Spent nuclear fuel policies in historical perspective: An international comparison

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ABSTRACT

The purpose of this article is to explain why the world’s nuclear power countries differ from each other with respect to their spent nuclear fuel (SNF) policies. The emergence and evolution of three principal SNF approaches are analyzed: direct disposal, reprocessing and SNF export. Five broad explanatory factors are identified and discussed in relation to the observed differences in policy outcomes: military ambitions and non-proliferation, technological culture, political culture and civil society, geological conditions, and energy policy. SNF policy outcomes can generally be seen to result from a complex interaction between these broad factors, but it is also possible to discern a number of important patterns. To the extent that the five factors may undergo far-reaching changes in the future, the historical experience of how they have shaped SNF policies also give a hint of possible future directions in SNF policymaking around the world.

1. Introduction

Issues related to spent nuclear fuel (SNF) belong to the most difficult and controversial fields of nuclear power policy. The debate—both within the nuclear community and in society at large—has been and continues to be characterized by a striking diversity of ideas, proposals and arguments concerning SNF approaches. The remarkable variation across countries with respect to the solutions that have received political backing reflects a lack of internationally accepted ‘best practice’ in SNF management. There have also been considerable changes over time in most countries with respect to their SNF policies. It is possible to discern three principal SNF approaches:

1. Direct disposal implies that the SNF, following a period of interim storage, be transferred to a permanent storage of one or the other kind. In most cases, it would take the form of (one or more) deep geological repositories, although up to today no such repository has actually been built.

2. Reprocessing aims to separate out plutonium and/or depleted uranium from the SNF in order to reinsert the recovered uranium and/or plutonium into nuclear reactors or nuclear weapons. Remaining materials (i.e. fission products and transuranic elements other than plutonium) are usually treated as high-level nuclear waste.

3. Export of SNF can also be regarded as a solution in its own right, to the extent that the producing country neither reprocesses SNF nor disposes of it directly in deep geological formations. Instead, SNF is taken care of abroad, where it might be either directly disposed of or reprocessed. However, high-level wastes from reprocessing abroad are often returned to the exporting country.

In some cases, different solutions may be preferred for different types of fuel. It should be mentioned that in practice, some countries have not decided upon any approach at all, awaiting future technological and political developments. SNF is in those cases stored on a long-term, but not permanent basis in interim storage facilities. Currently, of the world’s 32 nuclear power countries, approximately 13 can be seen to follow a direct disposal policy, whereas six follow the reprocessing alternative and six have opted for export. The remaining countries have not yet taken any clear decision (cf. Table 1).

There is also a great deal of variation within each of the three principal approaches. In the case of direct disposal, for example, there has been a lack of agreement—both across countries and over time—concerning the type of physical locations that are most suitable for deep SNF repositories; what depths are to be preferred; how many and what types of barriers are needed for long-term protection of the fuel; whether a country should aim at making the SNF accessible to future generations (retrievability); etc. In the case of reprocessing, there is currently a debate between proponents of traditional, ‘wet’ radiochemical
### Table 1
Overview of spent nuclear fuel policies in 32 countries

