USING A SYSTEMS ENGINEERING PROCESS TO DEVELOP ENGINEERED BARRIER SYSTEM DESIGN CONCEPTS

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ABSTRACT

A methodology based on an iterative systems engineering process can be used to develop conceptual designs for the engineered barrier system and the waste packages in a geologic repository. First, a set of general mission requirements is established and then detailed requirements analyses are conducted using functional analyses, system concept syntheses, and trade studies identifications to develop preliminary system concept descriptions. The feasible concept descriptions are ranked based on selection factors and criteria. A set of preferred concept descriptions is then selected for further development. For each of the selected concept descriptions, a specific set of requirements, including constraints, is written to provide design guidance for the next and more detailed phase of design. All relevant waste management system requirements are documented in the process so that the basis and source for the specific design requirements are traceable and clearly established. Successive iterations performed during design development help to insure that workable concepts are generated to satisfy the requirements.

INTRODUCTION

Systems engineering processes are used in various activities by the U.S. Department of Energy (DOE) and its subcontractors to evaluate the suitability of Yucca Mountain, Nevada as a potential geologic repository site. Lawrence Livermore National Laboratory is using a systems engineering process to generate a range of preliminary system concept descriptions for the engineered barrier system (EBS) and the waste packages. The EBS components and the waste packages must be designed for the site-specific underground service environment of a geologic repository. However, until sufficient site-specific test data are collected and access to the underground repository horizon is available, uncertainty remains about the design-basis service conditions. To address this uncertainty before a single concept is selected for detailed design, we are using the systems engineering process to document several design configurations that are alternatives to the current reference conceptual design configuration found in the Site Characterization Plan (SCP) (1) and the Site Characterization Plan Conceptual Design Report (SCP-CDR) (2).

During the early stages of many first-of-a-kind projects, two or more concept descriptions (depending upon the specific project and its overall schedule) are usually considered. This approach permits a broad base of feasible concepts to be developed within the expected range of design conditions. For the uncertainties at Yucca Mountain, this approach also provides a degree of project contingency planning for underground repository service conditions that may differ from our current expectations. In addition, the long-lead-time EBS component materials testing, waste form characterizations, and underground near-field environment test programs must cover a range of test conditions designed to encompass the uncertainty in service conditions. These testing programs are required to demonstrate regulatory compliance for the license application design and to evaluate the more robust alternatives. Such an undertaking increases confidence that viable design concepts exist and that workable concepts have been selected for further development and evaluation.

To devise conceptual designs for a geologic repository, we formulated a methodology based on systems engineering. The methodology allows for multiple design concepts to be developed and for the major constraints, requirements, and assumptions reflected in the different concepts to be tracked and documented. With the appropriate structure of constraints, requirements, and assumptions, we can develop traceable hierarchic, architectural design concepts in support of both the technical and nontechnical (e.g., programmatic or policy) needs. Because multiple design concepts are involved, we must develop criteria to rank and select the most viable concepts for further development. Using this approach, we can demonstrate that a range of alternatives were considered and documented before we selected a reduced set of concepts for more detailed development and evaluation. The extent of a project's resources and schedule time used for development of more than a single design configuration is a management decision.

The DOE's general approach for development of EBS and waste package concepts is described in the Waste Package Plan (3). This plan requires the development of two or more conceptual designs after access to the underground conditions is gained. Based on the most recently proposed DOE repository schedules, access will occur in 1996 (4). At the start of the license application design phase, a single design configuration for the EBS components and the waste packages will be selected for detailed development. Until that time, two or more conceptual design configurations, including where appropriate the development of prototypes to demonstrate feasibility, will be studied based on the implementation of the process described in the following discussions.

METHODOLOGY

The seven steps to systematically develop and document two or more conceptual design configurations for the EBS components and the waste packages in a geologic repository are shown in Fig. 1. The key aspects of each step are summarized in the following sections.

