

TRP Task 22
Project Title:
Design Concepts and Process Analysis for Transmuter Fuel Manufacturing

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Technical Focus Area: **Fuels Technology**

Project Duration: 3 years

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Design Concepts and Process Analysis for Transmuter Fuel Manufacturing

ABSTRACT

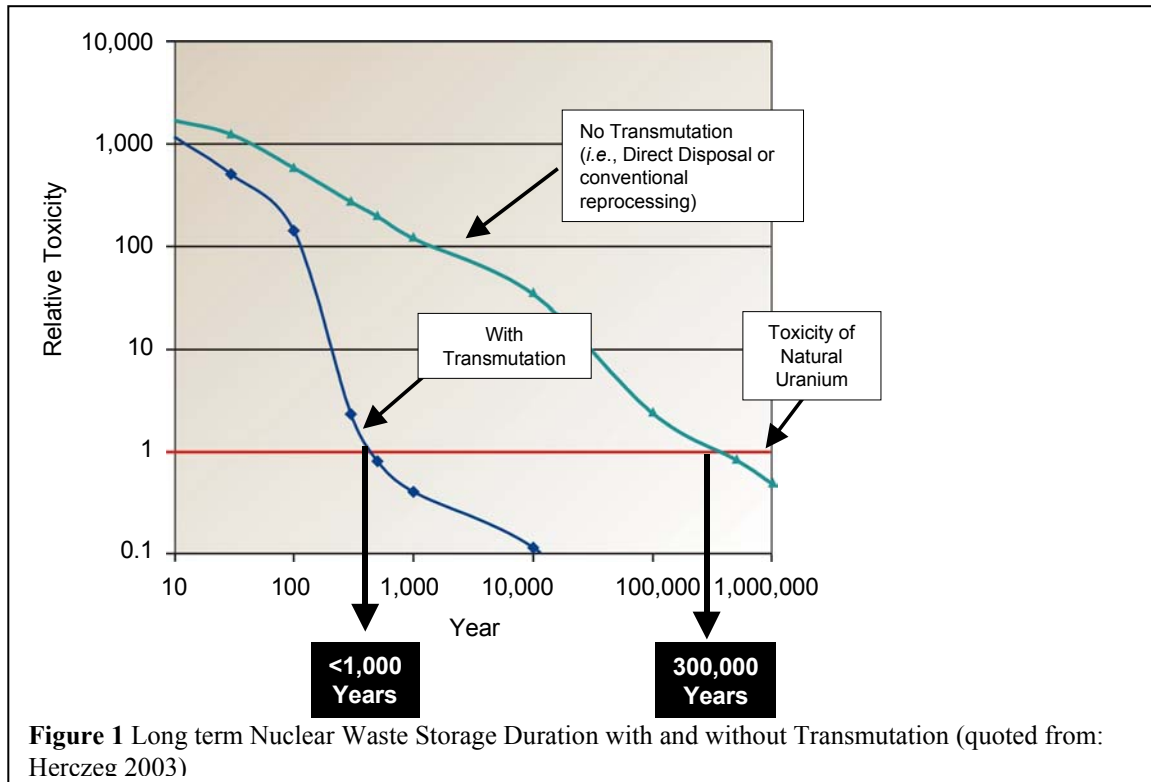
This proposal addresses the subject heading ‘Transmutation Fuel Development’ in the 2004 research topic list of the UNLV Transmutation Research Program (TRP) and DOE Advanced Fuel Cycle Initiative (AFCI). The large-scale deployment of remote fabrication and refabrication processes (with a capacity of approx. 100 metric tons of Minor Actinides (MA) annually) will be required for all transmutation scenarios. The objective of this project is the design, analysis, and evaluation of manufacturing processes for transmuter fuel fabrication. Fabrication processes for different fuel types differ in terms of equipment types, throughput, and cost. The evaluation of the fabrication processes will create a decision support data base that will document design, operations, plant safety, and costs. Differential manufacturing cost implications of various fuel choices will be quantified and documented in detail. The project will focus on

- (a) collecting information on existing technologies, equipment costs, and material throughput.
- (b) the design of robotic technology, robot supervision and control, including detailed temporal and spatial simulations of hot cell operations, accident recovery, and equipment reliability studies.

