Technical Changes that would Contribute to Success in the Civilian Radioactive Waste Management Program

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ABSTRACT

This paper briefly reviews the history of the United States program for high-level waste disposal. It then describes the current DOE strategy for licensing and safety for a repository at Yucca Mountain, Nevada. Changes that have occurred since the origin of the program and since publication of the Site Characterization Plan are reviewed. These include changes in external circumstances, changes in technology and new understanding of Yucca Mountain. An alternative approach is then described, based on four key concepts: a simple safety case, reversibility, demonstrability, and decompling operation of a repository from the operation of reactors.

A simple safety case begins with design goals that exceed the regulations and that are met redundantly. A simple safety case for Yucca Mountain is based on containment, meaning that radionuclides in the waste would be physically prevented from dissolving and migrating for hundreds of thousands of years.

Reversibility must be feasible and believable. The dryness of an unsaturated tuff repository enhances reversibility. Design options that increase the believability include designing for extended retrievability, drift emplacement, and surface storage capacity sufficient for the entire repository.

Demonstrability is enhanced by an experimental approach either by approaching full-operation in increments, or by experimental emplacement of an entire repository capacity. Both approaches recognize that assurance for 10,000 years cannot be based on 10 years or less of data.

In order to carry out any of these concepts, it is necessary to decouple repository operation from reactor operation. This can be done by means of an MRS

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facility without time or capacity constraints, or it can be done with at-reactor dry storage or multi-purpose storage casts.

The current U.S. safety strategy for developing a geologic repository for high-level radioactive waste depends on the properties of the site to control any escaped radioactivity to within defined limits for at least 10,000 years. Because it is documented in the DOE Site Characterization Plan (SCP), it is referred to hereafter as the SCP strategy. This strategy—based on the concept of mitigation—requires exhaustive (and expensive) characterization of the repository site. This strategy is based on a fundamental assumption that meeting the NRC regulations will result in a safe repository.

A containment strategy, which depends on both natural and engineered barriers to prevent any water from contacting the waste for at least 10,000 years, would keep the radioactive material where it was placed. Because this strategy—based on the concept of prevention—would require less extensive site characterization, the cost likely would be less and the time frame shortened. More importantly, because the strategy is simple to understand, it would focus the program, be easier to manage, and lead to a more certain outcome. It has no assumption that meeting the NRC regulations would result in a safe repository.

1.0 INTRODUCTION

The intellectual basis of the current U.S. high-level waste (HLW)\(^2\) disposal program has been evolving for several decades. Prior to 1978 it was assumed that the waste form would be reprocessed waste in some insoluble matrix. President Carter's indefinite deferral of reprocessing followed by the Interagency Review Group's determination that spent fuel could be safely disposed led to the current once-through fuel cycle. The 1980 Environmental Impact Statement (EIS) for commercial high-level waste selected geologic disposal as the preferred waste management technique. This was legally codified by the Waste Management Policy Act (WMPA) of 1982.

The Nuclear Regulatory Commission (NRC) regulations governing HLW disposal were issued in final form in 1983. Although the Environmental Protection

\(^2\)Where HLW is used in this paper, a general definition that includes spent reactor fuel as well as reprocessing waste is intended.
Agency (EPA) standard was not issued until 1985, its preparation had begun in 1976. Thus, by 1983, the present statutory and regulatory framework for the U.S. HLW program was in place.

The action by Congress in the Waste Management Policy Amendments Act (WMPAA) of 1987 was technically significant in that the one site selected for characterization was a site in unsaturated tuff, whereas the assumed disposal media through much of the development of the program and regulations had been salt or saturated granite or basalt. A Site Characterization Plan (SCP) had been in development for all sites as early as 1983, based on bottom-up, meet-the-regulations planning coupled with a bureaucratic desire to minimize rather than accentuate differences among the considered sites. Thus the 1988 SCP for Yucca Mountain (DOE, 1988) had been heavily influenced by the need to meet a generic standard developed for saturated sites, plus compromising among many sites for common programmatic ground. Though the plans and designs in the Yucca Mountain SCP reflect the uniqueness of the site, they have not been optimized for the site.

The net result is that much of the current program is ripe for reexamination and rethinking. Some assumptions have been unchallenged for more than a decade. Much new technical information has been obtained, new analytical techniques developed, and new sociopolitical, economic, regulatory, and institutional contexts have developed. This paper gives a re-examination for the technical issues.

2.0 THE CURRENT STRATEGY

Technical issues affect both the licensing and safety strategies for a repository at Yucca Mountain. The current licensing strategy is essentially a one-shot strategy, in which the application for a license is made assuming that, if granted, DOE will construct and operate a 70,000 metric ton repository. Retrievability is required during a period of about 25 years, during which a performance confirmation program will be maintained.

The safety strategy implicit in DOE's 1988 Site Characterization Plan (SCP) for Yucca Mountain is based on the assumption that compliance with the Nuclear Regulatory Commission's (NRC) regulation will result in a safe repository. Thus the safety strategy embedded in 10 CFR 60 is the underlying safety strategy of the SCP.
The NRC regulation sets four performance objectives. The overall system performance objective is to meet the EPA cumulative release limits. In meeting the overall system performance objective, the SCP strategy is that (1) releases from the engineered barrier system (EBS) will be limited to levels specified in the EBS performance objectives, and (2) the released material can be kept to below EPA limits by low water flux and high sorption in the matrix of the unsaturated Calico Hills formation below the repository. The ground water travel-time performance objective is also met in the unsaturated Calico Hills formation. The EBS sub-system performance objectives are met by a combination of site and engineered features that include quantitative goals for low water flux through the repository, benign water chemistry, corrosion and mass transfer resistance of the containers, and low solubility of the waste.

The top-level safety argument is that execution of plans in the SCP would assure meeting the regulations, and that the repository would therefore be safe.

3.0 CHANGES SINCE THE CURRENT STRATEGY WAS SELECTED

The current strategy described above is the documented official DOE SCP strategy, not the various suggested concepts that have been described in evolving form at recent public meetings. These potential revisions have been driven at least in part by changes that have taken place since the current strategy was selected. There are a very large number of such changes, and only a few have been selected for discussion in this section. The selection criterion was to emphasize changes that might invalidate the current strategy, or at least indicate a need for revision. These changes can be grouped as changes in circumstances, changes in technology, and new understanding of Yucca Mountain.

