CONCEPTUAL CONSIDERATIONS OF THE YUCCA MOUNTAIN GROUNDWATER SYSTEM WITH SPECIAL EMPHASIS ON THE ADEQUACY OF THIS SYSTEM TO ACCOMMODATE A HIGH-LEVEL NUCLEAR WASTE REPOSITORY

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TRANSMITTAL OF THE REPORT "CONCEPTUAL CONSIDERATIONS OF THE YUCCA MOUNTAIN GROUNDWATER SYSTEM WITH SPECIAL EMPHASIS ON THE ADEQUACY OF THIS SYSTEM TO ACCOMMODATE A HIGH-LEVEL NUCLEAR WASTE REPOSITORY"

Enclosed please find a copy of the subject report. This report is the result of revisiting my initial thinking as expressed in the earlier report entitled "Conceptual Considerations of the Death Valley Groundwater System with Special Emphasis on the Adequacy of this System to Accommodate a High-Level Nuclear Waste Repository," dated November 1987, but which was completed in the early draft form and provided to C. P. Gertz on December 22, 1987. Initially, I would like to express my gratitude for the openly supportive environment created by you and the Project Manager, Carl P. Gertz, for my work. Without such environment, the enclosed report would not have been possible.

The revisiting involved additional analyses as well as very extensive rewriting to clarify early concepts and interpretations of data. The following items were also included:

- Review and analyses of a large number of comments developed by the Yucca Mountain project. Over 40 individuals were involved in preparation of these comments; these individuals represented the following organizations: a) the U.S. Geological Survey (USGS); b) the Science Applications International Corporation (SAIC); c) the Sandia National Laboratory; and d) the Los Alamos National Laboratory.

- A nearly five-week-long period of discussions with representatives of the review team directed towards comment resolution. During the comment resolution period, a considerable number of comments was satisfactorily resolved. Most importantly, the process provided an effective forum to clarify; a) what I was saying, and b) why I was saying it. Typically, after a prolonged debate the comment was resolved. This, however, amounted to minor alterations of language but did not involve the substance of thoughts that were being expressed. Judging on the basis of the current version of the "internal" review report, it is unfortunate indeed that the comment resolution process did not grapple with more matters of substance (e.g., satisfactory understanding of the state of in-situ stress in a deforming fractured medium and of the Rayleigh's instabilities in faults and fractures; confrontation of the most salient aspects of the traditional understanding of the Yucca Mountain groundwater system with known data and facts; and adequacy of the traditional understanding to account for the entire data base). One may only hope that, in the future, the comment resolution process will be directed towards seeking an objective understanding that is in accord with known data and facts and which may be used "to make a number of predictions that could in principle be disproved or falsified by observations and measurements."

- o Review and in-depth analyses of comments developed by the State of Nevada's contractors which were transmitted to me privately. Over 10 individuals expressed their views and opinions; these individuals represented the following organizations: a) the University of Nevada, Reno (UNR); b) the Desert Research Institute; and c) Martin Mifflin and Associates. Although I did not have an opportunity to discuss the State of Nevada's comments with individuals involved, it would be fair to declare that these comments expressed similar reservations as those developed by the Yucca Mountain Project participants. In my opinion, the State of Nevada's comments were motivated likewise by the following three factors: a) inconsequential, as far as the conceptual understanding of the Yucca Mountain is concerned, inadequacies of the initial report; b) rigid adherence to traditional hydrologic concepts and practices; and c) non-familiarity with all aspects of the Nevada Test Site's (NTS) data base.

- o Development and delivery of several public presentations and seminars. Most noteworthy were presentations for the following organizations: a) the National Science Academy's Panel on Radioactive Waste Management; b) the U. S. Nuclear Regulatory Commission (NRC); c) the NRC's Advisory Committee on Nuclear Waste; d) faculty of the UNR; e) the USGS - Water Resources Division; and f) the British Petroleum's Research Center.

- o Review and analyses of additional data from the NTS and, specifically, from the Yucca Mountain site. Most important data sets were: a) the results of extensive in-situ stress determinations performed in the Climax Stock and Rainier - Aqueduct Mesas; b) the results of in-situ and laboratory measurements of hydraulic conductivity from the NTS, including the Yucca Mountain site; c) the results of geothermal measurements performed at the Yucca Mountain site; d) the results of periodic measurements of the Yucca Mountain water table; e) the results of chemical and isotopic analyses of groundwater samples from the NTS, and representing perched and semi-perched waters from the vadose zone as well as waters from below the water table; and f) the results of relativistic measurements of the P-wave velocity in the upper mantle of the NTS.

- o Discussions, field visits, and exchange of views with interested individuals employed by the SAIC. These activities have occurred during a 10 month long period of developing the subject report, and mainly involved Dr's G. A. Frazier, K. A. Kersch, and W. R. Sublette.

In my utmost sincere assessment, the revisiting failed to reveal a serious flaw of substantial scientific merit in my conceptual understanding of the Yucca Mountain groundwater system as outlined in the initial report. Instead, the understanding became more refined and, in my opinion, substantially reinforced. After careful considerations, I have concluded that the objections to the initial report, lodged by a majority of the reviewers as clearly expressed through their comments, encompass three broad categories.

The first category includes comments that were valuable and useful in performing the revisiting of my initial thoughts. Such comments pointed out or expressed one of the following: a) concepts that, although utilized by me but developed by other researchers, are not endorsed by the entire scientific community (principally Brady's understanding of faulting); b) requests for further explanation and clarification (mainly, in-situ stresses in a deforming fractured medium and Rayleigh's instabilities in faults and fractures); and c) errors and unintentional misrepresentations, for which I am alone to be blamed (for example, altitude of the land surface around Beatty, Nevada, and age of the Yucca Mountain veins). Deletion of the unacceptable concepts, development of the requested explanations and clarifications, as well as correction of errors, however, did not require or necessitate any substantive alteration of my initial thoughts.

The second category includes comments that are basically editorial in character. Such comments pertained to semantics and forms of expression, terminology, and mathematical equations and symbols as employed in the initial report. Responding to this category of comments resulted in substantial improvements of both the scientific and literary aspects of the report. The process, however, contributed little to creating a situation where a substantive alteration of my initial thoughts was required.

The third category includes comments the origin of which is related to a large gap between my never tried before approach to developing an understanding of the Yucca Mountain groundwater system and the more traditional approach embraced by the project's participants and the State of Nevada's contractors. Such comments either pointed out an unorthodox nature of interpretation of a given data set, or offered a traditional alternative to a given conclusion as developed by me. At the time of developing a conceptual understanding of the Yucca Mountain groundwater system, however, I was fully aware of both the orthodox/traditional interpretations and the range of permissible conceptual alternatives. Early in the process, I became convinced that it is the traditional manner of viewing a groundwater system which prevents the development of a realistic comprehension of the Yucca Mountain groundwater system and, in particular, its dynamic and long-term behavior. In my opinion, proceeding along traditional lines of hydrologic considerations, in this instance, yields interpretations that lack completeness and are full of uncertainties, controversies, and antinomies. It should not be a surprise, therefore, that also the third category of comments did little to alter my initial thoughts.

