Robust radioactive waste management
decision making in complex socio-technical systems

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Robust Radioactive Waste Management: Decision Making in Complex Socio-technical Systems

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Thomas Flüeler

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Part 1: Principles

Options in Radioactive Waste Management Revisited: A Proposed Framework for Robust Decision Making

Abstract

Deregulation, with concurrent pressure on electricity utilities, has fundamentally changed the once-“closed” radioactive waste management system controlled by the so-called “nuclear establishment.” Advocacy coalitions may change—who knows in which direction—but policy-learning may also take place. This article presents a framework to evaluate the management options for a specified concept of “sustainability.” When weighing the different objectives in view of the long-lasting potential danger of radiotoxic substances, the overall goal of a sound waste management is to demonstrate safety. The first-priority objective of a disposal system, therefore, is its stability, so that it can comply with the protection goal, that is, the long-term protection of humans and the environment from ionizing radiation. The complementary objective is flexibility, defined here as intervention potential. Because trade-offs within the “sustainability triangle” of ecology, economy, and society are unavoidable, the concept of “integral robustness”—technical and societal—is introduced into radioactive waste management. A system is robust if it is not sensitive to significant parameter changes. In the present case, it has to have a conservative, passively stable design with built-in control and intervention mechanisms. With regard to technical implementation, a concept called “monitored long-term geological disposal” is presented. Such an “extended” final disposal concept emphasizes technical robustness, recognizes evaluation demands (for a potential break-off of a project), and enhances process-based transparency. This open approach admittedly sets high challenges with regard to technicalities as well as the institutional setting and the management process. It requires “mutual learning” by and from all stakeholders to achieve a truly sustainable radioactive waste management.

Introduction and Background

Recent contributions in this journal have highlighted some salient issues of radioactive waste management, “one of the most intractable policy issues facing the United States and other nations using nuclear reactors for electric power generation” (p. 751). Proposals were put forward, among others, with regard to shifts in management options (away from final disposal) and the revision of the current paradigm of disposal by proposing an “ongoing safe management” which would result in a postponement of the repository closure, “perhaps indefinitely” (p. 912). Also discussed were organizational aspects, “regulatory dilemmas,” and the role of performance assessment “in the context of a wider public debate” (pp. 811-812, 838). At the latest International Atomic Energy Agency (IAEA) Córdoba Conference in March 2000 a proposition was put forth to establish a broad “international forum” because “in almost all of the Conference’s technical sessions, there was discussion of the need to involve all interested parties (‘stakeholders’) in the decision making processes related to radioactive waste management” (p. vi). The idea was also discussed at a Nuclear Energy Agency (NEA) workshop in August 2000, where a so-called “Forum on Stakeholder Confidence” was launched.

It is not by chance that the search for a new policy basis has been intensified. The management of radioactive waste is at a turning point. The political and socioeconomical framework has radically changed during the last years. Up to recently, the electricity utilities operating nuclear power plants received the support of most national authorities after having accepted their duty to establish a final disposal system. For years these parties maintained that the problem was solved “technically” but not “politically” (see, e.g., Carter). Such a technocratic approach often led to the so-called “DAD strategy” (“Decide–Announce–Defend”) common to both site proponents and regulators. This nonparticipatory concept was equally often followed by an intense political opposition, with the result that most countries still experience wide nonacceptance of waste sites and deep mistrust in involved institutions. Alternative dispute resolving techniques like consensus conferences, focus groups, and so forth were applied to the field. Their outcome was, broadly speaking, unsuccessful, but “at least” the “joint venture” between implementers and authorities—backed by the sufficient financial and human resources provided by the utilities—persisted.

This is no longer the case. Pressure on the radwaste proponents and implementers is not only exerted by large parts of the public but also by some radwaste producers who own implementing institutions. The present constellation is characterized by globalization; that is, the liberalization of the electricity market with concurrent increasing competition, and an enforced shareholder value perspective (lowest costs mean no further investment in the “back end”) with parallel cut backs in Research and Development funds. This becomes manifest in the

---

3 Trust even became a leitmotiv in radwaste risk perception research (see, e.g., Slovic et al., J. Flynn et al. For criticism on the seemingly decisive role of trust, see, e.g., Sjöberg, pp. 221-222).

4 Such a tendency could be an “early sign of declining performance” in the evaluation of organizational safety culture. Cost reduction with resulting deteriorating safety would violate Article 11 of the IAEA Nuclear Safety Convention.
search for “lean” solutions (e.g., on Pacific atolls and Russian dumps). One potential consequence is that an alliance could build up—namely, between pronuclear parties (shareholders with a wait-and-strike-later-strategy) and antinuclear groups (nuclear guardianship instead of final repositories)—which could result in indefinite intermediate storage.

We are now being confronted with a major change of external factors influencing the once-"closed" policy system “radioactive waste management” controlled by the "nuclear establishment." Advocacy coalitions may change, maybe for the worse, but policy learning may also take place. This article presents a framework to rigorously evaluate the technical community’s assessments and society’s choices of radioactive waste management approaches under the perspective of a specified understanding of sustainability. It is designed, in a transparent manner, to lay open basic value judgments and policy views of relevant stakeholders.

Dimensions, Stakeholder Views and Target Conflicts

The problem of adequately managing radioactive waste is multifaceted: In addition to the previously mentioned political dimension, it has specific technical and, of course, both ethical and social dimensions. Although radioactive waste is highly concentrated, its chemical and physical properties (no explosives, no criticality) are such that no catastrophic events have to be expected from a disposal site; in an underground (geological) site, there are no large driving forces. The main mechanism is a low-level, but long-term, chronic release into the environment. This long-term dimension of highly toxic waste is of outstanding relevance: The ones who make the profit (in this case of energy of which waste is one result) most likely do not bear the risk coming from the wastes.

The notion of sustainability attempts to recognize this characteristic. According to the Brundtland Commission in 1987, “sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (p. 46). When applied to toxic wastes, this approach of sustainability brings forth the polluter pays principle (PPP) and the precautionary principle (PP) in such a way that the present (benefitting) generations have to ensure the protection, as well as the freedom of action, of future generations.

