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Summary Report
Conceptual Design of a Pilot-Scale Pyroprocessing Facility

Prepared by

Argonne National Laboratory
Merrick and Company

for

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CRADA INFORMATION
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Availability of This Report

Argonne National Laboratory
Yoon I. Chang
Phone (630) 252-4856
Fax (630) 252-5161
ychang@anl.gov

Summary Report

Conceptual Design of a Pilot-Scale Pyroprocessing Facility

Project Manager: Yoon Il Chang

Major Contributors

Argonne National Laboratory
Robert W. Benedict, Matthew D. Bucknor, Javier Figueroa,
Joseph E. Herceg, Terry R. Johnson, Eugene R. Koehl,
Richard M. Lell, Young Soo Park, Chad Pope,
Stanley G. Wiedmeyer, Mark A. Williamson, James L. Willit,

Merrick and Company
Reid James, Steve Meyers, Bryan Spaulding, John Underdahl, Mike Wolf

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Foreword

The Landmark Foundation would like to express its appreciation to Argonne National Laboratory (Argonne) and Merrick & Company for their excellent work in producing the conceptual design and cost study of a pilot-scale pyroprocessing facility for spent nuclear fuel. As the private financial sponsor of this work under a Cooperative Research and Development Agreement with Argonne, the Landmark Foundation believes that the study is a very positive step forward towards developing such a pilot-scale facility and demonstrating the economic viability of pyroprocessing.

At present, the United States should and must rely on the current generation of commercial nuclear reactors and the “once-through” fuel cycle (in which spent nuclear fuel is stored for ultimate, permanent disposal and is not beneficially re-used). Pyroprocessing of spent nuclear fuel, followed by the later deployment of integral fast reactors (IFRs) that could use the pyroprocessing output as new fuel, is indeed a “next-generation” concept, but one that holds the promise of significant benefits. This would support a “closed” fuel cycle, in which spent fuel *is* recycled and reused to generate more electricity. A closed fuel cycle is a goal the U.S. should strive for.

In addition to the Argonne effort, the Landmark Foundation also funded a study of this closed fuel cycle concept by Energy Resources International (ERI). That study found that the potential benefits of pyroprocessing and IFRs include: 1) avoiding the cost of a second geologic repository for spent fuel by significantly reducing the total volume of radioactive waste requiring disposal (and thus freeing tens of billions of dollars of capital to fund a closed fuel cycle); 2) reducing the radiotoxicity and heat load of the waste form to be disposed of in a repository (thereby simplifying the design and construction, and reducing the cost, of a single repository; and 3) conserving uranium resources. Even before a next generation fuel cycle is established, pyroprocessing can be an important alternative spent fuel management strategy for the current generation of reactors. Pyroprocessing the spent nuclear fuel from existing commercial reactors can reduce the effective lifetime of the nuclear waste currently contained in that spent fuel, and the pyroprocessing output includes materials that can be used as new fuel in future IFRs.

A pilot-scale pyroprocessing facility is a worthwhile endeavor that warrants the allocation and expenditure of U.S. Government research and development funds. Developing and operating a 100 ton per year pilot-scale pyroprocessing facility of the type analyzed in depth in the Argonne report would help achieve a new, positive vision for electricity generation, nuclear power, and nuclear waste disposition in the U.S.

The Landmark Foundation

Executive Summary

Argonne National Laboratory (ANL) developed the conceptual design of a pilot-scale (100 T/yr) pyroprocessing facility for used fuel generated by domestic commercial nuclear power plants (i.e., Light Water Reactors). This project was carried out under a Cooperative Research and Development Agreement (CRADA) sponsored by the Landmark Foundation.

The primary purpose was to perform sufficient engineering for the pilot facility conceptual design so that credible capital and operating cost estimates could be developed. Such credible capital and operating cost estimates are crucial in facilitating a decision to proceed with implementing the pilot-scale project. Merrick & 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 made. The ultimate goal is to demonstrate the viability of pyroprocessing as a practical solution to used fuel management.

During Phase I, January 2013 through May 2015, ANL prepared a four-volume Conceptual Design Report to document the work performed under the CRADA. That Report, however, is not available for general distribution to the public because it contains protected/restricted information. This summary report provides, for public dissemination, an overview of the conceptual design and the cost and schedule estimates.

Upon completion of the Conceptual Design Report, the Landmark Foundation decided to extend its sponsorship of the CRADA into Phase II, January 2016 through March 2018. The Phase II efforts were focused on safety, safeguards, and security assessments, along with further design improvements and cost updates. The results of Phase II efforts are also summarized in this update.

Capital cost estimates were developed in 2015 dollars, using “overnight cost” with no escalations. Contingency factors between 10% and 25% were added, depending upon the specific facility (*e.g.*, Fuel Processing Facility, Waste Storage Facility, etc.), or the process equipment and support systems involved. Costs for licensing support were included. Land acquisition costs were not included.