<table>
<thead>
<tr>
<th>Country</th>
<th>Spent fuel history</th>
<th>Current policy</th>
<th>Trends</th>
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</thead>
<tbody>
<tr>
<td>Argentina</td>
<td>Experimental reprocessing facility operating in early 1970s</td>
<td>Interim storage, awaiting further decisions</td>
<td>New fuel cycle initiatives in connection to launch of new nuclear policy in August 2006</td>
</tr>
<tr>
<td>Armenia</td>
<td>Transfer to Russia without waste return</td>
<td>Interim storage, awaiting further decisions</td>
<td>Some interest in reprocessing</td>
</tr>
<tr>
<td>Belgium</td>
<td>Eurochemic international reprocessing facility (involving 12 OECD countries)</td>
<td>Export to France with waste return/ direct disposal</td>
<td>Two alternatives acknowledged: research on geological disposal focused on clays at Mol</td>
</tr>
<tr>
<td>Brazil</td>
<td>Most fuel-cycle activities were developed, but not reprocessing</td>
<td>Interim storage, awaiting further decisions</td>
<td>New NPP with Russian reactors to be built</td>
</tr>
<tr>
<td>Bulgaria</td>
<td>Export to Soviet Union without waste return; some interruptions in 1990s</td>
<td>Export to Russia without waste return</td>
<td>Losing important foreign reprocessing customers</td>
</tr>
<tr>
<td>Canada</td>
<td>Pilot reprocessing activities in 1940s and 1950s (Gowing, 1974)</td>
<td>Direct disposal and retrievability</td>
<td>Stagnation in SNF policymaking; new interim storage facilities under construction at each NPP in accordance with new legislation</td>
</tr>
<tr>
<td>China</td>
<td>Reprocessing plans, but slow growth of nuclear power</td>
<td>Reprocessing</td>
<td>Expansive reprocessing programme; diversifying from uranium- to thorium-cycle</td>
</tr>
<tr>
<td>Czech Republic</td>
<td>Export to Soviet Union without waste return</td>
<td>Open policy. NPP operators to decide</td>
<td>Site selection for geological waste repository expected in 2015</td>
</tr>
<tr>
<td>Finland</td>
<td>VVER SNF exported to Soviet Union until 1996; direct disposal of BWR SNF</td>
<td>Direct disposal of all fuel</td>
<td>Repository to be built at Olkiluoto</td>
</tr>
<tr>
<td>France</td>
<td>Reprocessing</td>
<td>Reprocessing</td>
<td>New NPPs planned</td>
</tr>
<tr>
<td>Germany</td>
<td>Failed attempts to establish large-scale domestic reprocessing; massive exports to</td>
<td>Direct disposal</td>
<td>The question of future civil reprocessing remains open</td>
</tr>
<tr>
<td></td>
<td>France and UK; SNF in GDR exported to Soviet Union without waste return (Tiggemann, 2004)</td>
<td></td>
<td>Preliminary investigations regarding geological repository</td>
</tr>
<tr>
<td>Hungary</td>
<td>Export to Soviet Union without waste return</td>
<td>Direct disposal</td>
<td>Aggressive nuclear fuel policy, but in practice stagnation in reprocessing expansion</td>
</tr>
<tr>
<td>India</td>
<td>Military reprocessing since 1964; civil reprocessing since 1982 (Berkhout and</td>
<td>Direct disposal</td>
<td>Site selection for geological repository expected in 2009</td>
</tr>
<tr>
<td></td>
<td>Gadakar, 1997)</td>
<td>Reprocessing</td>
<td>Interest in direct disposal abroad</td>
</tr>
<tr>
<td>Italy</td>
<td>NPPs decommissioned since 1987–1990; pilot reprocessing plant in operation until</td>
<td>Export of remaining fuel to France 2007–2015 with waste return</td>
<td>New nuclear energy policy envisages reprocessing as a strategic priority related to energy security</td>
</tr>
<tr>
<td>Japan</td>
<td>Pilot-scale reprocessing since 1977; export to France and UK while awaiting maturity</td>
<td>Reprocessing</td>
<td>Centralized interim storage planned for 2016; continued interest in reprocessing</td>
</tr>
<tr>
<td></td>
<td>of domestic reprocessing</td>
<td></td>
<td></td>
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<tr>
<td>Lithuania</td>
<td>Transfer to Russia without waste return</td>
<td>Direct disposal</td>
<td>Site selection for geological repository</td>
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<tr>
<td>Mexico</td>
<td>No ambitious fuel cycle activities</td>
<td>Interim storage, awaiting further decisions</td>
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</tr>
<tr>
<td>Netherlands</td>
<td>Export to France and UK</td>
<td>Export to France</td>
<td>For future reactors, a choice will be made by 2025 between export, direct disposal and ‘partition and transmutation’</td>
</tr>
<tr>
<td>Pakistan</td>
<td>Reprocessing project on basis of French technology cancelled in 1978</td>
<td>Interim storage, awaiting further decisions</td>
<td>The question of future civil reprocessing remains open</td>
</tr>
<tr>
<td>Romania</td>
<td>First commercial reactor on-line in 1996 (CANDU type)</td>
<td>Direct disposal</td>
<td>Preliminary investigations regarding geological repository</td>
</tr>
<tr>
<td>Russia</td>
<td>Military reprocessing since 1948; reprocessing of VVER SNF since 1977; construction of larger reprocessing plant started in 1985 (Ruzinetsrov and Nazarov, 2006)</td>
<td>Reprocessing of VVER SNF; no reprocessing of RBMK SNF</td>
<td>Aggressive nuclear fuel policy, but in practice stagnation in reprocessing expansion</td>
</tr>
<tr>
<td>Slovakia</td>
<td>Export to Soviet Union without waste return</td>
<td>Direct disposal</td>
<td></td>
</tr>
<tr>
<td>Slovenia</td>
<td>Strategy for Long-Term Spent Fuel Management adopted in 1996</td>
<td>Direct disposal or, possibly, export</td>
<td>Site selection for geological repository</td>
</tr>
<tr>
<td>South Africa</td>
<td>Ambitious fuel cycle policy, but no reprocessing facility built</td>
<td>Interim storage, awaiting further decisions</td>
<td>New nuclear energy policy envisages reprocessing as a strategic priority related to energy security</td>
</tr>
<tr>
<td>South Korea</td>
<td>Reprocessing ambitions halted in 1978 following US pressure (Kang and Feveson, 2001)</td>
<td>Direct disposal and possibly DUPIC</td>
<td>Continued interest in reprocessing</td>
</tr>
<tr>
<td>Spain</td>
<td>Export to France and UK without waste return; open fuel cycle policy since 1983</td>
<td>Direct disposal</td>
<td>Decision on disposal to be made after 2010. Granite, clay and salt formations under consideration</td>
</tr>
<tr>
<td></td>
<td>(Berkhout and Walker, 1991)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sweden</td>
<td>Domestic reprocessing opened up at early stage, minor exports to France and UK</td>
<td>Direct disposal</td>
<td>Site selection for geological repository expected in 2009</td>
</tr>
<tr>
<td></td>
<td>1977–1983</td>
<td></td>
<td>Exports halted for 10 years from 2006; continued interest in both reprocessing and export</td>
</tr>
<tr>
<td>Switzerland</td>
<td>Reprocessing ambitions officially given up in 1976 following US pressure</td>
<td>Direct disposal</td>
<td>Geological repository planned for 2032; continued interest in both reprocessing and export</td>
</tr>
<tr>
<td>Taiwan</td>
<td>Large-scale civil reprocessing since 1964</td>
<td>Reprocessing and/or direct disposal</td>
<td>Possibly moving to direct disposal; B205 Magnox reprocessing plant to be closed after Magnox reactors decommissioned around 2012</td>
</tr>
<tr>
<td>UK</td>
<td></td>
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</tbody>
</table>
approaches and ‘dry’ (non-aqueous) alternatives, such as ‘pyroprocessing’. An interesting debate is also to what extent it might become possible in future to combine reprocessing of SNF with ‘transmutation’ of dangerous fission products and/or transuranic elements into less problematic substances.\(^2\)

The aim of this article is to explain why countries differ in their past and present SNF approaches. The overall characteristics of SNF policies are relatively well-known at the level of individual countries. However, there has so far not been any systematic research on the evolution of SNF policies in globally comparative perspective. This article has the ambition to fill this gap, with a particular emphasis on developing an historical understanding of processes of divergence and convergence in terms of the three principal strategies outlined above.

The limited length of the article means that a great deal of detail has had to be sacrificed with respect to developments within individual countries. The ambition is rather to gain a broad understanding of how and why SNF approaches have evolved, and thereby identify factors that have contributed to shaping policy outcomes.

