

DESIGN CONCEPTS AND PROCESS ANALYSIS FOR TRANSMUTER FUEL MANUFACTURING

G. Mauer

Department of Mechanical Engineering
UNLV, Las Vegas, NV 89154-4027
E-mail: mauer@me.unlv.edu

Abstract

The large-scale deployment of remote fabrication and refabrication processes (approx. 100 tons of Minor Actinides (MA) annually) will be required for all transmutation scenarios. Process automation has the potential to decrease the cost of remote fuel fabrication and to make transmutation a more economically viable process. The paper describes the design of hot cell fuel manufacturing processes using robotic equipment in hot cells. The dynamics of the robots and the objects handled by them are analyzed in detail using state of the art software tools. In addition to the evaluation and testing of normal assembly operations, the 3D simulation provides for a comprehensive analysis of normal work flows and atypical events such as collisions. The results permit a detailed analysis of the robotic assembly process in terms of forces, torques, and accidents.

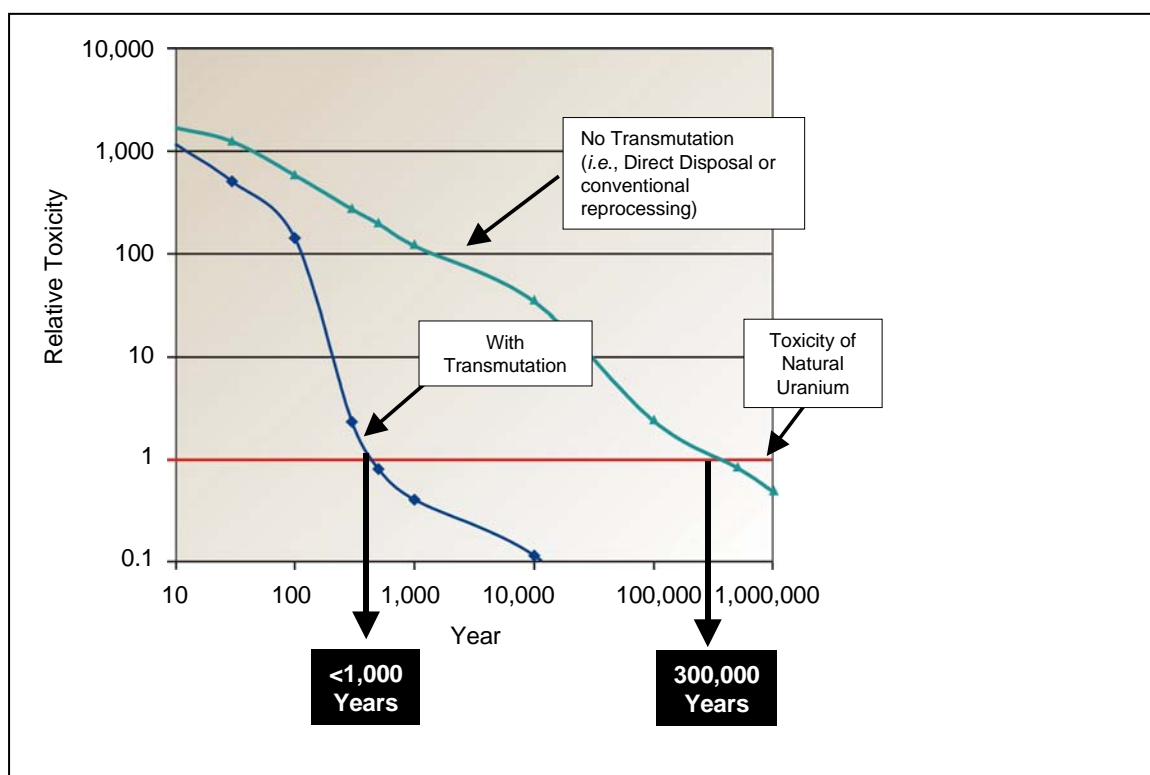
Detailed simulation results for several operations are presented.

Introduction

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 (MIT, 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 efficiently 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) and Bresee and Laidler (2000) describe 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.

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 paper 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.

