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**AN ASSESSMENT OF LWR
SPENT FUEL
DISPOSAL OPTIONS**

**VOLUME 1
SUMMARY AND CONCLUSIONS**

TECHNICAL REPORT

July 1979

ONWI
Office of Nuclear Waste Isolation
Battelle

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SUMMARY AND CONCLUSIONS**

TECHNICAL REPORT

July 1979

**Bechtel National, Inc.
Nuclear Fuel Operations
San Francisco, CA 94105**

This report was prepared by Bechtel National Inc. under Subcontract E512-00100 with Battelle Project Management Division Office of Nuclear Waste Isolation under Contract No. EY-76-C-06-1830 with the U.S. Department of Energy. This subcontract was administered by the Battelle Office of Nuclear Waste Isolation.

FOREWORD

This report is the final product of a Spent Fuel Disposal Study (SFDS) conducted by Bechtel National, Inc., which was initiated under Subcontract 86Y-42514C with Union Carbide Corporation — Nuclear Division, Office of Waste Isolation (OWI), and was concluded under Subcontract E512-00100 with the Battelle Project Management Division, Office of Nuclear Waste Isolation (ONWI), a prime contractor of the U.S. Department of Energy (DOE). The change was made when DOE reassigned the responsibility for certain nuclear waste management activities from OWI to ONWI.

The SFDS is part of the DOE's National Waste Terminal Storage (NWTs) program. The principal objective of the NWTs program is to provide facilities in various deep geologic formations at multiple locations within the United States in which the safe disposal of radioactive material from commercial nuclear power plants can be accomplished.

The study (1) identifies several spent fuel waste forms as well as the high level waste (HLW) and other waste forms from fuel reprocessing, (2) defines facility and system design features to handle, transport, process, encapsulate, and dispose of these spent fuel and waste forms, and (3) provides a comparative assessment of each of the spent fuel/waste alternatives with respect to technical feasibility, safeguards, criticality, radiological impact, retrievability, and economics.

The report is in three volumes. Volume 1, containing the summary and conclusions, provides the reader with a general overview of the study, coupled with the specific conclusions developed from the comparative assessments of the study cases and study variations. Volume 2, in addition to introducing and defining the requirements for the study, contains the detailed evaluation of the study cases in each of six assessment areas, and describes and evaluates a number of study variations. Volume 3 (Appendices) provides a tabulation of the bases and assumptions used in the study as well as preconceptual design descriptions and cost estimates of the facilities and transportation systems necessary to implement the various study cases.

A peer review group was appointed by ONWI to periodically review and contribute expert opinions on the technical progress of the study. The peer review group consists of the following members:

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R. D. Widrig	Battelle — PNL
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M. J. Steindler	Argonne National Laboratory
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G. H. Dyer	Bechtel National, Inc.

The contributions of the peer review group are gratefully acknowledged. While the opinions expressed during these reviews were carefully considered by Bechtel and ONWI in the development of this report, the conclusions reached do not necessarily reflect the positions of individual members of the group.

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Section 1

SUMMARY AND CONCLUSIONS

1.1 SUMMARY

1.1.1 Study Background and Goals

The U S government is actively promoting a policy of nuclear non-proliferation. In support of that policy, reprocessing of spent nuclear fuel has been delayed indefinitely in this country, while technical and institutional issues and alternatives are being reviewed world-wide. A consequence of the current reprocessing moratorium is that spent nuclear fuel is being considered, at least for some intermediate period, as a nuclear waste form by the U S government.

The Spent Fuel Disposal Study (SFDS) was conceived and initiated by the Office of Waste Isolation (OWI) of Union Carbide Corporation-Nuclear Division to provide an overview analysis of various proposals, alternatives and considerations relative to the geologic isolation of spent fuel from commercial nuclear reactors. This report, which is a product of that study, compares alternate strategies for treating, encapsulating and disposing of spent nuclear fuel, and contrasts them with a Reference Case which encompasses reprocessing and recycle of uranium and plutonium in light water reactors (LWRs). The study was conducted by Bechtel under a subcontract with Battelle Project Management Division, Office of Nuclear Waste Isolation (ONWI) which assumed responsibility for OWI contracts in July 1978.

The purpose of the study is to provide ONWI and the U S Department of Energy (DOE) with an evaluation of three specific ultimate disposition methods for spent nuclear fuel assemblies. To accomplish this, alternative forms of spent fuel are identified; the physical systems and facilities necessary to process, handle, and transport each of them (from the reactor to the repository) are defined at the preconceptual design level; a methodology is developed for comparing the various spent fuel alternatives, and the alternatives are analyzed and rated in terms of several assessment criteria.

This volume contains Section 1 of the final report, "Summary and Conclusions," in which a brief overview of the study is presented and specific conclusions developed from the comparative assessments of the study cases and study variations are reviewed.

1.1.2 Study Definition and Bases

1.1.2.1 General Study Bases. The spent fuel disposal system covered in this study includes the entire back end of the fuel cycle. The system begins at the point where spent fuel is removed from the reactor spent fuel storage pool and extends through all transportation, storage, processing, and encapsulation steps to the geologic repository.

The fuel cycle system investigated considers 5,000 MTHM of spent fuel per year as a segment of the total U.S. industry at some future point in time. All portions of the system are considered to be in equilibrium. The study does not address the question of nuclear power growth or depletion of the backlog of spent fuel, but focuses on waste management systems using the deep mined repository for disposal of spent nuclear fuel.

Spent fuel is assumed to be stored at the reactor storage basin until it is one year old. After leaving the reactor storage basin, it goes either to an away-from-reactor spent fuel storage facility (AFR) or to a processing and encapsulation (P/E) facility for further treatment, depending on the case.

A primary basis of the study was that the spent fuel will be placed in the repository 10 years following discharge from a reactor. The period of retrievability is the first 5 years after emplacement of spent fuel (or other waste material) in the repository. The study deals with a geologic repository in a salt formation, with no distinction made between bedded and domed salt. The effect of alternate geologic media is briefly considered as a study variation.

In the course of researching available literature for the SFDS, it was found that there was little consistency in study bases, source terms and other assumptions in the many waste management studies and projects being conducted by government and industry. This led to the requirement for development of a consistent set of bases and assumptions for spent fuel disposal, which are tabulated in Appendix A of Volume 3.