3.1 Changes in Circumstances

There have been numerous changes in the circumstances affecting nuclear waste disposal in the past 20 years. Nuclear power is not as widespread as projected. Reprocessing in the U.S. has been replaced by direct disposal of spent nuclear fuel. Intermediate storage has been established in all major nuclear countries except the U.S. Because of the lack of progress toward a monitored retrievable storage (MRS)
facility, some reactors are faced with a possible shut-down due to the lack of space in their spent fuel pools. Many other changes have occurred; those discussed below were selected because of their impact on the current safety strategy and potential new strategies.

### 4.1.1 Average age of fuel.

In 1978, the design basis for a repository was spent fuel five years out-of-core (YOC) with a 1994 repository start date. By 1983, the design basis was 10 YOC fuel and a 1998 repository. The design-basis spent-fuel age remained 10 YOC through publication of the SCP in 1988, although the repository slipped to 2003, and a 1989 reassessment by Secretary Watkins when the repository slipped to 2010. In 1990, a technical reassessment was undertaken that determined, for a 2010 repository start date, the average age of spent fuel at the time of emplacement would be 29 YOC.

Using a 30 YOC assumption, calculations of the effect of heat on repository response began to show different results than earlier. Because the heat output of spent fuel packages is dominated at early times by radionuclides with 30 year or less half-lives, the SCP design package drops from 3 kW at 10 YOC to 2 kW (33%) at 26 years and 1 (66%) kW at 75 years. By 200 years it has dropped 87%, but declines very slowly thereafter.

Whereas the SCP design (using 10 YOC fuel at an emplacement density of 57 kW/acre) produced rock temperatures above boiling for up to 1000 years, 30 YOC fuel at 57 kW/acre will maintain temperatures above boiling for nearly 4000 years. The SCP physical layout with 30 year old fuel produces about 36 kW/acre—a distribution calculated to produce conditions below the boiling point of water at all times (Buscheck and Nitao, 1993). This change—from boiling for 1000 years to either no boiling or boiling for many thousands of years—produces significant effects in the projected performance of a repository.

### 4.1.2 Dry storage at reactors

The question of storage of spent fuel outside of reactor pools was not an issue prior to President Carter's indefinite moratorium on reprocessing in 1978. With passage of the WMPA of 1982, it was assumed that spent fuel would go directly to
the repository, with a possible staging at an MRS. By 1989, when the repository date had slipped to the year 2010 and the DOE had made no progress in siting an MRS, interest in dry storage at reactors accelerated.

Dry storage tests funded in part by DOE have shown the feasibility of several designs for dry spent fuel storage outside of reactor pools. Spent fuel is in licensed dry storage in the U.S., with about 340 MTHM at three reactor sites as of 1991 (Schneider, Mitchell, and Johnson, 1992). Canada and the U.K. have also implemented dry storage on an industrial scale. The NRC has stated that such designs should be safe up to 100 years (Nuclear Regulatory Commission, 1990).

Dry storage at reactors has been suggested as a feasible alternative to an MRS facility. However, for some designs it is necessary to maintain access to the reactor pool to ship off-site (see Sec. 5.4).

4.2 Changes in Technology

Progress has continued in the many technical disciplines necessary for successful completion of a repository project. Only a few items are singled out for discussion here, including an improved ability to model the unsaturated zone, understanding of the role of episodic fracture flow in unsaturated rocks, and the development of fracture tough ceramics.

4.2.1 Improved ability to model unsaturated zone

Over the last 15 years, there has been a virtual revolution in computing. Not only do main frame computers have greater speed, larger memories, and parallel processing—making possible the solution of problems earlier considered too formidable for numerical solution—but also the advent and development of the personal computer has placed decade-old main frame capability on everyone's desk. In this environment, the ability to do repeated parametric variations for difficult problems has made sensitivity analysis far more feasible. This is particularly important because the purpose of the modeling is heuristic, not a deterministic prediction of exact repository behavior.

For example, the development of the TOUGH code for evaluation of nonisothermal unsaturated flow in fractured porous rock (Preuss and Wang, 1985)
gave a capability for analysis that in itself was a major technical advance. Needs in the Yucca Mountain project led to the development of a vectorized and streamlined version called V-TOUGH that is 25 times faster (Nitao, 1990). This enables many problems to be run on a personal computer. The speed also allows larger and more complex problems, such as those for Yucca Mountain, to be run efficiently on a mainframe.

Computing tools are of little utility without correct conceptual models. In analysis of contaminant transport in the saturated zone, the water flux (quantity per unit time) that flows past waste is an important parameter. When the unsaturated zone at Yucca Mountain was selected as a repository horizon in 1982, the question of flux seemed natural and efforts were made to bound the value. Although it was known that water transport in the unsaturated zone occurs by a combination of vapor transport, water migration in the matrix, and fracture flow (Montazer and Wilson, 1984), attention focused on the upper limit of the mean annual downward flux of water in the matrix.

Although various analyses showed that the net flux of water could be several mm/year upward (as vapor), debate centered on whether a bounding limit to the downward flux was 1 or 8 mm/year. All water generated by the selected value was then assumed to contact waste in performance analyses. The evolution of understanding has led to a reduced assumed bounding flux in the rock matrix of about 0.5 to 1 mm/year (see, for example, Wilson, 1992). However, the assumption continues that all of this water contacts the waste packages. Two features bring such a model into question.

First, there may not be any downward flux of liquid water. Accumulating evidence points to a model in which gravitational and capillary forces are in balance. Gauthier (1993) concludes that the most probable flux is between 0 and 0.1 mm/year — "virtually a hydrostatic condition." The implication of such an equilibrium state is that the amount of water in the rock matrix at any point depends only on 1) the height of the point above the water table, 2) the measurable effective porosity of the rock at that point, and 3) the measurable drainage characteristic of the rock at that point. Were such a model to be accepted, the existence of an equilibrium state could be established by measuring the above three parameters.
Second, at any of the fluxes considered, it is not likely that water will flow from the rock matrix into the repository. Theoretical studies confirm what practical observation shows — namely that water does not flow from the rock matrix into cylindrical openings in unsaturated rock under the conditions likely at Yucca Mountain (Philip, Knight, and Waechter, 1989). If water is to flow into the repository openings, it must be through fractures (Wang, et al., 1993).

4.2.2 Role of episodic nonequilibrium fracture flow in unsaturated rocks

Initial modeling of unsaturated flow at Yucca Mountain used an equivalent continuum model, which assumes local capillary equilibrium between fractures and matrix (Klavetter and Peters, 1988). Under this assumption, significant amounts of mobile liquid water cannot remain in the fractures unless the matrix becomes nearly saturated. Nitao and Buscheck developed and applied methods for analyzing movement of a liquid front without this assumption (Nitao and Buscheck, 1989, 1991; Buscheck, Nitao, and Chesnut, 1991; Nitao, Buscheck, and Chesnut, 1992).

