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Allocating Resources and Building Confidence in Public-Safety Decisions for Nuclear Waste Sites

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ALLOCATING RESOURCES AND BUILDING CONFIDENCE IN PUBLIC-SAFETY DECISIONS FOR NUCLEAR WASTE SITES

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ABSTRACT

A major challenge of nuclear waste disposal is not only providing for public safety, but also demonstrating that safety. There are three basic ways to protect the public from the hazards of exposure to radionuclides in nuclear waste: completely contain the waste; limit the rate at which radionuclides are released; and, once radionuclides are released, minimize their impact by reducing concentrations and retarding transport. A geologic repository system that implements all three provides maximum protection for the public: if one element fails, the others serve to protect. This is "defense-in-depth."

Demonstrating confidence in the ability of a designed system to provide the requisite safety to the public must rely on a combination of the following aspects relating to engineered and natural system components:

1 Knowledge or understanding of properties and processes
2 Uniformity of (or ability to understand or control) the range of variability associated with each component
3 Experience over time

This paper proposes a tool based on defining a "confidence region" determined by these three essential aspects of confidence. The defense-in-depth decision-making tool described identifies the portion of the ultimate confidence region that is not well demonstrated and indicates where there is potential for changing a specific component's confidence region, therefore providing information for decisions on emphasis—either for demonstrating performance or for focusing on further studies. The U.S. Yucca Mountain Site Characterization Project (YMP), wherein Yucca Mountain is being investigated as a potential site for a nuclear waste repository, and the Swedish geologic repository studies are used as examples of this tool.

I. INTRODUCTION

Defense-in-depth refers to redundancy or multiplicity of protective or operating components such that failure of a single component does not by itself lead to system failure. The greater the exposure to loss, the greater the requirements for design margins (the margin of conservatism associated with the fabrication and operation of important components in complex engineering projects) or for compensation by defense-in-depth. Thus, when designing a high-level nuclear waste storage repository, decisions must be made about the components on which to rely and where to focus effort and allocate resources.

The primary concern in nuclear waste disposal is public safety. There are three basic ways to protect the public from the hazards of exposure to radionuclides in nuclear waste:

1. Completely contain the waste (isolation).
2. Limit the rate at which radionuclides are released.
3. After release, minimize the impact of radionuclides by reducing their concentration and retarding their transport.

In repository studies, all three ways of protecting the public are assessed by considering performance of three primary components:

1. The geologic (or natural) system
2. The form of the waste
3. The waste container

II. USING THE DECISION-MAKING TOOL

Confidence in a repository's protection of the public over long time periods involves assessing the predictability of the components' performance. Maximum confidence requires a high level of understanding of the processes and parameters involved, experience extending over a period at least as long as that of repository-performance concerns, and the ability to account for variabilities or to constrain them to minimize unexpected results.

This can be illustrated by representing each of these factors along one of three axes, as shown in Figure 1. In this figure, we consider the zero point at the intersection of the axes to represent lack of knowledge of the parameters or processes, large heterogeneities or variability that cannot be assessed or controlled, and a very limited experience base for the respective component. The arrowheads indicate a value of sufficient confidence or of maximum feasibly achievable confidence, although there is no absolute maximum for any of these factors.

