APPLYING SYSTEM ENGINEERING METHODS TO SITE CHARACTERIZATION RESEARCH FOR NUCLEAR WASTE REPOSITORIES

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ABSTRACT

Nuclear research and engineering projects can benefit from the use of system engineering methods. Their use may even be imperative in those projects that must, through the licensing process, gain lay acceptance of the validity of technical conclusions. This paper is a brief overview illustrating how system engineering methods could be applied in structuring a site characterization effort for a candidate nuclear waste repository.

System engineering is simply an orderly process that has been widely used to transform a recognized need into a fully defined system. Such a "system" may be physical or abstract, natural or man-made, hardware or procedural, as is appropriate to the system's need or objective. The concept of "system" itself is abstract. It is a way of mentally visualizing all the constituent elements and their relationships necessary to fulfill a need, and doing so compliant with all constraining requirements attendant to that need. Such a system approach provides completeness, order, clarity, and direction. Admittedly, system engineering can be burdensome and inappropriate for those project objectives having simple and familiar solutions that are easily held and controlled mentally. However, some type of documented and structured approach is needed for those objectives that dictate extensive, unique, or complex programs, and/or creation of state-of-the-art machines and facilities. System engineering methods have been used extensively and successfully in these cases.

The scientific method has served well in ordering countless technical undertakings that address a specific question; (e.g., quantifying certain geochemical properties). Similarly, conventional construction and engineering job methods will continue to be quite adequate to organize routine building projects.

Nuclear waste repository site characterization projects involve multiple complex research questions and regulatory requirements that interface with each other and with advanced engineering and subsurface construction techniques. There is little doubt that system engineering is an appropriate orchestrating process to structure such diverse elements--and perhaps several types of approaches--into a cohesive, well defined project.

REQUISITES TO ACCEPTABILITY OF SITE FEASIBILITY CONCLUSIONS

Nuclear research and engineering work must be organized and conducted in a special way if a government license for construction or operation is at stake.

Scientists usually follow a somewhat different technical process in conducting research in laboratories than, say, an architect does in designing a manufacturing facility. Each differs even more dramatically from the approaches used in legal proceedings or formal government hearings. Why? One of the reasons is that those having authority to accept the results of each type of work do so with different values and from a different experience base. This, in turn, strongly shapes each type of process leading to those results. For example, the acceptability of research work is traditionally judged by technically qualified peers of the researcher. A facility design is usually reviewed by other engineers to determine if it meets the original requirements. When technical work is done in the nuclear licensing arena, however, validity of the conclusions may also be reviewed (and potentially challenged) by the lay public, local governments, Indian tribes, and the U.S. Nuclear Regulatory Commission, as well as the courts.

Projects tends to be more efficient if they are structured initially to document conclusions in a form suitable for those who will adjudge their acceptability.

System engineering methods cannot alter the destiny of projects whose research can only conclude infeasibility--except, perhaps, to add certainty to such findings. There are, however, bases other than infeasibility for an unfavorable outcome:

- The scientist or engineer may not be able to establish that he has not overlooked performing some essential investigation.
- There may be doubt that appropriate technical methods were used.
- It may not be possible to show that management controls were adequate.

Powerful system engineering methods are available to eliminate these as potential causes for disputes later in the project, long delays in completion, or project abandonment.

DEVELOPING A SYSTEM APPROACH TO SITE CHARACTERIZATION

There appears to be a fundamental thought pattern underlying many disciplines and formal methodologies such as basic research, problem solving, and operations research:

- Define the problem, purpose, objective, or mission
- Develop a theory of probable cause and effect relationships and identify all information to be acquired
- Define the technical work necessary to acquire all information

- Perform the technical work
- Analyze and evaluate acquired data
- Compile conclusions (iterate process as refined by new understanding obtained).

It has been argued that this pattern is ancient, predating even written language in forming cultural patterns, and is the basis of the scientific method. Figure 1 compares two examples extracted from this work:[1] the modern approach to basic research, and system engineering as applied to system design. The third column has been added to illustrate the close agreement when this pattern is utilized as an approach to structuring a site characterization project.

