ORNL/TM-2002/274

PRECONCEPTUAL DESIGN AND COST STUDY FOR A COMMERCIAL PLANT TO PRODUCE DUAGG FOR USE IN SHIELDED CASKS

December 2002

Juan J. Ferrada
Leslie R. Dole
Meeca Hamilton

ORNL/TM-2002/274

Nuclear Science and Technology Division

Preconceptual Design and Cost Study for a Commercial Plant To Produce DUAGG for Use in Shielded Casks

Juan J. Ferrada, Oak Ridge National Laboratory
Leslie R. Dole, Oak Ridge National Laboratory
Meeca Hamilton, North Carolina A&T State University

Date Published:
December 2002

Prepared by
OAK RIDGE NATIONAL LABORATORY
P.O. Box 2008
Oak Ridge, Tennessee 37831-6285
managed by
UT-Battelle, LLC
for the
U.S. DEPARTMENT OF ENERGY
under contract DE-AC05-00OR22725

CONTENTS

FIGURES

TABLES

ABBREVIATIONS AND ACRONYMS

DOE	U.S. Department of Energy
DU	depleted uranium
DUAGG	depleted uranium aggregate
DUCRETE	depleted uranium concrete
DUPoly	depleted uranium oxide powder
HLW	high-level waste
INEEL	Idaho National Engineering and Environmental Laboratory
NTS	Nevada Test Site
ORNL	Oak Ridge National Laboratory
PYRUC	pyrolytic uranium compound
SNF	spent nuclear fuel
UDS	Uranium Disposition Services
UO_2	urania
UO_x	uranium oxide

EXECUTIVE SUMMARY

The cost of producing DUAGG is an important consideration for any interested private firm in determining whether DUCRETE is economically viable as a material of construction in next-generation spent nuclear fuel casks. This study analyzed this project as if it was a stand-alone project. The capital cost includes engineering design, equipment costs and installation, start up, and management; the study is not intended to be a life-cycle cost analysis. The costs estimated by this study are shown in Table ES.1, and the conclusions of this study are listed in Table ES.2. The development of DUAGG and DUCRETE is a major thrust of the Depleted Uranium Uses Research and Development Project.[a] An obvious use of depleted uranium is as a shielding material (e.g., DUCRETE).[b] DUCRETE is made by replacing the conventional stone aggregate in concrete with DUAGG. One objective of this project is to bring the development of DUCRETE to a point at which a demonstrated basis exists for its commercial deployment. The estimation of the costs to manufacture DUAGG is an important part of this effort.

Paul Lessing and William Quapp[c] developed DUAGG and DUCRETE as part of an Idaho National Engineering and Environmental Laboratory (INEEL) program to find beneficial uses for depleted uranium (DU). Subsequently, this technology was licensed to Teton Technologies, Inc. The DUAGG process mixes DUO_2 with sintering materials and additives to form pressed briquettes. These briquettes are sintered at 1300°C, and the very dense sintered briquettes are then crushed and classified into gap-graded size fractions. The graded DUAGG is then ready to be used to make high-strength heavy DUCRETE. The DUCRETE shielding will be placed into an annular steel cask-shell mold, which has internal steel reinforcing bars.

The objectives of this study are to (1) use previous DUAGG process developments to design a plant that will produce DUAGG at a baseline rate, (2) determine the size of the equipment required to meet the DUAGG production scale, (3) estimate the facility's capital and operating costs, and (4) perform a parametric sensitivity analysis on those elements of cost that most affect the total operating expenses. Because the study does not include preoperational, decontamination, decommissioning, and closure costs, it cannot be considered a complete life-cycle cost analysis. However, the purpose of this analysis is to establish the potential viability of the DUAGG process as a private commercial venture to meet a market demand for advanced spent nuclear fuel (SNF) storage and transport casks.

This study uses DUO_2 as the starting feed material and assumes a baseline production rate to support a commercial SNF market penetration of 30% in the domestic demand for casks. This would require sufficient DUAGG production to make 50 SNF casks a year. To fabricate 50 SNF casks per year, 2834 tonnes of DUO_2 is needed to form 3114 tonnes of DUAGG per year. This production rate established the size of the equipment that will be needed to implement the production goals as shown on the DUAGG flowsheet. Site support facilities and plant layout were also based on this production capacity. Capital and operating costs for the United States were determined based on the unit-operations equipment used in the flowsheet, the layout of the plant, and the labor requirements.

---

[a] R.R. Price, M. J. Haire, and A.C. Croff, "Depleted Uranium Uses R&D Program," Waste Management 2001 Symposium, Tucson, AZ, Feb 25–March 1, 2001.

[b] L.R. Dole and W.J. Quapp, "Radiation Shielding Using Depleted Uranium Oxide in Nonmetallic Matrices," ORNL/TM-2002/111, Oak Ridge National Laboratory, Oak Ridge, Tenn., August 2002.

[c] W.J. Quapp and P.A. Lessing, U.S. Patent No. 5,786,611, "Radiation Shielding Composition," July 28, 1998.

Additional capital costs were estimated using industry-standard factors based on the total process equipment cost,[d] including (1) 25% for piping, (2) 13% for instrumentation and control, (3) 25% for safety systems, (4) 10% for electrical costs, (5) 5% for shipping, (6) 25% for installation, (7) 10% for civil site preparation, (8) 10% for buildings and structures, (9) 7% for spare parts, (10) 25% for management, and (11) 33% for engineering.

Operating costs included (1) labor, (2) management, (3) chemicals, (4) electrical, (5) transportation, and (6) capital recovery. Twenty-six employees is the industry standard for a plant of this size. Other assumptions for the baseline case are that (1) The U.S. Department of Energy (DOE) supplies the DUO_2 to the DUAGG plant at no cost, (2) the radiological worker labor cost is \$80/h, (3) the engineering cost is \$100/h, (4) the capital recovery cost rate is 20%, and (5) the current cask design uses 57 tonnes of DUAGG /cask.

The results of these assumptions are that the estimated baseline total capital costs are \$11.6M and the operating costs are \$6.4M per year. This results in a baseline cost for DUAGG of \$129K per cask, or \$2.27/kg. The most important cost elements are labor, representing 62% of the baseline operating costs, followed by capital recovery costs at 36%.

A sensitivity analysis was performed for a credit that would be given for using DUO_2 feed to the DUAGG manufacturing plant. The lower bound used in this study corresponds to the baseline case, for which there is no credit. For the upper bound, it was assumed that the company producing the DUAGG would receive a 100% credit, which would be equivalent to the savings for not having to transport and dispose of the DU_3O_8. The DU_3O_8 bulk specific gravity has been estimated conservatively as 2.5 for transportation and disposal costs. The disposal cost has been estimated at \$11/ft3. A credit of 100% is equivalent to \$384 per tonne of DUO_2, where about 50% of the credit corresponds to disposal and 50% to transportation, and the credit lowers the operating cost to \$5.3M per year, a decrease of 17% from the baseline. The cost per cask then drops to \$104K, or \$1.67/kg.

Another consideration included in this analysis was the assumption that the DUO_2 material could be delivered as briquettes within the specifications for producing DUAGG, resulting in further savings. The number of production units can be reduced, thereby reducing capital and operating costs. The capital cost will decrease to \$8.9M, and the operating cost will be lowered to \$4.1M. Considering these savings, the cost per cask drops to \$1.32/ kg of DUAGG, and the cost of each cask will be reduced to \$82K.

Labor cost is an operating cost item that may vary, depending on whether the plant is integrated to a federal facility or is operated by a private company. The baseline considers a labor cost of \$80/h and assumes integration to a federal facility. It is possible that a private company could decrease this cost to \$40/h under special circumstances. The cost per cask drops to \$94K and the DUAGG drops to \$1.67/kg using a \$40/h of labor rate. If the analysis also includes savings for credit and delivered briquettes, the cost per cask will drop to \$48K and the DUAGG will drop to \$0.84/kg using the \$40/h labor rate.

This preconceptual design is based on a stand-alone plant, which represents a very conservative assumption. Under this condition, this study concludes that DUAGG is unlikely to be cost competitive with conventional commodity concrete aggregate materials. For example, the cost of ¾-in. limestone aggregate delivered from Rogers Group, Inc., to Oak Ridge National Laboratory (ORNL) is \$10.50/tonne; the cost of DUAGG is about a factor of 80–200 times greater at ~\$840 to

---

[d] P. A. Lessing and H. Gillman, "DU-AGG Pilot Plant Design Study," INEL-96/0166. Idaho National Engineering and Environmental Laboratory, Idaho Falls, Idaho, July 1996.

$2100/tonne. It is likely that the outcome of this project will be greatly enhanced if the DUAGG production process is integrated with the DUF_6 conversion plant in Paducah or Portsmouth, taking advantage of this industrial facility's installations and skilled labor. In addition, for DUCRETE casks to be commercially competitive, DUCRETE must offer some new, unique, enhanced cask performance characteristic. DUCRETE casks are projected to be smaller and lighter than conventional casks, and they may permit removal of the extensive network of reinforcing steel bars present in current concrete casks to allow enhanced threat protection. Quantifying cost savings resulting from enhanced performance, however, is extremely difficult.