One may of course wonder whether a conceptual understanding may be correct if so many scientists are against it. Without implying a parity, my answer to such inquiries is similar to that given by Albert Einstein. When a book entitled "100 Authors Against Einstein" was published, he retorted "If I were wrong, then one would have been enough."

While performing the revisiting, there was no hesitation on my behalf to reconsider my initial positions, to take a fresh look at the data base, and once more to rethink the soundness of traditional interpretations. Facts, logic, and meritorious arguments were essential. Those, however, were not forthcoming. Pointing out imperfections of terminology and forms of expression used and the unorthodox character of the performed interpretations, "professional" judgments backed solely by empty rhetoric, and reinstatement of the project's positions, while sometimes distracting and time consuming, carried little weight in the final analyses. At the onset of the review process, however, I made it clear that, if in fact I am wrong, it is not difficult to demonstrate, based either on the already existing data or on data that may be acquired in the future, that my conceptual understanding of the Yucca Mountain groundwater system is either inapplicable or incorrect. Such demonstration may be achieved through substantive addressing of all or one of the following issues: a) contemporary stability of the Yucca Mountain water table, with and without influence of vibratory ground motion; b) presence or absence, at the Yucca Mountain site, of the in-situ values of closure pressure that are compatible with, at least, the overburden stress; c) origin and age (relative to the time of deposition of the country rock) of the Yucca Mountain "mosaic" breccias; and d) strain rates involved in the formation of wallrock separations that, at Yucca Mountain, contain the Late Quaternary calcite-opaline silica-sepiolite veins. Short of having either unequivocal positions with respect to these four issues or meritorious arguments pointing and demonstrating incorrectness of my views, I have no alternative but to keep insisting that: a) the conceptual understanding of the Yucca Mountain groundwater system that forms the foundation for nearly all activities related to the post-closure considerations as proposed in the Statutory Site Characterization Plan, so-called preferred conceptual model, is most likely wrong; and b) the conceptual understanding outlined in the subject report, although not necessarily complete and correct in all its aspects, most certainly is justifiable in terms of the known data and facts.

Considering my duties and professional responsibilities, and having arrived at a point where disagreeing with the review team is the only acceptable and responsible option left for me, I request the implementation of my agreement with the Project Manager, Carl P. Gertz, on July 29, 1988. Pursuant to the provisions of this agreement, I herewith request an external and independent peer review of the enclosed report. In accordance with the provisions of the agreement, I have selected two scientists to participate, along with three other scientists to be selected by the U.S. Department of Energy (DOE), in the review. These scientists are: Professor N. J. Price of the University Collage, London - United Kingdom; and Dr. C. B. Archambeau of the University of Colorado. Professor Price is the internationally recognized authority in the area of structural geology, impact tectonics, rock mechanics, and movements of fluids in the Earth's crust. Dr. Archambeau is the recognized expert in various aspects of geophysics and is familiar with the results of various geophysical investigations conducted at the NTS during the last 20 years. With regard to both of these scientists, the DOE may rest assured of their integrity, soundness of professional judgments, and complete absence of any conflict of interest. As far as I am concerned, I will accept their collective judgments without any reservations.

To avoid any possible misunderstanding and misdirecting the peer review process, I wish to state two main technical conclusions that, in my opinion, need to be evaluated as to their validity and soundness. The first conclusion that must be evaluated through the peer review process is:

> The currently available data base pertaining specifically to the Yucca Mountain groundwater system indicate that: a) the main factor which dominates and controls the hydraulic and bulk effective thermal conductivities of the local tuff "pile" is most likely the in-situ stress field; and b) the base of the Yucca Mountain groundwater system is a spacially variable "upward flux" boundary for both heat and fluid.

Evidence supporting this conclusion is in my opinion convincing and clear, therefore, I regard this conclusion as justified and, short of questioning the validity of data base, as secure beyond a reasonable doubt. Furthermore, this conclusion was drawn previously, and independently of my analyses, by some researchers from the USGS (Sass et al., 1983; and Brederhoeft, 1987).

In view of the importance of the above conclusion, and notwithstanding the high degree of confidence in its validity that in my opinion is warranted at this time, I do recommend verification and enlargement of the data base supporting it. This may be achieved with a modest investment of time and resources using the existing data base (principally the results of continuous monitoring of the Yucca Mountain water table) and the present network of deep boreholes.

The second conclusion is:

> Reasonable but conservative interpretations of the geologic record and of the data regarding contemporary state of the in-situ stress strongly suggest that: a) the local hydraulic and bulk effective thermal conductivity structures undergo significant and cyclic changes in time scale measured in terms of tens of thousand of years; and b) the "upward flux" boundary conditions, along the base of the Yucca Mountain groundwater system, are time-dependent and are sensitive to a variety of tectonic stimulations.

To be sure, validity of both aspects of the second conclusion may not yet be regarded as secure beyond a reasonable doubt. In order to advance confidence to a desired level, further studies and analyses of the geologic record are required. Such studies and analyses may be performed based on procedures and techniques routinely employed in geologic explorations. To this end, however, the development of extensive underground openings, the implementation of extensive subsurface exploration, and the performance of long-term seismotectonic investigations are not essential. In my opinion, the possibility that the entire second conclusion is valid, is real, and by all means not remote.

Taken together the above two conclusions, if translated in terms of intrinsic capabilities of the Yucca Mountain site to isolate radionuclides from the biosphere, are of paramount importance. These conclusions, if substantiated by the peer review and by additional field data, indicate that the Statutory Site Characterization Plan sets the management of high-level nuclear waste on a highly uncertain course. In my opinion, proceeding along this course, without prudent reservations and restraints, will result in: a) erosion of public confidence in the United States Government's ability to manage the problem of high-level nuclear waste with integrity; and b) long delays and misdirected large expenditures of public funds. Furthermore, the local geohydrologic conditions, as summed up by both of the conclusions, are very severe and, within the context of current federal regulations, create a situation whereby favorable licensing action with respect to the Yucca Mountain site is not a likely possibility.

Finally, I wish to express that I am truly sorry for difficulties I may have caused you, by not being available to perform other tasks, in discharging your management responsibilities. I feel strongly, however, that we at the DOE are obligated to provide a timely and realistic appraisal of the Yucca Mountain site for the benefit of both legislative and executive branches of the United States Government, the American public, and the nuclear industry.

Such appraisal must be motivated by the national interest, but not by our shortsighted individual or institutional and corporate interests. This job must be done right to protect, in the words of President Carter, "current and future generations."

Jerzy S. Szymanski

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Technical Analysis Branch
Regulatory & Site Evaluation Division
Yucca Mountain project Office

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Enclosure:
Subject Report

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Conceptual Considerations of the Yucca Mountain Groundwater System with Special Emphasis on the Adequacy of This System to Accommodate A High-Level Nuclear Waste Repository

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July 26, 1989

PREFACE

I consider it a privilege to write the preface to this report and express my thoughts as an applied scientist who is familiar with both the subject matter and the author, Jerry S. Szymanski. I believe this report could lead to a significant increase in the scientific understanding of ground water processes in the Great Basin. In essence, the report postulates major tectonic control over ground water flow. In some areas the water table may rise and fall hundreds of meters in response to earthquakes and other tectonic processes. The entire system is driven by ongoing dynamic processes in the earth's hot mantle, which are also responsible for earthquakes and volcanoes in the area.