1.1.2.2 Description of Study Cases. Three spent fuel encapsulation and disposal cases were studied and contrasted to a Reference Case. Several study variations were also reviewed and analyzed to a lesser degree. The study cases are briefly described below, and are illustrated in the fuel cycle diagrams of Figure 1-1.

Case 1. Case 1 involves simple encapsulation and disposal of spent fuel elements in a geologic repository. No processing beyond sealing the spent fuel assemblies in canisters is required. Case 1 includes the following processes and transportation elements:

- Shipment of spent fuel from the reactor spent fuel pool to an AFR after the fuel has been out of the reactor one year
- Maintenance of the spent fuel at an AFR until it is ten years old
- Shipment of the spent fuel to a P/E facility* for encapsulation when it is ten years old
- Shipment, as produced, of non-TRU LLW to shallow land burial from both the AFR and the P/E facility
- Shipment, as produced, of ILW, TRU waste, and encapsulated spent fuel from the P/E facility to the repository
- Maintenance, at the repository, of the encapsulated spent fuel in a retrievable mode during an initial five-year demonstration period, followed by back-filling the repository for permanent disposal

* The term "P/E facility" is a generic term within this study. It identifies the facility in which any and all processing and encapsulation is conducted prior to its being delivered to a geologic repository.

Figure 1-1.
Spent Fuel Disposal Study
Fuel Cycle Diagrams

Case 2. In Case 2, prior to encapsulation, the end fittings are removed from the spent fuel elements, and the fuel pins are chopped and voloxidized. This process permits the separation and collection of some of the volatile and gaseous fission products and tritium from the fuel material, prior to the fuel material being sealed in canisters for emplacement in the repository. Reasons for considering this case include some volume reduction and the potential improvement of long-term safety. Case 2 includes the same fixed facilities and transportation elements as Case 1.

Case 3. In Case 3, the spent fuel is subjected to the same processing steps as in Case 2. Following that, the chopped and voloxidized fuel is dissolved in nitric acid. The cladding hulls are separated and the dissolved fission products, together with the uranium and plutonium, are calcined, processed into vitrified form and encapsulated in canisters for emplacement in the geologic repository. Reasons for considering this case include the potential increase in long-term repository safety, resulting from the complete separation of volatile fission products and tritium from fuel-bearing material, plus the potential reduction in leachability of fuel-bearing material which has now been converted into a vitrified waste form to enhance long-term repository safety. Case 3 includes the same fixed facilities and transportation elements as Case 1.

Reference Case. The Reference Case recovers the contained energy values present in spent fuel, by recycling uranium and plutonium in LWRs, with the terminal disposal of fission products and other wastes generated during reprocessing. It contains the following processing and transportation elements:

- Transportation of spent fuel from the reactor spent fuel pool to a P/E facility after the fuel has been out of the reactor one year
- Immediate reprocessing at a P/E facility and immobilization of the HLW in vitrified form
- Shipment of intermediate level wastes (ILW) and all TRU wastes from the P/E facility to a repository as soon as they are produced
- Shipment of low-level non-TRU wastes from the P/E facility to shallow land burial as soon as they are produced
- Shipment of uranium and plutonium to recycle facilities as soon as they are produced
- Storage of vitrified HLW in the P/E facility water storage pool for nine years
- Shipment of vitrified HLW to a repository at age ten years
- Maintenance of ILW and HLW in a retrievable mode during an initial five-year repository demonstration program, followed by backfilling the repository for permanent disposal
- Storage of bottled fission gases at the P/E facility until after the repository demonstration period. At that time, they are shipped to the repository where they are placed in rooms ready for immediate backfilling

1.1.2.3 Study Variations. Many of the study bases, assumptions and design choices used in the SFDS are not firm criteria for an eventual spent fuel disposal system. Therefore, several variations to study bases used were analyzed as "sensitivity studies" to determine the impact of such changes on the basic Case 1. The study variations identified below are described and analyzed in Section 10 of Volume 2.

- The age of spent fuel leaving the reactor storage pool is assumed to be 1 year in all study cases. The impact of changing this to 5 years and 10 years was investigated
- The age of spent fuel at time of emplacement in the repository is assumed to be 10 years for all study cases. The impact of changing this to 5 years and 25 years was investigated
- The canister retrievability period is assumed to be 5 years in all study cases. The impact of extending the retrievability period from 5 years to 10 and 25 years was investigated

- The high-level waste canisters for all cases are assumed to be filled with helium. The effect of alternative fillers was investigated
- The waste canister (for either HLW or spent fuel) for all cases is assumed to be a single container with nominal wall thickness. The effect of canister overpacks and thicker wall canisters was investigated
- For Case 1, the canister contains either 1 PWR assembly or 3 BWR assemblies. The impact of placing 2 PWR or 6 BWR assemblies per canister was studied
- A repository room will only be cooled while being filled with waste. The impact of providing cooling to all filled rooms during the retrievability period, as an alternative, was considered
- Canisters are assumed to be emplaced vertically in the floor of the repository rooms. The impact of horizontal and diagonal emplacement of canisters was considered
- The principal radioactive waste in Case 1 is encapsulated spent fuel. In the Reference Case, it is vitrified HLW. The repositories for the two waste forms contain significant design differences. The impact of converting repository operations from spent fuel to HLW was assessed
- All study cases consider a salt repository. The impact of other geologic media was assessed
- For all study cases, all facilities are assumed to be independently located. Three colocation options were analyzed as study variations:
 - 3 AFRs and 1 P/E facility at each of three sites
 - 1 P/E facility and 1 repository at each of three sites
 - 3 AFRs, 1 P/E facility, and 1 repository at each of three sites
- The spent fuel assembly is canistered intact in Case 1. The impact of disassembling the fuel pins to close pack them in the canister was investigated

1.1.3 Facility Studies

Design and cost estimating studies were conducted as a part of the SFDS to provide a basic foundation for the assessment and comparison of the cases. Since the primary purpose of the study is to compare the relative merits of several spent fuel disposal alternatives, the scope of this activity was limited to a preconceptual design effort. The effort involved studying resource materials in order to develop broad descriptions of processes, facilities and systems in the back end of the fuel cycle, as well as related capital, operating and decommissioning cost estimates. Information from both government and industry sources was studied, covering:

- Existing facilities
- Detailed design projects
- Conceptual design studies
- Preliminary engineering studies
- Preliminary design criteria
- Technical reports
- Miscellaneous data

The descriptions and definitions are presented in narrative form in Appendices B, C and D of Volume 3 and supplemented by block diagrams and facility layouts, as required. The material as presented meets these objectives:

- Provides a basis, in terms of facilities configuration and process technology definition, for assessing and comparing the cases
- Furnishes information for developing order-of-magnitude capital and operating cost estimates
- Investigates the state of the art of equipment and process technology in order to assess the technical feasibility and to provide a basis for planning continuing work

With these objectives in mind, the design effort was limited to identifying the basic parameters, defining the process technology, outlining the principal features of the facilities, and identifying the major equipment and material flows. Design optimization was not within the scope of this work. The basic goal was to arrive at facility sizes and to incorporate the major process components and systems.