These analyses showed that episodic fracture flow was a definite possibility at Yucca Mountain. Although it might have little practical effect on safety, it would significantly affect the concepts underlying meeting the NRC's ground water travel time requirement (see 4.3.4 for further discussion). It also calls into question the assumptions in the total system analyses in which matrix flow through the underlying Calico Hills zeolitic tuff is the mechanism that limits radionuclide releases to less than those allowed by the EPA standard. More than any other, this series of papers has revealed flaws in the technical basis for the SCP strategy.

4.2.3 Fracture-tough ceramics

The purpose of containers in a repository is to prevent water from contacting the waste. In 1976, at the start of the present program, ceramic materials were generally regarded as brittle, thus subject to fracture, and therefore not feasible for container materials. Since that time, there has been a significant advance in understanding, development, and use of fracture-tough ceramic materials.

Ceramic materials are attractive for waste packages because some occur naturally as minerals [such as corundum (Al₂O₃) and rutile (TiO₂)] that are highly
stable in the Yucca Mountain environment. Metals are not stable in the Yucca Mountain environment, but they have excellent engineering properties for near-term (up to 100 years) requirements. With metals, what has to be shown is that they will resist corrosion for thousands of years — a very difficult task using 5 to 10 years of data. The ceramic materials can be shown to be geochemically stable for millions of years by analogy with natural materials. What has to be shown is that they will meet the short-term demands of fabrication, closure, sealing, handling, and retrieval. Fortunately these are standard engineering tests, if a suitable ceramic material can be found.

Virtually no work has been done in the U.S. on ceramic containers, other than feasibility studies. However, work has been done in Sweden on alumina (Al₂O₃) and titania (TiO₂). Alumina has been evaluated as hot isostatically pressed, high density materials for waste containers in the U.S. (Chang and Hoenig, 1990). Fracture toughened ceramics, such as zirconia-toughened alumina, are also possible (Wilfinger and Cannon, 1989).

Much better known fracture-tough materials are silicon nitride-silicon carbide composites and tungsten carbide. These materials have no geologic analogs to establish corrosion resistance, but understanding developed for such materials may be transferable to geologically stable ceramics. A more promising approach may be Si₃C whisker-reinforced alumina, which is used as a cutting-tool material for metal machining with better performance than tungsten carbide (Becher and Tiegs, 1987). With sufficiently low-volume percent of Si₃C whiskers, the material may behave similarly to alumina for chemical corrosion.

If one is serious about projecting container performance thousands of years into the future, then fracture-tough, geologically stable ceramics are now available to be considered for waste containers.

4.3 New Understanding of Yucca Mountain

Despite a widespread perception that no progress has been made at Yucca Mountain, numerous technical studies have continued, including monitoring of existing data stations, regional studies, surface-based investigations, and development of analytical tools. There has been a significant advance in the knowledge base in the
15 years that Yucca Mountain has been considered as a potential repository site. The Site Characterization Progress Reports issued every six months typically cite more than 100 reports that provide detailed information. Four specific areas are reviewed here: better understanding of the unsaturated zone hydrology, results from field work at G-Tunnel, understanding the importance of the role of heat at Yucca Mountain, and understanding the differences between unsaturated tuff and saturated sites that formed the basis for the present regulations.

4.3.1 Better understanding of the unsaturated zone hydrology

Sections 4.2.1 and 4.2.2 summarized advances in technology related to modeling the unsaturated zone at Yucca Mountain in general and the issue of episodic fracture flow in particular. This section addresses other aspects of Yucca Mountain hydrology, including the results of field work and recent analyses.

The issue of the present unsaturated liquid water flux was addressed in Sec. 4.2.1, and it was seen that the evidence available today is that the present flux is near-zero — an equilibrium state. However, much attention has been given to the issue of future increased flux driven by a change in climate. Two recent papers have evaluated this issue (Hevesi and Flint, 1993 and Flint, Flint and Hevesi, 1993).

The current estimate of average annual precipitation at Yucca Mountain is 170 mm, a very dry climate. Surface-based tests indicate evaporation exceeds infiltration at the top of Yucca Mountain, and that the mountain is drying out. Measured infiltration penetrates only a few meters, with modeling showing a limit of 7 m. In the modeling, increasing daily precipitation by a factor of 2.5 greater than presently observed resulted in an increase of water content to a maximum depth of 6.9 meters (Hevesi and Flint, 1993). A factor of 2.4 is the increase that has been suggested for infiltration under a future full glacial (pluvial) condition (Long and Childs, 1993).

Above 7 m, the rock is actually less than equilibrium saturation. Below that depth there is little evidence of infiltration, and at repository depths the saturation levels calculated with the equilibrium no-flow theory agree well with measurements. Calculations that vary infiltration at the surface of Yucca Mountain show that climatic fluctuations over the last 700,000 years have little effect on the very low fluxes
projected to occur below 250 meters (Flint, Flint, and Hevesi, 1993). They also show that the near surface is in a long term (3000 year) drying trend, which provides a place for short-term (< 25,000 years) increases in net infiltration. In calculating these results, infiltrations ranging from -0.2 to +0.12 mm/year were used. Numerical simulations from different times, analysts, and codes of the effect of the geothermal gradient on the balance between upward diffusive flux of water as vapor and downward liquid infiltration have yielded results showing an upward flux of between 0.03 to 0.045 mm/year (Pruess and Tsang, 1993, Ross, 1984, Buscheck and Nitao, 1992).

Low fluxes from the surface are of little benefit if the repository could flood from below. This issue was addressed by a National Academy Panel (National Research Council, 1992). They stated "The evidence cited here has convinced the panel that the ground-water level at the proposed Yucca Mountain repository site has not reached or exceeded the level of the proposed repository at any time during the last 100 ka." In reaching this conservative conclusion they cited work that indicates that the water level has not risen more than 60 meters above the present level for more than 11 million years.

This brief review of unsaturated zone hydrology at Yucca Mountain should not be taken to imply that there are not issues needing further work, nor that additional data are not needed. However, the unsaturated zone at Yucca Mountain was originally recommended by the U.S. Geological Survey because of its inherent dryness and the benefits that dryness could have for a repository (Roseboom, 1983). Work since that time has confirmed that the site is at least as dry as originally thought, and probably drier. There has also been a large increase in both observational and theoretical knowledge.