The Project Total Capital Cost for the pilot-scale facility is updated in Phase II at $334 million without contingency. With contingency factors added, the total capital cost is estimated at $399 million. The pilot facility could continue to be used to recycle spent nuclear fuel at a capacity of 100 T/yr after the demonstration is complete.

Annual operating costs were also estimated considering staffing, materials and services, process chemicals needed, spare parts, waste containers and utilities. The total estimated operating cost is $53 million per year, which was also updated in Phase II.

A project overview schedule, from licensing through construction of the pilot-scale facility, is estimated to take about seven years.

In Phase II, we also evaluated how the Pilot-Scale (100 T/yr) can be scaled up to a Commercial Prototype-Scale (400 T/yr). A potential approach for the Processing Facility layout was developed and a rough cost estimate was made. For the 400 T/yr Prototype Facility, the total capital cost is estimated at $911 million with contingencies, and the annual operating cost at $90 million/yr.

1 Introduction

1.1 Purpose

Argonne National Laboratory (ANL or Argonne) and the Landmark Foundation, headquartered in Norfolk, VA, entered into a Cooperative Research and Development Agreement (CRADA) [1] to develop the conceptual design of a pilot-scale (100 T/yr) pyroprocessing facility for treating domestic Light Water Reactor (LWR) used 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.

Such credible capital and operating cost and schedule estimates are crucial in facilitating a decision to proceed with implementing the pilot-scale project. Merrick & 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 made.

The ultimate goal is to demonstrate the viability of pyroprocessing as a practical solution to used fuel management.

1.2 Historical Background

The conceptual design under this CRADA project was based on work previously performed at Argonne for refurbishment of the EBR-II FCF using pyroprocessing equipment systems as well as on previous efforts in pre-conceptual design for pyroprocessing of LWR used fuel. Furthermore, more recent technical progress from the Fuel Cycle Technology programs of the Department of Energy (DOE) has been incorporated as well.

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. [2] However, melt-refining could not remove noble metal fission products and separate higher actinides from uranium. When the Integral Fast Reactor (IFR) Program [3] 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 Fuel Cycle Facility was refurbished using the new electrorefining-based equipment to demonstrate pyroprocessing at the engineering-scale.

Since the IFR Program and EBR-II ended in 1994, the refurbished FCF was utilized to treat the EBR-II used fuel for disposal purposes. The FCF has been in operation since 1996 treating the EBR-II used fuel. Hence, the application of pyroprocessing for metal-fueled fast reactor fuel has successfully been demonstrated at the engineering scale.

For the LWR used fuel application, two additional improvements were needed. First, a front-end step of oxide-to-metal conversion was required in order to use the metal fuel electrorefining process. In addition, scale-up of unit operations was required. For fast reactor application, a small batch size is a needed due to criticality safety considerations. For LWR used fuel application, the fissile content is about an order of magnitude smaller and, hence, a scale-up in throughput rate is achievable.

Although pyroprocessing was originally developed for recycling fast reactor used fuel, Japanese utilities were interested in the feasibility for LWR used fuel and provided the necessary funding for that research, and Argonne carried out research on the oxide-to-metal reduction processes. Initial efforts were focused on the lithium reduction step, which was determined not to be effective. In later years, electrolytic reduction has proven most effective. On the scale-up potential, parallel rectangular plate electrodes have been developed successfully.

1.3 Facility Design Approach

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 facility complex includes the necessary separation processes, waste processes, and interim storage to provide a complete technology demonstration from used fuel to useful fuel products and final waste forms.

The conceptual design is based on ANL'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) [4], which has operated successfully for almost 40 years without manned entry into its large inert hot cell. Any changes in the design of hot cell features proposed during the conceptual design process provide benefits (e.g., cost savings, improved remote operations) without reducing reliability.

Recent research and development progress has been incorporated into the overall process approach, and the process and waste equipment designs. The facility complex includes facilities and systems to support start-up and routine operations, including the necessary safety and security features, maintenance capabilities, interim waste storage facilities, shipping/receiving areas and general support capabilities (e.g., analytical laboratory, equipment repair, offices and utilities).

The pyroprocessing complex includes hot cell facilities that provide radiation shielding, radioactive material containment, and in some cases, a dry inert atmosphere for the separations processes and analytical laboratory sample preparation. The hot cell facilities include a spent fuel preparation/storage cell, a fuel processing cell, a waste treatment cell, a gas treatment cell, analytical sample handling cells, an equipment decontamination cell, and a radioactively contaminated (i.e., hot) equipment repair area. These facilities are arranged to facilitate transfer of equipment and materials between them, while allowing monitoring of these transfers to assure materials are adequately safeguarded against diversion. Ancillary systems for process and facility operations are included to provide a complete functional complex.

