COMPARISON OF ALTERNATIVES FOR THE TREATMENT OF NON-FUEL-BEARING HARDWARE

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ABSTRACT

This evaluation compares four alternatives for the treatment or processing of non-fuel-bearing hardware (NFBH) to reduce its volume and prepare it for disposal. These treatment alternatives are: shredding; shredding and low-pressure compaction; shredding and supercompaction; and melting. The alternatives are compared on the bases of system costs, waste form characteristics, and process considerations. The two alternatives with high volume reduction are estimated to save $400 million to $500 million compared with the shredding-only alternative. The study recommends that melting and supercompaction alternatives be considered further and that additional testing be conducted for these two alternatives.

INTRODUCTION

This paper summarizes a recently completed evaluation (1) which compares four alternatives for the treatment of non-fuel-bearing hardware (NFBH) from the consolidation of commercial spent nuclear fuel. The NFBH in this evaluation is assumed to be from the consolidation of spent fuel rods at the Monitored Retrievable Storage (MRS) Facility. However, a similar quantity of material would also be generated if the consolidation occurs at a repository. A total of 62,000 MTU of spent fuel was considered in the economic analysis. Processing of this amount of spent fuel was estimated to generate about 375 m^3 meters of shredded hardware with a weight of 340,000 kg/yr for 25 years. Other wastes from operation of the facility were not included in this study, but were considered in a previous study (2).

The four treatment alternatives considered in this study are shredding, low-pressure compaction of shredded hardware, supercompaction of shredded hardware, and melting. Selection of these alternatives provided a wide range of waste volumes for the analysis and included the options most applicable to low-density metallic wastes. No alternatives that involve the separation of the NFBH into different waste streams or different types of treatment and disposal were considered.

The alternatives are compared on the basis of system costs, waste form characteristics, and process considerations. Each of the major considerations are subdivided into additional categories as noted in Table I.

TABLE I

Considerations in the Evaluation of Treatment Alternatives

System Costs	Waste Form Characteristics	Process Considerations
- treatment	- release rate	- operational safety
- transportation	- particulate	- process simplicity
- disposal	- pyrophorics	- status of technology
	- bulk density	

WASTE STREAM

At the MRS facility (or the repository receiving and handling facility) spent fuel assemblies are received from nuclear power plants by truck or rail and taken into a processing cell where the fuel rods are removed from the remaining fuel assembly hardware. For the MRS conceptual design (3), the massive pieces of residual hardware are loaded directly into drums, and the remaining materials are shredded to facilitate handling and to reduce their volume. This hardware is a major waste stream from the consolidation operation. During the rod removal operation, most of the rods are expected to be removed intact. However, some of the rods may have failed (or may fail during removal) and may release some spent fuel particles to the hot cell and its ventilation system, contaminating the NFBH so that it may become TRUW. Table II shows the volume and mass of NFBH anticipated from consolidation operations at the MRS facility (or repository receiving and handling facility). The mass of material is somewhat uncertain, particularly for the boiling-water reactor (BWR) assemblies, which have an estimated mass from 34 to 64 kg/assembly (4). For this report, values of 38 kg/assembly for pressurized water reactor (PWR) assemblies and 40 kg/assembly for BWR assemblies have been used. The waste volumes have been adjusted from

TABLE II

Projected Annual Untreated Waste Volumes from Spent Fuel Rod Consolidation[a]

Waste Type	Number of Assembles	Unshredded Volume (m^3)	Shredded Volume (m^3)	Mass (Kg)
PWR Hardware	3,330	610	140	127,000
BWR Hardware	5,280	415	235	211,000
Total	8,610	1025	375	338,000

(a) Based on consolidation of 2500 MTU of intact fuel.