The challenge is how to adequately integrate both principles into one sound–sustainable–concept. The nuclear community adopted the former requirement (protection) in the principles 4, 5 and 7 of the 1995 IAEA Safety Fundamentals and in 1995 NEA Collective Opinion. The Swedish National Council for for Nuclear Waste (KASAM) 1988 also emphasized the latter (controllability and, as an extreme variant, recovery): “A repository should be constructed so that it makes controls and corrective measures unnecessary, while at the same

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5 The inclusive NEA definition of “stakeholder” is pragmatically adopted: “The term ... is at best a convenient label to cover all persons or groups with an ‘interest’ in the project,” “somebody with a role to play in the process” (see ref.[4], p. 118).
time not making controls and corrective measures impossible” (p. 15). The Dutch policy even requires controllability and retrievability. (25)

When weighing the different objectives in view of the long-lasting potential danger of radiotoxic substances, the overall goal of a sound waste management is to demonstrate long-term safety. The first-priority objective of a disposal system, therefore, is its stability, so that it can comply with the protection goal; that is, the long-term protection of humans and the environment from ionizing radiation. The complementary objective is flexibility, defined as intervention potential. If this freedom of action is assessed to be the overriding principle, the result is a contradictory target relation against the background of the hazard potential.

Whether the stakeholders like it or not, ultimately, there has to be a partnership between the implementers, the public, politicians, political officials, and regulators, because all are interested in acquiring a sufficient safety level of the disposal system, even if for different reasons:

- **Implementers** have to execute the project(s) based on given safety standards (that is, demonstrate safety), to fulfill the waste producers’ responsibility to safely dispose of the waste, they want no delays, but want clear-cut requirements, at “reasonable” costs.

- **(Today’s) public** wants safety, as well as control, transparency, and full participation.

- **Future generations** presumably put safety first, want no obligation to take safety measures, and no restriction in land use; but do want control in the case of grave system failure.

- **Politicians** want all requirements, depending on the political constellation (some favor delays according to a NIMTOO attitude, that means, “Not in my Term of Office”).

- **Political officials** (e.g., Department of Energy) have to accept liability in the long term and also have to integrate public requirements.

- **Regulators (safety authority)** have to supervise the demonstration of long-term safety (for “tomorrow’s” risk bearers, in a trustee’s role) and to define today’s (and tomorrow’s?) public requirements from a safety standpoint (that is, control may not entail a simple delay of closure but must also include instruments to additionally demonstrate safety).

Because all objectives of all stakeholders can never be attained, prioritization (according to target relations just mentioned) and negotiation have to take place so as to adopt the stakeholders’ respective responsibilities. (26) It would be daring to maintain that their belief systems could be changed—certainly not in their core principles, but perhaps modifications could be made in their secondary aspects (27)—in so far as the actors would identify some common interest or, in Carter’s (28) words, some “common ground.” The above-mentioned, negative socio-economical stimuli may paradoxically serve as a prerequisite for such social learning (29) with regard to sustainability. This concept encompasses the “magic triangle” of environment (safety, protection), society (protection, acceptance), and economy (costs for waste producers but also for society) as pictured in Fig. 1.
The “magic” sustainability triangle, in principle, remains unaltered over time. The decision makers of today, however, necessarily prioritize and decide on behalf of (or: against?) those of tomorrow. Crucial questions are in front of us, like: “What does ‘economy’ mean?” “Are the costs of today’s implementer compatible to the costs of tomorrow’s authority?” “What is ‘society’?” “Are the needs of today’s society the same as the needs of tomorrow’s society/societies?” “Are all triangles equal or are some more equal than others?”

The pre-eminent task is to balance the needs of ecology, society, and economy over the years (of potential impact). The element “ecology” denominates the protection of today’s and future environment(s) and–indirectly–the protection of humans; “economy” is not dealt with in a sustainable manner unless costs are internalized; that is, the waste producers (and today’s benefitting generations) have to accept responsibility for financing the “ongoing” safety management; and the element “society” addresses the participation of, and acceptance by, the public. Furthermore, all involved parties are confronted with a formidable constraint: unlike other controversial technical issues, “nuclear waste policy was not the engine that drove politics, but the product of political, economic, and social engines which drove the politics of nuclear waste”(p. 22).
Attempts to Implementation: Technical Options

Various options have been suggested to date to cope with the sustainability requirements of protection and intervention, although each has had a different emphasis (see Fig. 2).

Figure 2. Various recommended options to comply with the main objectives of sustainability: protection and control/intervention (PPP: polluter pays principle).

To a certain extent, the concept options may be combined. The internationally accepted standards do indeed allow space for interpretation. It is, for example, crucial how the following NEA requirements for long-term disposal are met:

... it is recognised that the future behaviour of the disposal system must be understood well enough to assure that no harmful releases of radioactive substances to the environment are likely to occur .... Safety assessments must proceed iteratively with disposal system siting and development, to determine if further information is needed and, if so, what type of information is needed .... Confidence is also built through the process of assuring (or validating) that the predictive models used in safety assessments adequately represent the behaviour of the real system .... To obtain such assurance indirectly requires a systematic evaluation of modelling results against data from experiments in laboratories and in the field. (pp. 10, 13)

Criteria to Judge the Options

Definitive disposal of radioactive wastes is no decision under risk but one under uncertainty because the associated probabilities are not completely known and, therefore, a “risk” (=damage x probability) cannot be calculated. Which types of uncertainties are pre-eminent is determined by the choice of concept. As pointed out above, with deep geological repositories used as final disposals, the main relevant release scenario is not associated with an acutely induced dramatic failure but, if at all, with a slow system degradation. Long-term storage, however, is–by definition–based on controls by present and future generations. For our purpose, uncertainty (or uncertainties) may be divided into two main types. With Type 1 uncertainty (or uncertainties) may be divided into two main types.

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6 Of course, there are many more ways to approach the notion of uncertainty; for example, all the way to decision uncertainty.

7 Type 1 approximately encompasses the principal causes of uncertainty #1 through 3, as stated by the U.S. Board on Radioactive Waste Management, 1990, type 2 depicts the principal cause # 4.
tainty, knowledge is theoretically possible: stochastic and statistical uncertainty depend on data information expenditure, and model uncertainty may be reduced with increased model refinement– that is, system knowledge is, at a given time, insufficient but, in principle, extendable. With Type 2 uncertainty, however, more or less plausible scenario assumptions are (and have to be) made with an accompanying temporal and structural uncertainty with regard to future developments and human behavior. Controlled long-term storage is dominated by non-calculable Type 2 uncertainties, because neither values nor probabilities may be attributed to the effectivity of active technical control measures over the required isolation periods.

Table I gives an overview of some of the consequences that can occur if contradictory sustainability objectives are prioritized. It portrays a continuum in which the decision makers have to speak up and lay open their arguments for one option or another.