Process simulations will be conducted with view towards the development of fully automated and reliable, autonomous manufacturing processes. Automation has the potential to decrease the cost of remote fuel fabrication and to make transmutation a more economically viable process. As before, this project will be conducted in close cooperation with the fabrication development group at Argonne National Laboratory. Manufacturing work cells for the following fuel types will be designed and evaluated:

- Oxide Fuels (powder processing)
- Metallic Fuels (from molten salt electrolytic separation)
- Dispersion Fuels
- TRISO Fuels

1. Background and Rationale



In comparison to the presently envisioned concept for the permanent disposal of high-level nuclear waste, transmutation promises both a significant reduction of waste quantities as well as a reduction of the duration of storage time (Beckjord 2003), see also Fig. 1. Transmutation is aimed at destroying primarily the long-lived fission products and the MA (Minor Actinides) by neutron bombardment. While Pu can be largely recycled by processing it into MOX (Mixed Oxide) reactor fuel, the minor actinides, especially Am, must be separated from the waste stream and transmuted to elements with shorter half-lives. Herczeg (2003), Pasamehmetoglu 2003, and Bresee (1999) describes a comprehensive scenario for waste separation and MA transmutation. A MA fuel manufacturing plant would require an annual processing capacity of approximately 100 tons of MA's.

2. Research Objectives and Goals

2.1 Objectives and Goals

- Conceptual design, plant layout, and cost estimates for possible Transmuter Fuel fabrication plants based on the following fuel types:
 - (i) Oxide Fuels (Powder processing)
 - (ii) Metallic Fuels (from electrolytic molten salt separation)
 - (iii) Dispersion Fuels
 - (iv) TRISO fuels

- Capital Cost estimate development for fuel options (i) through (iv). Plant capacity approx. 100 metric tons of MA's annually.
- Operations Cost estimate development for fuel type options (i) through (iv). Plant capacity approx. 100 metric tons of MA's annually.
- Detailed simulations of plant manufacturing operations for fuel type options (i) through (iv):
 - (a) MA fuel throughput: Number of required assembly lines, identification of bottlenecks, reliability studies,
 - (b) estimates of plant maintenance and downtime,
 - (c) virtual plant mockup studies for fuel options (i) through (iv), including material flow, time and throughput analyses, accident simulations and recovery from unpredicted events.
 - (d) Reliability studies (e.g. cost/benefit analysis for critical equipment redundancies in the hot cell to reduce downtime and to support more flexible equipment maintenance, estimates of equipment maintenance intervals, down times, simulations of replacement and repair procedures)

2.2 Parameters to be measured

- Plant throughput
- Comparative capital cost estimates for fuel type options (i) through (iv).
- Comparative operations cost estimates for fuel type options (i) through (iv).

2.3 Theories to be examined

Various fabrication processes as described in further detail below. See also references.

2.4 Phenomena to be examined

Evaluation of four distinct manufacturing concepts. Studies of MA throughput, detailed examination of accident scenarios and accident recovery. Mechanical loading (forces, torques, accelerations, impact impulses) of robots, other hot cell equipment, and in-process materials as a function of manufacturing process speed. Impact of robot speed on plant throughput, safety, reliability (mean time between failures), operating cost.

3. Technical Impact

3.1 Contribution to the national AFCI program

The Advanced Fuel Cycle Initiative (AFCI) is defined, among others, in presentations by DOE's John Herczeg (Herczeg, 2003) and Kemal O. Pasamehmetoglu (Pasamehmetoglu 2003), national technical director of AFCI Fuels Development at the Los Alamos National Laboratory. Both authors identified transmuter fuels development and fuels manufacturing technologies as essential elements of the AFCI program. The plant cost and operations cost comparison between candidate fuel types will be one of the decision elements in any future selection process for the AFCI fuel. In addition, the detailed 3D-simulation of any desired aspect of the fuel

manufacturing process will permit the substitution of parts of the physical plant mock-up design study prior to starting hot cell operations. The virtual mock-up is predicted to reduce design and testing times, as well as mock-up test costs.

