

PYROPROCESSING: A PRACTICAL SOLUTION TO SPENT FUEL MANAGEMENT

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Pyroprocessing was first utilized in the EBR-II Fuel Cycle Facility during 1964-69, and recently since 1996 to date. Pyroprocessing allows recovery of actinides in a single product stream. If actinides are then burned in a fast reactor, the effective lifetime of nuclear waste will be reduced by three orders of magnitude making the repository siting and design an easy task. A conceptual design of a pilot-scale (100 T/yr) pyroprocessing facility is described.

I. INTRODUCTION

An early version of pyroprocessing based on melt-refining was employed for the fuel cycle closure demonstration in Experimental Breeder Reactor-II (EBR-II). About 35,000 fuel pins were recycled based on melt-refining and injection-casting fabrication in the adjacent Fuel Cycle Facility (FCF) with a typical turnaround time of 45 days during 1965 through 1969. (Ref. 1) However, melt-refining could not remove noble metal fission products and separate higher actinides from uranium. When the Integral Fast Reactor (IFR) Program (Ref. 2) was initiated in 1983, an electrorefining process was adopted in place of melt-refining. The pyroprocessing technology was further developed during the IFR Program, and the original EBR-II FCF (see Fig. 1) was refurbished using the new electrorefining-based equipment to demonstrate pyroprocessing at the engineering-scale.

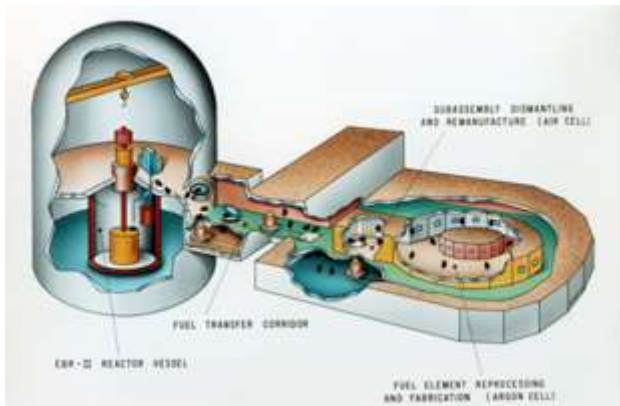


Fig. 1. Schematics of EBR-II and its Fuel Cycle Facility

The IFR Program and EBR-II operation ended in 1994, however the refurbished FCF has been in operation since 1996 treating the EBR-II spent fuel for disposal purposes. Hence, the application of pyroprocessing for metal-fueled fast reactor fuel has successfully been demonstrated at the engineering scale. Although the sodium-cooled fast reactor (SFR) with metal fuel and pyroprocessing will remain as a most promising long-term next-generation reactor/fuel cycle system, in the near-term, pyroprocessing can be applied for treatment of the current generation commercial Light Water Reactor (LWR) spent fuel to make its ultimate disposal simpler.

The radiological toxicity of typical LWR spent fuel over the years is shown in Fig. 2. The radiological toxicity due to the fission product portion of the waste decays below the natural uranium ore level in about 300 years, and becomes relatively harmless. On the other hand, the toxicity level associated with the actinide portion stays far above uranium ore and remains at least three orders of magnitude greater than fission products for hundreds of thousands of years. If 99.9% of actinides are removed from the waste form, then the radiological toxicity of the remaining 0.1% of actinides stays below the natural uranium ore at all times and the effective lifetime of the waste is reduced from about 300,000 years to about 300 years.

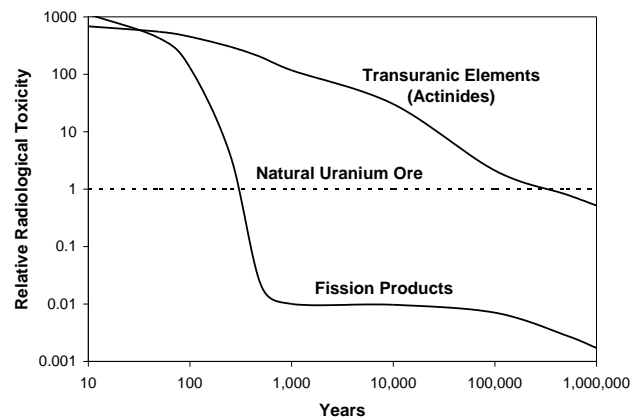


Fig. 2. Relative radiological toxicity of spent fuel constituents.

