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Design and Evaluation of Processes for Fuel Fabrication: Year 1 Final Report

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Design and Evaluation of Processes for Fuel Fabrication

YEAR 1 FINAL REPORT

UNLV AAA University Participation Program

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Design and Evaluation of Processes for Fuel Fabrication

Summary

The project objective is the design and evaluation of manufacturing processes for transmuter fuel fabrication. The large-scale deployment of remote fabrication and refabrication processes will be required for all transmutation scenarios. Current program emphasis is on a five-year effort to determine the feasibility of transmutation as a technology to limit the need for repository storage of spent commercial fuel. The evaluation of the fabrication processes will create a decision support data base to document design, operations, and costs. Fabrication processes required for different fuel types differ in terms of equipment types, throughput, and cost. The year 1 project was focused on collecting information on existing technologies, equipment costs, and material throughput. Another aspect during year 1 has been the assessment of robotic technology and robot supervision and control, and the simulation of material handling operations using 3D simulation tools with view towards the development of a fully automated and reliable, autonomous manufacturing process. Preliminary estimates of differential cost implications of various fuel choices have been developed.

Summary of Quarterly Project Results

First quarter:

- Literature review: A comprehensive study of the pertinent publications pertaining to transmuter fuels composition and manufacturing processes was conducted.
- Visit at ANL West in Idaho Falls, ID: Dr. Mauer visited the ANL West facility and met with his National Laboratory Collaborator, Dr. Mitchell K. Meyer, Group Leader, Fabrication Development on October 14 and 15, 2001.
- Student Paper Presentation at the ANS Annual Meeting by Ph.D. student Mr. Jae-Kyu Lee. Title: Transmuter Fuel Fabrication Processes.

Second quarter:

- Project review with Dr. Mitchell Meyer, ANL West: A project review of the transmuter fuels project was conducted during the January 2002 AAA meeting in Las Vegas.
- A second graduate student, Mr. Richard Silva, began working on the project. Rich will develop detailed 3-D process simulation models as his M.Sc. thesis project. Rich is employed with Bechtel at the Yucca Mountain project.
- AAA Seminar Presentation by Mr. Jae-Kyu Lee and G. Mauer. Title: Transmuter Fuel Fabrication Processes.

- More equipment detail and estimates were developed for different manufacturing plant design options.

Third quarter:

- Literature Search: The process of evaluating the pertinent literature continued.
- Graduate student Richard Silva developed an initial work cell simulation with two robots. Rich will continue to develop detailed 3-D process simulation models as his M.Sc. thesis project. Rich is employed with Bechtel at the Yucca Mountain project.
- The equipment detail and estimates were refined based on the literature survey results for different manufacturing plant design options.
- Ph.D. Thesis research: Concepts and Methods for Vision-Based Hot Cell Supervision and control (Ph.D. Student Jae-Kyu Lee)

Fourth quarter:

- Literature Search: The process of evaluating the pertinent literature continued. Results are summarized in the report body below.
- Mr. Richard Silva developed a simulation model with a Waelischmiller hot cell robot. Rich will continue to develop detailed 3-D process simulation models as his M.Sc. thesis project. Rich is employed with Bechtel at the Yucca Mountain project.
- Dr. Mauer visited CEA Cadarache and CEA Marcoule in France, the Institute for Transuranics in Karlsruhe, and the Framatome fuel manufacturing plant in Lingen, Germany.
- Ph.D. Thesis research: Concepts and Methods for Vision-Based Hot Cell Supervision and control (Ph.D. Student Jae-Kyu Lee)

1. Survey of Fabrication Processes

1.1 Fabrication basics

Nuclear waste reduction: Spent fuel quantities estimated at 86,000 metric tons must be safely stored for 10,000 years. Only about 1,000 tons are actinides and long-lived fission products.

Transmutation: Reduce the long term toxicity of long-lived fission products (mostly Pu and actinides such as Am, Cm, Tc, I). Fig. 1 illustrates the scope of the problem (quoted from J. Breese, DOE, 1999).

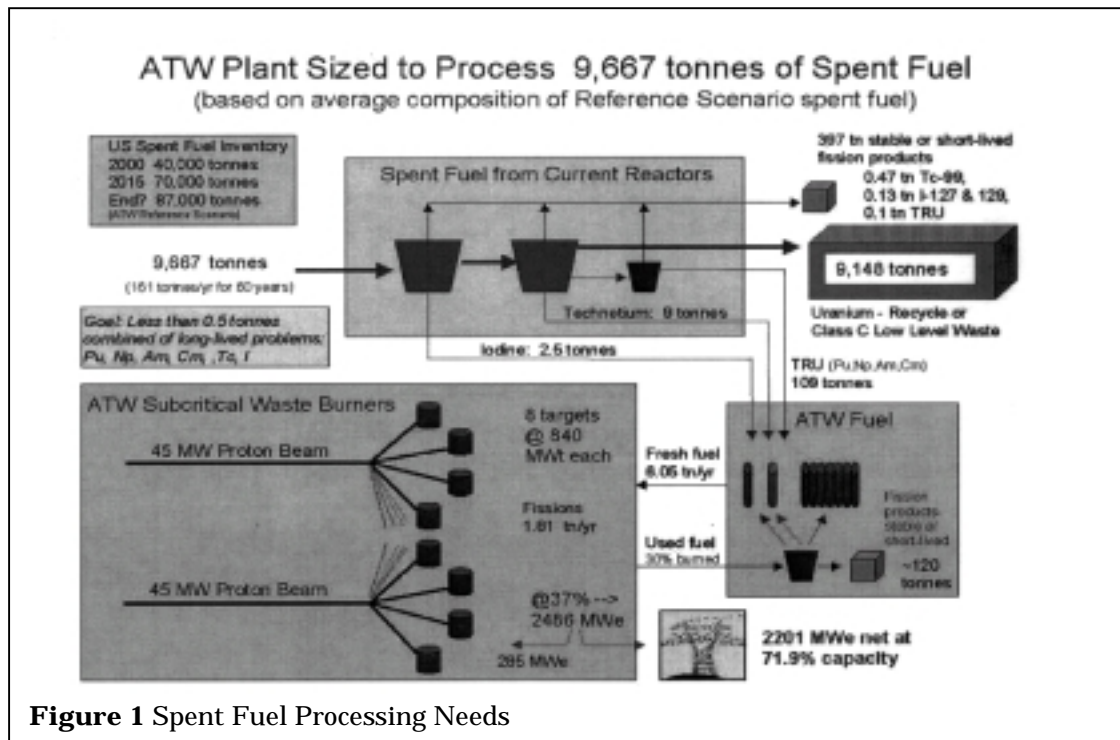


Figure 1 Spent Fuel Processing Needs

Fuel fabrication processes are either based on metal casting (metallic fuels) or powder processing, the latter leading to ceramic or dispersion fuels. R&D on fuel reprocessing and manufacturing has been ongoing for years in the US and other countries. With regard to fuel manufacturing, we may distinguish among three categories:

- Dispersion Fuels (several subtypes exist)
- Ceramic Fuels (several subtypes exist)
- Metallic Fuels

R&D on fuel reprocessing and manufacturing has been ongoing for years in the US and other countries.