1.1.4 Transportation Studies

Transportation studies were conducted as a part of the SFDS to analyze the special aspects of transporting all nuclear materials in the back end of the fuel cycle, including nuclear wastes. As with the facility studies, the purpose was to provide a basic foundation for making the assessments and comparisons of cases. The information developed included:

- Materials to be transported, including type, quantity, and their physical and nuclear characteristics
- Modes of transportation, including vehicle type, current and future availability, and capacity restrictions
- Transportation regulations, including federal, state and local and projected need for new regulations to handle fuel/waste forms not previously shipped
- Transportation logistics involving shipping times and distances between facilities for different transport modes
- Information on shipping casks for all forms of spent fuel and waste, including cask design parameters and cask fleet requirements
- Transportation cost estimates for all modes considered including sensitivity studies on shipping distances, rail speeds, and cask lease rates

The following transportation steps are included:

- Reactor to AFR
- Reactor to P/E facility
- AFR to P/E facility
- P/E facility to repository
- AFR to shallow land burial
- P/E facility to shallow land burial
- P/E facility to mixed oxide fabrication and enrichment facilities

The results of these studies are contained in Appendix E of Volume 3.

1.1.5 Technical Assessments

A fundamental requirement of this study is that the cases identified in Subsection 1.1.2, which are in effect ultimate disposition methods for nuclear wastes, be subjected to a comparative analysis. The analysis is conducted in terms of the following assessment areas or criteria:

- Technical feasibility
- Safeguards
- Criticality
- Radiological impact
- Retrievability
- Economics

1.1.5.1 Assessment Methodology. To conduct these assessments, a generalized methodology was developed as part of the study. The methodology enables the assessment to emphasize important considerations, to minimize duplication of considerations, and to focus attention on areas where additional study is required. Application of the methodology produces a qualitative or quantitative measure of the cases within each assessment area, and is supplemented by an analysis of technical factors to explain perceived differences among cases.

Using the methodology involves (for each assessment criterion) dividing the case being analyzed into its component facilities and transportation systems, and developing for each a measure of penalty* and a relative preference (weighting) factor. Combining these for a given case provides a composite assessment "measure" of that case. A comparison of these values for the various cases would provide a basis for selecting a preferred case with respect to the single assessment criterion being considered.

No attempt was made in this study to develop preference factors to sum the assessments of the individual criteria. Development of such preference factors is beyond the scope of this particular study.

The methodology described was adapted to the assessments in the study. The specific applications are described in the following paragraphs.

1.1.5.2 Technical Feasibility. This assessment in effect provides a measure of the degree of technical development and implementation achieved for the various processes, operations, facilities and systems within each study case. It employs a rating scale of 1 to 5, where 1 indicates a well-known process or operation with a proven history of satisfactory operation and 5 indicates a new process with no operating experience, at the early stage of development. In applying the methodology to technical feasibility, the different facilities and transportation systems in each case are divided into recognized process units or elements, and each is rated according to its present degree of technical development and implementation. Weighting factors, based on the relative complexity and importance of the individual segments, are used in combining the individual ratings into single ratings for each facility and system. The results, on a case comparison basis, are summarized in Subsection 1.2.2.

* As used here the penalty represents a measure of the cost or disadvantage associated with each component, facility or transportation system analyzed.

1.1.5.3 Safeguards. This assessment provides a measure of the risk to the public due to the potential sabotage or theft of nuclear material within each study case. It employs a rating scale of 1 to 3, where 1 indicates an extremely low risk to the public and 3 indicates a somewhat higher, but still low, risk. In applying the methodology to safeguards, the areas of sabotage and theft are assessed separately and not combined. Within each of these areas, and for each case, the applicable facilities and transportation system are rated according to their perceived degree of risk, using the 1 to 5 rating factors. The results, on a case comparison basis, are summarized in Subsection 1.2.3.

1.1.5.4 Long-Term Criticality. This assessment addresses the question of whether long-term geologic effects on the fissile material in a repository could cause an unplanned critical reaction to occur. It does not lend itself well to the methodology described above because over long geologic time periods the differences among the study cases diminish, and the (nuclear) reaction of the waste depends on its composition rather than the nature of treatment and encapsulation prior to disposal. The three spent fuel study cases are, therefore, seen to be nearly identical, and they are contrasted to the Reference Case mainly in terms of the relative amounts of fissile material within each waste canister at various points in time. The long-term criticality analysis (1) reviews the potential for critical mass formation in canistered waste, (2) defines the conditions necessary to achieve and sustain a critical reaction, (3) postulates the magnitude of a potential critical event, and (4) estimates the radiological impact from such an event. The results are summarized in Subsection 1.2.4.

1.1.5.5 Radiological Impact. This assessment provides a measure of the potential radiological impact on the public and on occupational workers due to the operation of facilities and the transportation system of each case. In applying the assessment methodology to radiological impact, three separate areas of impact are defined (they are not combined in the assessment) (1) near-term occupational impact due to normal and abnormal operations, (2) near-term non-occupational impact due to normal and abnormal operations, and (3) long-term impact from the repository due to natural or human intrusion. Each case is divided into its applicable facilities and transportation system, and each of these is further divided into its process components or subsystems, which are then evaluated using various radiation dose units as the measure. The resulting assessment, on a case comparison basis, is summarized in Subsection 1.2.5.

