R&D Plan for Immobilization Technologies Fissile Materials Disposition Revision 1.0

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**R&D Plan for
Immobilization Technologies
Fissile Materials Disposition Program**

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September 13, 1996

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1.0 INTRODUCTION -- IMMOBILIZATION TECHNOLOGIES

In the aftermath of the Cold War, the U.S. and Russia have agreed to large reductions in nuclear weapons. To aid in the selection of long-term fissile material management options, the Department of Energy's Fissile Materials Disposition Program (FMDP) is conducting studies of options for the storage and disposition of surplus plutonium (Pu). One set of alternatives for disposition involve immobilization. The immobilization alternatives provide for fixing surplus fissile materials in a host matrix in order to create a solid disposal form that is nuclear criticality-safe, proliferation-resistant, and environmentally acceptable for long-term storage or disposal.

There are three candidate technologies under consideration for immobilization: vitrification (*i.e.*, immobilization in glass); immobilization in ceramics; and immobilization in a glass-bonded zeolite matrix.

Each of these technologies require further research and development (R&D) to:

- (1) identify a material formulation that optimizes processability and long term performance;
- (2) develop processing equipment, material flow and process controls, operational strategies, and material accountability while minimizing impacts on workers, the environment, cost, and the ability to maintain an acceptable implementation schedule;
- (3) demonstrate on a pilot scale that individual operations or processing steps fit together seamlessly;
- (4) demonstrate that the specific disposal forms meet the spent fuel standard for proliferation resistance.

The R&D required to achieve or demonstrate these goals is described beginning in section 2.0 of this plan.

In late calendar year 1996, the Executive Branch of the U.S. Government will issue a Record of Decision (RoD) detailing the course of action the United States will follow with regard to the disposition of excess weapons Pu. For the purposes of this plan, it is assumed that immobilization will be included as one of the options to be pursued, but that the specific immobilization technology to be used will not be defined by the RoD. This plan will be updated as required to reflect changes in the program due to changes in national policy, programmatic guidance, or the findings of the R&D program itself.

1.1 Vitrification Variants

Three variants based on vitrification technology are under consideration:

- (1) a "can-in-canister" variant, in which inner cans containing a Pu- and neutron-absorber-bearing glass are surrounded by high-level waste glass from the Defense Waste Processing Facility (DWPF), which, in turn, is contained in an outer storage canister;
- (2) a variant consisting of an adjunct melter to the DWPF that produces a glass containing Pu, neutron absorber(s), and ^{137}Cs separated from high-level waste (HLW), and then encapsulates this glass in a storage canister;
- (3) a new greenfield facility that produces a glass containing Pu, neutron absorber(s), and ^{137}Cs (as a radiological barrier), and then encapsulates this glass in a storage canister.

The baseline glasses for all the variants are borosilicate formulations.

The need to incorporate Cs into the glass intended for the adjunct melter and greenfield variants leads to the requirement that the processing temperature of the glass for these variants be less than approximately 1150°C to minimize Cs volatility in the melter. The glass intended for the can-in-canister variant is not subject to this constraint. Consequently, two different families of glasses are being investigated: a "low temperature" glass (ATS glass) capable of dissolving ~5 wt. % Pu during production, and a "high temperature" lanthanide borosilicate (LaBS) glass capable of incorporating ~10 wt. % Pu during production. (This glass has also been referred to previously as the "Löffler" glass)

The major concerns for these variants relate to whether a glass for each variant can be formulated to meet the processing and performance requirements.

1.2 Ceramic Immobilization Variants

Two different immobilization variants based on ceramics technology are under consideration:

- (1) a "can-in-canister" variant in which inner cans containing a ceramic that incorporates the Pu and neutron absorber(s) is surrounded by high-level waste glass from the Defense Waste Processing Facility (DWPF), which, in turn, is contained in an outer storage canister;
- (2) a new ("greenfield") facility that produces a ceramic containing Pu, neutron absorber(s), and ^{137}Cs and then encapsulates the ceramic in a storage canister;

The baseline ceramic formulation is a Synroc-like Ti-Zr ceramic in which the Pu and neutron absorbers are incorporated into the crystalline lattice of the minerals zirconolite, pyrochlore, and hollandite. Alternative ceramic formulations will also be investigated during the course of R&D. The ceramic form has a production target of 12 wt. % Pu.

Two fabrication technologies for the production of the ceramic immobilization forms are being investigated: hot pressing and cold pressing/sintering.

As is the case for vitrification, the critical concerns for these variants relate to whether a ceramic can be formulated that meets the processing and performance requirements.

1.3 Electrometallurgical Treatment Technology

In the Electrometallurgical Treatment (ET) alternative, Pu-rich residues are converted to Pu-chlorides, dissolved in a molten salt solution, sorbed on zeolites, and then immobilized in a glass-bonded zeolite (GBZ) form. The immobilization options will be integrated with operations in the ANL/W hot cells to treat DOE-owned spent fuels. The fission products from these fuels will contribute some radiation to the immobilization forms, but ^{137}Cs from Hanford capsules will provide most of the radiation field to create a radiation barrier.

The R&D needed to formulate and produce the GBZ immobilization forms is not included in this plan. The responsibility for these efforts lies outside the FMDP. This plan only includes the performance testing and evaluation of the GBZ forms to ascertain the suitability of these forms for disposal in a geologic repository. Production of samples for these tests is the responsibility of the DOE fuels program, a portion of which is being executed by ANL. Similarly, the development of models to describe the in-repository behavior of the GBZ forms lies outside the scope of the activities described here.

The critical concern is whether such ET-prepared, glass-bonded zeolites can be formulated to meet the performance requirements necessary to qualify this material for disposal.

1.4 Immobilization R&D

The R&D necessary to achieve the goals of the immobilization alternatives is described in the following section. To facilitate planning and execution, the work has been organized into four major categories:

- Formulation and Performance Testing (WBS element 1.)
- Process Development (WBS element 2.)
- Pilot Facility Development (WBS element 3.)
- Non-proliferation Evaluation (WBS element 4.)

The primary participants in these activities are Lawrence Livermore National Laboratory (LLNL), Westinghouse Savannah River Company (WSRC), Argonne National Laboratory (ANL), Oak Ridge National Laboratory (ORNL), Pacific Northwest Laboratory (PNL), and the DOE Office of Civilian Radioactive Waste Management (OCRWM). Subcontractors currently include Bechtel Corporation, the University of Missouri-Rolla, Clemson University, and the Australian National Science and Technology Organization (ANSTO). Other subcontractors may be added in the future.

A high-level summary of the Immobilization Program major activities, key decisions, and the relationships between them is shown in Figure 1. (A detailed Gantt chart that includes all Program activities is given in Appendix I). As shown in Figure 1, the entire Program is aimed at the ultimate development and construction of a pilot immobilization facility that would begin hot operations in 9/03. Several programmatic decisions that rely on significant technical input must be made prior to the construction of such a facility. The first major technical decision point is a selection between candidate glass formulations (10/97). A similar level decision occurs a short time later (1/98) between the hot-press and cold-press-and-sinter methods of ceramic fabrication. Both of these decisions will be based upon the results of the glass and ceramic formulation and testing work, as well as the results of the early stages of scale-up of the production process (*e.g.*, the results of melt dissolution kinetics studies using an induction-heated, stirred, tilt-pour melter). In 8/98, based on the results of testing of candidate melters, a recommendation will be made as to the melter technology to be used for glass fabrication. This information, along with the results of continued testing of the "finalist" glass and ceramic forms will be used to make a final selection between glass and ceramic in 11/98. This decision, in turn, will drive the selection of the technologies to be used in a pilot facility.

Figure 1. Immobilization Program -- Key Events and Decisions

2.0 FORMULATION AND PERFORMANCE (WBS 1.)

The choice of the immobilized form and the composition of that form will strongly influence the design and cost of the immobilization facility, as well as the extent of characterization necessary for facility and immobilized form licensing, with direct impact on implementation schedule. For example, the maximum allowable plutonium loading will be determined by considerations of process safety and the long term performance of the immobilized form and will determine the size, throughput, and cost of the processing facility.

The R&D conducted under this WBS element has five major goals:

- the actual formulation of a glass or ceramic immobilized form, and measurement of the various physical and chemical properties of the material needed for production and qualification (WBS 1.1 and 1.2);
- development and execution of testing procedures to bound the long-term performance of the selected immobilized form(s) and provide input parameters for predictive models for (WBS 1.3)
- development of predictive models for the degradation of the immobilized forms over long time periods under repository conditions, with particular emphasis on the relative releases and mobilities of fissionable nuclides and neutron absorbers, so that they can be shown to be acceptable for repository disposal (WBS 1.4);
- development and execution of a process to select a single form for final production from among the candidate immobilized forms (WBS 1.5)
- development and execution (together with the DOE Office of Civilian Radioactive Waste Management) of a qualification process for the immobilized form, and the development of such information as is necessary to show that the immobilized form is acceptable for disposal in a geologic repository (WBS 1.6).

2.1 Formulation (WBS 1.1 - glass, and 1.2 - ceramic)

The development of a formulation for both vitrified and ceramic forms will take place in several stages. Prior to the Record of Decision (RoD), emphasis will be placed on demonstrating that it is feasible to formulate a glass or ceramic that incorporates the requisite quantity of Pu (see above) (WBS 1.1.2.1, 1.1.3.1, 1.2.1.1, 1.2.2.1). In addition, samples of these preliminary immobilized forms will be subject to short-term performance tests under WBS 1.3.1.1 and 1.3.2.1 to show that the degradation rate of these forms would be less than that assumed in the Environmental Assessment (EA) for geologic repositories. The processing characteristics of

each family of glasses will be determined so that melter performance requirements can be broadly defined and used as input to the Melter R&D WBS element (2.1.1). These preliminary, pre-RoD, efforts will provide the basis for a systematic exploration of the parameters affecting the production and performance of the forms.

The second phase of formulation R&D (post RoD) will consist of experiments (WBS 1.1.2.2, 1.1.3.2) intended to determine, as a function of glass composition, the kinetics of dissolution of Pu and neutron absorbers (if the absorber is not already present in the precursor frit) under static conditions. Experiments will be conducted to evaluate the effect of particle size and thermal treatment history of the Pu feed (*e.g.* high-fired PuO_2 vs. low-fired PuO_2). The effect of probable impurities in Pu feedstocks on the ability to form homogeneous glass will be studied. As the glass composition for each glass family (ATS and LaBS) is narrowed, experiments will be performed to establish the phase equilibria and devitrification properties (TTT diagrams) of each glass, as well as key physical properties (*e.g.* viscosity, thermal conductivity, *etc.*). Finally, the kinetics of Pu dissolution under conditions of controlled agitation will be studied using the stirred furnace developed under WBS element 2.1.1.3.

In early FY 1997, a set of glass selection criteria will be documented (WBS 1.1.4.1). In late FY97, the relative merits of the two glass families will be assessed against these criteria, and a single glass family will then be selected (WBS 1.1.4.2) for further development (WBS 1.1.5).

In the case of ceramic, pre-RoD activities involve the setup of the necessary laboratory-scale experimental facilities and the fabrication of Pu-bearing ceramic samples having the baseline zirconolite-rich composition (WBS 1.2.1.1, 1.2.2.1). Two different ceramic fabrication technologies will be explored: hot pressing, and cold pressing followed by sintering. Ceramic samples will be prepared using both technologies and examined to determine the extent to which the precursor materials and Pu-oxide feedstock react to form a stable phase assemblage. These initial samples, will be subjected to a suite of dissolution/leach tests (WBS 1.3.2.1) to provide preliminary data on the performance characteristics of the ceramic form.

