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ROLE OF FLEXIBLE DESIGN IN STAGED DEVELOPMENT OF REPOSITORIES FOR SPENT NUCLEAR FUEL AND HIGH-LEVEL WASTE

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At the early stages of a repository program an important decision is the selection of a system development strategy that will lead effectively and efficiently to a final operating system in the face of inevitable technical and institutional uncertainties about how the future will unfold. The approach to designing the repository can contribute to the flexibility required to allow a repository program to adapt to unforeseen developments. The evolution of the Yucca Mountain repository design from a large integrated facility optimized for a single reference development and operation scenario to a modular design that is more readily adaptable to a wide range of alternative futures is an example of both the importance of and an approach to designing flexibility into a repository system.

I. INTRODUCTION: ADAPTIVE STAGING

The Nuclear Energy Agency (NEA) reported in 2004 that the concept of staged development, or "adaptive staging" is attracting increasing attention internationally as a means of increasing the societal acceptability of waste management activities (Ref. 1) As described by NEA, "The key feature of these concepts is development by steps or stages that are reversible, within the limits of practicability. This is designed to provide reassurance that decisions can be reversed if experience shows them to have adverse or unwanted effects."

The management approach called "adaptive staging," was recommended in the 2003 report from the National Academies sponsored by the Department of Energy (*One Step at a Time: The Staged Development of Geologic Repositories for High-Level Radioactive Waste)* as "a promising means to develop geologic repositories for high-level waste such as the proposed repository at Yucca Mountain, Nevada"(Ref. 2). The NAS described adaptive staging as "a learn-as-you-go process that enables project managers to continuously reevaluate and adjust the program in response to new knowledge and stakeholder input" and defined two approaches to staging (Ref. 2): linear staging and adapted staging. According to the report, linear staging is "a single ,predetermined path to well-defined endpoint, with stages viewed as milestones." In contrast, adaptive staging is "a process that emphasizes deliberate continued learning and improvement and in which the ultimate path to success and the end points themselves are determined by knowledge and experience gathered along the way, rather than being predetermined at the outset."

The NAS stated adaptive staging is characterized by the simultaneous presence of the following attributes:

1. **Commitment to systematic learning**
2. **Flexibility**
3. **Reversibility**
4. **Transparency**
5. **Auditability**
6. **Integrity**
7. **Responsiveness**

Most of these characteristics deal with institutional features and processes in a waste management program, and are not considered further in this paper. Two – flexibility and reversibility – are also related to the physical design characteristics of the repository, as is suggested by the report's description of them:

- **Flexibility**. Project managers are able and willing to reevaluate earlier decisions and redesign or change course when new information warrants.
- **Reversibility**. Project managers are able to abandon an earlier path and reverse the course of action to a previous stage if new information warrants.

Clearly, the ability to redesign or change course, or even reverse it if desired, depends not only on the willingness of project managers to do so, but also on the cost and other impacts involved in making such changes. These can be strongly affected by the approach to the design of the repository system. This paper describes how flexibility was used as a key design objective in the evolution of the design for the surface and underground facilities of the proposed Yucca Mountain repository.

II. FLEXIBLE DECISION-MAKING AND IMPLICATIONS FOR REPOSITORY DESIGN

The experiences with the Waste Isolation Pilot Plant (WIPP) and Yucca Mountain underlined the importance of flexible decision-making, including the ability to stop and make significant design changes and development of designs that facilitate flexible responses to changing conditions. Key contingencies that require flexible planning and decision-making (during planning or after a repository has received an initial license) that have been identified include:

- Potential need for changes in design (e.g. waste package) or operating mode (e.g. thermal loading),
- Need for changes in the waste receipt and/or emplacement rate,
- Constrained and/or uncertain funding,
- Changes in national waste management policy,
- Opportunities to exploit design improvements (e.g. multipurpose canisters that could be used for transportation, storage, and disposal; or improved waste packages), and
- Uncertainties about the amounts, types, and timing of waste forms requiring storage and disposal (e.g. as a result of future fuel cycle changes).