**Table 1. Implications of the dominance of the two juxtaposed sustainability objectives (reversibility/retrievability is looked at as an extreme variant of “control”). Depending on the specification of the disposal concepts in question, convergences are possible.**

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Control [degree of importance]</th>
<th>Protection [degree of importance]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protection</td>
<td>Low (in view of the possibility to repair, safety standards might be reduced in the construction phase)</td>
<td>Higher (primary objective)</td>
</tr>
<tr>
<td>Short-term safety</td>
<td>High (depending on expenses)</td>
<td>High (depending on expenses)</td>
</tr>
<tr>
<td>Long-term safety</td>
<td>Lower (secondary objective)</td>
<td>Higher (primary objective)</td>
</tr>
<tr>
<td>(Possible) system flow</td>
<td>Fast movements of societal/technical properties, not stable</td>
<td>Slow degradation of geological systems, natural phenomena partly predictable</td>
</tr>
<tr>
<td>Safeguards</td>
<td>Bad (relatively easy recuperation)</td>
<td>Good</td>
</tr>
<tr>
<td>System change</td>
<td>Possibly abrupt</td>
<td>Gradual</td>
</tr>
<tr>
<td>Potential to intervene</td>
<td>High (primary objective)</td>
<td>Low (secondary objective)</td>
</tr>
<tr>
<td>Flexibility</td>
<td>High (intervention: modification of technical barriers)</td>
<td>Low (secondary objective)</td>
</tr>
<tr>
<td></td>
<td>Danger of proliferation (primary objective)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Danger of postponement</td>
<td></td>
</tr>
<tr>
<td>Constraints</td>
<td>High (control)</td>
<td>Medium (depending on the quality of the safety assessments)</td>
</tr>
<tr>
<td>Type 1 uncertainty</td>
<td>Medium (technical barriers)</td>
<td>High (deviation, sets of data)</td>
</tr>
<tr>
<td>Type 2 uncertainty</td>
<td>High (period of effectivity of control system; unwanted intervention)</td>
<td>Medium (depending on the robustness of the scenarios)</td>
</tr>
<tr>
<td>Experience</td>
<td>Short, bad</td>
<td>Almost none</td>
</tr>
<tr>
<td>Belief in technology (progress dependability)</td>
<td>High (future “solutions,” investment into nuclear research provided)</td>
<td>Medium (existing “solutions”)</td>
</tr>
<tr>
<td>Resources (valuable substances)</td>
<td>At hand, only feasible with continued and enforced utilization of nuclear technology (partitioning/transmutation, fast breeders, advanced reactors)</td>
<td>Difficult to recover</td>
</tr>
<tr>
<td>Polluter pays principle</td>
<td>Violated</td>
<td>Adhered to in principle</td>
</tr>
</tbody>
</table>
### Table I. (continued from previous page)

<table>
<thead>
<tr>
<th>Decision takers</th>
<th>Legitimated parts of present society representing interests of present and future risk bearers</th>
</tr>
</thead>
</table>
| Collisions in interest (equity aspects) | Present generations: partly benefitting and partly risk bearing (intragenerational equity issue)  
Future generations: risk bearing (intergenerational equity issue) |
| Externalities/expenses (human, technical and financial resources) | Very high, burden to future generations (higher degree of discounting), higher belief in technological and medical progress  
High, mainly burden to benefitting generations (lower degree of discounting), adherence to present technology (that is, at disposition up to definite sealing of system) |
| Strategic background: variety of possible “hidden agendas” (no hierarchy) | 1. Long-term commitment of society to radiological burdens (“guardianship”)  
2. Willingness to recovery actions in case of major system failure (one interpretation of the notion of “freedom of action”)  
3. Resource storage for a second nuclear era (retrieveability)  
4. Political opportunism (highest chance of receiving wide acceptance)  
5. Argument for “least-cost solution” for waste producers and present generations  
6. Argument to phase out nuclear power (no “permanent solution”)  
7. Fear of “technical fix” of final disposal (reversibility) |
| Extreme option variant | Surface storage shelter  
final geological repository |

### Sustainability of Options and Paradigms

In view of the presented evaluation grid according to Table 1, the response to the salient issues stated in Introduction and Background might be as follows:

**Management options**

On the condition that the present societies do not want to force a perpetuation of nuclear technology onto future generations or install Weinberg’s civil nuclear “priesthood,” sustainability and the PPP favor final disposal in deep geological underground repositories. Compulsory reliance on (societal) control is not feasible because anthropogenic complex systems are evidently not stable (e.g., the fall of the Berlin Wall only in 1989, although relevant intelligence reports dated a few years earlier did not give any indication of such a development). Because the disposal process from site characterization via construction, monitoring,
and operation to closure takes many decades, the chain of obligation principle (as set forth by a U.S. Panel[42]) is not violated: The needs of the present and some following succeeding generations are provided for, these even take major management decisions (see Fig. 3 under the column “Public involvement”).

Counting on a substantial alleviation of the hazard potential through separation and transmutation of radionuclides would presuppose radically improved reprocessing, a well-functioning nuclear management cycle on an industrial scale using both civil and military material, and a clear commitment to nuclear research and energy policy with consequent high funding. The prerequisites and handicaps have been enumerated elsewhere.[44,45,46]

Although technically interesting, subseabed disposal is discarded because of the lack of international consensus to deposit waste in a location that is not under national sovereignty.[47] An international geological option, though also favorable with respect to the technical safety criteria listed in Table I, is subject to even higher challenges than a national one: Apart of necessary site investigations, the partners (states on behalf of public and private waste producers) would have to settle questions with regard to warranties, surveillance, compliance with national regulations, liability, and so forth. The intragenerational equity issue would be even more controversial than in a national site, because the potentially affected public would bear risks imposed via massive amounts of “foreign” waste. Additionally, such an international approach might jeopardize ongoing national efforts.

Paradigm revision

Judging the different kinds of uncertainties, the choice of the storage concept—as opposed to final disposal—does not allow for a reduction of dominant and safety-compromising uncertainties. Human intrusion scenarios would gain relevance, and intervention would be a primary objective, because one major argument for storage—or, for that matter, enduring non-closure of a repository—would be the possibility to retrieve valuable energy resources. Therefore, it would be necessary to alleviate the access to a waste site.