Step A: Develop Input Mission Requirements

A clear and complete statement of the major objectives, environmental characteristics, system constraints, and performance measures (measures of effectiveness) for the EBS components and the waste packages must be developed and documented as the input mission requirements. In the initial concept exploration phase, this statement must remain at a high level and not be too constraining in the level of detail. It must clearly state the major functions and requirements to be met by the system. The concept development process, carried out after formulation of the input mission requirements, must track and capture all additional requirements used to generate a specific concept description. Using cyclic iterations, the statement is made more detailed and more constraining as the concept descriptions are further developed. The level of detail and the duration of the iteration cycles are specified as more of an art than either a "cookbook" or a science.

Figure 1 shows the four general classifications of input mission requirements: (1) mission objectives, (2) mission environment, (3) constraints, and (4) performance measures. The mission objectives must be specific enough to constrain the exploration to concept descriptions that merit further development for the specific site. The mission environment needs to include general guidance on both the internal (i.e., the waste form and other EBS component-driven conditions) and the external host rock service conditions. The specification of these internal and external conditions can originate from nontechnical sources (e.g., policy or programmatic) as well as from technical, legal, or regulatory requirements. Constraints may be imposed on budgets and schedules; however, these limitations are generally introduced after preliminary system concept descriptions are developed in process steps C through E. The performance measures must be consistent with the mission objectives and should be quantitative. The initial performance measures should be based on a total subsystem requirement as opposed to individual subcomponents