I discuss in particular five broad factors which can be seen to have contributed strongly to the formation of SNF policies around the world:

- **Military ambitions and non-proliferation**: How have nuclear weapons ambitions and non-proliferation policies contributed to shaping SNF approaches in different countries?
- **Technological culture**: How have the varying levels of scientific and technological competencies in relevant fields, along with the varying civil ambitions in nuclear technology, shaped national paths in SNF policymaking?
- **Political culture and civil society**: Are some political systems more prone than others to advocate a certain SNF policy? What role has the shifting character of anti-nuclear movements across countries played?
- **Geological conditions**: In what way has the availability or lack of suitable geological formations within countries influenced their willingness to focus on direct disposal of SNF? And what role has the availability of domestic uranium deposits played?
- **Energy policy**: How has the overall national energy policy context shaped countries’ paths in SNF policy? In particular, how has the (changing) degree of support to nuclear power contributed to shaping SNF approaches?

Thirty-two countries have been included into the analysis. They represent all countries that are currently operating nuclear power plants (NPPs) plus Italy (which has decommissioned its NPPs). The main characteristics of their past and present SNF policies are outlined in Table 1.

The study builds on official policy documents and reports from national and international nuclear-related organizations, as well as on a wide range of secondary literature published mainly in leading English-language journals in the field of energy and nuclear power. Three countries—Finland, Germany and Russia—have been subject to a more thorough investigation, including in-depth interviews with key actors.

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### Table 1 (continued)

<table>
<thead>
<tr>
<th>Country</th>
<th>Spent fuel history</th>
<th>Current policy</th>
<th>Trends</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ukraine</td>
<td>Transfer to Russia without waste return</td>
<td>Export of VVER fuel to Russia with waste return; interim storage of RBMK fuel</td>
<td>No clear long-term strategy; interest in DUPIC</td>
</tr>
<tr>
<td>USA</td>
<td>West Valley (NY) plant in operation 1966–1972; much larger plant at Barnwell (SC) was built but not commissioned following new SNF policy in 1977</td>
<td>Direct disposal</td>
<td>Reprocessing prospects revived in 2005 Energy Bill; exports to Russia also under consideration</td>
</tr>
</tbody>
</table>

Sources: World Nuclear Association; International Atomic Energy Agency; Federation of American Scientists; Nuclear Threat Initiative; and national organizations. Additional sources are indicated in the table.

Note: DUPIC = Direct Use of Spent PWR Fuel in CANDU reactors.

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1 The recent emphasis in some countries on developing ‘dry’ reprocessing methods can be seen as a response to the perceived problems of ‘wet’ reprocessing. Whereas today’s de facto standard reprocessing method, the PUREX process, may be used to recover weapons-grade plutonium, thereby exposing it to the risks of nuclear proliferation, pyroprocessing methods do not separate out pure plutonium, thereby reducing the proliferation risks. In addition, proponents of pyroprocessing argue that since the method recovers most of the long-lived actinides from the SNF, the radioactivity of the remaining waste will be more short-lived than in the PUREX case. It remains to be seen, however, whether pyroprocessing will be able to live up to its promises.

2 It should be noted that a prerequisite for transmutation is the availability of reprocessing services.

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2 The alternative is to produce nuclear weapons based on highly enriched uranium. However, the general conclusion drawn after World War II was that the technology of reprocessing was cheaper and easier to master than uranium enrichment.
over non-nuclear weapons countries in the race to realize large-scale civil reprocessing of SNF.

This logic is obvious in the nuclear histories of the United States, the Soviet Union, Great Britain and France and later on also, for example, in India and North Korea. As a result, the countries that pursue or have pursued an SNF approach based on large-scale reprocessing largely coincide with the world’s nuclear weapons powers.

(West) Germany and Japan form two notable exceptions from this pattern, having invested heavily in civil reprocessing but without ever having/had any (official) nuclear weapons ambitions. Significantly, however, in both countries reprocessing became controversial at an early stage exactly because of the potential and possibly hidden links to nuclear weapons (e.g. Klingelschmidt, 1986).

There are also countries that at a time have had nuclear weapons ambitions and which have pursued R&D in the field of reprocessing for this purpose, but which, at a later stage, have given up their military nuclear ambitions. An example is Sweden, which in the 1950s and early 1960s followed an ‘Indian’ strategy, i.e. aiming at the utilization of natural (i.e. non-enriched) uranium in heavy-water reactors, in combination with reprocessing for both military and civil purposes. However, in Sweden this strategy was later replaced by a civil-only approach based on light-water reactors and imported, enriched uranium (Lindström, 1991). In the absence of military ambitions, the reprocessing project was given up in the early 1970s and the Swedish SNF strategy shifted to export (reprocessing in France and Britain) and, from the late 1970s, direct disposal as the main alternative (Anshelm, 2006).

In another part of the world, South Korea initiated R&D activities relating to reprocessing in the 1960s, while also investing in Canadian-designed CANDU heavy-water reactors. The reprocessing efforts did initially not relate primarily to the military dimension, but later on the situation changed. In 1970, US President Nixon announced a new military doctrine for American involvement in Asia, calling for an increased responsibility of US allies in Asia to defend themselves. This stimulated South Korea to intensify its reprocessing ambitions, with a growing interest in developing nuclear weapons (Kang and Feiveson, 2001).

This interest was further stimulated by India’s successful nuclear weapons test in 1974. It seemed to demonstrate that a developing country could become a nuclear weapons power based on domestic reprocessing facilities. As a consequence, the efforts to acquire such facilities were intensified in a whole array of developing countries, such as North Korea, Pakistan and Argentina, whereby the military reprocessing strategy was often intimately linked with civil nuclear ambitions (Kim, 2006).

In the United States, from where the original blueprints for India’s first reprocessing facility had come (Ramana, 2006), the Indian nuclear test came as a shock and it became one of the main factors behind a new, more negative approach to reprocessing. If not earlier, non-proliferation ambitions became a central argument against reprocessing. In reality, reprocessing at that time already suffered from severe technical, economic and safety problems, and voices had already been raised against reprocessing for these broader reasons. But in the official argumentation, it was non-proliferation that was the key argument when US President Carter in spring 1977 issued a presidential directive to suspend all reprocessing for civil purposes in the United States. Instead, a new strategy, based on direct disposal, started to take shape. It signalled a new interpretation of reprocessing as a heritage from military activities, which did not necessarily have to be pursued in the civil sector.

