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OPTIMIZING THE DESIGN AND OPERATION OF AQUIFER THERMAL ENERGY SYSTEMS

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Optimizing the Design and Operation of Aquifer Thermal Energy Systems

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ABSTRACT

The design of Aquifer Thermal Energy Storage (ATES) systems is complicated by significant uncertainties in our ability to reliably predict the response of the aquifer to fluid and thermal fluxes. Overdesigning the system, to compensate for these uncertainties, reduces the potential economic and energy benefits of an ATES system. Underdesigning the system results in systems that fail to meet design targets. Unfortunately, standard aquifer characterization methods and hydrologic models do not provide adequate information to overcome these uncertainties. Thus, expensive full-scale tests are generally recommended to develop an adequate understanding of the systems' response. However, the standard engineering "design-build-operate" process is not appropriate for ATES systems because an optimal design cannot be completed without some operational experience, i.e., field tests. A more adaptive engineering process is required. This engineering process should be flexible enough to allow the design to be adjusted during the operation, as monitoring data become available and as an understanding of the system response increases. Engineering approaches being developed for environmental restoration of contaminated soil and groundwater can be adapted to optimally design and operate ATES systems.

INTRODUCTION

Aquifer Thermal Energy Storage (ATES) was proposed in the early 1970s [1,2]. Early estimates suggested that ATES could have a significant impact on the United States energy consumption. However, although several million dollars have been spent in ATES research, only one ATES system is currently in operation in the United States. The negligible penetration of ATES into the United States energy market resulted from relatively low energy prices and the unwillingness of the building energy technical community to accept the real risk of ATES systems failing to meet design goals. To reduce this risk, methods for dealing with the uncertainty of an ATES system's response must be employed.

Early assessments of ATES systematically overestimated the performance of ATES systems by neglecting to thoroughly address the variety of uncertainties that impact both the performance of the aquifer and the associated delivery/supply system. Uncertainties in aquifer response to thermal and fluid loads include:

- hydraulic conductivity
- porosity
- aquifer/strata thickness(es), and
- boundary conditions, such as recharge rates, transient piezometric heads.

For instance, early assessments were based on model simulations in which the aquifer was assumed to be homogeneous. Field experiments quickly showed that the level of stratification common to most shallow alluvial aquifers has a significant impact on the aquifer's thermal performance. Subsequent modeling studies confirmed this finding [3]. Early modeling studies also underestimated the impact of regional groundwater flow of many of the most readily accessible aquifers (i.e., shallow unconfined aquifers) on thermal recovery efficiency.

Uncertainty in the delivery and supply system performance also impacts the system design. Such uncertainties include:

- chemical treatment requirements
- transient nature of energy supply
- transient nature of energy demand
- transient nature of the recovery temperature.

Many of the early evaluations of ATES designs assumed that a constant recovery temperature would be servicing a steady demand. Such an assumption clearly overestimated the system's performance. Designers aware of these assumptions were obligated to overdesign the system. Overdesigning often resulted in systems that were no longer economically justified.

An alternative to overdesigning the system to compensate for uncertainties in the aquifer system's response is to further characterize the aquifer (e.g., pump tests, geophysical logging). However, even after extensive characterization, the ability to predict the aquifer's response is still limited. A characterization effort of sufficient magnitude to reduce the need for overdesign is likely to result in overcharacterization, hence in unnecessary cost. Characterization should be limited to the amount that can be expected to provide increased return on investment (i.e., the cost-benefit ratio of reduced risk of system failure) that is greater than the cost of the characterization itself.

The uncertainties mentioned above make the cost-effective design of an ATES system difficult. The design process must provide enough flexibility to allow the operating strategy, and any subsequent design opportunities, to be adapted to new knowledge gathered during the operation. Most of the uncertainties in aquifer response, as well as many demand or supply uncertainties, are commonly encountered in other fields, as discussed below.

RELATED DESIGN EXPERIENCE.

Approaches originally designed to reduce costs while meeting design criteria for foundation stability have undergone major development for the design and operation of systems to cleanup contaminated aquifers. These approaches (discussed below) and tools (e.g., models) are readily adapted to the design and operation of ATES systems. The techniques discussed here explicitly consider the impact of uncertainty on the design process.