Table ES. 1. Conclusions

1.	DUAGG cannot be produced at a cost that is competitive with conventional ¾-in. stone concrete aggregate. The cost of DUAGG is ~ $840–$2000/t whereas delivered ¾-in. stone aggregate is ~$10/t. The cost for DUAGG in an advanced SNF cask is ~$48,000–$129,000; whereas, the total cost per cask goal is $150,000.
2.	The commercial viability of DUAGG/DUCRETE depends on its enabling improved, unique cask performance characteristics. For example, DUCRETE may permit smaller, lighter-weight casks that can be transported by railcar. Conversely, DUCRETE may permit casks to contain more spent fuel assemblies at lower maximum temperatures within current volume and weight limits. DUCRETE may also enable the removal of the extensive matrix of rebar in current concrete cask designs.
3.	Operating costs dominate unit costs. Labor cost (at 62%) is the largest contributor to baseline operating costs. Capital cost recovery is ~36% of annual operating costs.
4.	Unit operating costs are sensitive to the credit of UO_2 feed materials. A change of –$384/t reduces the unit cost by 17%.
5.	Operating costs (security, health physics, licensing) could be greatly reduced if the DUAGG fabrication plant were colocated with another uranium processing facility.

Table ES. 2. Estimated DUAGG costs[*]

	$384/t DUO_2 credit		**Baseline: zero-cost DUO_2**		**$384/t DUO_2 credit [a] + savings for DUO_2 delivered as briquettes**	
	Labor cost ($/h)		**Labor cost ($/h)**		**Labor cost ($/h)**	
	80	**40**	**80**	**40**	**80**	**40**
Capital[b]	$11.6M	$11.6M	$11.6M	$11.6M	$8.9M	$8.9M
Operating[c] (year)	$5.2M	$3.8M	$6.4M	$4.7M	$4.2 M	$2.4M
Unit (cask)	$104K ($1.67/kg)	$76K ($1.34/kg)	$129K ($2.27/kg)	$94.9K ($1.67/kg)	$82K ($1.32/kg)	$48K ($0.84/kg)

[a]For fabrication of 50 DUCRETE casks per year, i.e., 3114 t DUAGG.
[b]27-person staff, engineer's cost at $100/h, capital recovery cost rate 20%.
[c]Assumes UO_2 as feed.

1. INTRODUCTION

The depleted uranium (DU) inventory in the United States exceeds 500,000 metric tonnes of material. Depleted uranium hexafluoride (DUF_6) is the non-fissionable residue from the enrichment process which was used to make nuclear-grade enriched uranium for reactors and weapons.[1] At this current time, no uses exist for the material. Therefore, an excessive amount of the material is stockpiled in Oak Ridge, Tennessee; Paducah, Kentucky; and Portsmouth, Ohio. The U.S. Department of Energy (DOE) has no choice other than to pay for disposal of the DUF_6 inventory, the cost of which has been estimated at $1.4 billion. Based on current technology and capabilities, the realistic price of disposal is $2–5 billion. Most of this material is in storage, and there is considerable debate concerning how to reuse or dispose of it. One of the most obvious uses for the DU is in nuclear shielding. If technically and economically feasible, a large portion of the U.S. inventory of DU could be used in the fabrication of nuclear shielding for the storage, transport, and disposal of spent nuclear fuel (SNF).

A research program being conducted by DOE envisions this type of use for the DU. DU metal has been used in casks as shielding because its high density provides the needed gamma attenuation for the lowest-weight and smallest casks. Studies have assessed the use of uranium metal for shielding in both spent fuel[2] and high-level waste (HLW)[3] casks. A review of DU metal production and fabrication costs showed that depleted metal was more expensive than other common shielding materials such as steel, lead, and concrete.[4] Therefore, the primary application for uranium metal shielding is for transportation casks, where the most stringent total-package size and weight limits exist and where high-cost, DU metal shielding can be justified. An added benefit to the nuclear community will be the removal of large quantities of DU from the existing national inventory.

These considerations led to a study of alternative uses for DU such as in a DU ceramic, which is still very dense but has considerably lower production and fabrication costs than DU metal. The first alternative developed was a concrete called DUCRETE™, which was followed by DUPoly, and PYRUC. DUPoly uses depleted uranium oxide powder as the filler material in a thermoplastic polyethylene binder material to produce a high-density shielding material. PYRUC uses a microaggregate DU oxide (DUO_2) that is produced by a sol-gel precipitation of uranium into microspheres in a process developed for nuclear fuel technology in the late 1960s. These sol-gel particles are then mixed with an organic binder and are pyrolyzed to make uranium carbide and/or UO_x pyrolytic carbon matrices.

All of these concepts have in common the use of DU in a neutron-absorbing binder. This provides a material that has characteristics of both an efficient gamma absorber (uranium) and a low-atomic number (low-Z), neutron-slowing material such as hydrogen or carbon. Figure 1 shows the effectiveness of using DUO_2, such as in DUCRETE, to reduce the size and weight of a dry-storage cask or silo for SNF.

The economic conclusion regarding DU metal shielding led to the consideration of alternatives such as a DU ceramic that is still very dense but has considerably lower production and fabrication costs than DU metal. The first alternative developed was depleted uranium concrete or DUCRETE. This material consists of depleted uranium ceramic that replaces the coarse aggregate used in normal concrete.[5] The DU coarse aggregate is combined with Portland cement, sand, and water in the normal volumetric ratios for ordinary concrete. If the ceramic can be produced at a sufficiently low cost, it would be practical to consider using DUCRETE as a shielding material.

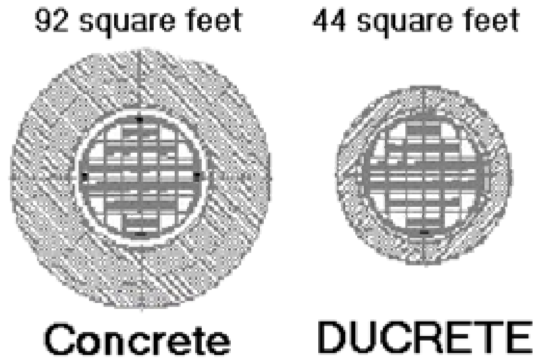


Fig. 1. Comparative diameters of concrete and DUCRETE dry-storage cask or silo. Using DUCRETE in a spent nuclear fuel cask or silo reduces the weight by 30%, the footprint by 50%, and the diameter from 132 in. (3.5 m) to 90 in. (2.3 m).

Based on this conceptual work, J. Sterbentz of Idaho National Engineering and Environmental Laboratory (INEEL) performed the first shielding calculations. [6] Initial shielding evaluations were made for DUCRETE shielding in a spent-fuel application. Figure 2 shows the nuclear shielding effectiveness of this conceptual DUCRETE shielding material. The figure compares the relative effectiveness for gamma and neutron attenuation of DUCRETE and that of other common shielding materials in a proposed SNF storage silo or cask.

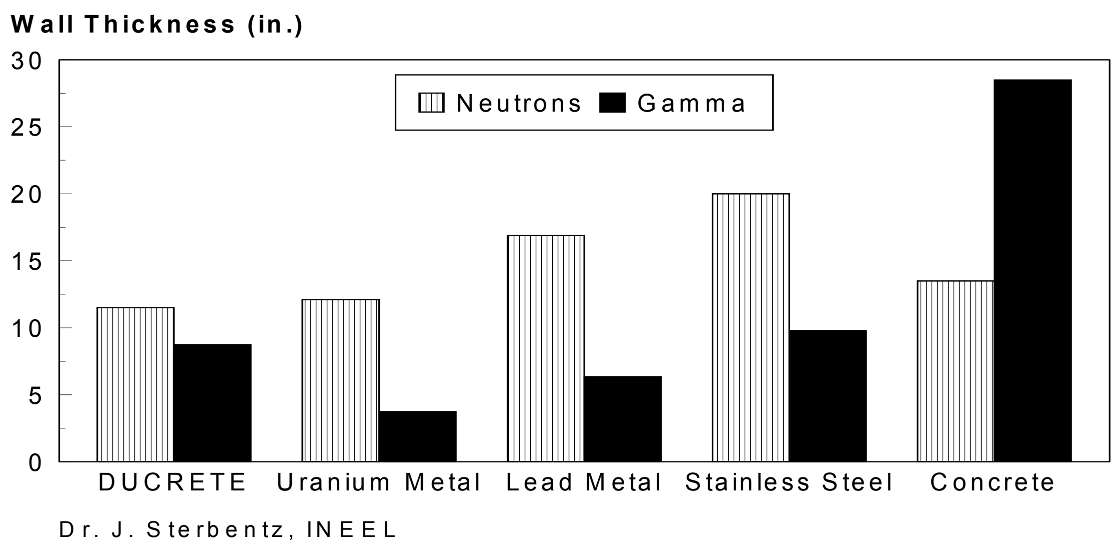


Fig. 2. Comparison of storage cask or silo wall thicknesses required to attenuate neutron and gamma doses from 24 pressurized water reactor spent nuclear fuel assemblies to 10 mR/h.

Based on this analysis, a prime application for the new shielding material is the storage, transport, and disposal of SNF. This could result in reduced weight, volume, and cost for dry-storage casks. Moreover, the domestic inventory of DU could be substantially reduced. Just for the storage of commercial SNF within the United States alone, 360,058 tonnes of DU could be used in dry-storage casks through the year 2020.

The key to effective shielding with DU ceramic concrete is maximum uranium oxide density. Unfortunately, the densest DU oxide is also the most chemically unstable. Depleted uranium dioxide, or DUO_2 , has a maximum theoretical density of 10.5 gm/cm^3 at 95% purity. However, this material readily transforms into the more stable depleted uranium trioxide (DUO_3) through oxidation or becomes the most stable depleted triuranium octaoxide (DU_3O_8).

DUAGG is the term applied to the stabilized DU oxide ceramic that was developed to reduce the rates of DUO_2 oxidation. In the formation of DUAGG, a coating covers the surfaces of sintered urania particles, fills the spaces between the grains, and acts as an oxygen barrier. This coating results in a DUO_2 that is more chemically stable and therefore may be used to produce concrete shielding material.

