Spent Fuel from Nuclear Power Reactors

Overview of a New Study by the International Panel on Fissile Materials (IPFM)

Washington DC
3 June 2011
Presentation hosted by
Center for Science, Technology and Security Policy
American Association for the Advancement of Science
Overview

Frank von Hippel, Princeton University
Co-Chair, IPFM
## Country Studies

<table>
<thead>
<tr>
<th>Country</th>
<th>Author(s)</th>
<th>Rank (GWe)</th>
</tr>
</thead>
<tbody>
<tr>
<td>United States</td>
<td>Frank von Hippel</td>
<td>1</td>
</tr>
<tr>
<td>France</td>
<td>Mycle Schneider</td>
<td>2</td>
</tr>
<tr>
<td>Japan</td>
<td>Tadahiro Katsuta and Masafumi Takubo</td>
<td>3</td>
</tr>
<tr>
<td>Russia</td>
<td>Anatoli Diakov and Pavel Podvig</td>
<td>4</td>
</tr>
<tr>
<td>Germany</td>
<td>Beate Kallenbach-Herbert</td>
<td>5</td>
</tr>
<tr>
<td>South Korea</td>
<td>Jungmin Kang</td>
<td>6</td>
</tr>
<tr>
<td>Canada</td>
<td>M.V. Ramana</td>
<td>8</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>Gordon MacKeron, Frans Berkhout</td>
<td>9</td>
</tr>
<tr>
<td>Sweden/Finland</td>
<td>Johan Swahn</td>
<td>11/14</td>
</tr>
<tr>
<td>Multinational Repositories</td>
<td>Hal Feiveson, M.V. Ramana</td>
<td>None</td>
</tr>
</tbody>
</table>
Topical Studies

Spent fuel inventories and characteristics
  – *Hal Feiveson* (Princeton)

Interim storage and transport
  – *Frank von Hippel* (Princeton)

Geological storage
  – Rodney Ewing (U. Michigan, Ann Arbor)

International (IAEA) monitoring
  – Thomas E. Shea (IAEA, retired)
Today’s fuel cycles: Once-through and reprocessing

30% of civilian spent fuel has been reprocessed – mostly by France & UK
Some observations from the 10 country studies

1. Reprocessing does not increase success in repository siting
2. For siting, consultation works better than top-down decisions
3. Favorable geology, waste packaging and backfill are all important and reversibility is important for some countries
4. Dry cask interim storage is becoming prevalent
5. No country is yet willing to take foreign spent power reactor fuel without reprocessing
6. Multinational repositories will have to wait on national ones
7. For some countries a nuclear phase-out decision may help with repository siting
### Reprocessing doesn’t help

<table>
<thead>
<tr>
<th>Country</th>
<th>Reprocessing?</th>
<th>Repository Siting Stage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Canada</td>
<td>No</td>
<td>Restarting</td>
</tr>
<tr>
<td>France</td>
<td>Yes</td>
<td>Early</td>
</tr>
<tr>
<td>Germany</td>
<td>No</td>
<td>Disputed site</td>
</tr>
<tr>
<td>Japan</td>
<td>Yes and no</td>
<td>Starting</td>
</tr>
<tr>
<td>South Korea</td>
<td>Considering</td>
<td>Zero</td>
</tr>
<tr>
<td>Russia</td>
<td>Yes</td>
<td>Zero</td>
</tr>
<tr>
<td>Sweden/Finland</td>
<td>No</td>
<td>Sited but not licensed</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>Yes</td>
<td>Restarting</td>
</tr>
<tr>
<td>United States</td>
<td>No</td>
<td>Zero for spent fuel operating for plutonium waste</td>
</tr>
</tbody>
</table>

1996 NAS study concluded benefits of “separation and transmutation” of long-lived radioisotopes in spent fuel would be small and costs would be huge.
Consultation works
Top down policy making ends up as
Decide, Announce, Defend, Abandon (DADA)