Post RoD activities will focus on a systematic study of the processing parameters necessary to fabricate dense, fully reacted ceramic monoliths (WBS 1.2.1.2, 1.2.2.2). For hot pressing, these parameters are the pressing temperature, pressure, time, and physical characteristics (*e.g.*, grain size, chemical form, *etc.*) of both the Pu and precursor feed for the ceramic matrix. For the cold-press and sinter process, the same parameters are of interest with the exception that it is the sintering time and temperature (as opposed to the time and temperature during pressing) that are relevant.

In addition to zirconolite-based ceramics, other ceramic formulations will be explored as time and interest permits, and the processing parameters required for their production established. For each ceramic studied, its ability to incorporate a range of Pu-bearing feedstocks in the ceramics will be evaluated. Samples of each ceramic produced will be subjected to a standard series of

dissolution tests so that their relative performance can be compared. A ceramic composition will be selected prior to the glass vs. ceramic decision process.

Note that the later stages of formulation work for both glass and ceramic are dependent on the development of near-production-scale melter and press facilities (WBS 2.1, 2.2). Such facilities are necessary so that scale-up issues related to reaction and dissolution kinetics, mixing/homogeneity, and safety can be assessed. Lab-scale ceramic fabrication will terminate when full-scale pressing experimental facilities become available as part of the Ceramic Processing WBS element (2.2.1, 2.2.2). Further formulation and process development will be conducted under that WBS element from that time onward.

Key Milestones

- 8/96 Preliminary glass and ceramic formulations established (for RoD)
- 1/97 Glass and ceramic downselection criteria documented
- 4/97 Ceramic composition fixed for use in final form selection process.
- 5/97 Criteria for selection between glass and ceramic documented
- 7/97 Revised glass formulations and physical characteristics established for use in glass downselect
- 10/97 Selection between "low-T" (ATS glass) and "high-T" (LaBS) glass families
- 6/98 Optimized glass composition fixed for use in final form selection process

2.2 Performance Testing (WBS 1.3)

From the standpoint of the immobilized form performance in a repository, the main issue of concern is the potential to segregate the fissionable nuclides Pu and U from neutron absorber(s) in the waste package environment. The rate of reaction of the immobilized form will be determined, and the distribution of Pu, U, and neutron absorbers between the test solution and residual waste form will be examined carefully.

For the purposes of planning this testing program, the following assumptions have been made:

- The repository will be Yucca Mountain and the most likely conditions for reaction of the immobilized form will be contact with water vapor, dripping water, and small amounts of standing water, or water slowly moving through the pores of barrier materials or corrosion products in intimate contact with the glass.

- In the case of the can-in-canister option, any liquid water contacting the Pu-bearing form will most likely have passed through the surrounding DWPF canister and interacted chemically with the DWPF glass. Testing must take this into account.
- Each immobilized form will be tested under identical conditions.
- Evaluation of the immobilized form reactions must include conditions that are realistic and also bounding in the sense of environment, extent and mechanism of reaction, and Pu/U/absorber speciation and distribution.

Previous experience in evaluating waste form behavior has demonstrated that the corrosion processes controlling waste form degradation and radionuclide release can take several years to fully manifest themselves. Thus, accelerated tests will be performed and in-service condition tests will be initiated early during the testing program. Similar matrices will be performed for each waste form and after the down selection has been completed, ongoing tests for non-selected forms will be terminated. It is recognized that the compositions of the immobilized forms will be subject to change, even after the down-selection process has been completed. It is believed that the tests performed initially will provide general information that can be applied to the down selection process, and selected tests would be repeated with new formulations.

During the pre-RoD period, a suite of abbreviated tests will be performed to provide a consistent, comparable set of data to demonstrate whether any of the immobilized forms would undergo catastrophic reaction under test conditions that are thought to bound the range of reaction scenarios. These tests will include (WBS 1.3.1.1, 1.3.2.1):

MCC-1 tests conducted for 3-days in deionized water (DIW) at 90°C and a surface area-to-volume ratio (SA/V) of 10 m⁻¹ for the purpose of obtaining an estimate of the forward rate of reaction for pre-RoD evaluations. This information bounds the rate of the reaction under a specific test condition, but does not directly provide information on realistic rates of release of the Pu or neutron absorber under repository conditions.

PCT-B tests conducted for variable lengths of time in DIW at 90°C and a SA/V of 20,000 m⁻¹ for the purpose of evaluating reaction under high SA/V static conditions known to result in the accelerated buildup in concentration of elements in the leachate and onset of alteration phase formation. This information provides an initial indication of Pu and neutron absorber release to solution and also can be used to develop an understanding of reaction mechanisms.

PCT-A tests conducted for 7-days in DIW at 90°C and a SA/V of 2,000 m⁻¹ for the purpose of obtaining comparative information needed to qualify the immobilized form according to current requirements in the Waste Acceptance Product Specifications (WAPS) for high-level waste.

Vapor Hydration Tests (VHT) conducted for 7 to 56 days at 200°C for the purpose of qualitatively determining the intrinsic tendency (*i.e.*, in the absence of other chemical components transported to the immobilized form by groundwater) of an immobilized form to react to alteration phases and reach "Stage III" reaction, and to evaluate the distribution of Pu and neutron absorber in the alteration phases.

Pressurized Unsaturated Flow (PUF) tests conducted for time periods of 14 to 56 days at 90°C for two purposes: 1) provide accelerated test data on the intrinsic tendency of an immobilized form to develop secondary phases and enter an accelerated reaction stage under more repository relevant conditions of lower temperature (90°C), low moisture content (<10% of water saturation), and open-system mass transport, and 2) for the purpose of determining whether chemical modification of water contacting DWPF glass induces formation of alteration phases that significantly impact the reaction path of the immobilized form.

Post-ROD testing (WBS 1.3.1.2, 1.3.2.2) is designed to provide information that will be useful in evaluating the reaction of the immobilized form under conditions more relevant to those that may occur in an unsaturated repository. Data from these tests will provide information on the distribution of Pu and neutron absorber between the leachate and the residual immobilized form, will provide information on reaction mechanisms, and can be used to validate predictive models describing waste form reaction. It is possible that the information developed in these tests will provide a partial basis for repository performance assessment calculations. This would be the case if models to describe the reaction of glass and/or ceramic are not fully developed or if the requisite thermodynamic data are not available at the time such assessments need to be conducted.

Tests will also be performed to provide parameters required by models (developed under WBS 1.4) for the reaction of the glass and ceramic forms. It has not yet been shown that the mechanisms controlling the reaction of water with the ATS and LaBS glasses are the same as those that have been identified for HLW borosilicate glasses. It is expected, however, that this will be the case, and that existing glass reaction models can be used to describe the degradation process, in which case, flow-through tests (see below) will provide the required parameters.

In the case of ceramic forms, the mechanisms controlling the reaction the zirconolite-based ceramic are not fully understood; thus it is premature to identify the tests required to provide input to the models. This plan includes the development and execution of tests designed both to elucidate the reaction mechanisms so that predictive models can be developed, and to obtain the values of any parameters required by these models.

It will be necessary to evaluate the effects of radioactive decay on the performance of the immobilized forms. These effects fall into three categories: transmutation (the conversion of Pu

to U over time, with attendant change in composition of the form); radiation damage; and radiolysis effects. Each of these effects will be studied.

Transmutation will affect the performance of the immobilized forms because Pu has significantly different aqueous chemistry than its uranium daughter product. This effect can be readily assessed by preparing immobilized formulations containing U instead of Pu and subjecting them to the same regimen of performance tests as will be used for the Pu-bearing forms. Although such tests cannot duplicate the potential effect of radiation damage (see below) on the release rate of U from the immobilized form, they can provide information on the formation of solubility-limiting secondary phases and the reaction path taken during the reaction of the forms with groundwater in a repository. (Note that it is expected that the release of both Pu and U from waste packages in a Yucca Mtn. repository will be limited not by the reaction rate of the immobilized form, but by the product of the elemental solubilities times the water flux.)

Both the glass and ceramic forms are expected to suffer extensive atomic-scale damage resulting from the release of energy during the alpha decay of Pu. This damage will be manifested by changes in the physical properties (volume, hardness, *etc.*) of the form. In addition, the decay product U will reside in damaged "sites" in the material, and this may affect the leaching properties of the form. These effects will be assessed in several ways. Samples of candidate immobilized forms that contain ^{238}Pu and/or ^{244}Cm in place of Pu will be synthesized (in some cases, such samples have already existed for on the order of a decade). ^{244}Cm has a half life of approximately 18 years, and significant alpha radiation damage will accumulate in a relatively short time. Cm, however, may not be a particularly good chemical analog for Pu in the immobilization forms under consideration due to differences in valence state and site occupancy in the ceramic phases and glasses. ^{238}Pu , of course, is a perfect chemical analog for other isotopes of Pu, but has a longer half-life (~88 y), so for a given mass loading, a "doped" immobilization form will accumulate damage more slowly with ^{238}Pu than with ^{244}Cm . Another problem with Cm-244 is that the self-heating will be 5 times higher for Pu-238 (for the same doping level), so even if high Cm content is possible, the self-heating may limit the Cm content. If it is only possible to incorporate 2 wt% Cm in a glass designed for 10 wt% Pu, a glass containing 10 wt% Pu-238 should be the choice for study since the damage rate is the same as for 2 wt% Cm-244 and the chemistry is unaltered.

In addition, there exist archival samples of relevant (though not identical to the present formulations) wastefoms doped with ^{238}Pu .

Because the highest dose levels the immobilized forms will experience greatly exceed the dose levels that can be achieved in reasonable laboratory time periods using ^{244}Cm or ^{238}Pu , additional samples of Pu- and U-bearing candidate forms will be subjected to external radiation bombardment (^4He and possibly heavy ions). This process is expected to severely damage the near-surface layers of the material, and, if carried out over a wide range of experimental conditions (*e.g.*, temperature and dose rate), should provide an upper limit on the effects of

radiation damage.

Both archival samples and new samples (after allowing for a decay period of ~1 year for the doped samples) will be subjected to the same regimen of performance tests as will be used for the Pu-bearing forms. Any new samples (containing ^{244}Cm or ^{238}Pu) will be stored at relevant higher temperatures (*e.g.*, 60 to 200°C) in small pot furnaces to bracket repository conditions and to allow some annealing of accumulated damage to occur..

The primary effect of radiolysis is expected to be the formation of reactive radicals by the irradiation of moist repository air. In particular, this process may affect the performance of the immobilized forms by the production of small quantities of nitric acid, which would lower the pH of the water reacting with the immobilized form. A slight tendency to lower the pH may actually improve the performance of alkali-containing glass forms because the reaction of such forms with water naturally produces high pH solutions, which are more reactive with the glass (*i.e.*, more "corrosive") than are near-neutral pH solutions.

The standard suite of tests to be performed in the post-RoD period are outlined below together with the rationale for conducting them.

The standard PCT-A test will be performed following the ASTM procedure C-1285 94. A full suite of elements will be analyzed, as the applicability of a comparison between the ceramic forms and the EA glass is difficult based solely on the solution concentrations of B, Li, and Na (the elements required by the WAPS). A rationale for comparison between ceramics and the EA glass will be made based on the release of matrix and marker elements from each. It may be necessary to develop and submit a new test procedure to the ASTM for the testing of ceramic forms (analogous to ASTM C-1285 94 for glass). This test is done in DIW in triplicate at 90°C at a SA/V of 2,000 m^{-1} . Tests will also be performed on the EA glass as required by the procedure. The information derived from this test will meet the HLW WAPS requirement.