Delaying the decision would violate the PPP, and the ability to build on motivation and waste handling know-how of future generations could not occur unless the nuclear path were vigorously followed. Note that postponement is not a viable “disposal option,” because the implementation of a strategy deserving such a name comprises more than building a concrete bunker, or an overdesigned interim storage facility. These restrictions do, however, not mean a refusal of an “on-going safe management”[48] albeit somewhat differently defined, as outlined below.
Robustness through “Extended” Final Disposal

Because trade-offs within the “sustainability triangle” (see Fig. 1) are unavoidable, the concept of an “integral robustness”–technical and societal–is introduced into radioactive waste management. With this approach, it is attempted to minimize negative side effects resulting from a long-term disposal system. In general, a system is robust if it is not sensitive to significant parameter changes; most arguments, evidence, social alignments, interests, and cultural values lead to a consistent option. In the case of radioactive waste management, the system has to have a conservative, passively stable design with built-in control and intervention mechanisms, as outlined below. The underlying assumption when dealing with a complex sociotechnical system such as radioactive waste management is that it be designed on the basis of an integrated perspective. Consequently, the system calls for technical barriers against releases of radioactivity, as well as societal checks to achieve and sustain confidence in technical assessments and, hence, acceptance. It is, in fact, an integration of societal aspects into the defense-in-depth strategy familiar to radioactive waste-performance assessments. In this sense, the system is dynamic, adaptive, and even experimental in its instruments, but not in its ultimate goal—that is, the passive protection of present and future generations and environments. “Robustness” with regard to economic sustainability implies the adoption of the PPP, which, in turn, means that the costs have to be internalized as much as possible. They are to be carried by the waste producers and the benefitting generations so that a financial burden is not imposed on future societies, in case of repository failure.

To satisfy the NEA requirements of proof of safety as outlined in Attempts to Implementation: Technical Options, at an early planning stage, an “extended” final disposal has to be set up, which includes a sufficient monitoring program in the operational as well as in the post-operational phase to validate the previous safety analyses (to demonstrate long-term safety). With regard to technicalities, a Swiss Government-appointed Expert Group on Disposal Concepts for Radioactive Waste (EKRA) proposed a so-called “monitored long-term geological disposal.” Its key elements are a disposal site with a Test facility and a Pilot facility, in addition to the Main disposal facility (see Figs. 3 and 4).

The Test facility is to serve as a rock laboratory for the investigation of safety-relevant processes, starting from the characterization phase. It is the entrance to the Main facility, whose caverns are to be backfilled as soon as the waste is deposited. The Pilot facility is hydraulically isolated and is to be loaded with a representative sample of the waste to be put into the Main facility. The Pilot facility is to function as a “demonstration facility” to assess the long-term behavior of the technical barriers and the near-field. Retrievability is facilitated without compromising safety by way of a carefully selected cavern structure.

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8 The combined notion of technical, societal and overall system “robustness” is investigated elsewhere [See Part 2 of this Working Paper].
9 In contrast to other so-called “geological” concepts, this option is firmly based on final disposal; the plan is that, after a validation, which includes a control period to be determined (and a positive result with regard to long-term safety), the site is to be sealed.
10 This concept goes beyond the Swedish “demonstration-scale repository.”
<table>
<thead>
<tr>
<th>Data acquisition</th>
<th>Phase</th>
<th>System component</th>
<th>Regulatory act</th>
<th>Responsibility (intensity of work)</th>
<th>Public involvement</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integrated</td>
<td>Framework: criteria for inventory and break-off, design basis, procedure</td>
<td></td>
<td></td>
<td>AA**, G</td>
<td></td>
<td>All period length depending on results</td>
</tr>
<tr>
<td></td>
<td>Characterization of site (siting)</td>
<td>Initial boreholes, etc.</td>
<td>License for preparatory work</td>
<td>II*</td>
<td>A, G</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Exploratory shaft</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Test facility</td>
<td></td>
<td></td>
<td></td>
<td>Vote/approval of site and preparatory work</td>
<td>Stepwise modification of design</td>
</tr>
<tr>
<td>Design</td>
<td></td>
<td>General license</td>
<td>II</td>
<td>A, G</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Construction</td>
<td>Main facility</td>
<td>Construction license</td>
<td>II</td>
<td>A, G</td>
<td></td>
<td>Systematic and continuous evaluation of the system</td>
</tr>
<tr>
<td></td>
<td>Pilot facility</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Operation</td>
<td></td>
<td>Operating license</td>
<td>III</td>
<td>A, G</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Stepwise cavern backfilling</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surveillance</td>
<td>(post-operational)</td>
<td></td>
<td>III</td>
<td>AA, G</td>
<td></td>
<td>Independent monitoring program (for quality assurance and credibility reasons)</td>
</tr>
<tr>
<td>Stepwise closure</td>
<td></td>
<td>Closure license</td>
<td>II</td>
<td>AA, G</td>
<td></td>
<td>Vote/approval of final sealing</td>
</tr>
<tr>
<td>Sealing</td>
<td>Main facility/ Test facility</td>
<td>Decommissioning license (on the grounds of positive Pilot facility results)</td>
<td>II</td>
<td>AA, G</td>
<td></td>
<td>Decision on sealing or break-off</td>
</tr>
<tr>
<td>Additional</td>
<td>(Passive) monitoring</td>
<td>Main facility</td>
<td>State ownership</td>
<td>AA</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Active monitoring</td>
<td>Pilot facility (access shaft closure undefined)</td>
<td></td>
<td>A, G</td>
<td>Vote/approval of “final” assessment</td>
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Figure 3. Proposed schematic overview of disposition phases, data gathering and responsibilities of the implementer (I*) and the safety authorities (A**). This is not to question the “undivided” responsibility of the waste producers, respectively the implementer, but to indicate the degree of intensity of work to be done by the parties (e.g., A<AA). Also indicated is the involvement of an independent oversight group (G) and of the public at major decision points. The concept of Test facility (a rock lab to produce the safety case), Main facility (the actual final repository) and Pilot facility (equipped with a controlling program to demonstrate long-term safety) is adopted from the Expert Group on Disposal Concepts for Radioactive Waste (EKRA). (43)
Figure 4. The key elements of the so-called “monitored long-term geological disposal” proposed by the Swiss Expert Group on Disposal Concepts for Radioactive Waste (EKRA)\(^{56}\) are three facilities: a Test facility, a Pilot facility, and the Main disposal facility. The Test facility shall be erected during or shortly after site characterization in the host rock and serves as a rock lab for the investigation of safety-relevant processes to specify the safety analysis and to adequately plan the design of the Main facility. The Test facility could be situated at the entrance to the Main facility, whose caverns containing 95 per cent of the waste (black boxes) are to be backfilled as soon as the waste is deposited. The Pilot facility is hydraulically isolated; the intent is to load it with a 5% representative sample of the total waste activity. The Pilot facility shall function as a so-called “demonstration facility” to assess the long-term behavior of the technical barriers and the near-field of the entire disposal system. It is conceivable that the Pilot facility could be kept open after the Main/Test facility is closed by backfilling. A carefully selected cavern structure facilitates retrievability from all facilities without compromising safety. For validation and surveillance purposes, several tunnels are foreseen to survey the facility near-fields and to carry out environmental monitoring in the surroundings of the host rock toward the biosphere. After the observation phase (period to be determined) the waste is retrieved (in case of system failure) or the facilities are sealed (in case of a positive final safety analysis). A passive self-closure mechanism is provided for, in case rapid sealing becomes necessary. Diagram from EKRA.\(^{56}\)

Such a modified final disposal concept emphasizes technical robustness (in line with Thompson\(^{57}\)), recognizes evaluation demands (for a potential break-off of a project), and enhances process-based transparency.\(^{58}\) Robustness builds on plausibility and step-by-step validations. This would counteract the technical community’s fear that “complexity kills confidence” by way of oversophisticated modeling. This approach enhances reliability and predictability—for society and for the implementers. On the one hand, it has to be technically and financially assured that the waste producers and their implementing institutions, respectively, safely execute closure of the repositories. On the other hand, from definitive closure on, it has to be admitted that continued environmental monitoring does not result in gaining more safety.