<table>
<thead>
<tr>
<th>Country</th>
<th>Repository Siting Stage</th>
<th>Consultation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Canada</td>
<td>Restarting</td>
<td>Early</td>
</tr>
<tr>
<td>France</td>
<td>Early</td>
<td>Yes</td>
</tr>
<tr>
<td>Germany</td>
<td>Disputed site</td>
<td>No</td>
</tr>
<tr>
<td>Japan</td>
<td>Starting</td>
<td>Being attempted</td>
</tr>
<tr>
<td>South Korea</td>
<td>Low/intermed-level waste (LILW) storage sited</td>
<td>In final successful effort for LILW repository</td>
</tr>
<tr>
<td></td>
<td>HLW: Zero</td>
<td>--</td>
</tr>
<tr>
<td>Russia</td>
<td>Zero</td>
<td>--</td>
</tr>
<tr>
<td>Sweden/Finland</td>
<td>Advanced</td>
<td>Completed</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>Restarting</td>
<td>Early</td>
</tr>
<tr>
<td>United States</td>
<td>Succeeded for WIPP</td>
<td>Forced by Congress for WIPP</td>
</tr>
<tr>
<td></td>
<td>Failed for Yucca Mt.</td>
<td>Congress selected Yucca Mt.</td>
</tr>
</tbody>
</table>
Long-term reversibility may be needed

**U.S. Nuclear Waste Policy Act:** “any repository…shall be designed and constructed to permit the retrieval of any spent nuclear fuel placed in such repository, during an appropriate period of operation of the facility, for any reason pertaining to the public health and safety, or the environment, or for the purpose of permitting the recovery of the economically valuable contents of such spent fuel.”

**Canada:** current plan is to have storage be reversible for 240 years after the opening of a repository.

**France:** guaranteed reversibility for at least 100 years as license condition.

**Germany:** Considering retrieval of waste from “experimental” Asse site.

But reversibility may reduce geological barrier to proliferation.
Defense in depth – even under ground

Waste packaging, backfill and geology all need to be right. France has chosen a clay bed. Sweden and other countries propose a copper cask surrounded by clay.

Yucca Mt. first thought dry but then recognized as wet. Plan to cover fuel packages with titanium drip shields. Very costly way to compensate for poor geology.
Dry cask storage is becoming prevalent

<table>
<thead>
<tr>
<th>Country</th>
<th>On-site</th>
<th>Off-site</th>
</tr>
</thead>
<tbody>
<tr>
<td>Canada</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>France</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Germany</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Japan</td>
<td>Two sites</td>
<td>Under construction</td>
</tr>
<tr>
<td>South Korea</td>
<td>One site</td>
<td>No</td>
</tr>
<tr>
<td>Russia</td>
<td>No</td>
<td>Under construction</td>
</tr>
<tr>
<td>Sweden</td>
<td>No</td>
<td>Underground central storage pool</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>United States</td>
<td>Yes</td>
<td>Blocked</td>
</tr>
</tbody>
</table>
Hosting foreign spent power reactor fuel

France and U.K. reprocess imported spent fuel but return the high-level radioactive waste. Virtually none have renewed.

Russia takes spent fuel from other countries for either:
1. Reprocessing (and has kept the reprocessing waste thus far)
2. “Temporary storage,” which can be converted into reprocessing.

Russia’s law is very “flexible.” Because of public opposition, however, it has so far taken back only Russian-origin fuel provided for a Soviet/Russian supplied reactor.