4.3.2 G-tunnel results

Theoretical calculations are of limited value without observational data for comparison. Fortunately, work was carried out for a few years in G-tunnel in Rainier Mesa at the Nevada Test Site (Ramirez et al, 1990). Much of our present understanding of repository-heat-driven hydrothermal flow in unsaturated fractured
tuff is based on observations made during those tests and associated modeling (Buscheck and Nitao, 1991).

A key point is that heat flow appeared to be conduction dominated, even with large fracture permeability relative to the matrix. Because the thermal properties of the rock vary by only about a factor of two, whereas the hydraulic properties vary by $10^{13}$, the predictability of repository response will not depend on rock heterogeneity if heat flow in the unsaturated zone is dominated by heat conduction. It is even possible that one could bound the thermal properties and not have to determine the hydraulic properties in great detail.

Non-equilibrium drainage was found to be important, leading to the understanding that condensate can shed around the heater rather than build-up above it. The observation of non-equilibrium drainage at G-tunnel led to the analyses of episodic fracture flow at a mountain-scale described in Sec. 4.2.2.

4.3.3 Importance of role of heat at Yucca Mountain

One of the significant characteristics of HLW is the large amount of radioactive decay heat it generates. That heat reduces exponentially with time, but for spent fuel at Yucca Mountain, the effect can last up to 100,000 years. For one design at Yucca Mountain, the heat from the emplaced waste declines to equal that from the earth's local heat flow in 30,000 years.

As pointed out in Sec. 4.1.1, this heat may be sufficient to keep the repository near-field above the boiling point of water for thousands of years. This heat can also mobilize near-field water that resides in the rock pores even if the temperature is kept below the boiling point. It can set up mountain-scale convection cells, and transport water vapor from the water table below the repository to above the repository, where it can condense and drain back to the repository. The surrounding rock can be hydrothermally altered. The thermo-hydrologic behavior of both the unsaturated zone and the saturated zone below the repository will be dominated by repository-heat-driven hydrothermal flow for tens of thousands of years at Yucca Mountain (Buscheck and Nitao, 1993).

The potentially deleterious effects of heat in high-level waste repositories have been known for decades. For salt repositories, the openings can flow closed during
the operational period. There is also limited brine migration toward a heat source. Of greatest long-term concern is the possible fracturing of the overlying rock seal as the rock is arched above a thermally expanded repository. None of these effects would be of any concern at a Yucca Mountain repository.

For granite repositories, the possible fracturing of an overlying rock seal is also considered, but the consequences are far less as water is expected to flow in a granite repository in any case. Of more concern has been the possible negative effects on montmorillonite backfill material around the waste canisters. Again, neither of these effects would be of concern at a Yucca Mountain repository.

In an unsaturated tuff repository, heat does not have to be viewed as a negative factor. In 1983, the Lawrence Livermore National Laboratory suggested the concept of constructive use of heat to keep the waste containers and surrounding rock dry (Ramsott, 1991b). The repository configuration described in the SCP keeps the waste temperature above boiling for up to 1000 years, even though no safety credit was taken for that feature.

As the date of repository operation was repeatedly delayed, it was initially feared that it would not be possible to keep repository temperatures above the boiling point of water, because the vertical boreholes were about as close together as feasible for safe operations and rock stability. However, it was recognized that drift emplacement would allow closer spacing, and analyses were made using aerial power loadings (APL) of 20 to 114 kW/acre for 30 year old waste (Buscheck and Nita, 1992). At 20 and 36 kW/acre, boiling was never achieved. At APL's of 57 and above, boiling was maintained for progressively longer times, persisting for 5000 years at 114 kW/acre. Furthermore, the peak wall-rock temperatures for drift emplacement are lower despite a longer persistence above boiling.

The Nuclear Waste Technical Review Board noted these phenomena in their Fifth Report (NWTRB, 1992) and strongly recommended that DOE undertake a comprehensive examination of alternative thermal loading strategies. The essence of the Board's concern was not that any particular strategy would fail to work, but rather that they varied profoundly in their potential effect on repository performance, and their potential effect on the entire repository system.
4.3.4 Differences between unsaturated tuff and saturated sites that formed the basis for present regulations

It was recognized very early that an unsaturated tuff repository at Yucca Mountain was different from the generic sites analyzed to form a basis for the EPA standard and the NRC regulations (Nuclear Regulatory Commission, 1983, p. 28; National Research Council, 1983). Subsequently an amendment for the unsaturated zone was promulgated, but too early to benefit from the significant body of data that has appeared to date. It was felt that issues could be resolved on a case by case basis.

One significant difference showed up for C-14. C-14 has the potential to form CO₂ gas and escape from containers that may be breached but not immersed in water. Other radionuclides that would exist in significant quantities beyond 100 years are not gaseous, and therefore require water to be released. The amounts of C-14 that would be released are in the picoREM range and of no practical concern for individual dose particularly when compared with the large reservoir of cosmogenic natural C-14. However, the C-14 issue was not resolved, and Congress in the Energy Policy Act of 1992 instructed the EPA to develop a site-specific standard for Yucca Mountain.

Another significant issue is the concept of pre-waste emplacement ground water travel time. In an unsaturated fractured site, episodic infiltration along fractures can move a very small amount of water very rapidly over great distances, including draining water away from a waste repository. In Sec. 4.2.2 we noted the potential role of episodic fracture flow at Yucca Mountain. Calculations have been reported that show travel times between the repository and the water table of 52 hours and 290 days for a 100 micrometer aperture fracture with and without a hydrostratigraphic unit that partially underlies the repository (Buscheck, Nitao, and Chesnut, 1991). If the water could drain that rapidly from the repository, it would not corrode containers or dissolve waste. Yet, such a condition, if confirmed to be the case, would technically violate the ground water travel time performance objective of 1000 years. That objective was developed for a saturated site concept.

5.0 AN ALTERNATIVE APPROACH

The NAS Rethinking Report (National Research Council, 1990) urged a more experimental, less prescriptive approach to establishing a safe repository. In
particular, it urged that computer calculations be regarded as heuristic rather than accurate descriptions of likely projections of repository behavior. The Nuclear Waste Technical Review Board (1993) has criticized the DOE program for its schedule-driven, non-integrated, and regulation-based nature. Other technical and non-technical groups have made similar observations, the essence of which is lack of confidence in the current approach.

In response to such criticism, approaches have been identified that would shift from a rigid, eclectic, schedule-driven, all-or-nothing program to an incremental, evolving, and experimental but integrated program. Four concepts are key to this shift: a simple safety case, reversibility, demonstrability, and decoupling operation of a repository from the operation of reactors. There are several potential strategies for implementing each of the concepts, a few of which are mutually exclusive, but most of which are compatible with group implementation.