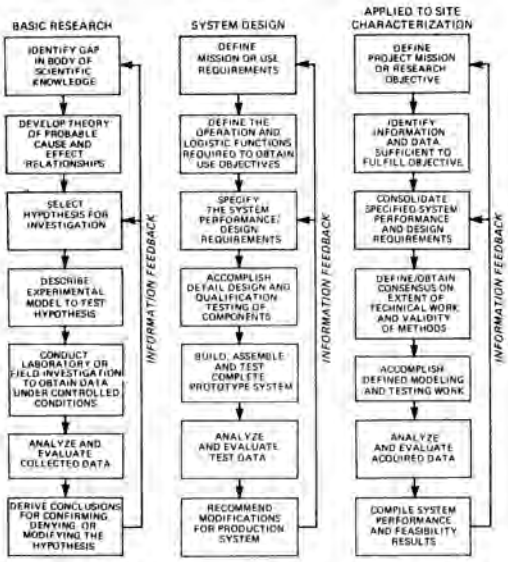

Fig. 1. Similarities between the Scientific Method and System Engineering, and their Application to Site Characterization.

APPLIED SYSTEM ENGINEERING METHODS: A GENERALIZED PROJECT MODEL

A model can be developed depicting how system engineering methods might structure a typical site characterization project. Notice in Fig. 2 that the site characterization approach developed in Fig. 1 has been maintained, although the second and third steps have been consolidated in the model to read, "identify information needs." Discussion of this, and each of the other elements of the model, constitutes the balance of the paper.

The model illustrates three of the most important attributes sought in structuring a licensable site characterization project--each is inherent in a system engineering approach:

1. All the technical work sufficient to fulfill the research objective, including all modeling, tests, analyses, and data interpretation methods, can be methodically identified and defined--and consensus sought--prior to the expenditure of a significant percentage of available time or resources. As understanding expands during the course of the project, this initial definition can be updated.
2. Having defined the technical work, the mechanics of the technical management systems can be tailored to the job to be done instead of vice versa. Change control, business management, configuration control, records management, and the like can be implemented to support the conduct of the technical work.
3. A well defined project can assure that the results to be obtained will provide a comprehensive basis for any required licensing documentation. This approach precludes the structure of the project from simply echoing the content requirements of the licensing documentation--and minimizes the trauma attendant to the inevitable revision of those requirements.

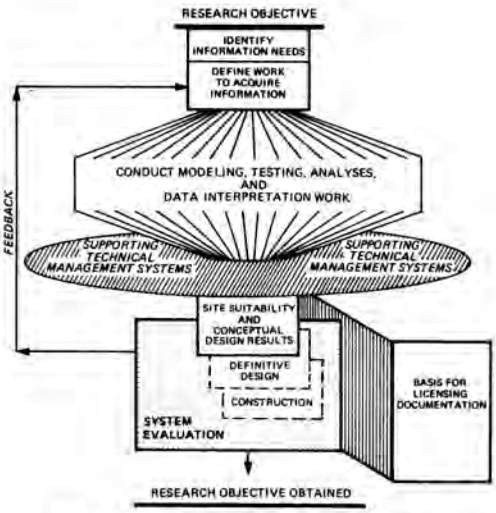

Fig. 2. A Generalized Model of a Site Characterization Project.

DEFINING THE PROJECT OBJECTIVE

Structuring a project through the application of system engineering techniques begins with a careful examination of the objective.

- Unless an accurate and exhaustive definition of the research objective can be framed, no form of system analysis--or any other approach--can reveal the extent of the research that has to be performed to complete the project.

In the case of site characterization for a candidate nuclear waste disposal system, particular care in defining the project objective is essential because of the nature of the site winnowing process prescribed by federal statute. There could be an inclination toward confining the objective to geotechnical research until--and if--feasibility is established. The characterization research must be oriented to the potential purpose for which the site might be used in order to avoid overlooking design-dependent work (e.g., materials and geochemistry research).

- It is this recognition of purpose that sets apart site-specific characterization research from general academic geotechnical characterization, and begins the process of shaping the structure of the project. Failure to emphasize this distinction may cast the project adrift in endless technological meanderings through a regulatory fog.

Accordingly, the research objective for a candidate nuclear waste site must include phrases such as: ...for the permanent disposal of high-level..., and ...maintaining the option to retrieve.., and ...deep geologic...; all obvious imperatives in today's directive literature, and each the origin of unique information needs. No attempt should be made at this point to anticipate actual characterization requirements; a few meticulous sentences are ample to crystallize the project objective.

