accelerator-driven system
  - Fusion
- Deep bore-hole disposal

Deep-Burn TRISO Fuel Scheme

90kg graphite per fuel element

5,000-10,000 TRISO per compact

3,000 Compacts per element

Adapted from
C. Rodriguez, et al. “Deep-Burn: making nuclear waste transmutation practical.” Nuclear Engineering and Design 222 (2003)

HTGR as Pu Burner

- thermal efficiency > 40%
- 90 ~ 120 GWday/MT
- Reactor with Inherent safety
  - Negative reactivity coefficient with temperature (stops chain reactions)
  - Low power density and robust fuel forms (cools reactor core naturally)
    - No melt down
    - No significant radiation release in accident
  - Demonstrate by actual test
- Deep burn of Pu-239
  - > 90% of Pu-239 is burnt by once-through
  - Possibility for termination of IAEA safeguard inspection for geological disposal
- High durability of graphite-TRISO fuel in virtually any geological conditions
  - Relaxation of temperature constraints for engineered barriers in a geological repository (higher density, i.e. smaller footprint; simpler repository design)

SFR as U burner (or Pu breeder)

- RepU and DU in the blanket → Pu.
- It increases short-term proliferation concern.
  - Creating Stockpile
  - Increasing interest in Pu breeding in emerging countries (technology proliferation)

HTGR vs. SFR

- Both the HTGR (utilizing thermal neutrons) and the SFR (utilizing fast neutrons) can destroy Pu, Np and Am. However, the quality of destruction is different.
- The HTGR can burn:
  - rapidly due to high cross sections with thermal neutrons,
  - deeply due to very high fuel burnup thanks to high material durability, but
  - somewhat incompletely due to unfavorable fission-to-capture ratios.
- The SFR can burn:
  - slowly due to small cross sections with fast neutrons,
  - lightly due to relatively low burnup particularly with metal fuel, but
  - completely due to favorable fission-to-capture ratios.
- Thus, it will be ideal to construct a system that integrates both types of reactors.

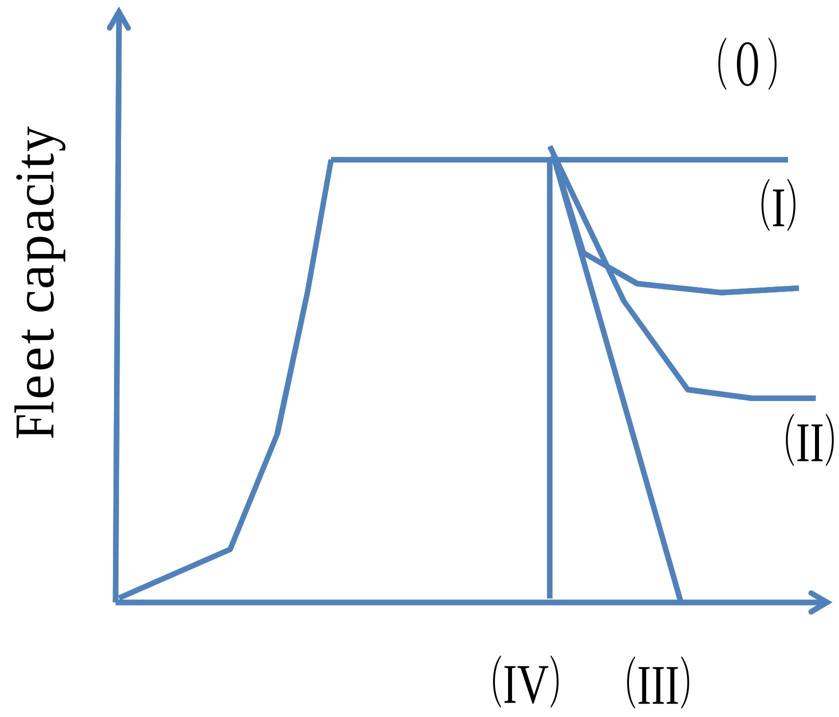
Contents

Multifaceted PA

- In the first round, "cost" comparison should not be the primary viewpoint.
  - Remember Muskie Act 1970.
  - The central question is, 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.

