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A Decision-Analysis Framework to Support Risk Assessment for Geologic Radioactive Waste Disposal Systems

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Abstract

Safety assessments for geologic radioactive waste disposal systems involve risk assessments that cover many topics within a wide range of technical disciplines. Priorities should be set for investigating these topics to ensure that the most important aspects of the repository behavior are well understood. This paper presents a decision-analysis framework designed to support such risk assessments by identifying important issues upon which to focus technical work. Key attributes of this framework are (i) an analytical procedure that integrates risk perception with technical evidence, (ii) an algorithm that does not involve execution of a mathematical simulation model, and (iii) a set of metrics that indicate the important technical issues for the risk assessments. A demonstration of the decision-analysis framework on a hypothetical geologic repository highlights the joint impact of perception and evidence on decisions that inform priorities for advancing technical work and building confidence in projections of future behavior for radioactive waste disposal systems. Potential applications to other systems analyses are discussed.

Keywords: Decision analysis; evidence; perception; radioactive waste; repository system; risk assessment

1 Introduction

Radioactive waste results from civil and military nuclear power generation, decommissioning of nuclear service facilities, medical and research uses of radioactive materials, and various industrial activities. In all cases radioactive waste

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needs to be managed responsibly to ensure public safety and protection of the environment now and in the future.

The concept of isolating radioactive waste from the human environment via permanent storage in deep underground repositories (geologic disposal) was developed in the 1950s and is currently the preferred option for long-term waste management worldwide (Nuclear Energy Agency, 1999). In general, geologic disposal involves a multi-barrier approach using engineered barriers, whereby the radioactive waste is converted to a physically and chemically stable form and encapsulated inside durable containers, and a natural or geologic barrier, whereby the containers are emplaced deep underground in a host rock, and all access to the underground facility is permanently closed using appropriate sealing materials. The host rock is typically chosen with the expectation of providing a stable physical and chemical environment for time frames on the order of a million years (Nuclear Energy Agency, 2004*a*). Such an environment can enhance the safety of the repository by prolonging the effectiveness of the engineered barriers—for example, containers can be more durable if they do not come in contact with corrosive groundwaters (Nuclear Energy Agency, 2003). Also, in the event that the radioactive waste escapes containment, movement of the released material may be substantially slowed by the hydrogeologic properties of the host rock which may include very slow groundwater velocities and reactive mineral assemblies that tend to fixate the waste. The net effect of these actions is to delay potential human contact with the released material, thus allowing more time for radioactive decay.

A geologic repository is considered safe if it meets the relevant standards for public health and protection of the environment. Most national regulations specify safety criteria for radioactive waste disposal in terms of radiological dose or risk (Nuclear Energy Agency, 2004*b*). Thus, risk assessment plays a key role in demonstrating the safety of geologic repositories. Risk assessment of a geologic repository involves an integration of technical evidence, mathematical models, and qualitative arguments aimed at building confidence in the safety of the repository. Such confidence forms the basis for regulatory and technical discussions and decisions at every stage during the planning, development and implementation of the repository. A key factor in building confidence relates to the very long time scales of concern. Clearly, special attention must be given to the associated uncertainties (Nuclear Energy Agency, 2004*a*). Deliberations on the long-term safety of geologic repository systems often reveal issues of concern that may require further technical investigation. Estimates of radiological doses for many thousands of years into the future are bound to be uncertain, more so if the attributes of waste isolation included in the risk assessment—namely containment, retardation and attenuation—depend on physical or chemical properties and processes that are not well known at present. Also, the perception of risk, informed by expert and non-expert opinions, may provoke research into specific aspects of the repository system. When these studies involve multidisciplinary technical issues, priorities should be established to ensure that the most important aspects of repository behavior are well understood. Decision-analysis methods can be critical in establishing a logical set of priorities.

