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PROJECT PLAN FOR THERMOHYDROLOGY PROJECT

Prepared for

Nuclear Regulatory Commission
Contract NRC-02-88-005

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PROJECT PLAN FOR THERMOHYDROLOGY

The Nuclear Waste Policy Act (NWPA) of 1982, as amended, establishes the responsibilities of the Department of Energy (the license applicant), the Nuclear Regulatory Commission (NRC) (the license review and license issuing agency), and the Environmental Protection Agency (the promulgator of standards for long-term repository performance). Siting and licensing of a high-level nuclear waste (HLW) repository requires that sophisticated technology, technical complexities, intense public scrutiny, and rigorous schedule constraints be integrated in one program. This mission has additional complications, those associated with a complex multiparty legal and regulatory evaluation and approval process.

In support of its high-level waste program under the NWPAA, NRC established the Center for Nuclear Waste Regulatory Analyses (hereafter referred to as "the Center"). The mission for the Center is to provide a sustained high quality of technical assistance and research in support of NRC's HLW program. Toward accomplishing this mission, the Center is required to establish research activities to aid in identifying and resolving technical and scientific issues associated with the NRC's licensing of a high-level nuclear waste repository.

Technical issues and uncertainties for the Yucca Mountain HLW repository candidate site derived from DOE, NRC, and EPA statutes and regulations, explicitly or implicitly indicate a need for research on thermohydrological phenomena, i.e. phenomena associated with heat and fluid flow, to provide information relevant to performance assessment and design criteria. The class of thermohydrological phenomena examined in this project primarily includes phenomena driven by heat emanating from HLW emplaced in a geologic repository. NRC regulation 10 CFR60 requires that the geologic setting for an HLW repository exhibit an appropriate combination of conditions to provide reasonable assurance of waste isolation. Information derived principally from research will be used to establish a knowledge base of thermohydrologic phenomena which will be utilized by the NRC to assess models of processes used in performance assessments during the repository licensing procedure. An understanding of critical thermohydrologic parameters will augment the analysis and interpretation of field data. Because the laboratory simulations will be subject to validation with field data, this program will involve experimental designs which facilitate the direct correlation of data collected in the model with data collected in the field.

Integration of the research projects that comprise the Center's Research Program will be an outgrowth of the systems engineering approach that guides all work of the Center in support of the NRC-HLW regulatory mission. Research needs are systematically identified and prioritized using the Program Architecture described in the Waste Systems Engineering and Integration Subelement Operations Plan.

Interrelationships among conditions and processes affecting site characterization, performance assessment, and design criteria will be evaluated in the Thermohydrology Research Project. This Project will provide important information concerning fundamental processes of heat and mass transfer, and fluid flow in the unsaturated zone of the proposed Yucca Mountain repository site. Close coordination with the Geochemistry, Seismic/Rock Mechanics, and Integrated Waste Package Research Project will ensure effective integration of the results of each of these Projects with the others.

The NRC has previously sponsored two HLW research projects related to Thermohydrology issues. These projects were entitled "Laboratory Studies of Thermoconvective Phenomena in High-Level Waste Disposal and Development of Empirical Heat Transfer Correlations for Repository Licensing;" FIN B8944 (University of Delaware) and FIN D1674 (Colorado State University). These projects demonstrated the feasibility of conducting laboratory simulations of thermohydrological phenomena that may occur in HLW disposal for the conditions of saturated porous and fractured media. The experiments conducted in these projects were designed on the basis of the principal of dynamic similarity. Relevant similarity parameters; i.e., Rayleigh and Peclet numbers, were selected in the laboratory experiments to bracket the expected values of the corresponding parameters in an HLW repository located in saturated media.

Two different scales of phenomena were examined in FIN's B8944 and D1674; i.e., those of the order of the repository scale, in which thermohydrological phenomena induced by the aggregate of emplaced HLW were studied, and those of the order of the waste package scale, in which thermohydrological phenomena in waste package packing materials were examined. All of the work done under FIN's B8944 and D1674 pertained to HLW disposal in saturated media. The two projects began when the HLW licensee, the U.S. Department of Energy, was examining the option of HLW disposal in saturated media. However, the Nuclear Waste Policy Amendments Act of 1987 has directed DOE to examine just the site at Yucca Mountain, Nevada, for HLW disposal. HLW disposal at this site would be in unsaturated fractured rocks. This situation presents NRC with a need to understand thermohydrological phenomena in unsaturated fractured media. The work performed in FIN's B8944 and D1674 is not directly relevant to the Yucca Mountain site; however, this work does provide a limiting case for the phenomena in unsaturated flow and, therefore, may be a useful data point in this research program.

Additional work done for the NRC under the HLW research projects, "Unsaturated Flow and Transport Through Fractured Rock Related to HLW Repositories," FIN B7291 (University of Arizona) and "Investigation of Coupled Interactions in Geothermal and Hydrothermal Systems for the Assessment of HLW Isolation," FIN B3046 (Lawrence Berkeley Laboratory) suggest that thermohydrologic phenomena will have an important impact on the hydrologic environment near emplaced HLW. Both projects have indicated the possibility that thermohydrological phenomena, on both the repository and waste package scales, may cause regions of local saturation interspersed with unsaturated regions. Saturated or unsaturated conditions in the hydrologic environment may have a strong impact on the geochemical environment in the neighborhood of emplaced HLW and on the types of corrosive processes affecting HLW package overpacks.

Finally, an understanding of thermohydrologic phenomena in unsaturated fractured media will be of value to the NRC in:

(1) accounting for thermal effects while assessing DOE's predictions of the period of containment of radionuclides in the waste package,

(2) accounting for thermal effects while assessing DOE's predictions of the release of radionuclides from the engineered barrier system,

(3) estimating the extent of the disturbed zone so that DOE's predictions of pre-emplacement groundwater travel times may be assessed, and

(4) estimating thermohydrologic effects on the transport of radionuclides from the emplaced waste to the accessible environment in order to assess DOE's claims of compliance with the EPA's HLW radiological standard.

This document presents the project plan for the Thermohydrology Research Project to be conducted as part of the Center's research program.

1. TECHNICAL OBJECTIVES

1.1 Purpose, Goals, and General Objectives

The purpose and general objectives of this research project on Thermohydrology are as follows:

(1) To improve understanding of thermohydrologic phenomena in unsaturated media, specifically that associated with high-level waste (HLW) repositories. This general objective supports evaluation of compliance with the requirements of Part 60 of Title 10 of the Code of Federal Regulations (CFR) for repository design, including the specific objectives of determining the magnitude of:

  (a) the effect of thermohydrologic phenomena on the period of containment of radionuclides in the waste package.

  (b) the effect of thermohydrologic phenomena on the release of radionuclides from the engineered barrier system.

  (c) the effect of thermohydrologic phenomena on the transport of radionuclides from the emplaced waste to the accessible environment.

(2) To delineate further the range of applicability of similarity techniques and to develop important dimensionless parameters in unsaturated media as a basis for designing and conducting laboratory simulations and experimental investigations of various thermohydrologic phenomena. This objective will form a basis for determining (a) the fundamental ability of laboratory experiments to resolve uncertainties in physical phenomena associated with HLW repositories, and (b) the limits to which laboratory simulations can be used to validate mathematical models and to assess their predictive capabilities with respect to HLW disposal.

(3) To validate further the use of dimensionless parameters through the design and implementation of a set of preliminary or single-effects experiments. Secondary objectives of these preliminary experiments are to (a) identify the requirements for large-scale experimental studies, (b) identify appropriate materials and their properties, representative of HLW repository media, and (c) identify instrumentation to measure quantities suitable for validation of mathematical models and to provide insights into the physics of phenomena associated with HLW repository dynamics.

(4) To design and conduct larger-scale experiments, whose design are based on the results of research performed in Tasks 1 and 2, as detailed in the following Technical Program Description. This work will be an integral part of the establishment of a complete experimental capability to conduct a planned program of directed research in thermohydrology and to provide timely investigations of a variety of concerns, identified with the aid of the NRC-HLW Program Architecture.

The goal of this research project is to enable NRC and the Center for Nuclear Waste Regulatory Analyses (CNWRA) to develop the technical knowledge base and the experimental capability to provide necessary guidance to the NRC and to review, investigate, and evaluate DOE submittals to NRC on thermohydrologic phenomena associated with a HLW repository.

1.2 Specific Objectives

The specific objectives of this research project may be summarized as follows:

(1) To perform a critical assessment of the state-of-knowledge of thermohydrology in unsaturated fractured media, in the context of present HLW-NRC program activities. This assessment will require an in-depth review of existing literature and on-going programs. The assessment will focus on flow processes, heat transfer mechanisms, and the state of experimental methods in porous and fractured media,

(2) To perform a detailed dynamic similarity or similitude analysis on the complete set of governing equations relevant to unsaturated flow and to determine the set of dimensionless parameters required to conduct appropriate laboratory simulations. In this analysis of modeling parameters, the range of parameter applicability and limitation on the magnitude of these parameters, as constrained by the principles of dynamic similarity, will be determined,

(3) To identify potential problems associated with the design and performance of laboratory simulations with scaled geometry, fluid, media, and other relevant properties subject to modeling distortion,

(4) To perform a series of separate effects experiments in order to identify and understand the role of each effect in the overall, coupled processes involved in thermohydrologic phenomena,

(5) To design and perform comprehensive experiments whose results will continue to identify key dependent and independent parameters and their relationships to each other in the context of thermohydrologic issues,

(6) To develop the laboratory facilities, experimental methods, measurement techniques, and associated analytic skills to evaluate and validate other program results and to provide a high quality of technical assistance and research in support of NRC's licensing of an HLW repository, and

(7) To examine and correlate laboratory results with field data, to aid in the design of future field experiments.

2. TECHNICAL PROGRAM DESCRIPTION

2.1 Technical Approach

Thermohydrologic behavior in the vicinity of HLW repositories is a highly complex phenomena involving many interacting processes characterized by many parameters, including geometric parameters, physical property parameters descriptive of both the fluid and media, and dynamic parameters descriptive of the fluid flow and heat transport. All individual thermohydrological processes occur simultaneously and interact, both in a linear and nonlinear manner, to create complex processes. These processes, in turn, determine the response of the unsaturated system and the distribution of fluid flow, heat transport, and transport of radionuclides.

If it is assumed that the media is a saturated continuum through which fluids, heat, and chemical species may migrate, sets of governing partial differential equations (their form being dependent on the assumptions used in their development) can be developed describing the transport of these quantities. In turn, finite difference and finite-element techniques may be used to discretize these equations. With the aid of computer programs, solutions can then be obtained for specified initial and boundary conditions in terms of the dependent variables. Currently, many such programs exist for this class of flow problem. Many of these programs have been verified and, in some cases, their associated mathematical models have been validated for idealized laboratory experiments.

As thermohydrologic research focuses on the proposed Yucca Mountain site, problems associated with the (1) determination of the physical and chemical properties of the media, (2) complex processes associated with unsaturated flow, and (3) potential for secondary forces becoming critically important to the total system analysis, have greatly complicated the repository candidate site evaluation process. Concurrently, our increasing understanding of the physical processes has revealed greater complexities so that increasingly more assumptions and limiting approximations to the governing partial differential equations are required to maintain a mathematically tractable problem for simulation. As physical complexities increase, laboratory and experimental investigations take on a more important role as mathematical models require more detailed data for validation, and complex nonlinear processes require more detailed investigations, and in turn, these laboratory experiments require more comprehensive scaling of the dynamic parameters in order to be effective.

The technical objectives of this proposed research, as indicated in Section 1, are directed at determining the role and limits of laboratory simulations and their reliability in the investigation of the thermohydrology of the candidate HLW repository site at Yucca Mountain, Nevada. As indicated above, laboratory simulations may be required to provide detailed information on thermohydrologic processes, processes which are not readily observed or measured in the field. In addition, for mathematical models to become an integral part of the site evaluation process, accurate and detailed data for a broad spectrum of system conditions must exist for their validation. In summary, the specific tasks to be performed in this research are:

Task 1: Assessment of the State-of-Knowledge on Thermohydrology in Unsaturated Media.

Task 2: Design and Execution of Preliminary Separate Effects Experiments

Task 3: Design of Unsaturated Zone Thermohydrological Experiments

Task 4: Thermohydrologic Phenomena Induced by the Aggregate of Emplaced HLW in Unsaturated Geologic Media

Task 5: Unsaturated Zone Thermohydrologic Phenomena Induced by Multiple Packages of HLW

A detailed discussion of the planned activities for each task is presented in Section 2.2.

2.2 Technical Tasks

Five major technical tasks have been identified for this project and are planned to be completed over a 39-month period. A detailed description of these tasks is given in this section. Activities for the tasks are shown with time sequencing in the Gantt Chart shown in Section 2.3.

2.2.1 *Task 1: Assessment of the State-of-Knowledge of Thermohydrology in Unsaturated Media*

OBJECTIVES

The objectives of this task are to:

(1) Assess the state-of-knowledge relating to:

- Applications and limitations of similarity techniques as a basis for the design and analysis of experimental investigations of thermohydrologic phenomena in unsaturated media.
- The requirements of experimental and computational simulations of thermohydrology in systems in unsaturated media.

(2) Identify critical attributes of the geologic setting of the Yucca Mountain HLW repository candidate site which must be characterized in order to simulate thermohydrologic processes and conditions accurately.

(3) Develop an understanding, sufficient to evaluate, on-going thermohydrology programs at other locations under NRC and other sponsorship.

(4) Provide the necessary and sufficient information for the successful direction of this research program.