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[a] Operated by the Department of Energy by Battelle Memorial Institute under Contract DE-AC06-76RLO 1830.

the 3600 MTU/yr rate used in the MRS conceptual design to a processing rate of 2500 MTU/yr for this report. Sixty percent of the spent fuel (1500 MTU/yr) is considered to be from PWR's and 40% (1000 MTU/yr) from BWR's.

TREATMENT ALTERNATIVES

The treated waste volumes, the loading in canisters, and thermal heat load are calculated and the basic processes are described for each of the alternatives in the following sections. Data for canisters for the three reference repositories are based on the maximum-size canisters acceptable for the respective designs. The results are compiled in Table III.

Shredding (MRS Reference)

This alternative duplicates the treatment currently planned for the proposed MRS facility except that the MRS conceptual design has a shredder in each of the four processing cells. For consistency, all of the processing is assumed to be done in two shredders adjacent to each pair of consolidation cells. This decision requires removal of the NFBH from the consolidation cells to the treatment areas. Shredding would be a one-step process. The NFBH would be removed from the cell to the shredder. The shredders would reduce the size of the metal pieces to fit them in the canisters and to provide a higher density than the residual assembly pieces. The shredded NFBH would then be loaded into an appropriate-size canister. The shredded NFBH would have a low bulk density of about 900 kg/m^3, but would still occupy less volume than the untreated NFBH.

Shredding and Low-Pressure Compaction

For this alternative, the shredded material would be subsequently compacted with a low-pressure compactor at a pressure of about 7 MPa. The low-pressure compactor would be located near the shredder so that successive batches of shredded NFBH would be added to the canister after compaction. Compaction will further reduce the volume and increase the density of the NFBH in the canister. The final bulk density is estimated to be about 1800 kg/m^3.

Shredding and Supercompaction

Supercompaction is similar to low-pressure compaction except that it uses pressures of about 60 MPa, which increases the final bulk density of the NFBH to an assumed density of 3700 kg/m^3. Even higher densities of individual compacts of simulated spent fuel hulls have been reported recently (5). Packaged densities are lower because of clearance requirements within the canisters and the extra volume from the canister used to hold the material for compaction.

Supercompaction provides this high-volume reduction of wastes without extensive treatment. The process is being used for the treatment of low-level wastes in both the U.S. and Europe (6,7). In this analysis the wastes are shredded and placed in 208-liter (55-gal) drums to prepare them for supercompaction. Other alternatives, such as cutting the hardware into acceptable-length sections or using a different size drum, could also be utilized.

Table III

Waste Volumes and Characteristics for Treatment Options

Repository Canister	Canister Volume(a) (m^3)	Canister Weight of NFBH(b) (Kg)	Number of PWR(c) Canisters	Thermal(d) Power(PWR) (watts)	Number of BWR Canisters	Thermal(d) Power(BWR) (watts)
Shredded NFBH						
Basalt	1.31	1180	116	387	203	41
Tuff	1.44	1290	106	424	185	45
Salt	1.27	1140	120	374	209	40
Shredded and Low-Pressure Compacted NFBH						
Basalt	1.31	2360	58	773	101	82
Tuff	1.44	2590	53	849	92	90
Salt	1.27	2280	60	749	105	79
Shredded and Supercompacted NFBH						
Basalt	1.31	4870	28	1600	49	169
Tuff	1.44	5340	23	1950	40	206
Salt	1.27	4720	29	1550	51	164
Melted NFBH						
Basalt	1.31	6680(e)	21	2190	36	232
Tuff	1.44	9340	13	3410	23	360
Salt	1.27	8240	17	2700	29	286

(a) Based on canister diameters of 63, 66, and 62 cm, respectively, and a canister length of 4.20 meters.

(b) For PWR spent fuel - weight of 38 kg/assembly and 0.462 assemblies per MTU. For BWR spent fuel - weight of 40 kg/assembly and 0.186 assemblies per MTU.

(c) Based on 1500 MTU/yr of PWR spent fuel and 1000 MTU/yr of BWR spent fuel. Canisters filled to 90% of capacity.