The author's interpretations of the behavior of the local ground water system were developed as part of the Department of Energy's program to evaluate Yucca Mountain for use as the nation's first high-level nuclear waste repository. Szymanski's job as a DOE employee has been to help administer site investigations. In the management plan, the actual scientific work is normally conducted by other governmental agencies and laboratories. What has made the development of these new interpretations possible is the unusual (possibly unprecedented) amount and variety of data that are available from Yucca Mountain and the adjacent Nevada Test Site.

The interpretations of this report are based largely on field observations and measurements from dozens of boreholes designed to measure properties of ground water and earth in the upper few kilometers. These include temperatures, pressures, stresses, chemistry, isotopes, conductivities, and rock properties. From these and other data, including measured effects of underground nuclear explosions, Szymanski deduces that ground water flow properties may change dramatically (possibly by many orders of magnitude) in response to ongoing tectonic processes. Typically, geohydrologists consider ground water flow to be relatively insensitive to earthquakes, apart from short-term transient effects. Szymanski also interprets major thermal and chemical influences on ground water flow that are not normally considered. Conventional thinking may need to be expanded to achieve our unprecedented goal for predicting or bounding ground water conditions, thousands of years into the future.

Inquiries into the scientifically intriguing phenomena of this report began in 1984, shortly after the author arrived in Las Vegas as a DOE employee. On his first visit to the Yucca Mountain site, he observed thick veins of calcium carbonate and silica in the local faults, and questioned the source of water that was responsible for these hydrogenic (water-derived) deposits. The conventional thinking was that, over many thousands of years, rainwater most likely dissolved minerals from windblown dust, ran into the open cracks, evaporated, and deposited the dissolved minerals, which are common throughout the region. Intuitively, this explanation was not satisfying to the author; he suspected that the veins may have been deposited by upwelling water, i.e., that they were actually spring deposits. He also questioned the origin of extensive silica-cemented breccias. Many scientists thought these had developed many millions of years ago, during the aftermath of volcanic processes that formed Yucca Mountain. Memos, comments, dialogue and more questions followed without satisfactory resolution.

The author's experience with geologic investigations for other large projects, particularly nuclear power plants, had driven him to believe that a strong technical basis would be required to satisfy rigorous licensing requirements. As a step toward resolving the scientific uncertainties, the author's supervisors at the DOE encouraged him to develop a report and document his concerns. This was in the late summer of 1987, when three sites were still being considered for the first nuclear waste repository, and it appeared that at least two years would be required to select from among these sites. In December of 1987, just a few weeks after the initial typing of an early draft was completed, Congress decided to confine future site characterization activities to the Yucca Mountain site. With what was known at the time, this appeared to be a prudent decision: all sites had uncertainties, and Yucca Mountain appeared to be the best suited site for the repository.

Szymanski's 1987 report failed to convince Project scientists of the technical merits for his concerns, although uncertainties were acknowledged. They objected to his unconventional interpretations of data and ground water processes, and insisted that a stronger case would need to be developed by the author. I note that science relies on conventions of many types, including testing and analysis procedures, concepts of physics, and even our languages; conventions are essential to the accumulation of knowledge. Science, by its nature, seeks order and conformity, while always acknowledging uncertainty. Sometimes, however, concepts and conventions need to be altered in response to new information, especially when the circumstances for which they were developed change. Geohydrologic concepts and conventions that have been developed to explain contemporary ground water systems may be deficient for explaining evolutions in an active geologic system over time scales of changing tectonic conditions. The new concepts, if merited, would include more interactive processes within the earth, or, to use a modern vernacular, they would be more "holistic".

Shortly after completion of the author's early report, I began to devote much of my time developing an understanding of his interpretations of data and why they differed from the more conventional interpretations. Through nearly daily interchanges with the author, which included many field trips to the site and surrounding areas, I gradually began to understand his concepts and eventually developed an appreciation for their underlying logic and internal consistency. His hypotheses could be inappropriate or incomplete, although they do appear plausible. In any case, the "burden of proof" is ours, the scientists who are responsible for investigating the site. He argues that to fulfill our social responsibilities as applied scientists, we must form our individual interpretations and debate their merits with ourselves and others.

The present report elaborates further on concepts introduced in the 1987 report, which I briefly summarize as follows: The deep water table at Yucca Mountain, which is about 500 m below the immediately adjacent valleys, can be explained by the presence of open fracture conduits to a depth of a kilometer or more which provide ample drainage. The water table can hardly rise under these conditions. However, if the fractures have opened in response to tectonic extension and shear, then they might close in response to faulting rebound and become plugged with calcium carbonate and silica minerals precipitated from upwelling waters. This could greatly reduce the opportunity for water to drain laterally, away from the site. Thus, a significant faulting event might squeeze water upward and dam ground water flow from adjacent areas of elevated water table to the north and west. Faulting-induced reductions in hydraulic conductivity would also retard the upward flow of terrestrial heat, which could be partially compensated by enhanced thermal convection, particularly along the local faults. In combination, these processes could cause a large rise in the water table at Yucca Mountain.

There is abundant evidence in rock samples taken from boreholes at Yucca Mountain and along surface exposures in the area for the tendency of fractures to be filled with minerals deposited by flowing waters. Also, under present conditions, water appears to be welling up local faults and dissipating into the highly conductive rocks. The key issue is the sensitivity of fracture apertures to faulting-induced changes in stress. By reinterpreting water-injection tests that were performed to measure flow properties, the author finds evidence for extreme sensitivitv to changes in stress. The interpreted values for minimum principal stress are surprisingly low; in many depth intervals they are well below what is generally classified as "incipient failure". This finding is reinforced by an apparent correlation between zones having low minimum principal stress and zones having high fracture conductivity; and, conversely, zones with a minimum principal stress at or above incipient failure appear to correlate with zones of tighter, less conducting rocks.

Unfortunately, the sensitivity of fracture apertures and hydraulic conductivity to changing conditions of stress in the earth is not easily determined using laboratory tests on small rock samples because of differences in scale. Whereas the fracture dimensions scale with sample size, the characteristic dimensions of intact rock grains and pores do not. Consequently, the properties of conducting fractures in the earth, where dimensions are measured in hundreds of meters or more, may not be adequately simulated in small laboratory samples, where dimensions are usually measured in centimeters.

If such major tectonic control of ground water is actually occurring, why has it not been recorded? Global observations of earthquake-induced effects on ground water record mostly short-term (< years) changes in the water table elevation that are limited to a few tens of meters. Earthquakes have been observed to radically influence groundwater flow and spring discharges, and there is evidence that ground water is sometimes expelled at the surface from a depth of many kilometers. However, few of these data have been obtained in areas undergoing tectonic extension, such as the Great Basin, where the effects on the water table are likely to be most pronounced, and I know of no measured effects from a local faulting event on such a deep water table. The more subdued effects of earthtides, distant earthquakes and underground nuclear explosions have been recorded at Yucca Mountain, but these results are not yet available for general interpretation.

Without direct observations for major changes in water-table elevation from natural earthquakes, the author presents evidence for large explosion-induced effects. Also, he has compiled considerable pressure, temperature, and chemistry data, which suggest that large rises in the regional water table may have occurred in the past, and he challenges previous interpretations for the origin of water that deposited the minerals in local faults and fractures at Yucca Mountain.