PCT-B tests will be performed in duplicate at 90°C at a SA/V of 20,000 m^{-1} to be terminated at time intervals commensurate with past testing of DWPF glasses and extending through four years. Several tests of to-be-determined duration will be included in the matrix. The tests will be performed with J-13 well water that has been equilibrated with tuff (a reference water used in YMP testing). Full analyses will be performed on the solutions and the residual solids. The information gained is representative of small amounts of standing water and the data will be comparable with existing data on DWPF glasses.

The standard MCC-1 procedure will be performed for short-time periods (3 days or shorter) to provide an indication of the forward rate of reaction.

An abbreviated matrix of "drip" tests (also known as "unsaturated" tests) will be performed using as-produced and vapor-aged forms. The tests will be done at 90°C in duplicate. The solutions will be analyzed periodically, and the test components would be analyzed at the completion of the test. This is an in-service condition test that provides bounding information in so far as the flow past the immobilized form is not restricted and there is air in contact with the form. The test would evaluate Pu/U/absorber distribution in an in-service environment.

pH-stat tests will be conducted to evaluate the effect of varying pH and solution compositions on the reaction of the forms. These variables are important parameters that are known to affect the reaction of ceramic (solution composition) and glass (pH). It is anticipated that these tests will be relatively short duration (< 30 days) and will provide information that will be useful to both modeling waste form reaction and understanding the effects of parameters under controlled conditions.

Water-saturated flow-through tests will be conducted at varying temperatures and pH to determine the forward reaction rate of the forms. These tests provide a parameter needed in existing models for glass reaction, and will likely be required for similar models developed for the reaction between water and the phases present in the ceramic form(s).

Pressurized Unsaturated Flow (PUF) tests will be conducted on immobilized forms at temperatures of 90°C and lower. The PUF test allows testing under continuous flow, open-system conditions like the saturated flow-through tests, but at low moisture contents (<10% of water saturation). Time acceleration along the glass/water reaction path of 20 to 100 times over high S/V PCT tests at the same temperature has been demonstrated. The PUF test can be run with crushed or fractured monoliths. Both DWPF glass and the immobilized form will be tested at the same time using a sequential flow path for the purpose of simulating a "can-in-canister" configuration where changes in the water chemistry that occur from contact with DWPF glass may induce the formation of alteration phases that positively or negatively impact the reaction path of the Pu immobilization form. Precipitation of secondary phases will be tracked in real time through the changes in the unsaturated hydraulic properties of the test materials that are manifested by changes in volumetric water content during the test. Effluent samples will be analyzed and complete solids characterization will be performed. In the "can-in-canister" interaction tests, the interface(s) between DWPF glass and immobilized form will be carefully examined for secondary phase formation.

Additional tests may need to be developed and conducted to accelerate the production of any secondary phases that incorporate Pu, U, and the neutron absorber(s) so that these phases can be identified. Such phases are expected to control the solubility of the fissionable nuclides and absorber elements in solution and it is important that any such phases be accounted for in modeling the degradation and elemental release behavior of the forms.

Key Milestones:

- 9/96 Testing for RoD complete
- 8/97 Testing for glass selection process complete
- 6/98 Testing for glass vs. ceramic selection complete
- 11/99 Testing for Waste Qualification Process complete
- 5/01 Testing for repository licensing complete

2.3 Performance Modeling (WBS 1.4)

It is intended that the ultimate resting place for the immobilized Pu will be a deep geologic repository, primarily designed for the disposal of high-level nuclear waste and civilian spent fuel. Therefore, it is important that the immobilized Pu be shown to be acceptable for disposal in such an environment. Demonstration of acceptability entails the ability to calculate the behavior of the immobilized form over the regulatory timeframe of the repository so that the form's impact on the repository safety can be assessed. Laboratory experiments alone cannot be used to evaluate the behavior of a wasteform over the very long timescales relevant to a repository -- at least 10^4 years, and perhaps as long as 10^6 years. It is well accepted in the waste disposal community that the only means by which such long-term performance assessments can be made is *via* mathematical models. To have confidence in these models, they must be based on a reasonably fundamental understanding of the chemical and physical mechanisms that control the in-repository behavior of the materials in question. The work planned in this WBS element is designed to provide that understanding.

The primary safety concern raised by the introduction of Pu-bearing immobilized forms into a HLW repository is the possibility of a criticality event. Current plans to assure that such an event cannot take place involve the incorporation of neutron-absorbing elements that have aqueous solubilities similar to that of the fissionable nuclides, and to develop immobilized forms that are intrinsically "robust" with respect to aqueous corrosion. The key requirement to show that the Pu-bearing forms can be safely included in a repository will be the ability to make scientifically credible calculations of the relative mobility of fissionable nuclides and neutron-absorbing elements in the repository environment.

Although the emplacement of the Pu-bearing immobilization forms in a repository will add to the radioactive inventory of the repository, this will be a relatively small perturbation on both the total inventory and the inventory of Pu in the repository as it is currently envisioned. (The first repository may contain up to 70,000 metric tonnes of spent nuclear fuel, which will dominate the

radioactive inventory.) Thus, although it will be necessary to provide predictions on the wasteform dissolution and the release of radioactive materials, this will probably not be the primary safety concern. In any case, the ability to make such predictions will follow as a natural result of the ability to predict the relative mobility of fissionable nuclides and neutron-absorbing elements.

The work on performance modeling is divided into four distinct tasks: (1) degradation model development for both glass and ceramic; (2) acquisition of thermochemical data needed by the models; (3) comparison with existing literature data and other ongoing projects involving natural and man-made analogs; and (4) use of the predictive models in performance assessments. Each of these aspects is briefly discussed in the following sections.

2.3.1 Degradation model development (WBS 1.4.1)

For both glass and ceramic, it will be necessary to have models that describe both the rate of reaction of the wasteform with water (both liquid and vapor) under repository-relevant conditions, and the time-dependent concentrations of elements present in water in contact with the immobilized form in a failed waste package. Two distinct types of models are required: models that embody rate laws that describe the reaction of the immobilized form with water; and models that describe the approach to equilibrium of an aqueous system initially containing a specified quantity of dissolved material, *i.e.*, models that evaluate aqueous speciation and dissolution/precipitation reactions in complex solutions under conditions of thermodynamic equilibrium. Both models must provide reliable simulations as a function of relevant environmental and chemical variables such as temperature, redox state, system composition, *etc.*. In addition, it may be necessary to develop models for the effect of both radiation damage and radiolysis on the reaction rate of the immobilized form and solubility of key solid phases in groundwater. The effect of the alpha radiation field, if any, will likely be the production of acidic radiolysis products of moist air. As discussed above, the primary goal is to develop models that describe the release of fissionable nuclides and neutron absorbers from the immobilized form so that the rates at which these elements are transported from a failed waste package by liquid water can be calculated.

In the case of glass, rate laws that describe the reaction of borosilicate glass with liquid water have been developed over the past decade by HLW glass producers around the world for use in repository performance assessments. We anticipate that the mechanisms considered in these models will also be relevant to the vitrified forms under consideration for the immobilization of Pu. This assertion will need to be checked experimentally and the necessary experiments will be conducted as part of the planned testing program (WBS 1.3.1). Naturally, the values of the input parameters (*e.g.*, rate constants) for the models depend on the specific glass under consideration and these parameters will also need to be measured for each glass (WBS 1.3.1.2).

Less is known about the dissolution mechanism(s) of the phases present in the ceramic forms. Thus, it will be necessary to conduct a series of experiments designed to expose the relevant reaction mechanisms (WBS 1.3.2.2), and to construct new models (WBS 1.4.1.2) that incorporate these mechanisms.

Models that predict the approach to equilibrium of multicomponent aqueous systems have been developed by the geochemical community. These computer codes, known as reaction-path codes, have also been used extensively by the international waste disposal community. We expect to use existing codes packages such as EQ3/6NR (developed at LLNL and used by the Yucca Mtn. Project) and REACT (from the Univ. of IL) for modeling the fate of elements in solution once they are released from the surface of a degrading wasteform. However, these code packages are limited to modeling closed-systems or simple single-node, water-saturated flow-through systems and so are not suitable for modeling the time and spatial evolution of the solution chemistry in an unsaturated repository environment. A new class of reactive-transport codes such as AREST-CT (developed at PNNL and used by the Yucca Mtn and Hanford TWRs Projects) is required for this type of analysis (WBS 1.4.4).

2.3.2 Thermodynamic data development (WBS 1.4.2)

The reaction-path models require thermochemical data for the aqueous species and solid phases that contain the important elemental components of the immobilized form, as well as elements initially present in significant quantities in the water contacting the immobilized form or that are present in other components of the waste package and engineered barrier system. Extensive databases exist for the common rock-forming elements, and the Yucca Mtn. Project has supported an effort to augment those data to produce a database for use in that Project. However, there are major deficiencies in the existing database for Pu and the rare earth elements (REE, currently the leading choices for neutron absorbers). It will therefore be necessary to develop the requisite data through a combination of literature searches, modeling (data estimation), and experiments. In particular, we anticipate the need to measure solubilities, enthalpies of formation, and heat capacities of the key solid phases that incorporate Pu and the REE that are identified in the testing program (WBS 1.3.1.1 and 1.3.2.2).

Under this program, we have reviewed the thermodynamic data for Gd and Pu that are currently being used in some of the computer models and have pointed out the data needs for these elements. In addition, the Swedish nuclear waste program recently published a critical review and compilation aqueous and solid-phase thermodynamic data for the REE, which we will use as a starting point for further work. In the case of Pu, there is currently an international effort being conducted under the auspices of the Nuclear Energy Agency (NEA) to produce a thermodynamic database for Pu. (A similar database for U was produced several years ago.) Beginning in FY96, we will participate in this effort. The benefit of our participation is early access to draft versions of the database. Despite these ongoing international efforts to review relevant data,

thermodynamic data for several important reactions involving Pu and the REE are not available. It is possible to fill some of these data gaps by different estimation schemes (e.g. using data from trivalent rare earths and Am as analogs for trivalent Pu), but these data eventually will have to be validated. The ultimate use of these thermodynamic data is in reliably calculating the release of these elements from glass and ceramic. In this regard, it will be extremely important to conduct experimental studies of doped Pu/Gd glasses and ceramics to identify solubility-controlling reactions and validate the use of thermodynamic data in these calculations. These experiments will be conducted as part of WBS element 1.3.

Thermodynamic data at 25°C and at elevated temperatures are required for both the REE and Pu. At present no reliable data at elevated temperatures are available and will have to be developed. The available data for Gd suggest that reliable data for the solubility product of $Gd(OH)_3(c)$ and for the second and third hydrolysis constants along with the carbonate complexes, which are expected to be important in pH regions >8.5 , are not available. Some data on the sulfate complexes of Gd are available but they were obtained at relatively high ionic strengths and extrapolations of these data to low ionic strengths are difficult. Since these data were obtained, we now have reliable electrolyte models (the Pitzer equations) that may provide a means to reinterpret these data for applications to low ionic strengths. Attempts will be made for such reinterpretations.

In the case of Pu, data for Pu(IV) complexes with carbonate are required but are being developed under other programs and will not have to be developed under this program. In addition data on kinetics of redox reactions involving Pu and common oxidants and reductants including radiolysis products expected to be present in the repository environments. Key data are missing for several Pu(III) solid phases (e.g. solids of phosphate and carbonate) that are expected to be relatively insoluble. Data for Pu(III) complexes with PO_4^{3-} , SO_4^{2-} , and carbonate are also missing. However, the environment of the candidate HLW repository at Yucca Mtn. is expected to be chemically oxidizing, thus we do not expect solid phases containing Pu(III) to be stable in that environment.