Russia currently has three customers Bulgaria, Iran and Ukraine. Reactor sale to Iran includes spent-fuel take-back.
Nuclear Spent Fuel Management: Sweden

Johan Swahn
Swedish NGO Office for Nuclear Waste Review, MKG
Nuclear Energy in Sweden

- Sweden has 10 power reactors at three sites.
- \( \approx 40-45\% \) of electricity is nuclear.
- 1980 referendum supported phase-out by 2010 but only two reactors have been shutdown.
- Present Government (conservative-liberal-center) energy policy is split on nuclear. Agrees on promoting renewables.
Nuclear Waste in Sweden

- Medical care, industry, and research
- Low- and intermediate-level waste
- Nuclear power plant
- Final repository for radioactive operational waste (SFR)
- Encapsulation plant
- Central interim storage facility for spent nuclear fuel (Clab)
- Final repository for spent nuclear fuel

SPENT NUCLEAR FUEL
Nuclear Waste in Sweden

CLAB – Underground, intermediate storage of spent nuclear fuel
Site at Oskarshamn nuclear power plant

Source: SKB
The KBS Method

A Swedish method for disposal of spent nuclear fuel has been developed since the early 1970s.

The waste is to be deposited in holes in the floor of tunnels about 500 meters underground in granite bedrock.

Its long-term isolation relies on two artificial barriers – a copper canister and a clay buffer.
Siting process started in mid-1970s but met local resistance and collapsed in 1986. Restarted with a voluntary process.

By late 1990s, search had narrowed to two nuclear communities: Oskarshamn and Östhammar.

June 2009 - Forsmark nuclear power plant (Östhammar) chosen as repository site.
License Application and Review

- Nuclear waste company SKB submitted license application for a repository at Forsmark on March 16, 2011
- Application is being reviewed by the Swedish Radiation Safety Authority and the Environmental Court. Final decision on a license will be taken by the Cabinet.
- Main issues will be
  - Whether the copper cask and the clay fill barriers will behave as modeled in the safety analysis.
  - The ability of the repository to withstand repeated glaciations.
  - The neglect of borehole disposal.
  - Whether an inland site would be better than a coastal site.
Nuclear Spent Fuel Management: Germany

Beate Kallenbach-Herbert, Öko-Institut, Darmstadt, Germany
Overview

17 reactors in operation, total capacity: 21.5 Gwe

Fukushima accident has strongly influenced Germany’s energy policy

30 May - Government reversed policy and announced:

- Final shutdown of 7 oldest reactors plus Krümmel (already shut down after incident in 2007)
- 9 remaining reactors will shutdown by 2022
Waste Management


• Konrad repository for LLW + MLW under construction since March 2006, start of operation expected about 2017

• Onsite interim storage of spent fuel mandatory today

• Interim storage of HLW from past reprocessing at centralized cask storage facility Gorleben.

• Return-shipments of HLW still ongoing
Gorleben exploration mine

Sites

Schacht Konrad repository under construction

Morsleben LAW/MAW repository closure ongoing

Asse (former “research mine“): investigations for waste retrieval ongoing

- Spent fuel interim storage (off site)
- Spent fuel interim storage (on site)
- Nuclear Research Center
- Repository or research mine
- Nuclear Power Plant (in operation)
- Nuclear Power Plant (shut down)
- Nuclear Power Plant (completely dismantled)
Nuclear waste disposal

• Research activities since 1960s focused on disposal of nuclear waste in salt formations.

• **Asse salt mine** was used as research repository for low- and intermediate level waste. Now in trouble. Feasibility assessments for retrieval of over 120,000 barrels of waste under way. Estimated costs $3-5 billion.

• Exploration activities for disposal of high active waste and spent fuel have focused on the **Gorleben salt dome** since late 1970s without decision on the suitability of the site.

• Gorleben controversial because of lack of transparency in site selection process and geology.

• Attempts to start a **new site selection process** have failed.
Spent fuel interim storage

- 2000: “Nuclear Consensus” of Government and electric utilities resulted in agreements to build on-site dry-cask interim storage facilities at each reactor site.
- Planning, licensing and construction of 12 storage facilities was carried out in about 8 years (1998 – 2006).
- Storage licenses are limited to 40 years
- Capacities limited to the expected amounts of spent fuel and restrictions on operating times were points of major interest for regional representatives and public
- The storage is based on robust dual-purpose casks in buildings with passive air cooling.
Spent fuel interim storage

Cross section interim storage facility,
source: EnBW

Castor® Casks in storage facility,
source: GNS

Interim storage Philippsburg,
source: EnBW
Impact of Fukushima accident

A new repository site selection process including possible regions in southern Germany is being discussed by Federal and State Governments.

