DESIGN CONCEPTS AND PROCESS ANALYSIS FOR RELIABLE, AUTOMATED TRANSMUTER FUEL MANUFACTURE

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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 more economically viable. The paper describes the design of automated fuel manufacturing processes using robotic equipment inside 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 costs of investment, operations, and economic losses during hot cell downtimes and repairs are analyzed comprehensively. The result is an algorithm for optimizing plant size, and the number of redundant components inside the hot cell for maximum throughput and minimum plant down times.
Detailed simulation results for several operations are presented.

I. INTRODUCTION

Transmutation promises both a significant reduction of waste quantities as well as a reduction of the duration of storage time (MIT, 2003) in comparison with the presently envisioned concept for the permanent disposal of high-level nuclear waste. While Pu can be efficiently recycled by processing it into MOX (Mixed Oxide) reactor fuel, the minor actinides (MA), 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. This paper describes options for 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.

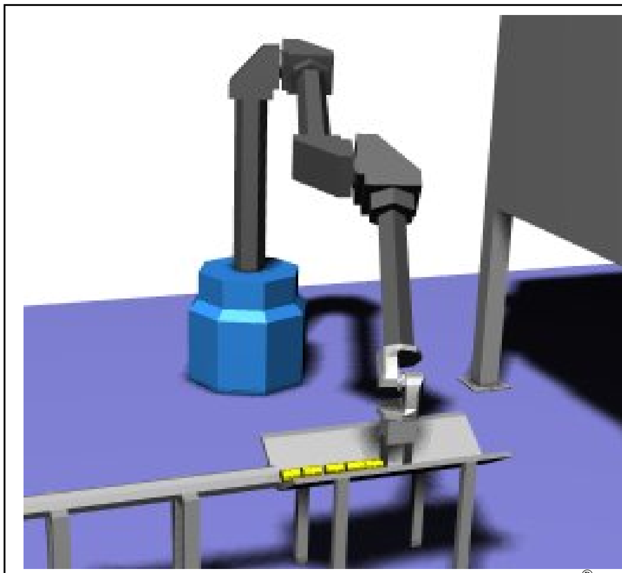

Figure 1 Robotic Fuel Assembly, MSC.visualNastranP® PSimulation

II. 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

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. 1) 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.

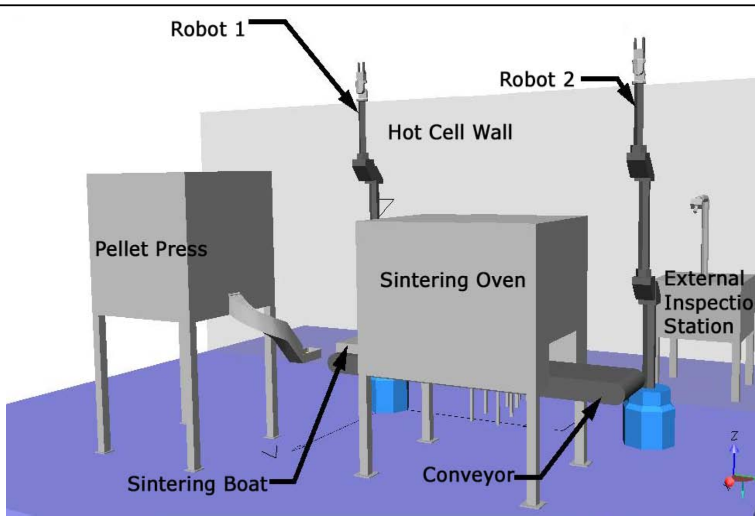

Figure 2 SimulationModel of Hot Cell Manufacturing Plant for Oxide Fuels. Visual Nastran Simulation

III. ROBOTIC WORKCELL DESIGN

In comparison with dedicated automated material handling equipment, robotic manipulators offer the benefits of greater flexibility and shorter lead times for cell design and testing, since fewer custom components are required. In the operational phase, robots offer operators greater flexibility for recovery from malfunctions, and for implementation of future process modifications without major retooling. Long-term reliability is ensured with hot cell robots whose maintenance-intensive parts are located outside the hotcell. Robot supervision by cameras and real time recognition can reliably monitor and document all operations.

Unlike UO_2 and MOX fuels, the fabrication of fuels containing Americium requires shielding from gamma and neutron radiation, and therefore remote operation in a hot cell. A simulation model of a hot cell for powder processing was created at UNLV. The model comprises inertial dynamics of all moving components in the hot cell, including robots and individual pellets being transported. Fig. 2 shows the simulation model, generated in VisualNastran ©. As seen in Fig. 2, the fuel pellets would be moved by the robots through the processing stages (pellet press, sintering, precision grinding, and dimensional inspection). The completed pellets would then be placed onto a tray and inserted into a cladding tube. The manufacture is completed by filling the completed fuel pin with Helium, end cap welding of the cladding tube, and leak inspection of the completed fuel pin.