Studies in FY 1997 will concentrate on developing thermodynamic data for the solubility product of $Gd(OH)_3$ and the hydrolysis and carbonate complexes of Gd. We will also evaluate whether it is possible to reinterpret old literature data on $Gd-SO_4^{2-}$ complexes. Studies of Pu(VI) hydrolysis will also be completed. In future years, it will be necessary to conduct studies on the solubility of selected Pu(VI) solids such as alkali plutonates and phosphates.

2.3.3 Comparison with analogs (WBS 1.4.3)

There are a number of natural and anthropogenic analogs that may provide the opportunity to increase confidence in the reliability of the models and the predictions of those models over long time periods. For example, the Pu-bearing phases (e.g., zirconolite) in the ceramic formulations

under consideration occur in nature, and naturally contain appreciable quantities of actinides (U and Th), as well as the rare earth elements (REE). Previous studies of retention of actinides in zirconolite are often cited as demonstrating the suitability of this phase for the long-term immobilization of Pu. As another example, there are ongoing studies of the mobility of radionuclides present in underground nuclear test cavities at the Nevada Test Site. Among the nuclides present are Pu and fission-product REE. Data from these studies may be very helpful in constraining the transport behavior of Pu and REE neutron absorbers in a Yucca Mtn. repository.

No new experimental or field studies are planned under this activity; instead, we plan to utilize the results of other studies as reported in the literature to bolster the repository safety case for the immobilized forms. In some cases (*e.g.*, the NTS studies) it may be possible to influence the direction of these other studies through discussions with the responsible investigators so that they produce information more relevant to the case of immobilized Pu.

2.3.4 Performance assessment (WBS 1.4.4)

The in-repository performance of the immobilized form will be one of the criteria by which a final form is selected. To support the selection of a single glass composition (WBS 1.1.4), and the selection between glass and ceramic (WBS 2.4), the models and data developed in the preceding tasks will be incorporated into a reactive transport simulator, such as the AREST-CT code, to assess the relative performance of the candidate immobilized forms under in-repository conditions. These assessments will be limited in scope and conducted solely for the purpose of selecting among the candidate forms. The primary responsibility for the assessment of repository impacts lies with OCRWM; it is anticipated that in general, the role of the MD program will be to provide specific information related to the immobilized Pu that would not otherwise be within the scope of the repository program. We will work with OCRWM to provide the necessary input to waste package and repository performance assessments that are carried out in support of the repository licensing process.

Key Milestones:

- 9/97 Assessment for glass downselect complete
- 6/98 Assessment for glass vs. ceramic downselect complete
- 8/99 All necessary thermodynamic data obtained
- 9/01 Modeling to support repository license application completed

2.4 Glass/Ceramic Downselect (WBS 1.5)

A major programmatic decision is the selection between glass and ceramic forms. This selection is scheduled to take place in November, 1998. In early FY1997, a set of selection criteria will be documented and these will form the technical basis for selecting between forms. The selection process will take into account the proliferation resistance of the forms, fabricability/processing requirements, repository performance, lifecycle cost, and technical maturity. If the glass-bonded zeolite form produced by the electrometallurgical process is still a viable candidate at this time, it will be included in the selection process.

Key Milestones:

5/97 Selection criteria documented

11/98 Final form selected

2.5 Qualification and Repository Licensing (WBS 1.6)

It is intended that the ultimate resting place for the immobilized Pu will be a deep geologic repository, primarily designed for the disposal of high-level nuclear waste and civilian spent fuel. Therefore, it is important that the immobilized Pu be shown to be acceptable for disposal in such an environment. As presently implemented by the DOE-RW, the process of demonstrating acceptability has two distinct aspects: (1) "qualification" of the material, and (2) development of the licensing safety arguments and supporting data that would be used to argue that it would be safe to dispose of the material in a specific repository. This two-stage process is what was followed for the only cases of wasteform qualification that have occurred thus far, these being the vitrified HLW that will be produced by the Defense Waste Processing Facility at Savannah River, S.C., and the West Valley Vitrification Plant at West Valley, N.Y.. We expect that a similar process will be followed for any immobilized forms containing surplus weapons Pu.

2.5.1 Qualification (WBS 1.6.1)

A waste producer qualifies a wasteform by showing that the material they produce meets the wasteform specifications set forth by the DOE Office of Civilian Radioactive Waste Management (OCRWM) in their systems requirements documents (the Waste Acceptance Systems Requirements Document or WASRD). These requirements are derived from the applicable regulations, as well as constraints imposed by generic repository designs and transportation needs. Waste acceptance product specifications (WAPS) consistent with the WASRD are developed for specific wasteforms or classes of wasteforms. The acceptance specifications largely relate to the physical and chemical form of the waste; the size, design, and

material properties of the packaging of the waste; limits on the radiation field and thermal output; and labeling requirements. It is important to note that in the current draft wasteform specifications for Pu-bearing materials, there are no repository-specific wasteform requirements (e.g., requirements related to the performance of the waste in a repository). The only performance-related requirements relate to tests (currently unspecified) that are needed to assure the consistency of the properties of the material being produced.

For the present case of immobilized Pu, preliminary acceptance specifications have been drafted, and we anticipate finalizing the wasteform specifications (WAPS) by the spring of 1997 (WBS 1.6.1.1, 1.6.1.2). Timely completion of this process will require the cooperation of OCRWM.

Following the example of DWPF, the next step in qualifying the immobilized forms will be the preparation of a Waste Compliance Plan (WCP) under WBS element 1.6.1.3.. This document details how the waste producer intends to meet the acceptance specifications (WAPS). Most of this document cannot be written until a choice is made on a "final" immobilized form, and its production process, which is scheduled to occur in the fall of 1998 as the output of WBS element 1.5.3. We intend to use the existing WCP that has been used for the DWPF as a model, and modify that document as necessary to account for the differences in wasteforms. Should ceramic be selected as the final immobilized form, a key uncertainty in the time needed to develop the WCP (and the WQR, see below) will be the time required to identify and develop sufficient understanding of the processing steps that control product consistency.

Upon selection of a final form and process, the process of gathering data to be used for qualification can begin in earnest (WBS 1.6.1.4). These data will be incorporated into a Waste Qualification Report (WQR) in order to demonstrate that the processes and operations detailed in the WCP do, indeed, result in a wasteform that meets the WAPS. Some of the data needed for qualification can only be generated using equipment and processes that faithfully represent those that will be used during actual production. Thus, some acquisition of some data is dependent on the availability of facilities in which these processes can be set up on a production scale. Such facilities will also be necessary to test and demonstrate every key unit operation and process, and will be available through the development of system development and demonstration WBS elements (WBS 2.1 and 2.2).

Preparation of the WQR will proceed in two steps (WBS 1.6.1.5). A draft WQR will be prepared in parallel with the gathering of data and will be submitted to OCRWM for review in November, 1999. It is anticipated that there will be unresolved issues arising from the draft Report, and a revised and final version will be prepared that incorporates comments received from OCRWM (and the NRC). The final Report will be submitted in August, 2001. Qualification of the immobilized form should follow shortly thereafter in December, 2001.

2.5.2 Licensing (WBS 1.6.2)

In general, the information provided to OCRWM as a result of qualifying a wasteform is necessary, but not sufficient, for OCRWM to include the wasteform in the safety and performance assessments used to support the license to construct a repository. (It is important to note that wasteforms themselves are not licensed; only the repository system as a whole is licensed.) To include a new wasteform in the licensing case for a repository, OCRWM also needs information on the behavior of the wasteform in the specific repository under consideration. This additional information includes experimental data on the wasteform dissolution characteristics, models for the prediction of long-term degradation, and the values of the parameters of the models (*e.g.*, kinetic rate constants, and thermodynamic data). Following the precedent set by DWPF and West Valley, it is the responsibility of the waste producer to work together with OCRWM to obtain the necessary information and develop the licensing arguments.

The actual data gathering and model development that will be needed for a repository license application will be carried out under WBS elements 1.3 and 1.4. This WBS element is included in the plan to provide a explicit level-of-effort task to coordinate these activities with OCRWM.

Key Milestones:

- 7/96 Preliminary Waste Acceptance Specifications available
- 3/97 Final Waste Acceptance Product Specification completed
- 5/99 Waste Compliance Plan completed
- 11/99 Data for draft Waste Qualification Report (WQR) gathered
- 11/99 Submit draft WQR
- 8/01 Submit revised (final) WQR
- 12/01 Waste qualified

3. PROCESS DEVELOPMENT (WBS 2.)

The work in this WBS element will focus on the development and demonstration of prototypical systems for the production scale incorporation of Pu in one of the forms currently under investigation. The glass systems require the development of a suitable melter system which includes both suitable feeders and product loadout systems contained in a glovebox enclosure to allow Pu operation. The ceramic systems require either: (1) the development of a suitable feed preparation and cold-pressing system coupled to an appropriate heat cycle to sinter the ceramic (similar to that used in the fabrication of nuclear reactor fuel), also contained within a Pu glovebox; or (2) the development of suitable feed preparation and hot-pressing system contained within a Pu glovebox.

For glass (WBS 2.1), three melter systems (stirred induction, Bushing, and cold-wall melters) will be simultaneously developed at LLNL, SRTC and in Russia. Each of these melters has unique characteristics such as fast cycle time, high temperature, renewable crucible walls, or stirring, some or all of which may be important to production-scale operations for glass immobilization.

The ceramic immobilization approach (WBS 2.2) will investigate both the hot press and the cold press and sinter approaches. All systems will be evaluated with dry Pu oxide feed, as well as alternative feeds, and, through a series of down-selects during the evaluation phase, the optimum system will be chosen for use in the pilot facility (WBS 3.)

In addition to the melter and press systems, all other key unit operations and systems will be demonstrated and tested (WBS 2.3) so that the final designs of the pilot facility can be completed.

3.1 Glass Processing (WBS 2.1)

3.1.1 Melter R&D (WBS 2.1.1, 2.1.2)

The primary goal of the glass melter development is a melter system that can reliably and safely melt batches of borosilicate glass containing kilogram quantities of plutonium and a suitable neutron absorber. The system will include the feed system, melter, discharge components, off-gas system, and glovebox adaptation.

Development of such a system in parallel with the development of the basic glass systems and dissolution kinetic determinations described earlier will require flexibility in the design of the melter to accommodate the range of temperatures, liners, stirrers, and potential feed and product discharge systems. All furnaces have several elements in common: all will have to operate at temperatures ranging from 1100 to 1500°C (depending on the glass formulation used) for cycle

times ranging up to 24 hours. All will operate in an inert or oxidizing atmosphere. All must be able to demonstrably control criticality for all feed and operating conditions for multiple cycles of operation. All must fit into a glovebox enclosure and be serviceable through glove ports. Liners must either be renewable (as with a one-time use crucible or a cold wall melter) or must have liners that will operate for many cycles without serious erosion or Pu build-up on the walls or elsewhere within the system. At the present time, the use of dry feeds is preferred so that all systems must be capable of accommodating a dry feed system, either semi-continuous or batch. It should be possible to add the additional off-gas system for slurry or liquid feed if dissolution kinetics indicate that this is necessary.

Melter development teams will be formed at Pacific Northwest Laboratory, Savannah River Technology Center, and Lawrence Livermore National Laboratory. PNL will work with LLNL to develop an induction-heated, stirred melter design with a bottom pour capability for glovebox installation at LLNL. SRTC will develop their Bushing Melter for the LaBS glass and will conduct preliminary studies. If deemed advantageous, SRTC will work with LLNL in building and installing a Bushing melter in a glovebox at SRTC if feasible or at LLNL for additional evaluation with Pu and prototype demonstration. LLNL will evaluate the use of stirred induction melters using both a tilt-pour furnace (which allows a rapid demonstration and evaluation of the need for stirring or otherwise "agitating" the melt) and a stirred, induction-heated, bottom-pour melter based on PNL design experience. Focused evaluations will be made of these individual melter approaches prior to the design and installation of the prototypical system for scale tests and demonstrations with Pu.