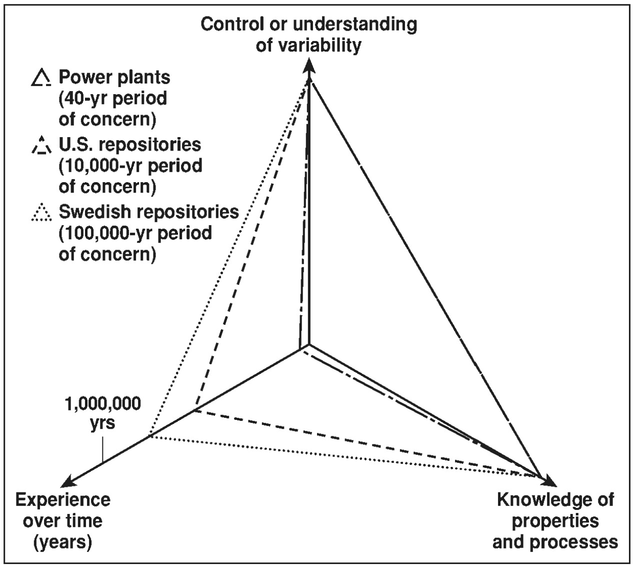

Figure 1. Optimum Confidence Region

The scale used for experience over time is logarithmic (log base 2) and starts at 30 years. The area enclosed by the dashed lines represent the confidence region that must be established for a 10,000-yr time frame (the regulatory period for the U.S. program). The dotted lines represent the full-confidence region (100,000 yr) required for longer regulatory periods more representative of other countries. For example, although no regulatory goals are described in the Swedish repository program, the 100,000-yr requirement for container integrity[1] can be used to define the confidence goal. The dotted–dashed lines represent the confidence required for power plants, which have typical lifetimes of but a few decades.

Generally speaking, projects with short life spans enjoy the greatest level of confidence because the engineering experience basis is comparable to or exceeds the period of concern. Thus, confidence can be provided entirely by engineered components, although this simplification obviously overlooks the differences in individual components of an engineered system. The decision tool being proposed could consider individual components, but, for simplicity, this paper will use the lumped or simplified systems.

As periods of concern lengthen, confidence levels decrease. Thus, the ability to build confidence for different time periods, for which safety must be demonstrated, may involve quite different approaches. For example, approaches that rely heavily on engineered systems that have short experience bases but that can be fairly well understood and variability-controlled would be appropriate for power plants with short safety lifetimes; however, such systems would be inappropriate to give confidence in providing safety for tens or hundreds of thousand years. In the latter case, greater reliance on geologic systems or on engineered systems that have geologic analogues would be required.

Considering each of the three primary components (waste container, waste form, and natural system) and how it contributes to building the overall confidence will allow the making of two different types of decisions as well as documentation of the justification for those decisions: 1) how much reliance to place on each of the components and 2) how much study or effort to put toward increasing knowledge, etc., of the components. These decisions are very dependent on geologic setting, on engineering design and materials, and on regulatory requirements. The method of deciding can be entirely qualitative (and subjective) or can be made more quantitative and include formalized decision-making techniques to estimate the confidence intervals along these axes.

For this paper, we use examples to illustrate this decision-making process and to discuss its implications. As our example, we focus on studies for a potential U.S. repository at Yucca Mountain, Nevada. Where appropriate to explain the usefulness of the method, comparisons will be made to options for the YMP or to other situations, such as nuclear power plants or Sweden's repository approach.

The examples depict a subjective approach (no formalized process was used to establish or estimate the points on the axes) and represent the authors' views, not necessarily those of any of the countries or projects discussed.

In using this tool, one should not confuse performance attributes with the establishment of confidence. It is quite possible to have high confidence in a component's performance even if that component only provides a minimal level of performance. For instance, the corrosion response of carbon steel is well understood, and the experience base is several centuries. However, these materials corrode readily and would not last very long. Less well understood materials with a very limited experience base (e.g., high-performance alloys) may have much longer life expectancies, but the ability to demonstrate this performance or establish confidence in this performance is limited.

This apparent dichotomy is not addressed by the method discussed in this paper; we are looking only the half that is confidence, and it would require considering an additional dimension to evaluate performance.

III. ASSESSING CONFIDENCE

In assessing confidence in a nuclear waste site's ability to provide required safety, two types of quantification are possible:

1. Use formulas to describe the geometric volumes of the optimum confidence region and of the confidence regions established by the three principal components (while the volumetric quantification is straightforward, it is not discussed here).
2. Use formalized methods to establish the values along the axes; this would lend itself very well to methods for collecting judgments of multiple experts and then establishing those points (formalizing the process of determining the points along the axis is beyond the scope of this paper).

For this analysis, no attempt has been made to place relative values (or weighting) on the three axes (i.e., knowledge is viewed as having equal value to confidence as is experience or variability).

In using this decision-making tool, we first determined confidence values for the three primary components (natural system, waste form, waste container) for the YMP, with comparisons of Sweden's repository system.