The Carter directive and the rise of direct disposal on the agenda contributed to a shift in SNF policies in several small Western countries, especially in countries that had kept an interest in domestic reprocessing but which had not yet invested any large resources into the actual construction of reprocessing facilities. In countries such as Sweden and Finland, the new American path seemed to confirm an already growing scepticism to reprocessing, and the Carter decision thereby accelerated the transition to a direct disposal policy in these countries.

By contrast, in Western countries that had already invested heavily in reprocessing, the new American policy did not result in any concrete change in overall approach to SNF. On the contrary, reprocessing programmes in Britain and France were further expanded in the 1980s. While many smaller Western democracies gave up their reprocessing efforts, France and Britain could thus strengthen their duopoly on the West European reprocessing market. They did not regard the threats of nuclear proliferation as an argument strong enough to motivate far-reaching policy changes. On the contrary, France further expanded its reprocessing activities by engaging in a number of international projects that aimed at transferring French reprocessing know-how to countries such as Pakistan, Korea and Japan.

There was also an historical inertia that seemed to demand a continued orientation towards reprocessing in France and Britain. Apart from considerable vested interests, which can be traced back to military reprocessing efforts, civil reprocessing was in some cases motivated by historical technical designs of the nuclear fuel. This was the case with the British Magnox reactors (which had also been exported to Italy and Japan, and imitated by Spain and North Korea). The development of these reactors can be traced back to R&D activities in nuclear weapons production, which generated competencies that have later on been adapted to civilian needs. Interestingly, the entire set of Magnox reactors embody, in a highly problematic way, the era of over-optimistic visions in the 1950s, when reprocessing was seen as totally central for the future of nuclear power (see also the next section). When the nuclear fuel for the Magnox reactors was developed, it was taken for granted that reprocessing was the method that would be used for taking care of the SNF, and the fuel was therefore constructed without taking into account the possibility that it might have to be stored in interim storage facilities for a longer time or be directly disposed of. In 1990, the Radioactive Waste Management Advisory Committee (RWMAC) concluded that the very construction of the Magnox fuel made reprocessing the only viable solution. The reason was that this fuel, if stored in water for a longer period of time, would corrode and leak radioactivity, while at the same time there was no method available for dry storage (RWMAC, 1990). In other words, Britain seemed to be locked into the heritage from past techno-utopian visions.

World-wide concerns about nuclear proliferation have grown substantially with the increasing stockpiles of plutonium that have accumulated at the reprocessing sites especially since the 1980s and 1990s. Gaining access to reprocessing competence and pursuing a strategy with close links between military and civil ambitions remains attractive for new countries with nuclear weapons ambitions. The developed world is, of course, well aware of this, and this logic contributes greatly to the never-ending controversies that accompany all developments within the field of reprocessing. In practice, this makes it politically difficult for any country to pursue reprocessing—even if it is clearly stated that it is for civil purposes only.

4 In Britain, the plans for a new, larger reprocessing plant—the THORP facility—were confirmed after an inquiry in 1977/78, paving the way for this facility to accept not only domestic, but also large amounts of foreign SNF. In France, decisions were taken at about the same time for the construction of a new reprocessing facility UP-3, financed largely by foreign customers (Schneider and Pavageau, 1997).
Not surprisingly, non-proliferation concerns have also made the export and import of SNF highly contested. Especially cross-border transfers of pure plutonium—whether or not weapons-grade—has become almost impossible, at least when democratic countries are involved. In some countries, such as Finland and Germany, this problem is referred to as a major factor behind the decision not to export any SNF (e.g., Tiggemann, 2004). The loss of important customers has thereby also come to threaten the economic future of reprocessing in France and Britain.

The latest impact of military and non-proliferation considerations on SNF strategies is the ‘Global Nuclear Energy Partnership’ (GNEP), launched by the United States in 2006. It is a programme in the spirit of the 1950s, in the sense of being extremely optimistic about the future prospects of nuclear power as an energy source. In the official argumentation, non-proliferation concerns constitute a main driving force behind the programme, with its aim to apply ‘proliferation-resistant’ reprocessing technologies. SNF, according to the GNEP vision, would be reprocessed ‘without separating out pure plutonium’ (GNEP, 2007a). It is thus an attempt to challenge the dominant view that reprocessing is inevitably linked to the dangers of nuclear proliferation. Obviously, however, the GNEP initiative must also be seen in relation to the US nuclear community’s lobbying efforts to revive nuclear power research and development in general, whereby the arguments must also be seen in relation to climate and energy policy more generally (see further the section on energy policy below).

3. Technological culture

When larger civil NPPs started to be taken into operation from the 1960s onwards, nuclear power came to be discussed in terms of the ‘nuclear fuel cycle’. At that time, most countries with an interest in nuclear power considered it crucial to master all steps in the fuel cycle, from uranium mining, conversion and enrichment to reactor construction and back-end activities such as interim storage of SNF, reprocessing and waste treatment.

Aiming to master all these steps was an extremely ambitious strategy, and not surprisingly, it were mainly countries which already possessed far-reaching competencies in the fields of nuclear physics, radiochemistry and mechanical engineering that developed the most far-reaching national aspirations with respect to the nuclear fuel cycle. Most of these countries had also nuclear weapons ambitions and could draw on their ongoing efforts in this field. Two exceptions, as pointed out above, were Germany and Japan. In these two countries, which had lost World War II, post-war technological culture centered around civil projects, which were seen to represent a legitimate area of building future national strength. In Germany, an additional stimulating factor was the awareness of this country being the actual origin of much pre-war research in nuclear chemistry and physics.

Of particular interest for the future of nuclear power were, already at an early stage, the tremendous challenge of constructing ‘fast breeder reactors’, in which plutonium could be used as a fuel while ‘breeding’ further fissionable material from the non-fissionable uranium isotope U-238. This meant that breeder reactors, if successfully realized, could use the energy potential of the uranium much more efficiently than thermal reactors. Breeder reactors were celebrated as a ‘second generation’ reactor type, and during the extremely optimistic years in the 1950s with regard to the future role of nuclear power in modern society, it was already taken for granted that this type of reactor would inevitably be introduced in large numbers. But breeder reactors needed plutonium, and a country that aimed to develop breeder technology therefore first had to master the techniques of reprocessing.