1.1.5.6 Retrievability. This assessment provides a measure of the degree of technical development and implementation achieved for the various operations, systems and necessary facilities to retrieve canistered spent fuel or waste from a repository several years after its emplacement. It employs a rating scale of 1 to 5, where 1 indicates a well-known system or operation with a proven history of satisfactory operations and 5 indicates a new operation at an early stage of development which has no operating experience. In applying the generalized methodology to retrievability, the various systems, operations and facilities necessary to accomplish canister retrieval within the repository are identified, and each is rated according to its present degree of technical development and implementation. Weighting factors, based on the relative complexity and importance of the individual components, are used in combining the individual ratings into a single value for each case. The results, on a case comparison basis, are summarized in Subsection 1.2.6.

1.1.5.7 Economics. This assessment provides a measure of the economic cost of implementing each of the study cases. It applies the generalized methodology in that each study case is divided into its applicable facilities and transportation systems, and these are further subdivided as necessary to develop appropriate cost segments. Net levelized economic costs are then developed for each facility and the transportation system within each case in \$/MTHM. The results of this assessment on a case comparison basis are summarized in Subsection 1.2.7.

1.2 CONCLUSIONS

This section presents conclusions reached in performing the Spent Fuel Disposal Study. The detailed assessments are contained in Sections 4 through 9 of Volume 2. Each deals with a single assessment area or criterion (e.g., safeguards). The descriptions and evaluations of the study variations are contained in Section 10 of Volume 2. These six assessments and the evaluation of study variations are summarized in Subsections 1.2.2 through 1.2.8 of this volume. Conclusion highlights are in Subsection 1.2.1 and an analysis of how well the assessment methodology met its goals is provided in Subsection 1.2.9.

1.2.1 Highlights

While it was not the purpose of the SFDS to provide a "bottom-line" summation of the results of all the assessment areas, this subsection brings together, in summary form, the results of the six fundamental assessments. It also considers the impacts that certain of the study variations may have on the selection of an optimum spent fuel disposal system.

1.2.1.1 Summary Comparison. It is helpful to be able to view — even on a summary basis — the results of all the assessments in one place. Table 1-1 provides this summation. Each of the assessment areas is represented, as are certain sub-areas which were considered independently. The reader is cautioned that a table such as this cannot and does not contain a complete representation of study results, and that, before a particular case is judged critically, the complete assessment should be reviewed.

1.2.1.2 Study Observations. As a result of the information gained from establishing preconceptual designs for spent fuel management and disposal facilities, developing technical material for each study area, and making the assessments themselves, a number of conclusions and observations have been made, as follows:

- All of the spent fuel disposal cases studied are technically feasible and there are no insurmountable technical problems inherent in their implementation
- Of the spent fuel disposal schemes, Case 1 is the simplest and it scores well in almost all of the separate assessments
- Transportation of all nuclear materials studied is feasible, and a cask fleet could be provided by the private sector if suitable guarantees against financial losses caused by major government policy changes are given
- The most urgent technical problem to system implementation is to define the specific technical bases and design criteria for facility development
- There are no radiological or nuclear safety impacts for the cases studied which should cause undue concern or which would subject the public to risks even approaching those which it routinely accepts
- Long-term criticality is not a significant hazard and would not preclude the implementation of spent fuel disposal schemes
- The spent fuel disposal cycle does not present an attractive target to a terrorist who seeks to fabricate a nuclear explosive device because the materials which might be stolen require considerable additional processing to be of value
- The Reference Case is more attractive for diversion of nuclear materials because of the existence of separated plutonium. However, the risk of theft can be reduced considerably by co-processing, spiking, or the colocation of a P/E facility with a MOX fuel fabrication facility

Table 1-1
ASSESSMENT SUMMARY COMPARISON

Assessment Criterion	Rating ^(c) Scale	Ref. Case	Case 1	Case 2	Case 3	Comments
Technical Feasibility	1 to 5	1 9	1 7	1 9	2 1	Based on average of P/E facility and transportation
Safeguards. Sabotage	1 to 3	3	3	3	3	Based on transportation system as weakest link
Theft	1 to 3	3	2	2	2	Based on transportation and P/E facility as weakest links
Criticality	None	No ratings developed		Risk extremely low		
Radiological Impact						
Near-Term ^(a)	man-rem	3900	2500	3000	5100	Based on normal operation of 5000 MTHM/yr system ^(e)
Occupational	/yr					
Near-Term ^(b)	man-rem	180	390	420	470	Based on normal operation of 5000 MTHM/yr system ^(f)
Non-Occupational	/yr					
Long-Term	rem/ event	340	90	100	44	Direct access drilling at 100 years. Dose to maximum exposed drilling crew member ^(g)
Retrievability	1 to 5	2 2	2 6	2 5	2 9	
Economics	\$/Kg	186 ^(d) (154)	116	115	167	

(a) The average dose to individual workers ranges from 0.9 to 1.7 rem/yr depending on the case, the work facility and the number of workers involved.

(b) For comparison the annual background dose is approximately 100 mrem/yr or 1.6×10^5 man-rem/year dose to the population living within a 50 mile radius of the site (based on 200 people per square mile).

(c) Numerical rating scales of 1 to 5 or 1 to 3 represent a comparative ranking of cases within a single criterion, with a value of 1 representing the preferred rating.

(d) The reference case cost, before crediting with uranium and plutonium recovery values, is \$186/Kg. After crediting this becomes a profit of \$154/Kg.

(e) Normal operation exposure to occupational workers is considered to be more significant, with respect to maximum allowable annual radiation dose, than exposure due to abnormal events.

(f) Normal operation exposure to the public, while far below background levels, is compared here because non-occupational exposure due to accidents is considered identical for each case, and does not contribute to case differentiation.

(g) The direct access drilling consequence is shown only because it indicates a higher impact than any of the other repository breaching events considered. The scenario for direct access drilling is extremely conservative, and the probability of such a consequence being experienced is quite small.

- While the retrievability assessment in this study showed little differentiation among cases, the study shows that designing a repository with retrieval capability is feasible.
- The Reference Case is significantly more economical than the spent fuel cases but all cases are considered to be feasible at reasonable cost to society.