I believe that this report will stimulate the interests of many scientists, and help focus investigations of ground water conditions at Yucca Mountain. If the concepts are valid, the area of proposed waste emplacement could be flooded. It is not currently known what effect this might have on waste isolation, although it could be significant.

Finding a suitable solution for nuclear waste is of paramount importance. Regardless of how this is achieved, we must have confidence in the technical merits for our approach. There may be little room for ineffective conventions, scientific or otherwise. The requirement for predicting or bounding ground water conditions, thousands of years into the future, is unprecedented, and innovative approaches are needed. We must not prejudge the site. I believe that present uncertainties can be substantially reduced, but certainty is not achievable; this is the nature of science. We must define what we do and do not know about the site, our expectations and our uncertainties, in forms that support rational decisions about waste isolation and reliable engineering measures.

I urge the reader to seek meaning behind the expressions in this report that, at times, may appear to be imperfect or unconventional. I believe that he is addressing issues at the cutting edge of science with enough knowledge, data and experience to formulate credible new understandings of geohydrology. The voluminous work has received only minor editorial and technical refinement beyond that provided by the author, an earth scientist who was born and educated in Poland. I congratulate the author for the diligence he has shown in developing this report. If there is but one chance in ten that his postulates are valid, then we must jointly share his concerns and seek resolution.

Dr. Gerald A. Frazier
Science Applications
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July 26, 1989

"... for the shortcoming of this inquiry grant us your pardon and for the discoveries contained therein your grateful thanks." from Organon, Aristotle, 352 B.C.

PREFACE

The previous, immature, draft version of the report entitled "Conceptual Considerations of the Death Valley Groundwater System with Special Emphasis on the Adequacy of This System to Accommodate a High-Level Nuclear Waste Repository," was released to the public prematurely, and was intended neither for wide public circulation, nor for publication in scientific journals. The rigor and, in places, the clarity of the presentation were not in accord with standards expected from a scientific publication. The focus was on substance and the end result, unfortunately, at the expense of forms of the presentation. From the onset of writing, I regarded the report as a "management tool" whose sole purpose was to correct, in my opinion, unacceptable conceptual considerations of the Yucca Mountain groundwater system as practiced by the Yucca Mountain Project. In 1986, while reviewing early drafts of Chapter 3 of the Yucca Mountain Project Site Characterization Plan, I characterized these conceptual considerations in the following manner: "The conceptual model of a groundwater system as proposed in Chapter 3, is not one developed based on careful considerations of alternatives in light of the existing data and within the constraints of some interpretation framework. The impression I get is that the model was given *a priori* and was not subjected to any alterations in response to evolution of the data base. In other words, the data base as it was being developed, was not utilized to refine the abstract visualization of the overall hydrologic system for purposes of identifying the specific hydrologic processes that are expected to operate within it. In some instances, petrified at the onset of investigations, the Yucca Mountain Project conceptual model of the groundwater system was being used to evaluate the potential significance of some direct field observations . . . are examples of this most peculiar and difficult to understand deduction process." The seemingly endless process of, on one hand, acquiring more and more sophisticated and thought provoking data and observations, and on the other hand, not acknowledging and interpreting these data, disappointed me as a scientist and deeply disturbed me as a human being, a civil servant, and a citizen of this country. As far as I am concerned, there is no doubt that the U.S. Department of Energy (DOE) cannot develop a high-level nuclear waste repository solely on the basis of beliefs and wishful thinking. Sooner or later, the facts must be accounted for and introduced into the process. This is what motivated me during the nearly two year long process of trying to undo the Gordian Knot of controversies and antinomies that presently exist between the currently accepted understanding of the Yucca Mountain groundwater system and the existing data base which, incidentally, is one of truly extraordinary proportions. The development of this report is not the act of a disgruntled employee or an anti-nuclear freak. Rather, it is the act of a deeply concerned scientist, a public servant, and a pro-nuclear activist.

In my opinion, by not recognizing a full range of permissable conceptual alternatives and, therefore, not addressing critical suitability issues in a timely manner, the Yucca Mountain Project is proceeding with substantial risk. This risk not only involves the eventual siting decision, but will also involve a lot of misdirected effort and wasted time during the site characterization process. Both of these factors, if translated in terms of public trust and acceptance, have the potential to cause a gradual loss of credibility. If not prevented, such a loss could eventually lead to an inability by the DOE to deal with the problem of permanent disposal of high-level nuclear wastes as mandated by the Nuclear Waste Policy Act.

Keeping in mind the above stated intentions and reservations, this report was designed and structured in a manner best described by four adjectives: provocative, speculative-conjectural, controversial, and constructive.

It is my explicit intention that this report be provocative. Its main purpose is "to provoke initiation of an understanding on a qualitative or conceptual basis," of the groundwater system operating in the area of Yucca Mountain. Such an understanding must be based not only on the existing data, but it must also account for two additional factors. On one hand, the groundwater system is known to operate in a specific tectonic environment whose main tectono-physical characteristics are readily apparent. On the other hand, depth of the desired conceptual understanding must reflect the fact that we are concerned with nothing less than evaluating the effectiveness of a nuclear waste disposal system in time scales of geologic proportions. Furthermore, adequate conceptual understanding of the groundwater system is essential for a) providing **responsible** input into siting decisions; b) developing a focused and **effective** exploration program; c) developing a **realistic** description of the natural system; and d) developing a **rational** approach to the performance assessment and the performance allocation process. Consequently, conceptual understanding of the groundwater system is a matter of the highest priority and shall not be deferred until late stages of the site characterization process.

This report is purposely designed to be speculative and conjectural. This description, however, should not distract a reader from the merits of the report. In my view, speculation and conjecture are essential prerequisites of any scientific endeavor. This is true, in particular, if one is trying to understand a complex geologic system. A system that consists of a number of potentially interactive parts; is of considerable spatial extent; and whose long-term behavior is the object of the inquiry. How else, but through speculation can one arrive at the Hegelian synthesis? How else, but through this synthesis can one establish a rational framework and a firm base for subsequent experimentations or, in the terminology employed by the great Dutch geologist Professor Van Bemmelen, for the diagnosis-prognosis test of scientific hypotheses? Of course, in order to be valid and useful, the speculation must be in accord with the first principles and must be permissable in terms of the existing data and observations. The speculation, however, does not have to be in accord with weakly supported conventions, popular beliefs, and dogmas. The presence of speculation is not troublesome at all. However, at the onset of the site characterization process, the absence of speculation is unacceptable. It virtually assures that the subsequently developed data base will not be suitable for unequivocal interpretations, that undoubtedly, are required for the purposes of developing a high-level nuclear waste repository.