The proposed research project will provide technical results in two areas germane to assessing the cost and feasibility of transmuter fuel manufacture. First, detailed process models will be developed that will allow the evaluation of the impact of fuel type on the fuel manufacturing process and the transmuter fuel cycle in terms of differential cost and potential for material loss. Secondly, manufacturing models for large scale production in a hot cell environment will be developed. These two results will allow the assessment of plant layout, and provide the framework for estimation of plant capital and operating cost estimates, and for feasibility in general. The need for development in the areas of robotic and sensor technology will be assessed.

Process models will be developed to better define the impact of fuel choice on the transmuter fuel cycle. In particular, the process models will be used to better define relative process losses, waste generation, and plant capital cost. These process models will allow a better definition of required plant size and number of plants needed to mesh with the fuel recycling line, as well as determining requirements for automation. Future fuel plant design efforts can rely on the groundwork laid here as a starting point for facility and process design.

Scientific advances in remote manufacturing technology required for efficient large-scale remote fuel fabrication will be identified. Besides hot cell compatible equipment, the supervision and control processes must rely on sensing technology that is both survivable as well as flexible in its usage, in order to address a wide variety of possible scenarios. Radiation hardened vision systems appear to be a promising technology: Vision systems can be adapted to a wide range of uses, from dimensional metrology (e.g. non-contact dimensional pellet inspection, determination of exact location and spatial orientation of parts) to supervision in process control, materials handling, and collision avoidance. We therefore propose to continue the vision systems R&D as a component of developing a system for flexible supervision and control of the autonomous manufacturing system. The manufacturing technology developed for the hot cell application will also be applicable to other, more general uses, where occupational hazards prevent human presence near processes.

The project will also result in advances in control and operation of manufacturing processes, will provide UNLV with a long-term research capability in machine intelligence and robotics, and will enhance the depth and attractiveness of its Ph.D. programs in computer science, mechanical and electrical engineering through broad student involvement in the project and through new advanced course offerings.

M.Sc. Theses: MEG graduate student Mr. Jamil Renno would continue his ongoing effort in hot cell manufacturing and mock-up simulation.

Educational and Research Infrastructure - The project will strengthen our analytical and experimental research capability in the emerging field of remote process control. Over the three-year project duration, we have made substantial progress towards developing and demonstrating auto-

mous supervision and control of robotic hot cell manufacturing, including vision based sensing, action planning and execution. In addition to the Ph.D. and M.Sc. students, we plan to continue the recruitment of quality undergraduate seniors for the project by involving them in the research effort.

3.2 Research objectives and goals in prose form

Project objectives comprise the conceptual design, plant layout, and cost estimates for possible transmuter fuel fabrication plants based on the following fuel types:

- Oxide Fuels (Powder processing)
- Metallic Fuels (from electrolytic molten salt separation)
- Dispersion Fuels
- TRISO fuels

We will develop capital cost and operations cost estimates for fuel options (i) through (iv) for plant capacities of approx. 100 metric tons of MA's annually.

Detailed simulations of plant manufacturing operations for fuel type options (i) through (iv) will be conducted in order to estimate the following process parameters:

- MA fuel throughput: Number of required assembly lines, identification of bottlenecks, reliability studies,
- plant maintenance and downtime,
- virtual plant mockup studies for fuel options (i) through (iv), including material flow, time and throughput analyses, accident simulations and recovery from unpredicted events.
- Reliability studies, e.g. cost/benefit analysis for critical equipment redundancies in the hot cell to reduce downtime and to support more flexible equipment maintenance, estimates of equipment maintenance intervals, down times, simulations of replacement and repair procedures.

Comparative capital cost and operations cost estimates for fuel type options (i) through (iv) will be developed.