1.2.1.3 Optimum System Selection. If the U.S. should adopt spent fuel disposal as official policy, it is quite certain that the design criteria and bases employed would not be identical with any one of the spent fuel cases assessed in this study. This is one reason for consideration of the study variations. The conclusions suggest that certain variations have considerable merit. While it is not the purpose of this study to recommend an optimum system — or to even select among the

three cases — one could describe a system which might have merit for implementation based on the cases and variations evaluated.

For example, Case 1 could be selected, because of its relative simplicity, as a starting point. The spent fuel disassembly option (study variation 10.6) has potential advantages in that there would be fewer canisters, they would be shorter and more compact, and significant repository cost savings may be achieved as a result. This might be an attractive alteration to Case 1, although it would need to be studied in more detail to identify problems of possible fuel pin rupture during handling and increased P/E facility costs.

Another attractive option would be to colocate the P/E facility with a repository on a regional basis (variation 10.5.2). There are obvious advantages to this.

Time factor variations are also likely to impinge on an ultimate spent fuel disposal system. The number of years of fuel storage at the reactor (variation 10.2.1) is clearly one that would change in a real spent fuel disposal system since so much spent fuel already exists at ages well over one year. This affects the number of AFRs required.

Other potentially promising variations should also be considered in selecting an ultimate disposal system.

1.2.2 Technical Feasibility

In the SFDS, technical feasibility is defined as the ability to design, construct, and place in satisfactory operation in a reasonable time any given process, facility or system within each study case. A qualitative assessment was made using a rating scale of 1 to 5. (A rating of 1 indicates a well-known process or operation with a proven history of satisfactory operation, while a rating of 5 indicates a new process at an early stage of development which has no operating experience.)

Applying this to the SFDS processes, facilities, and systems, yields the following comparative assessment:

Component Part	Ref. Case	Case 1	Case 2	Case 3
AFR	—	1.0	1.0	1.0
P/E Facility	2.2	2.1	2.4	2.8
Repository	1.8	1.8	1.8	1.8
Transportation	1.5	1.2	1.3	1.3

Because AFRs are equally required for all spent fuel cases, and there is little difference in repository design and operation from case to case, only the P/E facilities and transportation systems contribute to a differentiation among cases — and it is obvious that these differences are small. By combining the two ratings it can be shown that the Reference Case and Case 2 are essentially equal, and that Case 1 has a slight relative advantage and Case 3, a relative disadvantage.

The differences in assessment ratings within the transportation system result from higher (poorer) ratings being applied to shipments involving significant shielding and to shipments of canistered fuel, high-level waste and plutonium oxide. The Reference Case is affected the most by this, and Case 1 the least.

The P/E facility differences are based on the relative degree of technical development still required to achieve satisfactory operation. These are discussed by case below:

Case	Comments
Reference	Some aspects of the P/E facility require additional development and demonstration (e.g., hulls compaction and voloxidation) other aspects require full-scale demonstration (e.g., fission gas recovery and fixation).
1	Although encapsulation facilities as such have had only limited operation in the U.S., all significant design problems are considered to be resolved.
2	Some P/E facility processes (e.g., voloxidation and fission gas recovery and fixation) require further development and/or demonstration.
3	Some aspects of this P/E facility require more extensive development (e.g., calcination and vitrification of fuel material with high plutonium and uranium content) beyond that required for the Reference Case.

A more detailed discussion of the technical basis behind this evaluation is provided in Section 4 of Volume 2.

Other conclusions developed in this assessment can be summarized as follows:

- The technology for all cases exists or can be developed from existing technology on time schedules consistent with DOE's current waste management program, provided that needed work is initiated without delay

- AFRs are not a factor in differentiating among spent fuel cases since they are applied in an identical manner to Cases 1, 2, and 3; and they involve well-known processes with long operating histories
- The repositories are not a factor in case differentiation since the technologies are essentially the same for all cases. A testing program to verify corrosion resistance of canisters and sleeves is required. A review of thermal loading design criteria and calculation methodology is recommended
- Transportation of all nuclear materials is feasible, and a cask fleet could be provided by the private sector if a clear-cut commitment is made by the government with sufficient lead time, and suitable guarantees are given against financial losses caused by policy changes

1.2.3 Safeguards

In the SFDS, safeguards is defined as the protection of nuclear material from sabotage and theft. Sabotage is limited to the dispersion of radioactivity into the environment. Theft of nuclear material is considered to be conducted at the sub-national level for the sole purpose of fabricating a nuclear explosive device. A qualitative assessment was made using a numerical rating scale of 1 to 3. (A rating of 1 indicates an extremely low risk to the public, while a rating of 3 indicates a somewhat higher, but still low, risk.)

Applying this to the SFDS processes, facilities and systems yields the following comparative assessments for the two categories:

Category	Component Part	Ref. Case	Case 1	Case 2	Case 3
Sabotage	AFR	—	2	2	2
	P/E facility	2	2	2	2
	Repository	2	2	2	2
	Transportation	3	3	3	3
Theft	AFR	—	2	2	2
	P/E facility	3	2	2	2
	Repository	1	2	2	2
	Transportation	3	2	2	2

The following case-specific comments relate to the comparative assessments made

- From a sabotage point of view, the cases are essentially identical. This is largely because sabotage by the dispersal of radioactive materials in spent fuel is the largest sabotage risk and is common to all cases
- From a theft perspective, Cases 1, 2, and 3 are identical. The spent fuel cycle does not present an attractive target to a terrorist because materials which might be stolen require extensive, difficult and expensive processing and are relatively well protected by multiple barriers which would be difficult to breach
- The Reference Case is more attractive for diversion because of the existence of separated plutonium. It should be noted, however, that the exposure to theft for the Reference Case would be reduced considerably by current schemes such as co-processing, spiking and a P/E facility colocated with a mixed oxide fuel fabrication facility

The following general findings concern all cases:

- Final NRC safeguards requirements have not yet been established
- Satisfactory postulated safeguards systems and equipment are feasible
- Additional capital costs for safeguarding of facilities and transportation elements are estimated to be relatively small as a percentage of total waste management system capital costs
- Some hardware for safeguards systems has not yet been developed in detail although sound concepts have been postulated

1.2.4 Long-Term Criticality

In conventional nuclear facilities the potential for critical reactions occurring during handling, storage and process operations is minimized or eliminated by the inclusion of conservative design features, and rigid operating and administration controls. Criticality in the SFDS addresses the question of whether long-term geologic and geo-chemical effects on the fissile material in a repository are sufficient to negate the controls established at the time of emplacement, and create conditions needed for a criticality to occur.