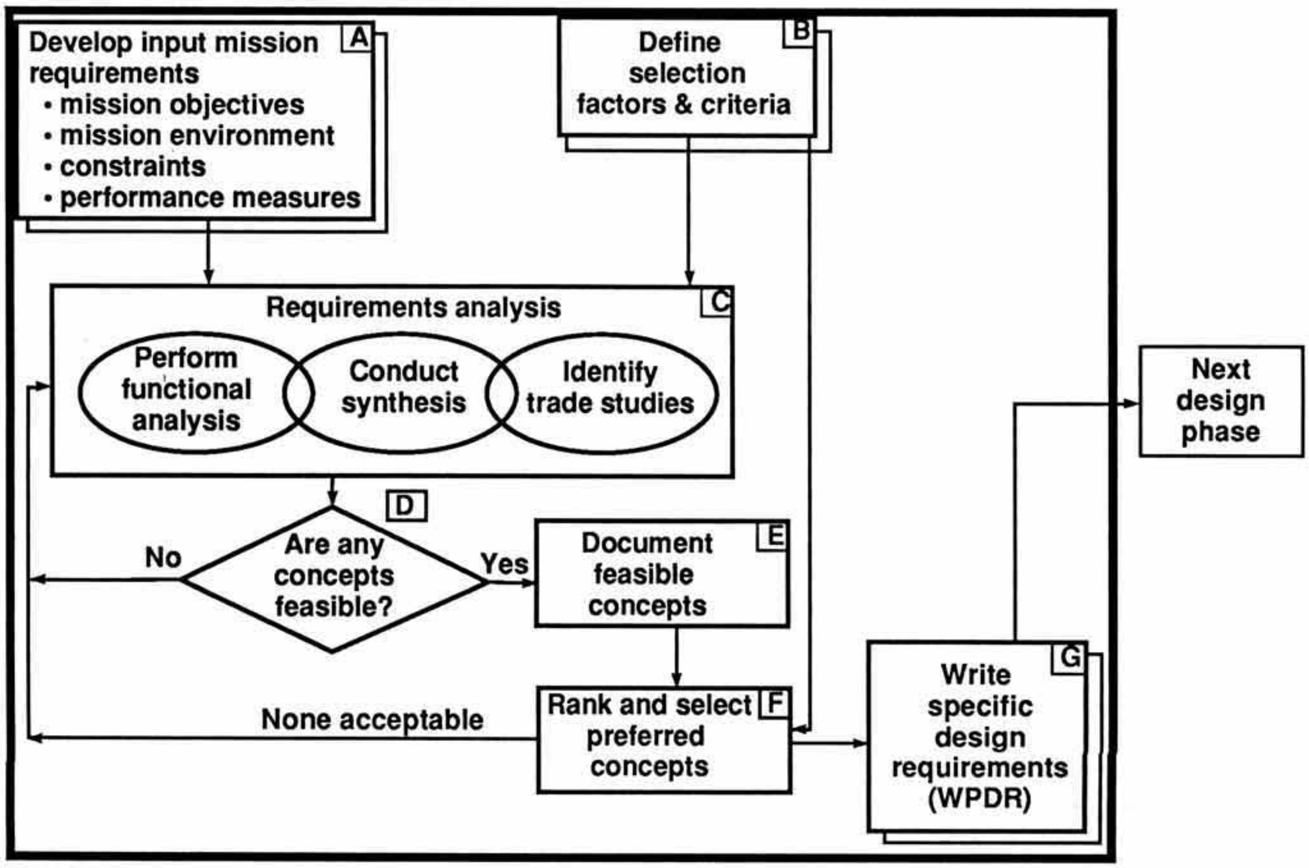

Fig. 1. Seven steps are used in the systems engineering process to develop and document two or more design configurations.

within the subsystem to provide the designer the flexibility to synthesize multiple concept descriptions. Attention is given to prevent overspecifying performance requirements at a component level too low in the system hierarchy.

Step B: Define Selection Factors and Criteria

Because more than a single concept description is being sought, a basis for the screening, ranking, and selecting from among multiple workable concepts must be developed. Figure 1 shows that this basis needs to be developed in the initial phase of the methodology implementation and then revised, if necessary, prior to the application of the formal selection step (step F). The criteria must be established early to avoid biases for a particular workable concept description. A revision may be needed to insure that both the selection factors and criteria are appropriate and encompass the workable concept descriptions generated from steps C through E. Criteria typically include cost, schedule, and performance measurement considerations.

Step C: Requirements Analysis: Functional Analysis, Synthesis, and Trade Studies

The development of preliminary system concept descriptions using the input mission requirements (step A) is initiated based on steps C, D, and E of the systems engineering process shown in Fig. 1. These three steps are highly interactive and interdependent. For example, functional analysis including requirements allocation (step C1) cannot be performed in depth until a concept is synthesized or a solution is created (step C2). Concept evaluations based largely on judgments of experienced designers (and on calculations in some cases) are conducted to verify that a proposed concept satisfies the required functions from step C1. The functional analysis and synthesis are performed concurrently and repeatedly. During this iterative process, additional requirements, assumptions, or constraints are generated as problems and their solutions are more clearly defined. All of these are associated with the concept description and must be carefully documented. This documentation is key to establishing the visibility, traceability, and flow down of requirements, assumptions, and constraints associated with each concept description generated in step C. In addition, the documentation provides the basis for selection among the various workable concepts in step F, itemizes the extent of uncertainty in the workable concepts, and demonstrates that a range of alternatives has been considered.

While the synthesis steps are conducted, extensive interfaces with other major system elements beyond the EBS subsystem components are identified. Major trade studies may be required to further verify the initial engineering judgments or concept evaluations. In the initial interactions, the trade studies only need to be identified and documented as an integral part of the concept description. The initial concept development process can proceed without completing all trade studies. Of course, the resulting synthesis is contingent on the future results of the trade studies. In some cases, the feasibility of a specific concept cannot be confirmed until one or more trade studies are initiated and completed.

The results of Step C will satisfy the input mission requirements with a set of concepts and the associated documentation of all the defined requirements, assumptions, and constraints.

Step D: Evaluate the Feasibility of Proposed Concepts

Step D determines whether or not any of the concepts are feasible and the basis for this determination must be documented. Current technology and existing site data to support the conclusions that the designs are feasible, along with the major trade studies that are identified (including recognition of any lack of detailed knowledge) must be recorded. This documentation becomes the basis for identifying and ranking both research and development and data needs should a specific workable concept be selected in step F for further development. Concepts that are judged to be infeasible are either rejected or modifications are made by returning to the requirements analysis in step C.