Manufacturing Sequence for Dispersion Fuel :

1. Manufacture spherical fuel particles by wet chemical process or direct reaction and attrition.
2. Coat the particles (process not yet determined)
3. Embed fuel particles in matrix metal
4. Press fuel and matrix blend into a compact
5. Assemble billet
6. Extrude billet at $\sim 800^{\circ}\text{C}$ into rods about 2 m long.
7. Finish fuel rods by trimming ends. Rod Inspection (radiography, dimensional, bonding, and clad defects)

Manufacturing Sequence for Metallic Fuel :

1. Cast fuel slugs. Pins are 4 to 5mm dia. and 0.8 m to 1.5 m long.
3. Insert fuel slugs into cladding tube.
2. Add bond phase (Na) in cladding tube
4. Seal cladding tube by welding end fitting onto the tube
5. Inspect fuel pin (radiography, dimensional, and clad defects)

Manufacturing Sequence for Ceramic Fuel :

1. Manufacture particles by wet chemical process or direct reaction (1 to 30 μm dia.)
2. Compaction of particles into pellet form.
3. Sinter the pellets at 1400°C - 1800°C .
4. Inspect pellets Assemble pellets into cladding tube.
5. Assemble pellets into cladding tube
6. Add bonding material (He or Na)
7. Seal cladding tube by welding
8. Inspect assembled fuel pin (radiography, dimensional and clad defects)

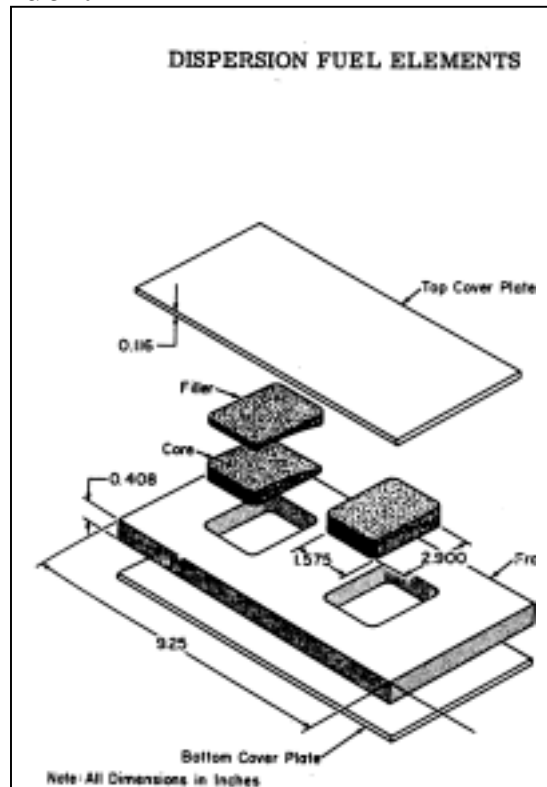


Figure 2 Dispersion Fuel Element

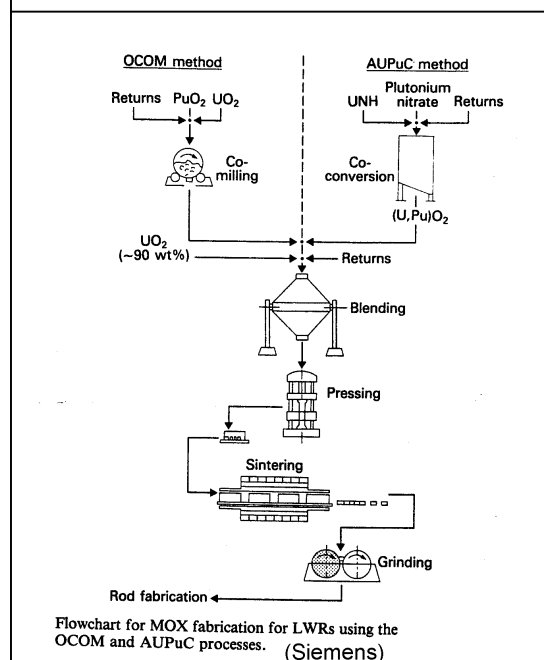


Figure 3 MOX Fabrication Process (Siemens)

Raw material for powder processing (oxide or nitride fuels) will most likely result from aqueous processing. Fig. 3 shows schematically a process developed by Siemens.

Other Considerations

- Hot cell required
- Criticality concerns mandate small batch sizes
- Large fuel quantities require process automation
- Equipment for hot cell operation must be identified or developed.
- Material flow and operational sequence
- Long term reliability must be ensured
- Design must prove the ability to cope with a wide range of contingencies (e.g. equipment failures, spillage, breakage)

Generic issues common to all fuel types:

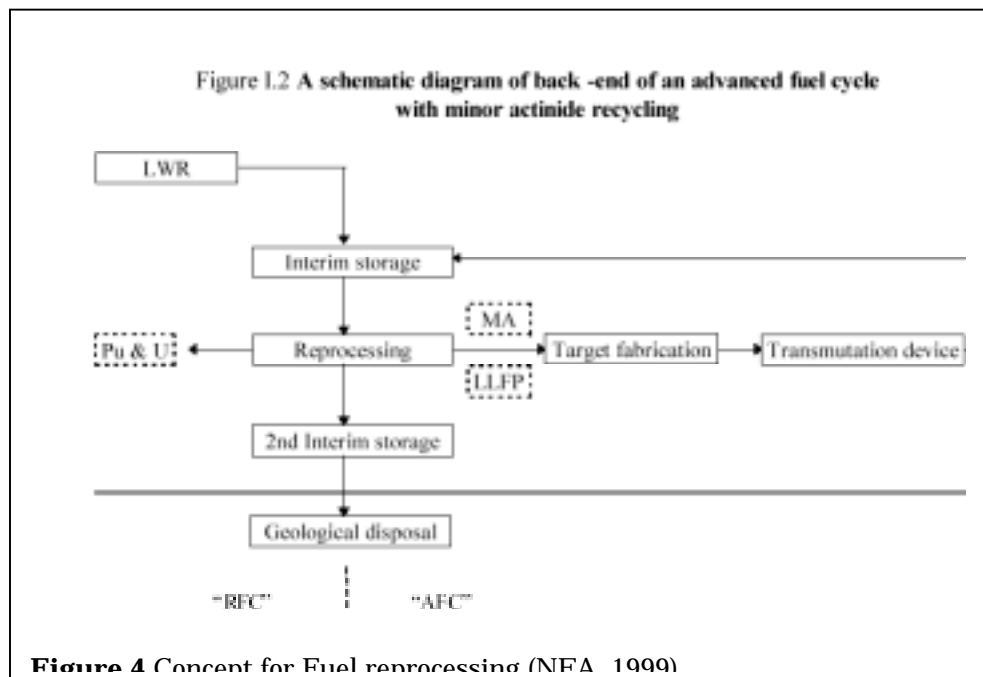
- Dimensional Inspection, intermediate and final
- Heating or melting
- Assembly: e.g. place pins or pellets into cladding tube

Issues common to dispersion and ceramic fuels:

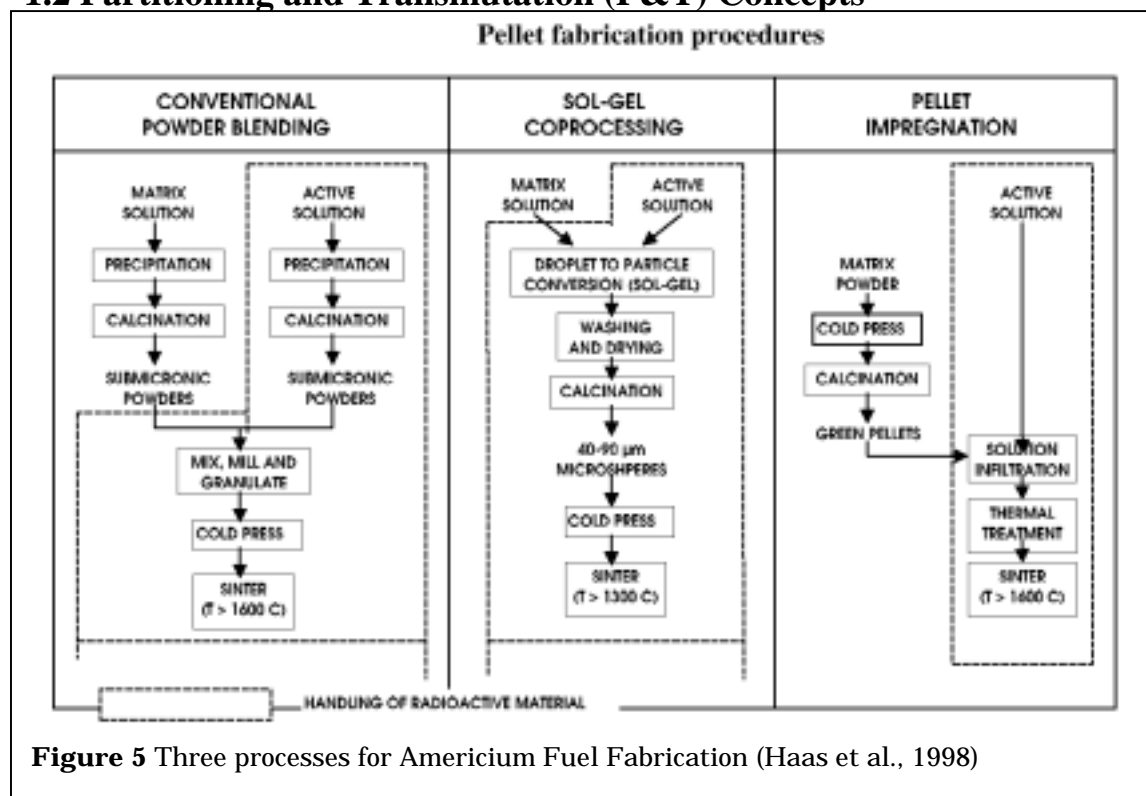
- Manufacture uniform particles
- Compact particles into some aggregate form (e.g. pellets)

Other needs:

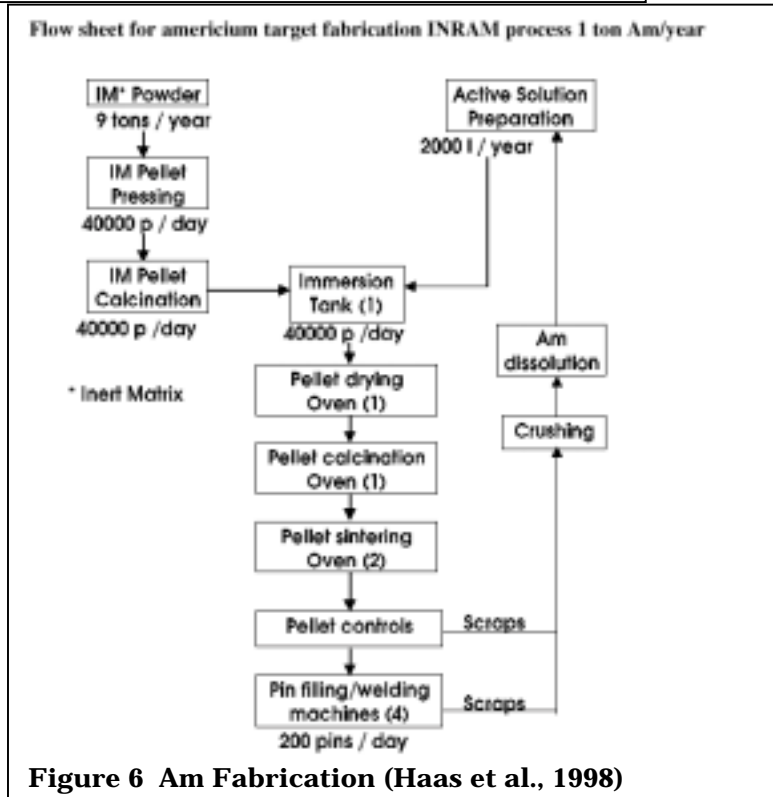
Welding
Sintering
Injecting He or Na
into cladding tube



1.2 Partitioning and Transmutation (P&T) Concepts



P&T concepts are discussed widely in pertinent publications and conference proceedings. Examples of comprehensive discussions are found in 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. Fig. 4 illustrates the NEA concept of separating Pu and U from spent fuel and transmuting the minor actinides (MA). The report to the French senate (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 feasibility of the fabrication of Americium targets in a NEA conference paper using an infiltration process and the 'sol-gel' method developed at the Institute for Transuranic Elements (ITU) in Karlsruhe, Germany. Fig. 5, quoted from Haas et al. (1998), compares both processes with established powder processing techniques. Fig. 6, quoted from Haas et al. (1998), illustrates the anticipated equipment needs for the fabrication of 1 ton of Am/year based on ITU's INRAM Process. V.V. Ignatiev et al. (1998) present a discussion of molten salt technologies and losses during manufacturing. More detailed descriptions of powder manufacturing processes and equipment are found in Ganguly (1989) and Balakrishna et al. (1999). The fuels described here are generally based on U- and Pu- oxides and were manufactured in glove boxes.

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). 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. The process for manufacturing fuel for the integral fast reactor (IFR) relied on remote 'injection' casting of metallic fuel slugs.

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.



Figure 7 Hot Cell Robots (Wälischmiller GmbH)

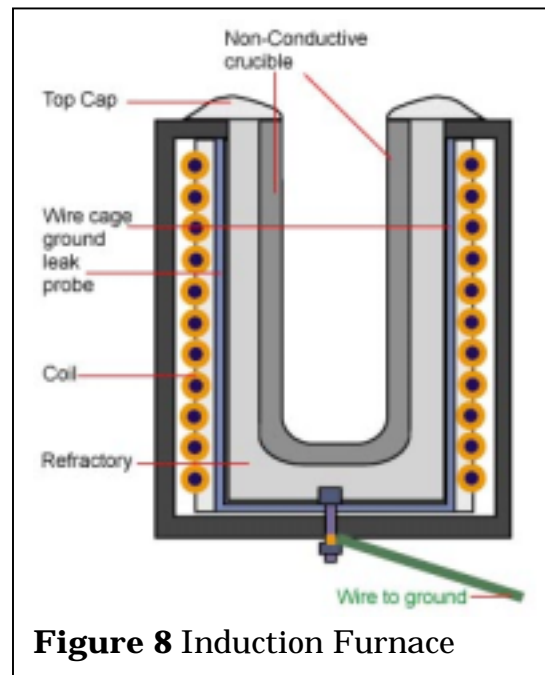
2. Survey of Manufacturing Equipment for Fuel Fabrication

Design Constraints: Criticality concerns mandate fabrication in small batch sizes. Limitations of batch sizes vary with fuel composition.