Experience shows that a decision on a phase-out schedule for nuclear power creates improved conditions for progress on radioactive waste disposal in Germany.

The expansion of renewable energy and of electricity grids will be Germany’s major challenges for the next decade.
Nuclear Spent Fuel Management: Russian Federation

Anatoli Diakov, Pavel Podvig
International Panel on Fissile Materials
## Russian reactor fleet

<table>
<thead>
<tr>
<th>Type</th>
<th>Units</th>
<th>Spent fuel (tons/yr)</th>
<th>Interim Storage</th>
<th>Reprocessing</th>
</tr>
</thead>
<tbody>
<tr>
<td>VVER-440 (LWR)</td>
<td>6</td>
<td>87</td>
<td>no</td>
<td>yes, at RT-1</td>
</tr>
<tr>
<td>VVER-1000</td>
<td>10</td>
<td>210</td>
<td>wet, at RT-2</td>
<td>planned</td>
</tr>
<tr>
<td>RBMK (graphite)</td>
<td>11</td>
<td>550</td>
<td>wet, at reactors, central storage planned</td>
<td>no</td>
</tr>
<tr>
<td>BN-600 (sodium)</td>
<td>1</td>
<td>6.2</td>
<td>no</td>
<td>yes, at RT-1</td>
</tr>
<tr>
<td>EPG-6 (graphite)</td>
<td>4</td>
<td>4</td>
<td>at reactors</td>
<td>no</td>
</tr>
<tr>
<td>Naval, research</td>
<td>80+</td>
<td></td>
<td>some</td>
<td>most types</td>
</tr>
</tbody>
</table>
### Spent fuel of Soviet/Russian-built reactors abroad
*(Finland, Hungary, Slovak Republic no longer ship to Russia)*

<table>
<thead>
<tr>
<th>Type</th>
<th>Units</th>
<th>Spent fuel (tons/yr)</th>
<th>Interim Storage</th>
<th>Reprocessing</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ukraine</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VVER-440</td>
<td>2</td>
<td>30</td>
<td>no</td>
<td>yes, in Russia</td>
</tr>
<tr>
<td>VVER-1000</td>
<td>7</td>
<td>150</td>
<td>Dry on site or sent to Russia</td>
<td></td>
</tr>
<tr>
<td><strong>Bulgaria</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VVER-1000</td>
<td>2</td>
<td>37.5</td>
<td>Sent to Russia</td>
<td></td>
</tr>
<tr>
<td><strong>Iran</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bushehr</td>
<td>1</td>
<td></td>
<td>Sent to Russia</td>
<td></td>
</tr>
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</table>
# Spent fuel storage

<table>
<thead>
<tr>
<th>Sites</th>
<th>Storage type</th>
<th>Capacity (tons)</th>
<th>Fuel in storage (tons)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>VVER sites</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>wet</td>
<td></td>
<td>1,000</td>
</tr>
<tr>
<td><strong>RBMK (graphite) sites</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>wet</td>
<td>12,000+</td>
<td>13,000</td>
</tr>
<tr>
<td><strong>BN-600, AMB site</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>wet, dry</td>
<td></td>
<td>225</td>
</tr>
<tr>
<td><strong>EGP-6</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>wet, dry</td>
<td></td>
<td>140</td>
</tr>
<tr>
<td><strong>Mayak</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>wet VVER-440</td>
<td></td>
<td>380</td>
</tr>
<tr>
<td><strong>Zheleznogorsk</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>wet VVER-1000</td>
<td>8,400</td>
<td>~8,400</td>
</tr>
<tr>
<td>1</td>
<td>dry VVER-1000</td>
<td>11,300 (under construction)</td>
<td>-</td>
</tr>
<tr>
<td>1</td>
<td>dry RBMK</td>
<td>26,500 (under construction)</td>
<td>-</td>
</tr>
</tbody>
</table>
Spent fuel take-back