4. Research Approach / Scientific Investigation Plan

The project will address the following topic areas:

- Design of production, materials handling, control and sensor systems for transmuter fuel manufacturing.
- Development of real-time remote control and diagnosis software for process supervision, diagnostics, and documentation.
- Update of plant sizing for a number specific transmutation scenarios and capital cost estimates, using a fixed set of assumptions as defined in cooperation with ANL personnel.
- Updated assessment of differential plant capital and operating costs resulting from fuel choices (e.g. fuel composition, inert matrix materials, wet/dry processes for pellet production, sintering pressures and temperatures, frequency of defects, machining needs after sintering or casting)

The conceptual fuel fabrication processes developed from 2001 to 2004 will be refined further in cooperation with ANL and other experts in the field, including European reactor fuel manufacturing scientists. Conceptual designs of the fuel fabrication processes will evaluate the issues of maintainability, robust design, and throughput rate, and lead to identification of areas where improvements in technology are required to meet the goals of the transmutation system. The process models will allow ANL AFCI personnel and consultants to determine the sensitivity of the processes to changes in fuel isotopic feed and mass throughput rates for the different system scenarios under consideration.

In summary, the project will result in conceptual plant designs, simulations of manufacturing operations and throughput, cost data and estimates on plant maintenance and plant life time.

4.1 Partitioning and Transmutation (P&T) Concepts (Literature Survey and previous work)

P&T concepts are discussed widely in pertinent publications and conference proceedings. Examples of comprehensive discussions are found, among others, in DOE and LANL presentations, in an MIT report by Beckjord et al. (2003), Ackson (2003), a Nuclear Energy Research Initiative report (NERI 2002), NEA reports (1999 and 2001) and in a report of the scientific office of the French parliament (1997, in French). The paper by Boidron et al (2000) presents a survey of P&T research efforts. The report to the French senate (Battaille and Galley, 1997) estimates the initial costs for a separation plant based on the PUREX process at 5Billion francs or approx. \$1Billion, for a throughput of 850 tons of spent fuel annually. Haas et al. (1998) discuss the anticipated equipment needs for the fabrication of 1 ton of Am/year based on ITU's INRAM Process.

While the technologies cited above generally employ wet chemical and powder processing methods, the Argonne National Laboratory (ANL) as well as other labs have developed molten salt separations technologies (UIC 2001, Meyer 2001, Crawford et al.). A significant number of papers describing multiple aspects of transmutation technology is contained at the web site of the AFCI Technical Review meeting in Jan. 2003, see <http://aaa.lanl.gov/tr0103.html>. Molten salt separations technologies appear to be most suitable for second tier recycling of fuel, with the benefit of avoiding the long cooling times associated with aqueous processes. A detailed account of the fuel refabrication experience at ANL West is presented by Stevenson (1987).

Dispersion fuel technologies are discussed in papers such as Keiser et al. (2003), Lee et al. (2002). TRISO fuel technologies are discussed in Williams (2002).

A comprehensive treatment of issues pertaining to Nuclear Waste is presented in the book "Nuclear Wastes: Technologies for Separations and Transmutation" published by the National Research Council (1996). The book also contains cost estimates for reprocessing plants.

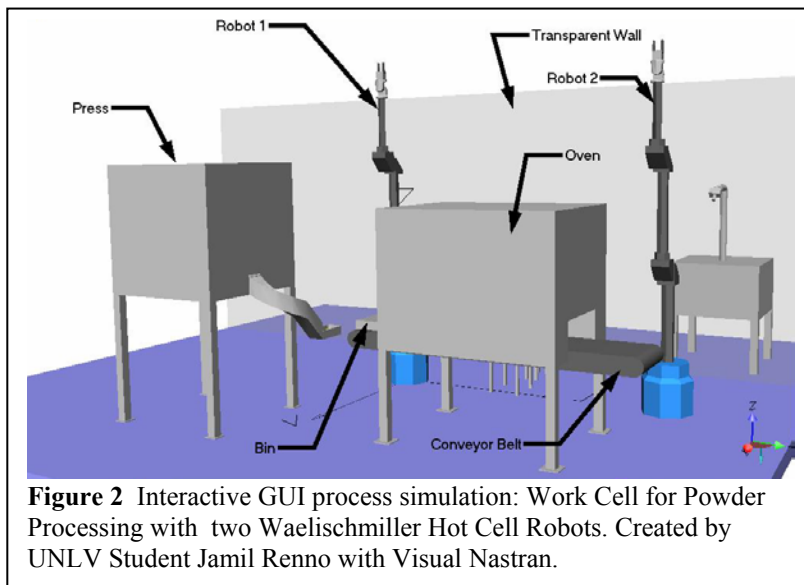
Previous work at UNLV comprises conceptual hot cell design studies, detailed analyses and 3D simulations of remotely controlled robotic fuel manufacturing processes in hot cells, and extensive literature surveys on transmuter fuels and their manufacture. Results were reported at annual ANS and other professional meetings, see also the bibliography, As a result of UNLV Transmutation Research Program funding, one Ph.D. student graduated in 2003, a M.Sc. student graduated in 2004, and a third graduate student is well on his path towards graduating early in 2005. The students contributed two papers at ANS student conferences in 2003 and 2004.