A separately funded program with the Russian Bochvar Institute will also participate in this program, pending completion of negotiations. At present, the Russian team will plan to provide valuable data on the Pu solubility and dissolution rates in the candidate glass systems using the cold-crucible induction melter (CCIM) at Bochvar. These melters have the potential advantages of reaching very high temperatures ($>1500^{\circ}\text{C}$) and high glass throughput rates. More importantly, they have the potential of having very long-lived liners (the glass liner is constantly renewed). In addition, the Russian team will study the effectiveness of various solid feed approaches to include both oxide feeds of different particle size and silica gel feeds.

If final arrangements are completed, the Russian team will develop a production prototype system including a dry feeder system for the CCIM melter which will operate semi-continuously and will provide the appropriate production rates consistent with the required dissolution times. In addition, crucible pour and load-out systems compatible with production operation will be designed to operate with the cold wall induction melters. The resulting melter prototype system will be operated with a suitable surrogate to demonstrate the required capability. Follow-on demonstration melter system adaptation to US Pu facility requirements will be jointly performed with LLNL for an LLNL Pu demonstration of the CCIM melter as a production unit.

Key Milestones:

- 3/97 Evaluate ATS and LaBS glass immobilization in large, stirred, induction melters (tilt-pour) at LLNL with Pu
- 6/97 Demonstrate Pu-capable production system Bushing melter (cold) at SRTC
- 1/98 Evaluate ATS and LaBS glass immobilization in large, stirred, induction melters (bottom-pour) at LLNL with Pu
- FY98 Demonstrate production system cold wall melter (cold) at Bochvar (funded elsewhere)
- 5/98 Evaluate Bushing production prototype with Pu

3.1.2 Melter Selection (WBS 2.1.3)

Following melter demonstrations of the stirred induction, Bushing, and cold wall melters (if applicable) and performance testing (WBS 1.3) of the resulting glass products, a down-select to a single melter approach and design will be made on the basis of performance of the candidate glass systems, melter operation and dissolution kinetics with various feed systems, and ease of operation. While multiple melters will be initially developed in order to expedite a successful large scale immobilization demonstration, only one melter/glass system will be selected and carried forward to the decision point which selects the immobilization form.

Key milestones:

- 8/98 Select melter technology

3.2 Ceramic Processing (WBS 2.2)

Development of the ceramic approach will be performed at LLNL with contractual support from the ANSTO as required. Two approaches will be evaluated: 1) hot press of a ceramic precursor mixture with the Pu incorporated as a solid Pu oxide feed and 2) cold press and sinter of the ceramic materials blended with the Pu oxide feed. As discussed above, the basic chemistry and material properties will be evaluated with laboratory-scale experiments in WBS element 1.2. However, development of the processing equipment necessary for production will be performed under this element. Note that the problems of scale associated with the use of large glass melts when extrapolating from small scale experiments are much less in the case of the ceramic approaches, particularly the cold press and sinter approach.

3.2.1 Hot Press Development (WBS 2.2.2)

In the case of the hot press and sinter, a hot press system will be developed and demonstrated that will consolidate a bellows canister at processing temperatures resulting in "hockey pucks" 3 to 4 inches in diameter. A critical problem to be resolved is the development of the heating and pressure plate systems that apply the required pressure at the sintering temperatures ($>1200^{\circ}\text{C}$) without serious degradation problems. The development work will involve obtaining a suitable press and furnace system and adapting it to a glovebox operation. Hot shoe materials will be evaluated, and production operation of the ceramic hot press system will be demonstrated. Detailed evaluation (WBS 1.2 and 1.3.2) of the resulting ceramics will be used in deciding which ceramic formation approach will be implemented.

Key milestones:

6/97-12/97 Evaluate production scale ceramic waste form production containing Pu using the hot press process

3.2.2 Cold-Press and Sinter Development (WBS 2.2.1)

The potential advantages of the cold press and sinter approach are substantial in terms of simplicity and ease of incorporating Pu and accompanying impurities into the ceramic crystalline matrix. In addition, there are no scaling problems because the smaller pellets would simply have to be produced in quantity and then sealed in the inner can for the can-in-canister immobilization approach. Preliminary work on this at LLNL indicates that high quality ceramics can be formed by this process using technology very similar to that used for MOX reactor fuel fabrication. The proposed work will involve obtaining and installing a press system to produce pellets at a reasonable rate for this demonstration. (Note that the commercial reactor fuel processors have presses available that can achieve very high rates of pellet production if this approach proves viable.) This press, along with a suitable mill and blender and a sintering furnace, will be installed within a glovebox system to produce demonstration quantities of Pu-containing sintered pellets for evaluation. Various ceramic precursors will be evaluated with Pu loadings up to 18% by weight in determining the optimum system for this approach.

Because the cold press and sinter approach depends on solid-solid diffusion at elevated temperatures, particle size and blending are expected to be important parameters in final product quality for Pu inclusion in the crystalline matrix. These parameters will be evaluated using the HYDOX system located at LLNL. Note that systems are currently available within the current MOX industry to achieve highly uniform blending of small particle sizes, particularly at BNFL using their "attritor" mill.

Key milestones:

3/97-10/97 Evaluate production scale ceramic waste form production containing Pu using cold-press and sinter process

3.2.2 Ceramic Process Selection (WBS 2.2.3)

Following the demonstration of both hot press and cold press and sinter ceramic materials and their evaluation, a down-selection will be made to determine the appropriate ceramic approach for follow-on development and pilot-scale demonstration if a ceramic form is ultimately carried forward as the final form for Pu immobilization. This activity involves the development of selection criteria, as well as the conduct of the selection process.

Key Milestones:

5/97 Selection criteria documented

1/98 Select ceramic fabrication technology

3.3 Demonstrate Unit Operations

Prior to completing a detailed facility design, it is essential to demonstrate at full scale each major system or unit operation that will be a part of the end-to-end immobilization process. The work conducted under this WBS element will demonstrate each of these key operations using realistic equipment and procedures so that the designs of the Pilot Facility can be completed. Demonstration of these operations will also be necessary to generate the experience and data needed to complete the Waste Qualification Report (WBS 1.6.1.5).

The operations that will require demonstration include the front end (Pu feed prep, blending, frit/precursor preparation), offgas systems, the melter or press system (feed systems, melting/pressing), container sealing, decontamination, labeling, assaying, and transport to storage. These operations will be demonstrated as part of the Melter and Ceramic Processing R&D (WBS 3.1, 3.2).

Key Milestones:

10/99 All key unit operations demonstrated

4.0 DEMONSTRATIONS & PILOT FACILITY DEVELOPMENT (WBS 3.)

The work described in the preceding sections will culminate in the design and construction of a pilot-scale immobilization facility that will be capable of one-quarter of the ultimately desired throughput. It is intended that this facility will be constructed at the same location as the final, full-scale plant, and that the pilot facility will be designed in such a way as to facilitate easy scale-up to full production. Because the exact nature of this facility will depend on the specific immobilization form selected and its method of production, it is difficult at this time to provide concrete details on the pilot plant that would ultimately be constructed. For the purposes of developing a schedule for this plan, we have assumed that some variant of the can-in-canister alternative (with Pu immobilized in either ceramic or glass) will be chosen.

The design of the pilot facility will begin with the development of conceptual, and then preliminary designs for each of the extant alternatives (WBS 3.4.2.1). Preliminary designs will be completed by March, 1998. These designs should be of sufficient detail that reliable and detailed cost and space estimates can be made for each alternative so these estimates can be factored into the selection process leading to a final immobilized form in November, 1998. In parallel with the immobilized form selection process, a decision will be made with respect to the production process to be used (WBS 3.4.1). Upon selection of an immobilization form and process, the design of the pilot facility can be finalized (WBS 3.4.2.2).

Modification of existing facilities and construction of the pilot should begin as soon as a site has been selected and the designs are sufficiently well advanced that construction can begin. In the schedule attached to this plan, we have assumed that the construction phase will take place over approximately three years, beginning in August, 1998, and ending in December of 2001 (WBS 3.4.2.3).

Production of "cold" (*i.e.*, non-Pu-bearing) immobilized material (WBS 3.4.2.4.1) can begin after construction is complete. We have assumed a 20-month cold operations period, much of which is devoted to the conduct of an operational readiness review prior to the commencement of Pu-operations (WBS 3.4.2.4.2). Hot production can begin in September of 2003.

Cost information for the pilot facility is not included in Appendix I because realistic costs cannot be developed until more detailed designs are developed, and a site for the facility has been selected.

Key Milestones:

3/98 Conceptual designs for all alternatives complete

11/98 Immobilization approach selected

10/99 Final designs complete

12/01 Construction complete

1/02 Begin cold production

3/02-9/03 Conduct operational readiness review

3/04 Begin production with Pu

5.0 NON-PROLIFERATION (WBS 4.)

Prior to implementation, it is important to demonstrate that the selected immobilization form meets the spent fuel standard. To that end, a series of paper studies and demonstrations are planned to provide confidence that the immobilized form meets the required proliferation-resistance goals.

The major activities under this WBS element include the preparation of a "white team" report on the proliferation resistance of the immobilized forms and disposition alternatives that will be used to support the RoD. Following the RoD, an evaluation will be made of the difficulty of recovery of the Pu-bearing cans from the can-in-canister alternative. Proliferation-resistant designs for the can-in-canister will be developed that incorporate features that will hinder the removal of the Pu-bearing cans from the canister by mechanical or other means. These designs will be tested for fabricability and the ability to "overpour" DWPF glass into the canister by producing full-scale, cold can-in-canisters using the melters available at PNNL (WBS 4.2)

Process flowsheets for the recovery of Pu from the immobilized forms will be developed, together with schedule and cost estimates. This information will be used in the glass vs. ceramic selection. Finally, a limited amount of validation testing of the recovery flowsheets will be conducted on representative samples of the selected immobilization form (WBS 4.3).