A repository is still required but any regulatory requirements or performance requirements placed on the repository can be met on a *a priori* basis, and hence the repository siting and the repository design will become an easier task.

Actinide transmutation, from actinide to non-actinide, or “actinide burning”, can be done by fission and by fission only. Neutron capture in the actinides without fission results only in their evolution to other actinides of ever higher mass, as a rule more and more radioactive. To burn actinides effectively, high-energy neutrons are needed. There is a huge difference between the transmutation possible from the low energy neutrons of thermal spectrum of an LWR and the high energies of the fast spectrum. The transmutation probability, the percentage of neutrons absorbed that cause fission, of typical thermal and fast spectra for the actinide isotopes are compared in Table I.

TABLE I. Transmutation Probabilities (in %)

Isotope	Thermal Spectrum	Fast Spectrum
Np-237	3	27
Pu-238	7	70
Pu-239	63	85
Pu-240	1	55
PU-241	75	87
Pu-242	1	53
Am-241	1	21
Am-242m	75	94
Am-243	1	23
Cm-242	1	10
Cm-243	78	94
Cm-244	4	33

In a thermal spectrum only a limited number of isotopes fission effectively. If fuel is recycled continuously, higher actinides will continue to build up until they approximately equal the amount of plutonium in the fuel. In a fast spectrum all the isotopes fission substantially and the equilibrium composition is reached with relatively small, quite normal, amounts of higher actinides. The isotopic evolution in thermal recycle is presented in Fig. 3. The isotopic evolution was accelerated assuming pure actinides fuel in inert matrix without uranium, which produces fresh actinides with irradiation. The fissile isotopes, such as Pu-239 and Pu-241 can be burned readily, but fertile isotopes, such as Pu-242 and various americium and curium isotopes, go on building up as burnup progresses. They have no reactivity value in a thermal spectrum and are useless there as fuel.

II. CONCEPTUAL DESIGN OF A PILOT-SCALE PYROPROCESSING FACILITY

Argonne National Laboratory and the Landmark Foundation, headquartered in Norfolk, VA, entered into a Cooperative Research and Development Agreement (CRADA) to develop the conceptual design of a pilot-scale (100 T/yr) pyroprocessing facility for treating domestic Light Water Reactor (LWR) spent nuclear fuel. The primary purpose of this CRADA project was to perform sufficient engineering for the pilot facility conceptual design so that credible capital and operating cost and schedule estimates could be developed to facilitate a decision to proceed.

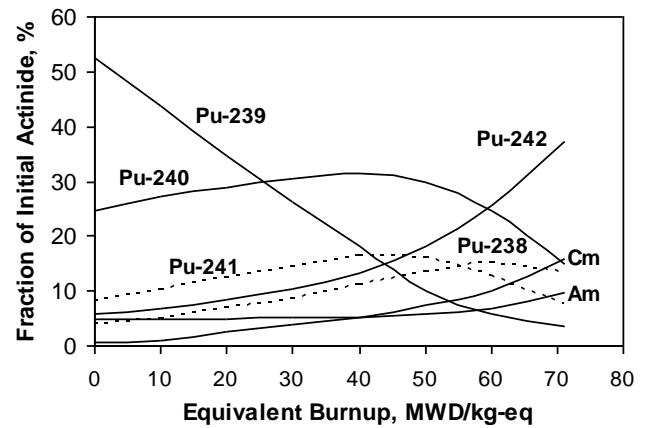


Fig. 3. Isotopic evolution of actinides in thermal spectrum.

Merrick and Company was subcontracted to develop the facility designs and provide construction cost and schedule estimates. Based on the results of this CRADA project, a decision whether to proceed to the detailed engineering phase for the pilot-scale demonstration can be pursued. The ultimate goal is to demonstrate the viability of pyroprocessing as a practical solution to spent fuel management.