(d) Heat generation at 10 years out of reactor from ORIGEN2 with 33,000 MWD/MTU for PWR's and 28,000 MWD/MTU for BWR's.

(e) Weight of NFBH in basalt canister limited by thermal power of spent fuel.

Melting

The melting alternative provides the highest possible volume reduction for the NFBH. Although heating of the metals to high temperatures is required, the melting point of the mixed-metal NFBH is lower than those of the individual alloys because new eutectics are formed. The lower melting point reduces the process temperature and should reduce the vaporization rate of radionuclides. The melting system design is expected to allow the whole residual assembly to be moved into the melter, rapidly fed into the melting crucible, and melted. Thus, shredding and its associated problems would be avoided.

The development of the melting process has been under way for several years for different types of metallic waste (8). The process appears applicable to the NFBH. The molten metal can be cast into any of the waste canisters on a batch basis.

The volume reduction of the melted materials is sufficiently high to raise concerns about the thermal power of the canister, canister weight, and radiation doses.

COST CONSIDERATIONS

Cost estimates were prepared for each of the NFBH treatment alternatives studied. The cost of each of the following activities was estimated: construction and operation of the NFBH treatment portions of the central treatment facility, including associated service facilities and decommissioning; transportation of the NFBH to the deep geologic repository; and disposal of the NFBH in a deep geologic repository. The costs are in current dollars on an undiscounted basis. Costs for research and development, licensing, selection, and development of the repository were not included.

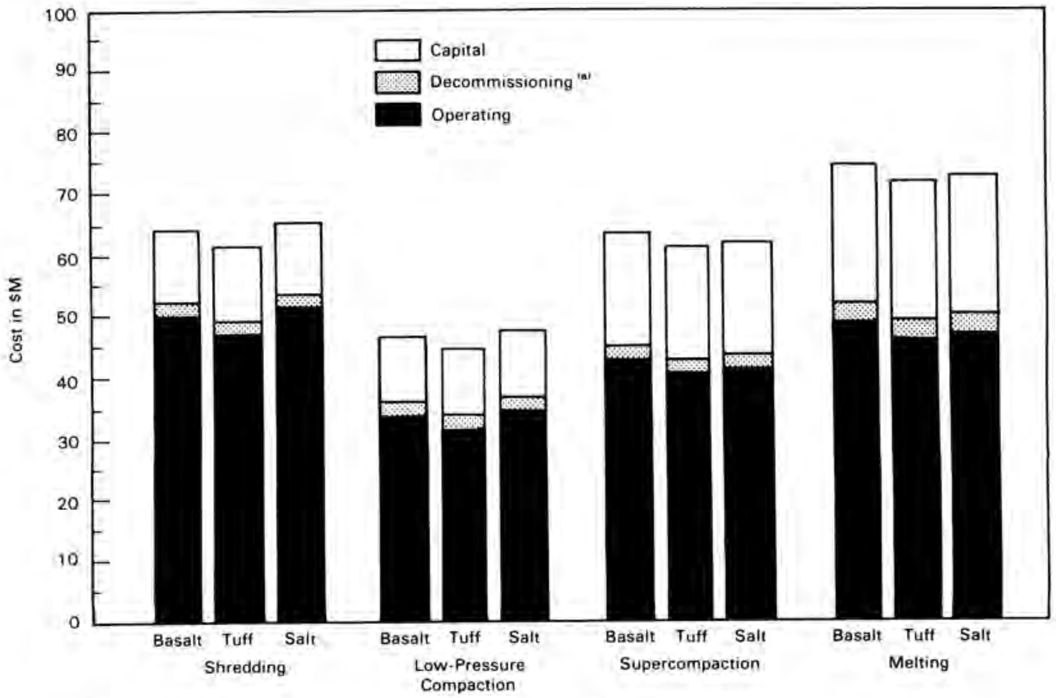
Treatment Costs

The capital cost estimates for this study are based on general unit factors (1). The capital costs for the alternatives are modest, ranging from about \$11 M to \$22 M. The four months of lag storage and the assay facilities for treated waste comprise the predominant treatment cost element for the alternatives with little or no volume reduction (shredding only and shredding with low-pressure compaction), but these costs are a small fraction of the total capital costs for the alternatives with significant volume reduction (shredding with supercompaction and melting).