Key Milestones:

- 11/96 White team report
- 4/97 Cold recovery demonstration for glass can-in-canister option
- 4/98 Recovery flowsheets developed for glass/ceramic downselect
- 6/99 Hot recovery demonstration of selected form

Appendix I -- Timeline for Immobilization R&D

ID	WBS	Task Name	Cost	Start	Finish	95	96	97	98	99	00	01	02	03	04
1	WBS #	<u>Immobilization Program Plan</u>	<u>\$47,515,205.67</u>	6/13/95	8/30/04										
2		<u>Waste Form Formulation and Testing Program</u>	\$30,616,680.00	6/13/95	5/16/02										
3	1	<u>Formulation</u>	\$7,601,680.00	6/13/95	6/22/98										
4	1.1	Glass Formulation	\$6,151,680.00	6/13/95	6/22/98										
5	1.1.1	Evaluate feed variability	\$350,000.00	10/1/96	1/20/97										
6	1.1.2	LaBS formulation	\$2,550,840.00	6/13/95	7/3/97										
7	1.1.2.1	Preliminary LaBS formulation	\$425,000.00	6/13/95	8/1/96										
8	1.1.2.1.1	Static Pu solubility tests	\$350,000.00	6/13/95	7/1/96										
9	1.1.2.1.2	Preliminary exam. of impurity effects	\$75,000.00	6/13/95	8/1/96										
10	1.1.2.1.3	Preliminary LaBS composition	\$0.00	8/1/96	8/1/96										
11	1.1.2.2	Revised formulation work	\$2,125,840.00	8/2/96	7/3/97										
12	1.1.2.2.1	Static dissolution kinetics	\$240,000.00	8/2/96	5/31/97										
13	1.1.2.2.2	Impure feed studies	\$420,000.00	12/6/96	7/3/97										
14	1.1.2.2.3	TTT studies	\$150,000.00	12/3/96	7/3/97										
15	1.1.2.2.4	Phase equilibria	\$150,000.00	4/3/97	7/3/97										
16	1.1.2.2.5	Physical property meas.	\$150,000.00	2/24/97	7/3/97										
17	1.1.2.2.6	Tilt Pour Pu Kinetic Studies	\$1,015,840.00	1/14/97	6/30/97										
18		Evaluation of Pu diss w/temp, time, an	\$847,040.00	1/14/97	6/30/97										
19		Evaluate glass performance w/Pu	\$168,800.00	1/14/97	6/30/97										
20	1.1.2.2.7	Revised LaBS composition	\$0.00	7/3/97	7/3/97										
21	1.1.3	ATS Formulation	\$2,875,840.00	6/13/95	10/14/97										
22	1.1.3.1	Preliminary ATS formulation	\$610,000.00	6/13/95	7/3/96										
23	1.1.3.1.1	Static Pu solubility tests	\$130,000.00	6/13/95	7/1/96										
24	1.1.3.1.2	Preliminary exam. of impurity effects	\$150,000.00	6/13/95	7/1/96										
25	1.1.3.1.3	Devitrification studies	\$80,000.00	7/2/96	7/2/96										

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26	1.1.3.1.4	Stirred dissolution kinetics	\$250,000.00	7/3/96	7/3/96										
27	1.1.3.1.5	Preliminary ATS composition	\$0.00	7/3/96	7/3/96										
28	1.1.3.2	Revised formulation work	\$2,265,840.00	7/4/96	10/14/97										
29	1.1.3.2.1	Static dissolution kinetics	\$500,000.00	7/4/96	10/14/97										
30	1.1.3.2.2	Impure feed studies	\$250,000.00	12/6/96	7/3/97										
31	1.1.3.2.3	TTT studies	\$200,000.00	12/3/96	7/3/97										
32	1.1.3.2.4	Phase equilibria	\$50,000.00	2/24/97	7/3/97										
33	1.1.3.2.5	Physical property meas.	\$250,000.00	2/24/97	7/3/97										
34	1.1.3.2.6	Tilt Pour Pu Kinetic Studies	\$1,015,840.00	1/14/97	6/30/97										
35		Evaluation of Pu diss w/temp, time, an	\$847,040.00	1/14/97	6/30/97										
36		Evaluate glass performance w/Pu	\$168,800.00	1/14/97	6/30/97										
37	1.1.3.2.7	Revised ATS composition	\$0.00	7/3/97	7/3/97										
38	1.1.4	Glass selection	\$100,000.00	9/2/96	10/13/97										
39	1.1.4.1	Develop glass selection criteria	\$70,000.00	9/2/96	12/30/96										
40	1.1.4.2	Glass selection process	\$30,000.00	9/1/97	10/13/97										
41	1.1.4.3	LaBS or ATS glass selected	\$0.00	10/13/97	10/13/97										
42	1.1.5	Optimize glass formulation	\$275,000.00	10/14/97	6/22/98										
43	1.1.5.1	Optimize final glass formulation	\$275,000.00	10/14/97	6/22/98										
44	1.1.5.2	Final glass composition	\$0.00	6/22/98	6/22/98										
45	1.2	Ceramic Formulation	\$1,450,000.00	7/7/95	12/2/97										
46	1.2.1	Cold press & sinter lab-scale	\$1,050,000.00	7/7/95	11/6/97										
47	1.2.1.1	Equipment setup	\$0.00	7/7/95	5/1/96										
48	1.2.1.1.1	Develop equipment	\$0.00	7/7/95	5/1/96										
49	1.2.1.1.2	Hot trials	\$0.00	3/19/96	5/1/96										
50	1.2.1.2	Hot lab-scale operation	\$50,000.00	5/2/96	11/6/97										

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ID	WBS	Task Name	Cost	Start	Finish	95	96	97	98	99	00	01	02	03	04
51	1.2.1.2.1	Evaluate press performance	\$0.00	5/2/96	9/6/96										
52	1.2.1.2.2	Establish operating requirements	\$50,000.00	6/14/96	7/31/96										
53	1.2.1.2.3	Evaluate alternative ceramics	\$0.00	5/2/96	11/6/97										
54		Evaluate compaction parameters	\$0.00	5/2/96	11/6/97										
55		Evaluate sintering kinetics (time & Te	\$0.00	5/2/96	11/6/97										
56		Establish feed tolerance	\$0.00	5/2/96	9/23/97										
57		Produce samples for perf. testing	\$0.00	5/2/96	11/6/97										
58	1.2.2	Hot Press Lab scale	\$300,000.00	8/2/95	12/2/97										
59	1.2.2.1	Equipment setup	\$0.00	8/2/95	3/1/96										
60	1.2.2.1.1	Develop equipment	\$0.00	8/2/95	3/1/96										
61	1.2.2.1.2	Hot trials	\$0.00	1/18/96	3/1/96										
62	1.2.2.2	Hot lab-scale operation	\$0.00	3/4/96	12/2/97										
63	1.2.2.2.1	Evaluate press performance	\$0.00	3/4/96	7/9/96										
64	1.2.2.2.2	Establish operating requirements	\$0.00	4/19/96	5/31/96										
65	1.2.2.2.3	Evaluate alternative ceramics	\$0.00	3/4/96	12/2/97										
66		Evaluate compaction parameters	\$0.00	3/4/96	12/2/97										
67		Establish feed tolerance	\$0.00	3/4/96	7/24/97										
68		Produce samples for perf. testing	\$0.00	3/4/96	12/2/97										
69	1.2.3	Ceramic formulation selection	\$100,000.00	9/24/96	4/11/97										
70	1.2.3.1	Develop selection criteria	\$70,000.00	9/24/96	12/30/96										
71	1.2.3.2	Selection process	\$30,000.00	3/3/97	4/11/97										
72	1.2.3.3	Ceramic composition selected	\$0.00	4/11/97	4/11/97										
73		<u>Testing, Modeling, and Qualification</u>	\$23,015,000.00	6/13/95	5/16/02										
74	1.3	Performance Testing	\$9,200,000.00	10/19/95	5/16/02										
75	1.3.1	Glass Testing	\$4,400,000.00	10/19/95	7/8/99										

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ID	WBS	Task Name	Cost	Start	Finish	95	96	97	98	99	00	01	02	03	04
76	1.3.1.1	ROD testing	\$1,100,000.00	10/19/95	8/30/96										
77	1.3.1.1.1	PCT-A tests	\$0.00	10/19/95	8/30/96										
78	1.3.1.1.2	PCT-B tests	\$0.00	10/19/95	8/30/96										
79	1.3.1.1.3	MCC-1 tests	\$0.00	10/19/95	8/30/96										
80	1.3.1.1.4	VH tests	\$0.00	10/19/95	8/30/96										
81	1.3.1.2	Post-ROD testing	\$3,300,000.00	9/2/96	7/8/99										
82	1.3.1.2.1	Radiation damage	\$0.00	9/2/96	6/18/99										
83	1.3.1.2.2	Vapor hydration	\$0.00	9/2/96	6/18/99										
84	1.3.1.2.3	PCT-A tests	\$0.00	9/2/96	6/18/99										
85	1.3.1.2.4	PCT-B tests	\$0.00	9/2/96	6/18/99										
86	1.3.1.2.5	pH-stat tests	\$0.00	9/2/96	3/13/98										
87	1.3.1.2.6	Unsaturated tests	\$0.00	9/2/96	6/18/99										
88	1.3.1.2.7	Saturated flow-through tests	\$0.00	11/1/96	7/8/99										
89	1.3.1.2.8	Unsaturated flow-through tests	\$0.00	7/17/97	7/1/98										
90	1.3.1.2.9	Test to form secondary phases	\$0.00	9/2/96	1/23/98										
91	1.3.2	Ceramic Testing	\$4,800,000.00	10/19/95	6/18/99										
92	1.3.2.1	ROD testing	\$1,200,000.00	10/19/95	8/30/96										
93	1.3.2.1.1	PCT-A tests	\$0.00	10/19/95	8/30/96										
94	1.3.2.1.2	PCT-B tests	\$0.00	10/19/95	8/30/96										
95	1.3.2.1.3	MCC-1 tests	\$0.00	10/19/95	8/30/96										
96	1.3.2.1.4	VH tests	\$0.00	10/19/95	8/30/96										
97	1.3.2.2	Post-ROD	\$3,600,000.00	9/2/96	6/18/99										
98	1.3.2.2.1	New test development	\$0.00	9/2/96	8/6/97										
99	1.3.2.2.2	revised PCT-A tests	\$0.00	8/7/97	6/18/99										
100	1.3.2.2.3	Radiation damage	\$0.00	9/2/96	3/29/99										

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101	1.3.2.2.4	Vapor hydration	\$0.00	9/2/96	3/29/99										
102	1.3.2.2.5	PCT-B tests	\$0.00	9/2/96	7/15/98										
103	1.3.2.2.6	Unsaturated tests	\$0.00	9/2/96	3/29/99										
104	1.3.2.2.7	pH-stat tests	\$0.00	9/2/96	9/2/96										
105	1.3.2.2.8	Unsaturated flow-through tests	\$0.00	9/2/96	9/2/96										
106	1.3.2.2.9	Saturated Flow-through tests	\$0.00	9/2/96	3/29/99										
107	1.3.2.2.10	Test to form secondary phases	\$0.00	9/2/96	12/12/97										
108	1.3.2.2.11	Dissolution mechanism tests	\$0.00	9/2/96	12/12/97										
109	1.3.3	Continued Testing of "Final" Form	\$0.00	12/4/98	5/16/02										
110	1.4	Performance Modeling	\$3,500,000.00	10/2/95	1/1/01										
111	1.4.1	Degradation Model Development	\$300,000.00	10/2/95	7/1/98										
112	1.4.1.1	Glass	\$0.00	10/2/95	7/1/98										
113	1.4.1.2	Ceramic	\$0.00	10/1/96	7/1/98										
114	1.4.1.3	Radiation effects/radiolysis	\$0.00	10/1/96	7/1/98										
115	1.4.2	Thermodynamic data development	\$2,225,000.00	3/1/96	6/30/00										
116	1.4.2.1	NEA Pu volume participation	\$250,000.00	7/1/96	6/30/00										
117	1.4.2.2	Literature surveys/DB maint.	\$125,000.00	3/1/96	3/1/99										
118	1.4.2.3	Solubility expts.	\$750,000.00	8/1/97	7/30/99										
119	1.4.2.4	Enthalpy, Cp measurements	\$500,000.00	8/1/97	7/30/99										
120	1.4.3	Natural analog comparisons	\$180,000.00	10/2/95	9/30/98										
121	1.4.4	Assess performance	\$795,000.00	10/2/95	1/1/01										
122	1.4.4.1	Preliminary assessment for ROD	\$50,000.00	10/2/95	9/30/96										
123	1.4.4.2	Assess glass performance for downselect	\$75,000.00	9/2/96	8/29/97										
124	1.4.4.3	Assess glass vs. ceramic performance	\$120,000.00	9/1/97	6/2/98										
125	1.4.4.4	Provide assessment to support licensing	\$250,000.00	1/1/96	1/1/01										