The production of DUAGG consists of mixing DUO_2 with sintering materials and additives to form pressed briquettes. These briquettes are sintered at 1300°C, and the very dense sintered briquettes are crushed and classified into gap-graded size fractions. The graded DUAGG is then ready to be used to make high-strength heavy DUCRETE. The DUCRETE shielding will be placed into an annular steel cask-shell mold, which has internal steel reinforcing bars, as shown in Fig. 3.

Fig. 3. Spent fuel cask manufacturing.

Previous economic studies of the production of DUAGG used DU_3O_8 as the starting material for the process.[7] However, the current study uses DUO_2 as the starting material and assumes a baseline production rate to support a commercial SNF market penetration of 30% in the domestic demand for casks. This would require sufficient DUAGG production to make 50 SNF casks a year. Using the current design basis, each cask uses approximately 57 tonnes of DUAGG in as a component of its shielding.

The objectives of this study are to (1) use previous DUAGG process[7] developments to design a plant that will produce DUAGG at the baseline rate of 50 casks per year, (2) determine the size of the equipment required to meet the production scale, (3) estimate facility capital and operating costs, and (4) perform a parametric sensitivity analysis on those elements of costs that most affect the total operating expenses. Because this study does not currently include preoperational, decontamination, decommissioning, and closure costs, it cannot be considered a complete life-cycle cost analysis. However, the purpose of this economic analysis is to establish the potential viability of the DUAGG process as a private, commercial venture to meet a market demand for advanced SNF storage and transport casks.

2. DUAGG PROCESS

Paul Lessing and William Quapp developed DUAGG and DUCRETE[5,8] as part of an INEEL program to find beneficial uses for DUF_6. The DUAGG process mixes DUO_2 with sintering materials and additives to form pressed briquettes. These briquettes are sintered at 1300°C, and the very dense sintered briquettes are crushed and classified into gap-graded size fractions. The graded DUAGG is then ready to be used to make high-strength heavy DUCRETE. The DUCRETE shielding will be placed into an annular steel cask-shell mold, which has internal steel reinforcing bars. DUCRETE is formed by combining DUAGG with normal concrete paste (cement, sand, and water). This matrix has both high-Z materials for gamma attenuation and low-Z materials for neutron attenuation. Emulating nuclear fuel technology, the sintered uranium oxide (UO_x) aggregate has a very high density (>95% theoretical density). Thus, a theoretical concrete density of 7.2g/cm^3 is possible.

DUAGG is the term applied to the stabilized, depleted UO_2 aggregate that was developed to reduce the rates of UO_2 oxidation to UO_3 and U_3O_8. In the formation of DUAGG, a coating covers the surfaces of sintered urania particles and fills the space between the grains. This coating serves as an oxygen barrier. The sintering temperature normally associated with UO_x sintering (~1700°C) is also reduced to below 1300°C, an added benefit from a manufacturing perspective. Other work at INEEL led Lessing to consider a basalt-based binder because of its demonstrated resistance to corrosion in hot aqueous environments. Therefore, DUAGG was formulated with inorganic binder materials consisting of clays, boria, iron oxide, and other materials similar in composition to basalt. Basalt is a dense crystalline rock of volcanic origin, composed largely of plagioclase feldspars ([Na, Ca] Al [Si, Al]Si_2O_8) and dark minerals such as pyroxene (~n[Si_2O_6]~) and olivine ([Mg, Fe_2] SiO_4)

As illustrated in Fig. 4, the process for making the DUAGG aggregates begins with the starting material, DUO_2. The DUO_2 is shipped into the plant in a special container, and is then dumped into a receiving hopper and transported to a crusher. The crusher sends the material to a DUO_2 silo or to a classifier. The classifier filters the DUO_2 to determine the correct size required and sends the material on to the DUO_2 silo or sends it back to the crusher to repeat the process. After the material is in the DUO_2 silo, it is transported to a mixer, where sintering and binding materials are added. The mixer blends the materials together and then, when the material gains density, transports it to a briquetter, which fabricates the briquettes into the desired size and transports them to a classifier. The classifier will separate the material and transport that which is the required size to a silo. If the size does not meet requirements, the classifier will transport the material back to the mixer, where it will repeat the process. The material will leave the silo and be transported to a sintering machine, which will be heated to about 1300°C until the maximum density of the material is reached. After the material leaves the sintering machine, it is cooled and transported to a crusher. The material leaves the crusher and is transported to a classifier. The classifier will send the material to five different silos or to a side silo, which is for the material that is finely ground. The finely ground material will be transported back to the mixer to repeat the process. The five silos will be connected to a blender. In the blender, the different-sized aggregates will be mixed with three different materials to create the final product. The final product will be placed inside the special containers and shipped to Starmet for production of the DUCRETE.

Bentonite clay, $Ca(OH)_2$, carbonates, and other chemicals are constituents of the DUAGG and will partially decompose at high temperature, concluding with the clay being dehydrated and the other additives in oxide form.

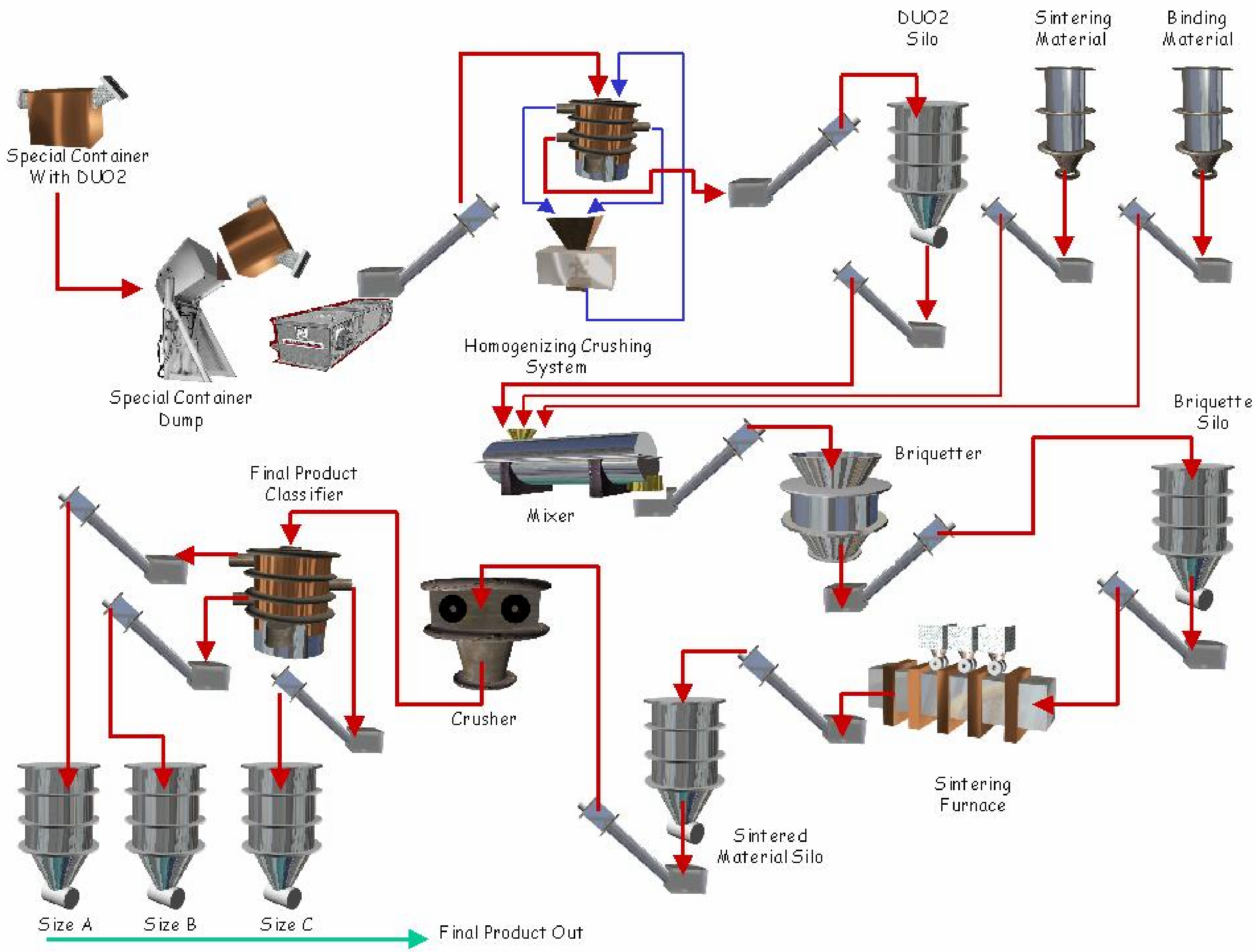


Fig. 4. Flow diagram of the DUAGG process.

3. ECONOMIC ANALYSIS

The economic analysis engaged in this study is geared to obtain the production cost of DUAGG as if a commercial company would be interested in pursuing the commercial venture of producing DUAGG. The study is not intended to estimate the life-cycle cost of the project; therefore, it does not include cost estimates for preengineering, Title 1, Title 2, decontamination and decommission of the plant, etc. The life-cycle duration of the plant has not been a part of this analysis. The study includes a baseline case and variations on the production cost due to changes to the specifications of the incoming DUO_2, credits given to a company for applying a beneficial use of the DU_3O_8, and labor costs.

The baseline case includes all the process equipment considered during the process development, and no attempt has been performed to optimize the flowsheet defined in Section 2 of this report. No credits are given to this project for the beneficial use of DU_3O_8. The production cost does not include contingencies. Section 4 of this study analyzes variations to the production cost by changing several parameters.