JUSTIFICATION

The assessment of existing literature and on-going programs will focus initially on dynamic similarity as applied to unsaturated media and on the identification of the range of dimensioned variables and nondimensional modeling parameters relevant to this problem. This will establish the extent to which the governing physics for thermohydrologic behavior in unsaturated media are known. This knowledge base is essential to the design of the experiments to be undertaken in the remaining tasks. The assessment will include sufficient investigation of thermohydrologic behavior in saturated media to obtain necessary insights on experimental methods, scale modeling of media properties and variability, and instrumentation techniques.

The following delineates areas of concern to the critical assessment of the state-of-knowledge.

2.2.1.1 *Knowledge Areas and Parameter Identification*

Interrogations of selected data bases have revealed large numbers of relevant references of potential value to this program. Keywords focusing on the unsaturated zone; i.e., fractured rock, heat transport, thermohydrology, modeling, and properties such as capillary pressure, buoyancy, vapor pressure, etc., reveal a substantial body of available literature. Similar results have been obtained using known author names, e.g., Kulacki, Pruess, Narasimham, Wang, Evans, Prasad, etc., as well as Berkeley, Sandia, Colorado State University, University of Arizona, University of Delaware, U.S. Geological Survey, and others.

Also important to this project are data and information on the geologic setting and on the physical parameters characterizing the site media. Field data from Yucca Mountain and from representative sites are required for this program of work. The physical parameters that are representative of the site-specific conditions at the HLW repository candidate site are its spatial dimensions, matrix permeability and porosity, fluid density and viscosity, fluid and media thermal conductivity and specific heat, media moisture retention and saturation level, fluid compressibility and fracture characteristics. Considerably more specificity of physical parameters will be required as governing equations are reviewed and analyzed, and the media-thermal-hydrologic interactions become more completely defined.

The data base searches will become more focused as the development of the knowledge base progresses. Review of some significant works will lead to further inquiries based on key words, authors, organizations, and other headers. The ability to define the entry headers more accurately will produce a continually, more directed assessment of the state-of-knowledge.

The activities of Task 1 will be conducted primarily during the first nine periods of the project. As the research progresses and receives peer recognition, staying abreast of new developments will be facilitated by exchange of published material, attendance at meetings, and visits to other organizations. It is anticipated, however, that regular searches will be made of data bases continually to update the Center's informational resources.

2.2.1.2 *Program Review*

As part of assessing the state of knowledge on thermohydrologic behavior in unsaturated media, it will be necessary to visit other laboratories and organizations where similar work is conducted. This will be especially true for NRC sponsored programs, as it is critical that the Center be aware of work in these programs. A thorough review of related NRC projects will be performed to allow emphasis on the techniques used in and results obtained from the aforementioned NRC programs FIN B8944 and D1674, and current projects such as FIN D2079, FIN B7291 (field heater tests), and FINs B3046 and B3109 (thermohydrologic interactions).

Attendance at a limited number of workshops, symposia, conferences, and similar meetings will also be necessary. These types of meetings frequently provide in-depth and detailed information on specified programs.

2.2.1.3 *Reporting*

An interim letter report is to be prepared which summarizes the results of this literature review and describes work conducted by investigators at different research facilities. This letter report is to be submitted to the NRC Project Manager in September 1989.

2.2.2 *Task 2: Design and Execution of Preliminary Separate Effects Experiments*

OBJECTIVES

The objectives of this task are to:

(1) Design, in a comprehensive plan, experiments to study thermohydrologic phenomena in unsaturated media. These experiments will range in scope and size from preliminary single effects experiments to limited coupled phenomenological experiments.

(2) Study, in separate or single effects experiments (at various levels of saturation), phenomena due to:

- surface tension effects
- fracture vs. matrix flow
- natural convection
- media quality effects
- forced vs. natural convection
- transient heat effects

and to evaluate:

- the effect of system initial and boundary conditions on model response
- measurement and flow visualization methods

(3) Implement dynamic similarity analysis in the design of all experiments and through the use of similarity analysis techniques, quantify and bracket the magnitudes of geometrical and physical parameters and dimensionless groups of variables.

(4) Develop the scientific knowledge, experimental methods, and analysis tools required for the design of the fully coupled phenomenological experiments of Tasks 4 and 5.

JUSTIFICATION

A large uncertainty presently exists regarding the limits to which laboratory simulations of thermohydrological flows in laboratory models of unsaturated, fractured, porous media can be used to validate computational models or be used as direct analogs of the HLW repository candidate site behavior. More fundamentally, the ability of laboratory models to resolve uncertainties in thermohydrological flow in the Yucca Mountain repository must be determined. This task is the required first step in designing and evaluating such laboratory models.

2.2.2.1 *Investigation of Thermohydrologic Phenomena Through Separate Effects Experiments*

Two broad categories of parameters and phenomena are to be studied in a series of single and multiple effects experiments; i.e.,

- Physical parameters that characterize thermohydrological flow phenomena in general, and
- Physical and geometrical characteristics of the repository and geologic setting.

The highly nonlinear nature of the thermohydrology of unsaturated media, and the tightly coupled interactions among the individual processes characteristic of this system, inherently precludes the identification of the role of each individual process in the coupled processes. For example, in the transport of fluid through a block of media consisting of fractures and matrix, one cannot readily identify the percent of transport through the matrix or fracture, nor can the parameters controlling the mechanism of transport through a complex media be identified. However, in a separate effects experiment the number of degrees of freedom may be limited such that a single process may be isolated and studied and its characteristic parameters measured. Through a series of separate effects experiments, a more detailed description of the coupled processes can be assembled in a scientifically rational manner. Based on the principal parameters and methods discussed below, simplified problems will be identified that illuminate the thermohydrological physics, one or two processes at a time.

Governing Physical Phenomena. Before a coupled phenomenological experiment can be proposed, the physical phenomena governing the flow of water and vapor in unsaturated porous media under the action of localized, unsteady heating must be understood. For unheated, saturated, porous media, the flow is driven by gravity. The flow rate is such that the hydraulic gradient due to gravity is balanced by Darcian viscous losses. For unheated, unsaturated, porous media, gravity is again the driving force. However, the flow is more complicated than for saturated media because capillary forces and osmotic potential also resist the flow. Air in the nonmoisture bearing pores has to be displaced by the moisture entering the pores. (To a fair approximation, the resistance due to air flow can probably be neglected.) Thus, for unheated, unsaturated porous media (the "natural" state of the repository), the physical phenomena governing the flow of water can be characterized by:

- Gravity,
- Liquid density,
- Darcian resistance (permeability and liquid viscosity),
- Capillary forces (pore size and liquid surface tension),
- Initial saturation percentage and distribution, and
- Infiltration rate at the boundaries.

When a porous medium is heated, the flow becomes much more difficult to describe and predict. If the porous medium is saturated, heating produces differences in the water density, especially near the heat sources (assuming that the heating is not sufficient to cause local boiling). The resulting density difference leads to a buoyancy-induced flow driven by gravity (Rajen and Kulacki, 1987). To characterize this natural convection flow requires the addition of:

- Heat-source characterization
- Coefficient of thermal expansion of the liquid (density differences)
- Thermal conductivity

If the porous medium is unsaturated, other physical phenomena become active. Because of the limited state of knowledge about the flow of moisture in heated, unsaturated porous media, it is not prudent to eliminate any of these phenomena without some study, such as that performed in a separate effects experiment. For example, if the heating causes vaporization and subsequent pressurization of the gas phase, the natural convection becomes multiphase and a "heat-pipe" type of flow may occur when certain conditions are met (Doughty and Pruess, 1985). Vapor flows away from the heat source and condenses in cooler regions. The liquid-phase saturation level thus increases away from the heat source, and a liquid flow is set up by capillary forces (similar to wicking) back toward the heat source. The additional parameters needed to characterize this circulation-like flow include the latent heat of vaporization of the liquid.

Heat-pipe flow is not the only additional type of flow that might occur. For example, heating will decrease the surface tension of the water in high-temperature regions. Hence, a surface-tension gradient as well as density and saturation-level gradients may occur. Convective flows can then be set up by these gradients, in which the stronger capillary forces in the cooler regions attract a flow of water from the hotter regions. The additional parameter needed to characterize capillary convective flow is the relation between surface tension and temperature (analogous to the thermal expansion coefficient of the liquid).

Other phenomena also may occur. The HLW repository is subject to transient effects that may be important. For example, during the initial, high heating rate, fluid (liquor or vapor) may be driven away from the heat source by any of the effects mentioned above. Later, when the heating rate decays, vapor may condense and be transported as liquid back to the vicinity of the heat source; and liquid may also be transported to the heat source. In any case, these effects would not constitute a steady state. Thus, time and HLW decay heat as a function of time are needed to characterize the transient effects.

All the physical, geometrical, and flow parameters discussed above should be considered in formulating the laboratory models of a HLW repository in a tuff media. Through the combination of separate effects experiments and similarity analysis, the role of each of these parameters on the global processes related to HLW repository dynamics can be determined.

Physical and Geometrical Characteristics. The proposed repository at Yucca Mountain is located above the water table in partially saturated, welded tuff. Although the matrix permeability of the tuff formation is low (on the order of microdarcies), the tuff is intensely fractured; and the fracture permeability is several orders of magnitude higher than the matrix permeability. Layers of unwelded tuff (Tsang and Pruess, 1987) are also present at the repository candidate site. Figure 2-1 shows a generalized east-west section through Yucca Mountain with an hypothesized system of moisture flow under natural conditions.

Because the tuff is unsaturated, it is thought that under natural conditions the water is contained in the pores of the matrix as a result of capillary forces. Since capillary forces depend on the pore diameter, the water will in fact remain in the pores if, on average, the pore diameter is much smaller than the fracture widths. On the other hand, if there are regions where the matrix becomes saturated, capillary forces are not present and moisture may be transported through the fractures. The transport velocity of the water through the fractures will be much higher than through the matrix because of the lower hydraulic resistance of the fractures.

Although the water may reside in the pores of the matrix under natural conditions, any vapor created by HLW heating may be transported through the fractures as well as through the pores. (Capillary forces are ineffective for gases.) Since the vapor may condense into water within the fractures when it reaches cooler parts of the repository host rock, the characteristics of the fractures will be important and need to be included in the coupled, phenomenological, experimental models, even if fractures are not needed to describe naturally occurring flows.

Initially in this study, the elastic-plastic properties of the repository site will be ignored, as will geochemical reactions.

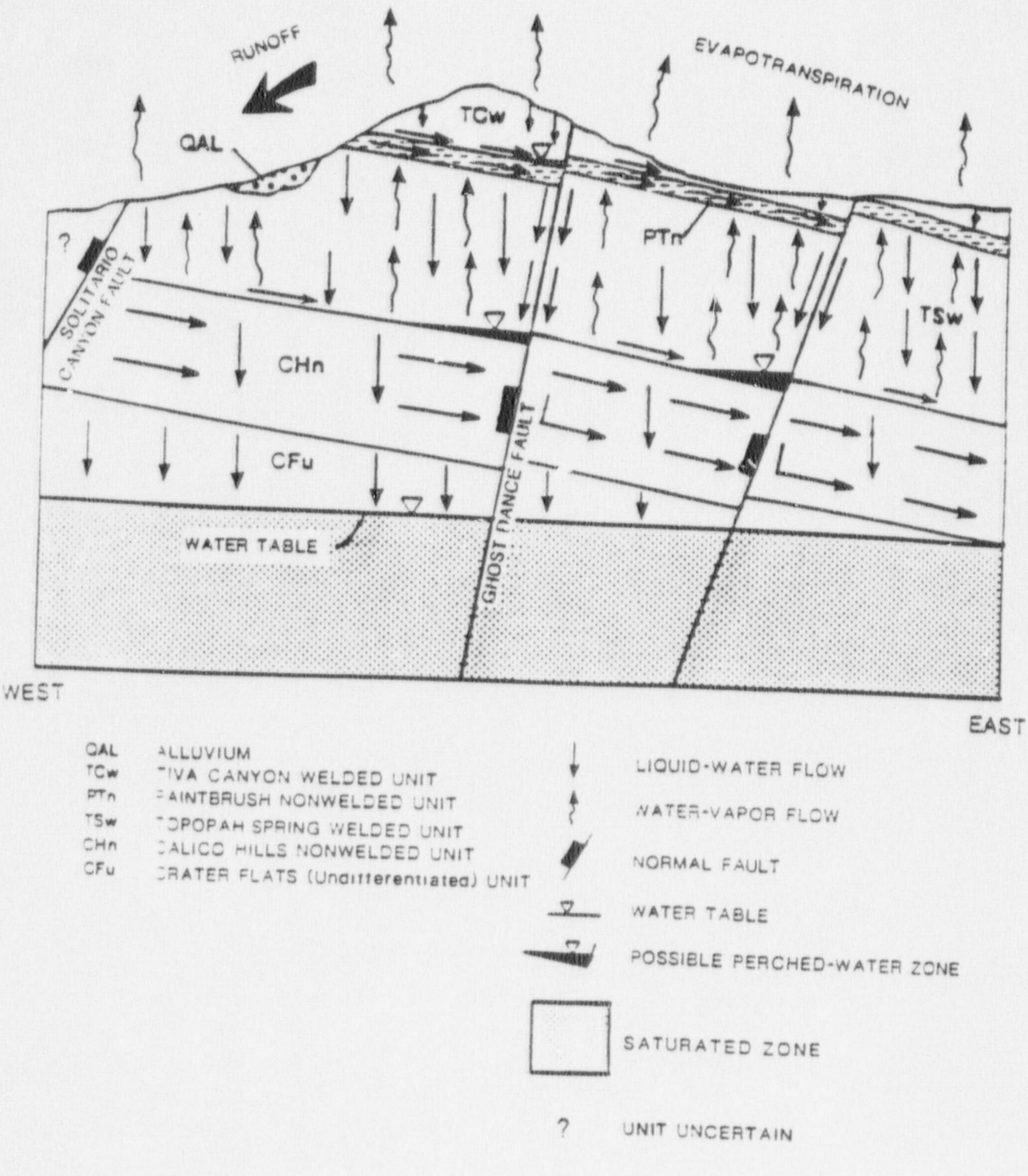


Figure 2-1. Generalized East-West Section through Yucca Mountain. Modified from DOE (1988).