Figure 1. Long term Nuclear Waste Storage Duration with and without Transmutation (quoted from: Herczeg 2003)



Remote Robotic Manufacturing Processes for Transmuter Fuels

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

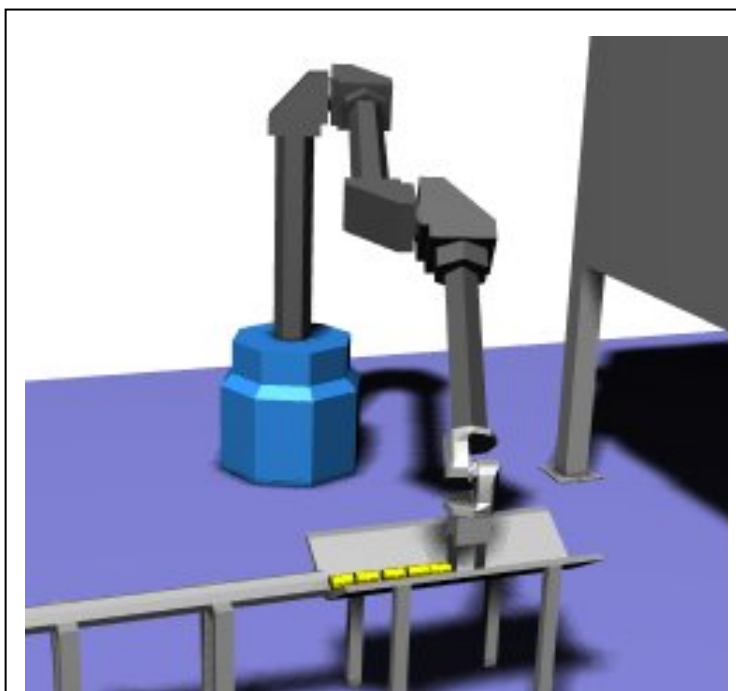


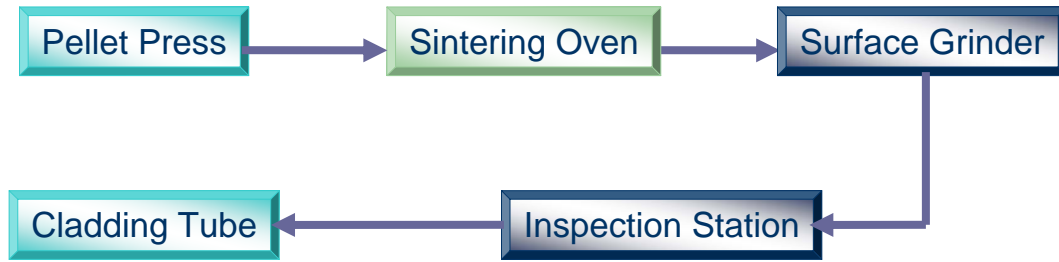
Figure 2. **Robotic Fuel Assembly, MSC.visualNastran® Simulation**

MA Transmuter fuels will be manufactured in hot cells. Components such as pellets and fuel pins must be handled individually. The large anticipated production volumes will likely be best handled by robotic rather than manual assembly of fuel elements.

Robotic equipment is well suited for the automatic handling of parts in hot cell fuel manufacturing, for tasks such as pellet insertion into fuel rods (see Fig. 2) and fuel rod handling. The dynamics of the robots and the objects handled by them are analyzed in detail using state of the art software tools. In addition to the evaluation and testing of normal assembly operations, the 3D simulation provides for a comprehensive analysis of forces and loads, including those occurring during atypical events such as collisions. The results permit a detailed, in-depth analysis of many aspects of the robotic assembly process, such as forces, torques, quantitative analyses of collisions, and other safety-relevant events.