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ID	WBS	Task Name	Cost	Start	Finish	95	96	97	98	99	00	01	02	03	04
126	1.5	Glass/Ceramic Downselect	\$100,000.00	1/1/97	11/23/98										
127	1.5.1	Develop Glass/ceramic selection criteria	\$70,000.00	1/1/97	5/1/97										
128	1.5.2	Glass/ceramic selection process	\$30,000.00	10/13/98	11/23/98										
129	1.5.3	Select glass or ceramic	\$0.00	11/23/98	11/23/98										
130	1.6	Qualification and Repository Licensing	\$10,215,000.00	6/13/95	12/5/01										
131	1.6.1	Qualification	\$5,115,000.00	6/13/95	12/5/01										
132	1.6.1.1	Preliminary specifications	\$35,000.00	6/13/95	7/1/96										
133	1.6.1.2	Final specifications	\$35,000.00	7/2/96	3/1/97										
134	1.6.1.3	Prepare WCP	\$200,000.00	5/4/98	5/1/99										
135	1.6.1.4	Gather data for WQR	\$4,500,000.00	2/18/98	11/1/99										
136	1.6.1.5	WQR preparation	\$345,000.00	6/8/98	12/5/01										
137	1.6.1.5.1	Prepare draft WQR	\$200,000.00	6/8/98	11/1/99										
138	1.6.1.5.2	Submit draft WQR	\$0.00	11/1/99	11/1/99										
139		(review)	\$0.00	11/2/99	7/13/00										
140	1.6.1.5.3	Revise WQR	\$145,000.00	7/14/00	8/1/01										
141		Submit revised WQR	\$0.00	8/1/01	8/1/01										
142		(review)	\$0.00	8/2/01	12/5/01										
143	1.6.1.5.4	Form qualified	\$0.00	12/5/01	12/5/01										
144	1.6.2	Repository licensing	\$300,000.00	5/1/96	9/11/01										
145	2	<u>Immobilization System Development</u>	\$9,557,320.00	10/2/95	8/17/98										
146	2.1	Glass Melter System Development	\$6,726,400.00	10/2/95	8/17/98										
147	2.1.1	<u>Induction Furnace Development</u>	\$3,870,440.00	10/2/95	5/15/98										
148	2.1.1.1	Tilt pour furnace development - LLNL	\$1,188,640.00	5/1/96	3/10/97										
149	2.1.1.1.1	Furnace modifications	\$183,000.00	5/1/96	10/1/96										
150		Crucible/mold redesign	\$14,400.00	5/1/96	6/25/96										

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ID	WBS	Task Name	Cost	Start	Finish	95	96	97	98	99	00	01	02	03	04
151		Induction coil/insulation modifications	\$15,400.00	5/1/96	5/14/96										
152		Splash shield modification	\$8,800.00	6/3/96	6/14/96										
153		Stirrer specification	\$9,400.00	6/3/96	6/14/96										
154		Crucible / mold / stirrer fabrication	\$125,000.00	8/1/96	9/25/96										
155		Furnace modifications completed	\$10,000.00	10/1/96	10/1/96										
156	2.1.1.1.2	Cold prove-in runs	\$251,200.00	10/1/96	1/6/97										
157		LaBS glass melt and pour in kg quantities	\$81,600.00	10/1/96	12/23/96										
158		Evaluate pour, mold, and lip freeze and mo	\$83,200.00	11/12/96	1/6/97										
159		Ce runs for dissolution / stirrer evaluation	\$86,400.00	10/29/96	12/23/96										
160	2.1.1.1.3	Tilt Pour Pu Hot	\$331,240.00	10/1/96	1/13/97										
161		Bring tilt pour box hot	\$72,440.00	10/1/96	11/11/96										
162		Furnace modifications to optimize performa	\$228,800.00	11/12/96	1/13/97										
163		Pu dissolution melt runs	\$30,000.00	1/13/97	1/13/97										
164	2.1.1.1.4	Can-in-can melting evaluation	\$423,200.00	5/15/96	3/10/97										
165		Select and procur cans	\$38,400.00	5/15/96	6/11/96										
166		Fabricate cans	\$20,000.00	6/12/96	8/6/96										
167		Melt cold glass in cans from pre-loaded frit	\$121,600.00	8/7/96	11/26/96										
168		Evaluate can erosion / performance	\$64,000.00	8/14/96	10/8/96										
169		Ce surrogate can runs	\$25,600.00	10/9/96	11/5/96										
170		Pu can runs	\$153,600.00	1/14/97	3/10/97										
171	2.1.1.2	Bottom pour furnace development- LLNL	\$2,681,800.00	10/2/95	5/15/98										
172	2.1.1.2.1	PNL Support Project Management - PNL	\$37,840.00	10/2/95	5/23/97										
173	2.1.1.2.2	Establish Crucible/Mold Materials - PNL	\$237,000.00	10/2/95	4/5/96										
174		Identify potential crucible/stirrer/mold mate	\$8,760.00	10/2/95	10/20/95										
175		Screen with coupon studies w/ATS and La	\$158,240.00	10/23/95	4/5/96										

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176		Analyze results and recommend	\$15,840.00	2/26/96	4/5/96										
177		Evaluate materials w/proposed furnace atm	\$54,160.00	10/2/95	11/24/95										
178	2.1.1.2.3	Furnace design and installation	\$2,006,640.00	10/2/95	10/24/97										
179		Design	\$847,040.00	10/2/95	2/7/97										
180		LLNL design	\$630,240.00	10/2/95	7/19/96										
181		Develop design concepts	\$148,800.00	10/2/95	12/22/95										
182		Design furnace, feeder, and load	\$375,200.00	12/25/95	7/5/96										
183		Design glovebox modifications	\$106,240.00	4/1/96	7/19/96										
184		PNL support for Stirred Bottom Pou	\$216,800.00	6/3/96	2/7/97										
185		Melter Design and Constructio	\$216,800.00	6/3/96	2/7/97										
186		Develop Design Concepts w/	\$31,200.00	6/3/96	7/12/96										
187		Develop and Approve Desig	\$19,200.00	7/15/96	8/2/96										
188		Assist LLNL with Furnace D	\$52,800.00	8/5/96	10/25/96										
189		Assist LLNL with Feed, offga	\$105,600.00	8/5/96	1/17/97										
190		Review Criticality Calculation	\$8,000.00	1/13/97	2/7/97										
191		Furnace Procurement and Installation	\$1,159,600.00	6/10/96	10/24/97										
192		LLNL procure / install	\$1,037,360.00	6/10/96	2/28/97										
193		Place furnace contract	\$15,840.00	6/10/96	8/30/96										
194		Fabricate furnace	\$581,840.00	9/2/96	1/17/97										
195		Modify glovebox	\$226,080.00	7/22/96	11/8/96										
196		Install furnace	\$213,600.00	11/11/96	2/28/97										
197		PNL Assist LLNL in equipment proc	\$122,240.00	1/20/97	10/24/97										
198		Induction Power Supply assistanc	\$1,600.00	1/20/97	2/14/97										
199		Instrumentation assistance - PNL	\$5,760.00	1/20/97	4/11/97										
200		Melter System Fabrication / instal	\$88,000.00	1/20/97	10/24/97										

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ID	WBS	Task Name	Cost	Start	Finish	95	96	97	98	99	00	01	02	03	04
201		Assist with Glovebox modification	\$26,880.00	2/10/97	5/30/97										
202	2.1.1.2.4	Stirred Bottom Pour Melter Operation at LLN	\$400,320.00	3/3/97	5/15/98										
203		Furnace startup	\$400,320.00	3/3/97	5/15/98										
204		LLNL startup	\$125,920.00	3/3/97	4/25/97										
205		Furnace startup operations	\$96,480.00	3/3/97	4/25/97										
206		Operations approval	\$29,440.00	3/3/97	4/25/97										
207		PNL startup support	\$107,200.00	10/27/97	5/15/98										
208		Startup Support - PNL	\$35,200.00	10/27/97	12/19/97										
209		Procedure Writing and Approval	\$24,000.00	10/27/97	12/5/97										
210		Shakedown Testing Support - PN	\$35,200.00	12/22/97	4/10/98										
211		Staff Training support - PNL	\$8,000.00	4/13/98	4/17/98										
212		Operational Procedures Support -	\$4,800.00	4/20/98	5/15/98										
213		Cold tests	\$167,200.00	3/3/97	5/9/97										
214		Conduct cold proof runs	\$94,400.00	3/3/97	4/11/97										
215		Conduct Ce surrogate evaluation	\$72,800.00	4/14/97	5/9/97										
216	2.1.2	<u>Bushing Furnace Development - SRTC</u>	\$2,825,880.00	10/1/96	3/19/98										
217	2.1.2.1	Cold demonstration - SRTC	\$1,207,400.00	10/1/96	6/9/97										
218	2.1.2.1.1	Cold melter modifications	\$991,400.00	10/1/96	3/17/97										
219		Design / install dry feed and off-gas system	\$480,800.00	10/1/96	2/3/97										
220		Design / install glass can decon and closur	\$397,600.00	10/1/96	1/20/97										
221		Verify melter operation with oxide and silica	\$113,000.00	2/4/97	3/17/97										
222	2.1.2.1.2	Cold melter verification runs	\$216,000.00	3/18/97	6/9/97										
223		Ce surrogate runs for dissolution / holdup	\$144,000.00	3/18/97	5/12/97										
224		Ce/Gd surrogate demonstration runs	\$72,000.00	5/13/97	6/9/97										
225	2.1.2.2	Hot Bushing Development - SRTC	\$1,618,480.00	10/15/96	3/19/98										

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226	2.1.2.2.1	Determine Hot Melter demonstration site	\$39,360.00	10/15/96	11/11/96										
227		Identify space for melter installation	\$10,880.00	11/12/96	11/25/96										
228	2.1.2.2.2	Melter design adaptation - SRTC	\$388,800.00	2/4/97	7/21/97										
229		Engineer system design for GB operation	\$235,200.00	2/4/97	4/28/97										
230		Complete design construction package	\$153,600.00	4/29/97	7/21/97										
231	2.1.2.2.3	Melter construction and installation - SRTC	\$1,179,440.00	11/26/96	3/19/98										
232		Bid construction	\$59,040.00	7/22/97	10/13/97										
233		Fabrication	\$715,840.00	10/14/97	2/16/98										
234		Prepare glovebox space	\$144,800.00	11/26/96	5/12/97										
235		Bushing melter GB system installation	\$259,760.00	11/13/97	3/19/98										
236	2.1.3	<u>Downselect Glass Melter</u>	\$30,080.00	7/4/97	8/17/98										
237	2.1.3.1	Develop downselect criteria	\$20,000.00	7/4/97	11/6/97										
238	2.1.3.2	Review Hot Bushing results	\$5,040.00	8/4/98	8/17/98										
239	2.1.3.3	Review stirred induction results	\$5,040.00	5/11/98	5/22/98										
240	2.1.3.4	Recommend melter design for pilot	\$0.00	8/17/98	8/17/98										
241	2.2	Ceramic Demonstration Facilities	\$2,830,920.00	8/1/96	1/9/98										
242	2.2.1	Cold Press and Sinter Facility - LLNL	\$1,895,640.00	8/1/96	10/23/97										
243	2.2.1.1	Identify suitable mill/blender/press/furnace	\$5,600.00	8/1/96	8/28/96										
244	2.2.1.2	Procure suitable mill/blender/press/furnace	\$452,160.00	11/11/96	2/28/97										
245	2.2.1.3	Adapt to GB and install for Pu work	\$79,520.00	1/20/97	3/15/97										
246	2.2.1.4	Form pellets to demo. Pu inclusion	\$376,480.00	3/17/97	10/3/97										
247	2.2.1.5	Evaluate pellets	\$266,800.00	3/17/97	10/3/97										
248	2.2.1.6	Evaluate feed form impact	\$417,600.00	3/17/97	10/3/97										
249	2.2.1.7	Evaluate Impurity / neutron poison impact	\$291,880.00	3/17/97	10/3/97										
250	2.2.1.8	Provide data for down-select	\$5,600.00	10/6/97	10/23/97