This discussion is not inclusive of all new ideas within the program, nor does it even cover all reasons why a particular idea is attractive. It is an attempt to fit a selected set of concepts and ideas within a framework of an integrated program that would have a higher chance of success than the current eclectic strategy.

5.1 Simple Safety Case

There are approaches to safety that have a very simple underlying premise, are based on fundamental science, and can be expressed briefly in plain language. This is what is meant by a simple safety case. Simplicity facilitates understanding of a program both internally and externally. It allows management focus, making progress evident and accountability more certain. The NWTRB called for clarification "so that the reasons for deciding on the Yucca Mountain Site can be understood in layperson's language" (Nuclear Waste Technical Review Board, 1990).

The first step in a simple safety case is to establish design goals that exceed the regulations and that are met redundantly. One does not have to split hairs about the amount of exceedance, or parse the word redundant. The plan should transparently exceed the regulations, and do so with more than one barrier. If no radionuclides left the repository at any time, then any reasonable environmental standard could be met.
A simple safety case for a Yucca Mountain repository is based on containment, meaning that radionuclides in the waste would be physically prevented from dissolving and migrating for hundreds of thousands of years. There are three reasons why reasonable assurance of containment is demonstrable in a Yucca Mountain repository:

- Openings in unsaturated tuff at the repository level are dry at present. This means that no water could contact the waste to dissolve and transport radionuclides.
- If in the future, water should seep into these openings due to climate changes or mobilization by heat, then engineered barriers could protect the waste from these limited quantities of water. By use of ceramic materials that are analogous with geologic materials, the barriers can be projected to function for more than 100,000 years.
- A fundamental physical property (radioactive decay heat) could assure dryness of the containers and waste for 10,000 years.

5.1.1 Examples of safety cases

The SCP safety strategy for Yucca Mountain is not simple. The goal is to meet the NRC regulations and the EPA standard, which are lengthy and complex and have no direct and simple relation to health and safety. The primary barrier is the ability of the Calico Hills unit that underlies the repository to reduce and control the migration of radionuclides after they have escaped from the waste packages. This is a strategy based on mitigation, control, or remediation of an event rather than prevention of that event. This mitigation strategy requires understanding of the equilibrium and kinetic chemistry of radionuclide solubility and sorption, the effect of organic complexing and colloidal transport on radionuclide retardation, two-phase diffusion and dispersion in a fractured, porous, unsaturated, heterogeneous rock, and the possible effect of heat on all of the above. The dryness of the site at and above the repository is secondary, and containment is required for only 1000 years.

Fortunately there are simple, easily understood arguments that indicate a repository should be safe.
The classical simple safety case goes back to 1955 (National Research Council, 1957). Salt deposits were known to have existed for hundreds of millions of years; and if any water had contacted them, they would have dissolved. Therefore, if waste were in a deep salt deposit in a geologically stable area, then it should be isolated from water for millions more years. Without water to dissolve it, the waste will remain immobile. What must be shown is that openings into the salt required to emplace the waste can be resealed to prevent water inflow.

In the case of a granite repository, even relatively unfractured sites allow a small quantity of water to flow at a low velocity. Thus, the absence of water cannot be invoked. Countries with granite repositories have developed a strategy in which robust containers protect the waste from water for very long times—up to a million years. Here a key point is to show that the containers will last as long as needed.

The Swedish safety case is an instructive example (KBS, 1983). The safety argument is stated in slightly more than a page in a 58 page double-spaced summary document. Contrast this with the SCP overview that is 164 single-spaced pages and does not explicitly state the safety strategy in its 7 page section titled, “Top-Level Strategy for the Yucca Mountain Site” (DOE, 1988).

A condensation of the Swedish case is that the spent fuel is surrounded by multiple barriers that are designed to isolate the fuel completely from the environment over a very long period of time (for example, a million year container) and to retard and dilute the radionuclides that can eventually leach out over an even longer period of time. The final repository is not expected to affect man’s environment at all. Under very pessimistic assumptions, calculated doses are insignificant — on the order of a thousandth to a hundredth of natural background — and they do not arise until a very distant future. Compared to current radiological standards, the repository provides a very large margin of safety.

5.1.2 The containment safety case

In any form of environmental management, prevention is always easier than remediation or mitigation of effects. It is also conceptually simpler. For the disposal of high-level nuclear waste, one wants to prevent the escape of radionuclides, not attempt to control, remediate, or mitigate after they have escaped. If no radionuclides
left the repository, then any reasonable environmental standard could be met. This containment strategy is the basis of a simple safety case for Yucca Mountain.

At Yucca Mountain, there are three major reasons why reasonable assurance of containment could be demonstrated. The first is the inherent dryness of openings into the rock. The second is the intentionally designed use of radioactive decay heat to keep the waste, containers, and surrounding rock dry for thousands of years. The third is use of long-lived containers as in the granite programs.

These are multiple, though not fully independent, barriers. The dryness insures the container will not fail, although the container should be designed to operate in wet conditions. Designing the container to operate in wet conditions provides assurance against future loss of dryness, either from climatically driven flux changes or mobilization of water by heat.

Dryness of openings. In the case of unsaturated rocks such as Yucca Mountain tuff, the absence of water can be invoked. Although the rock contains about 10 volume percent of water, it does not flow into openings such as emplacement drifts or holes. Without liquid water, there can be no aqueous corrosion, dissolution, or transport. What must be shown is that the openings will remain dry in the future with respect to both changes in the natural hydrology and effects from introduced heat.

Material discussed in Secs. 4.2.1, 4.2.2, and 4.3.1 indicates that water will not flow into the repository openings under present conditions, and that under expected increased flux due to climate changes, the openings would remain dry. Using a flux value of 1 mm/year, which is higher than considered likely, it will take 1000 years to produce a meter of water. Yet at 10 volume percent, there is one meter of water in 10 meters of rock. Thus the closest 10 meters of rock above the repository contains water equal to 1000 years flow. The point here is that too much attention has been given to flow from the surface, and not enough to mobilization of water already in the rock. This subject is discussed in the following section, which discusses a means of assuring dryness.