This paper presents a decision-analysis framework designed to integrate risk perception with technical evidence. It employs a simple computational procedure that generates metrics to rank the importance of technical issues considered in risk assessments for geologic repository systems. An exploratory application of the procedure to a hypothetical repository system demonstrates the joint impact of perception and evidence on decisions that inform priorities for advancing technical work, and for building confidence in projected performance of radioactive waste disposal systems. Although developed for radioactive waste disposal systems, this decision-analysis framework can be adapted for other complex natural and engineered systems.

2 Methods

The decision-analysis framework represents three interrelated aspects of safety assessment for geologic repositories—technical issues, risk factors and conceptual models (Figure 1). Technical issues are the focal topics for the development and implementation of the repository. Priorities for decision making are set in terms of the technical issues. Conceptual models include the various features, events, and processes believed to govern the long-term behavior of the repository. The conceptual models are assumed to include all technical evidence related to the repository. Risk factors are derived from multiple perspectives on threats and vulnerabilities that create perception of risk. Whereas, the conceptual models are developed strictly from expert judgment, the risk factors may be defined by knowledgeable non-experts. To implement the decision-analysis framework, a computational procedure is employed for mapping the risk factors and conceptual models to the technical issues. The procedure uses simple matrix data structures and operations resulting in a set of metrics for ranking the significance of the technical issues. The risk factors are organized in a hierarchical model (see, for example, Figure 2) and the procedure may be applied to information at any level of the hierarchy. Conceptual models for radioactive waste disposal systems are often assembled based on information extracted from an international database of features, events, and processes (FEPs) for geologic disposal of radioactive waste (Nuclear Energy Agency, 2000). For an exploratory application of this procedure, the number of records extracted from the FEP database is adopted as a measure of the technical evidence included in the conceptual models.

The data structures featured in the procedure include a connectivity matrix, $\mathbf{C}$, a score matrix, $\mathbf{S}$, and a topology matrix, $\mathbf{T}$. $\mathbf{C}$ is a binary matrix that links the risk factors (row headers) to the technical issues (column headers), and may be regarded as a crude sensitivity matrix in which an entry of 1 indicates that a direct relationship exists between the index risk factor and technical issue. $\mathbf{S}$ completes the mapping of the risk factors and conceptual models to the technical issues by representing the distribution of technical evidence among the non-zero elements of $\mathbf{C}$. $\mathbf{S}$ is used to estimate correlations and variations among the technical issues leading to $\mathbf{T}$, which depicts multiple rankings of the technical issues. The algorithm of the procedure is described in the following steps:

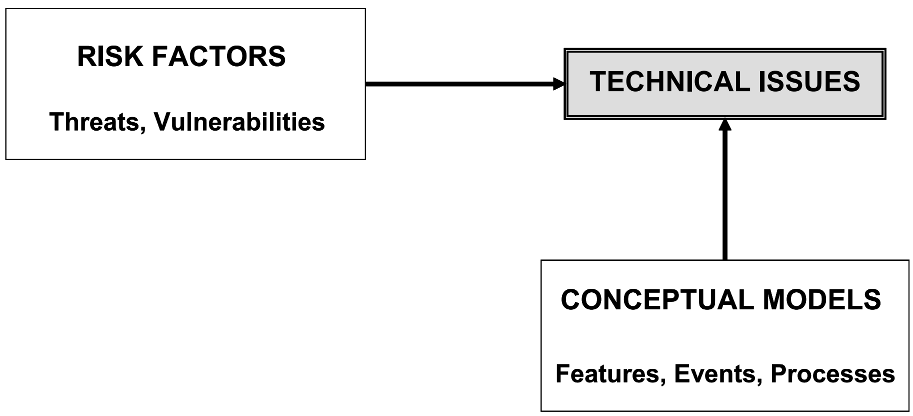

Figure 1: Decision-Analysis Framework for Integrating Risk Perception (Risk Factors) with Technical Evidence (Conceptual Models)