Hot Cell Design and Analysis for Powder processing

Figure 3. **Powder Processing: Material Flow in Hot Cell**

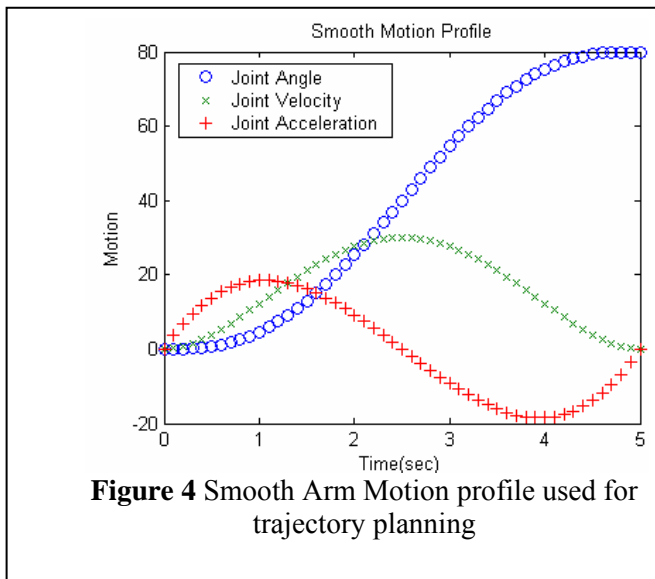


We analyzed robotic pick and place operations in the hot cell using hot cell robots (Wälischmiller manipulators with 6 revolute axes.) The simulation model comprises the inertial robot dynamics and the dynamics of objects in contact with the robots. Equation (1) presents the dynamic equation of a manipulator with n joints.

$$M(q)\ddot{q} + V(q, \dot{q})\dot{q} + G(q) = \tau \quad (\text{Equation 1})$$

where:

- M is the nxn mass matrix
- V is the nxn velocity matrix
- G is the nx1 gravity vector
- q , \dot{q} and \ddot{q} are the joint angles vector and is first and second time derivatives respectively
- τ is the joint torque vector



A path planner employing smooth start and end accelerations for each joint was implemented in MATLAB Simulink® and connected to the GUI robot model employed in the simulation (see Figure 4). The robot's 6 axes are controlled from MATLAB Simulink® (one controller for each joint) using a PID algorithm. The GUI robot model is controlled from the MATLAB Simulink® model, and provides real time feedback to the robot controller.

The simulations were developed on a dual processor workstation using ProEngineer® solid modeling software in conjunction with MSC.visualNastran® and with MATLAB Simulink® for control. The CAD solid model is augmented in the MSC.visualNastran® environment by dynamic system parameters such as material properties and motion constraints. The hot cell is configured with two robotic manipulators. The first manipulator picks and places the fuel pellets from the pellet press' chute to the sintering boat. The pellets are scattered randomly in the chute, thus the manipulator must orient the end effector parallel to the pellet's longitudinal axis. The manipulator approaches the chute, moves above the targeted pellet, descends to the pellet's position, and grasps the pellet.

After sintering, the second manipulator grasps individual fuel pins from the sintering boat and places them into a grinder. Thereafter, a camera, preferably positioned outside the hot cell, inspects the fuel pin dimensional parameters. The robot places inspected pellets a V-tray in front of an empty cladding tube. After the required number of fuel pins have been aligned on the V-tray, the manipulator end effector pushes the column of pins into the cladding tube.

Time-Motion Studies

Pellets can be fragile and brittle. It is therefore required to limit the maximum total acceleration of any pellet during robotic pick-and place motions. Our simulation limits the end effector acceleration to a maximum of 20 m/s^2 . The duration of pick and place operations is further influenced by the distance between transfer points. Our simulation assumes two robots, each of which handles a portion of the operations. Each robot is positioned in the hot cell such that it can perform the other's tasks in the event of breakdowns or maintenance of the other. The table below lists the time intervals observed through the simulation.

Table 1. **Pick and Place Time Intervals, per pellet**

Hot cell with two active robots. Robot 1 grasps pellets from the pellet press output bin and loads them onto the sintering boat. Robot 2 unloads sintered pellets from boat, inserts them into the grinder, presents them to the inspection station, and loads them onto the V-tray in preparation for their insertion into the cladding tube.	
Operation	Time in Seconds
Robot 1: Image Acquisition (Identify pellet in output tray of the pellet press, select pellet for grasping, compute pellet location and orientation)	5
Pellet Press to Sintering Boat	6
Return robot arm to Pellet Press	4
Total time Robot 1	14
Robot 2: Sintering Boat to Grinder	6
Return robot arm to Sintering Boat	4
Grinder to Dimensional Inspection Station	8
Dimensional Inspection Station to V-tray for Insertion into the cladding tube	6
Return robot arm to Sintering Boat	6
Total time Robot 2	30