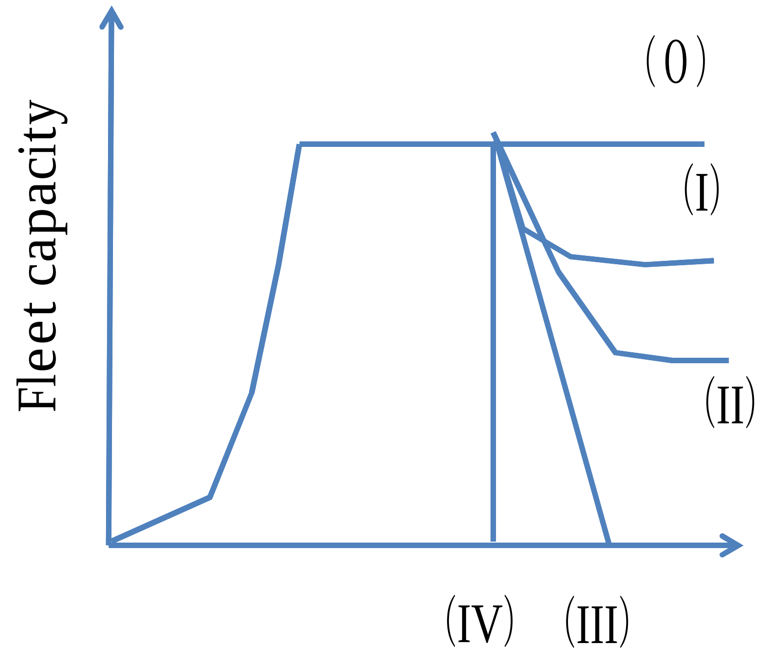
Options

- 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