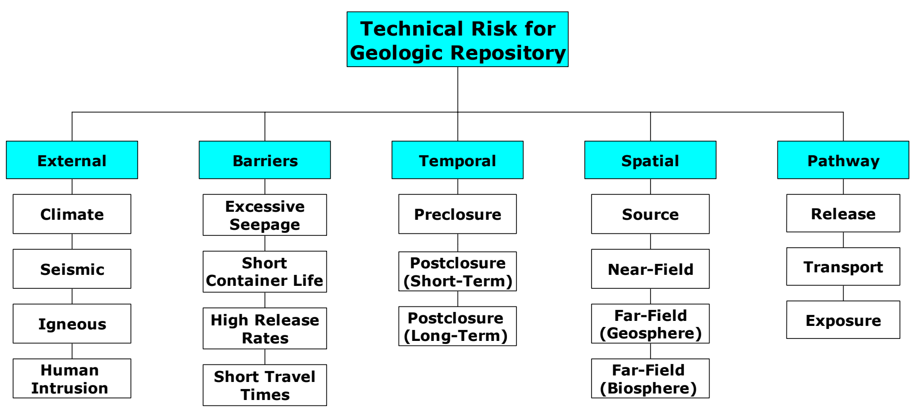

Figure 2: Hierarchical Model of Risk Factors for a Geologic Waste Repository System

1. List the technical issues to be considered for the repository system.
2. Select the desired hierarchy level for the analysis and list the relevant risk factors.
3. Generate the matrix **C** representing the link between the risk factors and the technical issues.

   $$\mathbf{C} = \begin{bmatrix} c_{1,1} & \cdots & c_{1,n} \\ \vdots & \ddots & \vdots \\ c_{m,1} & \cdots & c_{m,n} \end{bmatrix} \tag{1}$$

   where m is the number of risk factors at the selected level of the hierarchical model, and n is the number of technical issues defined in step 1.
4. Generate the vector **FEP-TI** containing the number of records selected from the FEP database for each of the technical issues defined in step 1. Each record of the FEP database may be associated with one or more technical issues.
5. Compute the matrix **S**. Distribute the count of features, events, and processes in **FEP-TI** (step 4) equally among the relevant risk factors under each technical issue. Only non-zero cells of **C** contain values in **S**.

   $$\mathbf{S} = \begin{bmatrix} s_{1,1} & \ldots & s_{1,n} \\ \vdots & \ddots & \vdots \\ s_{m,1} & \ldots & s_{m,n} \end{bmatrix} \tag{2}$$

6. Normalize the rows of **S**. Divide the elements of **S** by the Euclidean norms (square root of the sum of squares) of their respective row vectors. Thus, each risk factor is represented by a unit vector in the normalized matrix **S**.
7. Compute a symmetrical square matrix **A** of size n as

   $$\mathbf{A} = \mathbf{S}^{\mathbf{T}} \times \mathbf{S} \tag{3}$$

8. Compute the eigenvalues $\lambda_1, \ldots, \lambda_n$ and corresponding eigenvectors $\mathbf{V}_1, \ldots, \mathbf{V}_n$ of **A**
9. Compute the matrix, **T**. Scale the eigenvectors by their corresponding eigenvalues and return the absolute values.

   $$\mathbf{T} = \left| \begin{bmatrix} \mathbf{V}_1 & \mathbf{V}_2 & \ldots & \mathbf{V}_n \end{bmatrix} \times \begin{bmatrix} \lambda_1 & 0 & \ldots & 0 \\ 0 & \lambda_2 & & \vdots \\ \vdots & & \ddots & 0 \\ 0 & \ldots & 0 & \lambda_n \end{bmatrix} \right| \tag{4}$$

The columns of **T** depict n rankings of the importance of the n technical issues. The significance of these rankings is indicated by the relative magnitudes of their respective eigenvalues. In other words, the column in **T** corresponding to the maximum eigenvalue gives the dominant ranking.