A. Natural System

Yucca Mountain's geologic setting consists of a series of ash-fall volcanic tuffs with varying degrees of welding; the potential repository's horizon has been identified within a densely welded unit. The overall geologic setting and measurements of property values are fairly well characterized. Major issues of uncertainty deal with the amount of water that percolates (or that will under changed climatic conditions) through the subsurface and the water flow paths and travel times.

Furthermore, because YMP is considering emplacement of heat-generating waste, significant uncertainties are associated with coupled thermal-hydrologic-chemical-mechanical (THCM) processes. The uncertainties in these coupled processes are most significant for the first few hundred to thousand years. Although property values are fairly well constrained, the uncertainties in water flow and coupled processes are such that the authors chose to indicate a knowledge basis of about 60% of that required for optimum or sufficient confidence (Figure 2).

There are significant heterogeneities within the natural system of Yucca Mountain, especially heterogeneities of hydrologic properties. The differences between estimates of matrix and fracture permeabilities are assessed to be many orders of magnitude[2] and well beyond current ability to be directly accounted for in TH models, other than by statistical representations. To reflect the hydrologic properties variability (noting that there are also large, albeit not as significant, variations in the mineralogical and mechanical properties and conditions), the authors chose to show a fairly low value—approximately 15% of the optimum—on the variability axis (Figure 2).

Yucca Mountain's current natural system has existed for approximately 13 million years[3] and has gone through some of the THCM processes of concern. Although the natural system is not exactly the same today as it was at the time of deposition, the processes in its evolution are generally understood, and resultant changes are exhibited in the geologic materials. Furthermore, there are geologic analogues that can be used to assess the knowledge of these processes. The selection of an experience value of one million years (Figure 2) was based on a subjective determination of the dominant processes to be considered in assessing an overall value and does not apply to all the geologic processes and materials.

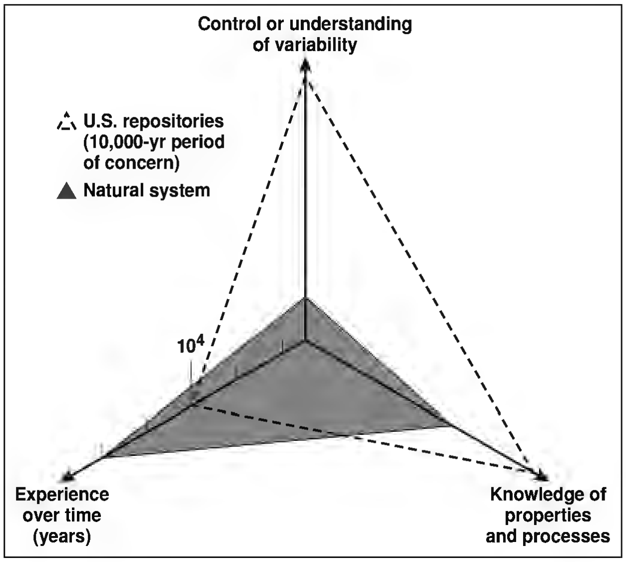

Figure 2. Natural System (YMP)

Estimates of confidence are site- or geology-specific. Granite rock at the Swedish site is less reactive and has been subjected to current environmental conditions for a long time, and the temperatures will not be as elevated as at Yucca Mountain. Consequently, the rock in Sweden is and will be essentially in equilibrium with the environmental conditions—except for those caused by emplacement of the repository itself (e.g., materials, ventilation)—and there are fewer processes or properties to be considered. Thus, in contrast to the situation at Yucca Mountain, processes that must be considered in Sweden are better understood; therefore, a value of approximately 75% of optimum or required knowledge was selected (Figure 3).

At sites where the geologic media considered is fractured crystalline rock, as is the case with Sweden, the heterogeneity in permeability is not as great because the matrix porosity does not contribute to flow and can be ignored. Also, there are minimal issues with imbibition or mobilization of water from the matrix pores. Thus, for the Swedish programs, the estimate of control or understanding of variability would be greater than would be the case for Yucca Mountain. Because of the impossibility of accounting, in models, for all fractures (except by statistical representations), the natural system's heterogeneity will still be much greater than that of engineered materials. Therefore, a value of 50% was chosen for the variability axis (Figure 3).