When criticality considerations are extended over such geologic time spans, the differences among the cases studied diminish and the reaction of the waste depends on its composition rather than the nature of treatment and encapsulation prior to disposal. This criticality assessment does not, therefore, attempt to differentiate among the cases. Instead it analyzes long-term criticality in the repository by (1) reviewing the potential for critical mass formation in the canistered waste material for each case, (2) defining the conditions which must be present to achieve and sustain a critical reaction, (3) postulating the magnitude of a potential critical event, and (4) estimating the radiological impact and risk from such an event.

It should be noted that, relative to the other cases, the Reference Case has less potential for causing a criticality during long-term isolation. This is because

- (1) It contains less total fissile material capable of forming a critical mass, and
- (2) The time needed for the fissile material to deplete to a mass lower than that which could go critical is shorter in the Reference Case.

No great significance has been attached to this, however, for two reasons: first, the high degree of practical difficulty in achieving a criticality with any of the waste forms, and second because it is essentially impossible to define the degree of Reference Case benefit, over the long time periods involved, in comparison with the extreme improbability of naturally occurring events providing the conditions needed for criticality.

The results of this analysis show

- There is sufficient fissile material in a single spent fuel, or high-level waste canister, in the cases considered in the SFDS, to form a critical mass if it were isolated and/or rearranged under optimum conditions.
- The probability of producing the conditions needed for a criticality in the repository by naturally occurring events is extremely low. The same forces that may be acting to create the conditions needed for criticality have an even greater potential for making such an event less plausible. Therefore, the probability of achieving all the conditions needed to reach criticality with uncontrolled events is judged to be diminishingly small.
- A criticality event, if it did occur, would be localized, self-limiting, and low powered, and would not involve the violent reaction associated with the rapid accumulation of a critical mass.
- The risks and radiological impacts to future populations because of a criticality within a deep geologic repository are diminishingly small.

1.2.5 Radiological Impact

For purposes of this study, radiological impact is defined as the potential radiation dose which would be received by an individual or a population segment as a result of both the operation of waste management facilities and transportation systems, and the long-term effects of waste isolated in a deep salt repository. The assessment for each case is a relative measure of the potential radiological impact. It is divided into three categories:

- (1) Near-term occupational impact due to normal operations and abnormal events.
- (2) Near-term non-occupational impact due to normal operations and abnormal events, and
- (3) Long-term impact from the repository as a result of water intrusion, direct access drilling, and the occurrence of catastrophic events

These areas are assessed separately with no attempt made to combine them. The radiation dose data are generally expressed in man-rem/yr, mrem/yr or mrem/event (in the case of accidents), according to the units found in the technical source used. No new radiological impact data were developed in this study. It was based entirely on work done by others, and the data were adapted to the SFDS facilities and systems by numeric proportioning and the broad use of engineering judgment.

The comparative assessment for the near-term is summarized as follows:

Case	WHOLE BODY DOSE			
	Occupational		Non-occupational	
	Normal (man-rem/yr)	Abnormal (man-rem/yr)	Normal (man-rem/yr)	Abnormal (mrem/event)
Reference Case	3900	880	180	1200
Case 1	2500	830	390	1200
Case 2	3000	870	420	1200
Case 3	5100	1400	470	1200

The normal operations identified above relate to a system of nine AFRs*, three P/E facilities, one repository and the full 5000 MTHM/yr transportation system, while each abnormal event is associated with only one facility or transportation step.

Case 3 has the highest radiological impact due primarily to the large number of complex processing steps required, as well as the largest number of spent fuel canisters for any case. The spent fuel cases dominate the non-occupational area due to the impact from the AFRs, which are not used in the Reference Case. All of the radiation dose values shown are quite low based on either normal background or acceptable values for occupational exposure. For example, in the detailed radiological assessment in Section 7 of Volume 2 it is shown that the values of occupational dose for normal operations and abnormal events (shown above) represent average exposures to individual workers ranging from 0.9 to 1.7 rem/yr depending upon the type of facility and the case. This compares with a maximum dose of 5 rem/yr allowable under 10 CFR 20. Furthermore, the values of non-occupational dose during normal operations are shown to be extremely low when compared to a normal background dose of 1.6×10^5 man-rem/yr for a 50-mile radius area.**

* The nine AFRs apply only to Cases 1, 2 and 3; they are not required in the Reference Case.

** Based on a population density of 200 people per square mile.

The comparative assessment for the long-term is summarized as follows

- The resultant whole-body dose to the maximum exposed individual from groundwater intrusion in the repository will vary from 1×10^{-6} to 7×10^{-4} mrem/yr depending upon the scenario. This is several orders of magnitude below normal background of 100 mrem/yr.
- Contact with the buried waste due to direct access drilling within 100 years, although considered extremely improbable, yields a high dose to the drilling crew (44 rem to 340 rem depending on the case). The maximum exposed individual living near the drill site receives a dose approximately equal to background radiation. If drilling is carried out at about 250 years, the dose to the drill crew is about three times that currently permitted per year to an occupational worker. The impact is greatest for the Reference Case and least for Case 3.
- A catastrophic breach of the repository due to a severe volcanic or seismic event would release enough radiation to make the site uninhabitable if the event occurs within the first few thousand years. However, the catastrophic event itself would have far greater impact on the population than limited exposure to the radiation. For perspective, the resulting radiological dose to a non-specific population would be about four times background if the event occurs after 1000 years but within the first few thousand years.

1.2.6 Retrievalability

In the SFDS, retrievalability is defined as the ability to extract and return the spent fuel and HLW canisters from geologic storage to the surface facility of the repository during an initial 5-year repository demonstration period. An assessment was made for the four study cases, using a retrievalability measurement scale of 1 to 5. The measurement, applied to each of the retrievalability system components, reflects the degree to which that component or subsystem is expected to perform satisfactorily. A rating of 1 indicates a well-known operation with a proven history of satisfactory operation, while a rating of 5 indicates a new operating concept that has not been developed beyond the design stage. The subsystems involved in the retrievalability assessment are:

- Sleeve integrity
- Canister integrity
- Transfer/overpack cell
- Decontamination/corrosion removal cell
- Repository ventilation system
- Radiological protection
- Monitoring and surveillance system
- Quantity of retrievable material
- Room closure

Applying the measurement scale to each of the subsystems, and applying weighting factors for complexity of the operation and its relative importance to the overall retrievalability system, yields the following numerical comparison:

Reference Case	Case 1	Case 2	Case 3
2.2	2.6	2.5	2.9

Within the accuracy of this assessment criterion, the indicated differences among the cases are not considered significant. This is especially true of sleeve integrity, repository ventilation system, monitoring and surveillance system, and room closure considerations, which provide essentially no differentiation among cases.