To demonstrate proof-of-concept of the decision-analysis framework, numerical experiments are performed using this procedure. In particular, the experiments examine the tendency for conceptual models (technical evidence) to dominate risk factors (risk perception) in ranking the importance of the technical issues. The case study for the experiments is a hypothetical repository system comprising radioactive waste in metal containers, placed in tunnels excavated deep underground in a saturated rock formation. The tunnels are sealed with clay materials. The groundwater flow field intersects a number of pumping wells that supply drinking water, thereby creating a radiological exposure pathway for humans. Also, the repository site is prone to volcanic activity. For simplicity, six technical issues are considered: water flow around and through the repository (WF), physical disruption of the repository and waste (PD), chemical degradation of waste containers (CD), subsurface transport of released radionuclides (ST), airborne transport of released radionuclides (AT), and characteristics of the human receptor environment (RE). Likewise, 18 risk factors are adopted for the experiments. These risk factors—the external threats and internal vulnerabilities of the repository system—are organized under five headings in the second level of the hierarchical model shown in Figure 2 namely External, Barriers, Temporal, Spatial, and Pathway.

3 Results and Discussion

Figure 3 through Figure 6 present the matrices **C** and **S** used in the experiments, and the derived matrix **T**. The results of these experiments are assessed only in terms of the maximum eigenvalue (λ_6), which indicates the most significant of the rankings depicted by **T**.

Case 1 describes the base case experiment (Figure 3). The matrix **T** shows that the top two ranked technical issues under λ_6. {CD, WF} also have high numbers of FEP records {110, 70} and risk factors {7, 5}. Since both the number of FEP records and risk factors directly affect the ranking, the matrix **T** obtained from Case 1 does not distinguish the contributions of technical evidence and risk perception to the ranking of these technical issues. It is essential to clearly demonstrate that the decision-analysis procedure can account for contributions from both inputs. If, for example, changes in the design of the repository lead to a new set of risk factors—hence a new matrix **C**—but the conceptual models do not change, then the procedure should be capable of revealing the effect of the changes on the ranking of the technical issues. In such a case, the distribution of links in **C** should solely determine the ranking. This concept was tested in Cases 2 through 4 (Figure 4 through Figure 6) by randomly assigning links to cells in **C**.

Case 1: Equal distribution of FEPs among RF--TI links under each TI; Normalized across TIs

	Connectivity Matrix						Score Matrix					
	WF	PD	CD	ST	AT	RE	WF	PD	CD	ST	AT	RE
Climate	1				1		0.99				0.12	
Seismic		1						1.00				
Volcanic		1						1.00				
Human Intrusion		1						1.00				
Excess Seepage			1						1.00			
Short Container Life			1						1.00			
High Release Rates			1						1.00			
Short Travel Times				1						1.00		
Preclosure		1						1.00				
Postclosure (Short-Term)	1	1					0.92	0.40				
Postclosure (Long-Term)			1	1		1			0.52	0.31		0.80
Source	1	1	1				0.64	0.28	0.72			
Near-Field	1		1				0.67		0.75			
Far-Field (Geosphere)				1	1					0.98	0.17	
Far-Field (Biosphere)						1						1.00
Release			1						1.00			
Transport	1			1	1		0.82			0.56	0.10	
Exposure						1						1.00
RF--TI	5	6	7	4	3	3						
FEP--TI							70	37	110	38	5	73

Topology Matrix

	$\lambda 1$	$\lambda 2$	$\lambda 3$	$\lambda 4$	$\lambda 5$	$\lambda 6$
	0.02	2.04	2.70	3.04	4.29	5.90
WF	0.00	0.85	0.53	2.33	0.88	2.34
PD	0.00	0.19	0.22	0.90	3.93	1.40
CD	0.00	0.26	0.26	0.97	1.43	5.15
ST	0.00	1.61	1.02	1.42	0.05	0.60
AT	0.02	0.10	0.05	0.26	0.04	0.10
RE	0.00	0.86	2.42	0.11	0.35	0.69

Figure 3: Matrices **C**, **S**, and **T** for numerical experiments, Case 1

Case 2: Randomly assigned links; Equal distribution of FEPs among RF--TI links under each TI; Normalized across TIs