The necessity to integrate different requirements and the step-by-step approach calls special attention to the role of the regulatory authorities. They have to be strong and independent in providing a technical and an institutional monitoring program, as well as, on the
whole, an open and transparent, yet reliable process (Fig. 3). Hence, the “regulatory dilemmas”
go far beyond those rightly put forth by Thompson. Before closure, the authorities have to
ensure that waste producers, applicants and operators carry out their work, until validation of
the safety analyses, according to the state of the art. After definitive closure ("sealing"), the
overall responsibility has to be taken over by an institution with a chance of surviving longer
historical periods (presumably a national state). Consequently, the authorities as trustees for
the public(s), have to guarantee long-term safety by independently monitoring the near-field of
the repository over a sufficient period of time. In IAEA peer discussions senior regulators, there-
fore, “agreed that regulatory bodies need to accept the value of being learning organiza-
tions” (60) (p. 11). This, in turn, presupposes adequate resources and international knowledge
transfer. (61)

Evidently, much conceptual and practical work remains to be done in terms of specifying
the notion of “extended” final disposal. (62) (For example, much effort has to be directed toward
the development of surveillance targets, measuring parameters, and monitoring period [in-
formation closure], and explanatory power of the Pilot facility with regard to the Main facil-
ity.) With respect to the proposed Swiss site for low- and intermediate-level radioactive waste
at Wellenberg in Central Switzerland, in mid 2000 the prospective “host” canton (state) of
Nidwalden appointed an independent “Cantonal Expert Group Wellenberg (KFW)” to advise the
local Government and public. The people of the Canton Nidwalden had rejected the propo-
nent’s application for a full site license in 1995. The Group is to accompany the revised proposal
of the Genossenschaft Nukleare Entsorgung Wellenberg (GNW), a co-operative owned by the
Swiss nuclear utilities, to first excavate an exploratory shaft for site characterization. Only upon
positive results shall a site license to construct and operate a disposal facility be applied for (see
Fig. 3). The oversight expert group mentioned is to formulate, and review implementation of,
criteria for inventory and break-off, design specification according to the mentioned EKRA con-
cept and procedure.

**Institutional Confidence Building**

To handle uncertainty, science gradually develops more sophisticated technical models
and methods, institutionally it utilizes peer-reviewing. In cases in which uncertainty is high,
safety margins are built in; so-called conservatism compensates for ignorance—that is, insuffi-
cient knowledge. The public is in an even harder position with regard to the waste issue. They
are confronted with a highly complex safety analysis methodology, a narrow expert commu-
nity with clear interests and tasks (e.g., legal requirement to prove safe disposal), stakeholders
who have even more pronounced interests (find a quick and cheap radwaste solution to pursue
the nuclear path), technical fixes, and the reproach to understand nothing but stay out of the
way of the “solution.” They are equally confronted with successful pressure groups who de-
mand the “best” disposal sites at any costs and present critical experts and safety-compromis-
ing examples. In the media, people read and hear of incidents or accidents in nuclear installa-
tions, contaminated railway wagons, “systematically” falsified safety documents in nuclear installations, and so forth.

In such situations, it is difficult to compensate lack of knowledge (societal uncertainty) with confidence in the responsible bodies, a procedure usually chosen. Confidence and trust are multifaceted\(^\text{(66)}\) and depend on the “degree of organized safety”\(^\text{(67)}\) set up by the institutions involved. Trust has to build on credibility, authenticity, consistence and coherence of argumentation as well as respective action by those institutions in charge.\(^\text{(68,69)}\)

If there is a confidence crisis, it is institutional;\(^\text{(70,71)}\) and it must be coped with institutionally. Certain prerequisites are given: Independent, strong and competent proponents, implementers, and regulatory bodies have to carry out their respective tasks, and their funding has to be alimented by the waste producers; the fund, however, should be state managed and utilized on recommendation of an external expert commission (this aspect deals with the robustness, that is, stability, of the corner “economy” in the sustainability triangle, as pictured in Fig. 1). Information provided to the public has to be adequate, truthful, open, active, and understandable.

This is not enough, however: The public (at least the interested parties) has to be given opportunity to truly participate in the process; the public should not just be informed and convinced (of “objective” facts), but be integrated as a major problem identifier.\(^\text{(72)}\) Nongovernmental organizations representing considerable numbers of concerned citizens and having notable technical competence might be looked at as “warning systems for established actors.”\(^\text{(73)}\) The analysis of the decision process in Switzerland\(^\text{(74)}\) revealed that salient critical points were raised by experts but also by the public and successively taken up by the responsible bodies. Among the critical points raised were the following: separation of promotion and control within the energy and nuclear authorities, adequate funding, full publication of studies, traceability (of argumentation, especially of siting), transparent formulation of criteria (for exclusion, for inventories, and so forth), controllability, retrievability, extensive independent reviewing, and involvement of the public (e.g., in advisory committees).

**Conclusion: Need for Learning from Each Other**

All stakeholders have to realize that, in the end, effectively sustainable radioactive waste management can only result from transdisciplinary “mutual learning”—learning from each other. “Transdisciplinarity aspires to make the change from research for society to research with society ... mutual learning sessions ... should be regarded as a tool to establish an efficient transfer of knowledge both from science to society and from problem owners (i.e. from science, industry, politics etc.) to science”\(^\text{(75)}\)(p. 13).

To secure knowledge and experience transfer, a comparison of “lessons learnt” in national and international projects and processes in view of diverse political, cultural and socio-economical contexts could amount to start an interchange of “good practices” that strive for an
“on-going” process-based sustainable management of radioactive waste.” We have to be aware of the fact that such an open approach sets high challenges to the management process by duly considering expert and dissenting opinions in time. Scientifically, unresolved issues remain, such as the question of how to integrate the main principles of sustainability (passive safety and control mechanisms) into an (open) disposal system. Additionally, several types of uncertainty have to be mastered. On the political level, several achievements have to be made by the different stakeholders—among others, a common perception of factual problems (minimum consensus on the nature of the problem), a common definition and, optimistically, view of protection goals (discussion and hierarchy of objectives), a consent on viable management options, including a set of methods to tackle the problem. Such findings should be so robust that they would not dissolve when it actually comes to siting.