The operating costs include all costs for labor, maintenance, utilities, canisters, all other materials, and occasional facility upgrading for operating the incremental NFBH treatment facility and associated service areas. The estimated operating costs for the alternatives vary only about 5%. The variance results from the differences in canister costs for the three repository types.

The lifetime operating costs for all alternatives are two to five times greater than the capital costs. Canister costs are a significant part of the operating costs for all alternatives and are the predominate operating costs for the shredding-only and shredding with low-pressure compaction alternatives. Storage and assay costs are also highest for these two alternatives with the highest final waste volumes.

The life-cycle capital and operating costs and the decommissioning costs for the incremental treatment facility are summarized in Fig. 1, which shows the dominance of the operating costs in the total lifetime costs of the incremental NFBH treatment facility. Decommissioning costs, which are based on a fraction of the initial capital costs (9), are the smallest cost element of the three major cost elements in Fig. 1.



[a] Decommissioning costs are taken to be 12% of capital cost per DOE 1986

Fig. 1. Lifetime (62,000 MTU) Capital, Operating, and Decommissioning Costs of NFBH Treatment Alternatives

Transportation Costs

The treated NFBH is assumed to be shipped to a deep geologic repository that is 2000 miles from the central treatment facility. It is shipped on a rail transportation system (9) owned and operated by the federal government, using five-car dedicated trains. The transportation costs are highly dependent on the treated waste volumes, and they exceed the total lifetime facility capital and operating costs for the alternatives with high volumes of treated wastes (the shredding-only and shredding with low-pressure compaction alternatives). The transportation costs can be noted with the total costs in Fig. 2.

Disposal Costs

The NFBH from the central treatment facility is assumed to be disposed of in a deep geologic repository. Three repository media have been considered in determining the costs. The costs have been developed for two cases: the first assumes that the canisters of NFBH are disposed of with canisters of spent fuel under a high-quality overpack to provide long-term protection; the second case assumes that the canisters of NFBH are stored in a separate part of the repository without the need for overpacks. The number of canisters processed, the overpack requirements, and the spacing of the waste canisters in the repositories based on the heat generation rates are the primary considerations in the development of repository disposal costs. Only the lower disposal cost estimate (either no overpack or heavy overpack) for each treatment alternative and repository media is shown in Fig. 2.

Total Life-Cycle Costs

The NFBH management total life-cycle costs (exclusive of research and development and repository siting development and engineering costs) for the four treatment alternatives are summarized in Fig. 2. It can be readily noted that volume reduction is cost effective and that a total savings of about $400 million to $500 million can be expected when using the high-volume-reduction technology of melting or supercompaction compared with the shredding-only alternative.

WASTE FORM CHARACTERISTICS

Spent fuel assemblies containing NFBH without any additional treatment are currently acceptable for disposal. Therefore, any of these treatment processes should produce an acceptable waste form. Review of potential waste form requirements, however, indicates that the waste form may be required to have specific characteristics. The most significant characteristics are:

- low release rate of radionuclides from the waste form, especially during water contact, which is viewed as the most likely release mechanism following geologic disposal
- immobilized particulates (to avoid release of material if a canister fails during handling or transportation and to reduce potential release rates)
- no pyrophoric potential in the waste materials (important during waste package handling, transportation, and storage)
- structural stability to assist in preventing mechanical failure of the canister, overpack, or container.

Since actual waste forms have not been prepared and characterized, detailed characteristics are not documented. However, experience with similar materials allows a general comparison to be made (Table IV).