Generic Equipment Needs: Depending on the process, dedicated equipment such as induction furnaces, V-blenders, Sintering presses, and Arc welders will be required. The transport of the material being processed can be performed using dedicated designs (“hard automation”) or robots equipped with suitable end effectors. Fig. 7 shows a line of commercial hot cell robots (Waelischmiller GmbH.) Hard automation (e.g. conveyors, part feeders) can be advantageous in simple transport applications. However, they cannot normally recover from unusual events such as part misfeeds or blockages. Robots are more complex, but can be programmed and operated flexibly so that normal operation as well as a wide range of possible contingencies can be covered. By changing a robot’s end of arm tools, the same robot can be equipped to perform multiple tasks, such as material handling and inspection.

Metallic Fuel Equipment

Induction furnace. The concept is schematically shown in Fig. 8. ANL West developed a custom furnace for its fuel conditioning facility, at an approximate cost of \$2Million. Source: Dale Wahlquist, ANL West. The ANL casting process employs vacuum casting into an array of quartz tubes. The tubes are broken after casting and must be disposed as waste. A casting process employing reusable molds will be required in order to reduce the quartz waste stream. Evaporation of Am from the liquid phase is a major drawback at present. Dr. Yitung Chen is presently investigating methods to recover the Am-vapor, possibly by deposition on a cold surface, so that the Am can be returned to the fuel stream. Am losses reach up to 40% in the ANL vacuum casting process.



The completed fuel pins must be inspected and inserted into a cladding tube. An NA bond phase must be added. An end cap welder seals the tube. The final inspection completes the process.

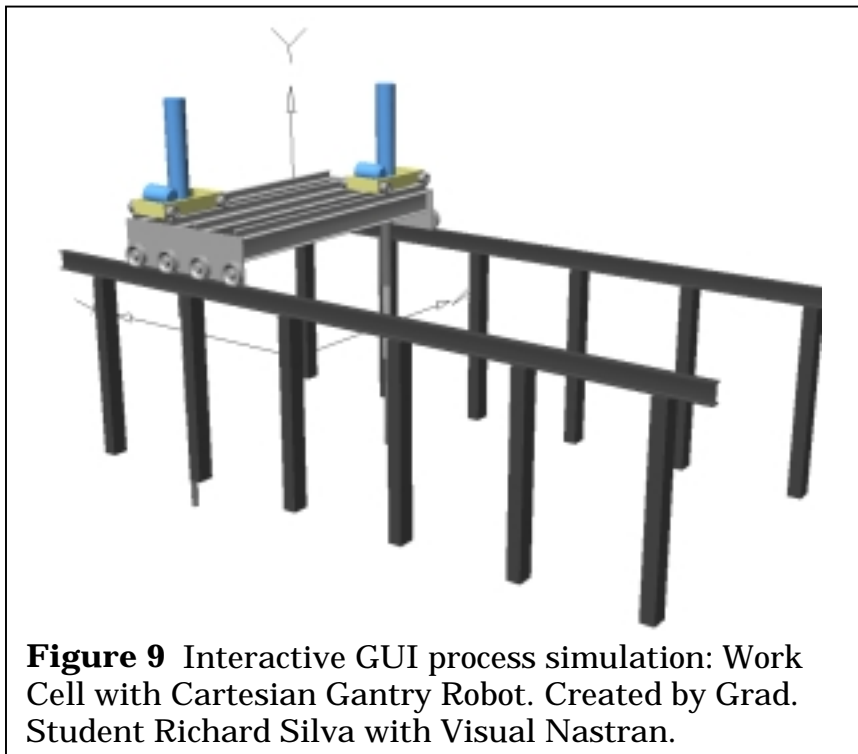
3. Manufacturing Automation Models

The goal is to develop simulations of manufacturing processes. The simulations will support the following elements of the plant design process:

- plant sizing, e.g. placement of equipment, determination of hot cell dimensions.
- Determination of the adequacy of current generation sensors and robotics
- Possible R&D needs for development of new technologies.
- Capability for extensive simulations of contingency and accident simulations, resulting in shortened duration of mock-up experiments and enhanced reliability of plant operations.

Properly designed 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. The candidate fuel manufacturing processes are being modeled using the MSC Visual Nastran and ProEngineer simulation software tools (see also the appendix.) One graduate student working on the project, Mr. Richard Silva, is developing the 3-D manufacturing process simulation CAD

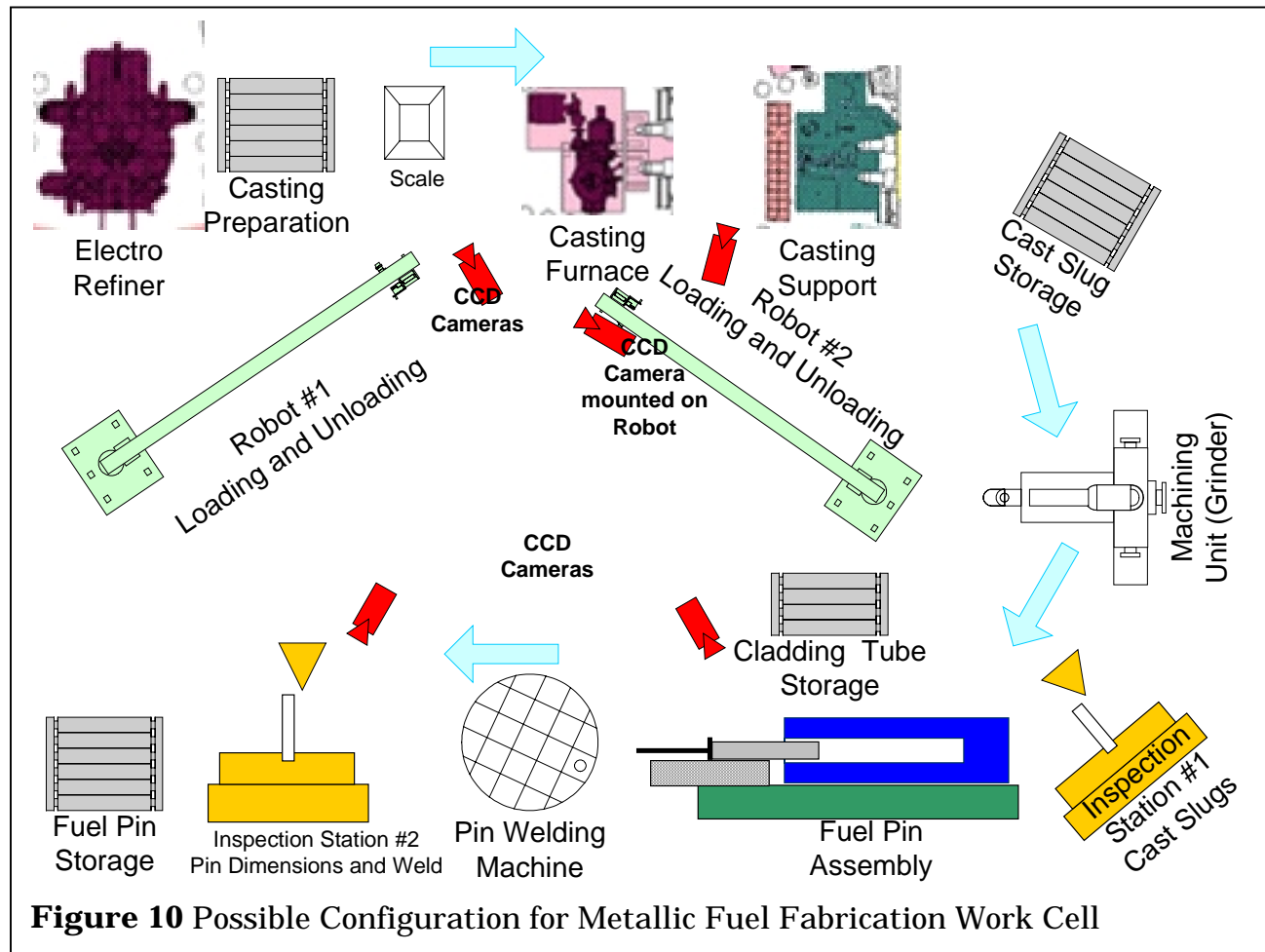
models. To date, several robot simulation models have been developed and their correct performance has been verified. Realistic simulations permit the prediction, analysis and elimination of potential problems such as collisions and unreachable locations before the actual execution of a programmed sequence. An accurate process simulation will aid in sizing fuel manufacturing hot cells, and help to model process losses. To date, Richard has developed four basic robot models (Prismatic, revolute, and the Cartesian gantry robot shown in Fig. 9. Please see the appendix at the end of this document for additional simulation screenshots.