The approach to the design of the repository's surface and underground facilities will significantly affect the ability of any decision-making process to adapt to changing circumstances such as those identified above. The evolution of the design of the Yucca Mountain repository provides useful insights into how considerations of flexibility can be incorporated into a repository design process.

Whenever it is decided to proceed with a repository, many uncertainties affecting the future development and operation of the repository will likely not be resolved at the time decisions about the design for a license will have to be made. Some uncertainties may remain even at the time a repository starts operating. Therefore, attempting to develop a design that is "optimized" for a particular postulated reference operating scenario might produce a design that does not perform as well as expected if actual conditions deviate significantly from the reference scenario.

An example of this potential risk can be found in the reference design concept used for the Yucca Mountain Viability Assessment in 1998 (Ref. 3). That design included one large integrated waste handling surface facility designed primarily for receiving and packaging 3000 tons a year of bare spent nuclear fuel (SNF) and an underground repository with a single large emplacement area for the 70,000 MTHM inventory that required construction of large underground infrastructure (i.e., perimeter drift and full ventilation system) before any emplacement operations could begin. This system design assumed direct disposal of all commercial SNF, with no reprocessing—consistent with general expectations at the time—and was optimized for that scenario, offering little flexibility to accommodate future changes of mission. This non-modular design concept tended to minimize the undiscounted total system lifecycle cost if the reference program scenario, which included an assumption of unconstrained funding, materialized. However, constrained funding or substantial changes in the expected operating scenario that necessitated design changes would lead to delays in the start of operations, increased overall costs, and adverse policy impacts. To reduce this risk, flexibility to function at some level no matter how uncertainties are resolved is an important criterion in evaluating both surface and subsurface designs for a repository.

Alternative development scenarios that involved staged construction and operation of the Yucca Mountain repository in modular fashion to reduce the costs required to achieve initial operation were considered beginning in the 1990s (Refs. 4, 5). These were considered largely as a means of providing flexibility to proceed despite annual funding constraints that would not support the timely construction of large, multi-purpose surface facilities, but they also offered broader benefits in terms of flexibility to adapt to a range of other contingencies. DOE also sponsored a study of staged development by the NAS, leading to the *One Step at a Time* report discussed above (Ref 2).

DOE explicitly used flexibility as a key design evaluation criterion in the evolution of the repository from the 1998 reference design. Flexibility was an important consideration in the License Application Design Selection (LADS) study that led to selection of the current reference underground design (Ref 6). The approach to evaluating "flexibility" used in the LADS process was to identify a set of contingencies (e.g. the need to dispose of more than the nominal 70,000 MTHM statutory limit) and to assess how each design option would perform when faced with these contingencies. "Flexibility" was used as a measure of the degree to which a design would be capable of remaining viable and/or able to change in the face of future regulatory or other changes.

Possible changes considered during the LADS process were:

- Increased disposal capacity beyond the 70,000 MTHM initial limit authorized in the Nuclear Waste Policy Act,
- Longer preclosure period (100 or 300 years following emplacement),
- Shorter preclosure period (10 years following end of emplacement),
- Receipt of 5-year-old SNF,
- Late design changes that were assumed to occur just prior to the start of construction (e.g., change from high to low areal mass loading, or vice versa, and adding or removing thermal blending of fuel assemblies to achieve more uniform waste package heat loads), and
- Unanticipated natural features or findings (volcanism, seismicity, water table rise, flooding)

The LADS process led to a lower temperature design with thermally-decoupled emplacement drifts, providing substantially greater thermal flexibility (i.e. ability to operate below or above boiling) than the high-temperature reference design that it replaced.