The capital cost estimate includes cost items such as engineering and design; equipment and installation; land, buildings, and facilities; and management cost. The operating cost includes only the main production cost items such as labor, energy, supervision, security, and chemicals. Because the process equipment is all off-the-shelf equipment, no contingency cost has been considered in the baseline case.

The economic analysis focuses on (1) the design of a DUAGG plant that receives DUO_2, (2) the processes to produce pressed and sintered briquettes, and (3) the methods to crush, size, and package the DUAGG that will be used in high-strength DUCRETE for SNF casks. The process receives DUO_2 from external source that most likely will be the DUF_6 conversion plant at Portsmouth or Paducah. Sintering and binding materials for milling, blending, pressing, sintering, and crushing are activities from this process. The final product consists of crushed, gap-graded and amended DUAGG product for use in DUCRETE that is formed off-site.

Production rate of this process has been assumed to be 2,834 tonne per year to meet 30% penetration of the domestic market for SNF storage and transport casks (about 50 casks). To fabricate 50 SNF casks per year, 2834 tonnes of DUO_2 are needed to produce 3114 tonnes of DUAGG per year. This production rate established the size of the equipment needed to implement the production schedule shown in the DUAGG flowsheet. Site support facilities and plant layout were also based on this production capacity. Based on the unit-operations equipment used in the flowsheet, the layout of the plant, the labor requirements, and the capital and operating costs were determined.

Conceptually, the process plant will be able to receive special containers with DUO_2 from the Paducah and Portsmouth uranium enrichment plants. Although the location for this production plant has not yet been determined, it is likely that the plant will be located close to Portsmouth or Paducah or co-located at one of these two sites that will produce the DUO_2. The material could then be stored in silos and moved to the production site using auger conveyors. The material will be sized appropriately for manufacturing the briquettes; this process may include size reduction and classification. After the sized/classified material is mixed with briquetting agents, it is sintered in a belt conveying sintering system. The sintered material will then be crushed and sized according to the needs of the DUCRETE manufacture and stored in product silos until it is dispatched to the manufacturing plant.

3.1 BASELINE CAPITAL COST

The determination of equipment involved in the baseline capital cost was based on the process developed by Lessing and Quapp. The baseline process was defined based on these authors' work without any attempt to optimize the flowsheet they provided. Later, a sensitivity analysis will consider possible modifications to this flowsheet based on the process to convert UF_6 into oxides that was recently contracted by DOE to a conglomerate of companies.

Based on the unit-operations and support equipment costs, the additional capital costs were estimated using industry-standard factors expressed as a percentage of the equipment costs;[7] these costs include (1) 25% for piping, (2) 13% for instrumentation and control, (3) 25% for safety systems, (4) 10% for electrical costs, (5) 5% for shipping, (6) 25% for installation, (7) 10% for civil site preparation, (8) 10% for buildings and structures, (9) 7% for spare parts, (10) 25% for management, and (11) 33% for engineering.

3.1.1 Equipment

The DUAGG process consists essentially of the following seven systems: (1) the DUO_2 receiving system, (2) the system for crushing agglomerated input DUO_2, (3) the system for receiving sintering and binding material, (4) the system for mixing of DUO_2 with sintering and binding materials, (5) the briquette-forming system, (6) the sintering system, and (7) the gap-grading system. Appendix A describes the number and estimated cost of pieces of equipment for each system within the process.

Process equipment for this plant is standard, and no customization will be necessary. There are only three sections of the plant that require some attention for the specificity of the unit operations: (1) the briquetter, (2) the sintering system, and (3) the dust control system.

3.1.1.1 Briquetter

This equipment will produce the briquettes that are DUO_2 mixed with basalt sintering agent and binding material. Figure 5 shows DUAGG briquettes made during the process development stage at Starmet. The briquetting process allows a thorough mixture of oxide and sintering and binding agents. In addition, the mixture gains in density.

Fig. 5. DUAGG briquettes.

This study considers a process design that incorporates only one shape and size of briquettes. However, for optimization purposes, it would be interesting to analyze the possibility of designing a briquetter that would produce agglomerated material of different shapes and sizes. If this option were successful, then the grinding stage with the corresponding vacuum and dust control system, which is part of this design, would not be necessary, thus decreasing the capital and operating costs.The gap-graded material also greatly enhances the strength of the final DUCRETE that is poured into the cask shield. The briquetter discussed in this report is shown in Fig. 6.

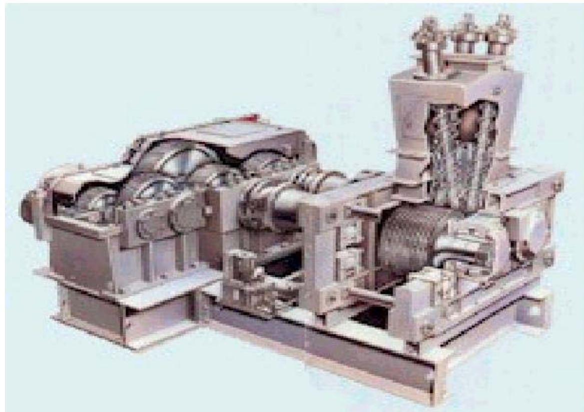


Fig. 6. DUAGG briquetter.

3.1.1.2 Sintering System

The sintering system is a type of specialized equipment used in the metallurgical industry. The system included in this study is essentially a covered metallic belt conveyor that is fed with the crushed briquettes. The briquettes are transported horizontally through zones of increasingly higher temperatures. The system is kept under a mild inert atmosphere. After an appropriate residence time at these temperatures, the crushed briquettes are sent to a temporary storage silo. Figure 7 illustrates the system included in this study.

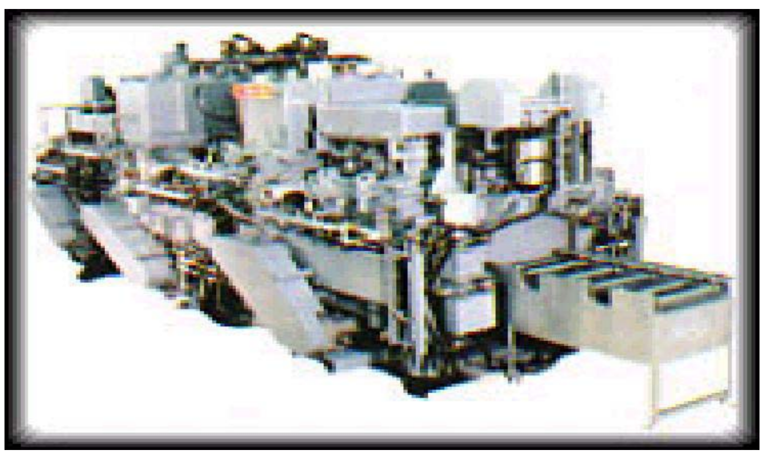


Fig. 7. Sintering system.

3.1.1.3 Vacuum and Dust Control System

The handling, grinding, and briquetting systems can produce a great deal of dust. A centralized vacuum system attached to a wet scrubber followed by air-drying equipment can eliminate the problem of air contamination with UO_2. A HEPA filtering system will conduct the air to the stacks. Each piece of dust-producing equipment will reside in separate rooms, furnished with ducts attached to the centralized dust control room that contains cyclones, scrubbers, vacuum pumps, air driers, and HEPA filters. The dried dust will be recycled to the process. Cost details are in Appendix A.

3.1.2 Land, Site, and Buildings

The different sections of the process are located in the physical space as illustrated in Fig. 8. Each of these process sections will be in a building that is subdivided into rooms, and each is connected to a vacuum system. The total area of the plant also includes space for utilities, maintenance, administrative offices, parking, roads around the plant, and an expansion lot for future growth. The required space is 170 ft by 265 ft. The cost of the land was estimated as $10K/acre. The buildings are constructed in concrete with vacuum air systems. The cost of the process building was estimated as $\$185/ft^2$.

The layout for the process sections within the building and the support buildings is shown in Fig. 9, which represents the main areas for the process in an approximate dimensional scale. Table 1 indicates the capital cost per section of the process and land and buildings. The capital cost for equipment, land, and buildings is $4844K.

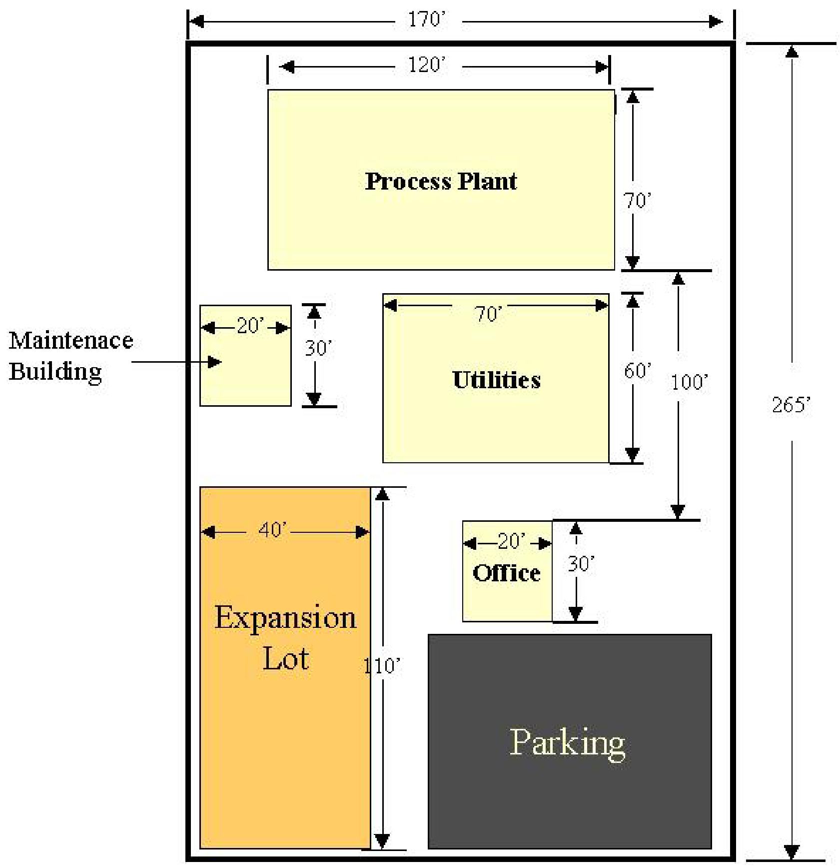


Fig. 8. Layout of the plant.