Step E: Document Feasible Concepts

In step E, all concepts determined to be feasible are fully documented. This includes drawings, sketches, and all the derived requirements, assumptions, constraints, major system interfaces, and recommended trade studies derived during the requirements analysis in step C. The flow down of the requirements, assumptions, and constraints must be visible and traceable.

Step F: Rank and Select Preferred Concepts

Because multiple concepts and their associated documentation are generated in steps C, D and E, a process must be developed to rank the feasible concepts. In step F, criteria generated initially in step B are used to rank and select the preferred concepts.

Step G: Write Specific Waste Package Design Requirements

For each of the two or more conceptual design configurations generated as products of steps A through F, a set of specific design requirements is written. The document contains all of the original input mission requirements, as well as the additional assumptions, constraints, major interfaces, and trade studies generated during the development of the selected design concepts. Both the content and the format of the specific design requirements should be targeted toward the system design developer's needs in the next more constrained and detailed design phase. The requirements also become the bases for repeating steps B through F with more constraints should another complete iterative cycle of systems engineering be necessary.

DISCUSSION

The methodology requires that multiple iterative pathways be pursued in developing alternative conceptual design configurations for the EBS components and the waste packages. The specific methodology uses a requirements hierarchy based on nontechnical (e.g., programmatic or policy) and technical factors. Figure 2 shows how this hierarchy is applied with the underground service conditions separated into three different pairs of nontechnical factors: (1) wet or dry, (2) hot or cold, and (3) container lifetimes of less than 1000 years (but greater than 300 years) or greater than 1000 years.

Figure 2 also shows one of eight possible combinations of these nontechnical factors, each of which could be used as a set of requirements that are applied to further constrain the concept development beyond those in the mission requirements. By quantitatively defining the three pairs of nontechnical factors, concepts can be developed subject to eight different sets of constraints. The resulting concepts then span a range of possible conditions. The selection of the specific number of constraints can be set by programmatic needs rather than technical needs.

Other factors that can affect the EBS and the waste package configurations include technical factors such as whether the waste packages are (1) emplaced in a borehole or in the drift, (2) emplaced in a vertical or horizontal configuration, (3) surrounded with packing or backfill, or (4) packed inside with filler materials. Different combinations of these technical factors can lead to quite different concepts for the waste packages. The different concepts all may be workable but may have different performance measurement expectations when analyzed. The selection of the appropriate combinations of these four technical factors must be based on a large number of technical considerations, including assessments of issues such as temperature, nuclear criticality, radiolysis effects, construction tolerances, fabrication tolerances, transfer cask weight and size, mining technology, in-situ inspection, handling strengths, and materials compatibility. The selection of workable design configurations will be based on a combination of