The Äspö site in Sweden[4] consists of granite and basic rocks that are more than 100 million years old. Because the processes of alteration, fluid flow, and water-chemistry development are not associated with this entire history, the authors selected an arbitrary value of 30 million years for geologic experience (Figure 3).

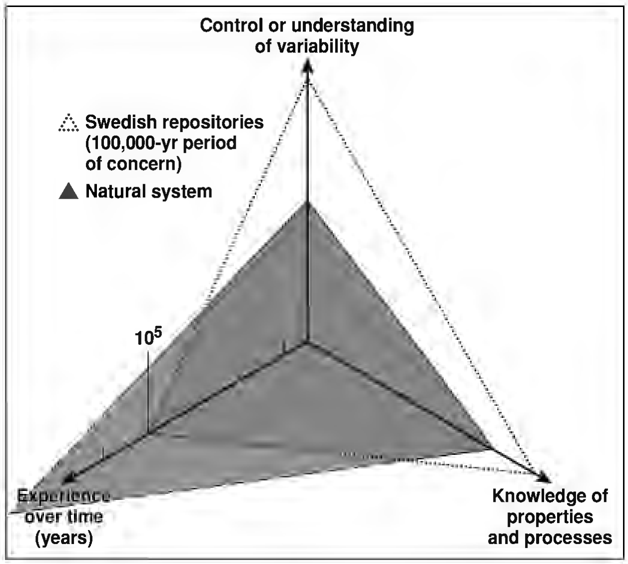

Figure 3 Natural System (Sweden)

In the first stage of decision making, we consider how much of the optimum confidence region is satisfied by the natural system. With the optimum confidence region (from Figure 1) superimposed onto the confidence established by the natural system (shaded area in Figures 2 and 3), we see that much of the optimum confidence region is not satisfied by this single component.

Although the logarithmic scale prevents direct comparison of the U.S. and Swedish scenarios, it can be concluded that the natural system for the Swedish situation satisfies a larger portion of the required confidence region than it does for the U.S. case. Thus, one might anticipate different decisions or approaches for the two programs.

B. Waste Form

Approximately 85–90% of the waste considered for disposal in the United States consists of spent fuel (primarily from civilian reactors) and approximately 10–15% vitrified defense wastes. The waste is fairly well characterized, and parameters such as thermodynamic data for the individual radionuclides are fairly well known. The condition of individual spent fuel rods, as they were removed from reactors, is not generally known. There is also uncertainty in characterization of some defense wastes considered for potential disposal. Therefore, a value of approximately 60% of the maximum feasible level of knowledge was selected to describe the confidence level for waste form (see Figure 4).

For some repository programs dealing with reprocessed waste, the confidence in understanding may be higher. In those repository programs wherein reprocessing of the waste will take place, heat generation would be considerably less. Also, the waste would be more uniform in character and better understood, and the shorter-lived radionuclides would not be present. The control of variability for waste forms in the U.S. repository is estimated at 40% (Figure 4) because of the mix of fuels types and because of unknown conditions at the time the spent fuel was removed from the reactor.

The radionuclides, except for some that are produced as result of nuclear reactions in the reactor, are naturally occurring and thus have geologic equivalents. Therefore, the experience base is shown as approximately 100,000 yr (Figure 4). This is, obviously, radionuclide-specific and is a subjective estimate of the overall experience for the ensemble of the radionuclides of concern.

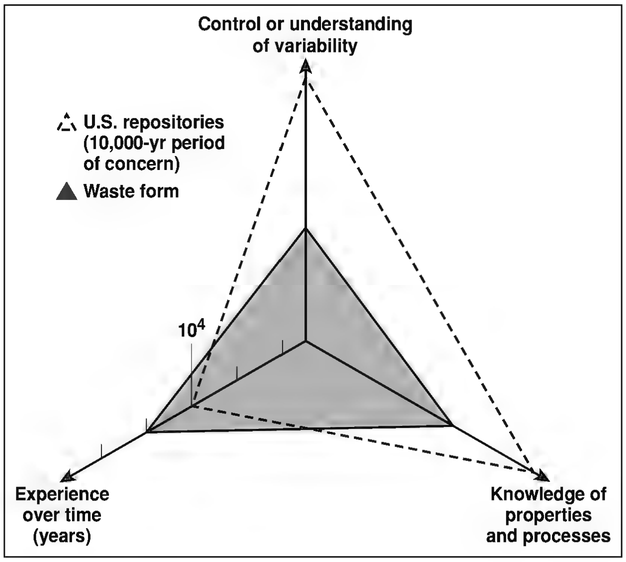

Figure 4. Waste Form (YMP)