3.1.3 Total Capital Cost

Table 2 indicates the total capital cost estimates, including engineering, piping, management, etc. The total estimated capital cost is $11,601K. Most of the equipment can be readily obtained off-the-shelf from national vendors. Consequently, the baseline calculations do not include contingency costs.

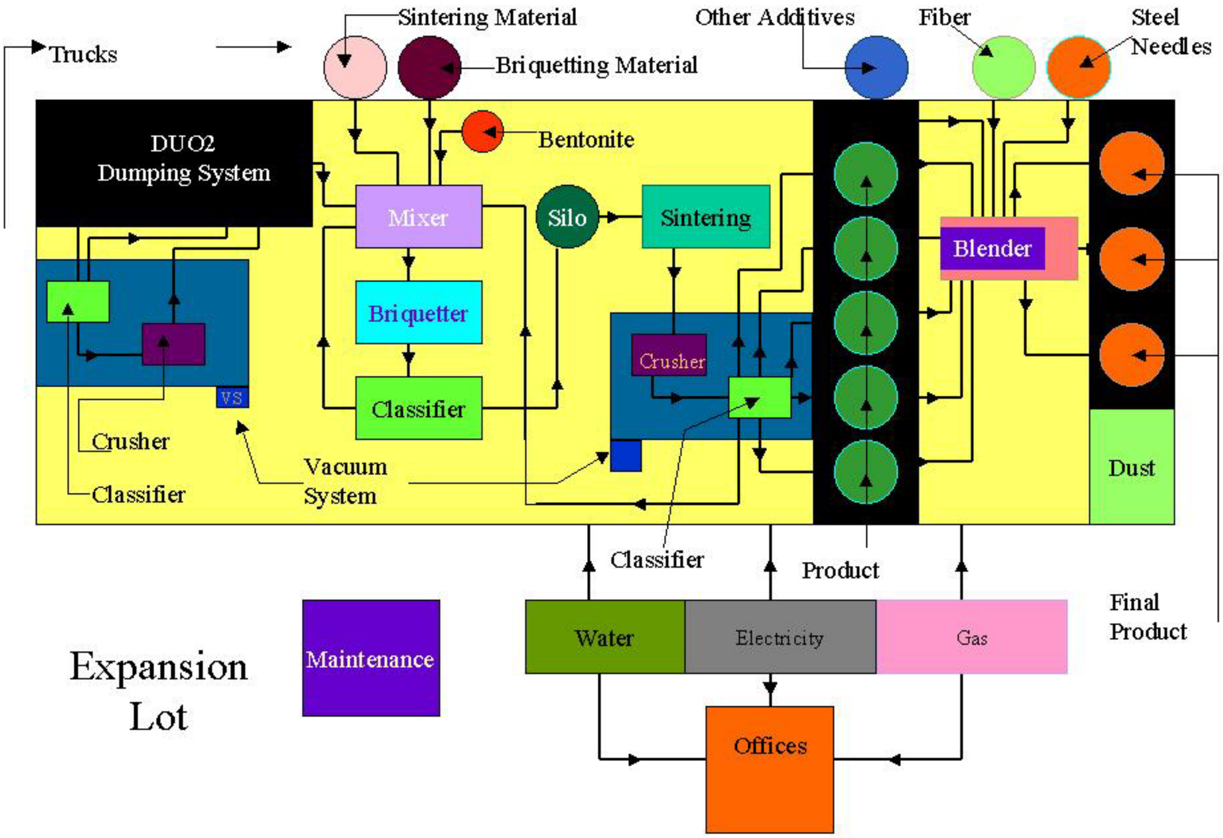


Fig. 9. Detailed layout of the process equipment.

Table 1. Capital cost estimate for the baseline case

Capital cost items	Cost estimates, $K
Equipment	
DUO_2 reception	196
Crushing of input material	106
Receipt of sintering material	67
Mixer sintering-DUO_2	94
Briquetter	220
Sintering system	163
Sintered briquette crusher/classifier	337
Vacuum, HEPA filters, drier, controls	1071
Land and building	2620
Total equipment, land, and building	**4844**

Table 2. Total capital cost estimate for the baseline case

Capital cost item	Cost estimate, $K
Civil/Site preparation	500
Utilities building services	56
Process equipment, land and buildings	4844
Special process services	35
Engineering	1591
Piping	1204
Installation labor	1205
Electrical	220
Spare parts	346
Management	1000
Shipping	110
Safety system	600
Total capital cost	**11,601**

3.2 BASELINE OPERATING COST

3.2.1 U.S. Labor Cost

The number of operating sections of the process determined the number of people who will work in this plant. Table 3 indicates the number of operators, engineers, and administrative personnel who will be needed. The hourly cost per radiological worker was estimated at $96/h, which includes the full burden for a federal facility; engineers at $100/h; and secretaries at $50/h. Eighteen workers comprise the operating crew. One manager, one secretary, two engineers and four security guards comprise the rest of the plant workers.

3.2.2 Cost of Chemicals

The chemicals to be utilized in the process are shown in Table 4. The cost for DUO_2 is considered to be $0/tonne in the baseline case.

3.2.3 Electrical Costs

The baseline process plant will use 270 kW and the annual consumption will be 1,390,000 kWh at 4¢/kWh. The energy cost per year will be $56K.

Table 3. Labor required for the baseline process plant

Position	Number required	Cost ($K/year)
Supervisor	1	125
Briquetter	1	166
Mixer	1	166
Blender	1	166
Sintering unit	1	166
Forklift	1	166
Loading	1	166
Unloading	1	166
Handlers	3	499
Maintenance	2	378
Electrician	1	166
Cleaning crew	4	332
Manager	1	166
Secretary	1	104
Engineer	2	416
Security	4	666
Total	**26**	**4014**

Table 4. Chemicals used in the baseline process

Material	Wt fraction	Amount needed (ton)	Price/ton ($)	Approx. cost ($K)
UO_2	0.9170	2834	0	0
Bentonite	0.0309	95.5	58	6
Pumice	0.0109	33.7	37.38	2
Talc	0.0013	4.0	26	1
$Ca(OH)_2$	0.0075	23.2	120	3
Na_2CO_3	0.0005	1.5	140.83	1
K_2CO_3	0.0024	7.4	122	10
TiO_2	0.0156	48.2	140	7
ZrO_2	0.0081	25.0	140	4
Boric acid	0.0059	18.2	340	7
B-1020 binder	0.01	30.9	100	4
			Total	**44**

3.2.4 Capital Recovery Factor

The capital recovery factor is considered to be 20%. In other words, the operational cost must include a cost item that reflects the capital recuperation in 5 years. The annual cost for this facility is $2320K.

3.2.5 Total Operating Costs

The total operating cost does not include replacement parts on this preconceptual design. These costs will be analyzed during the design phase. The total operating costs are summarized in Table 5.

Table 5. Total operating cost for the baseline case

Operating cost item	Cost ($K/year)
Labor	4015
Electricity	56
Chemicals	44
Capital recovery	2320
Cost of UO_2	0
Total operating cost	**6435**

The total operating cost for the baseline case is $6435K/year. The fabrication of 50 spent fuel casks requires 2834 tonnes of DUAGG per year. Consequently, the total operating cost per tonne of DUAGG is $2270, or $2.27/kg. The corresponding cost contribution of DUAGG to the manufacture of casks is $128.7 per cask.

As indicated in Fig. 10, the most important elements of the operating expenses are labor, representing 62% of the baseline costs, followed by capital recovery costs at 36%.

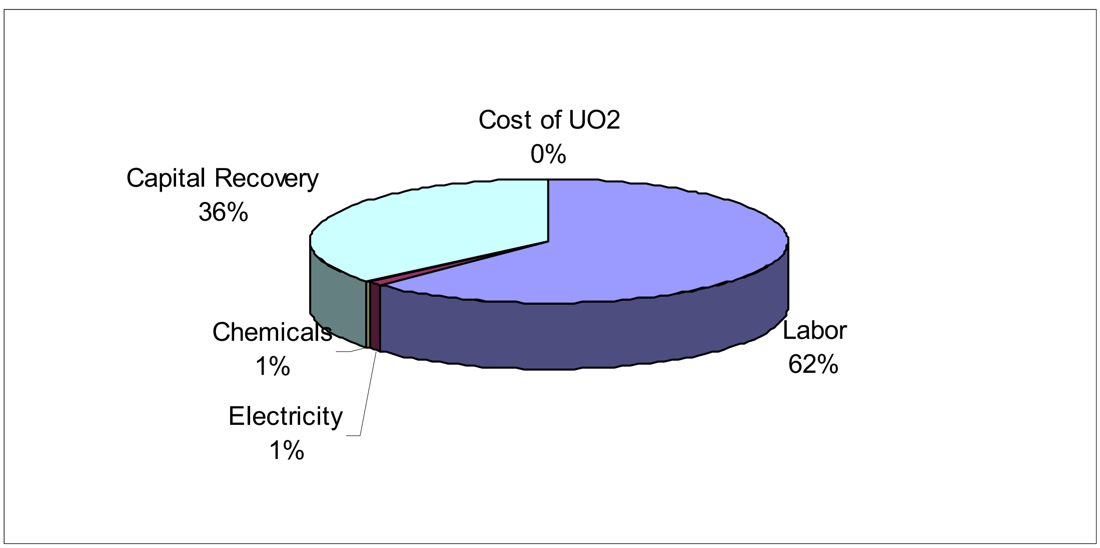


Fig. 10. Percentage contributions to the operating costs for the baseline case.