ESTABLISHING SUFFICIENCY OF TECHNICAL SCOPE

In a licensing environment, it is essential to establish that no relevant investigation has been overlooked. Expert opinion simply asserting, after-the-fact, that such is the case is likely to be ineffective. On the other hand, if it can be shown analytically that all requisite work has been accounted for, it is much less likely that there can be valid arguments for additional investigative work.

One of the most powerful concepts available from system engineering thinking is the notion that, given an incisive understanding of the project objective, all the information and data needed to compile supportable conclusions can be derived from an analysis of that objective--limited, of course, to the depth of understanding previous research has established for the processes involved. Researchers are routinely aware, through experience and observation, of information that is necessary to determine feasibility. However, some type of formal methodology must be employed before it can be established that the body of research information identified is not only essential, but also sufficient to produce supportable conclusions.

- In the absence of a methodology, a project's investigations could become both unbounded and inadequate to fulfill its objective.

The basis, and even the mechanics, of the identification method can vary substantially so long as the selected technique produces the same information needs when directed in the same way at the same phenomena.

One such identification method can be developed by adapting a system engineering technique known as functional analysis. Sets of simple questions and tests can be framed that, when addressed to the knowledgeable scientists and engineers, permit the construction of a hierarchy of the disposal system's physical functions that must exist to fulfill requirements. Additional questions can then be directed at each one of these functions to define their requisite properties, and in turn, the site-dependent data and engineering information that must be acquired to characterization each of these properties.

The resulting hierarchy of disposal system functions and needed information can be the basis for a number of additional analyses critical to completing the structure of the project. One of the most important of these analyses is to identify, for each system function, the most stringent performance constraints. These constraints will usually be found in federal regulatory criteria. However, state and local regulations, codes and ordinances cannot be discounted. As each system function (i.e., each cell in the hierarchy) is reconciled with all regulations, it will become apparent that:

- The disposal system must provide functions not recognized by the regulatory criteria. In other words, the sum total of all regulations are inherently incomplete as a sole basis on which to determine the extent of science and engineering work that must be done. In the case of a nuclear waste repository, this should not be surprising. None has ever been built. This, once again, underscores:
  - the necessity for a formal methodology that can derive from the research objective what information must be acquired
  - the risks of basing a project only on existing regulatory requirements.
- There can be no applicable regulatory-technical-criterion, code requirement, or technical issue--presently existing or yet to be framed--that does not correlate directly to one or more of the hierarchy cells. Consequently, every test, experiment, or analysis can be easily related to the cogent elements of all federal, state, and local directives, as well as all issues.

The identification methodology does not provide importance ranking of the parameters to be characterized. Information priority is, in large measure, dependent upon the technical strategy the project adopts. For instance, the decision to build above or below the ground water level would change the relative importance of the geochemistry information needed. This part of the system engineering process is performed as one of the early steps in the definition of technical work.

DEFINITION OF TECHNICAL WORK

The project's technical work consists, very simply, of the acquisition of the data and information that has been identified through a system analysis as discussed above. It is during this portion of the system engineering process that all the data acquisition methods are selected. Tests and experiments are designed, analytical methods are chosen, and modeling approaches are defined.

Truly exhaustive methods used to identify needed information also mandate prioritization of the work to acquire that information. Project strategies can be developed from trade-off studies and risk assessments. Sensitivity analyses are effective in determining which parameters provide the dominate contribution to the site properties being characterized. Models used in assessing radionuclide isolation performance of the site can provide a major tool for understanding parameter sensitivities, but should not be viewed as sufficient for determining all technical priorities. For example, characterization of rock mass properties may occupy a high priority because of construction feasibility considerations.

The hierarchy of information needs consists of a number of discrete branches that correspond to the groups of system properties to be characterized. It is useful to subdivide the technical work definition effort, and its documentation, into these same groups (e.g., characterization of hydrologic properties). One important advantage to grouping the descriptions of technical work in this manner is that it provides a practical focus for subsequent workshops and other consensus-seeking efforts. Similarly, the subdivision of work definition documentation for the engineered portion of the system seems most useful when grouped by a subsystem and component breakdown structure. Each such document is, in effect, a mini-project plan; it describes all the work required to fulfill a subsystem objective.