It can also be said, and justifiably so, that this report is controversial. The essence of this report challenges and questions two fundamental assumptions that underlie the currently accepted understanding of the Yucca Mountain groundwater system. The first assumption is that the hydraulic conductivity structure of this groundwater system is related solely to the litho-structural framework of the system and, therefore, for all practical purposes is independent of time. The second assumption is that the flux of terrestrial heat is not a factor that may impact long-term behavior of the groundwater system. Both of these assumptions also underlie most of the widely used numerical models of groundwater systems and are, therefore, commonly employed in numerical simulations of many other flow fields. Such assumptions become familiar, comfortable, and seldom-questioned axioms of the applied hydrology as commonly practiced today. It is understandable, therefore, that controversy emerges if one challenges those assumptions. But, is it wrong to challenge them? Of course not. Especially if one is concerned with a groundwater system that is situated in a youthful volcano-tectonic terrain and is being seriously considered for permanent disposal of high-level nuclear waste.

Finally, it is my specific intention that this report, even in its earlier version, be constructive and helpful in the process of searching for a geologic environment where reasonably safe and socially responsible disposal of high-level nuclear waste may be achieved. As an expression of such intentions, the report recommends a number of cost-effective investigations to be performed in the immediate future. These investigations were designed to obtain data, judged by me, required for validating the proposed conceptual understanding of the Yucca Mountain groundwater system. Establishing the validated conceptual understanding of this system, early in the site characterization process is an important step toward building a solid base to support three important assessments: a) site **suitability**; b) site **licenseability**; and c) **appropriateness** of the currently proposed site characterization effort.

The early draft version of this report, released by former Nevada Governor, Richard H. Bryan, on January 22, 1988, received very extensive internal and external reviews. As a result, I received a great number of comments. Some were encouraging and supportive, some were hostile, if not downright nasty, and some were extremely helpful in suggesting improvements to the report. I thank the reviewers for their contributions in the form of written commentaries and verbal discussions. Their ideas and requests for further explanations and clarifications, as well as pointing out errors and unintentional misrepresentations, substantially improved both the scientific and literary aspects of the report.

The report, in terms of its fundamental conclusions and recommendations, remains unchanged. I have still to hear mentioned a serious, scientifically based flaw in the proposed conceptual understanding of the Yucca Mountain groundwater system. In my opinion, further considerations of the validity of my concerns, regarding the ability of the Yucca Mountain site to effectively isolate radionuclides from the biosphere, should be made based on the results of field investigations recommended in this report.

Additional Yucca Mountain Project field programs have been recently completed; others will be completed in the near future. I expect that the results of such efforts may well justify the conceptual considerations undertaken in this report. Many of the interpretations here are at odds with previously published works dealing with the Nevada Test Site and, specifically, with the Yucca Mountain groundwater system. For some of these controversies, an unequivocal resolution is not possible at this time. I do firmly believe, however, that the hypotheses, as developed in this report, are not only plausible but they are almost certainly correct. Evaluation of the ultimate credibility of each of these hypotheses rests with you, the reader, and the test of more data and time.

While studying this report, the reader is advised to keep firmly in mind that a conceptual understanding, as with any physical theory, is always provisional in the sense that it is only a hypothesis; one cannot prove it. As British scientist S.W. Hawking puts it: "No matter how many times the results of experiments agree with some theory, you can never be sure that the next time the results will not contradict the theory. On the other hand, you can disprove a theory by finding a single observation that disagrees with the predictions of the theory. As philosopher of science Karl Popper has emphasized, a good theory is characterized by the fact that it makes a number of predictions that could in principle be disproved or falsified by observations. Each time new experiments are observed to agree with the predictions, the theory survives, and our confidence in it is increased; but if ever a new observation is found to disagree, we have to abandon or modify the theory. At least that is what is supposed to happen, but you can always question the competence of the person who carried out the observation."

In light of these remarks, it is clear that it is not prudent to focus the attention on evaluating whether or not I have proven the proposed conceptual understanding of the Yucca Mountain groundwater system. Rather, the efforts should be directed toward evaluating whether this understanding constitutes a "good theory." One that a) accounts and explains known data and observations and b) "makes a number of predictions that could in principle be disproved or falsified by observations." I do submit that the conceptual understanding, as outlined in this report, fulfills both of these requirements. On the other hand, the conceptual understanding of the Yucca Mountain groundwater system, so-called "preferred" conceptual model, as expressed in the statutory version of the Site Characterization Plan may only be maintained by ignoring and otherwise discounting a gamut of data and observations. This understanding yields a number of predictions that are already known to be in sharp conflict with observations. Its sole strength is that it is in accordance with hydrologic conventions and practices. In my opinion, such an attribute does not constitute a sufficient cause for accepting, even on a provisional basis, the latter understanding as a foundation for the process of developing a high-level nuclear waste repository.

While performing the analyses contained in this report, I have become increasingly aware that it is rather difficult to devise a conceptual model to represent a portion of the Earth all at once. Instead, we tend to break the problem up into bits and invent a number of partial conceptual models. Each of these partial models represents and predicts a certain limited class of information, neglecting the effects of other factors. In my opinion, such an approach to developing a conceptual understanding of the Yucca Mountain groundwater system, if employed in harmony with data and known facts, is beneficial and proper.

However, if such an approach is employed in its most drastic form (i.e., maintaining conformity with conventions and *a priori* positions but ignoring observations and common sense assessments of data) is completely wrong and may be harmful. If something in the Earth depends on a number of factors in a fundamental manner, it is impossible to get close to a correct solution by investigating parts of the problem in isolation.

I wish to acknowledge the openly supportive environment provided by the DOE. The understanding, need to know, and support of the former Director of the Yucca Mountain Project Office, Dr. D.L. Vieth, as well as the present Director of that organization, Mr. C.P. Gertz, are gratefully acknowledged. I would like to express my special gratitude to Mr. J.J. Lorenz of the Reynolds Electrical and Engineering Company, Inc. for assisting me in the development of this report. His understanding and knowledge of the Yucca Mountain data base were very helpful. Also, Mr. Lorenz has contributed to improving the literary aspects of this report. Thanks are also due to Science Applications International Corporation (SAIC) for ably typing this report and for drafting most of the illustrations. Specifically, I would like to thank Ms. Linda Durham of SAIC for substantially improving the literary aspects of this report and other members of the SAIC Technical Writing Division who assisted in the effort.

Jerry S. Szymanski
Las Vegas, Nevada
July 26, 1989

SECTION 1.0

INTRODUCTION

Options seriously considered for the isolation of high-level nuclear wastes that involve geologic media differ primarily in emplacement technique and location. Of these options, emplacement in a deep, excavated cavity, or geologic repository, is the currently favored method.

The most likely means of releasing radionuclides from a sealed geologic repository to the biosphere is by dissolution and transport of radionuclides by groundwater. The potential hazard from buried radionuclides, therefore, depends primarily upon four factors: a) the amount and rate of the supply of radionuclides to the groundwater; b) the pathways and rate of groundwater movement; c) the degree of geochemical retardation imposed by geologic media; and d) the dissolution rate of radionuclides in the groundwater.

The assessment of possible suitable sites for a geologic repository must involve critical evaluation of a) the performance of the existing geologic system; b) the probable future performance of the natural system, taking into consideration evolutionary changes and potentially disruptive events; and c) the disturbance to the natural system caused by excavation, waste emplacement, sealing, and the presence thereafter of the waste facility. The assessment of risk is possible only if reasonable predictions can be made regarding the repository environment. Because actual tests and demonstrations of repository system behavior cannot be conducted under various changing conditions over representative periods of time, mathematical models must be used to evaluate the long-term behavior of the system.