Extended Dry heat management. The inherent dryness of openings in unsaturated rock at Yucca Mountain could be lost by natural means, such as a future climate change, or by mobilization of water by heat from the emplaced waste. Waste
in low heat-loading configurations (below-boiling emplacement) could mobilize water. That water might not leave the repository area, and might be available as liquid water for corrosion, dissolution, and transport. Such water could enter the drifts through fractures.³

Constructive use of radioactive decay heat could assure that water will not contact the waste containers for tens of thousands of years (Buscheck and Nitao, 1993). The heat that produces this effect is a fundamental property of matter, for which there are no predictive uncertainties. If waste that has aged at least one half-life of the short lived fission products (about 30 years) is placed at a high heat loading (about 100 kW/acre), then the waste, waste containers, and surrounding rock will be kept above the boiling point of water for nearly 10,000 years. During this time, liquid water is not available to corrode the containers or dissolve the waste. During the time above boiling, a large volume of rock is dried out, which could take up to 100,000 years to rewet.

The concept described in the preceding paragraph is called the Extended Dry heat management concept, to distinguish it from the SCP design concept whereby higher temperatures for a shorter time would lead to about 1000 years above boiling. It is an evolutionary development of the SCP design, based on the following new information: advances in understanding from the G-tunnel tests (Sec. 4.3.2), advances in understanding from repeated parametric calculations and extending the calculations to include the entire mountain instead of just the near-field (Secs. 4.2.1 and 4.3.3), accounting for the impact in age of spent fuel to be disposed (Sec. 4.1.1), and evaluating the thermal advantages of drift emplacement (Sec. 5.2.2). The primary advantage of the Extended Dry concept is that it produces longer times above boiling with lower peak temperatures than the SCP concept.

**Long-lived Containers.** Containers should be designed using materials for which there are natural analogs. Use of engineering materials without analogs requires extrapolation of short term data (10 years) to long times (ten thousand to a million years). Use of materials for which there are natural analogs allows

³ A significant number of technical people hold the view that restricting the repository to temperatures below 50°C would have advantages in licensing related to the closeness of that value to the 30°C ambient temperature. Choice between these concepts is either/or, and the sub-boiling concept is not reviewed here.
interpolation between short term data and millions of years. A fundamental part of the Swedish safety case is the survival of native copper in similar rock for millions of years. At Yucca Mountain, there are ceramic materials with geologic analogs (alumina, titania) that would be stable in that environment (see Sec. 4.2.3).

The SCP safety case uses extrapolation-based container materials, whereas the Containment safety case uses interpolation-based container materials. In the Yucca Mountain SCP safety case, containment is only invoked for the first 1000 years, and only as an intrinsic property of the containers, not as a property of the site's inherent dryness. The SCP limits would allow all radionuclides to dissolve after 100,000 years. The Containment strategy envisioned here would look to containment (no dissolution) to well beyond 100,000 years, based on ceramic materials.

Components of the containment barrier system. In addition to the three major elements of the containment barrier system discussed above, there are a number of others. All of these elements are available to the SCP safety strategy described in Sec. 3. Only the context and emphasis (priorities) are different.

The SCP recognizes either engineered or natural (site) barriers. In the containment barrier system, there are four sequential sub-systems; that is, water must breach the first before attacking the second, etc. Because the subsystems are sequential, the inventory is reduced by decay during the time each subsystem functions. Therefore, radionuclide decay is shown (in parentheses) under each. In order, the components of the containment barrier system are as follows (site elements are in italics):

1. Dry container subsystem
   - Natural dryness of the site
   - Diversion barriers and drains
   - Use of waste heat to keep containers dry
     (Radionuclide decay)

2. Dry waste subsystem
   - Limited quantity of water
   - Sacrificial and conditioning materials
   - Casks and containers
   - Restricted flow through openings in casks and containers
   - Pour canister or fuel cladding
   - Fillers and coatings
     (Radionuclide decay)
3. Insolubility subsystem
   Limited quantity of water
   Insolubility of waste form
   Insolubility of many radionuclides
   (Radionuclide decay)

4. Mitigation subsystem (main focus of SCP)
   Limited quantity of water
   Sorption
   Diffusion, dispersion, and filtering
   Low water velocity
   Distance
   (Radionuclide decay)

In the containment strategy, none of the elements used in the SCP strategy are foregone. Some (the mitigation subsystem) have a lower priority and therefore could be resolved with less effort than if they were central to the safety argument, as in the SCP case.

There are a number of key contrasts between the SCP strategy and a containment strategy:

- The SCP strategy focuses on mitigation of the effects of escaped radionuclides, which is demonstrated by computer codes with complex algorithms describing complex processes to predict annual migration of radionuclides over 10,000 years.
  - A containment strategy focuses on prevention of dissolution and release of radionuclides, which is demonstrated by showing the current and past dryness of the site, and the resistance of engineered barrier materials to penetration by water.

- The SCP strategy allocates site characterization priority to the Calico Hills tuff unit below the repository, because it assumes releases from the EBS.
  - The containment strategy allocates priority to the geologic units at and above the repository, because it is aimed at preventing liquid water contact with the waste.

- The SCP strategy divides the repository system into engineered and natural barriers, and places emphasis on the natural.
The Containment strategy divides the repository system into dry container, dry waste, insolubility, and mitigation barriers, and places emphasis on first two, which are a mixture of natural and engineered features.

The SCP is 6000 pages long and does not explicitly state in one place the fundamental strategy which provides safety. This is my summary of its strategy: Assume that water will contact the waste, dissolve it, and transport the radionuclides. Then place major emphasis on the hydrologic and geochemical properties of the Calico Hills unsaturated unit below the repository to control the migration of radionuclides to man's environment to levels below those allowed by the regulations. By meeting regulatory limits, the site is safe.

The containment strategy is simple and direct: Show that water will not contact the waste packages, and if it should, that the packages will keep water from contacting the waste—no radionuclides will be dissolved and transported.

The SCP strategy could be affected by changes in the EPA and NRC rules—A containment strategy would not.

5.2 Reversibility

An important benefit of geologic disposal compared with other HLW management concepts, such as space disposal, deep sea disposal, and very deep hole disposal, is reversibility. Reversibility offers an additional assurance of safety. If some flaw in the disposal strategy is discovered in the future, the entire process could be reversed. In order for the concept of reversibility to be useful, it must be demonstrably feasible and believable.

Reversibility is feasible for geologic disposal of waste material that is concentrated and has a relatively high value per unit volume, such as HLW. Rocks like unsaturated tuff offer a greater degree of reversibility than disposal in salt. Thus, reversibility is technically and economically feasible for high-level waste in unsaturated tuff.
Given an unsaturated tuff repository, there are design options that increase the believability of reversibility. These are extended retrievability, drift emplacement, and full-capacity surface storage at the Repository.

5.2.1 Extended retrievability

The purpose of extended retrievability is to provide an answer to the legitimate question: "I'll accept that things look OK now; what happens if things change in the future?" The SCP (mandated by the WMPA of 1982 and the NRC regulations) calls for maintaining retrievability for 25 to 50 years. We now know that certain peak temperatures may occur as late as 100 years, and that other phenomena that might impact very long-term safety may not occur until after 100 years.