This Conceptual Design has been developed for a Pilot-Scale Pyroprocessing Facility to process 100 metric tons of LWR used nuclear fuel per year. This facility concept is based on a green field approach and will describe the necessary structures and process equipment that are required to demonstrate this unique technology.

The conceptual design is based on Argonne’s successful approach to refurbishment of the EBR-II FCF, where a successful demonstration of the pyroprocess for fast reactor fuel has been conducted since 1996. The facility conceptual design is also based on the successful features of the Hot Fuel Examination Facility (HFEF) (Ref. 3), which has operated successfully without manned entry into its large inert hot cell. Furthermore, more recent

technical progress from the Fuel Cycle Technology programs of the Department of Energy has been incorporated as well.

The Processing Facility (Fig. 4) has a complex of primary buildings and ancillary systems that provide the necessary services to receive and store fuel from commercial reactors, operate the process equipment, store waste and products and ship waste to disposal sites. The facility design requirements are based on the process equipment needs and Argonne's experience operating nuclear facilities. The fuel is first received in the Protected Area Receiving Building where the fuel cask is unloaded from the truck and the cask is lowered to the cask transfer tunnel. The Processing Facility performs operations from fuel receipt to product storage and waste shipment. A TRU Vault for the storage of 10 years of TRU product is located in the lower level of the Processing Facility.



Fig. 4. Processing Facility

Four large hot cells in the Processing Facility (Fig. 5) provide the necessary shielding, contamination control, and atmospheres for the process operations and necessary process storage locations. Fig. 5 shows major equipment and storage locations within the Fuel Preparation/Storage Cell, Fuel Processing Cell, Waste Treatment Cell, and Gas Treatment Cell.

These cells are sized to provide storage areas for spent nuclear fuel assemblies, space for process equipment, storage areas between process steps and waste storage buffer areas. Remote operations and maintenance use overhead cranes and robotic cranes with minimal viewing windows. Process equipment shown in Fig 5 includes the disassembler, fuel rod slitter, kasket module loader, electrolytic reducer, electrorefiner, basket module loader, TRU processor, TRU down-blending furnace, uranium processor, drawdown vessel, noble metal processor, salt crystallization vessel, salt storage tank, and ceramic waste processor.

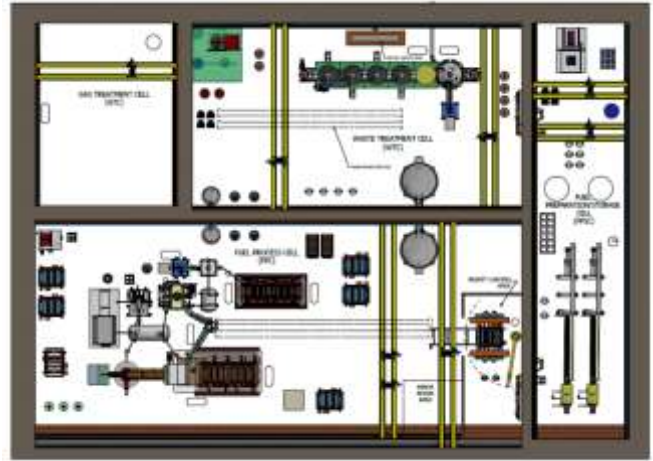


Fig. 5. Processing hot cells with process equipment layout

III. CAPITAL AND OPERATING COSTS

The facility capital cost estimate by Merrick and Company is based on the floor plans, roof plans, sections and elevations for all buildings plus the SSC list for the primary support systems. Detailed measurements of quantities are used, where possible. The detailed estimates are divided into the following categories for each building: foundations, vertical structure, floor and roof structures, exterior cladding, roofing, interior construction, conveying, mechanical systems, electrical systems, and equipment. Each of these categories is divided into elements where the estimates are based on square footage, cubic yards, or linear feet with applicable costs for these units of measures.