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 without physical contact, 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 as well as the completed fuel pins.

4. Conceptual Hot Cell Layout and Cost Estimates



4.1 Metallic Fuel Work Cell Layout

Fig. 10 shows schematically a possible work cell for metallic fuel production. The function of the electrorefiner shown in Fig. 10 is separation. It is included here to illustrate the compactness of the metallic fuels concept. The icons in the upper row were copied from the ANL West illustration of its fuel conditioning facility. With reusable molds, the fuel pin dimensions may deviate from design specifications. A machining unit was therefore added. The two inspection stations would quantify the dimensions of the cast slugs and inspect the completed fuel pins. Two stationary robots would likely suffice to meet all material handling demands. Fig. 10 shows five cameras, one attached to a robot arm. At this time, the intent is merely to illustrate potential camera uses. The exact number and placement of cameras would result from a determination of the supervision and measurement needs in the hot cell. The table below reflects the updated

estimates for plant and equipment cost and space requirements.

Equipment for Metallic Fuel Production - ANL West developed a custom furnace for its fuel conditioning facility, at an approximate cost of \$2Million. Source: Dale Wahlquist, ANL West. The ANL casting process employs vacuum casting into an array of quartz tubes. The tubes are broken after casting and must be disposed as waste. A casting process employing reusable molds will be required in order to reduce the quartz waste stream. Evaporation of Am from the liquid phase is a major drawback at present. Dr. Yitung Chen is presently investigating methods to recover the Am-vapor, possibly by deposition on a cold surface, so that the Am can be returned to the fuel stream. Am losses reach up to 40% in the ANL vacuum casting process.

The completed fuel pins must be inspected and inserted into a cladding tube. A Na bond phase must be added. An end cap welder seals the tube. The final inspection completes the process.

4.2 Preliminary Cost Estimates, Metallic Fuel Fabrication.

Equipment	Estim. Cost in US \$	Estimated Area requirement ft ²	Comments
Induction furnace + Preparation Area	2.0Million	50	Source: ANL West
Reusable Mold	500K		No standard process exists. Conventional methods have not been adapted to hot cell use.
Fuel Pin Assembly Unit (Insertion, Encapsulation and bonding)	2.0 Million	20	Custom equipment
Automatic Welder	1.0 Million	20	Custom equipment
2 Robots, approx. 1.5 m work envelope at 270 deg. range	1.0 Million	40	
Inspection stations 1 and 2 (10 sq.ft. ea.)	100k	20	
Machining Unit	500K	20	Provide for Dust Containment
Supervision (cameras and controllers)	500k	none	
Product storage		10	
Totals	\$7.6 Million	180	

A single manufacturing cell would require approx. 180 sq. ft. of hot cell space at a cost of approx. \$30,000/ft² or \$5.4M for the hot cell space. Total installation cost approx. \$13Million.

Productivity – Criticality concerns limit the batch size to approx. 3 kg, according to Dr. Mitchell Meyer at ANL West. The longest time constant in the metallic fuel fabrication process is likely the casting and subsequent cooling of the metallic slugs. Assuming a cycle time of two hours for this process, the inspection, assembly, and welding functions will likely be completed below two hours. Assuming a down time of 1/3 of the total operation and 24 hour production, 8 batches at 3kg each could be produced daily. Assuming 360 days of operation annually, approx. 8500 kg of metallic fuel could be produced annually.

4.3 Powder Processing Equipment

Fig. 6, quoted from Haas et al. (1998), illustrates the anticipated equipment needs for the fabrication of 1 ton of Am/year based on ITU's INRAM Process. The conventional pellet manufacturing process is dry, and would not require the drying ovens listed in Fig. 6. The size of the required sintering oven depends on the duration of the process. Possibly more than one oven may be required. The cost of the sintering oven varies with the process parameters, all yet to be identified. Literature data indicate wide variations in sinter pressures (vacuum to hundreds of MPa pressure), and temperatures (1400 to 1700 deg. C.)

The table below assumes a single sintering oven, and one pin filling/welding machine in analogy to Hass et al., 1998. A machining center (grinder) to ensure consistent pellet dimensions is also listed.