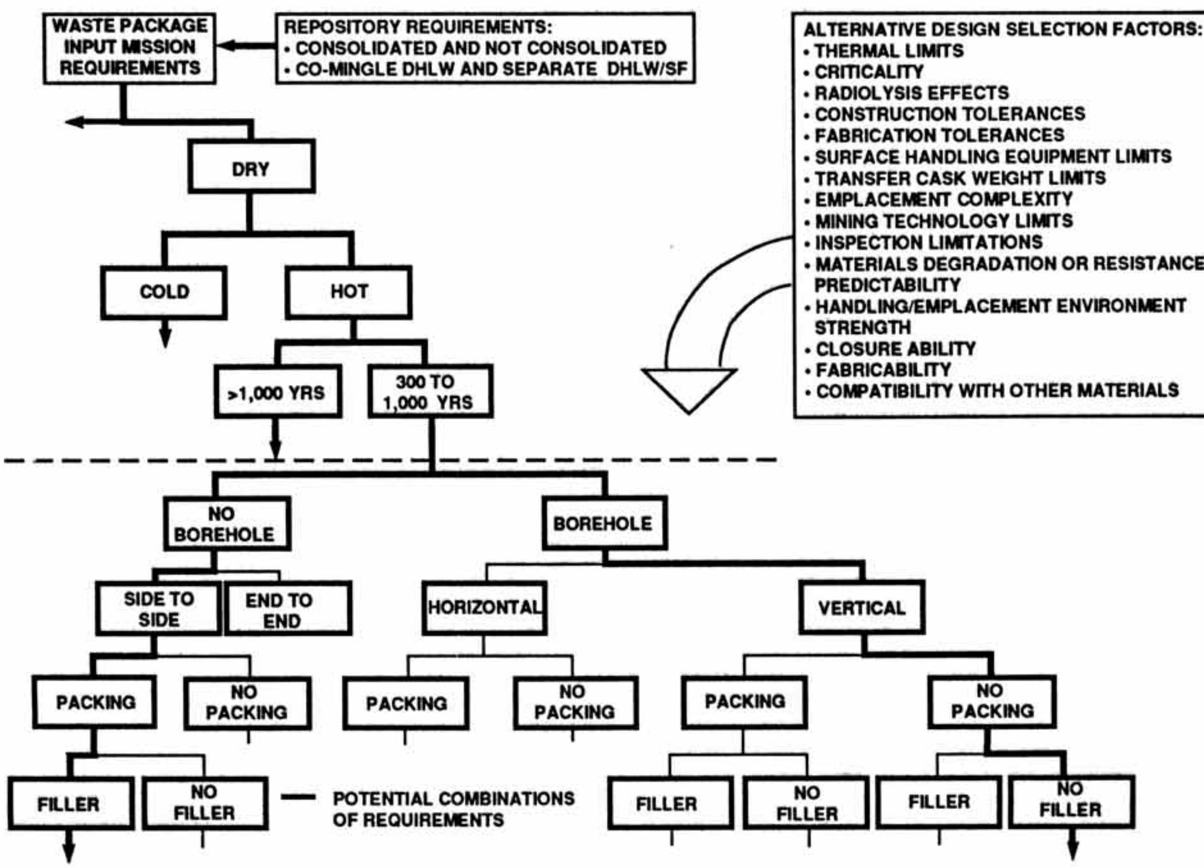

Fig. 2. A middle-tier requirements hierarchy can be used to pursue multiple pathways for alternative conceptual designs. (For illustrative purposes - figure is not representative of an actual DOE-proposed hierarchy.)

judgments, engineering evaluations, trade studies, and other analyses.

When the upper-tier requirements are specified, the number of preliminary system concept descriptions that can satisfy them is generally more than one. In many cases the best concept does not have to be proven; instead, the designer must be able to demonstrate that the selected concept is workable. Examples of these specific designer choices include the materials to be employed, number of assemblies to be placed in a single waste package, precise shape of the waste package, length of the container, and internal geometries. Such designer choices need to be based on technical considerations and interfaces with other parts of the waste management and repository system. Consideration must also be given to the surface and subsurface waste handling and emplacement operations.

FINAL REMARKS

We are continuing to define this methodology while using it to implement the Waste Package Plan. We are delivering a range of EBS and waste package design concepts, in addition to those described in the SCP and SCP-CDR. These alternative concepts address a range of underground service requirements that are being defined and documented as the concepts are developed in more depth. By specifying some requirements as nontechnical constraints, concepts can be developed to generate inputs as part of the DOE programmatic contingency planning. The various feasible concepts will be documented and ranked based on screening criteria and a formalized ranking process. As stated in the Waste Package Plan, the DOE will decide on the specific number of alternative conceptual design configurations to be developed in the next major design phase, but it will likely be two or more concepts.

ACKNOWLEDGEMENT

Work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract No. W-7405-ENG-48.

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