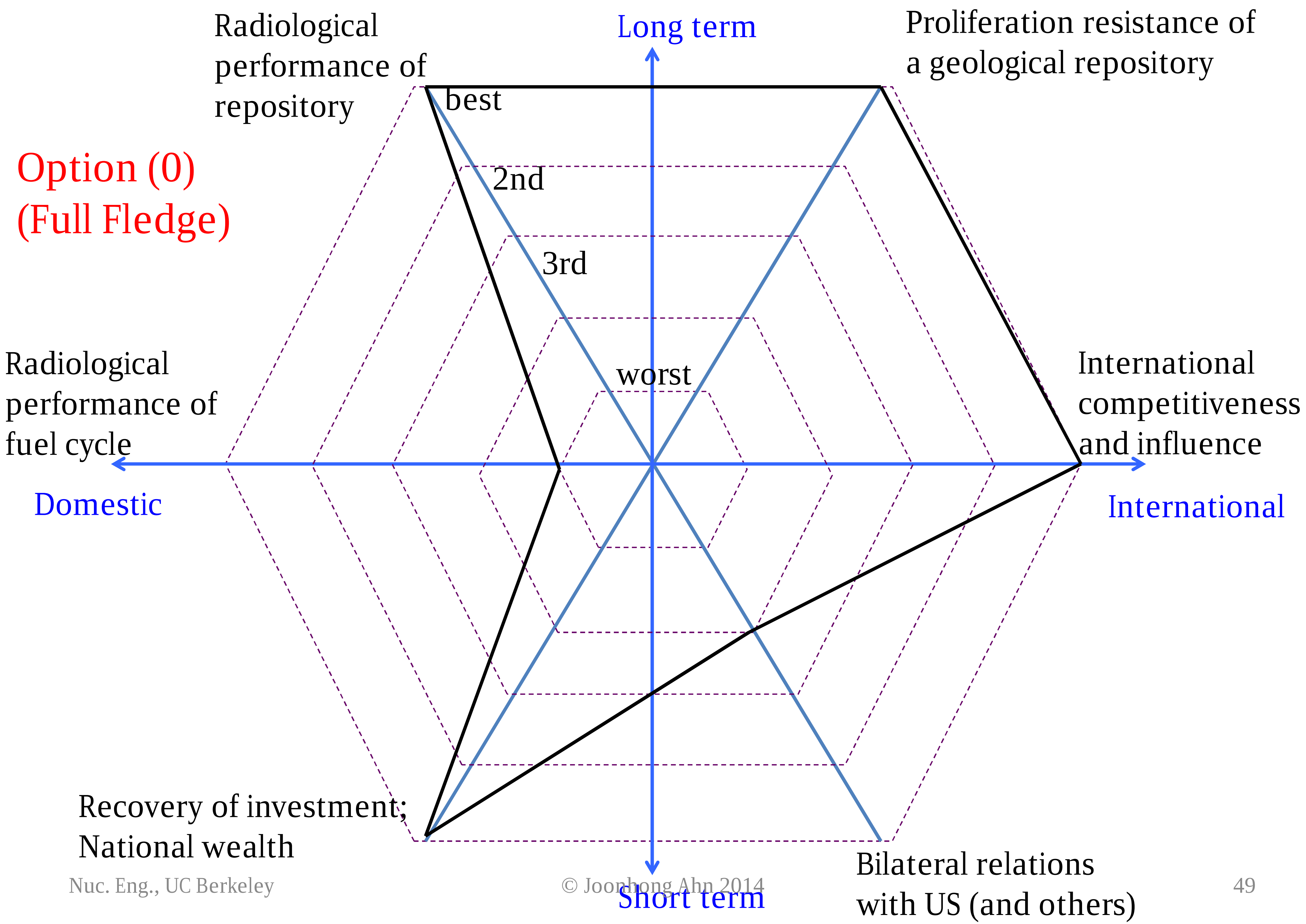
Performance Viewpoints (Domestic)