Again, because of the logarithmic scale, one must be cautious when comparing; however, the portion of the required confidence region satisfied by the spent fuel includes the region satisfied by the natural system, but extends over a greater area. This indicates there is some redundancy of confidence between these two components.

The repository program in Sweden includes disposal of spent fuel that is unreprocessed but which will be in storage for 40 yr prior to disposal.[5] Further, no more than 12 BWR or 4 PWR assemblies will be in each waste container. Consequently, the peak temperatures can be controlled to remain below 90°C. As a result, many of the kinetics issues, such as fuel oxidation, as well as thermal fuel rupture and or cladding will not be as significant. Thus, some of the more challenging processes that must be assessed in the U.S. program are not an issue in Sweden. Consequently, a higher level of process understanding potentially exists for those programs. For these reasons, the authors choose to indicate that knowledge for the waste form in the Swedish program is 70% of the optimum (Figure 5).

Because waste in the Swedish program consists only of spent fuel from civilian reactors, less variability exists than would with the U.S. waste form, which includes many types or sources of waste. However, the conditions of spent fuel would be unknown at the time of removal, and storage for 40 yr prior to encapsulation introduces additional uncertainties or potential variation in waste-form conditions. Therefore, the authors selected a value of 70% for the variability axis (Figure 5).

The experience base of the waste form in the Swedish program should be similar to that of the United States. Therefore the Swedish 100,000-yr requirement for keeping water out of waste packages is selected as the value on the experience axis (Figure 5).

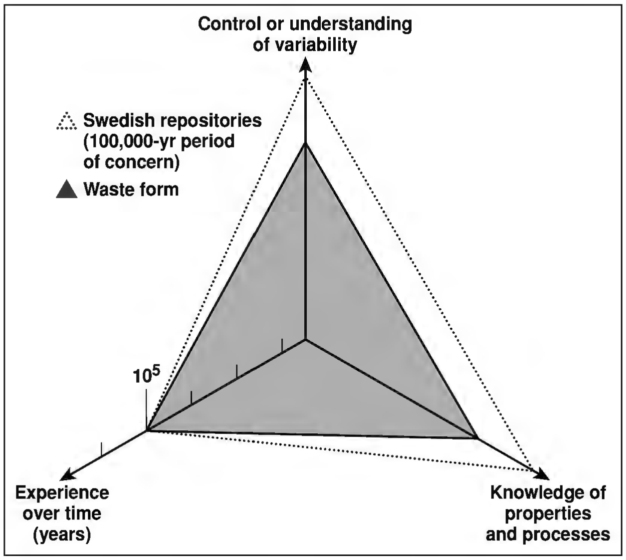

Figure 5. Waste Form (Sweden)

Observing the shaded areas in Figures 4 and 5 (the confidence established by the form of the waste) and its relation to the optimum confidence region, we see that much of that region is still not satisfied by the waste form alone within the U.S. program, whereas a significant amount will be in the Swedish program. This does not mean, however, that the waste form would provide the needed isolation or performance, merely that the assessment of its performance could be made with a higher degree of confidence.

C. Waste Container

The materials intended for use in the potential U.S. repository at Yucca Mountain are high-performance alloys. The waste container, as currently envisioned, consists of a 2-cm-thick layer of C-22 over a 5-cm-thick layer of 316 stainless steel.[6] The experience base for these high performance alloys is very short, on the order of 60 yr, as reflected in Figure 6.