At about the same time as the LADS study, DOE undertook a series of studies that examined a modular approach supporting staged development of the repository. The objectives of the studies were to address ways to reduce peak construction costs (an issue of increasing concern because of past and anticipated annual funding constraints), and to investigate changes to system architecture, system operations, system requirements, or program implementation that would:

- enhance confidence in meeting target schedules,
- provide flexibility in accommodating different waste acceptance rates,
- allow for the implementation of a small, inexpensive, initial acceptance and disposal capability,
- support operation over a range of thermal modes, and
- separate receipt rates from emplacement rates.

The May 2001 CRWMS Modular Design/ Construction and Operation Options Report (Ref. 7), which updated and expanded the earlier studies, considered two basic approaches to increasing design and operations flexibility:

- a modular dry waste handling building with expandable surface storage, and
- modular subsurface construction.

Various design and operations scenarios were investigated, including constrained funding, early receipt, and flexible subsurface design (to allow lower temperature operating modes). The study concluded that a modular design and implementation approach would address key programmatic and technical uncertainties facing the program by:

- providing a significant reduction in peak construction costs, allowing earlier achievement of initial operating capability,
- enhancing flexibility for
  - fuel blending for thermal management,
  - accommodating various thermal strategies,
  - accommodating different utility fuel selections for delivery, and
  - accommodating different fuel characteristics (burnup and enrichment) due to reactor license extensions,
- increasing confidence in meeting the program's commitments, including opportunities for early performance, and
- significantly reducing the sensitivity of the program to uncertainties.

Subsequent value engineering studies led to a flexible modular underground design with a number of smaller emplacement zones instead of the single large zone assumed in the LADS study. The resulting design (Fig. 1)

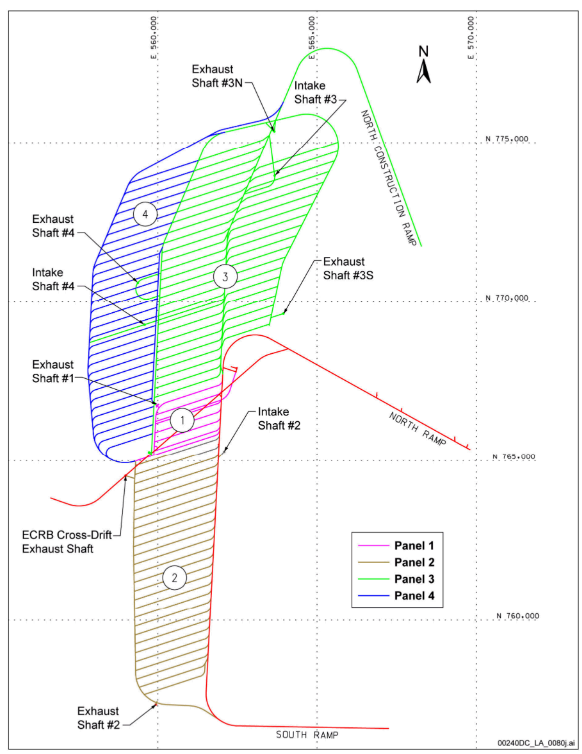


Fig. 1. Zoned underground emplacement design (Ref. 8)

involves four smaller independent waste emplacement panels, reducing the front-end investment required before emplacement begins and allowing for changes in the design and layout, if required, during the operational period (Ref. 8, Figure 2-3, Vol 1). For example, this approach could accommodate a change to disposal of different waste forms in separate zones, if that proved to be desirable.

More recently, the final revisions to the Yucca Mountain repository surface facility design to be incorporated in the license application involved use of a comparison of alternatives in which "flexibility in responding to changing circumstances" was a key criterion (Ref. 9). Flexibility was defined in terms of ability to adapt to specific postulated contingencies, including constrained funding, uncertainties in the waste stream (types, timing, quantities), future changes in design or operations, and phased development. Consistent with the earlier modular studies, flexibility was also assumed to involve use of modular facilities.