The important physical and geometrical properties of laboratory models of the proposed repository must include:

- Low permeability matrix,
- Higher permeability, extensive fracturing, and
- Unsaturated conditions.

2.2.2.2 Development of Similitude Analysis of Governing Phenomena as Applied to Experimental Design

In this activity, thermohydrologic phenomena and the geometric and physical characteristics of the repository, as discussed in Section 2.2.2.1, are to be considered together in the development of dynamic similarity parameters. These parameters will be required in both the design and analysis of laboratory experiments and in validation of mathematical models of thermohydrological phenomena.

Similitude analysis may be performed by (Baker, Westine, Dodge, 1973):

(1) Characterizing each geometrical and physical parameter and each type of flow phenomenon by one or more specific variables. For example, fractures might be characterized by a typical width and length; natural convection might be characterized by (a) liquid coefficient of thermal expansion, viscosity, and average density; (b) gravity, (c) a typical temperature difference (or, equivalently, a heating rate); and (d) a typical flow area.

(2) Forming dimensionless ratios of the variables.

(3) Examining the dimensionless ratios for significance, using analysis, experience, and physically-based reasoning.

Generally, the dimensionless parameters can be grouped into three categories:

(1) Geometric ratios – these ratios describe the factors that govern the geometric construction of the model when a geometric scale factor has been fixed.

(2) Property ratios – these ratios of physical properties govern the manner in which physical properties of the model materials should be chosen.

(3) Physical effect ratios – these are combinations of variables that can be interpreted physically as ratios of physical effects; for example, one parameter might express the ratio of liquid inertia forces to liquid viscous forces (i.e., the Reynolds number).

The third category is the most important. These dimensionless parameters specify the way laboratory experiments should be conducted if they are to represent full-scale behavior; i.e., the way that measurements made on the laboratory model (e.g., flow rate or temperature distribution) must be interpreted to predict full-scale results. They essentially govern the selection of the first and second categories; that is, they determine which geometric and property ratios must be accurately duplicated between the model and the full-scale repository.

The number of "assumptions" that can be made in developing the laboratory model is equal to the number of "dimensions" of the physical phenomena to be studied. (The assumptions are essentially the variables that can be chosen arbitrarily.) A HLW repository has four fundamental dimensions: length, time, mass, and temperature. Thus, four assumptions can be made. These might typically be: (1) model size (i.e., overall geometric scale factor), (2) viscosity, (3) density of the liquid, and (4) model temperature. Alternatively, the surface tension of the liquid might be included in the assumptions as well as the density and viscosity of the liquid, since this would make it possible to use the same liquid in the model as in full-scale. However, no assumption could then be made about the temperature of the model. With these four assumptions, the dimensionless parameters corresponding to the physical effect ratios specify the required scale factors for all physical and geometric variables.

An alternative procedure is to nondimensionalize the governing equations (Baker, Westine, and Dodge, 1973). Representative geometrical and physical variables are used for this purpose. The same or equivalent dimensionless parameters are derived from this procedure as from the one discussed above. One advantage to the procedure of nondimensionalizing the governing equations is that insight to the various coupled heat and flow processes may be obtained, especially if the general equations of heat and mass transfer can be specialized to the specific problem at hand. However, if the equations in their full, general, nonspecific form are used, this insight is not usually forthcoming.

Either procedure may work well. That is, it may lead to a description of reliable, feasible laboratory models when the underlying physical phenomena are well understood and when all the geometric length scales are of the same order. Unfortunately, neither of these two prerequisites are met here.

For heated, unsaturated, fractured, porous media, many of the physical phenomena are not well understood or have not been studied previously. Thus, it is not evident if, for example, one or several of the coupled heat and mass transfer processes described earlier dominate the response of the repository, or whether all the processes must be included simultaneously in the phenomenological laboratory models. Of course, the more processes that must be included, the less likely it is that laboratory models can adequately represent the response of the repository for all conditions. It would be desirable to eliminate, therefore, minor or second-order effects from consideration.

Further, the length scales of the repository are of widely different magnitudes. The full-scale fracture width is small, although large compared to the matrix pore size. The relevant extent of the repository itself is of the order of kilometers. Thus, a uniform one-to-one scale reduction of the repository to laboratory size would reduce the laboratory fracture widths to the order of the pore size of the repository media, and the laboratory pore size would be vanishingly small. The flow phenomena in the laboratory might therefore be altogether different from those in the repository; that is, the driving forces and resistances would not be reduced or scaled in proportion. This kind of conflict implies that the laboratory model must be distorted geometrically. Distortions can only be used confidently, however, when the underlying physical phenomena are understood.

As a consequence of the complexities of the physical dynamics related to a HLW repository environment and the limitations of analysis methods to characterize a repository completely, both analytic and separate effects experimentation must be employed to develop a reduced, but still reliable set of dynamic similarity parameters. After identification of the roles of dynamic similarity and separate effects experimentation in the analysis of the HLW repository system, the scope and types of separate effects experiments required will be delineated. These experiments, described in the next section, will be designed based on analytical methods, results from computational simulations, dynamic similarity, and other experimental results.

2.2.2.3 Design of Separate-Effects Experiments

This activity will identify, design, and perform separate effects experiments to investigate the key processes in nonisothermal flow in consolidated, fractured, unsaturated media. Enumerated below are the initial phenomena or processes which are to be investigated. However, as each separate effects experiment is designed and performed, this list of key processes will be revised and updated based on the latest research results. Prior to the initiation of this activity a detailed experimental plan will be transmitted to the NRC staff for review and comment.

Surface Tension and Buoyancy. In a saturated medium influenced by a high-temperature heat source, buoyancy forces either create or augment fluid flow. Surface tension has no role in this process. Buoyant forces result from spatial variations in the density of the fluid. These variations are due to thermal conduction between the HLW package and the saturated medium in the near-field, and thermal convection in the far-field. These gradients of fluid properties result in fluid flow from hot regions to cold regions and cold regions to hot regions, potentially creating Rayleigh convection cells or thermal plumes. The works of Kulacki et al. have demonstrated this saturated flow phenomenon through experimental modeling experience.

In an unsaturated medium influenced by a high-temperature heat source, both buoyancy and surface tension will control the distribution of heat and mass. Typically surface tension is a force resisting movement of the fluid; however, gradients of surface tension created by differential heating may provide a driving force supplementing that due to buoyancy. What is clear is that the interaction of capillary and buoyancy forces in fractured media is complex and that the relative importance of each of these mechanisms to the global flow structure is not known. Therefore, a separate-effects experiment, designed to delineate the roles of buoyancy and capillary forces, will be performed. This experiment will use both idealized and realistic media, since the magnitude of these forces is dependent on the medium characteristics.

Rayleigh Convection. The classic Rayleigh-Benard Convection problem, [where fluid flow develops between two horizontal plates that are differentially heated (the lower plate at a warmer temperature than the upper plate)], may be an idealization of the post-installation HLW repository environment. Research performed at Colorado State University (Kulacki et al.) for a variation of this Rayleigh problem (where a finite hot plate is embedded in an idealized saturated media) indicates that a global circulation pattern will develop in the medium above the heat source. Rajen and Kulacki conclude from their experiments and simulations of this phenomena that the hydrothermal impact of a repository in saturated media is a function of the Rayleigh number, the depth of the repository, the horizontal length of the repository, and the time elapsed since emplacement of the HLW.

In the case of HLW emplacement in unsaturated media, the additional mechanisms present due to multiphase components may preclude the development of Rayleigh convection phenomena or at least modify their structure. As indicated above, the relative dynamic importance between the different thermal boundary layers that may develop in unsaturated media, the different time scales of heat transfer between the media and each phase component, and the relative variation in fluid properties–all may significantly modify the flow structure that has been observed and simulated in saturated conditions. Therefore, a fundamental experiment is to be designed and performed whose purpose is to resolve the structure of the thermohydrologic environment in unsaturated media. This experiment will use both idealized and realistic media.

Transient Heat Effects. The structure of the thermohydrologic flow fields in an HLW repository region is a function of the magnitude of thermal input to the system. Immediately after emplacement of the HLW into a host medium with multiphase fluid present, convection may dominate conduction; that is, the system will attempt to remove the greatest amount of heat from the waste package. The high rate of heat removal will cause thermal boundary layers near the waste package to be minimized (convective processes are more effective at minimizing boundary layer thickness). As the waste package cools, convection will be replaced by conductive heat transfer as the dominant process. The rate of heat removal from the waste package will then begin to decrease, and the thermohydrologic flow structure will be modified. The important parameters in this scenario are the time scales of the stages of heat removal, and parameters characterizing the structure of the flow field in the repository environment (length and time scales of flow structures) during these stages. The purpose of this experiment is to delineate the coupled mechanisms that occur over time as the magnitude of the heat released by the HLW diminishes. This experiment will use both idealized and realistic media.

Forced Convection vs. Natural Convection. If the HLW repository resides in a host media through which a pre-emplacement groundwater flow field is present (forced convection), then the post-emplacement flow field will be a combination of forced and natural or buoyant convection. The relative importance of momentum or forcing and buoyancy in fluid flows may then be described by the ratio of the Grashof number to the Reynolds number squared, which is the relevant dimensionless parameter for fluid flow not in a porous medium. If this ratio is of order less than one, then forced convection dominates the flow process; and if the ratio is of order greater than one, then natural convection will typically dominate an internal flow. However, for flow in a porous, fractured media, the relationship between forced and buoyant convection is not so clearly delineated. In order to predict the dominate convective process in the post-emplacement flow field and the time dependency of the relationship between these convective mechanisms, a separate effects experiment will be designed and performed. Again, since the response of a system is dependent on the characteristics of the medium, both idealized and realistic media will be used.

Fracture vs. Matrix Flow. The candidate site of the HLW repository is located in the Topopah Spring tuff of Yucca Mountain, at a depth of approximately 350 m beneath the ground surface and 225 m above the water table. At this horizon, approximately 80% of the formation pore volume contains water held in the pores by capillary suction (Pruess and Wang, 1987). However, as indicated above, the Topopah Spring tuff is highly fractured. The percentage distribution of water between the pores and fractures is not yet established, nor are the mechanisms controlling heat and mass transport through this complex medium, in the post-emplacement environment.

In the heat-pipe scenario, a volatile liquid is vaporized in response to heat injection. The vapor flows away from the heat source and condenses in cooler regions, depositing its latent heat of vaporization there. This condensation may lead to the development of a saturated layer with liquid-phase saturation increasing away from the heat source. The corresponding gradient of capillary pressure (between the saturated and unsaturated regions) will cause a flow of liquid back to the heat source where it can vaporize again. In engineered heat pipes, a steady-state condition will develop (a closed system), with no net mass transport between the saturated and unsaturated zones. However, in a repository environment, the heat-pipe conditions are transient because the flow system is open and heat input is time dependent.

Numerical simulations indicate that the fate of the liquid in the saturated zones (the condensate) depends on the relative permeability characteristics of the fractures and matrix (Doughty and Pruess, 1985; Montan, 1986). Liquid can be held by capillarity (under ambient conditions) only in fractures with apertures less than 0.1 micron. Therefore, the bulk of fractures will be drained in unsaturated layers; however, liquid may still be present in the form of thin films adhering to the fracture walls. In addition, if the variation in capillary forces or surface tension due to temperature is significant enough, then in the post-emplacement environment, a greater percentage of fluid may reside in the fractures than the matrix. As the heat flux from the HLW packages dissipates, then the fractures may account for a larger percentage of mass flux. Because of the unknown role that fractures may play in the post-emplacement environment, an experiment is to be designed and performed to delineate this role.

As indicated at the beginning of this section, a detailed separate effects experimental plan was submitted for review and comment in May 1989.

2.2.2.4 *Determination of Implications for Analysis, Laboratory Experimentation, and Code Validation.*

This activity is a crucial one for Task 2. It will determine what the various dimensionless parameters imply with respect to laboratory experimentation and validation of mathematical models. It will lead to a more fundamental understanding of the mechanisms controlling and influencing fluid flow in unsaturated media, through the analysis of the separate effects experiments. The different levels of coupling between mechanisms will be delineated. Finally, an evaluation of the concepts and principles used to design the separate-effects experiments will be completed to identify the limits of laboratory simulations. With this information, the design of the coupled phenomenological experiments of Task 4 and 5 can be completed.

2.2.2.5 *Reporting*

Two different reports will be submitted based on work performed in Task 2. First, in April 1989, the separate effects experimental design plan (a letter report) is to be submitted for NRC staff review and comment. Second, in September 1989, a report detailing the results of the separate effects experiments (performed to date) will be transmitted to the NRC Project Manager. It is an objective of all experimental design plans and their reporting to allow for continuous review and evaluation by the SwRI/CNWRA research staff and NRC Project Manager and Staff.

2.2.3 *Task 3: Design of Unsaturated Zone Thermohydrological Experiments*

OBJECTIVES

The sole objective of this task is to design the comprehensive experimental plan for Tasks 4 and 5, based on the results of the separate effects experiments, similarity analysis, and analytic methods developed due to Tasks 1 and 2.