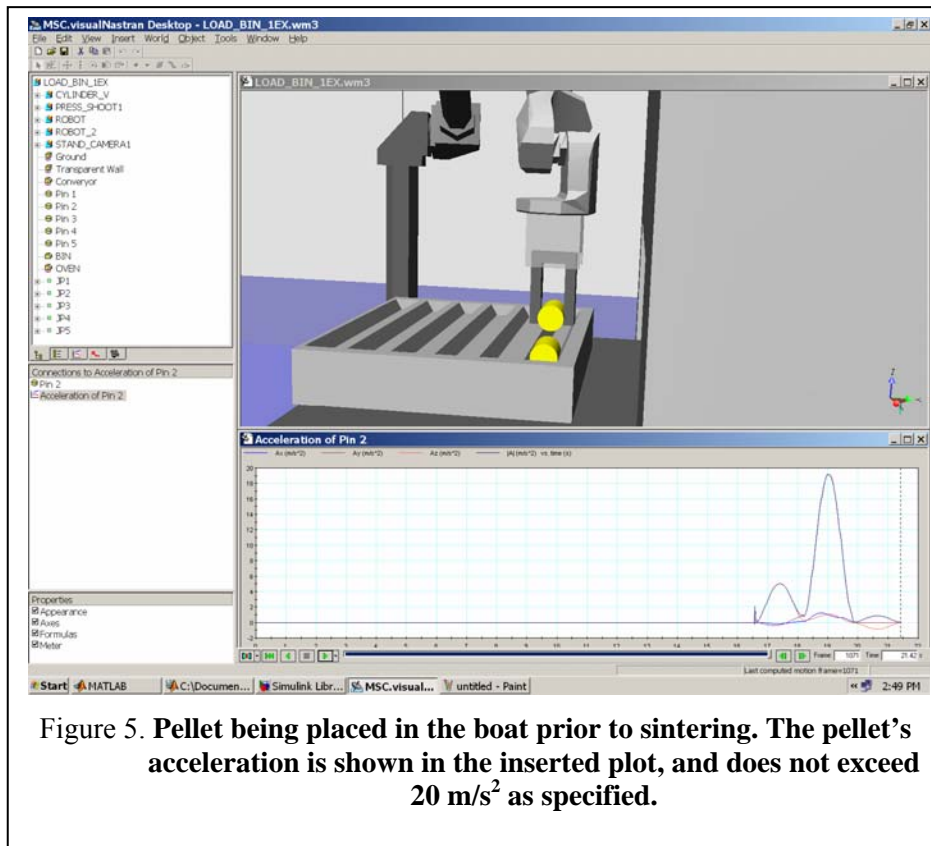


Figure 5. Pellet being placed in the boat prior to sintering. The pellet's acceleration is shown in the inserted plot, and does not exceed 20 m/s^2 as specified.

The cycle times for each robot result as 14 s and 30 s per pellet, respectively. The times to load or unload a sintering boat with 30 pellets result as 420 s and 900 s, respectively. The robotic material handling times are thus small as compared to the processing time in the sintering oven, which often range from 1 to 18 hours, depending on processing parameters. Two robots in the hot cell provide redundancy in case of maintenance or breakdowns. Cycle times with one robot will be a third longer, but still slow in comparison to the sintering time.

The insertion of the stack of pellets into the cladding tube requires approx. 30 seconds.

Hot Cell Design and Analysis for Metallic Fuel Processing

Robots can support the manufacture of metallic fuels through material handling. The fuel slugs produced by the casting oven must be ground to the required diameter, inspected, and then be inserted into the cladding tube. The hot cell supervision will be accomplished by using CCD cameras.

Figure 6 shows a schematic of the grinding, inspection, and pin loading process. The process is similar to the previously discussed pellet handling, albeit without the requirement to load and unload sintering boats. A single robot suffices for the operations. Robot cycle times are similar to those for Robot #2 in the powder processing case.