4.2 Plant Cost Estimates

The goal of this task is to continuously update the database necessary to provide estimates of cost and differential cost for the various fuel manufacturing options. Preliminary cost figures for fuel manufacture from preprocessed materials (e.g. wet separation or molten salt electrolysis) were presented in Progress Report #3 (Mauer, May 2002).

4.3 Manufacturing Automation

The goal of this task is to develop simulations of manufacturing processes to allow for plant sizing and to determine adequacy of current generation sensors and robotics and the need for development of new technology in this area. The progress reports # 1 through #10 for this project (Mauer 2001 through 2004) contain an assessment of generic equipment needs, surveys of commercially available manufacturing and robotic handling equipment, and detailed simulation results on machine based object recognition within a work cell, robot dynamics and control. Robotic work cells would likely result in reduced cost of operation as well as increased reliability by reducing the potential for human error during materials handling operations. One former M.Sc. student, Mr. Richard Silva, and a mechanical engineering graduate student, Mr. Jamil Renno, have been developing the CAD models for 3-D manufacturing process simulation. Results to date exist in the form of movies, data sets, and images, see Fig. 2. To date, simulations for several robot types have been developed and a workcell simulation for powder processing has been completed. This simulation starts from pellet pressing, to continue with sintering, grinding, and the loading of pellets into a fuel pin.



Dr. Jae-Kyu Lee (a Ph.D student in the TRP project until 2003) developed a vision-based methodology for locating and identifying objects within the robot's workspace, and developed an AI (Artificial Intelligence) algorithm for object identification. All analytical concepts were verified using real world camera images.

Our simulations employ 3-D simulation tools with view towards the development of a fully automated and reliable, autonomous manufacturing

process. The proposed automation technology has the potential to decrease the cost of remote fuel fabrication and to make transmutation a more economically viable process.

Accurate process supervision will be essential for the reliability and safety of the fuels manufacturing process. This will likely be accomplished by a combination of process sensors and visual supervision. Machine vision can detect and analyze situations automatically, and camera images can be transmitted directly to supervising personnel. In addition, calibrated vision

systems can perform and document automated dimensional and surface quality measurements on the completed pellets/slugs as well as the completed fuel pins.

4.4 Process Simulation and Simulation Software R&D

The goal of this task is to model manufacturing processes to allow realistic assessment of plant layout, size, feasibility, and technology development required for large-scale remote fabrication of fuel. The candidate fuel manufacturing processes are modeled using the MSC Visual Nastran and ProEngineer simulation software tools, with the process control and supervision functions performed by Matlab software. Realistic simulations permit the prediction, analysis and elimination of potential problems such as collisions and unreachable locations before the actual execution of a programmed sequence. An accurate process simulation creates a virtual mockup work cell, and will thus aid in sizing fuel manufacturing hot cells, and help to model process losses. Fig. 2 shows an example of a Waelischmiller hot cell robot simulation in VisualNastran. Waelischmiller robots have a unique design where the maintenance intensive parts (motors and most gears) are contained in the robot base, which can be housed outside the hot cell. VisualNastran Motion by MSC software (<http://www.mssoftware.com/>) is a state of the art simulation tool. Results from the simulation are available as quantitative data as well as through animated graphics. In addition to the simulation of normal operations, the dynamic process model can simulate and analyze maintenance and troubleshooting situations, such as the removal and replacement of malfunctioning equipment components. Robot control is done in Matlab, which interacts directly with VisualNastran (see also progress reports #6 through 10, Mauer 2003 - 2004).