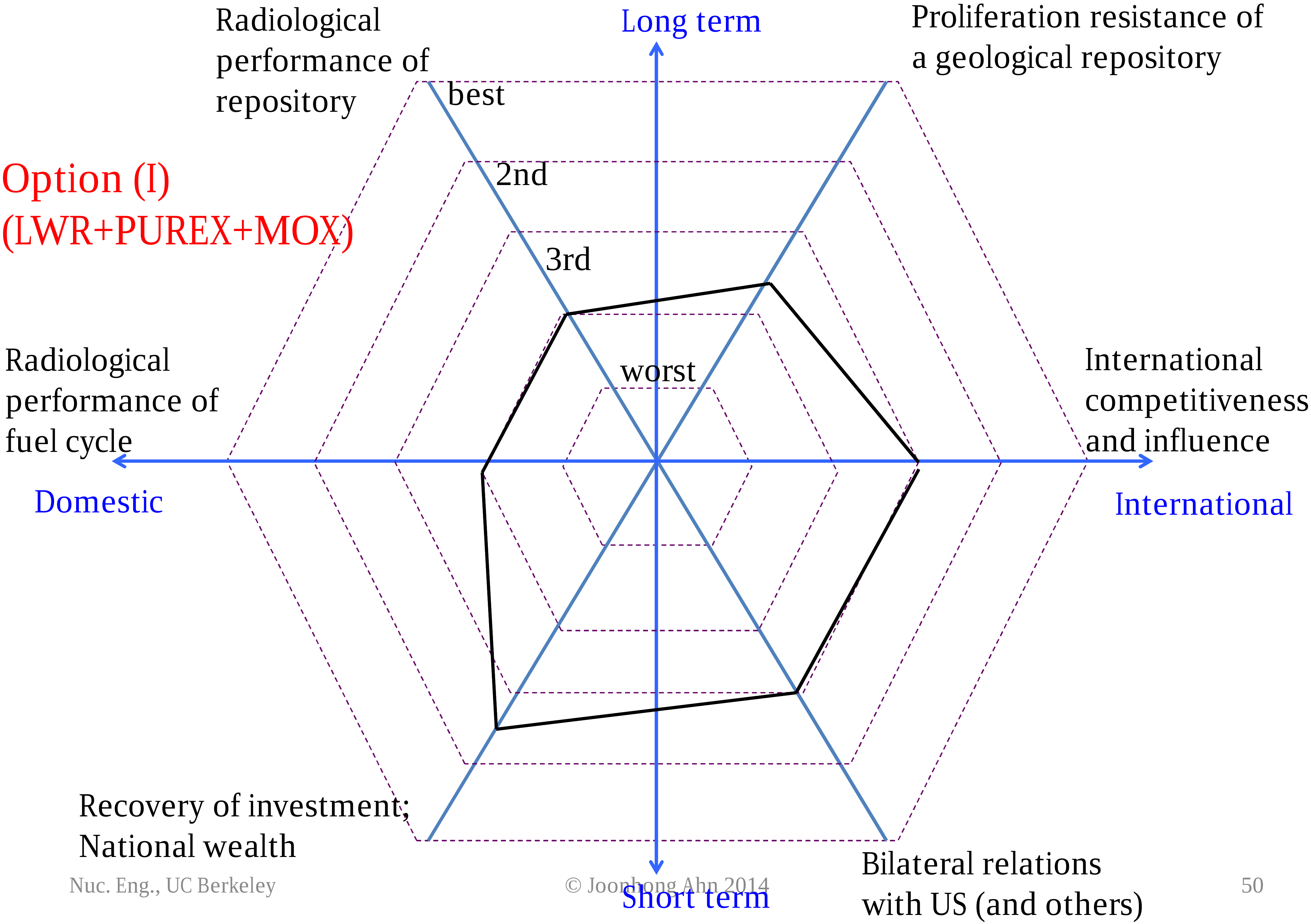
- Radiological performance of repository
  - difficulty for meeting regulatory requirements;
  - radiological risk resulting from a severe accident.
- Radiological performance of fuel cycle
  - complexity of processes and activities included in respective options, and so
  - amount of regulatory work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