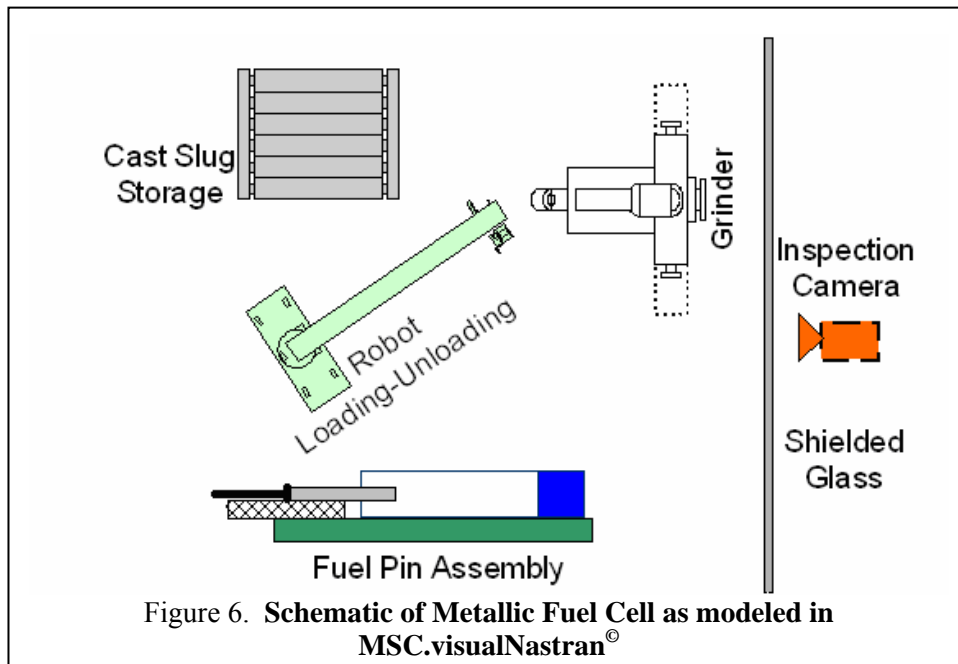
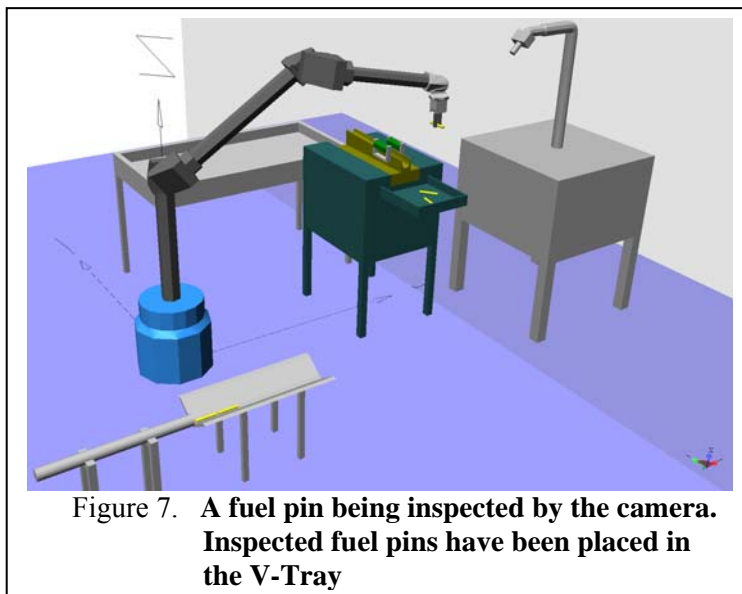
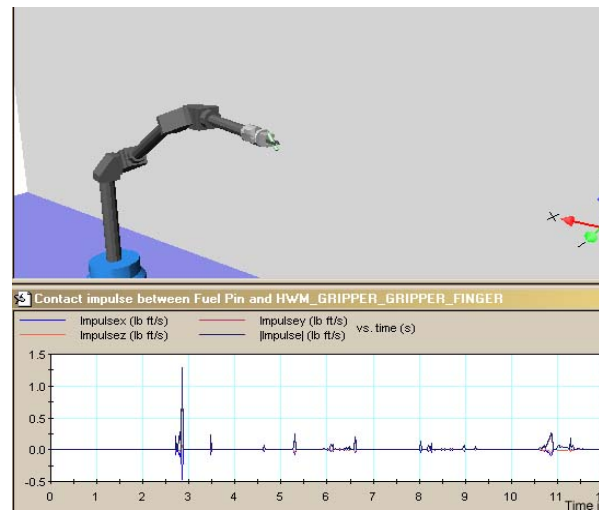
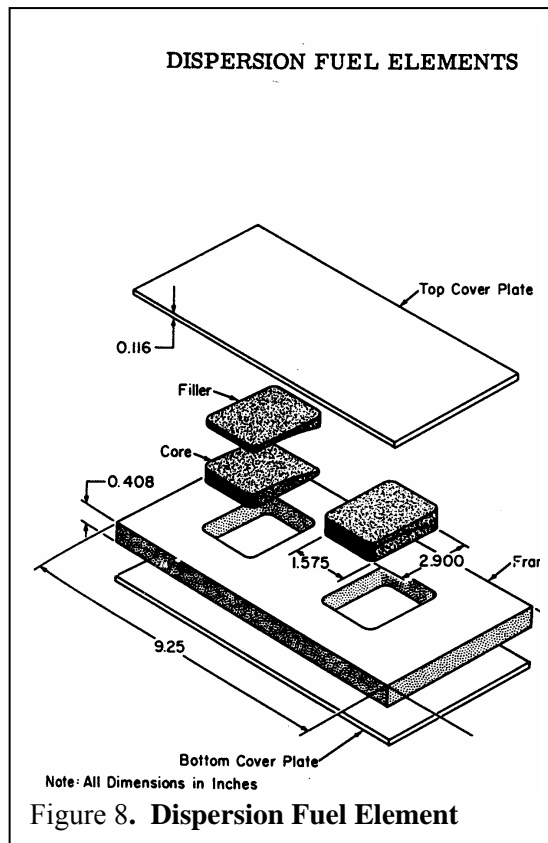