4.5 Processes and Equipment for Autonomous Manufacturing

The goal of this task is to develop an understanding of the cost and capability of current generation remotely operated equipment suitable for use in radiation environments. We will continue to monitor the market for equipment and components with regard to suitability for automated manufacturing under hot cell conditions. As mentioned, sensor systems, both those embedded in the equipment as well as additional sensors added for process supervision and control, must be insensitive to radiation or radiation hardened.

4.6 Sensors, Controls and Operational Safety

The goal of this task is to determine the adequacy of current technology and the need for development in sensor technology suitable for deployment in hard radiation environments. In remote manufacturing, it is crucial to be able to determine the exact locations of parts, points and surfaces where tools or objects need to be placed. The exact knowledge of the location and spatial orientation of all parts in the robot's work envelope, as well as the ability to position all material handling and trouble shooting equipment exactly at a desired location inside the work cell is crucial for the safety and reliability of any successful remote operation. The type and location of sensing equipment will determine the accuracy and repeatability of each respective operation, and therefore have a direct bearing on the quality and reliability of the fuel manufacturing process. To the extent that sensors and controls cannot be placed outside the hot cell, they must be radiation-hardened. The absence of suitable sensors would have a significant impact on plant operations and operating cost, since more human supervision would likely be required.

Computer Vision - In our R&D to date, we focused on vision based sensing systems. Cameras can be positioned both inside and outside the hot cell. We have successfully demonstrated the ability to

identify geometric objects from camera images. This identification is largely independent of the viewing angle, and allows also the identification of partially occluded objects, however at reduced confidence levels.

4.7 Estimation of Cost, Feasibility, and Requirements for Large Scale Deployment

The goal of this task is to use all information developed or collected on the topics listed above in order to evaluate assess the cost, feasibility, and suitability for large scale deployment of the candidate manufacturing processes. The results will be tabulated, and quantitative estimates regarding projected cost, reliability, and plant life time will be developed.

5. Capabilities at UNLV and National Laboratories

Equipment needs are limited to fast computers and the software licenses required to conduct the simulations. An older dual-processor PC is presently being used for the simulations. A faster multiple processor PC is requested in the equipment part of the budget in order to keep up with the expanding scope of simulations and the associated long durations of a single simulation, which can easily exceed one hour.

Graduate Students

Mr. Jamil Renno started work on investigating the dynamics and control of fuels manufacturing processes in January 2003 while still an undergraduate senior student in Mechanical engineering. Jamil graduated in May 2003 near the top of his class and has been a graduate student in UNLV's M.Sc. program in Mechanical Engineering since 2003. Jamil has matured into a highly motivated and productive student.

6. Project Timeline

The research effort will focus on the completion of the four tasks listed below. The major components will be defined and identified in cooperation with ANL personnel.

Milestones

- Conceptual Design of production, materials handling, control and sensor systems.
- Conceptual 3D computer modeling of the manufacturing processes. Development of AI-based real-time remote control and diagnosis software for process supervision, diagnostics, and documentation.
- Update of plant sizing for 2-3 specific transmutation scenarios and capital cost estimates using a fixed set of assumptions. Estimation of component and plant costs, maintenance requirements and plant life expectancy. Updated assessment of differential plant capital and operating costs resulting from fuel choices (e.g. fuel composition, inert matrix materials, wet/dry processes for pellet production, sintering pressures and temperatures, frequency of defects, machining needs after sintering or casting)
- Documentation of study results and recommendations for large-scale fuel fabrication.

The project tasks below will be executed concurrently.

Task 1 Design of Equipment and Processes - We will continue, in close cooperation with ANL, the literature survey and detailed analysis of the R&D pertaining to candidate processes for transmuter fuel manufacture. We will refine equipment, instrumentation, and control specifications, and assess the reliability and safety of operations using industry standards. We will continue to identify manufacturing processes, industrial and custom equipment in nuclear research and production facilities. This knowledge will result in more realistic assessment of plant layout, size, feasibility, and technology development required for the large-scale remote fabrication of transmuter fuel. We will continue to monitor the market for equipment and components with regard to suitability for automated manufacturing under hot cell conditions. As mentioned, sensor systems, both those embedded in the equipment as well as additional sensors added for process supervision and control, must be insensitive to radiation or radiation hardened.

Lead: G. Mauer

Cumulative Duration: 1 month.