Observational Approach

The Observational Approach was put forward by Karl Terzaghi and further developed by Peck [4] as a means of balancing characterization costs and the residual characterization uncertainty relative to the stability of foundations and earthen works. This approach has been applied to groundwater monitoring problems [5] and to environmental restoration problems [6]. The National Research Council, the U.S. Department of Energy (DOE), and the U.S. Environmental Protection Agency (EPA) have encouraged application of this method to subsurface remediation. It provides a framework for managing uncertainty and planning decision-making on an iterative basis throughout the life of a project. The merit of the observational approach lies in two cost reduction aspects. First, the approach explicitly recognizes that it is cost-effective to postpone some decisions until after portions of the construction have been completed, using the information gained to increase understanding of the environment. Second, uncertainty in earth material properties is managed in a cost-effective manner by planning alternatives that are allowed for in the original construction and are only implemented when, and if, required.

The Observational Approach applied to ATES involves collecting and reviewing available regional records of wells drilled in the same formation(s) to determine the range in variables of interest, e.g., thickness of strata, frequency of occurrence of high and low porosity and permeability layers, ranges and distribution of hydraulic conductivity and porosity, and water chemistry. This information is used to derive a conceptual model of the aquifer system including fluid, energy, and geochemical aspects. A mathematical model of groundwater flow and energy transport can be used to estimate unmeasured parameters (e.g., head, velocity) for numerous equally-feasible realizations of the subsurface environment once adequate characterization data is available. These results can also help define future characterization data needs. The conceptual model will include recharge and discharge locations and processes, the relative importance of different zones, and any important water chemistry interactions (such as clay dispersal if Na-exchange is to be used to avoid carbonate scaling). Conceptual model development is followed by limited initial site characterization if information from wells drilled locally is unavailable or is clearly insufficient. This characterization will use information derived from wells that are intended for subsequent use for monitoring, injection, or recovery. The conceptual groundwater model is iteratively refined as characterization information is acquired.

An important aspect of the Observational Approach, as developed by Terzaghi and used in environmental restoration, is the formulation of alternatives in the design stage as opposed to after the low-probability failure has occurred. Design decisions are made with the full intent to modify them as characterization and monitoring information becomes available as construction and installation proceeds. As D'Appolonia [5] pointed out, "The essential ingredient, without which all the others may lead to nothing, is the visualization of all possible eventualities and the preparation in advance of courses of action to meet whatever situation develops."

A relatively direct application of the Observational Approach to ATES would involve the development of risk identification and risk management matrices. Table 1 shows an example of such a matrix. The objective of this matrix is to identify all significant risks and their respective likelihood; of occurring. This is followed by the development of a risk management matrix (Table 2). This matrix clearly identifies the contingent actions that are triggered when a specific event has occurred. It also defines the preventive actions that reduce the likelihood that the risk will occur. Table 3 identifies some of the risks and possible preventive actions and design contingencies to mitigate identified risks.

Data Quality Objectives

The Data Quality Objectives (DQO) approach establishes the quality and quantity of data required for resolving a given problem by formalizing the linkage between data collection and decision-making. The purpose of Data Quality Objectives is to "Specify the decision maker's acceptable limits on decision errors, which are used to establish appropriate performance goals for limiting uncertainty in the data." [7]. The EPA [7] defines five steps to accomplish this purpose:

- determine the possible range of the parameter of concern
- identify the potential consequences of error of hypothesis testing
- specify a range of possible parameter values over which the consequences of decision errors are relatively minor
- assign probability values to points above and below the action level that reflect the acceptable probability for the occurrence of decision errors
- check the limits on decision errors to ensure that they accurately reflect the decision maker's concern about the relative consequences for each type of decision error.

These activities follow the development of a decision rule. To limit both costs and the likelihood of making decision errors, the acceptable probabilities of decision errors are defined. This allows the design to be optimized with iteration between decision error probability definition and design optimization.

Data Quality Objectives can provide guidance on the quantity and frequency of characterization data required to provide statistically valid data on which to base ATES design decisions. For instance, one could define the number of ambient water chemistry samples required to design a water treatment system for an ATES facility. Whereas Data Quality Objectives focus on overcoming analytical measurement errors, the focus would shift to sampling and modeling errors for ATES systems.