	Connectivity Matrix						Score Matrix					
	WF	PD	CD	ST	AT	RE	WF	PD	CD	ST	AT	RE
Climate	1		1	1	1		0.40		0.89	0.22	0.02	
Seismic	1		1			1	0.38		0.84			0.40
Volcanic		1						1.00				
Human Intrusion		1		1	1	1		0.41		0.42	0.04	0.81
Excess Seepage	1	1		1	1		0.80	0.42		0.43	0.04	
Short Container Life				1	1					0.99	0.10	
High Release Rates		1				1		0.45				0.89
Short Travel Times				1	1	1				0.46	0.05	0.89
Preclosure	1						1.00					
Postclosure (Short-Term)		1	1					0.23	0.97			
Postclosure (Long-Term)		1	1	1				0.23	0.95	0.23		
Source			1		1				1.00		0.03	
Near-Field	1						1.00					
Far-Field (Geosphere)					1	1					0.05	1.00
Far-Field (Biosphere)		1			1	1		0.45			0.05	0.89
Release	1			1		1	0.65			0.35		0.68
Transport	1						1.00					
Exposure					1						1.00	
RF--TI	7	7	5	7	9	7						
FEP--TI							70	37	110	38	5	73

Topology Matrix

	$\lambda 1$	$\lambda 2$	$\lambda 3$	$\lambda 4$	$\lambda 5$	$\lambda 6$
	0.98	1.41	1.43	3.65	4.28	6.24
WF	0.03	0.12	0.16	2.75	1.72	3.13
PD	0.03	1.01	0.88	0.37	0.59	1.72
CD	0.01	0.04	0.17	2.32	2.74	2.59
ST	0.25	0.93	0.92	0.10	0.27	1.77
AT	0.95	0.27	0.22	0.03	0.11	0.26
RE	0.01	0.07	0.56	0.52	2.73	4.03

Figure 4: Matrices **C**, **S**, and **T** for numerical experiments, Case 2

Case 3: Randomly assigned links; Equal distribution of FEPs among RF--TI links under each TI; Normalized across TIs

Connectivity Matrix and **Score Matrix**

	WF	PD	CD	ST	AT	RE	WF	PD	CD	ST	AT	RE
Climate	1	1		1	1		0.69	0.61		0.38	0.08	
Seismic		1						1.00				
Volcanic					1						1.00	
Human Intrusion	1						1.00					
Excess Seepage	1						1.00					
Short Container Life				1		1				0.20		0.98
High Release Rates	1	1		1	1	1	0.34	0.30		0.18	0.04	0.87
Short Travel Times	1			1			0.88			0.48		
Preclosure	1						1.00					
Postclosure (Short-Term)			1						1.00			
Postclosure (Long-Term)	1			1	1	1	0.35			0.19	0.04	0.92
Source	1		1	1			0.24		0.96	0.13		
Near-Field	1	1	1				0.24	0.21	0.95			
Far-Field (Geosphere)	1			1			0.88			0.48		
Far-Field (Biosphere)				1						1.00		
Release		1			1	1		0.32			0.04	0.95
Transport		1	1	1	1			0.22	0.97	0.13	0.03	
Exposure				1						1.00		
RF--TI	10	6	4	10	6	4						
FEP--TI							70	37	110	38	5	73

Topology Matrix

	λ1	λ2	λ3	λ4	λ5	λ6
	1.00	1.40	2.17	3.35	3.70	6.37
WF	0.00	0.11	0.66	1.40	0.46	5.37
PD	0.11	1.34	0.11	0.70	0.23	1.14
CD	0.01	0.21	0.10	0.71	3.48	1.36
ST	0.00	0.05	2.01	0.27	0.22	2.32
AT	1.00	0.14	0.02	0.13	0.02	0.17
RE	0.02	0.33	0.46	2.86	1.13	1.79

Figure 5: Matrices **C**, **S**, and **T** for numerical experiments, Case 3

The matrix **T** obtained for Case 2 (Figure 4) shows that, under λ_6 and for the same conceptual model as Case 1, the top two technical issues {RE, WF} also have high numbers of risk factors in **C** {7, 7}, but {CD} with highest number of FEP records {110} is ranked third because it has only five risk factors in **C**. In Case 3 (see Figure 5, the top two subjects {WF, ST} also have the highest numbers of risk factors in **C** {10, 10}, but even lower numbers of FEP records {70, 38} than in Cases 1 and 2. Case 4 (see Figure 6 shows a similar pattern of results with {ST, RE} ranked highest, with two of the three highest numbers of risk factors in **C** {7, 5} and lower numbers of FEP records {38, 73} than in Case 1. These results confirm that the density of links under each technical issue in **C** can be more influential in determining the ranking of the technical issues than the number of FEP records included in the conceptual models.