Performance Viewpoints (International)

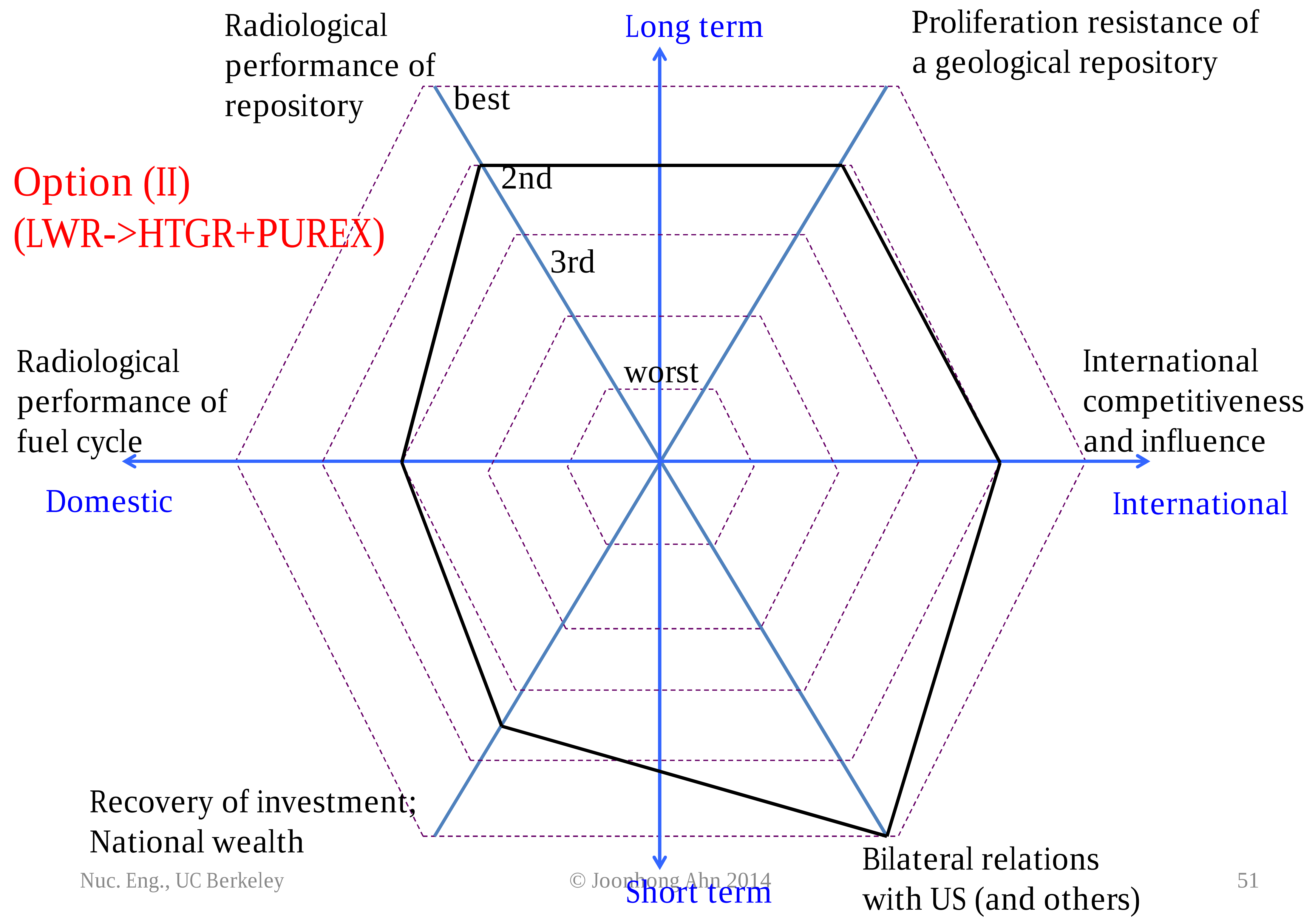
- Proliferation resistance of a geological repository
  - attractiveness as weapons-usable materials.
- International competitiveness and influence
  - Economical, technological, political
- Bilateral relations with US (and others)
  - Pu stockpile

Option (0)
(Full Fledge)