Streamlined Approach for Environmental Restoration

A Streamlined Approach for Environmental Restoration (SAFER) was developed in response to the DOE's recognition of the need for increased speed and cost-effectiveness of environmental restoration. It is a methodology that integrates the quantitative tools of the Data Quality Objectives with the qualitative philosophy implicit in the Observational Approach [6]. SAFER explicitly recognizes the inherent uncertainty of groundwater flow and composition. An important concept of SAFER is an emphasis on quantitatively defining the adequacy of site characterization data by means of a decision rule. The rationale for the decision rule is that it specifies the level of data adequacy that will reduce the residual uncertainty to some acceptable level for decision-making. The intent is to link the hydrologic uncertainty and the objective function to data requirements. This must be done iteratively as data availability increases and the conceptual model is refined. Probable conditions are identified, and the level of certainty is determined by the decision rule. The acceptable uncertainty is viewed as deviations from the probable conditions and contingency plans are developed to deal with deviations from the probable conditions.

Adaptive Management

Another relevant approach called Adaptive Management comes from the field of ecosystem management. Adaptive Management was developed by a team of biologists and systems analysts in the 1970s [8]. Adaptive management employs deliberate experimentation to improve the understanding of the ecosystem behavior while attempting to avoid adversely effecting the ecosystem. A similar approach called 'dual control' has been developed in the field of electrical engineering.

In the design of ATES systems, Adaptive Management encourages the ATES designer to proceed with deliberate experimentation (e.g., field tests) that improve knowledge of aquifer response with minimum adverse effects (e.g., poor thermal efficiency, high costs) on the performance of the system. This requires balancing a potential decrease in efficiency with the need to gain knowledge of the system.

Integrated Environmental Monitoring

The Integrated Environmental Monitoring Initiative is a current Pacific Northwest Laboratory initiative to develop an integrated framework for the design of monitoring systems. The framework (Figure 1) identifies the process involved in defining the tradeoffs between multiple objectives. The ATES system designer selects optimized designs once the design objectives are established. The optimized designs are flexible and adjust to the results of the deliberate experiments included in the design. Integrated Environmental Monitoring provides a formal and quantitative framework consistent with the Observational Approach, Data Quality Objectives, SAFER, and Adaptive Management.

The Integrated Environmental Monitoring framework includes the requirement specifications for a variety of software tools including physically based models, optimization methods (e.g., genetic algorithms, dynamic programming), uncertainty assessment tools (e.g., geostatistical software), database management systems, and visualization tools. A model of uncertainty is a critical element of the Integrated Environmental Monitoring framework. Such a model of uncertainty embeds both expert judgment and the results of probabilistic and statistical analyses. Integrated Environmental Monitoring provides a framework to evaluate the worth of additional data by relating the reduction of uncertainty to expected changes in each of the objectives. Relevant uncertainty models for ATES need to be developed.

Aquifer Thermal Energy Storage System Simulator

The Aquifer Thermal Energy Storage System Simulator [9, 10] provides ATES designers with a user-friendly, interactive model using a simple aquifer and aboveground heat transfer compartments. It is intended to evaluate energy recovery as a function of interrelationships among design specifications, operational strategies, and variable energy usage rates. The aboveground compartment exchanges heat between the aquifer and distribution fluid and includes energy demand loads. The aquifer compartment assumes perfect stratification (e.g., it does not consider buoyancy, thus large-scale convective mixing is not simulated) and transfers heat by horizontal convection and vertical conduction within the storage layer(s). The three-dimensional flow is conceptualized as a set of two-dimensional streamline planes, i.e., a vertical projection of a fluid volume moving away perpendicular to a storage well. Diffusion (or dispersion) coefficients need not be estimated; the dispersive effects indicated in model results arise primarily from the variability in the hydraulic conductivity values. The consequences to energy recovery of the number of aquifer layers in which thermally altered water is stored can be readily examined with this model. Stochastic generators (crude uncertainty models) for system inputs (energy for storage) and outputs (demand for energy), available in earlier versions of the model, have been removed until better uncertainty models become available. This simulator does not consider the uncertainty in aquifer parameters (e.g., hydraulic conductivity, porosity).

CONCLUSIONS

ATES is a technology whose cost-effectiveness is increased by deploying it in steps that are consistent with monitoring and deliberate experimentation. An expansion of ATES capacity in steps provides an opportunity to adapt to the improved understanding that occurs during operation and probing of the system before the capacity expansion phase and additional characterization that results from it.

Development of an ATES system in steps is not always consistent with the demand that the system it is intended to supply. In many facilities, the building energy infrastructure is considered a one-time capital investment. If it is not feasible for the demand to increase in steps as the ATES capacity is expanded, temporary backup energy sources must be included in the design. Typical periods of expected return on investment are too short to justify investing in the required temporary capacity. Energy system opportunities that are amenable to capacity expansion in steps should be targeted to facilitate the penetration of the energy market by ATES systems.