Mined openings that are hundreds of years old are common, and tunnels dating to Biblical times are known (Willett, 1979). Unsaturated tuff is particularly suited to the design of openings that might last for hundreds of years. Thus, the ability to retrieve waste for hundreds of years is believable at Yucca Mountain.

5.2.2 Drift emplacement

The conceptual design in the 1988 Yucca Mountain SCP is based on emplacement of unshielded (intensely radioactive) waste containers in vertical boreholes. This is not a particularly difficult technology, and was demonstrated (including retrieval) in the early 1980's at the Spent Fuel Test-Climax at the Nevada Test Site. However, given the possibility of retrieval 50 years in the future, or even 200 years under extended retrievability, reversibility would be more believable if self-shielded casks were emplaced in the repository drifts. Drift emplacement also provides the option of emplacement on rail cars that could be left in place for a greatly simplified withdrawal.

Both normal and off-normal operations are much simpler with shielded material because of the greatly reduced radiation safety requirements. In addition, the self-shielded casks could easily be stored at the surface upon retrieval, unlike unshielded containers that would have to be kept in a hot cell or placed in storage casks.
A key feature of drift emplacement is that it facilitates heat management. As noted in Sec. 5.1.2, drift emplacement — all other parameters being equal — leads to lower peak temperatures in the wall rock than borehole emplacement. The lower temperatures enhance reversibility.

5.2.3 Full capacity surface storage at repository

In order to make retrievability believable, there has to be some place to put the waste. Dispersing it back to 100 decommissioned reactors all across the country is not believable. Nor is shipping it back to an MRS located 2000 miles away. If the repository had full-capacity surface storage, then retrieving the waste from the repository would not be inhibited by the question of where to put it pending final disposal.

5.3 Demonstrability

Demonstrability means the ability to demonstrate that the repository will be safe. Among technical specialists, a demonstration consisting of computer predictions bolstered by laboratory and field measurements might be convincing. However, in the legal, regulatory, and political environment that a repository must survive, demonstrations must be simpler and more physical. Evidence that complex models will not be persuasive is found in the hearings on the candidate low-level nuclear waste site at Martinsville, Illinois (Siting Commission, 1991) and the Nevada hearings (State of Nevada, 1992) on a water permit for site characterization at Yucca Mountain. The latter case is particularly instructive in that the permit was granted after rejecting the model predictions, but based on the monitoring program in the permit application.

If one assumes that a complex prediction using computer models to extrapolate 10 years of data to 10,000 years will not win acceptance, what alternatives exist? The present SCP program would seek a license for full operation of a 70,000 MT repository whose expected performance spans 10,000 years, based on less than 10 years of data. Two concepts would approach the demonstration of reasonable assurance for a license experimentally, the one in incremental steps, and the other
after a 100-200 year test. Another concept is to argue that use of natural analogs leads to interpolation, not extrapolation.

5.3.1 Incremental implementation

The concept of incremental implementation also has been termed phased or staged licensing, and means that a 70,000 MT repository would be approached in steps. While details vary, the concept includes initial operation with a very small amount of waste that would be followed at regular intervals with increasing amounts until the repository was full. Although this is physically similar to what could happen under present plans, or even the URS concept described below, the difference lies in the relation to the licensing process.

At present, DOE must file a license application for the entire repository. The first significant step would be a construction authorization for the entire repository, followed by a license to receive and possess (emplace) 70,000 MT of waste. The final stage would be a license amendment for permanent closure. Under incremental implementation, DOE might seek a license to construct the repository in stages and approach full loading in increments, with a review at each step. A presumed benefit is that it should be easier to license a small step than a large step.

There is no case history of what will constitute “reasonable expectation” (EPA) or “reasonable assurance” (NRC) of repository safety. Because a high-level waste repository is a first-of-a-kind facility, the definition of what constitutes “reasonable” will emerge from the licensing process. For this reason, it is imperative to start the formal licensing process as soon as feasible. We are not ready to load 70,000 MT, but we are ready to design tests with 100 MT. This is a more significant argument for an incremental approach — start sooner rather than emphasize small steps.

There is a natural staging of testing that must be followed, regardless of the licensing rules. First there is an initial period of data gathering in the field and laboratory followed by analysis. Development of techniques may be required. This stage is complete at Yucca Mountain. Second, there are prototype tests, followed by analysis. This stage was truncated by the cancellation of the G-tunnel tests at Rainier Mesa, but useful data were obtained (Ramirez et al, 1990). Then there would be a
small-scale in situ test with electrical heaters. This would be followed by additional small-scale tests to assure spanning the range of heterogeneity in the repository. Then there would be a scale-up, probably involving real waste in the 100 MT range. This would be followed by a pilot emplacement of about 1000 MT. At this point, expansion to a full-scale repository could likely occur. An issue that is debated in discussing an incremental approach is whether the 100 and 1000 MT tests would be after a license, or before—to gain supporting information for a license. The WM Policy Act of 1982 allows up to 10 MT of HLW or spent fuel for testing purposes, but no more.

Under conditions in the SCP design, it was expected that peak temperatures would occur in 20-40 years, and that a retrievability period that extended 50 years from initial emplacement would allow monitoring to beyond this peak. With 30 and 60 year old spent fuel and the designs now being considered, most of the temperature rise in the near field will occur by 100 years—94% for 30 yr and about 80% for 60 year (Buscheck and Nitao, 1993). Thus, retrievability and monitoring may need to be extended to beyond 100 years. Actual times to peak temperature range to more than 800 years.

Given these technical facts, it may be reasonable to plan for a period of performance confirmation between repository loading and the end of retrievability (final closure) as provided for in the NRC regulation 10 CFR 60. What is different about this concept from what is in the SCP and current NRC thinking is that it may not be possible to make a definitive prediction about the effect of waste emplacement until after decades of repository operation. A repository is different from a reactor in that the significant risk addressed in licensing a reactor begins at the start of operation, but the significant risk addressed in licensing a repository begins at closure. The step at which "reasonable assurance" of postclosure performance is necessary is the closure amendment, not the operating license.

5.3.2 Underground retrievable storage (URS)

The URS concept (Ramspott, 1991a) approaches the issue of demonstrating reasonable assurance by proposing 200 to 300 years of experimental storage of 70,000 MT of waste under a storage regulation. Only then, with a large amount of
data about the interaction of the waste and the surrounding rock, would a license be sought for a repository. There would be a heavy emphasis on assured retrievability for 300 years. Effort on 10,000 year issues would be in the context of a parallel site characterization effort for a repository. It would be made clear that the site would be converted to a repository when and if sufficient information to assure safety became available.