Traditionally, the scientific community, concerned with development of technology to be used for purposes of achieving the disposal of radioactive materials, considered the repository siting options, but only in the context of "stable geologic formations" situated in "tectonically stable areas". Roots of this perception may be related to our human inability to fully comprehend tectonic forces and processes, and how these factors relate to long-term containment and isolation capabilities of geologic systems. It is fair to state of course, that such reservations were expressed for saturated conditions alone. The Yucca Mountain site is different. Water, which is considered to be the most important factor in radionuclide transport, is presently available but only in very limited quantities in the vadose zone. What is the value of this attribute in light of the volcano-tectonic setting of the site? How do both of these factors balance each other in the context of repository performance and uncertainties associated with it? These are the questions that must be answered.

The most important part of understanding the role of tectonic processes, in the context of radionuclide releases, is a phenomenologic linkage between the behavior of a groundwater system and tectonically generated energy and/or substance in various forms and quantities. The subject is poorly known and the means of addressing it require rather difficult mathematical formulations that relate more to thermodynamic concepts of coupled systems than to traditional hydrogeology.

It is likely that for an active tectonic environment that involves extension and includes alkalic volcanism, the majority of assumptions utilized to develop mathematical models to describe "simple" groundwater systems are of questionable validity. Some of those assumptions are that

- Gravitational hydraulic pressures acting at the vertical boundaries of a groundwater system are solely responsible for groundwater movement;

- The flux of terrestrial heat is not an important factor;

- Three-dimensional distribution of hydraulic potentials is simple and is describable through configuration of the water table;

- Boundary conditions, with respect to an assumed horizontal base of a groundwater system as they exist in time and space, are of no importance;

- Boundary value problems, as solved for a groundwater system consisting of surface recharge and discharge areas and composed of a non-deforming porous medium, is adequate to describe all behavioral aspects of a groundwater system; and

- The relationship between the flow field in the saturated zone and the flow field in the vadose zone is such that, in the vadose zone and apart from repository-induced effects, only predominately downward, gravity motivated, movement of water is possible.

Notwithstanding these obvious limitations, a position on tectonics and seismicity and how these subjects relate to the performance of a high-level nuclear waste repository at the Yucca Mountain site has not been established by the Yucca Mountain Project. This is true, in particular, for relationships between tectonics and the groundwater system which, of course, is a key player in the performance of a high-level nuclear waste repository.

The regulatory framework, as it currently exists, tends to emphasize the issue of tectonics. However, both 10 CFR 60 and 10 CFR 960 deal with this issue in terms of vague generalities providing little help in developing siting decisions and site characterization plans. Tectonics and its direct hydrologic impacts may have an important bearing on the compliance of a disposal system with requirements set forth in 10 CFR 60. Conceivably, all specified performance objectives, either directly or indirectly, are involved, including

Pre-closure

- Retrievability; and

- Operational releases of radioactive materials.

Post-closure

- Groundwater travel-time;

- Life of waste package;

- Release rates from engineered barriers; and

- Release rates to accessible environment.

Tectonic processes come into play with equal importance, if one is concerned with compliance of a disposal system with requirements set forth in 10 CFR 960. Both pre-closure and post-closure system guidelines may be involved. Tectonics is also important with respect to many technical guidelines, both pre-

SECTION 2.0

MATHEMATICAL AND CONCEPTUAL MODELS OF GROUNDWATER SYSTEMS STATEMENT OF THE PROBLEM

2.1 GENERAL

In studies of natural groundwater systems, hydrologists use mathematical models to represent those systems as a dynamic continuum in two or three dimensions. Such representations can be used to estimate two important characteristics of a groundwater system: a) the geometry of a flow path between any two arbitrary points or surfaces and b) the corresponding groundwater travel-time. Mathematical models can also be useful in studies of a groundwater system's response to various provocations (e.g., the hydrologic consequences of a climatic change or a tectonic disruption).

The mathematical model of a groundwater system constitutes a foundation for the analyses of groundwater transport of buried radionuclides from a repository to the biosphere, including analyses of all significant transport attenuation processes. Through the utilization of sensitivity analyses, realistic descriptions of natural environments, and reasonable assumptions about possible future disruptive processes, mathematical models provide the basis for judgments regarding the acceptability of a site for the development of a geologic repository for nuclear waste. Furthermore, much of the general understanding and so-called professional judgment involving long-term behavior of groundwater systems, including their responses to various tectonic stimulations, is developed based on mathematical models of "simple" groundwater systems. It is important, therefore, to understand how such models are constructed, what their limitations are, and what uncertainties are involved in their utilization.

2.2 MATHEMATICAL MODELS OF NATURAL GROUNDWATER SYSTEMS

Plate 2.2-1 presents the basic structure of a mathematical model for any "simple" groundwater system. Such a structure involves three separate parts: a) the governing equation; b) boundary conditions; and c) initial conditions.

The **governing equation** is constructed by combining Darcy's Law – relates the groundwater velocity vector to the gradient of hydraulic potential – with the continuity law that requires the conservation of fluid mass.

Boundary conditions describe inputs of fluid mass into a groundwater system. They constrain a groundwater system and make solutions to the governing equation unique. The different types of boundary conditions are a) Dirichlet conditions, where the head is known for surfaces bounding the flow region; b) Neumann conditions, where the flow is known across surfaces bounding the region; and c) some combination of (a) and (b) for surfaces bounding the flow region. If inconsistent or incomplete boundary conditions are specified, the flow field is ill defined.

The mathematical model of a groundwater system, in which hydraulic potentials change with time, is a model for nonequilibrium or transient flow. Such a model, in addition to the governing equation and the boundary conditions, must also include **initial conditions**. These conditions are given through a set of head values at a time when the transient flow process was initiated.

There are three governing equations that are used in studies of "simple" groundwater systems. These equations are presented on Plates 2.2-2 through 2.2-4. An explanation of mathematical notations used is presented on Plate 2.2-5.

The first and most commonly used equation is the Laplace equation. It states that the sum of the second partial derivatives of hydraulic potential with respect to x, y, and z is equal to zero (i.e., $\nabla^2 h = 0$). A flow system described by this equation is at steady-state. An aquifer, or a discrete portion of it, is assumed to be homogeneous and isotropic. The solution to the Laplace equation satisfies specific boundary conditions for a given hydraulic conductivity and expresses the distribution of hydraulic potentials as a function of x, y, and z.

The second equation, which also describes steady-state flow, is Poisson's equation. It states that the sum of the second partial derivatives of hydraulic potential with respect to x, y, and z is equal to a time-independent, but space-variable, value [i.e., $\nabla^2 h = \pm \mathrm{R}_{(x,y,z)} \cdot T^{-1}$ (where T is transmissivity)]. Poisson's equation allows for the consideration of distributed or point sources and sinks of groundwater. The term $\mathrm{R}_{(x,y,z)}$ expresses the volume of water added per unit of time per unit aquifer area. If $\mathrm{R}_{(x,y,z)}$ is equal to zero, then Poisson's equation reduces to the Laplace equation. The solution to Poisson's equation satisfies specific boundary conditions for a given hydraulic conductivity and expresses the distribution of hydraulic potentials as a function of x, y, and z.