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Table 1. Risk Identification Matrix

Identified Risk	Likelihood of Occurrence	Difficulty of Timely Detection	Potential Impact	Overall Risk to Project

Table 2. Risk Management Matrix

Identified Risk	Preventive Action	Contingency Action	Trigger

Table 3. Examples of Risks and Preventive/Contingency Designs/Plans

Risk	Preventive/Contingency Design
Improper well field design	Flexible piping design (capability to use any specific well for storage or injection during any period)
Higher than expected regional flow	Flexible piping, New wells
Lower than expected recovery temperature	Backup units, Selective withdrawal
Underdesigned for peak capacity	Short-term storage

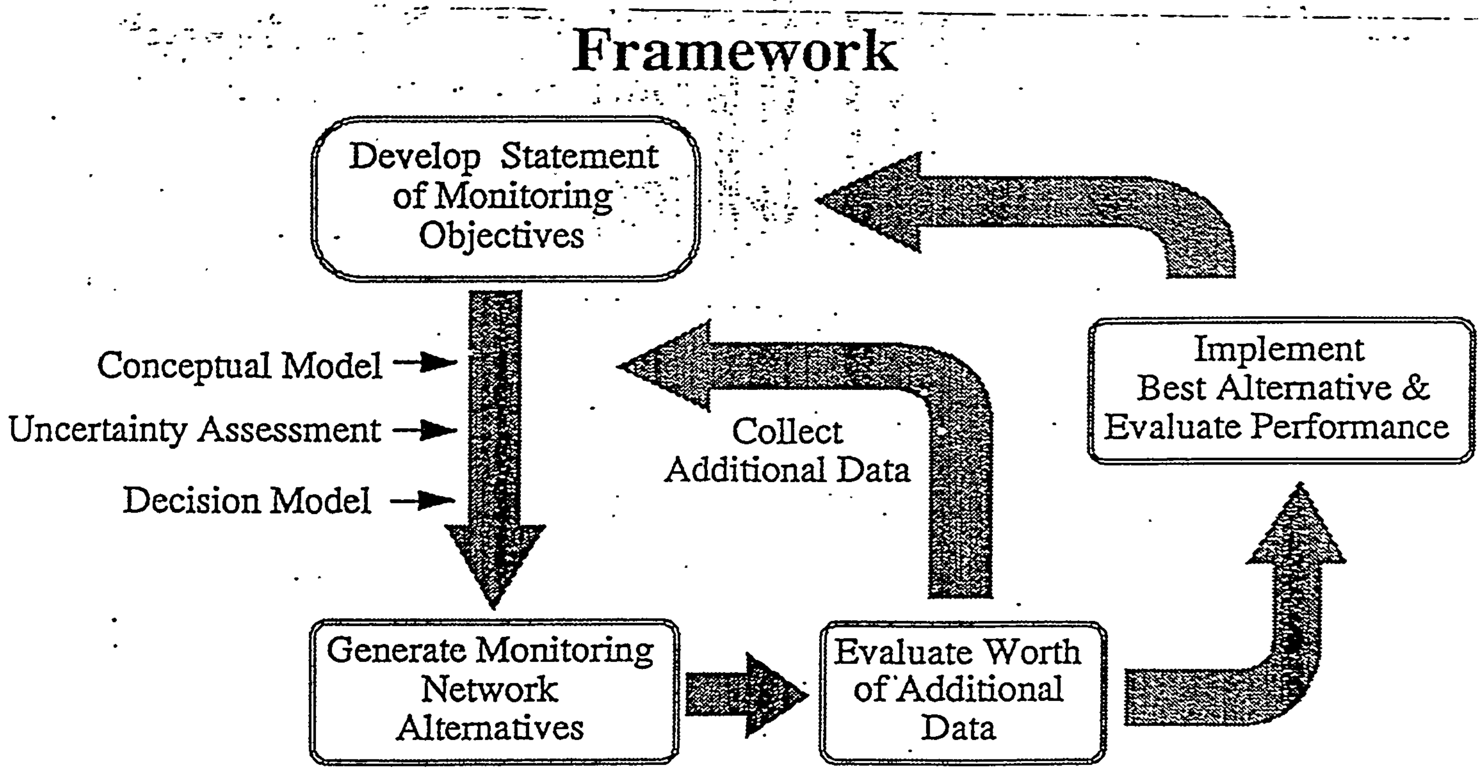

Figure 1. Integrated Environmental Monitoring Components