JUSTIFICATION

Currently, there is a limited understanding of the effect of the coupled processes which control thermohydrologic phenomena in unsaturated, fractured media, as discussed above. In order to investigate experimentally and delineate accurately the role of the coupled processes in the post-emplacement environment a detailed experimental plan is required. Without such a plan, the objective of a fully coupled phenomenological experiment may not be achieved.

2.2.3.1 *Development of Experimental Plans for Tasks 4 and 5*

The ultimate objective of Tasks 1 and 2 is to accumulate the knowledge and expertise to design a series of fully coupled phenomenological experiments, which are to be performed in Tasks 4 and 5. Upon completion of Tasks 1 and 2, the necessary dimensionless groups and similarity methodology, experimental methodology and instrumentation, and analytic techniques will be developed. These tools will then be employed in the development of Tasks 4 and 5 experimental design plans.

2.2.3.2 *Reporting*

A letter report discussing the fully coupled phenomenological experimental design plan will be submitted for NRC staff review and comment in September 1989.

2.2.4 *Task 4: Thermohydrologic Phenomena Induced by the Aggregate of Emplaced HLW in Unsaturated Geologic Media*

OBJECTIVES

The objectives of this task are to investigate thermohydrologic phenomena caused by the entire aggregate of emplaced HLW in unsaturated geologic media. The flow regimes studied shall range from purely buoyancy driven flow to coupled unsaturated flow regimes. The saturated flow cases shall be investigated as limiting cases to the unsaturated flow cases being examined. Thermohydrologic phenomena in both porous and fractured media shall be investigated.

JUSTIFICATION

The understanding of coupled flow processes in the unsaturated (vadose) zone is in the developmental stage with the greatest lack of knowledge being in the interaction between fracture and matrix flow and transport properties. Only in recent years has attention been focused on unsaturated zones in consolidated geologic media (Evans and Nicholson, 1987). Consolidated rock formations contain fractures with varying densities, orientations, spatial extents, and apertures.

There is a limited understanding of the processes involved in the thermally driven formation of regions of saturation in otherwise partially saturated or unsaturated geologic media composed of fractures and matrix. In addition, the mechanisms responsible for mass transport in the vicinity of a HLW repository are not clearly understood.

2.2.4.1 *Experimental Considerations*

The detailed experimental design plan for this task will be developed in Task 3. However, the major HLW-related issues to be investigated in this task are:

- By what mechanism does heat flux, generated by the aggregate of emplaced HLW, affect the formation of zones of saturation in otherwise unsaturated media?; and,
- By what mechanism does heat flux, generated by the aggregate of emplaced HLW, affect the movement of liquid water between the region of the HLW and the water table below it?

The preliminary concept for the experimental apparatus used in this task to answer these questions is that it will consist of a rectangular cell with boundaries on which thermal and fluid mechanical conditions may be controlled. The cell may be filled with porous or fractured material and air/water mixtures to simulate anticipated repository conditions. These experiments are to be designed such that the ranges of relevant dimensionless parameters will bracket the ranges of response expected in actual repository conditions.

It is anticipated (contingent on the results of work performed in Task 2) that the following combinations of porous and fractured media, heat source configurations, and boundary conditions are to be implemented in this experimental series.

Porous and Fractured Media:

- Materials of uniform porosity.
- Materials with periodic crack systems of known periodicity with the cracks running between impermeable blocks.
- Materials with periodic crack systems of known periodicity with the cracks running between permeable blocks.
- Materials forming a nonuniform crack system with the cracks running between blocks of varying permeability.

Heat Source Configurations:

- No heat source. Experiments with this configuration are intended only for the purpose of characterizing the hydrologic and thermal transport properties of the apparatus.
- Porous heat source placed horizontally in the middle of the test cell and of a lateral extent less than that of the test cell. This heat source will be scaled on the order of the aggregate of emplaced HLW.

Boundary Conditions:

- For free convection due to vertical temperature gradients: vertical cell walls thermally insulated and maintained at the same pressure, upper horizontal surface of the cell maintained at a temperature lower than that of the lower horizontal surface of the cell.
- For mixed convection with the free convective component driven by vertical temperature gradients: vertical cell walls thermally insulated but maintained at different pressures, upper horizontal surface of the cell maintained at a temperature lower than that of the lower horizontal surface of the cell.
- For free convection due to horizontal temperature gradients: vertical cell walls maintained at different temperatures but at the same pressure, upper horizontal surface of the cell maintained at the same temperature as the lower horizontal surface of the cell.
- For mixed convection with the free convective component driven by horizontal temperature gradients: vertical cell walls maintained at different temperatures and different pressures, upper horizontal surface of the cell maintained at the same temperature as the lower horizontal surface of the cell.

Analytic and computational methods will be used as required for both analysis and evaluation of experimental data. In addition, mathematical simulations will be performed of the laboratory simulations in order to evaluate existing mathematical models of thermohydrologic phenomena in unsaturated media.

This task will commence following NRC approval of the experimental design plan developed in Task 3.

2.2.4.2 *Reporting*

The work performed in this task will be reported to the NRC Project Manager based on the following schedule:

Report Topic	Type of Report	Tentative Due Date
Repository-scale thermohydrologic phenomena in unsaturated porous media and uniformly fractured media with impermeable blocks	NUREG/CR	9/90
Repository-scale thermohydrologic phenomena in unsaturated uniformly fractured media with permeable blocks	NUREG/CR	8/91
Repository-scale thermohydrologic phenomena in unsaturated randomly fractured media with permeable blocks	NUREG/CR	8/92
Final report on all repository-scale unsaturated-zone thermohydrologic phenomena experiments	NUREG/CR	8/92

2.2.5 *Task 5: Unsaturated Zone Thermohydrologic Phenomena Induced by Multiple Packages of HLW*

OBJECTIVE

The objective of this task is to investigate thermohydrologic phenomena in unsaturated media in the neighborhood of single and multiple (two or three) packages of HLW, so that the effects of waste package orientation and the selection of packing materials on water movement, in the neighborhood of the waste package, can be ascertained.

JUSTIFICATION

The heat flux generated by a single or a few HLW packages may cause fluid migration such that corrosive elements may be transported to and come in contact with the waste package. This contact may prematurely promote radionuclide transport into the surrounding geologic environment and ultimately the accessible environment. Thermohydrologic phenomena at scales on the order of the waste package and their interaction with thermohydrological phenomena at larger scales need to be investigated.

2.2.5.1 *Experimental Considerations*

The detailed experimental design plan for this task will be developed in Task 3. However, the major issue to be addressed in this task is:

- Does the heat flux generated by an individual (or a few) waste package(s) cause water (as a liquid or as steam) to contact the waste package?

The preliminary concept for these experiments is that they will involve the placement of a cylindrical heater to represent the HLW package, in various types of unsaturated porous and fractured media. It is anticipated (contingent on the results of work performed in Task 2) that the following simulant geologic materials and heater configurations are to be used.

Porous and Fractured Media:

- Materials of uniform porosity.
- Materials with periodic crack systems of known periodicity with the cracks running between impermeable blocks.
- Materials with periodic crack systems of known periodicity with the cracks running between permeable blocks.
- Materials forming a nonuniform crack system with the cracks running between blocks of varying permeability.

Heater Configurations:

- Vertical emplacement with an air gap between the heater and the surrounding material.
- Vertical emplacement with packing material filling the air gap.
- Horizontal emplacement with an air gap between the heater and the surrounding material.
- Horizontal emplacement with packing material filling the air gap.

An important consideration in the selection of these experiments will be the availability of field data for validation of the laboratory simulation. The Center will evaluate and recommend to NRC the feasibility of cooperative investigations with the University of Arizona utilizing their test site at the Apache Leap tuff site near Superior, Arizona. These experiments may also incorporate components from natural analogue studies, in particular those associated with coupled geothermal and hydrothermal interactions such as investigations at Valles Caldera in New Mexico conducted by Sandia National Laboratories with NRC funding.

Validation of the laboratory simulation results with field-collected data is a goal of this experimental effort. Such agreement between the model and a prototype scale investigation will provide evidence that similarity is an appropriate scaling method whereby full-scale HLW repository thermohydrologic behavior can be reliably predicted at the laboratory scale.

Analytic and computational methods will be used as required for both analysis and evaluation of experimental data. In addition, numerical simulations will be performed of the laboratory simulations in order to evaluate existing mathematical models of thermohydrologic phenomena in unsaturated media.

This task will begin following NRC approval of the experimental design plan developed in Task 3.

2.2.5.2 *Reporting*

The work performed in this task will be reported to the NRC Project Manager based on the following schedule:

Report Topic	Type of Report	Tentative Due Date
Waste-Package-Scale thermohydrologic phenomena in unsaturated porous media and uniformly fractured media with impermeable blocks	NUREG/CR	9/90
Waste-Package-Scale thermohydrologic phenomena in unsaturated uniformly fractured media with permeable blocks	NUREG/CR	8/91
Waste-Package-Scale thermohydrologic phenomena in unsaturated randomly fractured media with permeable blocks	NUREG/CR	8/92
Final report on all waste-package-scale unsaturated-zone thermohydrologic phenomena experiments	NUREG/CR	8/92

2.3 Schedules, Milestones, Deliverables

The specific deliverables and milestones for Tasks 1, 2, 3, 4, and 5 have already been delineated in Section 2.2 and are summarized in the Gantt Chart in Figure 2-2. Additional information on deliverables is presented below.

2.3.1 *Progress Reports*

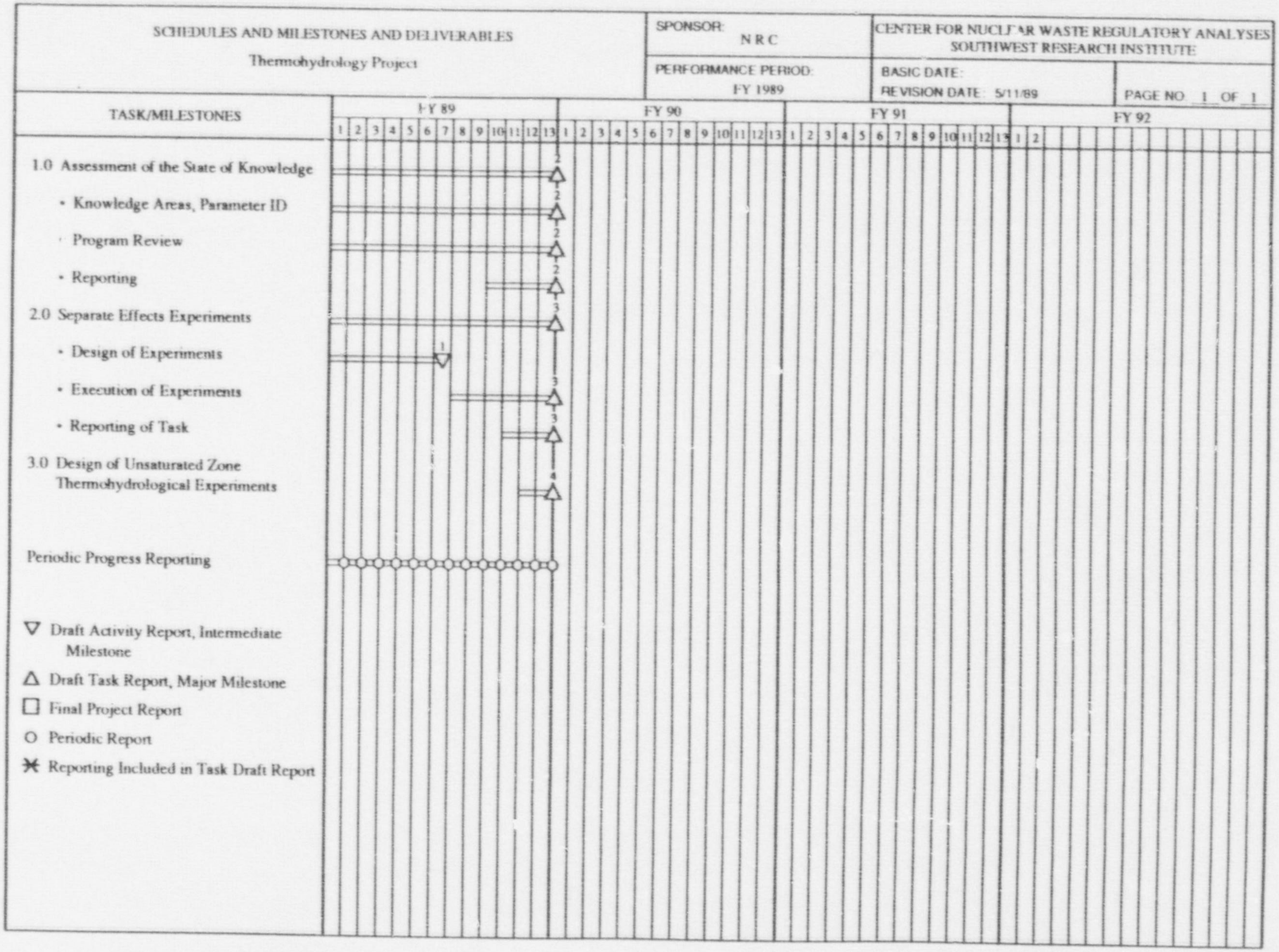
A progress report included as part of each periodic (approximately monthly) Center report is to be submitted to the NRC Project Manager, which summarizes by task:

(1) The work performed during the previous month, milestones reached, findings important to NRC's HLW program, and a summary of subcontractor (if any) activities.

(2) Potential or actual contractual problem areas and their impacts on the project. In the case of budgetary and scheduling problems, reasons for the occurrence of the problems shall be given.