The third equation describes a groundwater system for which values of hydraulic potentials change with time. It states that the sum of the second partial derivatives of hydraulic potential with respect to x, y, and z is equal to a time-dependent value [i.e., $\nabla^2 h = S \cdot T^{-1} \partial h/\partial t$ (where S is storativity; i.e., it represents the volume of water released from storage per unit area of aquifer, per unit decline in head)]. Allowing for the presence of groundwater sources and sinks, the transient flow equation becomes: $\nabla^2 h = S \cdot T^{-1} \partial h/\partial t \pm \mathrm{R}_{(x,y,z,t)} \cdot T^{-1}$. If term $\partial h/\partial t$ is equal to zero, then the transient flow equation reduces to Poisson's equation. However, if both terms $\partial h/\partial t$ and $\mathrm{R}_{(x,y,z,t)}$ are equal to zero, then the transient flow equation reduces to the Laplace equation. The solution to the transient flow equation satisfies specific boundary conditions and initial conditions for a given hydraulic conductivity and storativity, and expresses the distribution of hydraulic potentials as a function of x, y, and z and as a function of time.

For most groundwater systems, the assumption of isotropic and homogenous aquifer conditions is unrealistic. The flow equations must, therefore, be stated in a form that allows for the inclusion of heterogeneity and anisotropy (Plate 2.2-6). For given boundary and initial conditions, the solution to the flow equations are unique, but only for a specified hydraulic conductivity structure.

The above three governing equations constitute the essence of mathematical representations of groundwater systems as dynamic continua and have two common characteristics. The first characteristic is that these equations, in terms of the thermodynamic concept of coupled flow, describe a "simple" flow. For such a flow, the groundwater velocity vector is the result of the gradient of hydraulic potential. The magnitude of this gradient is related solely to hydraulic pressures acting at boundaries of a flow system and hydraulic losses sustained during flow. The role of other energy gradients (e.g., the temperature gradient) must be negligible, otherwise flow process is misrepresented.

The second characteristic of the governing equations for a "simple" flow is that a medium in which such a flow occurs, as expressed in terms of its hydraulic parameters (hydraulic conductivity and storativity), does not involve time-dependency. The hydraulic parameters are considered as material properties that are independent of time and time-related factors (e.g., the *in situ* stress).

It can be expected, however, that a groundwater system developed in a medium which is subjected to various tectonic stimulations, operating on either continuous or episodic basis, involves other than a "simple" flow. In such a situation, none of the discussed governing equations constitutes an adequate mathematical representation of the thermodynamic continuum involved.

Potential limitations and uncertainties associated with the commonly used mathematical models of groundwater systems are not restricted to the governing equations. They also pertain to the boundary conditions and, in the case of heterogenous and anisotropic groundwater systems, to the hydraulic conductivity structure.

The definition of boundary conditions, in terms of their spatial distribution and temporal continuity, is one of the most difficult problems. In most situations, such a definition is a matter of an educated "guess". This "guess", however, seldom accounts for the tectonic environment in which a groundwater system operates.

Knowledge of the hydraulic conductivity structure is seldom based on complete and unequivocal information. It is common practice to estimate the distribution of hydraulic properties based on limited *in situ* measurements, and based on a more or less complete understanding of litho-stratigraphic and structural frameworks of a groundwater system. In the case of interstitial flow, such practice may yield an adequate approximation. In the case of fracture flow, however, correspondence between the litho-stratigraphic framework and the hydraulic conductivity structure may be very poor or non-existent. Furthermore, the results of *in situ* measurements of hydraulic properties do not identify the origin of such properties. Is it a litho-stratigraphic or structural framework controlled primary or secondary porosity or is it an *in situ* stress controlled conducting aperture of fractures? Such questions are seldom asked and almost never answered. They are, however, of paramount importance with regard to informed judgments involving the long-term stability of a groundwater system.

Adequacy of the estimates and guesses involving both the boundary condition and the hydraulic conductivity structure is commonly judged by comparing the computed distribution of hydraulic potentials with the actual values of such potentials as measured *in situ* at a number of observation stations. The desired correspondence between computed and observed values, is achieved through an iterative procedure, which usually involves arbitrary adjustments of the hydraulic conductivity structure. However, there is no guarantee that a combination of groundwater system's characteristics identified by this trial and error technique is unique. The same distribution of hydraulic potentials may be derived by assuming: a) various distributions of hydraulic properties; b) various boundary conditions; and c) various combinations of the hydraulic conductivity structure and the boundary conditions.

In summary, even this brief and casual critique of the commonly used mathematical models reveals that numerous opportunities are available by which a groundwater system can be misrepresented. Judgments concerning the long-term stability of a groundwater system can be grossly misleading and irrelevant if based on an inappropriate mathematical model. This is especially true if concern is focused on a groundwater system that operates in a fractured medium and is subjected to various volcano-tectonic stimulations. For such a system, the mathematical model must be constructed with due caution and must be based on a representative conceptual understanding of this system (i.e., accounting for a tectonic environment in which such a system operates). These types of mathematical models should be used for the purposes of developing judgments regarding suitability of a site to accommodate a geologic repository for high-level nuclear wastes.

2.3 CONCEPTUAL MODELS OF NATURAL GROUNDWATER SYSTEMS

In order for a mathematical model to be an adequate and reliable representation of a groundwater system, the model must have a rational base. As shown on Plate 2.3-1, this base is provided by a conceptual model, that may be regarded as an interface between reality and the description of it as provided by the mathematical model. The conceptual model represents totality of comprehension of a groundwater system.

For the purposes of these considerations, the term "conceptual model" may be defined as a set of thoughts or concepts that a) pertain to a system and b) are organized and essential for elucidating or describing the fundamental nature of this system and/or the circumstances under which it operates. The term "**system**" is not used here in the traditional geologic sense, but according to a wider thermodynamic usage to denote a body composed of interdependent parts interacting to form an evolutionary whole. Such an understanding has three major implications. First, geologic processes, including the flow of groundwater, seldom operate in isolation. This implies, that in reality, superficially different facets of a geologic system act in concert to govern a given process. Second, geologic processes characteristically involve transformations of energy forms. In traditionally applied hydrology, these transformations are regarded as unimportant and are largely ignored. It is not difficult, however, to demonstrate that a) strain of a solid phase can influence hydraulic conductivity and may be converted to hydraulic potential and vice versa; b) hydraulic conductivity may influence effective thermal conductivity of a solid phase; and c) heat may be converted to strain and hydraulic potential. Third, there exists a need for a unified description of a geologic system that is considered for the purposes of disposal of high-level nuclear wastes. Only by developing such a description can we provide a rational base for a comprehensive understanding of geologic processes operating in this system. From a system perspective, a groundwater field cannot be regarded as an independent entity but rather as a part of an overall geologic system. The often used term "characterization" indicates the recognition that we cannot expect to define all the parts and interactions of a system as large or as complex as a geologic system. The overall objective must be to gain an understanding of those processes that are pertinent to containment of radionuclides within a system and to a degree that is sufficient to rationalize the potential for waste-system interaction.