Fuel of Soviet-built reactors
- Finland, Hungary, Slovakia – shipments stopped
- Bulgaria, Ukraine – shipments continue

Seen as competitive advantage for reactor sales (e.g. Turkey)

Plans for international repository
- 1990s interest in importing foreign-origin spent fuel
- Laws were changed in 2001 to allow import
- Temporary storage and/or reprocessing allowed but not final disposal
- 2006, Rosatom forced by public outcry to announce “no foreign-origin fuel” policy but laws still in force
Reprocessing

- RT-1 Plant, Mayak, Ozersk, Urals
  - Capacity: 400 MT/y
  - Actual load: 100 MT/y
  - VVER-440, BN (breeder), naval and research reactor fuel

- Mining and Chemical Combine, Zheleznogorsk, Siberia
  - Expansion of storage capacity to ~40,000 MT
  - Pilot reprocessing plant ca 2015?
  - New large-scale reprocessing plant in 2020-2025?

- Plutonium to be used in breeders
  - BN-600 operational, BN-800 under construction
  - Plutonium fuel for breeders has not been demonstrated
Nuclear Spent Fuel Management:
United Kingdom

M. V. Ramana
Princeton
IPFM
Reprocessing

MAGNOX spent fuel and significant fraction of AGR fuel reprocessed
Legacy is ~100 tons of separated plutonium and $100 billion cleanup.
Decide, Announce, Defend – and then Abandon (DADA)

Government, nuclear industry and selected scientists:

• Decided on sites
• Announced them
• Defended them against the inevitable opposition, and
• Eventually were forced to abandon them

1970s - drilling program to find sites for HLW disposal ended after intense local resistance.

In 1981, Government decided to shelve HLW policy for 50 years and concentrate on finding sites for low level and intermediate level wastes.
DADA for ILW and Dissolution of Nirex

1982: Set-up Nirex (industry-body) to identify LLW/ILW sites
Late 1980s: 12 sites shortlisted
Settled on a site near Sellafield
1997: Nirex proposal rejected
1999: House of Lords Science and Technology Committee report:
public and stakeholders need to be engaged from the start, and not just to approve after the fact.
Recommended a new Commission to oversee policy
Committee on Radioactive Waste Management (CoRWM)

CoRWM set up in 2003 and told to give “equal weight” to:
- Inspiring public confidence
- Protecting people and the environment

CoRWM members were appointed from diverse backgrounds
- Founding member of Greenpeace UK
- UK nuclear industry scientist
- Chair of UK Equal Opportunities Commission
- Member of the non-government *National Consensus Conference on Radioactive Waste Management*
- Academic social scientists
2006 CoRWM Recommendations and Policy

CoRWM recommended:

• Geological disposal for all legacy HLW and ILW;
• Interim storage, possibly for up to 100 years, as an integral part of policy
• Siting of major new facilities to be based on voluntarism and partnership
• Local communities allowed to withdraw from negotiations up to a pre-determined point if not satisfied with the terms being offered.

Policy impact:

• October 2006: Government accepted all CoRWM’s main recommendations, including the ideas of voluntarism and partnership
• Nuclear Decommissioning Authority established with responsibility for the long-term management of all UK radioactive wastes
Recap

1. Reprocessing does not help.
2. For siting, consultation works better
3. Geology, waste packaging and backfill are all important
4. Dry cask interim storage is becoming prevalent
5. No country is yet willing to take foreign spent power reactor fuel without reprocessing
6. Multinational repositories will have to wait on national ones
7. A nuclear phase-out decision can help with repository siting