(3) Costs and uncosted obligations incurred (a) during the previous month and (b) for the entire project duration through the previous month. The contractor shall also project future expenditures by month through the end of the contract.

Figure 2-2. Year 2 (FY 89) Schedules, Milestones, and Deliverables



2.3.2 *Letter Reports on Meetings and Field Trips*

For each technical meeting (with personnel not associated with this project) and each field trip attended by this project's staff, the contractor shall prepare a letter report on the meeting or field trip and submit the letter report to the NRC Project Manager within 10 working days of the meeting or field trip. These letter reports shall identify the purpose, participants, itinerary, and significant findings of the meeting or field trip.

2.4 Required Interfaces with Other Organizations

In the execution of this research project, the Center staff will actively interact with SwRI staff, Center subcontractors, Center consultants, and the NRC staff. The interactions will be by regular telephone communications, scheduled program review meetings, and exchange and review or draft reports. It is anticipated that there will be an average of four meetings per year with the NRC staff for project review purposes. It is planned that two of these meetings will be held at the NRC offices in Washington and two will be in San Antonio at the Center.

Activities of the Thermohydrology Research Program will also require interaction with NRC contractors conducting investigations on the HLW program, particularly Colorado State University during FY88 and FY89 and with the University of Arizona. Interactions will also be necessary with DOE and DOE contractors (e.g. Lawrence Livermore National Laboratory) to ensure cognizance of pertinent aspects of investigations in thermohydrologics associated with DOE's geologic repository for HLW program. Acquisition of some site specific samples will be conducted, when necessary, in accordance with Appendix 5 of the DOE and NRC Site Specific Procedural Agreement (September 19, 1984) entitled: "Acquisition of Site-Specific Samples During Site Investigation and Site Characterization by NRC Contractors".

This project shall be coordinated with several other NRC projects that have been conducted or are being conducted by contractors other than the Center for Nuclear Waste Regulatory Analyses. The coordination shall consist of direct contacts between this project's personnel and personnel working on the other projects, and additional interactions deemed necessary by this project's or the other projects' NRC Program Managers. NRC projects which have special relevance to this project are listed below.

FIN's B8944 and D1674, the University of Delaware's and the Colorado State University's projects on laboratory simulations of thermoconvective phenomena induced by geologic disposal of HLW in saturated geologic media. FIN's B8944 and D1674 are the precursors to this project and their results provide many of the saturated-zone limits for the experiments to be conducted in this project.

FIN D2079, the Colorado State University's projects on laboratory simulations of thermoconvective phenomena induced by geologic disposal of HLW in saturated geologic media. FIN D2079 is a short sequel to FIN D1674 and will end on December 31, 1988. Its relationship to this project is the same as that of FIN's B8944 and D1674.

FIN's B7291 and D1662, the University of Arizona's projects on flow and transport in unsaturated rocks. Under FIN B7291, the University of Arizona conducted, in the field, a heater test in unsaturated media that indicated that the heat emitted by emplaced HLW may cause liquid water to contact the waste package. More refined field experiments that will investigate this possibility further are planned under FIN D1662. The experiments in Task 4 of this project will be laboratory complements to the heater tests performed in FIN's B7291 and D1662 and shall be coordinated closely with them.

FIN B3046. Lawrence Berkeley Laboratory's project on thermal, hydrologic, mechanical, and chemical interactions in the host rock near the emplaced waste. The products of this project will be of direct value to the LBL staff in estimating the magnitude of temperature changes which need to be considered in evaluating the role of thermal effects in the interactions listed.

FIN A1266. Sandia's development of a performance assessment methodology for HLW disposal in unsaturated tuff. This project will provide a data base for validating the thermal models which Sandia will be using in the computer program TOUGH. This project may also provide data that will be useful for INTERVAL, for which calculations are being performed under FIN A1266.

FIN B6985. CorStar's benchmarking of computer programs that implement models of phenomena relevant to HLW disposal. The reports from FIN B6985 will provide an information base of models of thermal effects on repository performance which may be useful in guiding the experimental activities of this project.

FIN B3109. LBL's geotechnical sciences program. Reports from B3109 contain comprehensive summaries of the work of DOE and others on evaluating temperature changes in HLW repositories. These reports will be useful to this project in the design of the experiments for both Tasks 1 and 2. The experimental results obtained in this project will also serve as a check on the repository temperatures and heat transfer rates reported in FIN B3109's reports.

3. PROGRAM MANAGEMENT

3.1 Organizational Structure and Responsibility

The organizational structure, responsibilities, and management and control techniques applicable to the Research Element at the Center will be fully described in the Center Management Plan. The Thermohydrology Project will be conducted under the Research Element of the Center's Program. Also this project directly supports the needs of the Geologic Setting Elements. Dr. John L. Russell will be the Center Project Manager for this project. The task support, direction, and resource allocation relationships are shown in Figure 3-1.

The project is to be conducted over a 36-month period. The project staff support and the project organization are shown in Figure 3-2. The project has made allowance for independent review of technical papers and/or technical reports generated by the project.

The Center Project Manager (CPM) has overall responsibility for the technical content and execution of the project. Technical Task Leaders/Principal Investigators (TL/PI) are identified on Figure 3.2 for each task. The TL/PIs have the technical expertise to conduct and be responsible for the specific scope of work within the task. The TL/PI will interact with peers in the field and be available to the NRC Research Project Officer for technical consultation on specific matters related to the execution of the task. The TL/PI will recommend any midstream modifications within the task to the cognizant CPM. The CPM will review the proposed changes and determine the extent of these changes to the overall project. In the event the changes are beyond the resources, scope, and constraints established by the NRC approved project plan, a request for the proposed changes will be submitted by the CPM to the cognizant NRC Project Officer for the necessary NRC approvals. For all research projects placed at the Center, there will be a CPM assigned. The CPM will be the single point-of-contact for matters affecting more than one task. The TL/PIs will be primarily selected on the basis of their technical expertise. They will be Center and/or SwRI staff members and, when necessary, they will be selected from among Center subcontractors/consultants.

3.2 Quality Assurance

The resources of SwRI Quality Assurance (QA), as coordinated by the Center Director of QA, are available as necessary for carrying out QA work. The project work itself includes the requirement to generate and maintain sufficient documentation to assure the reproducibility of the results of the research. Therefore, the methods and techniques used to collect, reduce, and interpret data shall be sufficiently accurate, traceable, and articulate so that others can duplicate the work done and independently evaluate the results.

3.2.1 Quality Assurance Program

The QA provisions stated herein and selected sections of the Center QA Manual (CQAM) apply to this Center Research Project. These QA requirements apply to work at the Center (including SwRI) and work by subcontractors and consultants. The referenced sections of the CQAM and the QA provisions identified here form the basis of QA on this research project.

3.2.2 Project Organization

The QA coverage for this Research Project shall be under the direction of Bruce Mabrito, Center Director of Quality Assurance. QA support personnel are provided by the Center or by the SwRI QA Department and

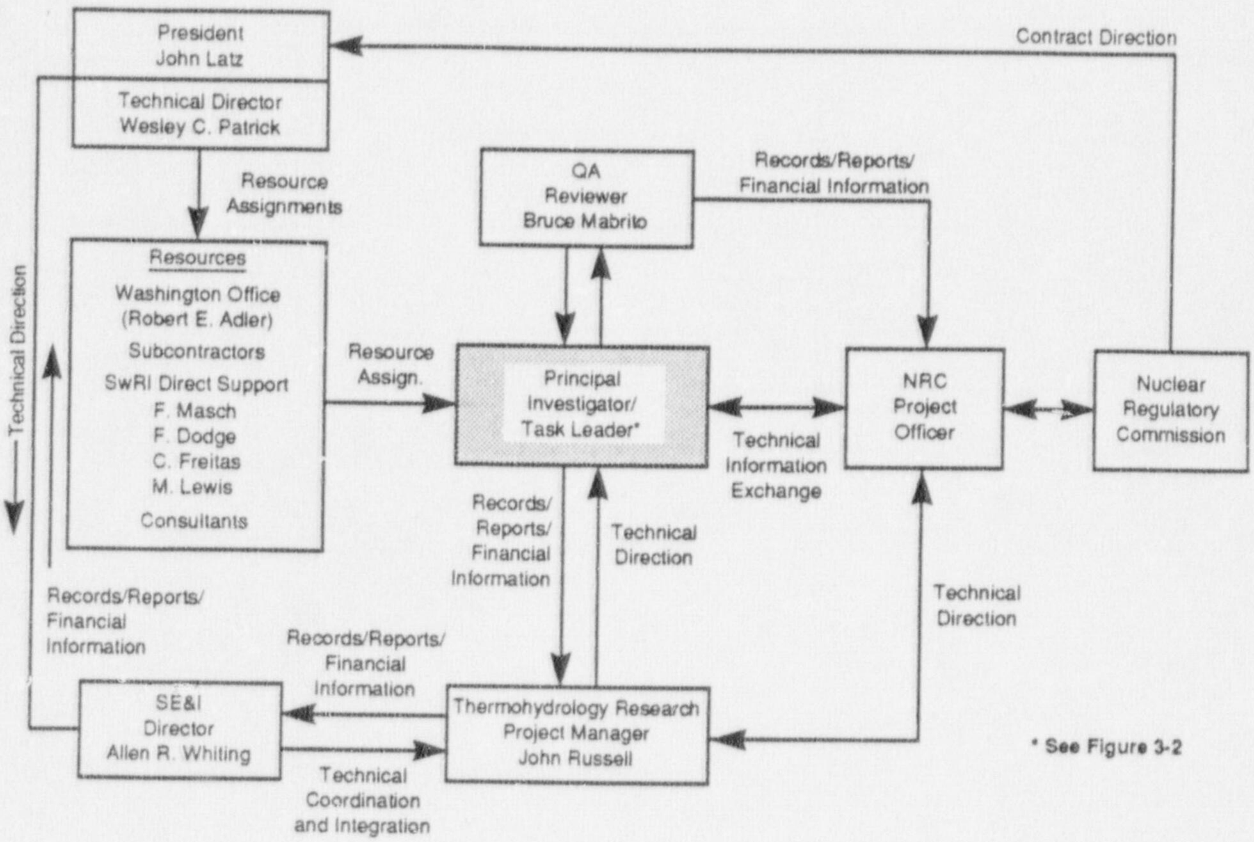


Figure 3-1. Center Management Process for Direction and Control of the Thermohydrology Research Project.

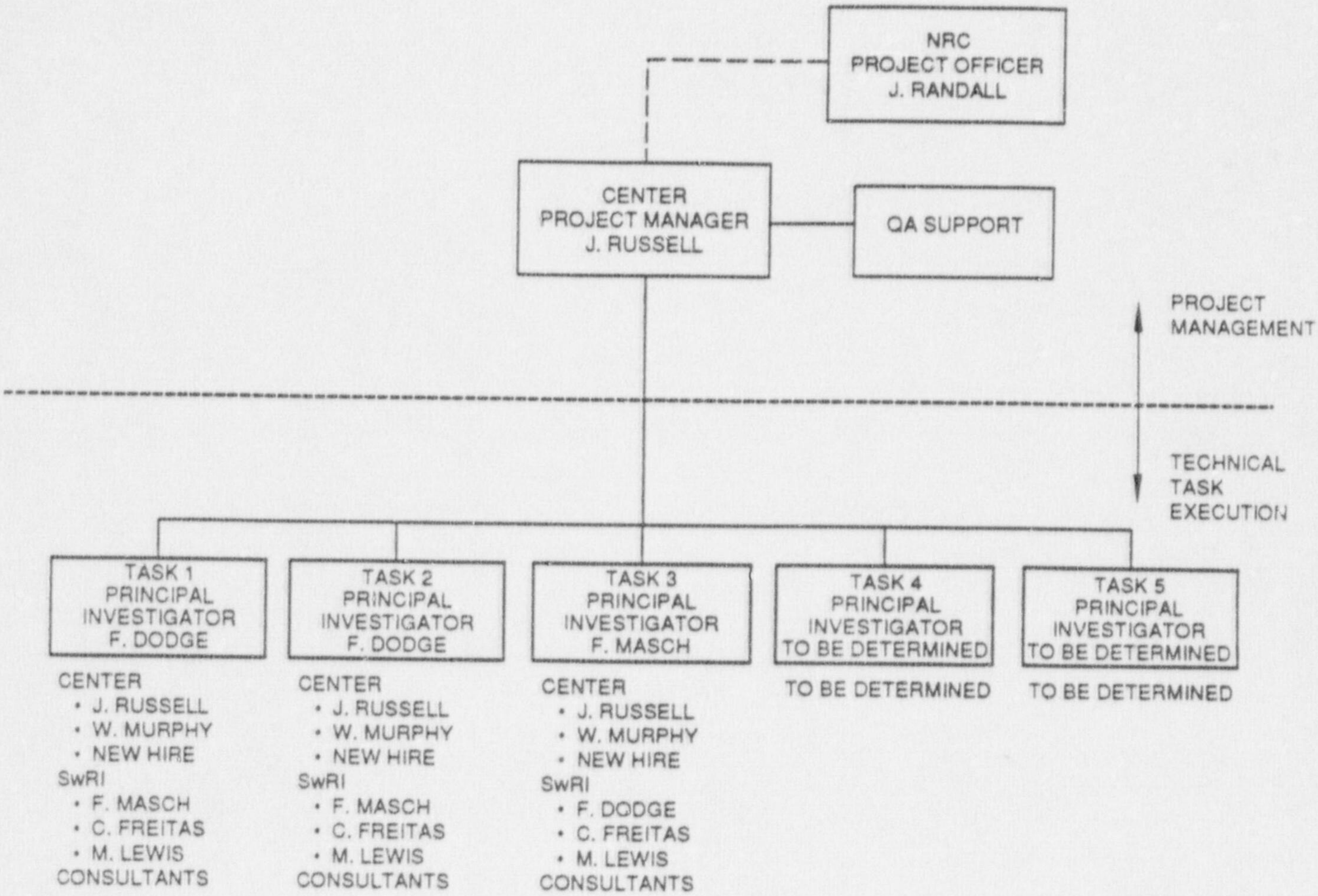


Figure 3-2. Project Staff Support

all QA personnel have lines of reporting responsibility separate from the project activities and report to Management through different authority lines. The organizational structure for this project is shown in Figure 3-2 of this Project Plan.