To be useful, the conceptual model of a groundwater system must be **organized** in accordance with the requirements of mathematical models. Specifically, the conceptual model should contain all the information required to construct a mathematical model in all aspects: a) establishment of governing equations that address conservation of mass and energy, state of the system; b) definition of boundary conditions that address mass and energy inputs into the system; c) description, in time and space, of properties that relate work and energy; and d) identification of relevant constitutive relationships. Also, the conceptual model must recognize and incorporate fundamental factors that have, are, and will continue to influence a groundwater system. For a system that is situated within a youthful volcano-tectonic terrain, there are two obvious factors that are intrinsic to a viable conceptual model. These are a) flux of terrestrial heat, giving rise to a possibility that a coupled heat-fluid flow is present and b) deforming nature of a fractured medium, giving rise to a possibility that the hydraulic and thermal conductivity structures are time-dependent.

As shown on Plates 2.3-2 and 2.3-3, the development of a conceptual model for a groundwater system is both a sequential and iterative process. The starting point in such a process is the development of a conceptual model for the overall geologic system. The groundwater system is only a part of the overall system and, therefore, cannot be treated in isolation from it. Similarly, the flow system in the vadose zone is only a part of the hosting groundwater system and, likewise, cannot be treated in isolation from it, nor can it be treated in isolation from the overall geologic system.

In developing a conceptual model for the overall geologic system, we are principally concerned with factors that are, or may be, important for a conceptual understanding of groundwater flow in this system. In the case of a groundwater system that is situated within a youthful volcano-tectonic terrain, these factors are thermal energy and strain energy. Definition of the conceptual model, with emphasis on both of these factors, is largely a matter of interpretation of results of various geologic and geophysical measurements and observations, including a) gravity measurements; b) measurements of propagation velocity of seismic waves; c) measurements of intensity of flux of terrestrial heat; d) measurements of *in situ* strain and rates of straining; e) observations pertaining to fault movement and other forms of deformation of the ground surface; and f) observations concerning seismic, volcanic, and hydrothermal activities.

The development of a conceptual model for a groundwater system is also an iterative process. The first step in such a process is the definition of characteristics of this system based on measurements and observations made *in situ*. Examples of such characteristics are a) position and configuration of the water table; b) spatial distribution of hydraulic potentials; c) temporal changes in hydraulic potentials; d) spatial and temporal variability of temperature; e) spatial and temporal variability of groundwater chemistry; and f) spatial and temporal variability of *in situ* stress.

The second and conceptually most important step is the development of an understanding of phenomenology involved in producing a given characteristic of a groundwater system. In seeking such an understanding, however, we must be aware that similarly appearing characteristics may be produced by different processes, each with distinct conceptual implications. It is important, therefore, to a) first identify a full range of conceptual alternatives that, in terms of the conceptual understanding of the overall geologic system, are permissible and then to b) select and justify the correct one. Usually, such a selection and justification requires an extension of the inquiry beyond a characteristic in question, and a specific enlargement of the data base. In this process, however, we must be aware of differences between fluctuating appearances and a knowledge that is essential and substantial, and between plausible interpretations and a knowledge that is certain. To say about a given characteristic that it is so and so, may indeed be saying merely that it is of such and such quantity or quality or in such and such a place or condition, naming just its changeable and conceptually irrelevant features. Or it may be saying what it is, naming its true and essential nature. To say, for example, about the water table, it is deep, it is flat here but steep there, may be giving it accidential qualities at the moment. To say, for example, of the water table, it is an integrated expression of the boundary conditions and the hydraulic conductivity structure, and that it changes as these factors change, is to express the one essential and permanent thing about it, which is its substance. Also, we must make sure that the first or basic conceptual proposition is true and comprehensive. One who starts with the conviction that the hydraulic conductivity structure is independent of time and reasons therefrom that the water table constitutes a permanent feature of the system and, consequently, any body of perched water represents solely a retardation of infiltrating water directly from atmospheric precipitation, has the forms of his syllogism correct, but the value of it to him or anyone else may be nil. In an active tectonic environment, for example, his basic conceptual proposition, which is the time-independence of the hydraulic conductivity structure, is open to too much doubt and the conclusions drawn from it may, therefore, be worthless if not downright harmful. In constructing a conceptual model, as in any deductive reasoning, the danger is that one may build such a model on a general principle that either does not cover the case or is itself unsound.

In ordinary applications, hydrologists dealing with the problem of constructing a conceptual model seldom, if ever, have at their disposal a data base that adequately addresses a range of conceivable conceptual alternatives that may be pertinent to a given circumstance. Also, these hydrologists seldom, if ever, have a need for addressing the long-term behavior of a groundwater system. The circumstances are different, however, if one is constructing a conceptual model for the purposes of developing a nuclear waste disposal system. In this situation, the process of defining the groundwater system characteristics, and their conceptual implications, must involve purposeful experimentations that are designed to obtain specific data required for unequivocal interpretations. The conceptual model for a groundwater system must be the result of conscious sorting out of the conceptual possibilities using actual data. In this process, there is little room for hydrologic beliefs, dogmas, and weakly supported conventions. There is also little room for mathematical and numerical conveniences that are not supported by facts and common sense assessments of a given circumstance. There is a lot of room, however, for a fresh look at the existing data base, particularly, if such a data base happens to be of extraordinary proportions.

In the case of the Yucca Mountain groundwater system, definition of a valid conceptual model is clearly a matter of the highest priority and must not be deferred until later stages of the site characterization process. As shown on Plate 2.3-4, the validated conceptual model constitutes a foundation for all activities leading to the demonstration of compliance of a nuclear waste disposal system with requirements set forth in Federal regulations. These activities include a) construction of mathematical models; b) definition of anticipated processes and events; c) establishment of regulatory compliance strategies and performance allocations; and d) definition of data and information needs. **Baselining such activities to a conceptual model that either does not cover an actual case or is built upon inappropriate principles invites a situation whereby, after six or seven years, a lot of money and time have been spent, a lot of credibility has been exhausted, but nothing has been accomplished in return.**

In summary, the conceptual model for a groundwater system occupies a very special position in the process of searching for geologic environments where reasonably safe and socially responsible disposal of high-level nuclear wastes may be achieved. On the following pages, therefore, the conceptual model for the Yucca Mountain groundwater system will receive a lot of greatly deserved attention.

The remainder of this report has been broadly sub-divided into three parts. The first part, Section 3.0, is concerned with a conceptual understanding of the tectonic environment of the southern Great Basin, and with the conceptual model for the related groundwater system. The latter is considered as an interacting and interdependent subsystem of the former. The Hegelien synthesis, which in this case is the conceptual model of a coupled heat-fluid groundwater system in a deforming fractured medium, is arrived at utilizing dialectic reasoning. This synthesis is then used to identify a number of diagnostic characteristics of such a flow system.

The second part, Section 4.0, is concerned with testing a validity of the proposed conceptual model by subjecting it to the "diagnosis-prognosis" test (Van Bemmelen, 1961; 1972). In this process, the existing data base from the Death Valley groundwater system is used. A number of *a priori* defined conceptual expectations is confronted with the actual data.

The third part, Section 5.0, presents overall conclusions and recommends a number of field investigations to be conducted in the immediate future. The recommended investigations were designed to obtain data that are judged to be required to validate the proposed conceptual understanding of the Yucca Mountain groundwater system.