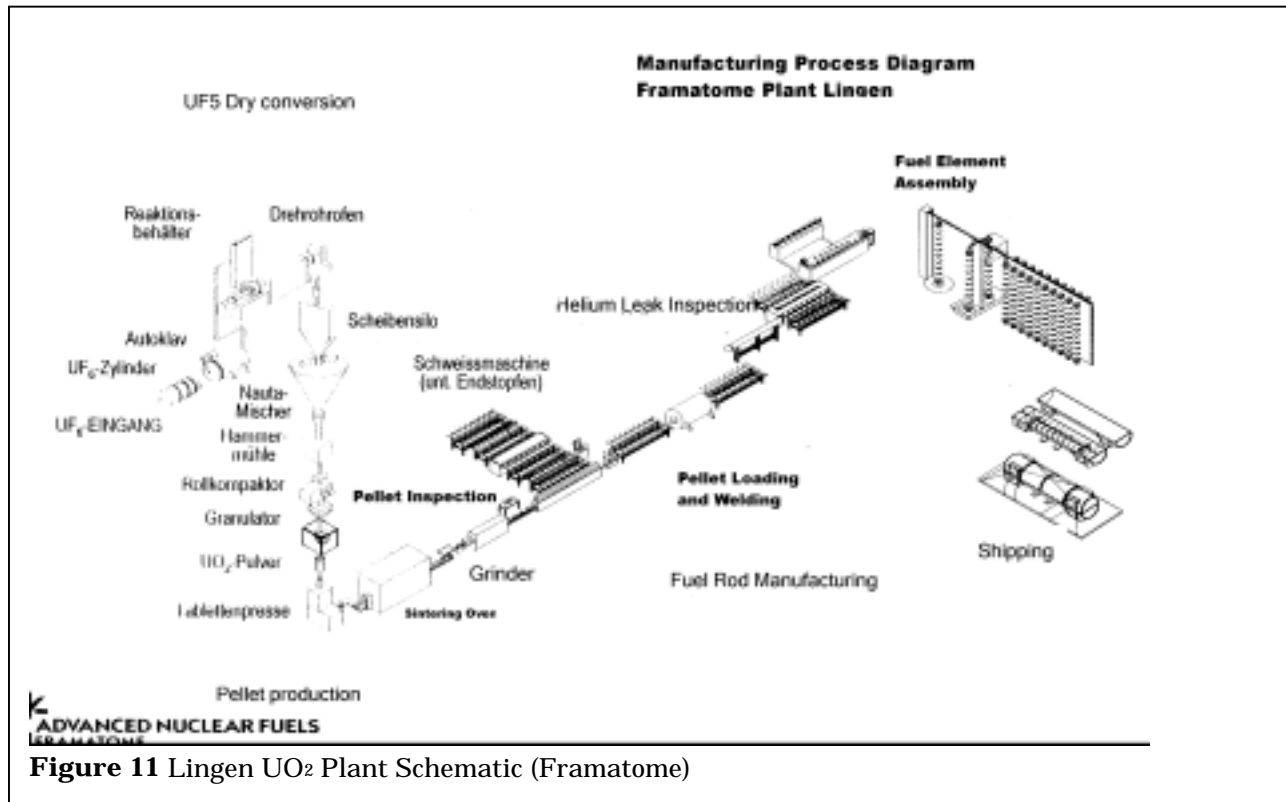
4.4 Preliminary Cost Estimates, Powder Processing

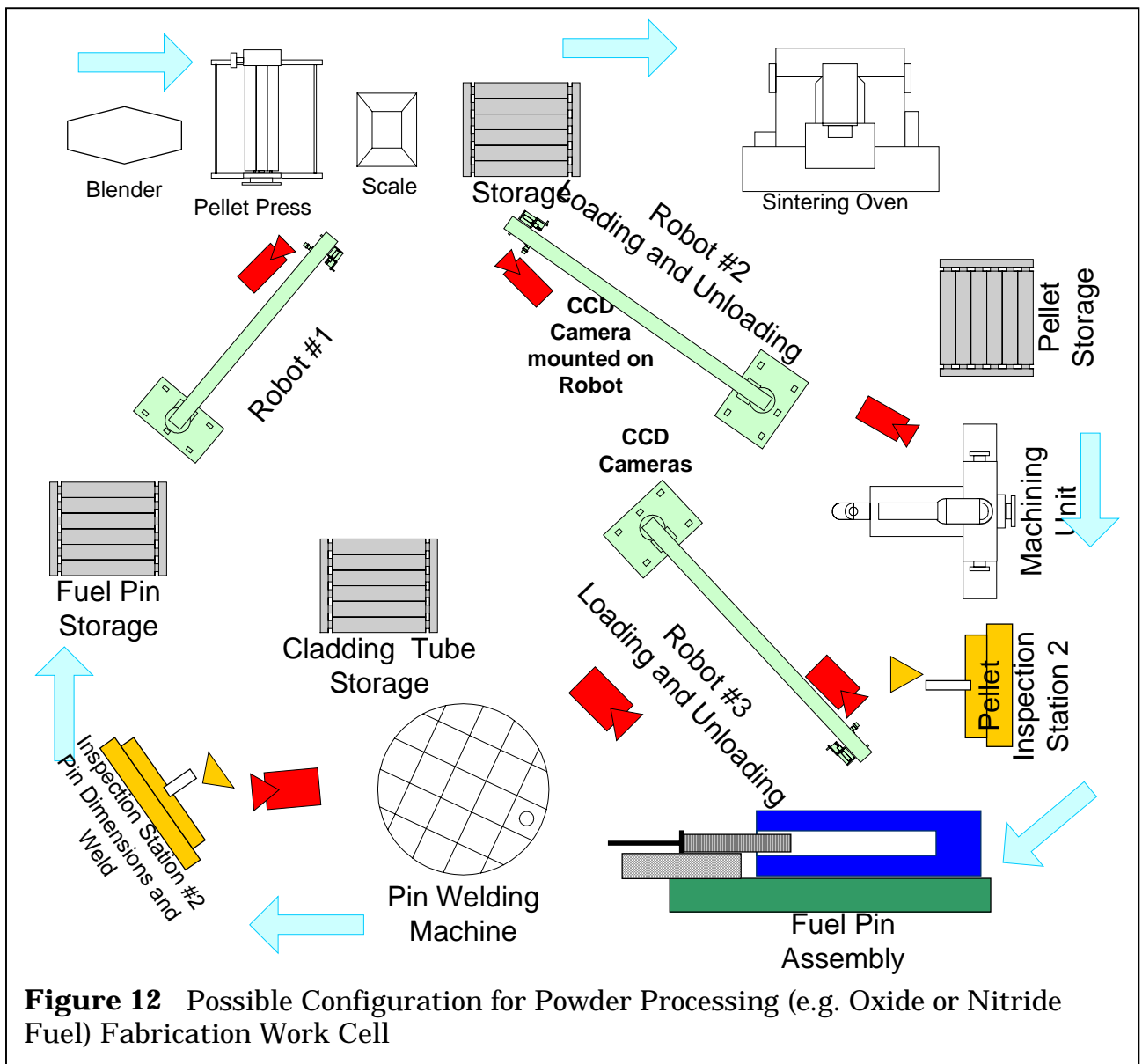
Equipment	Estim. Cost in US \$	Estimated Area requirement ft ²	Comments
Blender	50K	10	
Pellet press	500K	20	
Sintering oven	1.5Million	50	Custom equipment
Machining Center (Grinder)	500K	20	Custom equipment. Dust seal and dust suppression required. E.g.: wet process would reduce dust and surface temperatures during grinding.
Pellet Inspection Station	1Million	10	Custom equipment
Fuel Pin Assembly Unit (Pellet insertion, encapsulation and bonding, welding)	2Million	40	Custom equipment

3 Robots, approx. 1.5 m work envelope ea. at 270 deg. range	1.5 Million	60	
Supervision (cameras and controllers)	500k		
Product storage		20	
Final Inspection station (Fuel rod dimensions and weld)	1Million	20	
	\$8.55M	250 ft ²	

A single manufacturing cell would require approx. 250 sq. ft. of hot cell space at a cost of approx. \$30,000/ft² or \$7.5M for the hot cell space. Total installation cost approx. \$16.05Million.