Task 2: Conceptual 3D modeling: Hot Cell Robotics Simulation – – The goal of this task is to develop simulations of manufacturing processes to allow for plant sizing and to determine adequacy of current generation sensors and robotics and the need for development of new technology in this area. The candidate fuel manufacturing processes will be modeled using the MSC Visual Nastran and ProEngineer simulation software tools, and will be controlled using Matlab Simulink GUI tools. Master's student Mr. Jamil Renno is presently working on this effort and has developed considerable expertise. Realistic simulations can complement or substitute the customary mock-up testing before installing equipment in a hot cell. Simulations permit the prediction, analysis and elimination of potential problems such as collisions and unreachable locations before the actual execution of a programmed sequence. An accurate process simulation will aid in sizing fuel manufacturing hot cells, enhance the safety and reliability of the operation, and assist in modeling process losses.

Leads: Jamil Renno and G. Mauer

Duration: 12 months.

Task 3 Cost, Feasibility, and Large Scale Deployment – The goal of this task is to develop the database necessary to provide estimates of cost and differential cost for the various fuel manufacturing options. All information developed or collected on the topics listed above will be evaluated in terms of assessing the cost, feasibility, and suitability for large scale deployment of the candidate manufacturing processes. The results will be tabulated, and quantitative estimates regarding projected cost, reliability, and plant life time will be developed. This task will be carried out intermittently as progress warrants.

Lead: G. Mauer

Cumulative Duration: 1 month.

Task 4 Reports

- Monthly Progress Report
 - Update technical progress and indicate administrative issues
 - Provide a percentage of project completion

- Quarterly Progress Report
 - Technical highlights
 - Discuss completion of milestones, deliverables
 - Discuss progress in relation to budget schedule
 - Discuss quarterly research progress
- Semi-Annual Progress Report
- Final Report

A detailed documentation of analytical results and recommendations will be submitted at the end of the project.

G. Mauer

Duration: 1 month.

Project Schedule Years 1 through 3

Task	Description	Year		
		1	2	3
1	Methods and Processes	-----		
2	Process Simulation	-----		
3	Cost and Feasibility Evaluations	-	-	---
4	Progress and Final Reports			

Deliverables

Main Deliverable: At the end of each project year, a final report will document the findings, describing the relative merits and limitations of the various manufacturing processes. Detailed process and material flow simulations will be developed and documented for the four fuel type scenarios listed above. Documentations will cover material flow, time-motion analyses, mechanical forces and torques throughout the plant, accident simulations such as collisions and impacts, control and supervision algorithms for normal operations and for recovery from accidents.

In addition to written documentation, animated computer simulations will be developed that will illustrate the flow of material and equipment operations from through the entire plant.

Monthly, quarterly, semi-annual, and annual progress reports will be delivered as per the schedule listed in Task 4:

- **Collaboration with DOE project:** Monthly communications (by phone or in person) with National Project collaborator and/or technical lead to update on progress, discuss problems, and allow for re-focusing if necessary to address shifts in direction by the National Project.
- **Progress Reports:** Brief reports indicating progress will be provided every month and quarter (to support DOE AFCI monthly and quarterly reporting requirements).
- **Annual Reports:** Written reports detailing experiments performed, data collected and results to date.
- **Final Report:** Written report detailing experiments performed, data collected, results, and conclusions to be submitted at the end of the project.

Other Deliverables: Refereed Journal Papers - Results will be published in refereed journals. We anticipate the publication of papers on pattern recognition, decision and control, and on precision manipulation of targets acquired by the robotic sensors.

Education: The project will encourage qualified students towards studies of artificial intelligence and robotics. One student (Mr. Jamil Renno) is currently engaged in the project and expected to complete his Master's degree in 2005. We will be recruiting undergraduate students to work on the project, and encourage promising candidates to continue towards advanced degrees. In summary, 2 M.Sc. degrees, or one M.Sc. and one Ph.D. degree, are predicted to result directly from the project. Additional students are expected to participate in undergraduate senior design projects.

Undergraduate Students - We will actively recruit **undergraduate students** to participate in the research through design projects, experiments, and software R&D. Undergraduate seniors annually will have the opportunity gain valuable research, design and experimentation experience.

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