(A titanium drip shield has been designed to protect the waste container and to extend the life of the waste package for 9000 yr. Titanium has natural analogues that would significantly increase the experience base beyond the 60 yr shown for the container alone, However, the drip shield is designed as a sacrificial barrier to protect the containers and does not directly provide isolation of waste. Therefore, the authors chose not to assess confidence in the entire engineered barrier system but rather to discuss the waste container and the waste form separately.)

Because these container materials are manufactured, the control of variability is judged to be quite high; therefore we chose a value of 85% of feasible maximum (Figure 6). The remaining 15% not only accounts for some material variability and fabrication issues, but also recognizes the potential for juvenile failures (e.g., undetected defects in manufacturing) that would be equivalent to variability.

Determining the level of advancement in knowledge of properties and processes is more problematic. While the fundamental understanding is high (i.e., there is understanding of basic thermodynamics, the processes of corrosion, and metallurgical properties), limited data exist on chemical (corrosion) and mechanical (phase stability) processes of those alloys. The authors thus used a value of 60% on the knowledge axis (Figure 6). As can be seen, confidence is established very well for short times, but beyond few decades requires great extrapolation.

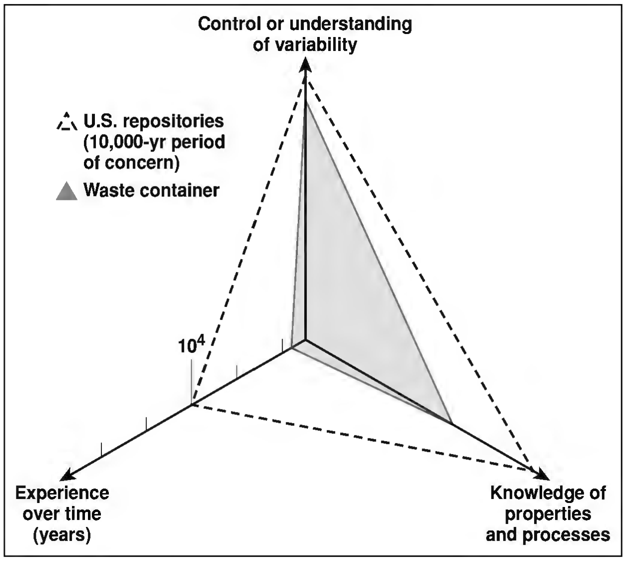

Figure 6. Waste Container (YMP)

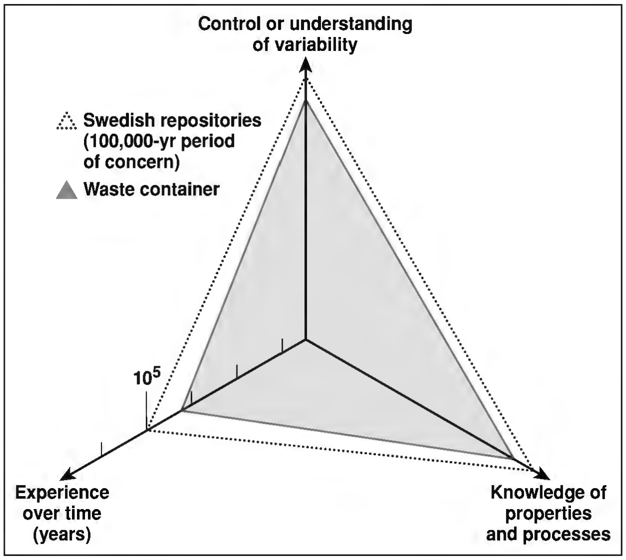

Figure 7. Waste Container (Sweden)

Demonstrating confidence for containers is quite different for the programs in Sweden. The Swedish canister design is a 50-mm thick copper container with a 50-mm (minimum thickness) cast-iron insert for strength.[7] The corrosion properties of copper are well known, and there is low susceptibility to stress-corrosion cracking. Thus, we selected a value of 85% of the reasonably achievable knowledge (Figure 7).

The specifications for the Swedish waste container are for oxygen-free copper with low phosphorous content. The manufacturing process for the waste container will have to be tightly controlled to meet these tight specifications; if so, the properties should be fairly homogeneous. However, recognizing the possibility of some undetected defects, we have chosen a value of 85% for the variability axis (Figure 7).