The proof of success of the process envisaged above would be via complete and early public involvement. With regard to “societal robustness,” based on continuous safety reporting, the public of concerned siting regions would vote on the decisive phases like site characterization, construction, closure, and final assessment (see Fig. 3). With regard to evidentiary equity, the siting region would have the right to establish an accompanying expert group or even a “three-party liaison group” at the state’s or waste producers’ expense so that it would be able to costeer and evaluate the ongoing technical and institutional process at least over several decades until the sealing of the main repository and the Pilot facility, respectively, occurred. Technicians have to be aware of the fact that the problem of a sustainable management of radioactive waste is eminently driven by technology, but has to be solved by society.

A parallel approach such as the one as described above should facilitate and enhance the confidence of both experts and the public in the repository system and the institutional supervision, as well as the confidence of implementers and regulators in political back-up. Stepwise time-consuming procedure does not equal postponement as was mistakenly said of the strategy followed by “most European countries” (p. 1282); in fact, the Swedish experience seems to be promising. Especially in view of the long-term risks, we ought not to strive for a short-sighted, short-term “efficiency.” Overriding the public has proven counter-productive, and latency periods have enabled the stakeholders to propose more robust concepts, as the case of “extended” final disposal demonstrates. Finally, transactional costs via delays and unpredictability of the process must not be neglected, especially in the context of the above-mentioned deregulation aspects.

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11 The interchange of “lessons learnt” with regard to performance assessments is a good inter-expert start. See ref. (76,77) See ref. (4, 4a)

12 Ballard and Kuhn propose such a constellation, albeit for general siting purposes: one group to analyze pros, one to go into cons of a planned site, together with an “impartial mediator committee.”
Acknowledgments

The author’s opinion is expressly his own. He is grateful to the anonymous reviewers for their critical, but supportive, comments and to Ph. Tipping for language-editing. This article was based on three contributions: a speech held before the Parliamentarian Group for Education, Science, Research, and Technology of the Swiss House of Representatives, Berne, 1998-3-2, an Input Paper for a workshop organized by the National Academies of Science/Board on Radioactive Waste Management (see ref. [47]) in Irvine, CA, 1999-11-4/5; and a paper for a so-called “mutual learning session” at the International Transdisciplinarity Conference, Zurich, 2000-2-29. Criteria for a comparison of management concepts are drawn from the author’s doctoral dissertation at ETH. It empirically relies—among others—on content analysis, a recommendation recently made by Thompson.

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Part 2: Implementation

Robustness in Radioactive Waste Management. A Contribution to Decision Making in Complex Socio-technical Systems

Abstract

The nuclear waste community has come to acknowledge that not only technical challenges have to be integrated into a total-system performance of waste disposal but also interested stakeholders should be adequately involved in the decision process. The objective is to propose a stepwise approach to integrate both tracks, technical and societal robustness, into performance assessments. It is considered a vital need in view of the changing environment in radioactive waste management entailing cutbacks of investments in the “back end” of energy and material cycles. This calls for a prudent but determined approach to tackle the issue along a sustainable route while the present generations benefit from the use of nuclear power and resources—human, technical, and financial—are still sufficiently available.

Introduction

In a review of the developments in the last decade, the Nuclear Energy Agency Radioactive Waste Management Committee (NEA RWMC) recognized a better integration of the main technical challenges of deep geological disposal projects, such as the design of engineered systems, the characterization of potential disposal sites, and the evaluation of total-system performance [1]. A year later, in 2000, the RWMC conceded that “radioactive waste management institutions have become more and more aware that technical expertise and expert confidence in the safety of geologic disposal of radioactive waste are insufficient, on their own, to justify to a wider audience geologic disposal ... the decisions, whether, when and how to implement [it] will need a thorough public examination and involvement of all relevant stakeholders”. Accordingly, in line with endeavours of the International Atomic Energy Agency (IAEA) [2], it established a so-called “Forum on Stakeholder Confidence” whose format is currently being developed [3][4].

Methodology

General

The interconnection of technical and social aspects is also topic of a study carried out at the Swiss Federal Institute of Technology (ETH) Zurich since 1997 [5]. One goal is, by means of a content analysis [6] to reconstruct the decision processes of the two concrete Swiss case studies, viz., the repository siting of high-level radioactive waste as well as low- and intermediate-level radioactive waste, respectively. The second goal is to introduce and specify the concept of “integrated (overall system) robustness”—technical and societal—into radioactive waste management on the basis of the performance assessment literature and the findings of the document analysis. The extreme options under scrutiny are geological disposal in the deep underground and controlled long-term surface storage.

Generally spoken, a system is robust if it is not sensitive to significant parameter changes, e.g., due to external influence. As a matter of course, robust procedures as defined in a narrow sense can only be achieved when the problem at hand is strictly technical. Yet, the system characteristics of radioactive—and chemically toxic—waste are unique and technically complex. Once defined, radioactive waste is to be stored in a safe way since it emits hazardous ionizing radiation. According to their hazard potential, the substances involved have to be kept away from the biosphere for several hundreds of years in the case of low- and intermediate-level radioactive waste and up to, say, several hundred-thousands of years for high-level and long-lived intermediate-level radioactive waste.

Though the waste is highly concentrated, its chemical and physical properties (no explosives, no criticality) are such that no catastrophic events have to be expected from a disposal site; in an underground (geological) site, there even are no large driving forces. The main mechanism is a low-level but long-term, chronic release into the environment; it is a slow degradation of an open system with concurrent large uncertainties. Such potential impacts are hard to detect with respect to location and time (except for some scenarios of human intrusion). These system characteristics lead to the admission that the required long-term safety “is not intended to imply a rigorous proof of safety, in a mathematical sense, but rather a convincing set of arguments that support a case for safety” [7][8]. Therefore, even technical robustness cannot be treated as in “conventional” technical systems. Nevertheless, it is precisely the robust control systems that are designed to manage the mentioned uncertainties.

Handling uncertainties

Definitive disposal of radioactive waste is no decision under risk but one under uncertainty because the associated probabilities are incompletely known [9]. Which types of uncertainties are pre-eminent is determined by the choice of concept. As pointed out above, with deep geological repositories used as final disposals, the main relevant release scenario is not linked to an acutely induced dramatic failure but, if at all, to a slow system degradation. Long-term storage, however, is—by definition—based on controls by present and future generations. For our purpose, uncertainty—or uncertainties—can be divided into two main types: stochastic,
statistical and model uncertainty on the one hand, scenario uncertainty on the other hand. With scenario uncertainty, more or less plausible scenario assumptions are (and have to be) made with an accompanying temporal and structural uncertainty with regard to future developments and human behaviour. Controlled long-term storage is dominated by this second type of uncertainty because neither values nor probabilities may be attributed to the effectivity of active technical control measures over the required isolation periods. The example demonstrates the interrelationship of technical and societal aspects in radioactive waste management and, hence, the usefulness of the notion of “integrated” robustness.