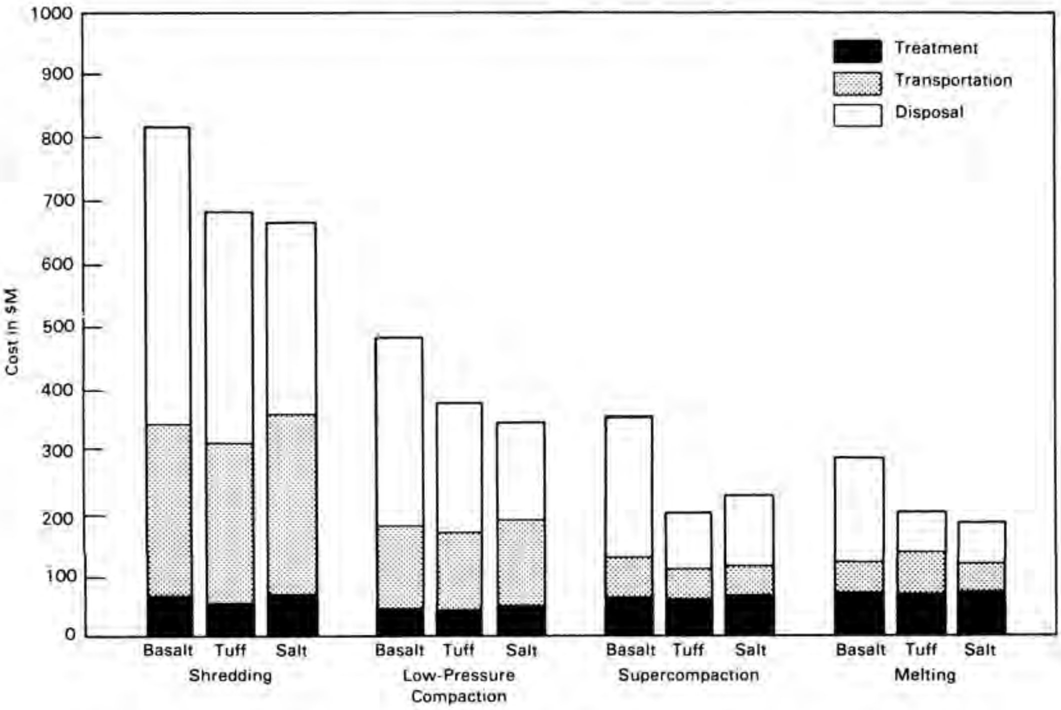


Fig. 2 Lifetime (62,000 MTU) Treatment, Transportation, and Disposal Costs for NFBH Treatment Alternatives.

TABLE IV

Evaluation of Waste Form Characteristics for Process Alternatives

Evaluation Factor	Shredding	Shred/Low-Pressure Compaction	Shred/Supercompaction	Melting
Release Rate	-	-	o	+
Particulates	-	-	o	+
Pyrophoricity	-	-	o	+
Structural Stability	-	o	+	+
Acceptability	Questionable	Questionable	Questionable	Acceptable

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Key
+ = Attractive
o = Moderate
- = Less Desirable

The release rate is expected to decrease with increasing density of the waste forms and should be significantly better for the melted product. The porous structure of the supercompacted material would permit leachants ready access. But because of its higher density, the supercompacted material may provide a higher resistance to leaching than the lower-density alternatives. The compaction and melting of the NFBH should reduce the availability of the particles for release. The melted product should not have a significant number of particles, and the supercompacted particulate should be trapped within the compacted mass. Therefore, these two waste forms are rated higher than the low-pressure compaction and shredded materials.

Shredding can be expected to generate some fines, and compaction may also generate some new surfaces and fines that can react with atmospheric oxygen and be slightly pyrophoric. Fines within the supercompacted mass should be less available and therefore less reactive. Fines would be eliminated by melting, and therefore, melting has the best pyrophoricity rating.