- Other approaches to documentation--compiling all the test work to be conducted at a special test facility, for instance, or all the modeling that seems important--tend to subjugate and obscure the real technical objective (e.g., determining regional tectonic stability). This, in turn, leads to a fragmented and disoriented project that is unable to establish whether or not essential work has been overlooked.

For each subsystem property to be characterized, work plans must portray an auditable chain of rationale that links all first generation data to the conceptual models that indicated its need; to all the evolutionary steps of synthesis, computation, analysis, and interpretation of the data; and ultimately, to the matured conclusions that mark full understanding of each subsystem's behavior.

- A plan must be developed that displays, a priori, each step in the rationale that will lead to the conclusions that will ultimately characterize each property.

SYSTEM ENGINEERING MANAGEMENT: SUPPORTING THE TECHNICAL WORK

System engineering management is the activity that integrates the technical effort and tailors the system engineering process to the differing phases of the project. Specific administrative procedures and management controls are essential, but like each element of the technical work, their purpose must be to support the fulfillment of the project objective.

Many of the same system engineering principles discussed to this point in the context of the project's technical work are also useful in designing each management system (e.g., change management, configuration control, records management, data traceability, software management, procurement). Typically, inherited administrative procedural systems are, at best, not optimized for the project and, at their worst, have long ago become mechanical paper nightmares. Perhaps the simplest test to determine their suitability is to see if they can fulfill their intended management purpose of the project at hand without impeding the conduct of the technical work they should be supporting.

In a broader sense the several technical management systems necessary to the execution of a project should be viewed as subsystems of an overall project management system. Without this perspective, redundancies and omissions are probable.

- The system analysis approach for these systems should now be very familiar: define and understand the overall management objective(s), determine what management functions are indispensable to that objective, and identify the properties those functions must possess.

Once these steps have been thought through, the operational mechanics of each subordinate management subsystem can then be designed to exhibit those properties and be tailored to the specific technical work at hand--an invaluable synergism made possible only by a good understanding of the technical work to be performed.

SYSTEM EVALUATION

Project management has many definitions, but one of the most succinct states simply:

Know what to do.
Do it.
Know what was done.

System evaluation is one element of that last phase: results have to be continually assessed.

One of the activities important to the characterization of a potential nuclear waste site is the waste isolation performance assessment of the site's properties. Note from the model (Fig. 2) that the needs of the performance assessment function constitute a primary influence on the definition of the technical tasks, initially as well as during the course of the research. It is difficult to imagine a viable performance assessment effort that fails to utilize a system approach. Indeed, the performance assessment role of allocating isolation performance minima among the subsystems is a textbook example of a system engineering requirements allocation process. As another example, site performance modeling involves a form of system function flow analysis.

Isolation performance, while dominant, is not the only system performance parameter of interest, however. System evaluation also embraces how well all the other system functions must be--and are being--performed (e.g., the extent to which the underground shafts and tunnels are structurally stable). Provided this evaluation process is architected around a consistent system engineering approach as discussed throughout this article, it too should be a straightforward, solid facet of the project. Recall that all subsystems, their functions, the properties required of each function, and the information and data to be acquired to characterize these properties have all been defined previously. Integration of results simply reverses the pattern of methodically subdividing the system--if the integrity of the pattern has been preserved throughout the execution of the project.

SUMMARY

This discussion of a system engineering approach to project definition has proceeded through five pragmatic steps:

1. Thoroughly understand the project objective.
2. Identify the information that must be acquired to attain that objective and correlate all applicable regulatory requirements to the respective information elements
3. Define the technical methods and work necessary to acquire the needed information.
4. Methodically design all technical management systems to support that specific acquisition work.
5. Integrate and assess the emerging results and refine the technical methods as indicated by the expanded understanding of the phenomena under study.

Were the results of thinking through a project in this way to be precipitated into operational documentation and arrayed by precedence, a structure would take shape similar to the hierarchy in Fig. 3. The project objective, the policies applicable to all project participants, and the architecture to which all project activities would adhere is captured in the Executive Direction documentation. The other documentation groups are labeled to relate to roles discussed throughout this article.

- Note that test facility documentation serves only to programmatically integrate the data acquisition work as defined in detail in the Science and Engineering Work Definition plans. With this approach, these Test Facility Operating Plans are not permitted to originate any work methods affecting the ultimate validity of data or acceptability of results.