The dream of breeder reactors thus enhanced the central role of reprocessing in the nuclear power programmes of many countries, and the completion of large-scale, commercial reprocessing plants in the mid–1960s in Great Britain, the United States and France became the ultimate representation and symbol of this dream. There was also a joint West European reprocessing project: the Eurochemic pilot facility at Mol in Belgium, which was already taken for granted that this type of reactor would inevitably be introduced in large numbers. But breeder reactors were an extremely ambitious strategy, and not surprisingly, it were mainly countries which already possessed far-reaching competencies in the fields of nuclear physics, radiochemistry and mechanical engineering that developed the most far-reaching national aspirations with respect to the nuclear fuel cycle. Most of these countries had also nuclear weapons ambitions and could draw on their ongoing efforts in this field.

At the same time, however, it was becoming clear in the 1970s that civil, large-scale reprocessing of SNF was considerably more difficult, expensive and environmentally hazardous than initially expected. A turning point came in 1973/74, when a number of accidents and functional problems occurred at roughly the same time in French, British and American reprocessing plants (Radkau, 1981). A consequence of this was that these facilities had to be reconstructed or decommitted, and together with the broader trends referred to above, the result was that a technological pessimism started to diffuse around the world with respect to the future of reprocessing.

Disillusioned for the prospects of reprocessing was also the stagnation that took place in the development of breeder reactors. Numerous delays in the expected breakthrough for the breeder technology meant that there did not yet exist any civil, but only a military demand for plutonium, the most important product delivered by the reprocessing facilities.

From this perspective, it was hardly surprising that many smaller nuclear power states stepped back from their earlier national ambitions with respect to the nuclear fuel cycle. When national reprocessing ambitions were thus given up, the most popular alternative was the export of SNF to foreign reprocessing facilities. This was so in several, mostly smaller West European countries such as Belgium, the Netherlands, Switzerland and Spain. But export also became the de facto strategy for larger

5 At Sellafield in England the facility B205, for the reprocessing of fuel from the Magnox reactors, was operational in 1964. In France, the UP–2 facility at La Hague was taken into operation in 1966. In the United States, the West Valley (NV) reprocessing plant was inaugurated in 1964. Their designed capacities were 1500, 400 and 300 tons of uranium per year, respectively.
countries such as Germany, Italy and Japan, as a consequence of delays in the construction of domestic reprocessing plants in these countries.\textsuperscript{6}  

Subsequently, with the continuing technological and environmental problems of reprocessing, in combination with non-proliferation concerns, many smaller nuclear power countries have taken a further step away not only from reprocessing but also from their export of SNF. Particularly in the West, many countries nowadays orient themselves increasingly towards direct disposal rather than export. Here, too, a certain ‘technological pride’ can sometimes be discerned. In Sweden, for example, the old nuclear weapons ambitions have now been replaced by prestigious, arguably world-leading R&D activities in the field of geological repositories. An interesting issue is whether the emergence of leading countries in the development of direct disposal solutions might stimulate small nuclear power countries to pool their resources by investing in joint geological repositories in those leading countries. Such an approach would have an obvious technological and economic attractiveness, but the related political issues would be more difficult to deal with.

4. Political culture and civil society

Type of political system is a factor that has played a major role for countries’ divergent choices of SNF strategies. In particular, strong differences are evident between democratic and nondemocratic countries. It is obvious that countries with authoritarian and semi-authoritarian governance structures, such as Russia, China or North Korea, have found it easier to sustain reprocessing-oriented strategies in times when these have been subject to heavy criticism in other parts of the world. In the absence of influential anti-nuclear movements, the lobbying efforts from within the nuclear-industrial complex, which have usually been strongly in favor of a closed nuclear fuel cycle, have as a rule been more successful.

Historically, and with a continuing legacy, the communist regimes of Central and Eastern Europe constitute a special case of authoritarian regimes in the history of nuclear power. The Soviet Union, Czechoslovakia, East Germany, Hungary and Bulgaria formed a bloc of nuclear countries with a joint SNF regime. SNF management was here subject to the fundamental political principle of the leading role of the Soviet Union, which implied that the communist satellite states in Central and Eastern Europe were not allowed to develop their own solutions for taking care of their SNF. Instead, they were forced to export their SNF to the Soviet Union—whether they wished to or not. In principle, this was a form of political coercion. In practice, the exporting countries were happy with the arrangement, at least as long as it actually worked smoothly. Two Soviet-designed reactors in Finland were also part of this SNF regime up to 1996.

The principle of exporting SNF to the Soviet Union contributed strongly to an East European nuclear power culture in which SNF was never a major issue. The idea of the closed nuclear fuel cycle was communicated to the public in a way as if there did not exist any nuclear waste. The message was that the fuel was reprocessed in the Soviet Union, whereupon it could be used again without any further problems. Hence, the deep ethical and historical-philoso-

\textsuperscript{6} Export also became attractive for countries such as Australia and Denmark, which, in the end, did not develop any commercial, large-scale reactor programmes but nevertheless operated smaller research reactors. SNF management was in these countries often arranged for in special paragraphs in the original fuel supply contracts. Especially the United States was a major supplier of (often highly enriched) research reactor fuel to a variety of countries around the world, and as a result there has later on been a wave of spent reactor fuel return to the US. 

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The enormous strength of the German anti-nuclear movement contributed to making both the nuclear power companies and the chemical industry increasingly suspicious concerning the suitability of a large domestic reprocessing facility, and in the end a strategy based on SNF export to France and Britain appeared more attractive. However, in the 1990s a wave of violent protests accompanied the transportation of SNF to the French and British sites, and in 2002 the federal government decided to legalize all exports of German SNF, shifting to a strategy based on direct disposal (Tiggemann, 2004). Even so, the immense political difficulties when it comes to transports of SNF (within the country) have led to a situation where NPPs, instead of sending their SNF to centralized interim storage facilities, are obliged to invest in decentralized interim storage facilities at each NPP site. The growing role of interim storage facilities in Germany may also
be seen in relation to technical advances in the field of dry cask storage, a development which seems to have contributed to reducing the perceived urgency regarding the construction of a deep geological repository.