Structural stability is mostly dependent on the void volume within the canister that may provide space for backfill materials to flow into in the event of an overpack failure during disposal. Thinning of the backfill could reduce the long-term containment of the radionuclides.

The waste forms have been rated in relationship to their final density. The above analyses show that the melted product is most attractive and that density influences the behavior of the waste form for most of the characteristics considered.

PROCESS EVALUATIONS

The processes required for these waste treatment alternatives also were evaluated based on experience with these processes using other types of materials. A summary of the comparisons of the four treatment alternatives is shown in Table V. Summary comments are listed for each alternative for each of the three major process evaluation categories (operational safety, process simplicity, and technology status). As noted in the detailed comments below, the shredding alternative has preferable processing characteristics, and the melting and supercompaction alternatives will need additional development before they can be utilized.

Operational Safety

The operational safety category is subdivided into chemical hazards, fire hazards, mechanical hazards, electrical hazards, and radionuclide release.

The off-gas system, part of the melting alternative would probably contain liquids and chemical agents and therefore represents the greatest chemical hazard. However, this hazard is of minor significance. The shredder and compactors do not use any chemicals and would have a low hazard potential.

Fire hazards result from the generation of pyrophoric particulates, the use of combustible fluids, and operations at high temperature. The shredder has the potential for generating pyrophoric materials, and the melter, operating at high temperatures and handling hot zirconium metal, also has potential safety concerns.

Mechanical hazards were judged based on the degree of mechanical action. Thus, the shredder has the highest potential. Electrical hazards are related to the amount of electrical power used in the process and any significant potential problems in handling it. The shredder, supercompactor, and melter will use significant amounts of power (about 75 to 100 kW). However, this amount of power does not represent a major hazard because it can be easily handled with conventional technology.

The radionuclide release hazard is based on the potential of release to the atmosphere. The melter was judged to have the highest release potential because material will be volatilized in the melter and will have to be removed by the off-gas treatment system. The shredder and the compactors would generate particulate (mostly "crud") that would be released to the cell. No hazard appears to disqualify any of the processes from satisfactory operation in remote conditions.

Process Simplicity

The three primary factors in process simplicity are equipment complexity, operational complexity, and maintenance requirements. For equipment design complexity, the shredder was judged to be the simplest with only one step. Low-pressure compactors have a simple hydraulic ram and were also considered simple except that the canisters were considered to be filled

TABLE V

Evaluation of Process Characteristics for Processing Alternatives

Evaluation Factor	Shredding	Shred/Low-Pressure Compaction	Shred/ Supercompaction	Melting
Operational Safety	Satisfactory	Satisfactory	Satisfactory	Satisfactory
Chemical	+	+	+	o
Fire	-	-	-	-
Mechanical	-	-	-	+
Electrical	+	+	+	+
Radionuclide Release	o	o	o	-
Process Simplicity	Greatest Simplicity	Moderate	Complex	Complex
Equipment Design	+	o	-	-
Operations	+	o	-	-
Maintenance	+	o	-	-
Technology Status	Available	Available	Some Development	Development Needed
Hot Cell Use	o	o	o	-
Radioactive Use	+	+	+	o
Industrial Use	+	+	-	+
Time to Implement	+	+	o	-

Key
+ = Attractive
o = Moderate
- = Less Desirable

and compacted in a series of successive operations. The supercompactor was judged complex because it requires an accurate drum positioner; has high-pressure hydraulics, massive rams, and dies that must resist mechanical yielding; and must be designed to remove the compacts from the dies following the extrusion of metal materials in the die. It must also have a more complicated canister-loading system to prevent overloading and to optimize the filling. The melter would have an atmospheric protection chamber to avoid oxygen in the melting chamber, a control method for the electrical power, a cooling system for the melting chamber, a method for feeding the NFBH into the melting region, and a method to monitor the fill in the receiving canister. However, the melting system is conceptually considered to be much smaller than the supercompactor.