The underlying assumption of the study is that an integrated perspective is needed to deal with a complex sociotechnical system [10]. A sound radioactive waste management calls for technical barriers against releases of radioactivity as well as for societal checks to achieve and sustain confidence in technical assessments and, hence, acceptance. It is, in fact, an integration of societal aspects into the defence-in-depth strategy familiar to radioactive waste performance assessments (Fig. 1).

Figure 1. The various types of robustness are idealized as lines (or “shells”) of defence in depth. The overall system robustness comprises two main sub-shells: the technical robustness and the societal (=decision) robustness. They are not strictly sequenced as depicted but interlaced (e.g., societal decisions on nuclear legislation have impacts on the disposal design directly influencing engineered and intrinsic robustness). This is also to say that the approach is not “objectivistic” by putting technical and societal “robustness” on the same level. The final and decisive validation is the implementation of a disposal concept with demonstrated long-term safety backed up by respective decisions and actions.
Track 1: From technical robustness ...

There is wide international consensus that long-term radiation safety should not depend unduly on active measures. Hence, protection should be implemented primarily at the design stage [11]. Due to the required longevity of the disposal system, “[t]he aim of the performance assessment is not to predict the behaviour of the system in the long term, but rather to test the robustness of the concept as regards safety criteria” [12].

According to NEA [13], technical robustness can be subdivided into:

- engineered robustness: “[i]ntentional design provisions that improve performance” like overbuilding of barriers, waste conditioning in a stable matrix, and physical separation of the waste into sets of package of limited size

- intrinsic robustness: “[i]ntentional siting and design provisions that avoid detrimental phenomena and the sources of uncertainty” like siting in deep underground of sedimentary layers with self-healing properties and uneventful history, away from potential resources

- (technical) system robustness: combination of siting and design provisions supplemented by peer-review and quality assurance procedures.

Prediction of health detriments over very long time periods is critical. Therefore, it is useful to consider other safety indicators than dose and risk criteria [14]. This approach leads to

- performance robustness: comparison of the anthropocentric criteria individual human dose and risk with waste and environmental safety indicators which are ruled by less uncertainty than the aggregated radiological protection goals.

Track 2: ... to societal robustness ...

The latter, systems, approach recalls the fact that the various project stages of a disposal site—from site selection, characterization, design, construction, operation, to closure—take at least several decades. Therefore, managerial concepts and principles have to be integrated into a consistent and incremental decision-making path.

To analyze society’s relevant requirements for a waste disposal, suitable categories for the document analysis starting in the 1950’s had to be worked out. The approach was from two angles: The first perspective started from the concerned public. It adopted insights from risk perception research dealing with the public’s view of risks. Over a thousand documents were checked against the following criteria [15]:

- type of risk notion: risk definition, risk type, risk „target”

- type of hazard: damage potential, scientific uncertainties/controversies, experience with hazard, voluntariness resp. the compulsory conditions to take a risk, (individual) controllability of a risk, reversibility of actions, „familiarity” of damage type

- social context: perceived profit resulting from a specific risk (incl. responsibility), temporal and geographical distribution of risk, concern, degree of information, possibility to
recognize and to understand technical risk sources, individual's and public confidence into institutions managing and controlling risk sources.

The second perspective was that of institutional decision-making. It utilized insights from normative as well as empirical decision research assuming that complex decision situations may only be met adequately if certain prerequisites are given, i.e., sufficient system knowledge, recognition of perception and communication problems (see first perspective), avoidance of logical fallacies, consideration and adaptation of problem structures, and analysis of target relations (such as passive safety vs. active control measures). The documents mentioned were examined likewise. It was refrained from statistically evaluating the results because sampling was not done at random and the documents were too heterogeneous. The aim was not statistical representativity but the generation of patterns and lines of reasoning.

**Results and Discussion**

During the decision process salient critical points were raised (by experts and the public) and successively responded to by the responsible bodies. Among them are the following: separation of promotion and control within the energy and nuclear safety authorities, adequate funding, full publication of studies, traceability (of argumentation, esp. of siting), transparent formulation of criteria (for exclusion, for inventories, etc.), controllability, retrievability (without compromising passive safety), extensive independent reviewing, stepwise and incremental procedure, and involvement of the public (e.g., in advisory committees). These requirements are in line with conclusions the nuclear community has recently drawn from their experience [16]. The key need is assessed to be the involvement of the public.

A system is socially robust if most arguments, evidence, social alignments, interests, and cultural values lead to a consistent option [17]. So the affected and interested stakeholders have to agree on some common interest and, eventually, reach a robust, i.e., stable decision. The ethical basis could be the principle of sustainability. It tries to recognize the outstanding characteristic of highly toxic waste: its long-term dimension. According to the Brundtland Commission “sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs” [18]. Applied to toxic wastes, this approach of sustainability brings forth the polluter pays principle and the precautionary principle in such a way that the present (benefitting) generations have to ensure protection as well as freedom of action of the future generations. The challenge is how to adequately integrate both principles into one sound–sustainable–concept. A framework for a comparison of disposal options is presented elsewhere [19].

Society’s shared view might be found along the following lines of reasoning. Whether the stakeholders like it or not: Ultimately there has to be a partnership between implementers, public, politicians, public administrators, and regulators since all are interested in acquiring a sufficient safety level of the disposal system even if it is for different reasons:
implementers: have to execute the project(s) based on given safety standards (i.e., demonstrate safety) in order to fulfil the waste producers’ responsibility to safely dispose of the waste, they want no delays but clear-cut requirements, at “reasonable” costs

(today’s) public: want safety as well as control, transparency and full participation

future generations: presumably put safety first, want no obligation to take safety measures, no restriction in land use; possibly control in the case of grave system failure

politicians: want all depending on the political constellation (some favour delays according to a NIMTOO attitude, i.e., “Not In My Term Of Office”)

public administrators (e.g., Department of Energy): have to accept liability in the long term and to integrate public requirements

regulators (safety authorities): have to supervise the demonstration of long-term safety (for “tomorrow’s” risk bearers, in a trustee’s role) and to define today’s (and tomorrow’s?) public requirements from a safety standpoint (i.e., control may not be a simple delay of closure but must be an instrument to additionally demonstrate safety).