The dominant subsystems in the assessment are the quantity of material to be retrieved and radiological protection. The number of canisters maintained in a retrievable mode impacts directly on both of these aspects of the assessment. The canister integrity subsystem also impacts against Case 2 because the (hazardous) contents of the canister could be so easily dispersed compared to the other spent fuel/waste forms.

1.2.7 Economics

The economic assessment develops the net levelized economic cost, in \$/MTHM, for each case. Credits are assigned in the Reference Case for the value of recovered U and Pu.

The economic cost considerations include all capital, operating, transportation, and decommissioning costs. Key assumptions incorporated in the economic analysis include:

- The analysis evaluates net costs to society but ignores profit and taxes
- A present worth analysis was used, incorporating a 10 percent discount rate
- All costs are in January 1979 dollars
- No escalation is included
- Uranium cost is \$43/lb U_3O_8
- Plutonium has a value of \$30/gram of fissile plutonium
- Enrichment cost is \$110/SWU

The average levelized economic costs in \$ per MTHM for the four cases are shown in Table 1-2. The economic costs of Cases 1 and 2 are nearly identical, while Case 3 is substantially more costly in almost all its elements except AFRs. The economic cost for the Reference Case is, however, significantly lower than for the other cases, because of the value of recovered plutonium and uranium.

A sensitivity study was conducted to identify the total economic costs for discount rates of 0%, 5%, and 15%. This showed that changing the discount rate does not alter the relative costliness of the four cases in any significant way.

Table 1-2
AVERAGE LEVELIZED ECONOMIC COSTS FOR
FOUR CASES OF SPENT FUEL DISPOSAL^(a)
(\$/MTHM)

Cost Centers	Reference Case	Case 1	Case 2	Case 3
Transportation	29,700	26,900	23,600	37,600
AFR	—	53,300	53,300	53,300
P/E facility	124,000	16,700	20,900	45,900
Repository	<u>32,200</u>	<u>19,400</u>	<u>16,900</u>	<u>30,600</u>
Total cost	185,900	116,300	114,700	167,400
Credit value of recycled UF_6	(130,000)	—	—	—
Credit value of recycled Pu	<u>(210,000)</u>	<u>—</u>	<u>—</u>	<u>—</u>
Total cost (rounded), or	—	116,000	115,000	167,000
Net profit (rounded)	(154,000)	—	—	—

(a) Calculated using January 1979 prices with 10 percent discount rate and 40-year study period.

1.2.8 Impact of Study Variations

The study variations of Case 1 are discussed in Section 10 of Volume 2. Each of the variations is analyzed in terms of the six assessment criteria. These analyses are in less detail than the assessment analyses for the four study cases.

The results of the assessments are summarized in Table 1-3. the study variations listed below appear to have merit and warrant consideration in spent fuel disposal case selection.

Study Variation	Criteria Likely to Be Favorably Impacted	Criteria Likely to Be Unfavorably Impacted
Canister Void Filler Options	Criticality Radiological Impact Retrievability	Economics
Overpacks and Thicker Wall Containers	Retrievability Radiological Impact	Economics
More Assemblies per Canister	Economics Radiological Impact	Retrievability Technical Feasibility
Colocation of AFR & P/E	Economics Radiological Impact Safeguards	None
Other Colocation Options	Safeguards Radiological Impact	Economics
Horizontal Emplacement of Canisters	Economics	Retrievability Technical Feasibility
Room Cooling During Retrievability	Retrievability	Economics Radiological Impact

Table 1-3**SUMMARY OF STUDY VARIATION ASSESSMENTS**

	Technical Feasibility	Safeguards	Criticality	Radiological Impact	Retrievability	Economic \$/KgHM
5-Year Old Spent Fuel Leaving Reactor	Same as Case 1	Same as Case 1	Same as Case 1	Possible Improvement	Same as Case 1	\$25 less
10 Year-Old Spent Fuel Leaving Reactor	Same as Case 1	Same as Case 1	Same as Case 1	Improvement	Same as Case 1	\$66 less
5 Year-Old Fuel at Time of Emplacement	Same as Case 1	Same as Case 1	Same as Case 1	Negative Impact	Negative Impact	\$4 more
25 Year-Old Fuel at Time of Emplacement	Same as Case 1	Same as Case 1	Same as Case 1	Improvement	Improvement	Unknown
10 Year Retrievability	Same as Case 1	Same as Case 1	Same as Case 1	Slight Negative Impact	Slight Negative Impact	Not Determined
25-Year Retrievability	Same as Case 1	Same as Case 1	Same as Case 1	Negative Impact	Slight Negative Impact	Not Determined
Canister Void Filler Options	Same as Case 1	Same as Case 1	Possible Improvement	Possible Improvement	Possible Improvement	Possible Increase Cost
Overpacks & Thicker Wall Containers	Same as Case 1	Same as Case 1	Same as Case 1	Improvement	Possible Improvement	Higher P/E Facility Cost
More Assemblies Per Canister	Possible Minor Neg Impact	Same as Case 1	Same as Case 1	Improvement	Minor Negative Impact	Reduced Cost
Room Cooling During Retrievability Period	Same as Case 1	Same as Case 1	Same as Case 1	Slight Negative Impact	Allows Longer Retrievability Periods	Slight Cost Increase
Horizontal Emplacement of Canisters	Additional Thermal Analyses Required	Same as Case 1	Same as Case 1	Same as Case 1	Probable Negative Impact	Possible Cost Saving
Combined Spent Fuel/HLW Repository	Same as Case 1	As per Case 1 & Reference Case	As per Case 1 & Reference Case	As per Case 1 & Reference Case	As per Case 1 & Reference Case	Approaches Ref Case Cost
Non-Salt Repositories	Same as Case 1	Same as Case 1	Same as Case 1	Possible Negative Impact	Undetermined Depends on Specific Geology	Cost Increase
Colocation of AFR & P/E Facility	Same as Case 1	Minor Improvement	Same as Case 1	Significant Improvement	Same as Case 1	\$2 less
Colocation of P/E & Repository	Same as Case 1	Minor Improvement	Same as Case 1	Significant Improvement	Same as Case 1	\$7 more
Colocation of AFR P/E and Repository	Same as Case 1	Minor Improvement	Same as Case 1	Significant Improvement	Same as Case 1	\$5 more
Spent Fuel Disassembly	Minor Additional Development	Same as Case 1	Same as Case 1	Probably No Change	Same as Case 1	Possible Decreased Cost