The result was a surface design in which various functions (e.g. disposal packaging, receipt of bare fuel assemblies, receipt of canistered waste) were distributed among a suite of modules with different capabilities that could be added at different times as needed to accommodate future developments. The key modules of the surface facilities are:

- Initial Handling Facility: Receives high-level radioactive waste and naval spent nuclear fuel canisters, loads canisters into waste packages, and closes the waste packages.

- Canister Receipt and Closure Facilities: Receive DOE disposable canisters and Transportation-Aging-Disposal (TAD) canisters, load canisters into waste packages, and close waste packages.

- Receipt Facility: Transfers TAD and dual-purpose canisters, as appropriate, to the Wet Handling Facility, a Canister Receipt and Closure Facility, or the Aging Facility.

- Wet Handling Facility: Handles uncanistered commercial spent nuclear fuel and opens and unloads dual-purpose canisters; its essential purpose is loading TAD canisters.

- Aging Facility: Provides two aging pads and associated equipment to age commercial spent nuclear fuel as necessary to meet waste package thermal limits

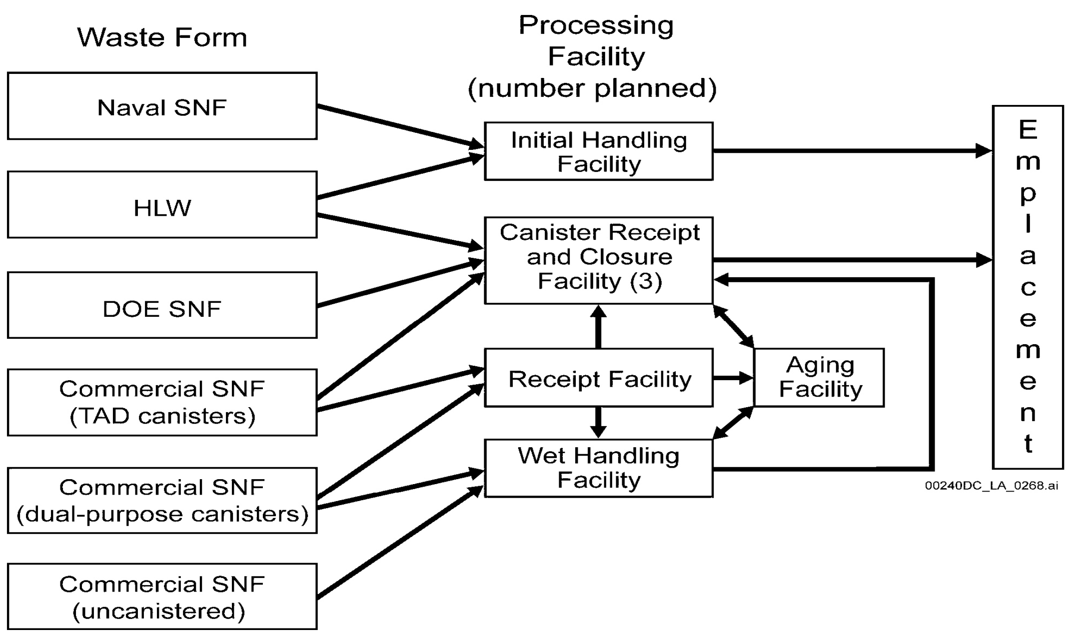
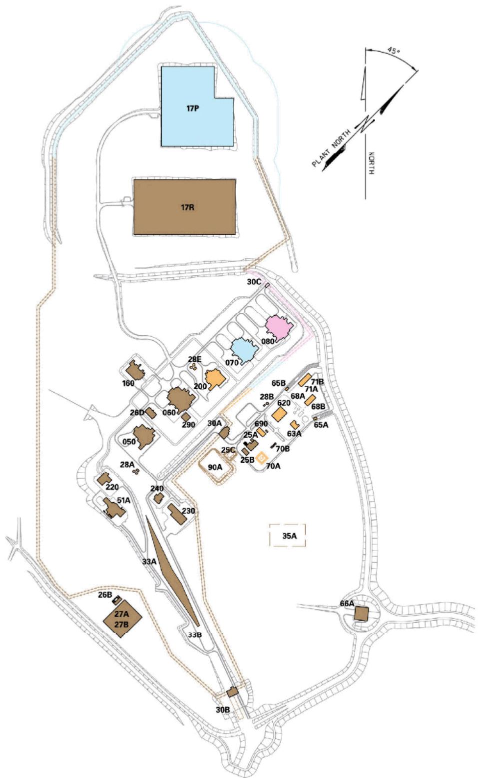