Figure 7 shows a snapshot of the metal fuel assembly hot cell, developed in the MSC.visualNastran® environment.



Hot Cell Design and Analysis for Dispersion Fuel Processing

The design of dispersion fuels lends itself to a lesser degree to manufacturing automation with robots. A fuel compact is embedded in the matrix metal. Robots can be cost-efficient for the placement of the fuel compact into the fuel element before extrusion seen in Figure 8. The completed billet is then extruded at approximately 800°C.

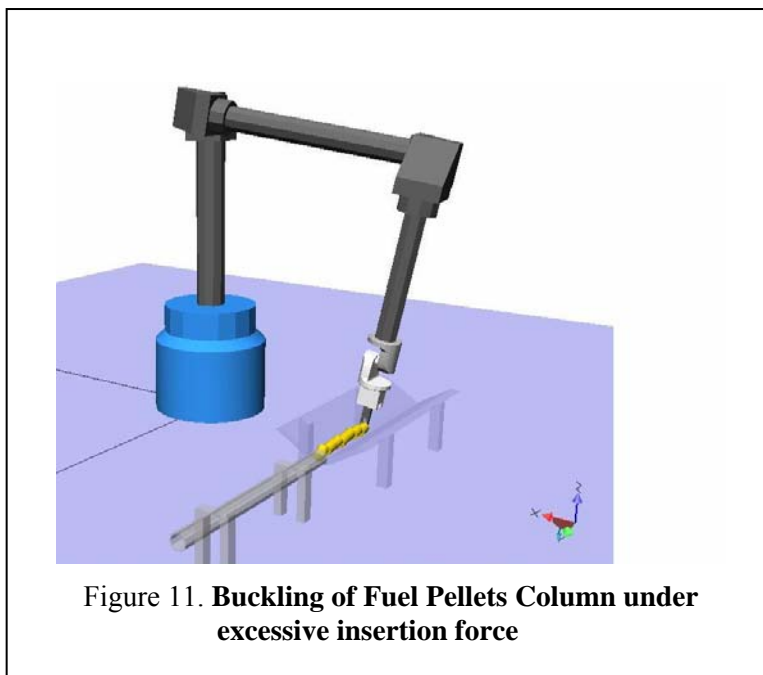
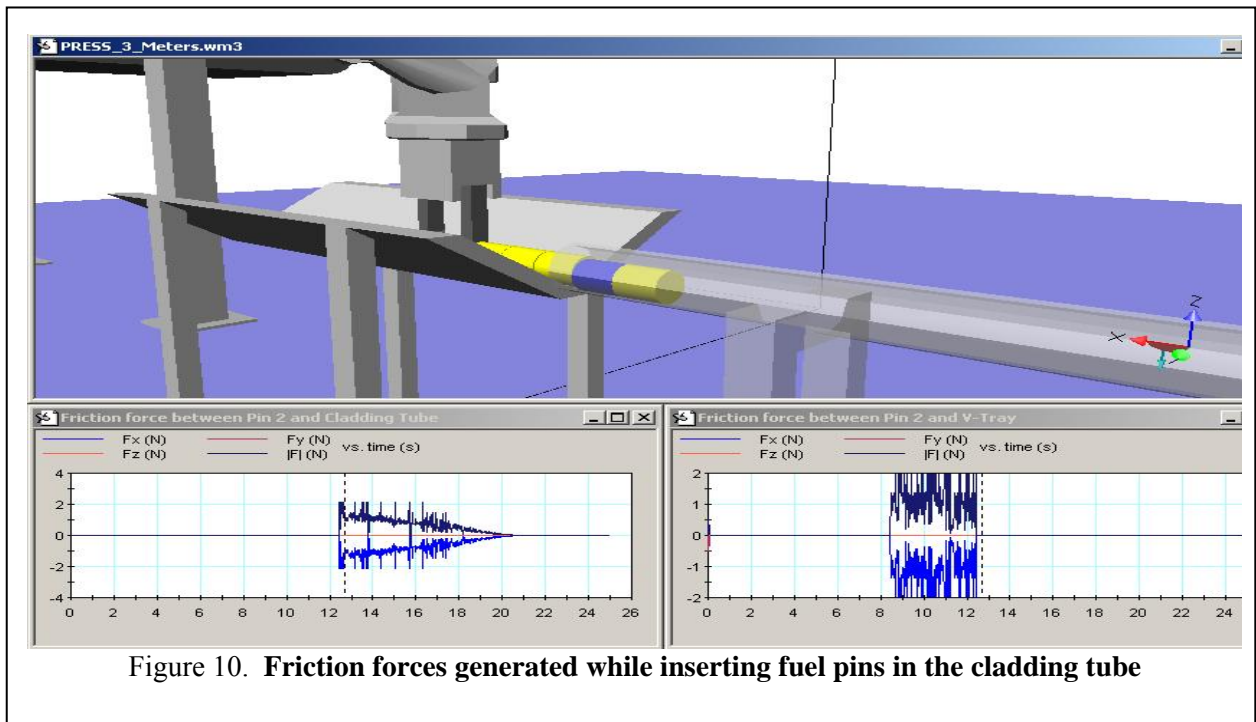