The results of these experiments suggest, in principle, that the perception of risk could outweigh the technical evidence in assigning importance to technical issues. Whereas, risk perception features prominently in the early stages of risk assessments for radioactive waste disposal systems (often during scenario development), its importance quickly diminishes with the progress of laboratory experiments, field investigations, risk modeling, and other technical activities that generate evidence to corroborate or refute earlier perceptions. Whenever risk assessments are revised in response to changes in design criteria or new scientific knowledge about the projected behavior of the repository, it is essential that risk perception be reconsidered. The decision-analysis procedure examined here provides an iterative method of accounting for risk perception as further technical evidence emerges.

Case 4: Randomly assigned links; Equal distribution of FEPs among RF--TI links under each TI; Normalized across TIs

Connectivity Matrix / **Score Matrix**

	WF	PD	CD	ST	AT	RE	WF	PD	CD	ST	AT	RE
Climate			1		1				1.00		0.02	
Seismic	1			1			0.97			0.23		
Volcanic			1			1			0.93			0.37
Human Intrusion				1						1.00		
Excess Seepage					1						1.00	
Short Container Life						1						1.00
High Release Rates		1						1.00				
Short Travel Times					1						1.00	
Preclosure				1						1.00		
Postclosure (Short-Term)				1		1				0.35		0.94
Postclosure (Long-Term)		1		1	1			0.91		0.40	0.05	
Source				1	1	1				0.35	0.04	0.94
Near-Field		1						1.00				
Far-Field (Geosphere)	1				1		1.00				0.03	
Far-Field (Biosphere)					1						1.00	
Release	1					1	0.85					0.53
Transport				1						1.00		
Exposure			1		1				1.00		0.02	
RF--TI	3	3	3	7	8	5						
FEP--TI							70	37	110	38	5	73

Topology Matrix

	$\lambda 1$	$\lambda 2$	$\lambda 3$	$\lambda 4$	$\lambda 5$	$\lambda 6$
	2.27	2.56	2.80	3.01	3.15	4.22
WF	1.26	1.60	1.18	0.12	0.65	1.17
PD	0.46	1.57	1.41	0.35	1.66	0.79
CD	0.85	0.20	2.05	0.26	1.69	0.66
ST	0.71	1.17	0.07	0.18	1.40	2.94
AT	0.02	0.16	0.42	2.96	0.08	0.23
RE	1.46	0.20	0.30	0.18	1.38	2.57

Figure 6: Matrices **C**, **S**, and **T** for numerical experiments, Case 4

4 Conclusions

This paper has presented a decision-analysis framework that integrates perception with evidence for ranking the important technical issues considered in risk assessments for geologic radioactive waste disposal systems. Exploratory studies on a case study of a simple geologic repository have proven successful in demonstrating the effectiveness of a matrix-based ranking algorithm. Risk assessments for geologic disposal of radioactive waste has benefited from the availability of an internationally-vetted database of features, events and processes, especially in developing conceptual system models. However, to apply this decision-analysis framework to other complex disciplines—such as wastewater treatment, environmental management, natural resource exploration, and disaster mitigation—it is essential to develop alternative means of quantifying the technical content of conceptual models. One such alternative involves the use of expert judgment in assigning scores to the technical issues in terms of both importance and degree of uncertainty. The combination of these two scores would indicate the current level of understanding of the technical issues within their relevant technical disciplines. Further studies are currently under way to explore these ideas for application to complex decision problems in multiple disciplines.

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