Fig.12 shows the conceptual fabrication cell layout. Fig. 11 shows schematically the organization of a working powder processing plant, the Framatome UO₂ fuel manufacturing plant in Lingen, Germany. The Lingen plant operates without shielding or hot cells, but places tight controls on UO₂ losses, which occur mostly in particulate form.





5. Plant Visits

G. Mauer visited hot cell and diagnostic facilities at CEA Cadarache (Dr. Silvie Pillon) and CEA Marcoule (M. Louis Donnet). The Marcoule center is in the process of manufacturing a fuel rod containing Americium pellets. The rod will be inserted into the Phénix reactor for transmutation experiments. The pellets themselves are being manufactured at the Institute for Transuranics in Karlsruhe. The pellets are being produced by the sol-gel method developed in Karlsruhe and described earlier.

At the Institute for Transuranics in Karlsruhe, Drs Rudy Konings and Didier Haas guided me through their labs. A new hot cell facility is under construction there which will also comprise a number of robotic and other automation tools. Since the facility is not yet operational, I was able to inspect all equipment in the new cell closely. The Karlsruhe hot cell comprises small robots which will be used to automate some operations. Sensitive electronic components for the robots will be located outside the hot cell. It appears that some electronic equipment, such as electronic laboratory balances, have functioned without problems in several installations in both France and Karlsruhe. ITU Karlsruhe will manufacture the AM pellets using the Sol-Gel process developed there. Figures 3 and 4 illustrate the process (also reported in Report 3 of June 2002.)

The last visit was to the Framatome manufacturing plant in Lingen, Germany. The plant produces UO_2 commercial reactor fuel from Uranium hexafluoride. The UO_2 powder is pressed into pellets and sintered for 18 hrs. at approx. 1800°C . The sintered pellets are ground automatically to their specified diameter, arranged in long rows, and automatically inserted into fuel rods. According to the Lingen plant's safety engineer, material losses are kept below 0.1%. The manufacturing automation in Lingen was largely developed locally. Lingen operates without shielding such as glove boxes or hot cells. Nevertheless, all plant modifications must undergo a laborious approval process which takes approximately two years. Fig. 12 show the manufacturing process schematically, augmented by translations of some captions into English.

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Appendix

Selected Simulation Results

The simulations presented here were developed using ProEngineer solid modeling software in conjunction with MSC VisualNastran4D. Together, the software tools create realistic 3D animations. They also permit accurate calculations of the dynamics of components and loads, collisions, and other aspects of the hot cell operations. Animated simulations of the simulations depicted below have been submitted to the UNLV AAA web site (<http://aaa.nevada.edu/>) for posting.

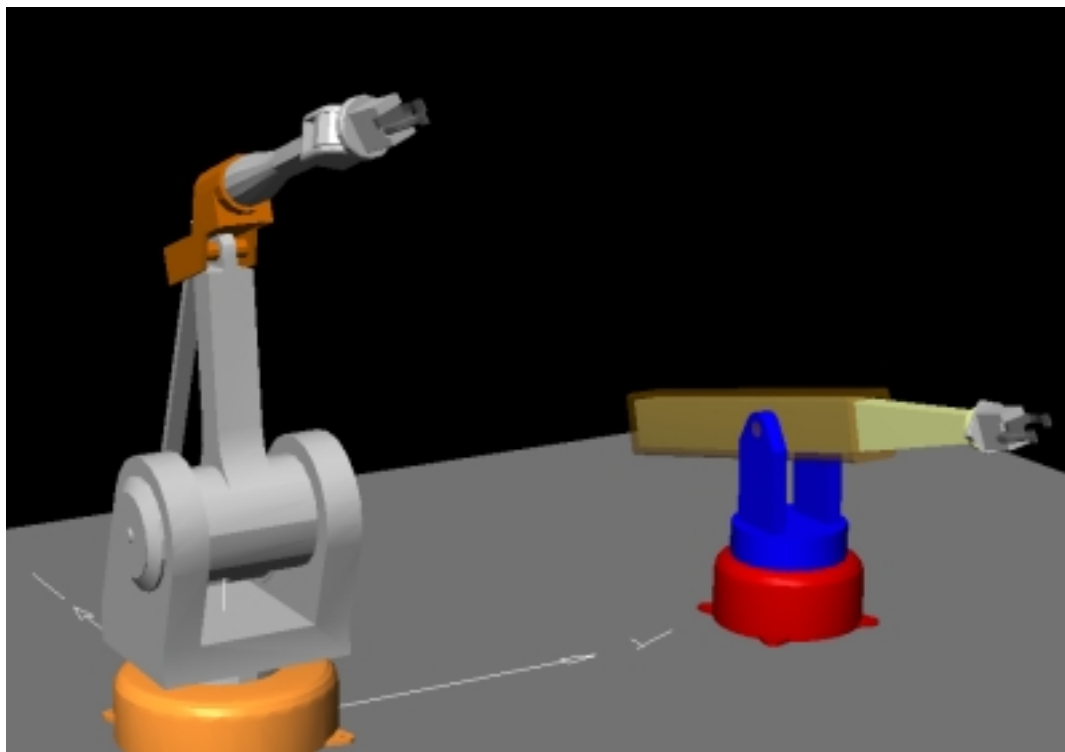


Figure A1 Interactive GUI process simulation: Two Robots Workcell. Created by Richard Silva with Visual Nastran.

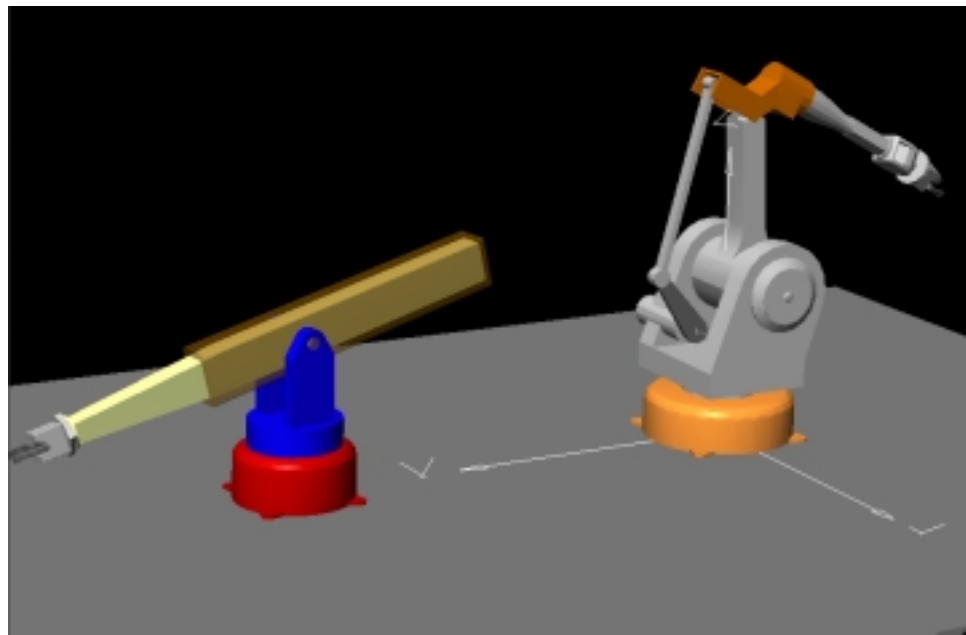


Figure A2 Interactive GUI process simulation: Two Robots Workcell. Created by Richard Silva with Visual Nastran.