4. ANALYSIS

4.1 IMPACT OF DUO_2 COST ON THE OPERATING COSTS

The DU_3O_8 will be produced at the conversion facilities in Portsmouth and Paducah by Uranium Disposition Services (UDS), a joint-venture company. Formed specifically for this project, it is composed of three partners: Framatome ANP, an AREVA and Siemens company ; Duratek Federal Services, headquartered in Denver, Colorado; and Burns and ROE Enterprises of Oradell, New Jersey. DOE has awarded UDS a contract, valued at $558 million, to transform and dispose of its DU inventory. Based on the UDS process, it will be a matter of modifying the H_2 and H_2O input into the main reactor to transform DUF_6 into DUO_2. The production of DUAGG from the DUO_2 for making the DUCRETE will be performed by a private company that will manufacture spent fuel casks. The conversion of DUF_6 into DU_3O_8 involves the final disposal of the DU at the Nevada Test Site (NTS), which will involve transportation and disposal costs of the oxide. If a third party uses the DUO_2 for manufacturing spent fuel casks, these costs will not be incurred. Under these conditions, it is reasonable to consider that a credit is due to the company that produces the DUAGG. A policy to establish a value for DUO_2 has not been established at this time. However, it is certain that this issue will surface when any beneficial use of DU_3O_8 or DUO_2 produced from the conversion process is considered. A sensitivity analysis on the operating costs of producing DUAGG will be performed to see the impact of variations in the credit allowances for the beneficial uses of the oxide.

Credits for Transportation and Disposal Costs

The credits will include the savings for transportation and disposal costs. Transportation cost will assume 1750 miles for each trip, at a cost per mile of $2. The specific gravity of the material was assumed at a conservative valued of 2.5. A total of 42 drums will be accepted in each shipment, each drum having a capacity of 432 kg and costing $50. There will be 156 trips per year. Therefore, the costs of shipping the drums will be $548K.

The savings will also assume a disposal cost of $11/ft^3 at NTS. Each drum occupies 7.5 ft^3 and the material would be packed in 6552 drums. The disposal savings would be $540K/year. The total potential savings per year (transportation and disposal) is $1088K.

DOE may consider a credit allowance for the entire potential savings or a fraction of the amount. Figure 11 illustrates the impact in the final cost of the DUAGG for different percentages of credit allowances. If no credit is allowed, the cost per kilogram of DUAGG will be $2.27, and the DUAGG cost contribution per cask will be $128.7.

If 100% of the savings is allowed as credit, equivalent to a credit of $384/tonne of DUAGG, the operating cost will be lowered to $5349K/year (see Table 6). The cost of DUAGG will be reduced to $1.71/kg, or $1710/tonne of DUAGG, and the DUAGG cost contribution per cask will be $107. Figure 12 illustrates the cost contribution per cask for different percentages of credit allowance.

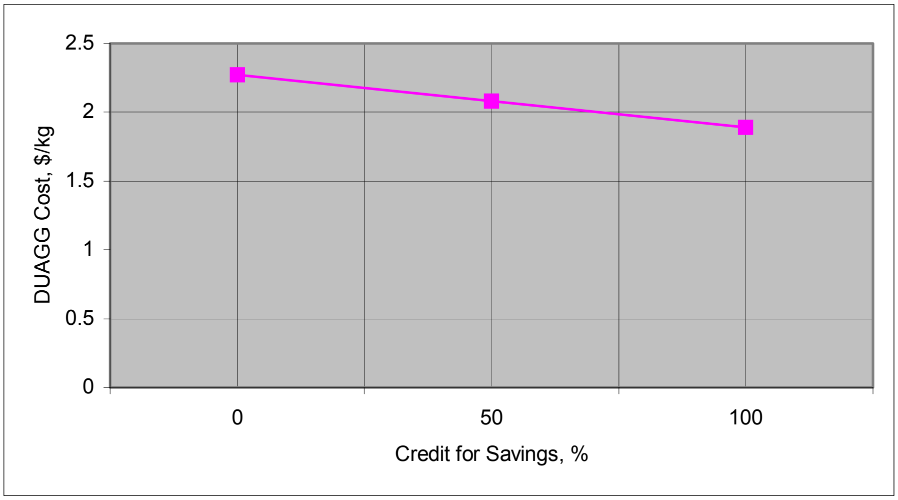


Fig. 11. Cost of DUAGG, considering credit for savings.

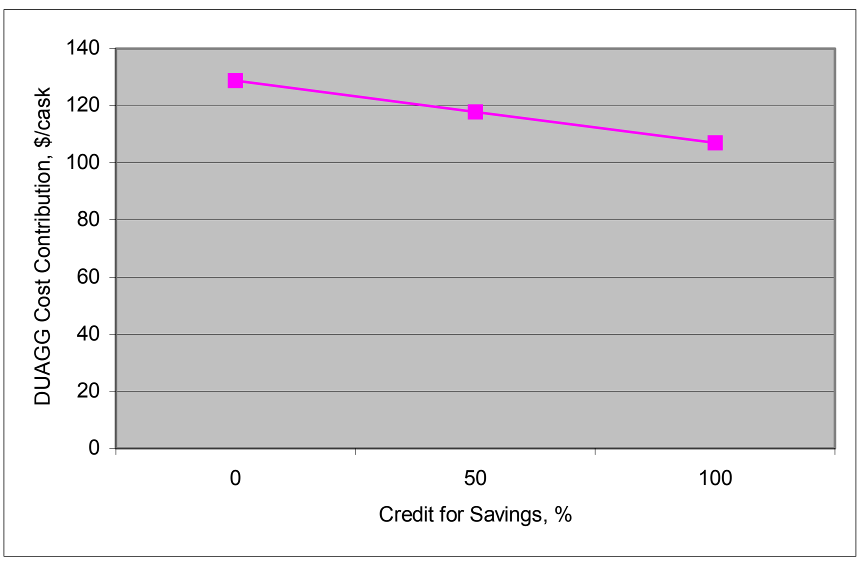


Fig. 12. DUAGG cost contribution per cask, considering credit for savings.

Table 6. Total operating cost, considering 100% credit for savings

Operating cost item	Cost ($K/year)
Labor	4015
Electricity	56
Chemicals	44
Capital recovery	2320
Cost of UO_2	−1086
Total operating cost	**5349**

4.2 IMPACT OF REDUCING CAPITAL INVESTMENT

The process used in this analysis was developed at INEEL, and optimization studies have not yet been conducted. However, it is conceivable that the DUO_2 used in this process may be produced under the requested DUAGG specifications. The reasons for this concession reside in the fact that the DUAGG production represents a beneficial use of DUO_2, which implies an avoidance of disposal cost and, consequently, an environmental gain. If the USD conglomerate of companies produces DUO_2 under the DUAGG specifications and delivers the product as a briquette, several elements of the capital cost will be reduced, subsequently reducing the operating costs. Table 7 shows the new equipment list assuming that DUO_2 will be delivered already formulated as briquettes. Table 8 shows the new capital cost using this consideration.

Table 7. Equipment cost, considering delivery of DUO_2 as briquettes

Capital cost items	Cost estimate ($K)
Equipment	
DUO_2 reception	196
Reception sintering material	67
Mixer sintering-DUO_2	94
Sintering system	163
Sintered briquette crusher/classifier	337
Vacuum, HEPA filters, controls	750
Land and buildings	2000
Total equipment, land and buildings	**3607**

Under these assumptions the operating costs will also be reduced by receipt of the DUO_2 in the form of briquettes. Table 9 shows the revised composition of labor costs. Table 10 shows the revised operating cost under this assumption.

Table 8. Capital cost, considering delivery of DUO_2 as briquettes

Capital cost item	Cost estimate ($K)
Civil/site preparation	500
Utilities building services	56
Process equipment, land and buildings	3607
Special process services	35
Engineering	1190
Piping	902
Installation labor	902
Electrical	162
Spare parts	253
Management	743
Shipping	110
Safety system	450
Total capital cost	**8910**

Table 9. Revised labor cost, considering delivery of DUO_2 as briquettes

Position	Number required	Cost ($K/year)
Supervisor	1	166
Blender	1	166
Sintering unit	1	166
Forklift	1	166
Loading	1	166
Unloading	1	166
Handlers	2	332
Maintenance	2	166
Electrician	1	166
Cleaning crew	3	498
Manager	1	166
Secretary	1	166
Engineer	2	416
Security	3	416
Total		**3320**

Table 10. Revised operating cost, considering delivery of DUO_2 as briquettes

Operating cost item	Cost ($K/year)
Labor	3320
Electricity	46
Chemicals	44
Capital recovery	1782
Cost of UO_2	0
Total operating cost	**5192**

Under these circumstances, the operating cost will be lowered to $5192K/year. The cost of DUAGG will be reduced to $1.67/kg, or $1670/tonne, and the DUAGG cost contribution per cask will be $104. Figure 12 illustrates the cost contribution per cask at different levels of credit allowance.