Analysis of Atypical Events

The Visual Nastran environment allows the detailed simulation and analysis of atypical events such as collisions, impacts, misalignments between parts that should be matching. This section presents a study on robot arm collisions, and an examination of the forces required for pellet insertion into the cladding tube.

Figure 9 shows the robot colliding repeatedly with a rigid wall at varying speeds. The plot below the robot documents the resulting impulses on the end effector.

Figure 10 illustrates a Waelischmiller 6-axis hot cell robot placing a series of fuel pellets into a trough, and inserting the stack of pellets into a fuel pin. The two diagrams at the bottom of Figure 10 show the resulting friction forces between the (blue) pin and the V-Tray, and the (blue) pin and the Cladding Tube. The friction of the pin with the cladding tube (left plot) decays to zero in a smooth manner, as the end effector pushing the pins comes to a smooth stop. Figure 11 shows the effect of excessive force when pushing the pellets. The column of pellets undergoes buckling.



Conclusion

Design and simulation results for the automated manufacture of three different kinds of transmuter fuels in hot cells have been presented. The simulation provides a capability for analyzing the entire process in a manner comparable to a mock-up experiment. The simulation allows for the detailed analysis of the entire material handling process, including irregular events such as collisions and failed part placements or insertions. The simulation allows for the comprehensive examination and testing of failure scenarios as well as recovery procedures, and thus for the iterative optimization of all mechanical hot cell components, ensuring maximum reliability and safety.

REFERENCES

- [1] Herczeg, J.W. (2003) "Advanced Fuel Cycle Initiative Advanced Fuel Cycle Initiative" Semi-Annual Review Meeting, Albuquerque, New Mexico, January.
http://aaa.lanl.gov/tr0103pres/introduction_1_herczeg.pdf
- [2] Bresee J. C. and J. J. Laidler (2000) "The Status Of The Us Accelerator Transmutation Of Waste Programme," Proc. Conf. on Partitioning and Transmutation, Madrid, Dec.
<http://www.nea.fr/html/pt/docs/iem/madrid00/Proceedings/Paper33.pdf>
- [3] Meyer, M. (2001) "The U.S. Program for the Development of Inert-Matrix Fuel for Transmutation Systems" Presentation to the AAA project, Las Vegas, NV, June
http://aaa.nevada.edu/pdffiles/Meyer6_21_01.pdf
MIT (2003) "The Future of Nuclear Power, AN INTERDISCIPLINARY MIT STUDY," Cambridge, MA, ISBN 0-615-12420-8.
- [4] Paul, Richard C. (1981) "Robot manipulators: Mathematics, Programming and Control," The MIT Press, Cambridge, MA.