Because all objectives of all stakeholders can never be reached, prioritization and negotiation have to take place so as to adopt their respective responsibility [20]. It would be daring to maintain that the stakeholders’ belief systems could be changed, certainly not in their cores but maybe modified in their secondary aspects [21] in so far as the actors would identify some common interest or find some “common ground” [22] for a consistent option. Such a shared interest relies on some form of co-operation which is driven by social trust based on common group membership. Social trust, in turn, affects performance-oriented confidence by conditioning judged performance. It is, therefore, obvious that only if a minimum relationship of trust is given, discussions of technical aspects of risk management are usefully conducted [23].

These relations have to be kept in mind when setting up institutional lines of defence in depth. The choice of regulatory and other control is largely decided by non-scientific considerations. Institutional control is active (maintenance and monitoring/validation, reviewing), passive (zoning and land marking against human intrusion), and intermediate (documentation, know-how transfer, and training). As the IAEA puts it: “Control must, thus, contribute to making the storage site a social reality, i.e., the control should be implemented in an ‘active’ way, allowing the stakeholders involvement in it” [24].

In the case of radioactive waste management, the disposal system has to have a conservative, passively stable design with built-in control and intervention mechanisms, as outlined below. In this sense, the approach is dynamic, adaptive, even experimental [25] in its instruments but not in its ultimate goal, i.e., the passive protection of present and future generations and environments. “Robustness” with regard to economic sustainability implies the adoption of the polluter pays principle which, in turn, means that the costs have to be internalized as much as possible. They are to be carried by the waste producers and the benefitting generations in order not to lay a financial burden on future societies in case of repository failure.
... on the route of sustainable Implementation: “extended” final disposal

To satisfy the NEA requirements for demonstration of safety [26], at an early planning stage, an “extended” final disposal has to be set up, with a sufficient monitoring programme in the operational as well as post-operational phase to validate the previous safety analyses (to demonstrate long-term safety). With regard to technicalities, a Swiss Government-appointed Expert Group on Disposal Concepts for Radioactive Waste proposed a so-called “monitored long-term geological disposal” [27]. Its key elements are a disposal site with a Pilot facility besides the Main disposal and Test (lab) facilities. The Pilot facility is hydraulically isolated and intended to be loaded with representative ca. 5 per cent of the total waste activity. It is to function as a so-called “demonstration facility” to assess the long-term behaviour of the technical barriers and the near-field of the entire disposal system. It is conceivable to keep the Pilot facility open after the Main/Test facility is closed by backfilling. A carefully selected cavern structure facilitates retrievability from all facilities without compromising safety. After the observation phase (period to be determined) the waste is retrieved (in case of system failure) or the facilities are sealed (in case of a positive final safety analysis).

Such a modified final disposal concept emphasizes technical robustness, recognizes evaluation demands (for a potential break-off of a project), and enhances process-based transparency [28]. Overall system robustness with its institutional measures builds on plausibility and step-by-step validations. This can counteract the technical community’s fear that “complexity kills confidence” by way of over-sophisticated modelling. It enhances reliability and predictability–for society and for the implementers.

The necessity to integrate different requirements and the step-by-step approach calls special attention to the role of the regulatory authorities. They have to be strong and independent in providing a technical and an institutional monitoring programme as well as, on the whole, an open and transparent, yet reliable process. Before closure, the authorities have to supervise that waste producers, applicants and operators carry out their work, until validation of the safety analyses, according the state of the art. After definitive closure ("sealing"), the overall responsibility has to be taken over by an institution with a chance of surviving longer historical periods (presumably a national state); consequently, the authorities as trustees for the public(s) have to guarantee long-term safety by independently monitoring the near-field of the repository over a sufficient period of time. In IAEA peer discussions senior regulators, therefore, “agreed that regulatory bodies need to accept the value of being learning organizations” [29]. This, consequently, presupposes adequate resources and international knowledge transfer [30].

Evidently, much conceptual and practical work remains to be done in specifying the notion of “extended” final disposal, e.g., concerning surveillance targets, measuring parameters and monitoring period as well as explanatory power of the Pilot facility. With respect to the proposed Swiss site for low- and intermediate-level radioactive waste at Wellenberg in Central Switzerland, in mid 2000 the prospective “host” canton (state) Nidwalden appointed an inde-
pendent “Cantonal Expert Group Wellenberg” to advise the local Government and public. This oversight expert group is to formulate, and review implementation of, criteria for inventory and break-off, design basis according to the mentioned EKRA concept, and procedure.

With regard to societal (decision) robustness, based on continuous safety reporting, the public is to vote on the decisive phases like site characterization, construction, closure, and final assessment. Such a parallel approach shall facilitate sufficient confidence both of experts and public in the repository system and trust in the institutional supervision as well as of implementers and regulators in political back-up.

**Conclusion: Mutual Learning Wanted to Eventually Achieve Mutual Trust**

All stakeholders have to realize that, in the end, effectively sustainable radioactive waste management can only result from transdisciplinary “mutual learning”—learning from each other. To secure knowledge and experience transfer, a comparison of “lessons learnt” in national and international projects and processes in view of diverse political, cultural and socio-economical contexts could amount to start an interchange of “good practices” [31] striving for an “on-going” process-based sustainable management of radioactive waste.

We have to be aware of the fact that such an open approach sets high challenges to the management process [32] by duly considering expert and dissenting opinions in time [33]. Scientifically, unresolved issues remain such as the question of how to integrate the main principles of sustainability (passive safety and control mechanisms) into an (open) disposal system. Additionally, several types of uncertainty have to be mastered. On the political level, several achievements have to be made by the different stakeholders, i.a., a common perception of factual problems (minimum consensus on the nature of the problem), a common definition and, optimistically, view of protection goals (discussion and hierarchy of objectives), a consent on viable management options, including a set of methods to tackle the problem. Such findings should be so robust that they would not dissolve when it actually comes to siting.

At any rate, technicians have to be aware—and I believe they have become aware—of the fact that the problem of a sustainable management of radioactive waste is eminently technology-driven but has to be solved by society. As the philosopher of science, Helga Nowotny, puts it in a general way: “A 21st century view of science must embrace not only a wider societal context, but be prepared for the context to begin to talk back. Reliable knowledge will no longer suffice, at least in those cases, where the consensuality reached within the scientific community fails to impress those outside ... more will be demanded ..., namely a shift towards socially robust or context-sensitive knowledge” [34].

In light of this complex setting, it must have become evident that no recipe list or standardized design for “successful radwaste siting” can be achieved. The outline should rather propose an approach to a coherent strategy, scientifically sound not to lead to arbitrary decisions but flexible enough to be tailored to the respective local/regional political, social and cultural context [35].
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