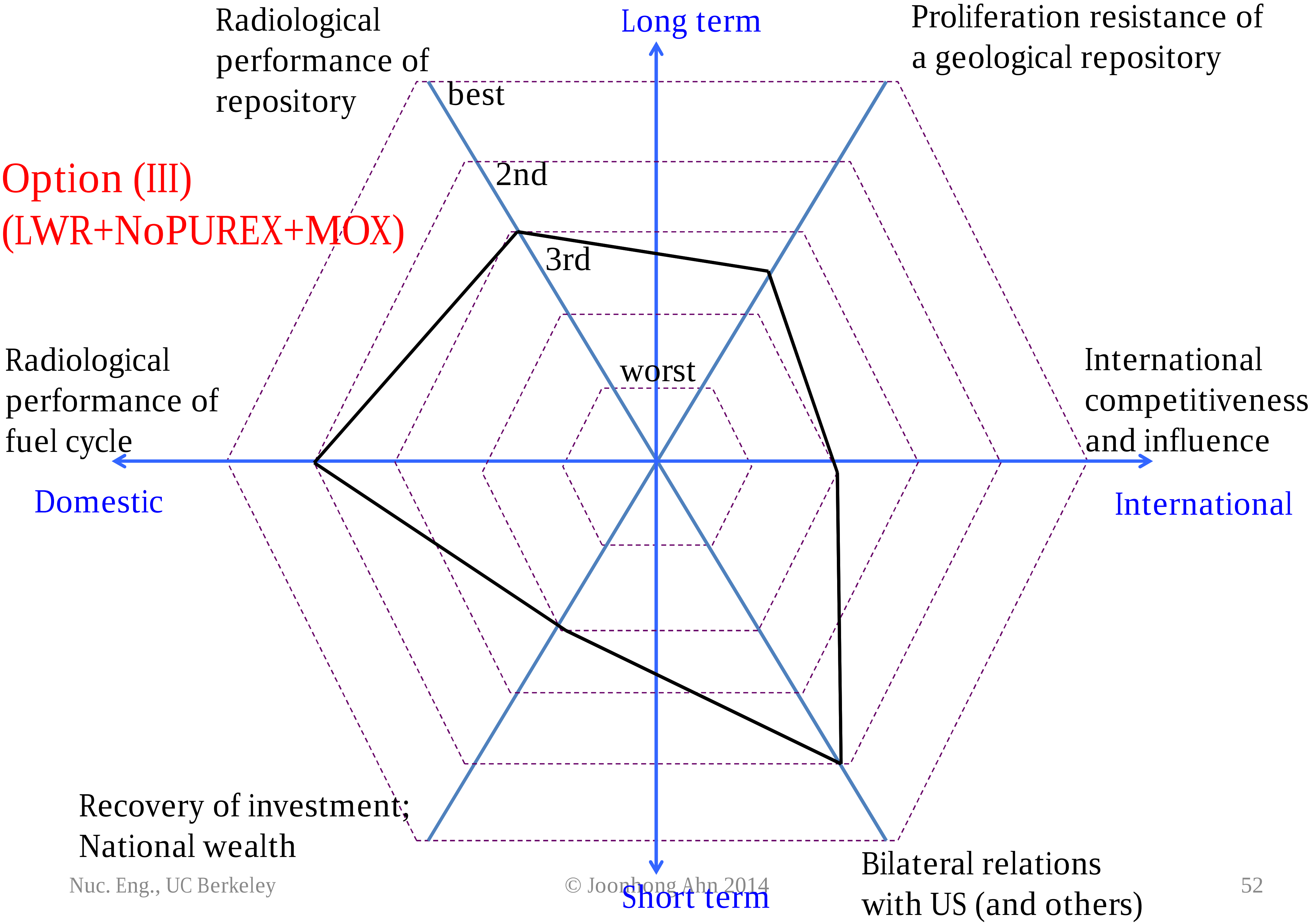



Radiological performance of repository
Long term
Proliferation resistance of a geological repository
Option (I) (LWR+PUREX+MOX)
best
2nd
3rd
worst
Radiological performance of fuel cycle
International competitiveness and influence
Domestic
International
Recovery of investment; National wealth
Bilateral relations with US (and others)
Short term