The major difference between the U.S. and Swedish containers is that pure copper has a geologic analogue; thus, this material (not considering fabrication and welding) has a long history. Even if geologic analogues are not considered, experience in the use of copper extends several centuries.

However, because the duration of experience is limited for electron-beam welding, we chose to use a subjective value of 50,000 years for experience (Figure 7). If this experience estimate is appropriate, the required confidence is fairly well established by containers.

Observing the portion of the optimum region of confidence that is satisfied by the waste container (Figures 6 and 7), we see that within the U.S. program, the confidence is insufficient to rely upon when assessing that component's ability to provide adequate protection to the public; in Sweden, on the other hand, the confidence region is fairly well established by the waste form. As noted, however, if the titanium drip shield were included in the container, the percentage of the confidence region satisfied by the U.S. program might be more comparable to the case in Sweden.

IV. MAKING PROGRAMMATIC DECISIONS

In reality, there will never be sufficient time and resources to address all issues that impact confidence of a given system. Use of this tool, however, can assist in the making of two types of decisions:

1. Those relating to overall disposal strategy
2. Those regarding individual repository components

A. Strategy Decisions

Determining on which of the three repository components to rely to demonstrate isolation of waste requires weighing the actual performance of the components (not addressed by this method) against the ability to demonstrate or build confidence in those performance estimates (the focus of this decision-making method).

The shaded areas in Figures 8 illustrate estimated confidence regions for the natural system, waste forms, and waste containers. Each component provides a different aspect of the confidence so that, while not perfect, the confidence in the predictability of the *entire* system is much greater than that provided by a single component.

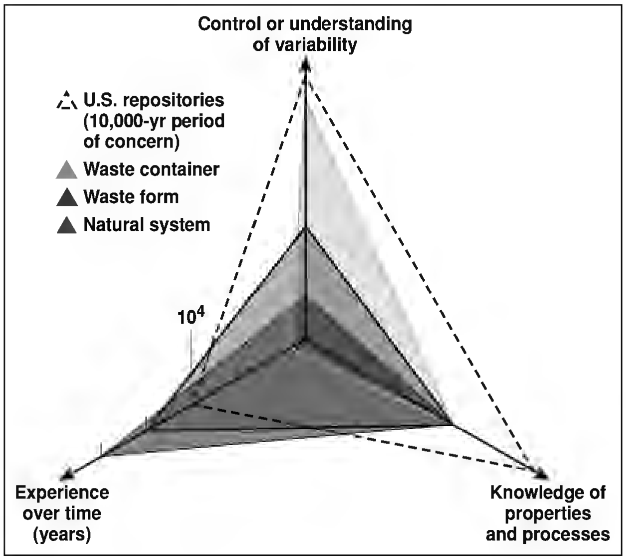

Figure 8. Confidence Regions of All Components (YMP)

It is apparent that the confidence appropriate for the 10,000-yr regulatory time can be established best for the waste form, with somewhat similar confidence established by the natural system. Only the natural system, however, can be used to build confidence in analysis of performance beyond 50,000–100,000 yr. Therefore, the natural system cannot be ignored, unless only time scales less than 50,000 yr are of concern.

Confidence in the waste container is established in a different part of the regime: control of variability and knowledge of processes and properties. It does not duplicate much of the portions of the confidence region addressed by the waste form and natural system. If merely considering the confidence values, it might appear that YMP should not rely on the container because of its limited confidence region. Container performance, however, is critical to providing for public safety.

Thus, it is important to consider how the individual components' confidence areas are complementary. As noted, the natural system and waste form define similar confidence areas, whereas the waste container establishes a separate portion of the overall confidence region. Thus, the container plus either of the other components provide confidence that no single component can.

The magnitude of the unsatisfied confidence region is very dependent on the time scale of the regulatory or safety issue. In the case of Sweden (Figure 9), the long period of concern makes it impossible to satisfy much of the optimal confidence region without relying on the natural system or on engineering materials that have geologic time experience bases.