The rationale of the URS is to meet two conflicting goals of high level nuclear waste management—early isolation for immediate safety and assurance of future safety. The reason they are in conflict is that disposing of waste as fast as practicable may compromise future performance of a repository, whereas delay in disposal compromises immediate safety. All studies show that waste disposed underground is less hazardous now and in the immediate future than if it were sitting on the surface.

The Board on Radioactive Waste Management in their "Rethinking" report (National Research Council, 1990) stated that "A principal source of concern over the U.S. program is the uncertainty in estimating the risks from a radioactive waste repository." It points out that proof of safety in the conventional sense "cannot be available until we have experience with the behavior of an engineered repository system—precisely what we are trying to predict ahead of time". The URS concept directly addresses this latter issue by providing experience before licensing by designing the URS in a repository configuration. A URS facility combines the functions of surface monitored retrievable storage and the first stages of an underground repository.

Unsaturated sites such as Yucca Mountain are particularly attractive for URS because underground openings are dry and require no dewatering system. During the period of storage under a storage license, data could be obtained about the response of the system to introduction of the waste. These data could be used to determine whether the URS could be converted safely to a repository. Thus, a repository license would be based on up to 300 years of data rather than 10 to 20, as presently envisioned.

One of the most important features of an URS facility is that it does not foreclose any options for our descendants, while at the same time it offers a solution (conversion to a repository) that could be implemented.
5.3.3 Natural analogs

Demonstrating a long-term safety case requires the use of analogs. Computer extrapolations of short-term data need a reality check, and only two exist — analogs and fundamental science (sometimes called expert judgment). Analog are evidence of the containment of radioactivity or the performance of materials under conditions relevant to those expected at a repository. They can provide evidence of potential performance up to millions of years. Although analogs are data from past performance, if projected into the future they allow interpolation (prediction across a data gap) instead of extrapolation (prediction beyond the data).

Analog are sometimes narrowly defined as physical bodies similar to a repository, such as uranium/thorium deposits. However, they can include natural history and artifacts. Natural history analogs are evidence from the historical sciences (archaeology, anthropology, historical geology) about past climatic and hydrological conditions that might reasonably be extrapolated to the future. Artifacts are man-made materials that through exposure to natural conditions provide evidence of resistance to corrosion, dissolution, or phase changes.

Analog are already included in the SCP studies. However, they are merely a few among hundreds of studies. What we are talking about here is the explicit planning for use of analogs in the main safety case. An example is the use of geological analogs to ceramic materials for waste containers. This is comparable to the use by the Swedes of native copper in Swedish granites as an analog to their copper containers.

5.4 Decouple Repository Operation from Reactor Operation

The WMPA of 1982 set a deadline of January 1998 for start of receipt of waste at the repository. As this date has approached with little apparent progress, there has been increasing concern because many utilities made plans based on starting to ship waste shortly after that time. In 1989 DOE proposed that receipt of waste at an MRS would be equal in effect as far as the utilities were concerned. However, as of 1993 there has been no concrete progress on a site for an MRS.
There were a number of other deadlines in the WMPA of 1982, and DOE has attempted to meet them. As a result, critics have charged that the program is schedule driven, possibly at the expense of safety. An effective way to counter such criticism would be to totally decouple repository operation from reactor operation. Obviously an MRS facility without capacity limits would do this, but no MRS site appears to be available. Over the past few years several other concepts have emerged.

5.4.1 At-reactor dry storage

In a general sense, at-reactor dry storage means removing spent fuel from the reactor pool and storing it outside the reactor. Although such storage frees space in the reactor pool, it does not necessarily allow the utility to shut down the reactor pool, as some systems of dry storage require transfer back to the pool in order to ship off-site. Without dry storage, some utilities might have to shut-down a reactor because of lack of storage space in the reactor pool. Though not an optimum solution, at-reactor dry storage does somewhat decouple reactor operation from repository operation. The NRC has acknowledged that such storage could be safe for up to 100 years if necessary (Nuclear Regulatory Commission, 1990).

5.4.2 Multipurpose storage canister/casks

A more attractive option is a multipurpose storage canister for at-reactor dry storage followed by transportation. "Multi-purpose canisters would be sealed, metallic containers maintaining multiple spent fuel assemblies in a dry, inert environment and overpacked separately and uniquely for the various system elements of storage, transportation, and disposal." (Holloway, et al, 1993a) This canister, once loaded, does not have to be returned to the reactor pool for shipping off-site, and thus would allow a utility to close its reactor pool without removing all spent fuel from the site.

There are numerous designs and concepts, falling into two main categories — dual purpose or triple purpose. Dual purpose canister/casks would serve for both storage and shipping, whereas triple-purpose would serve for storage, shipping, and ultimate disposal. Among triple purpose concepts, there is distinction between a small element that would be overpacked separately for the functions of storage,
transportation, and disposal (the MPC, Holloway et al, 1993a), and a single large multipurpose unit (the MPU, Holloway et al, 1993b) that would fulfill all three functions.

These concepts achieve the goal of decoupling reactor operation from repository operation. They lack the economy of scale, uniformity, and control of an MRS. However, they can be deployed incrementally and already licensed systems are available. If adopted and specified by the DOE, some amount of uniformity and control could be regained.

6.0 CONCLUSIONS

Many changes have taken place since the SCP safety strategy was formulated; it needs to be revised or replaced. Four concepts would aid in the shift from a rigid, eclectic, schedule-driven, all-or-nothing program to an incremental, evolving, and experimental but integrated program. These are a simple safety case, reversibility, demonstrability, and decoupling operations of a repository from operation of reactors.

A simple safety case based on containment can be made for a repository at Yucca Mountain. This containment strategy is based on the dryness of openings at Yucca Mountain, Extended Dry heat management, and long-lived containers.

Reversibility is technically believable at Yucca Mountain because of extended retrievability and drift emplacement, if there is full-capacity surface storage at the repository. Because the rock is unsaturated, extended retrievability is technically feasible at Yucca Mountain.

Demonstrability could be improved at Yucca Mountain by planning for incremental progression toward operation and closure of a repository, possibly including a shift to underground retrievable storage (URS). Demonstrability can also be improved by using natural analogs.

Repository operation can be decoupled from reactor operation by use of an unconstrained MRS facility or at-reactor dry storage and multipurpose storage canister/casks.
REFERENCES


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