Operational complexity is similar to equipment complexity. Because of the need for an atmospheric control system in the melter, it is expected to be operationally complex. The multiple mechanical systems of the supercompactor make it operationally complex also.

Maintenance requirements will not be known until the systems have been operated with the anticipated wastes, but the melter would likely require regular maintenance on the electrodes or heat sources. The high-pressure hydraulic system and the high mechanical forces used in the supercompactor are also expected to necessitate frequent maintenance.

Status of Technology

The status of the technology is evaluated based on experience with the process in hot cells, radioactive service, and industrial usage, and on the time needed to implement the technology if it is selected.

The only process operation that has seen hot cell service is the off-gas system. Low-pressure compactors have been used in a remote environment for reducing reactor wastes, and some installations also have supercompactors that are remotely operated. Melters and shredders have not been previously used in hot cells. Low-pressure compactors have seen the greatest radioactive use outside of hot cells. Shredders have been used in limited applications, and supercompactor use is increasing with the increasing costs of low-level waste disposal. Melters have been used to treat lightly contaminated metals at both Oak Ridge National Laboratory and Idaho Nuclear Engineering Laboratory. Industrial use of the equipment provides a base of technology that can be very useful in the design and operation of the processes. Melting systems are very common in the preparation and processing of metals. Shredding is likewise used heavily in industry for a wide variety of applications. Low-pressure compaction is a common technology, but supercompaction is relatively new technology.

A shredding system with or without a low-pressure compaction option could be designed most quickly. The melter system would take the longest to implement since it needs to be designed for this application and then tested. Supercompaction, with its need for significant maintenance and process complexity, would also require an extended design and testing period.

Summary of Process Ratings

The summary of process ratings in Table VI shows that the shredding alternative has the greatest simplicity and is most available. These characteristics were important in the selection of shredding as the reference process for the MRS. The melting and supercompaction alternatives are more complex and will require some development time if they are selected for implementation.

TABLE VI

Comparison of Strengths and Weaknesses of Treatment Alternatives

Alternative	Major Strengths	Major Weaknesses
Shredding	- Process Simplicity - State of Technology	- Pyrophoric Fines - Low Bulk Density - High System Costs
Low-pressure Compaction	- Simple Technology - Significant Volume Reduction - Remote Experience	- Pyrophoric Fines - Low Bulk Density - High System Costs
Supercompaction	- High Volume Reduction - Low System Costs - Better Waste Form Properties	- Mechanically Complex - High Potential Maintenance - Limited Remote Experience - No Destruction of Organic Materials
Melting	- Low System Costs - Best Waste Form Properties - No Fines Generation - Highest Volume Reduction - Few Mechanical Parts	- High Temperature Operation - Atmospheric Control Needed - Need Technology Demonstration - Maintenance of Electrodes and Crucibles - Coolants Needed

EVALUATION OF TREATMENT METHODS

A comparison of the strengths and weaknesses of the four treatment alternatives is shown in Table V. As indicated in the table, the shredding alternative has better process characteristics, but it is higher in cost and produces a less desirable waste form than the other alternatives. Melting has the lowest cost and the best waste form but the least desirable process characteristics. Supercompaction is similar in costs and process to melting and has a better waste form than shredding. Low-pressure compaction, although a simple technology, is more complex than shredding. It offers some cost improvement, but not as great as the savings with melting and supercompaction. Low-pressure compaction waste forms characteristics are similar to those of shredding.

Any of the four alternatives provide for the treatment of the NFBH. However, the selection should take into consideration all of the comparative strengths and weaknesses. Both melting and supercompaction have major strengths, including the potential to save up to $500 million dollars in the MRS system and to improve the quality of the waste form. A testing program would provide more detailed information upon which to make a final selection. Such testing is recommended for the melting and the supercompaction alternatives.

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