3.2.3 Project Plan Control

This Project Plan shall be prepared and approved by the cognizant Center Element Manager, Director of QA, and cognizant Director, and approved by the NRC. Revisions or changes to the approved document shall be clearly identified and controlled. Center Quality Assurance shall verify that the NRC has approved this Project Plan, and any revisions, changes, or deviations thereto.

Three levels of procedures are anticipated to be utilized in the conduct of this project:

- Standardized tests (such as ASTM, ACS standard methods, and methods specified by the U.S. Environmental Protection Agency),
- Formalized Operating Procedures (such as Center Technical Operating Procedures), and
- Special research experiment guidelines, unique to individual tests, which are purposely written with general criteria so that sufficient freedom is allowed the researcher during exploratory phases of work.

Technical Operating Procedures shall be controlled and the results of formalized experiments/tests documented.

3.2.4 Analyses Control

On this Research Project, numerical computations, mathematical equations, and derivations used as the basis for reported conclusions shall be independently reviewed and verified by qualified personnel other than the originator(s). This may be accomplished in the peer review process.

3.2.5 Test Control

Although this section identifies QA-related activities, the quality of testing, research, and resultant data is a function of the personnel, equipment, and controls established. Assurance of quality is a QA activity. Quality project performance and data accuracy are achieved by application of proper scientific, engineering and laboratory practices, not QA work. In the course of project performance, control of quality is a project activity, and assurance of quality is a QA task.

The following are the activities to be accomplished by the Center where applicable:

1. Prior to the initiation of this research, QA shall ensure that the various samples have been identified and stored so that there is no loss of identification or change in specimen characteristics.
2. During the course of the Research Project, sample selection, sampling frequency, and control of samples will be documented. The experimental design and rationale of approach will also be described in this Project Plan or in the Research Project Final Report.
3. The measurement techniques employed shall be described in the final report and provide a description and identification of the equipment used. The calibration methods, including frequency, techniques, reference standards, and traceability, shall be made available.

4. The data recording techniques, including methods of recording data and identification of person(s) recording and/or certifying data, shall be included in the laboratory data books or on the data recording itself.

5. Data reduction methods and codes, including revisions, modifications, and updates, shall be documented and available for review.

6. The identification, location, and retention time of data, various analyses, and associated records shall be specified by the Element Manager.

7. When, in the conduct of the Research Project, statistical evaluation and interpretation of data are made, it shall make reference to the accuracy and precision of results achieved.

8. Project documentation shall be maintained in a format that is retrievable, with means to identify appropriate personnel performing the research and the dates of activities. If an error is made in documenting entries, a single line shall be drawn through the incorrect entry and the correct information written nearby, with the initials of the person making the correction and the full date of correction shown.

9. QA shall review the codes, standards, and criteria, where applicable, in this Project Plan to ensure compliance of the work performed.

3.2.6 Test and Measuring Equipment Control

Prior to or during the conduct of proceduralized testing on specimens identified for this project, test and measuring equipment shall be calibrated to within acceptable limits.

3.2.7 Audits and Surveillance

QA audits will be reported in full, and a copy of the audit results will be distributed to appropriate Center personnel. Audit reports will be maintained in a retrievable condition and available for NRC review for a period of 6 years (defined by practice within the nuclear industry). Project-specific audits will be performed once per year of project duration and at any time specified by the Center Director of QA, or upon request of a Center Director or the Cognizant Element Manager. Audits shall be performed in accordance with CQAM Section 18.

QA shall conduct surveillance of research tests periodically during the course of the project or as requested by the Center Director of QA. Formal surveillance reports shall be generated for each QA surveillance activity and distributed to the Center QA Director, Technical Director, cognizant Element Manager, and other appropriate personnel. Surveillance includes, but is not limited to, direct observation of project work to determine procedure compliance.

3.2.8 Corrective Action and Nonconformance Control

Any deviations or nonconformances noted during audits or surveillance by QA shall be reported in the audit report or surveillance report and shall be controlled by the CQAM Section 15. Corrective actions resulting from a Deviation and Nonconformance Report shall be controlled by CQAM Section 16.

3.2.9 Reports and Records

The Research Project Final Report shall receive Center Management and technical review which is documented on the submittal to the NRC. The Research Project Final Report shall be issued in draft form to the NRC, but after the final document is submitted, any changes to the report shall be clearly identified.

3.3 Personnel

For the successful execution of an approved project plan, a combination of Center staff, Center subcontractor, SwRI staff, and a selected number of consultants have been identified.

3.3.1 Key Personnel

The following personnel have been identified as essential personnel for the successful execution of the work described in Section 2.2 of this Project Plan.

Name	Tasks	Expertise	Level of Effort (%) During Periods 9-13
J. Russell	1	Geology	5
	2	Hydrology	
	3	Geochemistry	
W. Murphy	1	Thermodynamics	5
	2	Mass Transfer	
	3	Computer Modeling	
B. Mabrito	All	Quality Assurance	3
New Hire	1	Flow and Transport	11
	2	in Unsaturated Zone	
	3	Numerical Modelling	
F. Masch	1	Scale Modelling	32
	2	Porous Media Flow	
	3	Experimental Methods	
F. Dodge	1	Experimental Design	26
	2	Similitude	
	3	Geothermal processes	
C. Freitas	1	Numerical Modelling	41
	2	Fluid Mechanics	
	3	Thermodynamics	

3.3.2 Other Personnel

The following personnel have been identified as providing support expertise to the Thermohydrology Research Project.

Name	Tasks	Expertise	Level of Effort (%) During Periods 8-13
M. Lewis	1	Geologic Engineer	66
	2	Geologic Media Characterization	
	3	Experimental Mechanics	
W. Edwards	2	Construction of Experimental Models	54

3.4 Corporate Resources

3.4.1 General Resources

The resources of the Division of Engineering and Material Sciences at Southwest Rsearch will be utilized in the Thermohydrology project including:

- Department of Civil Engineering and Energetic Systems
- Department of Mechanical Sciences

The following equipment in SwRI will be used in the project:

- Spectral Physics Laser Doppler Velocitometer
- Dantec 2-Component Laser Doppler Velocitometer
- Flash X-Ray Imager
- Spin Physics SP 2000 High-Speed Video
- Fluorometer
- Hot Wire and Hot Film Anemometry
- Thermocouples
- Thermisters
- Tracor Northern TN-8500 High Performance Image Analysis System

Other SwRI resources which will be used in the Thermohydrology Research Project are:

- Quality Assurance
- Computer Facility
- Library including data base research services (NTIS, DOE, GEOREF, GEOARCHIVE, Chemical Abstracts Search, etc.) and document retrieval
- Machine/Model Shops
- Photographic Services
- Publicaiion Services
- Other SwRI services for drafting, general administration, etc.

3.4.2 *Special Resources*

The Center has approximately 20 IBM-AT, -XT, and PS/2 microcomputers and related compatible personal microcomputers. Peripheral devices at the Center include dot matrix and laser printers and two plotters, including a Hewlett-Packard Draft Master II plotter which can accommodate plots up to 40 inches wide. A fiber-optic local area network links the Center to SwRI's Central Computer Facility which has two mainframe systems (IBM 4381, VAX 8700). Computer communications are available to the NRC. It is anticipated that graphics workstations will be acquired for the Center during late FY89.

3.5 Travel

Project personnel will incur expenses for travel and associated subsistence while conducting the business of the Center in support of the Thermohydrology Research Project. The minimum necessary travel anticipated for the project is described below and shown in the attached travel requirements schedule. Essential travel is shown in four groups, generally by destination. Travel necessary to accomplish project activities will be undertaken by the appropriate task personnel.

Technical and Program Meetings. Meetings between the CNWRA Thermohydrology Research Project team and the NRC will be attended to review the project technical status and accomplishments and to discuss project management items. These meetings will commonly be in the NRC facilities in Rockville, Maryland.

TABLE 3. TRAVEL REQUIREMENTS
Thermohydrology Research Project

Purpose/Dest.	FY89		
	No. Trips	Man Days	No. Persons/Trip
Technical and Program Review			
Washington	1	6	2
Conferences, Seminar, Workshop			
to be determined	2	7	1
Technical Interchange			
LLNL, LBL & USGS, Menlo Pk	1	9	3
Colo. State U. & USGS, Denver	1	9	3
SANL & LANL	1	6	3
DOE, Las Vegas	1	8	4
Univ. AZ	1	9	3
Sample Acquisition			
Yucca Mountain, NV	1	8	4
Apache Leap, AZ	(combined with Univ. AZ visit.)		
TOTALS	9	62	23

Conferences, Seminars, and Workshops. Trips to technical conferences, seminars, and workshops will be necessary to enable the Center's technical staff to present papers and/or participate in technical seminars and workshops. This will encourage peer review of the research program activities and results. It will also encourage acquisition of knowledge on the activities of other organizations and individuals performing pertinent research. Conferences of professional societies (e.g., American Geophysical Union) will be attended.

Technical Interchange and Technology Transfer Meetings. Travel is necessary to meet with individuals and organizations conducting thermohydrologic investigations pertinent to the Center's research project. Travel in this category commonly will be required to observe facilities, equipment and technical procedures used in investigations and to examine materials which may be used in the Center's research project.

Travel for Sample Acquisition. Travel will be necessary to acquire samples of geologic materials which will be used in laboratory experiments. It is presently anticipated that samples will be obtained from the Yucca Mountain HLW repository candidate site area and from the University of Arizona research area at Apache Leap, Arizona. Acquisition of the site-specific samples may be most readily accomplished by collection from outcrops and by acquisition of specimens obtained by excavation of the exploratory shaft and drilling of additional boreholes.

4. ESTIMATED COST BREAKDOWN

4.1 Detailed Cost Breakdown

This Thermohydrology Research Project Plan is a major revision of the initial Project Plan submitted to the NRC in June, 1988. Cost and schedules presented in this section are only for FY89.

The tables presented in this section delineate the costs for the proposed research effort on a task basis for project year 2, with the year being divided into thirteen four-week periods as an accrual basis. Total dollar costs are enumerated for each of the technical labor categories for the Center. Costs are also listed for Center Management of the project, along with SwRI direct labor, SwRI support services, subcontractors, consultants, travel, equipment, material, cost of facility capital, ADP support, fee and fringe/overhead charges of the Center and SwRI. Tables showing a composite summary of all the tasks on a fiscal year basis are also included.

Tables 4-1 through 4-3 contain the projected costs for Tasks 1, 2, and 3 during Periods 8 through 13 of Year 2 (FY89). Table 4-4 is the Year 2 composite cost data. Table 4-5 shows the manpower loading for 1989.

For each of these tables, the "Total" column contains the estimated contribution of each cost category for the entire task. Numbers in this column can be compared directly to the task totals shown in the spending plans (see Section 4.2).

Initial funding authorization of $200,000 for the Thermohydrology Research Project was received by the Center in FY88 (Year 1). No expenditures occurred in FY88 resulting in a "carry over" of $200,000 into FY89 (Year 2). The total proposed budget for FY89 is $357,065 consisting of $200,000 carried over from FY88 and $157,065 of additional funds for FY89 (Year 2) .

The Composite Spending Plan graph (Figure 4.4) and Table 4.4, giving composite costs for all tasks in Year 2 (FY89), include all thirteen periods for Fiscal Year 1989. Actual expenditures were used to derive values for Periods 1 through 7 of FY89. Proposed values for Periods subsequent to Period 7 reflect costing of the activities proposed in this Project Plan.

4.2 Spending Plan

The spending plan for the various tasks for FY89 (Year 2) are presented in graphic form. Figures 4-1 through 4-4 correspond to the plan costs presented in Tables 4-1 through 4-4.