Finally, the consolidation of results that constitute the current understanding of the system being studied are maintained in an evolving System Description document.

In summary, the hypothesis-based approach to architecting a project continues to be suitable for scientific research, the discovery of new truths and laws, and in the early phases of development of a new technology. This approach may also remain useful for specific research portions of more complex projects. A system engineering approach is significantly more effective in those projects requiring the application of known facts and technical methods, in the production of end products of a technology, and in the realization of a physical product or facility.

It is important that system engineering methods become common-place in nuclear projects.

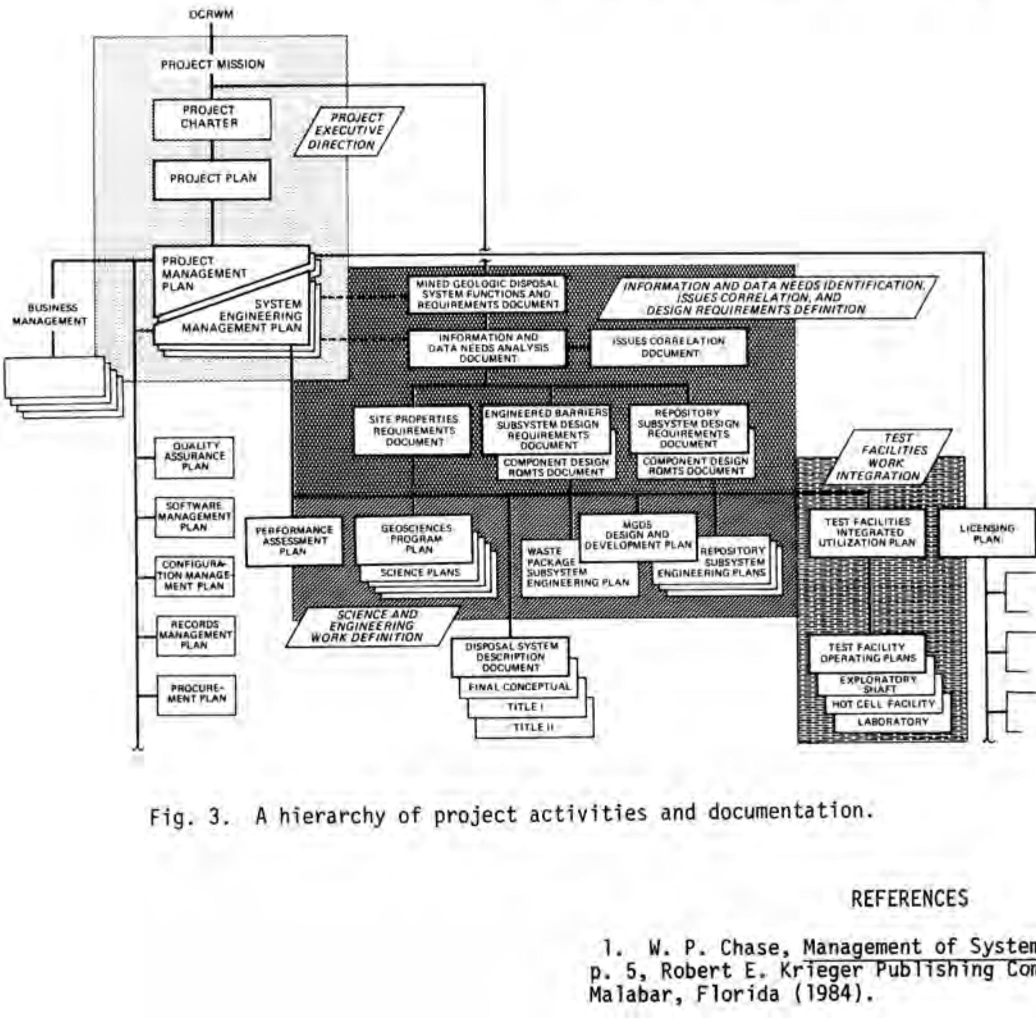

Fig. 3. A hierarchy of project activities and documentation.

REFERENCES

1. W. P. Chase, Management of System Engineering, p. 5, Robert E. Krieger Publishing Company, Inc., Malabar, Florida (1984).