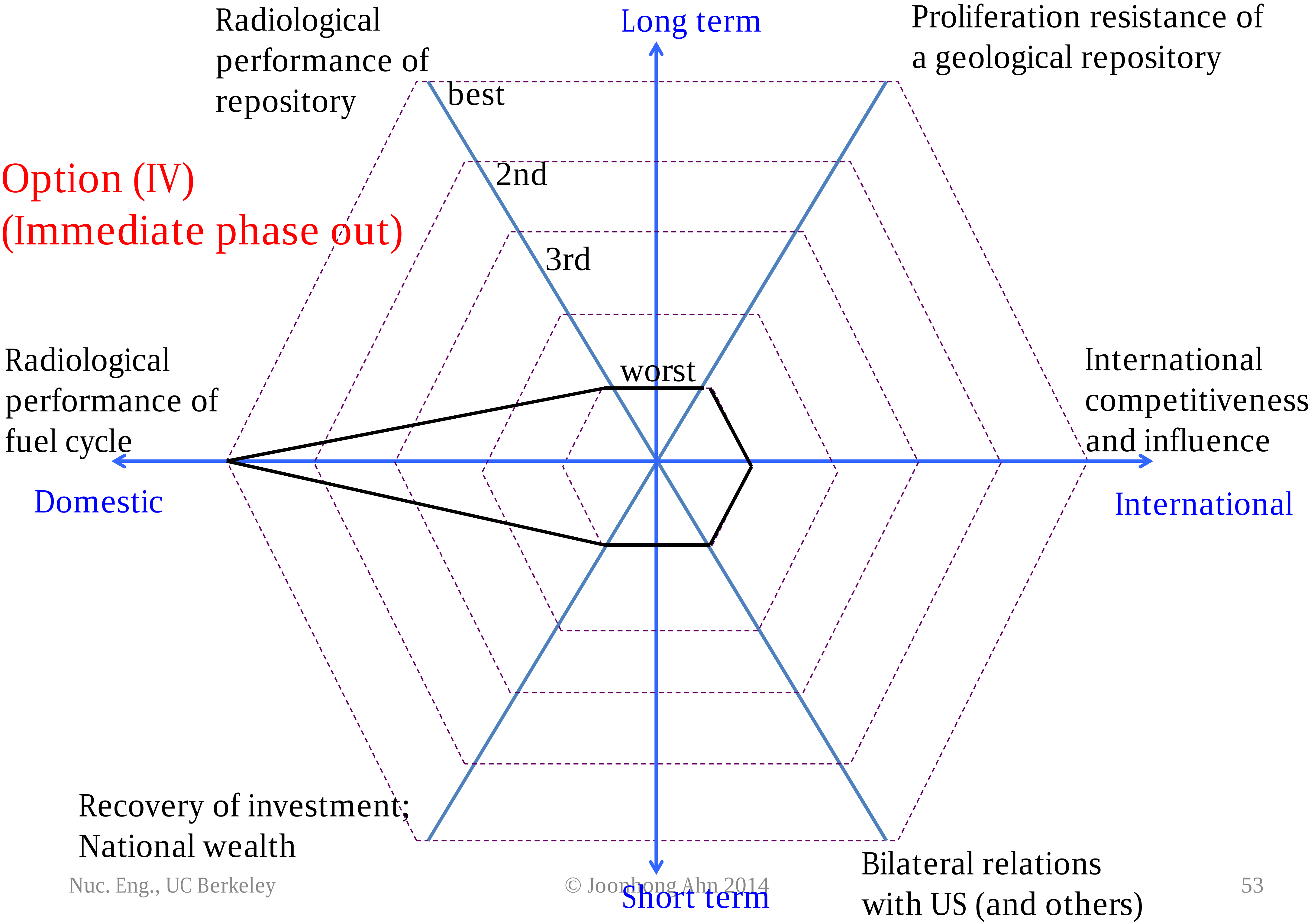
Option (II) (LWR->HTGR+PUREX)



Option (III)
(LWR+NoPUREX+MOX)



Option (IV)
(Immediate phase out)



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.

Contents

- Prologue
- Status quo for spent fuel management
- Technological options available
- Multifaceted performance assessment
- Closing thoughts

Closing thoughts (1)

- The accident should be characterized more as failure of social/organizational systems than as failure of technological systems.
  - Japan's nuclear community did not develop good social-scientific understanding about nuclear power utilization.
  - Nuclear power utilization was isolated from people and controlled primarily by technocrats.
  - Social scientists did not pay attention, or did not give objective analyses
- Establishing scientific basis for resilience is necessary.
  - Right understanding about "defense in depth," particularly, about the 5th level defense, with
  - Comprehensive understanding about "damages" of a severe accident to be imposed on various stakeholders in the society.
- Establishing a strategy for legacy materials management is necessary for redefining new motive/objective for nuclear technologies.

Closing thoughts (2)

- Public participatory decision making process is essential for implementing resilience.
  - Public participatory decision making process needs to be reversible and adaptive.
  - There should be sufficient variety in options available for comparison.
- Technology plays crucial roles in public participatory decision making process by providing greater variety in options, but it must serve for public good.
- To serve for such decision-making process, multifaceted performance assessment for technological options is useful.
  - Performance metrics should be selected, based on in-depth analysis of issues that the society faces, and the goal that the society agrees.
  - Performance assessment should be conducted not only by experts but also by lay people.
  - Metrics, goals, and assessment should be done iteratively.