4.3 IMPACT OF REDUCING THE CAPITAL INVESTMENT AND OBTAINING CREDIT FOR USING DUO_2

The savings will also assume a disposal cost of $11/ft^{3}at NTS. Each drum occupies 7.5 ft^3 and the material would be packed in 6552 drums. Thus, the disposal savings would be $540K/year, with total potential annual savings of $1086K. Table 11 shows the operating cost under the assumption that capital cost can be reduced and that DOE would grant a credit of $1086K a year for the savings resulting from the avoided transportation and disposal of DUO_2.

Table 11. Revised operating cost, considering delivery of DUO_2 as briquettes and 100% credit for savings

Operating cost item	Cost ($K/year)
Labor	3320
Electricity	46
Chemicals	44
Capital recovery	1782
Cost of UO_2	−1086
Total operating cost	**4106**

DOE may consider a credit allowance for the entire potential savings or for a fraction of the amount. Figure 13 illustrates the impact on the final cost of the DUAGG for different levels of credit allowances. If no credit is allowed, the cost per kilogram of DUAGG will be $1.67 and the DUAGG cost contribution per cask will be $104K.

If 100% of the savings is allowed as credit, equivalent to a credit of $384/tonne of DUAGG, the operating cost will be lowered to $4106K/year. The cost of DUAGG will be reduced to $1.32/kg, or $1320/tonne, and the DUAGG cost contribution per cask will be $82. Figure 14 illustrates the cost contribution per cask at different levels of credit allowance.

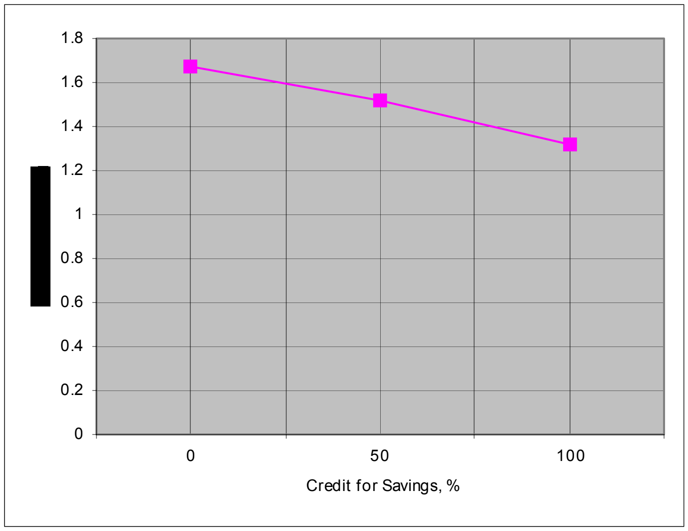


Fig. 13. Cost of DUAGG, considering credit for savings and equipment reduction.

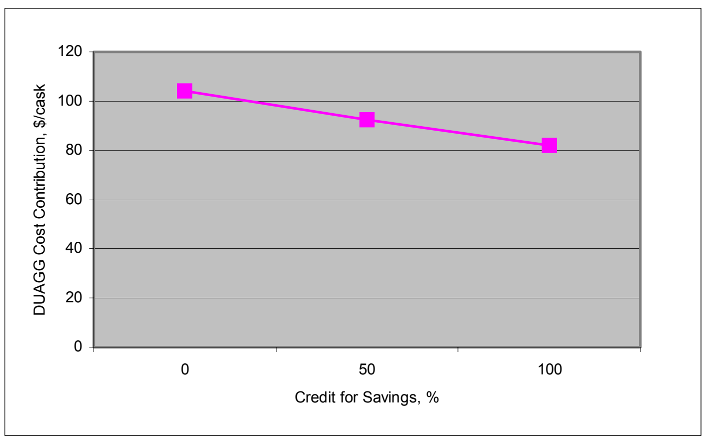


Fig. 14. DUAGG cost contribution per cask, considering credit for savings and equipment reduction.

4.4 IMPACT OF LABOR COST VARIATIONS

The labor cost assumed for the baseline case was $96/h fully burdened for a federal facility operation. It may be possible that a private company could operate this plant with lower labor costs. To analyze this potential variation in labor cost, the operating costs will be calculated using $80, $60, and $40/h.

4.4.1 Labor Cost Variations for the Baseline

This analysis assumes the same cost structure as the baseline case, except that variation on the labor cost from $80 to $40/h are applied to the total operating costs. Table 12 shows the results of these calculations.

Table 12. Total operating cost for different labor cost estimates ($K/year)

	Labor cost ($/h)		
Operating cost item	**80**	**60**	**40**
Labor	4015	3196	2323
Electricity	56	56	56
Chemicals	44	44	44
Capital recovery	2320	2320	2320
Cost of UO_2	0	0	0
Total operating cost	**6435**	**5616**	**4743**

The variations in the DUAGG cost for labor cost variation is illustrated in Fig. 15. At $40/h the DUAGG cost is $1.67/kg and $1.98/kg at $60/h. The DUAGG cost per cask is reduced from $128.7 to $94.9 when the labor cost is reduced from $80 to $40/h.

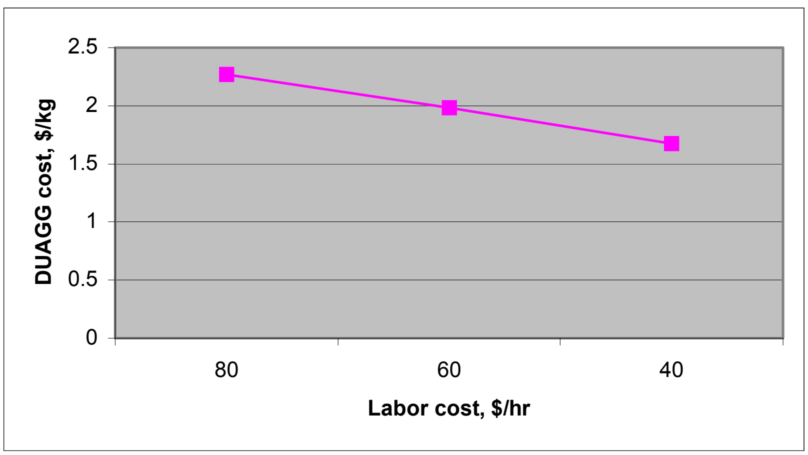


Fig. 15. Variations of the baseline DUAGG cost for various labor costs.

4.4.2 Labor Cost Variations for the Case in which Full Credit and Capital Investment Reduction Have Been Considered

To account for the most favorable case, a calculation was also made that assumed the process has been optimized and full credit is applied to the production of DUAGG. Table 13 shows the results of these calculations.

Table 13. Revised operating cost, considering delivery of DUO_2 as briquettes and 100% credit for savings for different labor cost rates ($K/year)

	Labor Cost ($/h)		
Operating cost item	**80**	**60**	**40**
Labor	3320	2506	1620
Electricity	46	46	46
Chemicals	44	44	44
Capital recovery	1782	1782	1782
Cost of UO_2	−1086	−1086	−1086
Total operating cost	**4106**	**3292**	**2406**

The variations in the DUAGG cost for labor cost variation is illustrated in Fig. 15. At $40/h the DUAGG cost is $0.84/kg and $1.16/kg at $60/h. The DUAGG cost per cask is reduced from $82 to $48 when the labor cost is reduced from $80 to $40/h.

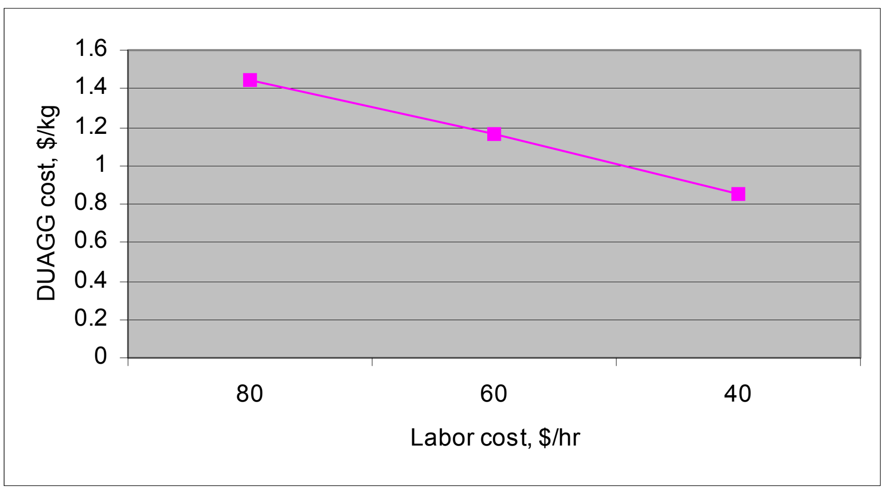


Fig. 16. DUAGG cost variations for changes in the labor cost for the full-credit and investment reduction case.

4.5 IMPACT OF CONTINGENCIES ON THE BASELINE

In a preconceptual cost analysis, some cost elements may vary when the project becomes a reality. Some equipment-estimated values may change from the time of this study to the startup of the project. In addition, the cost of operations may also be subject to change. It is customary for a plant in which most of the equipment is off-the-shelf to include 10–20% as a contingency factor calculated over the equipment cost. Conservatively, this study added a contingency factor of 20% to both equipment cost and operating cost. The total operating cost under these circumstances is $7722 per year. The total operating cost per tonne of DUAGG is $2724 or $2.72/kg. The corresponding contribution of DUAGG to the manufacture of casks is $154.40 per cask.

4.6 ANALYSIS SUMMARY

Based on the sensitivity analysis, the estimated DUAGG costs are shown in Table 14.