An interesting contrast to Germany is Finland, where the development of SNF policy has been strongly influenced by a consensus-oriented political culture. Finland has not lacked public protests against new nuclear projects, but the degree of pragmatism has been much greater than in Germany, so that eventually even the Green Party voted in favor of the solution proposed by the nuclear companies, based on direct disposal. In the parliamentary vote on the ‘decision in principle’ that in 2001 paved the way for the realization of this strategy, only three votes out of 162 were against (Posiva, 2001). While the German anti-nuclear movement can be said to have contributed to paralyzing the SNF policymaking process, the Finnish movement has rather contributed to strengthening and legitimizing the solution that has emerged.

It is also interesting to compare Germany with Japan. Both have historically been oriented towards a closed nuclear fuel cycle, aiming at large-scale SNF reprocessing. Yet the two countries have ended up in totally different situations, with Japan largely proceeding with its original strategy and now preparing for the commercial launch of its large Rokkasho reprocessing plant. Part of the explanation can be found in a weaker and less coordinated anti-nuclear movement in Japan, which has not managed to form any strong nationally coordinated efforts (Kajiser and Högselius, 2007). This does not mean that Japan has not seen any public protests, but the difference with Germany is nevertheless striking.

The political situation in South Korea is also intriguing, especially because the role of international relations becomes obvious for the choice of SNF strategy. As mentioned earlier, the country has long viewed reprocessing as the preferable basis for SNF management. However, South Korea has had great political difficulties to go ahead with this policy due to its reliance on the United States as a geopolitical ally. Since 1974, when India carried out its first nuclear test, the United States has refused to accept any reprocessing ambitions in Korea. In 1975, the country had reached an agreement with France for the transfer of French reprocessing technology, but Korean politicians found themselves forced to give up the deal in 1976 due to US pressure. In the 1990s South Korea faced a difficult situation as it became obvious that SNF interim storage space was becoming scarce. As a solution Korea then turned to France and Britain for negotiating a possible export of Korean SNF to Europe. The deal was seen as attractive by Korea then turned to France and Britain for negotiating a possible SNF interim storage space was becoming scarce. As a solution South Korea faced a difficult situation as it became obvious that reprocessing technology, but Korean politicians found themselves

interrupting the ongoing construction of a new large reprocessing plant (‘RT-2’) in 1989, although some Russian analysts believe the construction would have been interrupted anyway, due to lack of funding (Kuznetsov and Nazarov, 2006). Local anti-nuclear groups also managed to persuade the regional government in Chelyabinsk oblast to limit the operation of the Mayak reprocessing plant (‘RT-1’) to one-third of its nominal capacity. Since the mid-1990s, however, the room for anti-nuclear action has become narrower, following the strengthening of the central political powers in the Putin era. The lobbying power of the nuclear industry in Russia has also grown, and in general Russian nuclear policy can today be said to be reminiscent of the utopian visions of the 1950s (Josephson, 2005).

The political culture of the European Union is also a factor that in the future may influence SNF strategies in its 27 member states. This concerns, in particular, the idea that different countries could build a joint final repository for SNF and/or a joint interim storage facility. Especially the International Atomic Energy Agency (IAEA) has repeatedly pointed at this option as a rational and desirable alternative both in Europe and elsewhere (e.g. IAEA, 2004). The legal issues are here of particular interest, whereby for example Swedish researchers have asked under what circumstances Sweden may be forced to accept foreign SNF for permanent storage (Cramér et al., 2006). Historically, Western Europe has already a long past of extensive collaboration in SNF management, first in the 1960s and 1970s through the joint reprocessing facility at Mol in Belgium, and later on through the export of SNF from several smaller nuclear power countries to France and Britain. However, given the extreme political sensitivity of SNF responsibilities within the EU, particularly when it comes to SNF transfer across borders, it seems at present highly unlikely that a joint SNF regime would be realized within a foreseeable future.

Instead, the most far-reaching efforts to establish new multinational regimes in the world are currently led by Russia and the United States. In 2000, Russia announced an ambitious new SNF policy centered around the idea of importing vast amounts of SNF from abroad, for reprocessing or long-term (but not permanent) storage (Stulberg, 2004). The import programme can be seen as a return to the old Soviet model of leasing fresh nuclear fuel to East European NPPs with the subsequent return of SNF to Russia, while extending this strategy to include imports of SNF of non-Russian origin. For most Western countries, it remains politically out of the question to export SNF to Russia. The fuel to be imported would rather have to come either from Eastern Europe (as in the past) or from newly industrializing countries in Asia and elsewhere—particularly countries that have imported or wish to import Russian-designed nuclear reactors, such as China and Iran.

In 2005, the United States announced an interest in collaborating with Russia in terms of SNF exports from the US (Burbart and Gorn, 2005). It is not clear, however, how this stands in relation to the American-initiated GNEP programme, which rather seems to indicate an interest in importing SNF to the United States (see GNEP, 2007b). In any case, both the Russian and the American development can be seen to evolve in line with IAEA’s growing interest in promoting multinational SNF and waste management regimes.

A typical feature of democratic countries is that, if they reprocess foreign SNF, they agree to do so only under the condition that the exporting country is willing to re-import the high-level radioactive wastes that result from the reprocessing. This principle was established in the second half of the 1970s in France and Britain in connection to the foreign contracts that paved the way for new and larger reprocessing facilities (Berkhout and Walker, 1991). With the increasing amounts of SNF being shipped to France and Britain, it became politically impossible to accept that large stocks of foreign nuclear waste remained in the
reprocessing countries. Under the more authoritarian regime of the Soviet Union, in contrast, there never emerged any political pressure to force the Central and East European countries to accept waste return from Soviet reprocessing. Only when the Soviet Union collapsed in 1991 did this become an issue—but even after that the principle of waste return has not been established to the same extent as in the West. In future, it is not unimaginable that we will see authoritarian countries that seek a competitive advantage in this respect, offering reprocessing services to foreign actors without demanding waste return.

5. Geological conditions

Direct disposal is usually considered technologically less demanding than reprocessing. However, direct disposal is an enormous challenge from a geological perspective. This is so both with respect to the availability of scientific and technological competencies within the geological sciences and to the existence of suitable geological formations within the country. From this perspective, it is clear that countries that lack competencies or suitable conditions have stronger incentives to seek alternatives to direct disposal.