1.2.9 Attainment of Assessment Goals

The assessment methodology used in this study involves evaluating each of the study cases and case variations in terms of six assessment criteria. The definitions, measurement scales and key assumptions connected with each of the assessment criteria are found in Sections 4.1, 5.1, 6.1, 7.1, 8.1 and 9.4 of Volume 2.

Assessment criteria were chosen and defined with the following objectives:

- (1) Each assessment criterion should be independent of the others.
- (2) The sum of the penalties and benefits associated with each evaluation criterion reflects the comparative ranking of the cases, for that criterion.
- (3) Each assessment criterion contributes to a differentiation among cases.
- (4) The criteria are measurable in relative numerical terms.

These objectives have generally been met. Some problems in meeting them are discussed below.

1.2.9.1 Assessment Criteria Independence. The degree to which independence was met is discussed by individual assessment criterion in the following paragraphs.

Technical Feasibility. The technical feasibility assessment overlaps economics and retrievability.

An aspect of technical feasibility not considered in this study is the economic cost associated with developing technology refinements. The cost of developing two or more parallel technologies in order to keep an option open may be an important aspect of feasibility.

Alternative technologies may inherently differ in reliability of operation. Differences in reliability can influence system performance and economics. The methodology used in this study can not readily include the affect of reliability. However, a more sophisticated spent fuel disposal system model could be applied to evaluate reliability of operations.

Safeguards. The risks assessed in this area are the consequences of sabotage and theft (or diversion) of fissile materials. These consequences are, in part, radiological. For this study, radiological risks resulting from failure of the safeguards systems are assessed independently of radiological risks due to other considerations (i.e., operation and decommissioning of the required facilities).

Criticality. The final impact of criticality in the repository is in terms of expected radiological impact. Thus, a possible overlap with the radiological impact assessment exists. The independence of the two assessment criteria (criticality and radiological impact) was achieved by defining that all radiological impacts of system operation and of long-term disposal are part of the radiological impact assessment. Radiological impacts specifically resulting from criticality events in the repository after canister emplacement are treated in the criticality assessment.

Radiological Impact. The radiological impact assessment overlaps criticality, retrievability, and safeguards assessments. However, these areas of overlap have been independently evaluated as discussed elsewhere in this section.

Retrievability. The retrievability assessment produces a measure of confidence that certain designated canisters can be satisfactorily retrieved. The assessment measure is defined in terms of feasibility of retrievability similar to the technical feasibility assessment methodology. The retrievability assessment also includes a measure of the relative radiological impact if retrieval of the canisters becomes necessary. Thus, technical feasibility and radiological impact assessment represent potential areas of overlap of retrievability assessment. Independence of assessments was achieved by restricting the feasibility as much as possible to retrievability considerations and considering radiological impacts in the radiological impacts assessment area.

Economics. The economic criterion is interrelated with all other assessment criteria. For example, all cases could theoretically be brought to the same level of assessment acceptability in all areas if sufficient funding was provided. In this way, the comparison of cases could theoretically be reduced to a single economic comparison. However, such optimization considerations are outside the scope of this study. Facilities have been designed to currently known or projected standards and objectives.

1.2.9.2 Summing Assessment Criteria. The sum of the assessment criteria theoretically would result in a measure of the total penalty for a given case. It was not possible within the scope of the present study to actually perform this summing operation because weighting factors would be required to properly sum the assessment criteria. The development of these weighting factors was beyond the scope of this study.

1.2.9.3 Assessment Criteria Contribution to Case Differentiation. The assessment criteria have been developed such that each criterion, except criticality, contributes to case differentiation. As the criticality assessment developed, the preliminary results indicated that a criticality event is extremely unlikely and, if it occurs, the radiological impact to the biosphere would be inconsequential. Therefore, consideration of a criticality event does not contribute to a differentiation among the cases. The other assessments have produced results that do differentiate between two or more of the cases, although with varying degrees of accuracy.

Measurability of Assessment Criteria. These criteria have been generally satisfied for all of the assessments. For the criticality assessment the data is sparse but, even so, the criticality assessments made are believed to fairly reflect the relative impacts of criticality for the four cases.

1.2.10 Assessment Summary

The study provides a technical assessment and comparative analysis of the three defined spent fuel cases as well as the Reference Case. All systems, facilities and transportation steps required for each case are defined in detail in the appendices of Volume 3 to provide a sound and comparable basis for the assessments contained in Volume 2.

In addition to the three principal spent fuel cases, a number of study variations on Case 1 were evaluated and are discussed in Section 10 of Volume 2. Their evaluation has been briefly reviewed in this volume, in Section 1.2.8, and naturally leads to a first preliminary indication of a refined spent fuel case for further, more detailed, evaluation as an extension of this work with the objective of optimizing the preferred case.

The variations on Case 1 which appear most promising include:

- Colocation of the AFR, P/E facility and the repository
- Time factor variations such as:
 - Increasing the age of spent fuel stored at reactor sites, and
 - Increasing the age of spent fuel before emplacement in the repository
- Canister void fillers, and
- Spent fuel disassembly, and optimized repacking

The study supports the premise that there are no insurmountable problems associated with the safe management and disposal of spent nuclear fuel. It shows that most technical problems have been solved and that where additional technical work is required to demonstrate and prove theoretical solutions that such work appears well within the scope of current technology and does not require exploration into new theory or science. The assessments support the position that all required facilities and operations can be accomplished safely and well within normal radiological exposure limits for both operating personnel and the public, and that these can be achieved at reasonable cost to society.