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Table 4.1 - Thermohydrology Task 1 Spending Plan (Periods 8-13), Year 2

	1	2	3	4	5	6	7	8	9	10	11	12	13	
CENTER DIRECT LABOR (TECH)														
PL-4	0	0	0	0	0	0	0	84	84	84	84	84	84	506
PL-3	0	0	0	0	0	0	0	93	93	93	93	93	93	559
PL-2	0	0	0	0	0	0	0	127	127	127	127	127	127	759
PL-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SR. TECH.	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CLERICAL	0	0	0	0	0	0	0	282	282	282	282	282	282	1,690
MGT & TECHNICAL SUPPORT	0	0	0	0	0	0	0	2,185	2,335	1,474	1,457	1,403	727	9,582
SwRI DIRECT LABOR	0	0	0	0	0	0	0	3,191	1,949	403	1,234	590	380	7,747
CENTER FRINGE	0	0	0	0	0	0	0	240	240	240	240	240	240	1,441
CENTER OVERHEAD	0	0	0	0	0	0	0	677	677	677	677	677	677	4,064
SwRI FRINGE	0	0	0	0	0	0	0	1,308	799	165	506	242	156	3,176
SwRI OVERHEAD	0	0	0	0	0	0	0	5,219	3,187	659	2,019	965	621	12,671
SwRI ADP SUPPORT	0	0	0	0	0	0	0	60	60	60	60	60	60	360
SwRI REPORT SERVICES	0	0	0	0	0	0	0	0	0	0	0	0	1,000	1,000
SwRI OTHER SERVICES	0	0	0	0	0	0	0	200	200	200	200	200	200	1,200
SUBCONTRACTORS														
ITASCA	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ADRIAN BROWN CONSULTANTS	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CONSULTANTS	0	0	0	0	0	0	0	0	2,000	2,000	0	0	0	4,000
TRAVEL	0	0	0	0	0	0	0	0	2,844	3,063	2,287	4,071	0	12,265
EQUIPMENT & MATERIALS	0	0	0	0	0	0	0	0	0	0	0	0	0	0
COST OF FACILITY CAPITAL	0	0	0	0	0	0	0	626	396	110	264	144	105	1,645
TOTAL ESTIMATED COST	0	0	0	0	0	0	0	14,293	15,274	9,637	9,531	9,179	4,752	62,665
FEE (8%)	0	0	0	0	0	0	0	1,093	1,190	762	741	723	372	4,882
TOTAL COST INCLUDING FEE	0	0	0	0	0	0	0	15,387	16,464	10,400	10,272	9,902	5,123	67,547
% COMPLETION	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	22.8%	24.4%	15.4%	15.2%	14.7%	7.6%	
CUMULATIVE COST	0	0	0	0	0	0	0	15,387	31,851	42,250	52,522	62,424	67,547	
CUMULATIVE % COMPLETION	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	22.8%	47.2%	62.5%	77.[illegible]%	92.4%	100.0%	

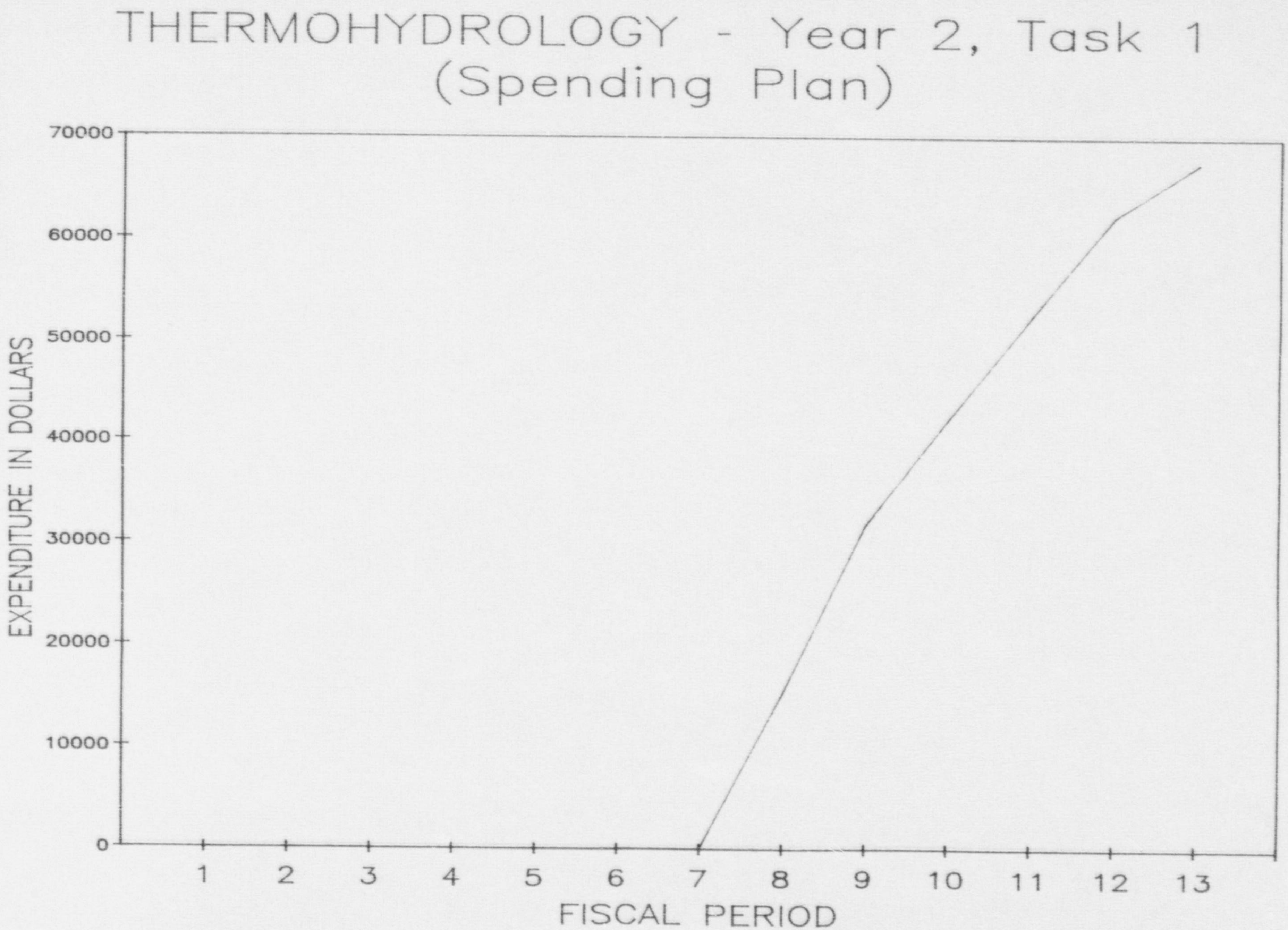

Figure 4.1 - Task 1 Spending Plan, Year 2

Table 4.2 - Thermohydrology Task 2 Spending Plan (Periods 8-13), Year 2

	1	2	3	4	5	6	7	8	9	10	11	12	13	
CENTER DIRECT LABOR (TECH)														
PL-4	0	0	0	0	0	0	0	84	84	84	84	84	84	506
PL-3	0	0	0	0	0	0	0	93	93	93	93	93	93	559
PL-2	0	0	0	0	0	0	0	380	380	380	380	380	380	2,278
PL-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SR. TECH.	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CLERICAL	0	0	0	0	0	0	0	329	329	329	329	329	329	1,972
MGT & TECHNICAL SUPPORT	0	0	0	0	0	0	0	1,667	3,682	4,708	4,314	4,115	3,741	22,227
SwRI DIRECT LABOR	0	0	0	0	0	0	0	2,059	4,894	6,188	6,133	5,791	4,840	29,906
CENTER FRINGE	0	0	0	0	0	0	0	363	363	363	363	363	363	2,179
CENTER OVERHEAD	0	0	0	0	0	0	0	1,024	1,024	1,024	1,024	1,024	1,024	6,145
SwRI FRINGE	0	0	0	0	0	0	0	844	2,007	2,537	2,515	2,374	1,985	12,262
SwRI OVERHEAD	0	0	0	0	0	0	0	3,367	8,005	10,122	10,032	9,472	7,917	48,915
SwRI ADP SUPPORT	0	0	0	0	0	0	0	60	60	60	60	60	60	360
SwRI REPORT SERVICES	0	0	0	0	0	0	0	0	0	0	0	0	1,000	1,000
SwRI OTHER SERVICES	0	0	0	0	0	0	0	200	200	200	200	200	200	1,200
SUBCONTRACTORS														
ITASCA	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ADRIAN BROWN CONSULTANTS	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CONSULTANTS	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TRAVEL	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EQUIPMENT & MATERIALS	0	0	0	0	0	0	0	0	2,000	3,500	1,500	1,500	1,500	10,000
COST OF FACILITY CAPITAL	0	0	0	0	0	0	0	434	960	1,200	1,190	1,126	950	5,860
TOTAL ESTIMATED COST	0	0	0	0	0	0	0	10,904	24,082	30,788	28,217	26,912	24,466	145,369
FEE (8%)	0	0	0	0	0	0	0	838	1,850	2,367	2,162	2,063	1,881	11,161
TOTAL COST INCLUDING FEE	0	0	0	0	0	0	0	11,742	25,931	33,155	30,379	28,975	26,347	156,530
% COMPLETION	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	7.5%	16.6%	21.2%	19.4%	18.5%	16.8%	
CUMULATIVE COST	0	0	0	0	0	0	0	11,742	37,673	70,829	101,208	130,183	156,530	
CUMULATIVE % COMPLETION	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	7.5%	24.1%	45.2%	64.7%	83.2%	100.0%	

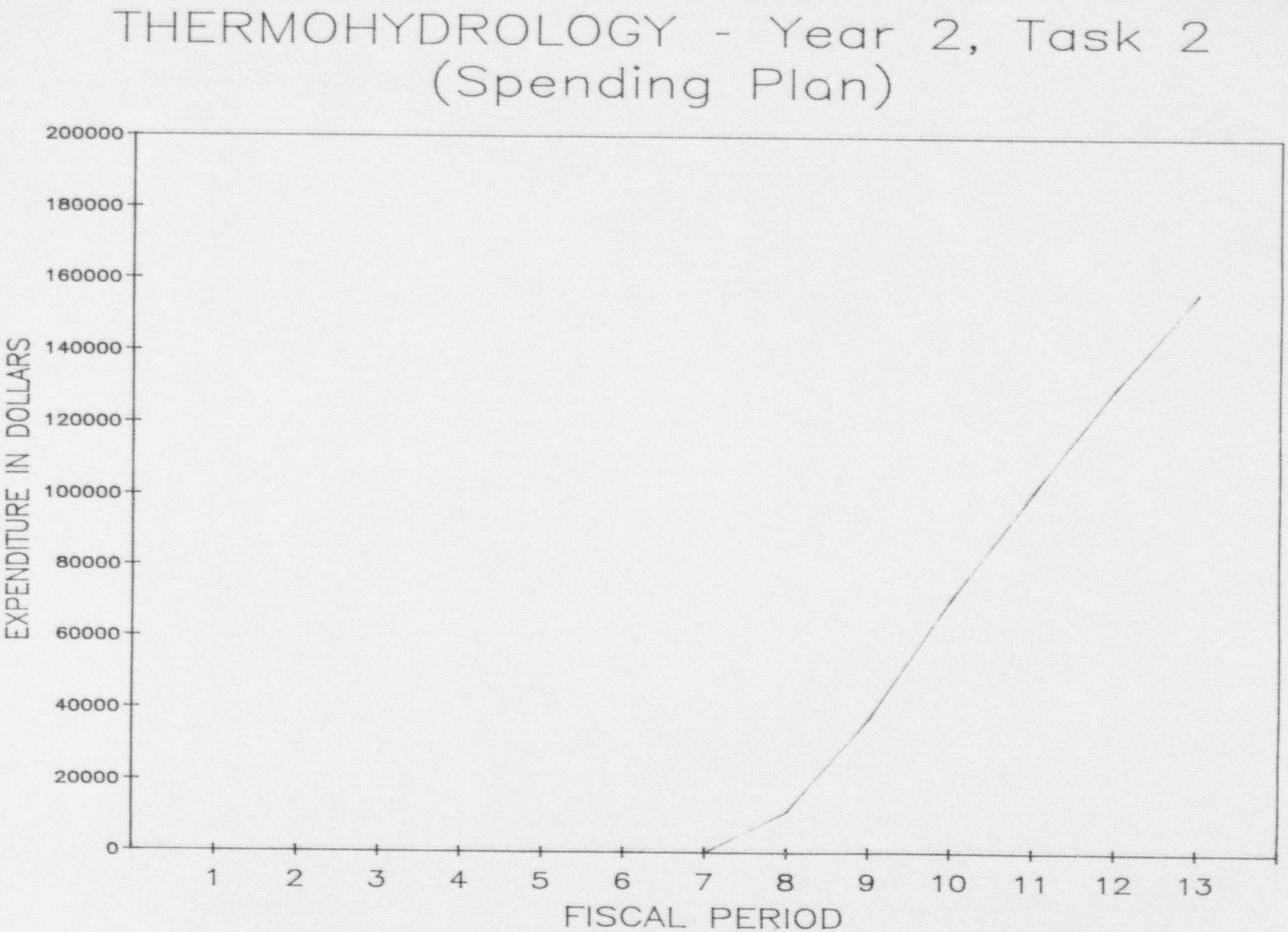

Figure 4.2 - Task 2 Spending Plan, Year 2

Table 4.3 - Thermohydrology Task 3 Spending Plan (Periods 8-13), Year 2

	1	2	3	4	5	6	7	8	9	10	11	12	13	
CENTER DIRECT LABOR (TECH)														
PL-4	0	0	0	0	0	0	0	0	0	0	0	84	84	169
PL-3	0	0	0	0	0	0	0	0	0	0	0	155	155	311
PL-2	0	0	0	0	0	0	0	0	0	0	0	202	202	405
PL-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SR. TECH.	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CLERICAL	0	0	0	0	0	0	0	0	0	0	0	188	188	376
MGT & TECHNICAL SUPPORT	0	0	0	0	0	0	0	0	0	0	0	807	2,304	3,110
SwRI DIRECT LABOR	0	0	0	0	0	0	0	0	0	0	0	791	2,248	3,039
CENTER FRINGE	0	0	0	0	0	0	0	0	0	0	0	258	258	517
CENTER OVERHEAD	0	0	0	0	0	0	0	0	0	0	0	728	728	1,457
SwRI FRINGE	0	0	0	0	0	0	0	0	0	0	0	324	922	1,246
SwRI OVERHEAD	0	0	0	0	0	0	0	0	0	0	0	1,294	3,677	4,971
SwRI ADP SUPPORT	0	0	0	0	0	0	0	0	0	0	0	60	60	120
SwRI REPORT SERVICES	0	0	0	0	0	0	0	0	0	0	0	0	1,000	1,000
SwRI OTHER SERVICES	0	0	0	0	0	0	0	0	0	0	0	200	200	400
SUBCONTRACTORS														
ITASCA	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ADRIAN BROWN CONSULTANTS	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CONSULTANTS	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TRAVEL	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EQUIPMENT & MATERIALS	0	0	0	0	0	0	0	0	0	0	0	0	2,585	2,585
COST OF FACILITY CAPITAL	0	0	0	0	0	0	0	0	0	0	0	184	454	638
TOTAL ESTIMATED COST	0	0	0	0	0	0	0	0	0	0	0	5,277	15,066	20,343
FEE (8%)	0	0	0	0	0	0	0	0	0	0	0	407	1,159	1,576
TOTAL COST INCLUDING FEE	0	0	0	0	0	0	0	0	0	0	0	5,684	16,235	21,919
% COMPLETION	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	25.9%	74.1%	
CUMULATIVE COST	0	0	0	0	0	0	0	0	0	0	0	5,684	21,919	
CUMULATIVE % COMPLETION	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	25.9%	100.0%	