This is obvious, for example, in the case of Japan, where an unstable geology in combination with a very dense population has made it highly unattractive to pursue a direct disposal strategy. This has contributed to a continued reliance on reprocessing as the main SNF strategy in Japan. Waiting maturation of domestic reprocessing competencies, export to Europe has been the preferred strategy. The geological instability is also reflected in a considerable local opposition even to preliminary geological investigations all over Japan (Kajiser and Högselius, 2007). Local opposition to nuclear waste facilities is certainly a phenomenon in many countries, but the Japanese case can be contrasted to, for example, Finland and Sweden, where several municipalities, confident about the geological stability of their bedrock, have volunteered for investigations aiming at the construction of deep geological repositories. The recent (July 2007) earthquake that seriously damaged the huge Kashiwazaki-Kariwa nuclear power plant, has hardly contributed to reducing Japanese fear of geology as a threatening factor in SNF management. This fear might also have an impact on the commercial commissioning of the Rokkasho reprocessing plant; in June 2008 a group of Japanese geologists reported that the reprocessing plant is sited ‘directly above an active geological fault line’, and references were made to the impact of the 2007 earthquake (Cyranoski, 2008).

5. Geological conditions  

Germany is also an interesting example where the SNF debate has been influenced by geological factors. Traditionally, it was regarded as self-evident that Germany would use its well-known salt formations for disposing of all types of radioactive waste. But in recent years, several groups have raised doubts concerning the optimality of these geological formations for direct disposal, and have demanded that alternative types of bedrock be investigated. The nuclear industry is highly irritated about what it sees as a deliberate attempt by anti-nuclear groups to slow down the overall SNF decision-making process. A slowdown, not to say a political paralysis, is also what currently characterizes the German situation in SNF issues.

A related political trend in some countries, notably Sweden and Finland, has been a gradual shift from a search for the ‘optimal’ bedrock to a bedrock that does not necessarily have to be optimal, but which meets clearly specified criteria. This has enabled the involved authorities and organizations to concentrate their site selection efforts to regions and municipalities where the bedrock is ‘acceptable’ and where, in addition, the population has a positive stance towards the construction of a deep repository. It has been called a shift from a ‘systematic’ to a ‘flexible’ siting strategy (Kojo, 2006). The result has been that the Swedish and Finnish site selection has moved towards a focus on municipalities that already host NPPs and which are thus used to the existence of nuclear facilities in their immediate surroundings.

Another geological factor that has played a role are the strong variations amongst countries with regard to the availability of domestic uranium deposits. For a country such as Canada, which is the world’s largest producer of uranium, it has never appeared particularly tempting to invest in reprocessing technology on the basis of the need to economize on uranium resources. The fact that the United States abandoned its reprocessing strategy in the late 1970s might in a similar way not have been seen as a realistic alternative, had this country not been in possession of substantial domestic uranium deposits.

In many other countries, however, there was, for a long time, a consensus within the nuclear engineering community that reprocessing was necessary for economizing on scarce uranium resources. The non-recycling of SNF was seen to represent an enormous waste of uranium. The technology of reprocessing was in this perspective particularly attractive for countries that controlled only minor or low-quality uranium deposits and which, at the same time strove for national energy independence. Sweden, India and Japan are interesting examples, of which the latter two still pursue a reprocessing-oriented strategy. India, however, while lacking uranium, does possess large thorium deposits, which have stimulated considerable efforts to develop a thorium-based nuclear fuel cycle as a complement to the uranium cycle (Bajaj and Gore, 2006).

The economizing argument has through the years been weakened, as a result of the discovery of new uranium sources and a slower growth in uranium demand than initially expected. The world market price of uranium has therefore declined radically; in the period from 1978 to 2001, the spot price for natural uranium fell from 261 to 19$/kg (in constant 2001 dollars) (von Hippel, 2001). A relatively frictionless trade with uranium at low prices has increasingly made the access to domestic uranium deposits less important in the political debate. The trend, however, may be turning again, following the increase in uranium prices since around 2003.

6. Energy policy

How does the overall energy policy of a country influence its SNF strategy? Countries nowadays differ widely from each other with respect to the role of nuclear power in their energy systems, and this has had far-reaching implications for their SNF approaches. Reprocessing-oriented fuel strategies have historically developed almost exclusively within the framework of strongly expansive nuclear policies. Prospects of a rapid growth of nuclear power—often with hundreds of large reactors—have been accompanied by expectations of enormously increasing volumes of SNF to be accumulated over decades and perhaps centuries. This has provided an incentive for countries with expansive nuclear power policies to invest in reprocessing projects, as a way to reduce the volumes of SNF while economizing on uranium resources and preparing for breeder technology. This logic was particularly strong in the 1970s, which can be regarded as the golden age of civil nuclear power, at least in the developed world. A very large number of large-scale reactors were taken into operation during these years, which meant that rapidly growing stockpiles of SNF started to become a physical reality. For small countries which did not have the resources to develop their own reprocessing facilities but which still pursued an expansionist nuclear power policy, the solution was often to ‘outsource’
reprocessing to foreign operators. It is thus no coincidence that so many smaller nuclear power countries—such as the Netherlands, Belgium, Switzerland, Spain, Sweden and Italy—were very eager to sign contracts with French and British reprocessing companies in the late 1970s.

In the 1980s, however, following the accidents in Harrisburg (1979) and Chernobyl (1986), several countries with ambitious nuclear power programmes decided to halt expansion and in some cases even totally abandon nuclear power. Italy, Sweden and Germany are countries with a proud and ambitious nuclear history, but they all decided to phase out their NPPs. For such stagnating nuclear power countries, domestic reprocessing is in practice out of the question, since reprocessing assumes that there be a long-term steady flow of SNF to be reprocessed, and this is obviously not the case if a country has decided to phase out its nuclear power. In this situation, export remains an alternative, but in addition, it has become attractive to investigate the prospects for direct disposal of SNF—a bold strategy that in the early 1980s was still considered highly exotic in most parts of the world. It is thereby hardly a coincidence that Sweden and Germany, with their stagnating nuclear power sectors, have belonged to the leaders in research and development activities relating to direct disposal.