Table 14. Estimated DUAGG costs

	\$384/t DUO_2 credit		**Baseline: zero-cost DUO_2**		**\$384/t DUO_2 credit + savings for DUO_2 delivered as briquettes**	
	Labor cost (\$/h)		**Labor cost (\$/h)**		**Labor cost (\$/h)**	
	80	**40**	**80**	**40**	**80**	**40**
Capital	\$11.6M	\$11.6M	\$11.6M	\$11.6M	\$8.9M	\$8.9M
Operating (year)	\$5.2M	\$3.8M	\$6.4M	\$4.7M	\$4.2M	\$2.4M
Unit (cask)	\$104K (\$1.67/kg)	\$76K (\$1.34/kg)	\$129K (\$2.27/kg)	\$94.9K (\$1.67/kg)	\$82K (\$1.32/kg)	\$48K (\$0.84/kg)

5. CONCLUSIONS AND RECOMMENDATIONS

One of the advantages of the process analyzed in this study is that the equipment included in the process flowsheet is simple and can be obtained off-the-shelf from different vendors. It is not a sophisticated technology and equipment items are available in the market.

Several uncertainties were identified during the course of this study. The size distribution of the DUO_2 feed material will affect the capital and the operating cost for the plant. UDS has not yet built the plant transforming the DUF_6 into DUO_2, so it may be possible to design a plant to make homogeneous DUO_2 as formulated briquettes to use in the production of DUAGG. It is, then, necessary to work with UDS to determine the oxide specifications and the integration of the DUAGG process with the future DUF_6 conversion facility. The natural consequence of this integration is the reduction in production cost by sharing labor and facilities.

Because this study proposes a more effluent continuous process, there are uncertainties in the mixing and sintering processes, both of which were originally conducted in batch mode. Furthermore, tests must be conducted to support the continuous-process assumptions. To increase the density of the product, an alternative agglomeration process should be considered for forming the briquettes. Also, determining the correct pressure to use in making the briquettes is essential to ensure mechanically stable briquettes.

The preconceptual design presented in this study is based on a stand-alone plant, which represents a very conservative assumption. Under these conditions, this study concludes that DUAGG is unlikely to be cost competitive with conventional commodity concrete aggregate materials. It is likely that the outcome of this project will be greatly enhanced if the DUAGG production process is integrated with either of the DUF_6 conversion plants located in Paducah and Portsmouth, taking advantage of one of these industrial facility's installations and skilled labor. In addition, for DUCRETE casks to be commercially competitive, DUCRETE must offer some new, unique, enhanced cask performance characteristic. One such characteristic is that DUCRETE casks are projected to be smaller and lighter weigh than conventional casks and may permit removal of the extensive network of reinforcing steel bar present in current concrete casks. Other benefits of using DUCRETE for spent fuel casks are the increased strength of the casks and added protection against threat. However, it is extremely difficult to quantify cost savings resulting from enhanced performance. Another benefit of this project is that utility companies will incur a lower disposal because of the smaller cask needed to store the spent nuclear fuel.

The DUAGG process flowsheet must undergo several changes to increase the competitiveness of the process. Clear and precise specifications for the DU oxide will reduce the amount of front and end treatment of the material. Reduction of equipment will result in a reduction in the labor force needed to operate the plant as well. Crushing and sizing steps could be avoided with a careful specification of the DU oxide.

The DUAGG production project would be clearly benefited if DOE establishes a realistic incentive program for the beneficial uses of DUF_6. Such a program would make this process economically feasible, thus allowing this technology to be implemented.

In order to improve the process and economic efficiency of the DUAGG project, it is suggested that joint work with the briquette manufacturer be conducted to produce appropriately sized particles to avoid the crushing of the briquettes.

Additional research is needed on micro reinforcement of DUCRETE in order to increase its mechanical toughness and thereby increasing its resistance to threats. These improvements in DUCRETE's physical characteristics would make the material more effective for threat reduction and would enhance the benefits of using DUCRETE by offsetting some of its additional costs with additional advantages.

6. REFERENCES

1. L.R. Dole and W.J. Quapp, "Radiation Shielding Using Depleted Uranium Oxide in Nonmetallic Matrices," ORNL/TM-2002/111, Oak Ridge National Laboratory, Oak Ridge, Tenn., August 2002.

2. T. J. Hertzler and D. D. Nishimoto, *Depleted Uranium Management Alternatives,* EGG/MS-11416, Washington, D.C., August 1994.

3. H. R. Yoshimura et al., *Use of Depleted Uranium Metal as Cask Shielding in High-Level Waste Storage, Transport, and Disposal Systems*, Sand94-0826/TTC-1311, Sandia National Laboratories, Livermore, Calif., 1994.

4. F. E. Kosinski, "Review of Commercial Uranium Processing Capability," Letter Report to C. R. Cooley, U.S. DOE, EM50, TDC-100, Rev. 1, Technics Development Corporation, October 29, 1993.

5. W.J. Quapp and P.A. Lessing, U.S. Patent No. 5,786,611, "Radiation Shielding Composition," July 28, 1998.

6. J. W. Sterbentz, *Shielding Evaluation of a Depleted Uranium Heavy Aggregate Concrete for Spent Fuel Storage Casks*, INEL-94/0092, Idaho National Engineering and Environmental Laboratory, Idaho Falls, Idaho, October 1994.

7. P. A. Lessing and H. Gillman, "DU-AGG Pilot Plant Design Study," INEL-96/0166. Idaho National Engineering and Environmental Laboratory, Idaho Falls, Idaho, July 1996.

8. W.J. Quapp and P.A. Lessing, U.S. Patent No. 6,166,390, "Radiation Shielding Composition," Dec. 26, 2000.

APPENDIX A
EQUIPMENT LIST AND COST ESTIMATES

Table A. 1 Equipment List and Cost Estimates

Section of the process	Equipment	Quantity	Estimated cost ($K)	Description
DUO2 reception	DUO_2 silo	2	24	
	Special container	10	10	
	Conveyor reception -> DUO_2 silo	1	11	
	Chute	6	6	
	Feeder weigh	5	40	
	Surge bin	1	10	
	Cover plate	1	5	
	Downspout	2	2	
	Platform: silo	1	11	
	Support: mixer	1	5	
	Platform: mixer	1	5	
	Spout	1	2	
	Support legs: silo	1	5	
	Screw feeder	1	8	
	Hopper	1	5	
	Hopper	1	5	
	Dumper	1	7	
	Enclosure	1	5	
	Slide gate	4	10	
	Forklift	1	20	
Crushing of input material	Conveyor DUO_2 silo → crusher	1	11	
	DUO_2 crusher	1	60	
	Conveyor crusher → crushed DUO_2 silo	1	11	

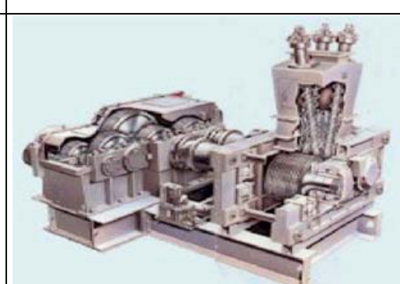
Table A. 1 Equipment List and Cost Estimates				
Section of the process	**Equipment**	**Quantity**	**Estimated cost ($K)**	**Description**
	Crushed DUO_2 silo	2	24	
Reception sintering material	Reception bin for sintering material	1	10	
	Conveyor sint. mat bin → sint. mat. silo	1	11	
	Reception bin for binding compound	1	11	
	Conveyor: binder compound bin	1	11	
	Binder silo	1	12	
	Sintering material silo	1	12	
Mixer sintering DUO_2	Mixer	1	50	
	Conveyor binder silo →mixer	1	11	
	Conveyor sintering silo → mixer	1	11	
	Conveyor crushed UO_2 → mixer	1	11	
	Conveyor mixer → briquette former	1	11	
Briquetter	Briquetter	1	105	
	Hopper	1	5	
	Liquid pump & tank	1	5	
	Vibrating screen	1	10	
	Supports briquetter	1	5	

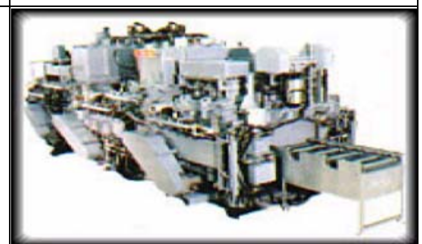
Table A. 1 Equipment List and Cost Estimates				
Section of the process	**Equipment**	**Quantity**	**Estimated cost ($K)**	**Description**
	Conveying lines		20	
	Air line		5	
	Conveyor briquetter → pellet silo	1	11	
	Pellet silo	1	12	
	Conveyor pellet silo → sintering unit	1	12	
Sintering system	Sintering process unit	1	130	
	Platform sintering unit	1	10	
	Conveyor sintering unit → sintering silo	1	11	
	Sintered briquette silo	1	12	
Sintered briquette crusher/ classifier	Briquette crusher	1	60	
	Classifier	2	60	

Table A. 1 Equipment List and Cost Estimates				
Section of the process	**Equipment**	**Quantity**	**Estimated cost ($K)**	**Description**
	Crushed briquette silo	2	24	
	Conveyor crusher briquette silo → classifier	1	11	
	Conveyor classifier → silo size 1	1	11	
	Conveyor: classifier → silo size 2	1	11	
	Conveyor: classifier → silo size 3	1	11	
	Conveyor: classifier → silo size 4	1	11	
	Silo size 1	1	12	
	Silo size 2	1	12	
	Silo size 3	1	12	
	Silo size 4	1	12	
	Rotary air lock feeder	1	10	
	Drum cover	1	1	
	Level controls	1	5	
Dust Control System	Vacuum pumps	2	20	
	HEPA filters	4	40	
	Air Drier	2	120	
	Air Scrubbing System	2	80	
	Dust Collectors, cyclone	2	20	
	Vacuum Box, bag filters	1	35	
	Air compressor	1	20	
	Fan, silencer, and air ducts		736	