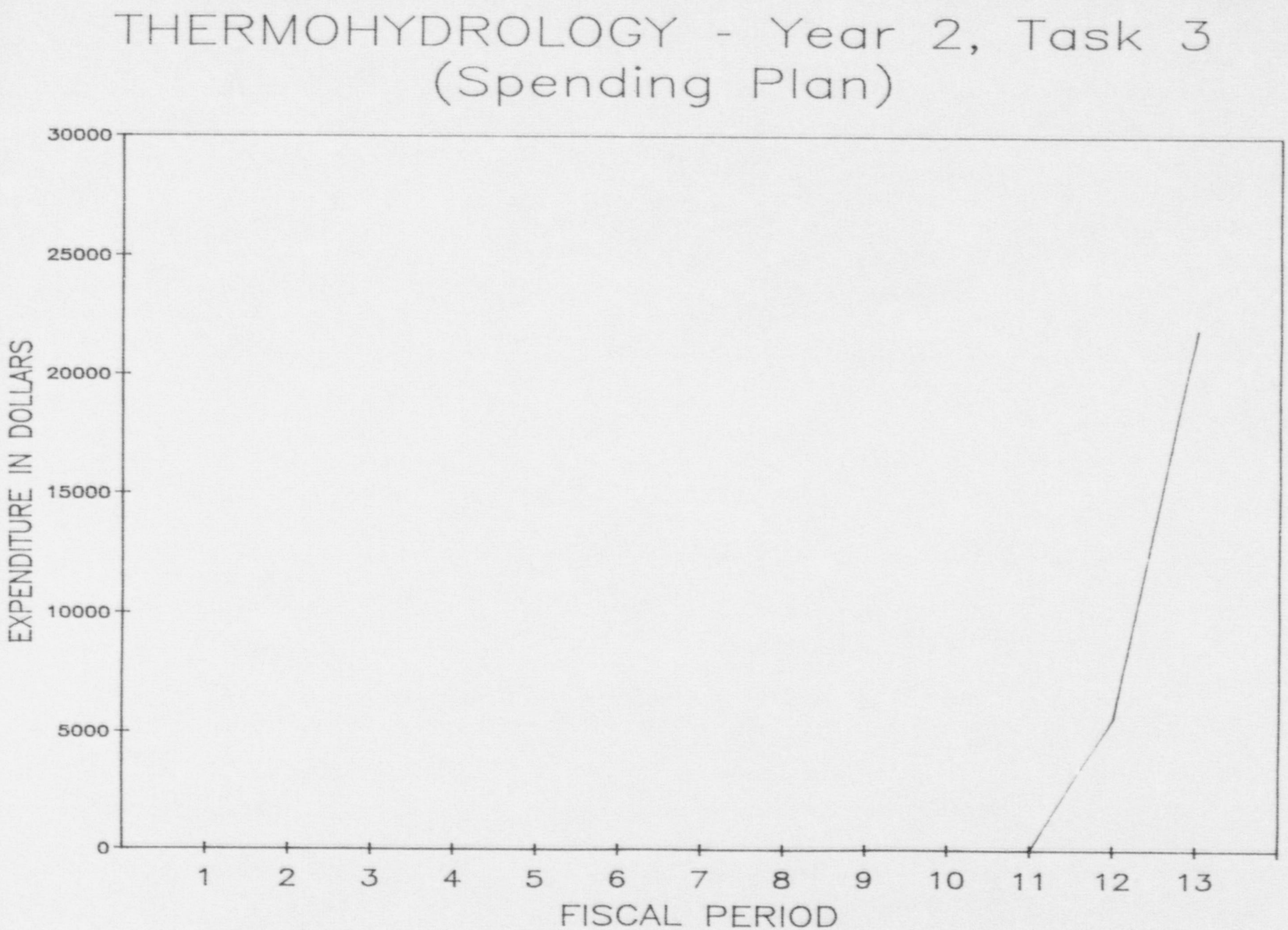

Figure 4.3 - Task 3 Spending Plan, Year 2

Table 4.4 - Thermohydrology Composite Spending Plan, Year 2

	1	2	3	4	5	6	7	8	9	10	11	12	13	
CENTER DIRECT LABOR (TECH)														
PL-4	22	34	124	56	124	27	80	169	169	169	169	253	253	1,647
PL-3	25	38	91	60	130	33	94	186	186	186	186	342	342	1,900
PL-2	195	299	713	464	1,018	238	693	506	506	506	506	709	709	7,063
PL-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SR. TECH.	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CLERICAL	35	50	122	79	173	39	114	610	610	610	610	798	798	4,650
MGT & TECHNICAL SUPPORT	11,002	622	856	995	640	197	1,230	3,853	6,017	6,181	5,772	6,325	6,771	50,461
SwRI DIRECT LABOR	950	1,882	2,115	3,272	1,147	319	3,974	5,249	6,843	6,592	7,368	7,172	7,468	54,351
CENTER FRINGE	4,624	428	781	678	855	219	907	603	603	603	603	862	862	12,629
CENTER OVERHEAD	13,041	1,206	2,204	1,911	2,411	618	2,558	1,701	1,701	1,701	1,701	2,430	2,430	35,614
SwRI FRINGE	389	771	867	1,341	470	131	1,629	2,152	2,806	2,703	3,021	2,941	3,062	22,282
SwRI OVERHEAD	1,390	2,981	2,830	6,242	1,876	522	6,499	8,586	11,193	10,781	12,051	11,731	12,215	88,896
SwRI ADP SUPPORT	67	88	96	179	140	74	229	120	120	120	120	180	180	1,713
SwRI REPORT SERVICES	0	0	0	0	26	2	0	0	0	0	0	0	3,000	3,028
SwRI OTHER SERVICES	43	186	759	203	212	54	817	400	400	400	400	600	600	5,074
SUBCONTRACTORS														
ITASCA	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ADRIAN BROWN CONSULTANTS	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CONSULTANTS	0	0	0	0	0	0	0	0	2,000	2,000	0	0	0	4,000
TRAVEL	26	21	42	1,387	76	16	118	0	2,844	3,063	2,287	4,071	2,585	16,536
EQUIPMENT & MATERIALS	3	0	1	3	0	0	1	0	2,000	3,500	1,500	1,500	1,500	10,008
COST OF FACILITY CAPITAL	673	354	299	883	302	91	870	1,061	1,356	1,310	1,453	1,455	1,510	11,616
TOTAL ESTIMATED COST	32,485	8,961	11,900	17,754	9,600	2,581	19,813	25,198	39,355	40,425	37,747	41,368	44,284	331,469
FEE (8%)	2,545	689	928	1,350	744	199	1,515	1,931	3,040	3,129	2,904	3,193	3,422	25,588
TOTAL COST INCLUDING FEE	35,029	9,649	12,828	19,103	10,344	2,780	21,328	27,129	42,395	43,555	40,651	44,561	47,706	357,057
% COMPLETION	9.8%	2.7%	3.6%	5.4%	2.9%	0.8%	6.0%	7.6%	11.9%	12.2%	11.4%	12.5%	13.4%	
CUMULATIVE COST	35,029	44,678	57,507	76,610	86,953	89,733	111,061	138,190	180,585	224,140	264,791	309,352	357,057	
CUMULATIVE % COMPLETION	9.8%	12.5%	16.1%	21.5%	24.4%	25.1%	31.1%	38.7%	50.6%	62.8%	74.2%	86.6%	100.0%	

Note: Period 1 reflects an adjustment requested by NRC contracts.

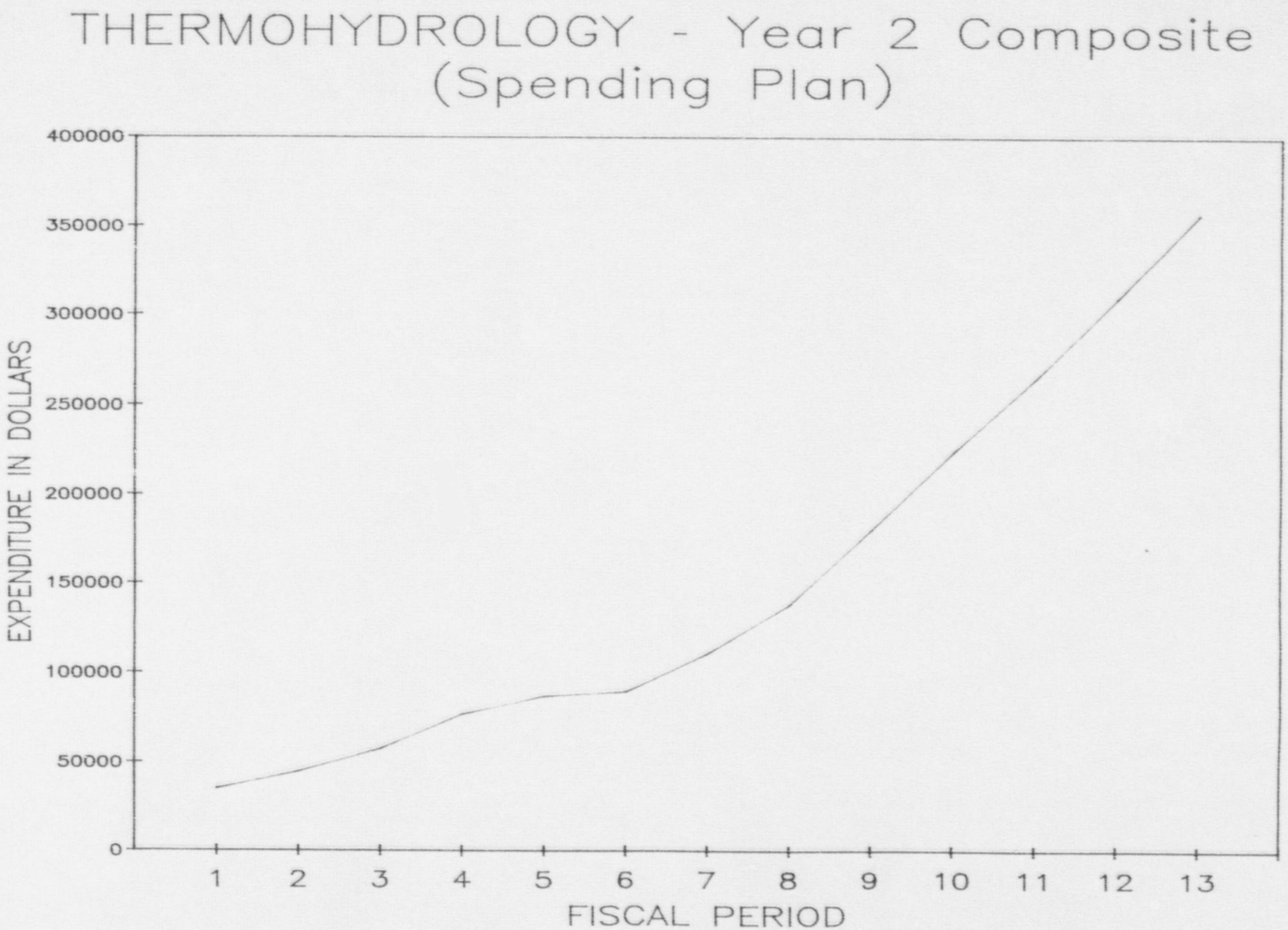

Figure 4.4 - Composite Spending Plan, Year 2

Table 4.5 - Thermohydrology Composite Manpower Plan, Year 2

	1	2	3	4	5	6	7	8	9	10	11	12	13	
CENTER DIRECT LABOR (TECH)														
PL-4	0	0	0	0	0	0	0	4	4	4	4	6	6	28
PL-3	0	0	0	0	0	0	0	6	6	6	6	11	11	46
PL-2	0	0	0	0	0	0	0	20	20	20	20	28	28	136
PL-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SR. TECH.	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CLERICAL	0	0	0	0	0	0	0	65	65	65	65	85	85	430
TOTAL CENTER LABOR	0	0	0	0	0	0	0	95	95	95	95	130	130	640

SWRI DIRECT LABOR	1	2	3	4	5	6	7	8	9	10	11	12	13	
PL-4	0	0	0	0	0	0	0	32	48	24	32	40	44	220
PL-3	0	0	0	0	0	0	0	20	32	50	64	50	58	274
PL-2	0	0	0	0	0	0	0	80	68	64	64	48	30	354
PL-1	0	0	0	0	0	0	0	88	80	64	96	114	118	560
SR TECH	0	0	0	0	0	0	0	0	80	120	80	80	100	460
CLERICAL	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TOTAL SWRI DIRECT LABOR	0	0	0	0	0	0	0	220	308	322	336	332	350	1,868