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251	2.2.2	Ceramic Hot Press Facility - LLNL	\$935,280.00	10/1/96	11/28/97										
252	2.2.2.1	Identify suitable press and furnace	\$26,080.00	10/1/96	10/28/96										
253	2.2.2.2	Procure system and install in glovebox	\$588,000.00	10/29/96	5/26/97										
254	2.2.2.3	Form hot press compacts w/ Pu	\$126,000.00	5/27/97	8/18/97										
255	2.2.2.4	Evaluate hot shoe performance	\$60,800.00	8/19/97	10/13/97										
256	2.2.2.5	Evaluate waste form products	\$134,400.00	8/19/97	11/10/97										
257	2.2.2.6	Provide data for down-select	\$0.00	11/11/97	11/28/97										
258	2.2.3	Select hot-press or cold-press	\$0.00	3/3/97	1/9/98										
259	2.2.3.1	Develop selection criteria	\$0.00	3/3/97	5/23/97										
260	2.2.3.2	Selection process	\$0.00	12/1/97	1/9/98										
261	2.2.3.3	Process selected	\$0.00	1/9/98	1/9/98										
262	3	Demonstration Programs	\$2,782,848.33	10/2/95	8/30/04										
263	3.1	Glass Demonstration	\$2,194,360.00	9/1/97	8/3/98										
264	3.1.1	Hot bottom pour demonstrations - LLNL	\$1,208,880.00	9/1/97	5/8/98										
265	3.1.1.1	Bring bottom pour box hot	\$75,520.00	9/1/97	11/7/97										
266	3.1.1.2	Conduct Pu evaluations	\$631,360.00	11/10/97	4/24/98										
267	3.1.1.3	Pour Pu demonstration runs	\$502,000.00	12/22/97	5/8/98										
268	3.1.2	Bushing Melter demonstrations - SRTC	\$985,480.00	3/19/98	8/3/98										
269	3.1.2.1	Bushing Melter into hot operation - SRTC	\$111,120.00	3/19/98	5/11/98										
270	3.1.2.1.1	Cold prove-in runs	\$98,400.00	3/19/98	4/30/98										
271	3.1.2.1.2	Paperwork/testing complete	\$12,720.00	3/31/98	5/11/98										
272	3.1.2.1.3	GB into hot operation	\$0.00	5/11/98	5/11/98										
273	3.1.2.2	Bushing Pu demonstrations - SRTC	\$874,360.00	5/12/98	8/3/98										
274	3.1.2.2.1	Pu / Gd melts	\$401,080.00	5/12/98	8/3/98										
275	3.1.2.2.2	Pu demonstration runs	\$473,280.00	5/12/98	8/3/98										

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276	3.2	Ceramic Demonstration Program	\$588,488.33	5/27/97	4/13/98										
277	3.2.1	Select Plant Demonstration Approach	\$18,240.00	5/27/97	7/7/97										
278	3.2.2	Procure Pu and raw materials	\$76,800.00	5/27/97	2/2/98										
279	3.2.3	Prepare prototype for demonstration	\$250,808.33	7/8/97	11/10/97										
280	3.2.4	Immobilize and can Pu ceramic	\$200,160.00	11/11/97	1/5/98										
281	3.2.5	Transfer to DWPF for canister load	\$26,480.00	1/6/98	2/2/98										
282	3.2.6	Evaluate ceramic results	\$16,000.00	3/17/98	4/13/98										
283	3.3	DWPF Demonstrations	\$0.00	10/2/95	6/7/99										
284	3.3.1	DWPF demonstration preparation - SRS	\$0.00	10/2/95	3/22/96										
285	3.3.1.1	DWPF modifications	\$0.00	10/2/95	3/22/96										
286	3.3.1.2	Obtain approval to fill canister w/HLW glass	\$0.00	10/2/95	1/19/96										
287	3.3.2	Select Plant Demonstration Approach	\$0.00	8/4/98	8/31/98										
288	3.3.3	Bring prototype into operation	\$0.00	9/1/98	11/23/98										
289	3.3.5	Obtain Pu inventory	\$0.00	9/1/98	11/23/98										
290	3.3.6	F-Arch preparation	\$0.00	9/1/98	6/7/99										
291	3.3.7	Fill 20 cans with plant scale waste form	\$0.00	11/24/98	2/15/99										
292	3.3.8	Fill DWPF Canister	\$0.00	2/16/99	3/8/99										
293	3.3.9	Closure / checkout	\$0.00	3/9/99	4/5/99										
294	3.4	Pilot Plant Demonstration - Site TBD	\$0.00	1/15/97	8/30/04										
295	3.4.1	Select Immobilization prototype	\$0.00	11/23/98	11/23/98										
296	3.4.2	Design	\$0.00	1/15/97	10/4/99										
297	3.4.2.1	Preliminary designs	\$0.00	1/15/97	3/10/98										
298	3.4.2.2	Final designs	\$0.00	11/24/98	10/4/99										
299	3.4.2.2.1	Design pilot immobilization system	\$0.00	11/24/98	10/4/99										
300	3.4.2.2.2	Design support systems	\$0.00	11/24/98	10/4/99										

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301	3.4.2.3	Construction	\$0.00	8/3/98	12/24/01										
302	3.4.2.3.1	Modify Pu operations space	\$0.00	8/3/98	11/2/01										
303	3.4.2.3.2	Procure pilot and support systems	\$0.00	10/5/99	9/4/00										
304	3.4.2.3.3	Install pilot and support systems	\$0.00	1/25/00	12/24/01										
305	3.4.2.4	Operation	\$0.00	12/25/01	8/30/04										
306	3.4.2.4.1	Cold startup & operations	\$0.00	12/25/01	12/23/02										
307	3.4.2.4.2	Op. readiness review	\$0.00	3/26/02	9/1/03										
308	3.4.2.4.3	Hot Operations startup	\$0.00	9/2/03	3/15/04										
309	3.4.2.4.4	Hot demonstrations	\$0.00	3/16/04	8/30/04										
310	4	<u>Canister Design for Prolif. Resistance</u>	\$4,558,357.34	1/1/96	10/12/98										
311	4.1	LLNL Proliferation resistance studies	\$2,326,113.34	1/1/96	4/6/98										
312	4.1.1	NON-PROLIFERATION	\$0.00	1/1/96	4/1/98										
313	4.1.1.1	20-can cold demo	\$0.00	7/19/96	4/1/97										
314	4.1.1.2	White team report	\$0.00	1/1/96	9/13/96										
315	4.1.1.3	Recovery flowsheet development	\$0.00	7/21/97	4/1/98										
316	4.1.2	LLNL Canister Design	\$2,326,113.34	9/16/96	4/6/98										
317	4.1.2.1	LLNL Modeling and Analyses for proliferation resista	\$633,600.00	9/16/96	2/28/97										
318	4.1.2.2	Analysis of experimental results	\$395,600.00	1/12/98	4/6/98										
319	4.2	Cold Canister Dev. & Testing Support - PNNL	\$1,432,244.00	10/21/96	6/17/98										
320	4.2.1	Develop Cold Canister Test Plan	\$281,184.00	11/1/96	6/17/98										
321	4.2.1.1	Review w/LLNL and get approval to proceed	\$4,800.00	11/1/96	11/14/96										
322	4.2.1.2	Project Management/Integration	\$72,864.00	11/15/96	6/17/98										
323	4.2.2	Overflow repair	\$15,200.00	11/15/96	12/6/96										
324	4.2.2.1	Design	\$4,800.00	11/15/96	11/22/96										
325	4.2.2.2	Repair	\$10,400.00	11/25/96	12/6/96										

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326	4.2.3	Pretest #1	\$5,760.00	12/9/96	12/18/96										
327	4.2.4	Melter Preparation	\$22,480.00	12/19/96	1/6/97										
328	4.2.4.1	Overflow Reconfiguration	\$15,680.00	12/19/96	12/30/96										
329	4.2.4.2	Bellow Preparation	\$6,800.00	12/31/96	1/6/97										
330	4.2.5	Solids Feeder Installation	\$19,720.00	12/19/96	12/26/96										
331	4.2.5.1	Feeder Frame Fab	\$8,240.00	12/19/96	12/26/96										
332	4.2.5.2	Feeder Installation	\$6,240.00	12/19/96	12/23/96										
333	4.2.5.3	Feeder Control Installation	\$5,240.00	12/19/96	12/23/96										
334	4.2.6	Melt Tank Composition Adjustment	\$48,000.00	12/24/96	1/6/97										
335	4.2.7	Canister Instrumentation (external)	\$26,800.00	1/13/97	2/21/97										
336	4.2.7.1	Install T/C Communications	\$14,800.00	1/13/97	2/7/97										
337	4.2.7.2	Configure Instrumentation System	\$12,000.00	2/10/97	2/21/97										
338	4.2.8	Pretest #2	\$6,400.00	1/7/97	1/8/97										
339	4.2.9	Develop Can Arrangment Options	\$342,200.00	10/21/96	8/8/97										
340	4.2.9.1	Perform Modeling @ LLNL	\$57,600.00	10/21/96	1/10/97										
341	4.2.9.2	Develop Can/Assembly Designs	\$30,000.00	1/13/97	2/21/97										
342	4.2.9.3	Procure Canisters	\$68,000.00	2/24/97	7/11/97										
343	4.2.9.4	Produce 200 Cans @ Vendor's Site	\$100,000.00	2/24/97	4/4/97										
344	4.2.9.5	Procure Assemblies	\$0.00	2/24/97	5/16/97										
345	4.2.9.6	Assemble Canisters	\$43,200.00	7/14/97	7/25/97										
346	4.2.9.7	Weld Lids to Canisters	\$43,400.00	7/28/97	8/8/97										
347	4.2.10	Test Plan Preparation	\$37,200.00	10/21/96	1/31/97										
348	4.2.10.1	Prepare Test Plan	\$19,200.00	10/21/96	1/10/97										
349	4.2.10.2	Prepare Procedures	\$18,000.00	12/2/96	1/31/97										
350	4.2.11	Canister filling	\$223,700.00	7/28/97	11/14/97										

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351	4.2.11.1	Can fill test #1	\$44,740.00	7/28/97	8/6/97										
352	4.2.11.2	Can fill test #2	\$44,740.00	8/21/97	9/1/97										
353	4.2.11.3	Can fill test #3	\$44,740.00	9/16/97	9/25/97										
354	4.2.11.4	Can fill test #4	\$44,740.00	10/10/97	10/21/97										
355	4.2.11.5	Can fill test #5	\$44,740.00	11/5/97	11/14/97										
356	4.2.12	Can & Data Analyses	\$338,600.00	8/7/97	1/21/98										
357		Analyze Test Data	\$54,000.00	9/2/97	12/1/97										
358	4.2.13	Ship to SRTC for Dest. Exam.	\$19,600.00	8/7/97	9/3/97										
359	4.2.14	SRTC to Perform Destructive Exam	\$265,000.00	9/4/97	1/21/98										
360	4.2.15	Data Analyses & Reporting	\$65,000.00	12/1/97	1/12/98										
361		PNNL Reporting	\$65,000.00	12/1/97	1/12/98										
362	4.3	Hot recovery demo	\$800,000.00	10/14/97	10/12/98										
363	4.3.1	SRTC Analysis of Proliferation resistance	\$300,000.00	10/14/97	10/12/98										

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