Fig. 2 Modular surface facilities provide multiple options for handling different waste forms (Ref. 8, Figure 1-8, Vol. 1)

Fig. 2 shows the multiple potential flow paths for different waste forms through the modules of the processing facility to either an aging pad or emplacement in the repository (Ref. 8, Figure 1-8, Vol. 1).

These modules offer flexibility to adjust to changing circumstances or policies, since they can be combined as needed to meet any desired sequence of receipt, aging, and disposal, and the design of later modules can be modified prior to construction to accommodate different waste streams, subject to revised safety analyses and approval by the NRC (Ref. 10).

This modular design accommodates a phased development process easily. The repository development plan presented in the Yucca Mountain license application involves construction of the surface in phases, shown in Fig. 3 below (Ref. 8).



LEGEND			
Initial Operating Capability			
Phase 1			
050	Wet Handling Facility	26D	Emergency Diesel Generator Facility
060	Canister Receipt and Closure Facility 1	27A	Switchyard (138kV)
51A	Initial Handling Facility	27B	13.8kV Switchgear Facility
17R	Aging Pad R	28A	Fire Water Facility
160	Low-Level Waste Facility	28B	Fire Water Facility
220	Heavy Equipment Maintenance Facility	30A	Central Security Station
230	Warehouse and Non-Nuclear Receipt Facility	30B	Cask Receipt Security Station
240	Central Control Center Facility	33A	Rail Car Buffer Area
25A	Utility Facility	33B	Truck Buffer Area
25B	Cooling Tower	35A	Septic Tank and Leach Field
25C	Evaporation Pond	66A	Helicopter Pad
26B	Standby Diesel Generator Facility	290	Aging Overpack Staging Facility
90A	Storm Water Retention Pond		
Full Operating Capability			
Phase 2			
200	Receipt Facility	68B	Materials/Yard Storage
28E	Fire Water Facility	690	Vehicle Maintenance and Motor Pool
620	Administration Facility	70A	Diesel Fuel Oil Storage
63A	Fire, Rescue and Medical Facility	70B	Fueling Stations
65A	Administration Security Station	71A	Craft Shops
65B	Administration Security Station	71B	Equipment/Yard Storage
60A	Warehouse/Central Receiving		
Phase 3			
070	Canister Receipt and Closure Facility 2	17P	Aging Pad P
Phase 4			
080	Canister Receipt and Closure Facility 3	30C	North Perimeter Security Station

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Fig. 3. Phased development of repository surface facilities (Ref. 8).

III. OBSERVATIONS ABOUT FLEXIBLE DESIGN

Flexibility to adapt to changing circumstances is an important feature for repository designs intended for staged development processes. The need for adaptability in the face of constrained funding and other programmatic uncertainties led to evolution of the Yucca Mountain design from expensive and relatively inflexible large surface and subsurface facilities to the highly modular design concept in the 2008 License Application (Ref. 8). The ability to begin operation as soon as initial modules are constructed allows demonstrated progress in disposal even under constrained funding**,** a situation that might be faced by other repository programs. At the same time, the modular design enhances the opportunity for implementing lessons learned (e.g., to optimize later phases based on operating experience) and provides flexibility for future decision makers to adapt to a wide range of possible waste management scenarios. This flexible design concept, while developed for a repository at Yucca Mountain, might provide a useful model for a design for other repositories that is compatible with adaptive, staged development.

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