An interesting case in this context is also Britain, whose national stagnation from the 1990s has stimulated the demands for decommissioning of the highly controversial reprocessing facilities at Sellafield. With its outdated reactor park, it would seem natural that a gradual phase-out of nuclear power in Britain would be accompanied by a shutdown of Sellafield, though with some time lag. If, however, the new active approach to nuclear power proclaimed by the Brown government (as part of an energy policy to combat climate change) actually leads to the construction of new NPPs, domestic reprocessing might have better chances of surviving.

Finland is an interesting case with its combination of an expansive nuclear power policy and a clear commitment to direct disposal. Nuclear expansion can here be seen to have accelerated decision-making with respect to SNF, since the current expansion has been politically conditioned by the existence of a domestic solution to the SNF issue. Finland has thereby become the perhaps most active country in the world when it comes to concrete preparations for the construction of a deep geological repository. The Finnish case shows that there is not necessarily any clear, linear relationship between the degree of expansionism in nuclear power and the choice of SNF strategy.

The complexity of the issue is further illustrated by the situation in Russia. While the overall Russian nuclear power policy currently belongs to the world’s most expansive, one of the ‘classical’ Russian reactor models, the RBMK (Chernobyl) type, is since the 1970s on its way out of the system. This was a main argument when the Soviet Union decided not to invest in any reprocessing facility for RBMK fuel. At the same time, the continuing investments in VVER reactor technology and its possible successors have raised the motivation considerably to continue a reprocessing-oriented strategy for VVER fuel. The long-term solution would thus be reprocessing for some types of SNF and direct disposal for other types. However, in times of overall nuclear stagnation in Russia, as was the case during the post-Chernobyl decade, reprocessing activities have followed this stagnation, so that new projects have been cancelled or frozen.

Finally, it should be noted that the original argument for reprocessing as a way to reduce the volumes of waste in expansive nuclear programmes has not remained unchallenged. This is because reprocessing itself gives rise to radioactive waste that needs to be disposed of. According to the World Nuclear Association, non-reprocessed SNF takes up about nine times the volume of equivalent vitrified high-level waste which results from reprocessing (WNA, 2007). However, in contrast to direct disposal, reprocessing also produces significant volumes of—partly long-lived—low- and intermediate-level waste which needs to be disposed of. Opponent to reprocessing emphasize that even if the amount of high-level waste from reprocessing is lower than in the case of direct disposal, there will still be a need for deep repositories.

7. Concluding reflections

This article has discussed the ways in which five broad factors—military ambitions and non-proliferation, technological culture, political culture and civil society, geographical conditions and energy policy—have shaped SNF policies in the world from the 1950s till today. To the extent that these factors may undergo far-reaching changes in the future, they also give us a hint of possible future directions in SNF policymaking.

For example, the rapidly changing energy policy agenda following the rise of climate issues has led to a revived interest in nuclear power in many countries. This may cause worries about scarce uranium resources and thus strengthen the interest in reprocessing as an SNF option. Especially in the West, it must be remembered that SNF regimes in the post-Chernobyl decades have evolved against the background of a stagnation in the growth of nuclear power. A renewed growth of nuclear power in the West may thus contribute to shift the development to new paths. On the other hand, given the low sensitivity of NPP operating costs to fuel price fluctuations, uranium prices are in themselves unlikely to lead to major changes in SNF policy. Thus, for example, the recent rise in uranium prices can hardly explain the renewed American interest in reprocessing.

One of the most interesting issues, however, is what SNF policies will emerge in countries which do not yet operate large-scale NPPs but which hope to do so in the future—particularly in the developing world. While the ‘old’ nuclear power states to a considerable extent may find themselves bound by the momentum of past developments, ‘new’ nuclear countries are freer to adapt their policies to current trends. However, any reprocessing ambitions in the developing world will give rise to concerns about possible nuclear weapons ambitions. It is against this background that the US GNEP initiative, focusing on ‘proliferation-resistant reprocessing’, must be understood. But large developing countries such as China, Thailand and Brazil, whose rise is typically accompanied by an increasing technological nationalism, may in the end be more interested in sustaining their own domestic technological ambitions than developing a dependence on US nuclear technology.

Major political developments such as democratization, as experienced in the years around 1990 in Central and Eastern Europe, may also contribute to considerable future shifts in SNF policies. In Europe, it remains an open issue how the process of EU integration will affect SNF regimes. The economic logic of international cooperation here stands against the perceived risks (proliferation, terrorism, accidents, anti-nuclear blockades, etc.) that accompany the transfer of nuclear materials across borders. Any joint SNF project within the EU will also have to challenge the momentum of already formulated and partly implemented national SNF policies.

The importance of geology in SNF issues was recently illustrated in summer 2007, when an earthquake in Japan exposed a nuclear power plant to serious danger. Such reminders of geological instabilities and their links to nuclear issues tend to make direct disposal appear dubious and risky in public opinion. Potentially, they might strengthen the interest in multinational
solutions, with the argument that geological repositories should be located in countries with a more suitable geology.

Reprocessing has in recent years lost much of its attractiveness in large parts of the developed world, for reasons discussed in the preceding sections. According to proponents of the reprocessing alternative, however, this trend may be a temporary. They argue that new reprocessing methods (such as pyroprocessing) will radically reduce the currently problematic environmental impacts of reprocessing, and that the high-level waste from reprocessing may be almost eliminated through future advanced transmutation techniques and other methods. Opponents, however, think that this will create new risks and that the new technological innovations in this area will not make economic sense. As always when it comes to the introduction of new complex technologies, it is hardly possible to tell in advance whether these new solutions will actually live up to their promises in practice.

It is against these uncertainties, in a variety of dimensions, that some countries (e.g. the Netherlands) have preferred not to formulate any long-term SNF policy at all. They want to await future developments. The perceived risks of becoming locked-into sub-optimal technical solutions here stand against the costs and risks of long-term interim storage of SNF, and against the ethical issue of handing over today’s problems to future generations.

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