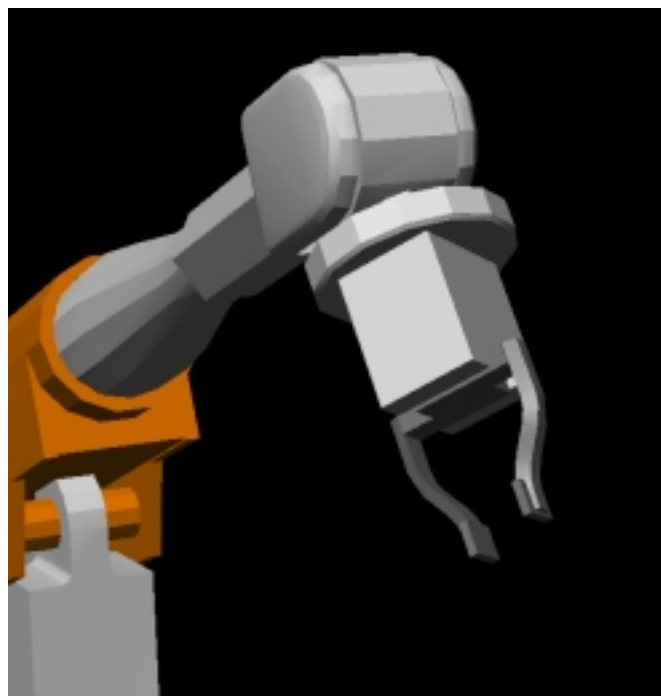


Figure A3 Interactive GUI process simulation: The gripper of the revolute Robots of Fig. A2. Created by Richard Silva with Visual Nastran.

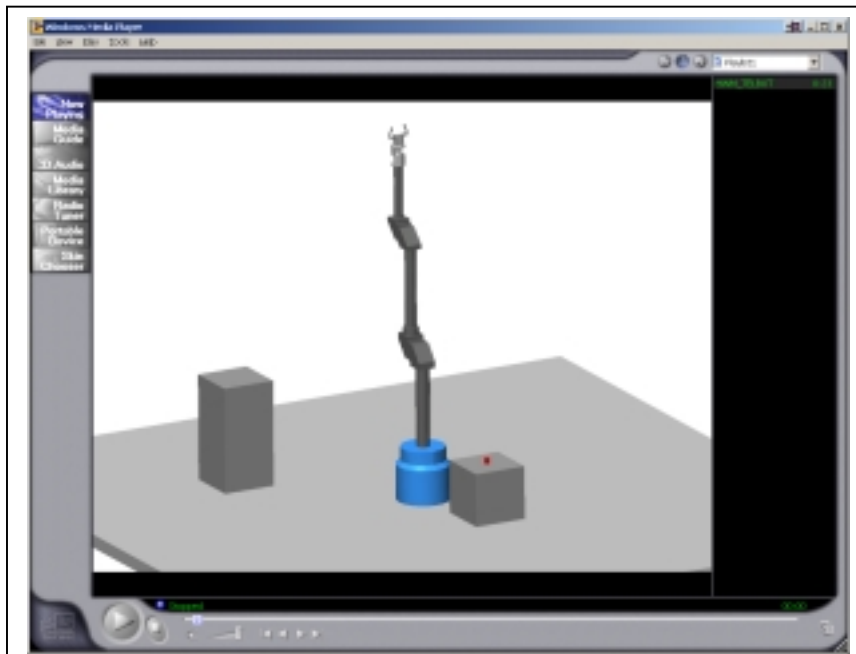
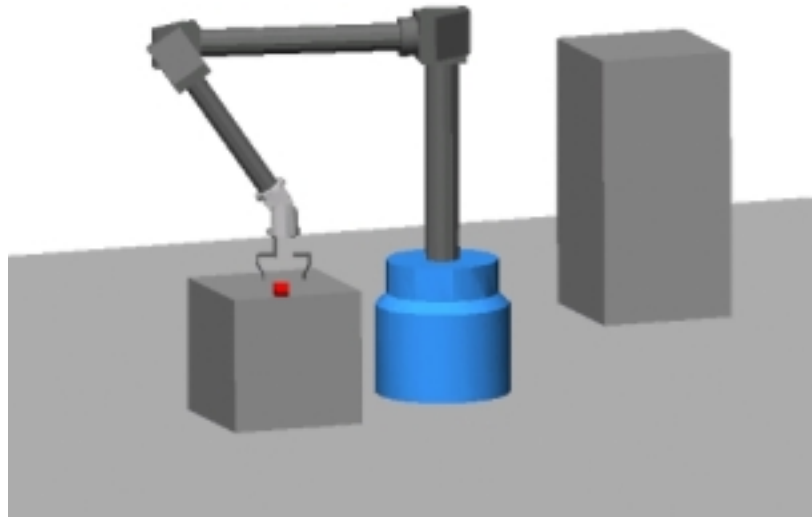
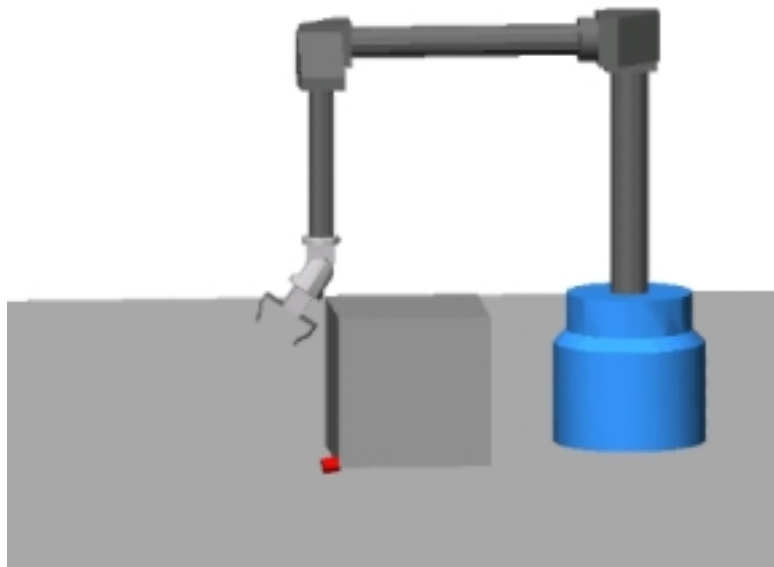


Figure A4 Interactive GUI process simulation: Hot Cell Robot (Waelischmiller.) Created by Grad. Student Richard Silva with Visual Nastran. The robot base (shown in blue color) contains all mechanical parts and can be placed outside the ionized region. The cylindrical pipe would form a conduit through the hot cell wall.

Figures A4 through A5 contain hot cell robot simulations based on the Waelischmiller designs shown in Fig. 4 above. The correct performance of the Waelischmiller hot cell robot model has been verified. The dynamic robot model will be interactively controlled with the Matlab control design software. Robot controllers will be developed and tested.



(c) Trying to grasp Manually



(d) .. and missing

Figure A5 (Screenshots Continued)