The ten different categories sum to give direct building costs, and 10% general conditions and construction management costs are added to the direct costs. In addition, a contingency is added to this total based on level of design maturity and type of construction. For standard buildings with equivalent industrial examples, the contingency is 15% whereas the site security system (20%) and processing facility (25%) contingencies reflect their complex design requirements and specialized systems.

The costs for the process equipment and support system as well as the operating cost are estimated by the Argonne design team. Costs for each equipment system or component (if not a part of a specific system) cover four general categories: engineering design and analysis, fabrication, purchased parts, and qualification. Qualification consists of three distinct phases: Phase 1 - Fit-up, integration, and outfitting, Phase 2 - Out-of-cell qualification including remote operations, and Phase 3 - Final in-cell installation and remote qualification. The same methodology applies to the process support systems.

However, the overhead lifting and robotics cost estimates use vendor quotations.

The project total capital cost estimate is summarized in Table II. The cost estimate is in 2015 dollars and is “overnight cost” with no escalations. The contingency factors range from 10% to 25% depending on the building type and the maturity of technology and design. The land acquisition cost, if needed, is not included.

TABLE II. Project total capital cost (\$ in thousands).

Category	Cost w/o C.F.	C.F, %.	Cost with C.F.
Facility			
Fuel Processing Facility	84,543	25	105,679
Protected Area Receiving	3,982	15	4,580
Waste Storage Facility	7,957	15	9,150
Lab & Operations Bldg	19,468	15	22,388
Maintenance & Mockup	9,815	15	11,288
Utility Building	13,585	15	15,623
Warehouse & Staging	4,302	15	4,948
Generator Bldg	2,776	15	3,192
Emergency Op Center	6,775	15	7,791
Fire Station	3,438	15	3,954
Site Work	29,593	15	34,032
Site Physical Protection	25,100	20	30,120
Design Engineering	<u>43,253</u>	20	<u>51,904</u>
Facility Subtotal	254,587		304,649
Equipment & Support			
Process Equipment	21,905	25	27,381
Transfer Locks & Feed	10,109	25	12,636
Overhead & Robotics	26,599	10	29,259
Electrical Systems	2,251	25	2,814
Monitoring & Control	4,480	25	5,600
MC&A	1,030	25	1,288
Safeguards & Sec. Eq.	4,645	25	5,806
Analytical Laboratory	3,800	20	4,750
Startup Materials	<u>2,859</u>	20	<u>3,431</u>
Equipment Subtotal	78,098		92,965
Total	324,308		397,614

The annual operating cost is summarized in Table III.

TABLE III Annual operating cost (\$ in thousands).

Category	Cost
Staffing	41,790
Materials and Services	4,180
Process Chemicals	579
Spare Parts	120
Product & Waste Containers	5,472
Utilities	984
Total	53,125

IV. POTENTIAL FOR SCALING UP TO COMMERCIAL-SCALE FACILITY

A common misperception or myth is that there are economies of scale going from pilot-scale to commercial scale for aqueous reprocessing, but not for pyroprocessing due to batch-type operation, and even further, pyroprocessing is viable for a small throughput but not for large throughput operation. The project has evaluated a potential approach for scaling the current pilot-scale design up to a 400 T/yr facility. A similar approach would apply to scale up to whatever throughput rate is needed.

The resulting project total capital cost with contingencies is \$911 million and the annual operating cost is \$90 million for the 400 T/yr facility. The basis for this cost estimate is for a first-of-a-kind and not a follow-on to the 100 T/yr pilot-scale facility. In the latter case, the cost would be further reduced without the first-of-a-kind costs.

IV SUMMARY

Direct disposal in a geological repository is a viable, technically feasible spent fuel management approach. And it is the *de facto* U.S. nuclear waste management policy. However, the public views adequate nuclear waste management as a critical linchpin in further development of nuclear energy. Pyroprocessing is far superior than aqueous reprocessing technologies in terms of the economic potential and safeguardability and can provide a technological alternative to the direct disposal. Pyroprocessing will reduce the effective lifetime of nuclear waste in the near-term at the same time bridging toward a true advanced next-generation fast reactor economy with complete fuel cycle closure.

ACKNOWLEDGEMENT

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