The robots perform smooth acceleration and decelerations of the fuel pellts and pins being transported. Similarly, the maximum permissible acceleration of any end effector was limted to 20 m/s^2 in order to limit both damage risk and to reduce robot maintenance needs.

IV. THROUGHPUT ANALYSIS

Time-Motion analysis from Hot cell Simulation

Process Step	Duration in seconds (per pellet)
Pellet press to sintering boat (Robot #1)	14
Sintering boat to grinder (Robot #2)	8
Grinder to inspection station and positioning for fuel pin loading (Robot #2)	14
Fuel pin insertion into cladding tube (Robot #2)	2

The time-motion analysis is based on the geometrical hot cell layout shown in Fig. 3, assuming powder processing. The robots move the fuel pellets between processing and inspection stations, at a maximum acceleration at the end effector of 20 m/s^2. The simulations employ ProEngineer solid modeling software in conjunction with MSC VisualNastran4D and with Matlab Simulink for control.

Sintering may take from 5 to 18 hours, depending on the method. For optimal throughput, the sintering oven should be designed for a throughput of approx. 180 pellets/hr. The manufacturing capacity is limited by robot #2, with a cycle time of 24 s/pellet. The addition of a third robot to reduce the workload of robot #2 could reduce the cycle time to 14s per pellet.

Plant Capacity – If operating at 70% of nominal capacity, a single hot cell could manufacture and process approximately 3,000 pellets per day. Assuming an Americium content of 10 g Am per pellet, the annual hot cell capacity would amount to 11 metric tons of Am.

Robot Selection and Placement – The maintenance-intensive elements of hot cell robots such as the Waelischmiller Telbot can be accessed outside the hot cell. The robots can placed on the floor as shown in Fig. 1, or mounted from walls or ceilings.

Other Fuel Types - The robotic operations are limited to pick-and-place material handling, and visual inspection. These functions are readily adapted to other process sequences, e.g, for metallic and dispersion fuels.

V. CONCLUSIONS

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.

ACKNOWLEDGMENTS

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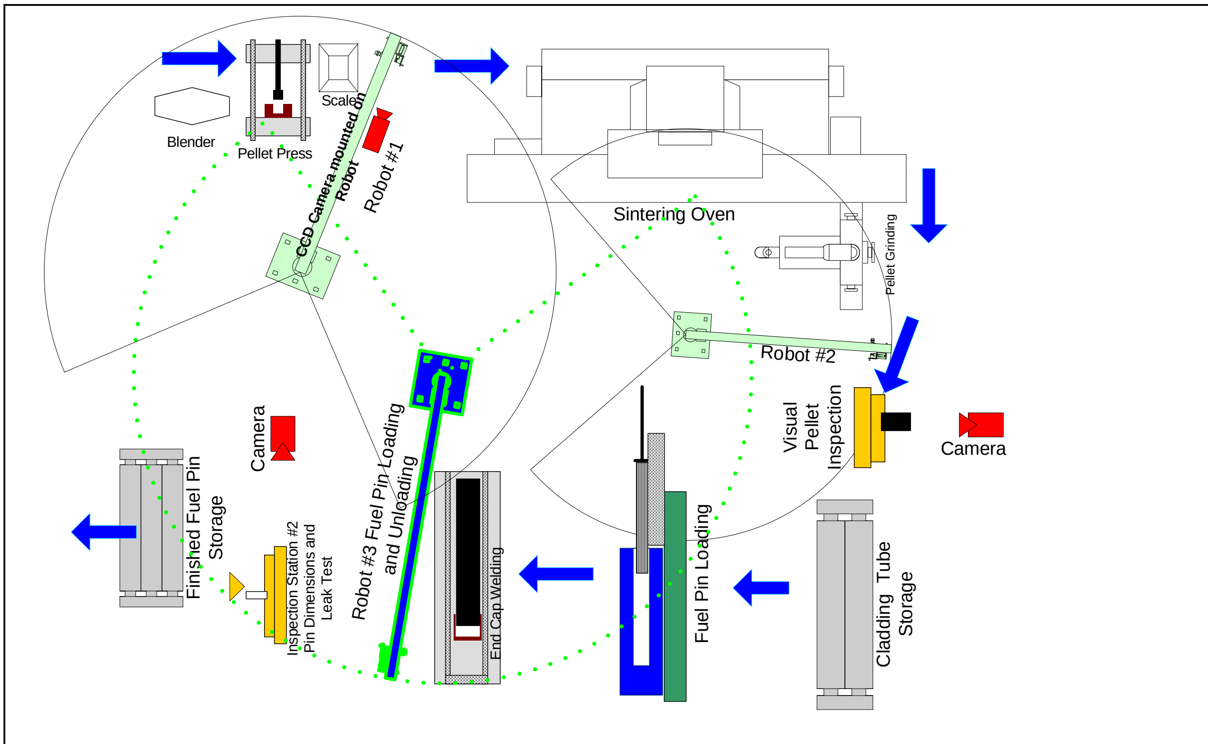

Figure 3 Powder Processing: Conceptual Plant Layout for Robotic Transmuter Fuel Fabrication

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