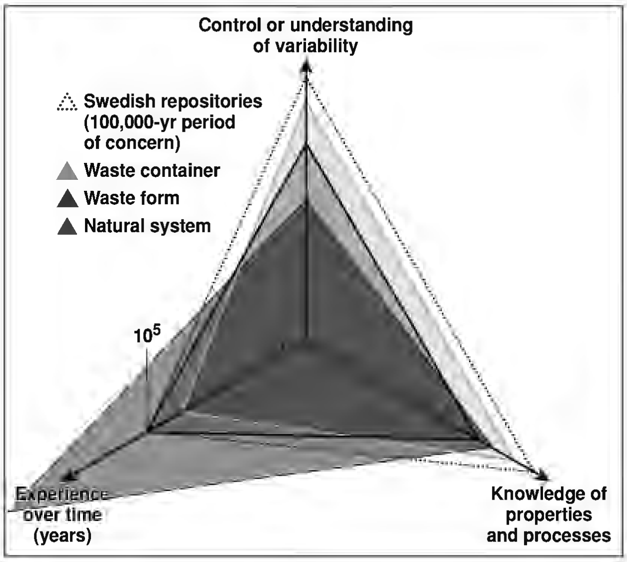

Figure 9. Confidence Regions of All Components (Sweden)

The confidence established by the natural system includes most of that established by the waste form, and the waste container confidence nearly fills the entire optimum confidence region. In this case, the decision to be made is how much additional confidence is required (i.e., should all three components be used to build confidence, or will just one or two suffice?).

B. Individual Component Decisions

In addition to determining the primary component on which to rely for provision of public safety, this tool can be used to determine how much additional effort is justified for expanding any component's confidence region. This determination can be made by noting the regions in which confidence is not demonstrated and deciding whether expenditure of effort will add significantly to establishing that confidence.

In the YMP example, there is not much possibility of increasing the experience base in the natural system because it is already based on geologic materials with 10,000- to 100,000-yr history (see Figure 2).

On the other hand, the understanding of natural system processes could be increased with some effort. It might also be possible to expand the region of confidence for the natural system by developing methods to analyze the heterogeneity or account for it in models.

The increase in knowledge and the ability to account for heterogeneity in models are not totally independent of one another. Recent investigations performed underground at Yucca Mountain indicate that the fracture system consists more of short fractures that are ubiquitous. This allows for modeling with less complex models than might be required for discrete fractures. A judgment may be made that the matrix permeability is sufficiently small that it need not be included in models. This might necessitate studies in support, but such studies could focus on this issue.

Furthermore, statistical methods for accounting for heterogeneities could be developed. If any of these were successful—thereby increasing the natural-system confidence value on the variability axis from 15% to 50% or 60%—a significant difference would be made in establishing the confidence of this component. The challenge for the decision-maker would be to determine the likelihood of this much improvement.

If the assessments shown are appropriate, similar decisions on conclusions can be drawn for the components within the Swedish program (see Figure 3).

Similarly, other than finding new analogues, there is very little that can be done to increase the time of experience for waste form for YMP (see Figure 4), nor is there much that can be done to increase confidence in control or understanding of variability (unless reprocessing is considered), although methods could be developed to quantify the variability. A similar analysis could be done for the waste form to determine relative benefits of investing in analytic techniques to account for heterogeneity or in understanding fundamental processes and properties.

Likewise, little can be done to amplify the experience base of the waste container materials being considered for a potential Yucca Mountain repository (see Figure 6). It may be possible, however, to extend the confidence established for waste container by selecting container materials that have geologic counterparts.

For example, Sweden's choice of pure copper has a natural analogue in native copper ore bodies. Ceramics and perhaps titanium have geologic analogues. These analogues can significantly impact the confidence in the assessment (not necessarily in the actual life of the container, but in the assessment) because they provide an experience base that is comparable to the problem. In contrast, internal properties of these alloys can be fairly tightly constrained; thus, the heterogeneity is minimal.

This approach should not be extended beyond assessing confidence into issues of performance. For instance, based on these figures, one might conclude that granitic rocks would be preferable to volcanic tuffs, or that a saturated site is preferable to an unsaturated site. This would ignore some of the real potential benefits of an unsaturated site (minimal water contact) or of the sorptive minerals within tuffs.

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