1.4 Safety and Security Approach

Both DOE and Nuclear Regulatory Commission (NRC) requirements were used to provide a basis for safety, safeguards, and security. Applicable requirements for nuclear fuel fabrication facilities, radioactive material handling facilities, nuclear material storage facilities, radiological control practices, and many other specific topics have been reviewed to provide guidance regarding NRC licensing considerations, as well as potential development by DOE at a DOE owned and controlled site. Over about the last ten years, considerable analyses have been performed on the suitability of existing NRC licensing requirements for application to a reprocessing facility (including pyroprocessing). No set of existing NRC regulations is considered to be fully adequate for licensing such a facility. Additional work will be needed to establish a clear and predictable NRC licensing regime for a pyroprocessing facility. (Siting and development of such a facility by DOE likely would be subject to DOE requirements.)

The facility safety approach is based on a risk informed approach where consequences to the worker and public are the basis for classifying different systems. Hot cell systems, structures and components are classified into three categories by their safety and operational importance: items relied on for safety (e.g., cell confinement, cell shielding), controlled system (e.g., overhead handling system), or industrial grade (e.g., cell lighting). The safety approach maximizes passive systems to help control both initial and operating costs while providing a high quality product.

Safeguards are based on “defense-in-depth” for physical protection of Special Nuclear Material (SNM). At least three physical barriers (walls, fences, sealed containers, etc.) are used between the general public and the SNM. Personnel movements are restricted using security zones with monitored access control points. These security zones are secure areas, protected areas (PA), isolation zones, material access areas (MAA), and vital areas (VA). The hot cells and supporting area with items relied on for safety are considered vital areas. The vital areas are assigned Safeguards Categories using a graded approach based on quantity of SNM and attractiveness.

1.5 Operations Strategy

Facility and process systems are designed to meet operating times that can be expected for nuclear facilities. Process equipment is sized for 255 days of process operations (including loading and unloading of batch processes) and 52 days is allocated for equipment maintenance and repairs [approximately 83% availability]. Nuclear materials control and accounting activities use 30 days for specific inventory and item verification. During this period, no material movement is allowed, so process operation and repairs are not allowed. The facility systems are designed so any specific testing (e.g., stack monitor calibration, emergency power testing) and maintenance (e.g., ventilation system maintenance) occur during 28 days or two weeks, twice a year. As systems are designed, the appropriate numbers of spare and redundant equipment will be considered to meet these objectives.

1.6 Reference Process Flowsheet

The process flowsheet designed for the treatment of LWR used nuclear fuel is shown in Figure 1. The treatment process can be divided into five functional areas - fuel preparation, oxide-to-metal conversion, actinide and fission product separations, material recycle, and waste treatment. Actinide products resulting from the process, uranium and uranium-transuranic alloy, are colored light blue in the flowsheet, and waste products such as cladding are colored yellow. The flow of material between each of the unit operations is color coded (Figure 1 legend) according to the type of material transferred. For example, solid material transferred from the fuel preparation process to the electrolytic reduction operation is indicated by a dark blue line, while salt transfers between operations such as the actinide drawdown and rare earth drawdown processes are identified by a red line. A summary of the material flow through the system follows.

The head-end of the flowsheet consists of the fuel preparation process. In this process, the fuel assembly is taken apart by the disassembler so the individual pins can be separated from the guide tubes and assembly hardware. Once the individual pins have been removed from the assembly, the end caps are mechanically sheared from each of the pins, the cladding is removed from each pin by a slitter, and the oxide fuel meat is collected in a transport container. This container is transferred into the process cell so the oxide fuel can be loaded into basket modules for treatment by the electrolytic reducer. Cladding is disposed of as high-level waste. Guide tubes and other assembly hardware are disposed of as low-level waste. Fission gases released during the cladding removal process account for less than one percent of the total amount of fission gas in the used fuel, thus they are released into the fuel preparation cell atmosphere and vented from the facility.

Electrolytic reduction converts the fuel oxides into metals for treatment in the electrorefining process. The oxide fuel, contained in the basket modules, serves as the cathode of the electrolytic cell where the oxide-to-metal conversion occurs. Oxide ions released from the fuel during the conversion process are transported in the molten salt electrolyte (i.e., lithium chloride with one weight percent lithium oxide maintained at 650°C) to the carbon anode where they react to produce a mixture of CO and CO_2 gas, that is then sent to off-gas treatment. Active metal (e.g., Cs, Sr, Rb, Ba), halide (e.g., I) and chalcogenide (e.g., Se, Te) fission products partition to the salt phase during the process. The bulk of the fission product gases (e.g., Xe, Kr) in the oxide fuel are released from the fuel matrix during the electrolytic reduction process and sent to the off-gas treatment system along with the CO and CO_2 gas stream. The basket module that now contains the metal product is transferred to the electrorefining process.

The electrorefiner separates a purified uranium product and a co-deposited uranium-transuranic (U/TRU) product from the fission products contained in the used fuel. The metal product contained in the basket module functions as the anode. As electric current is passed between the anode(s) and cathode(s) of the system, actinides are anodically dissolved into the molten salt, transported through the electrolyte, which is comprised of lithium chloride plus actinide and fission product chlorides at 650°C, and deposited onto two types of cathodes that differ in design and electric potential. One set of cathodes is for uranium deposition, and the other set of cathodes is for the co-deposition of a U/TRU product.

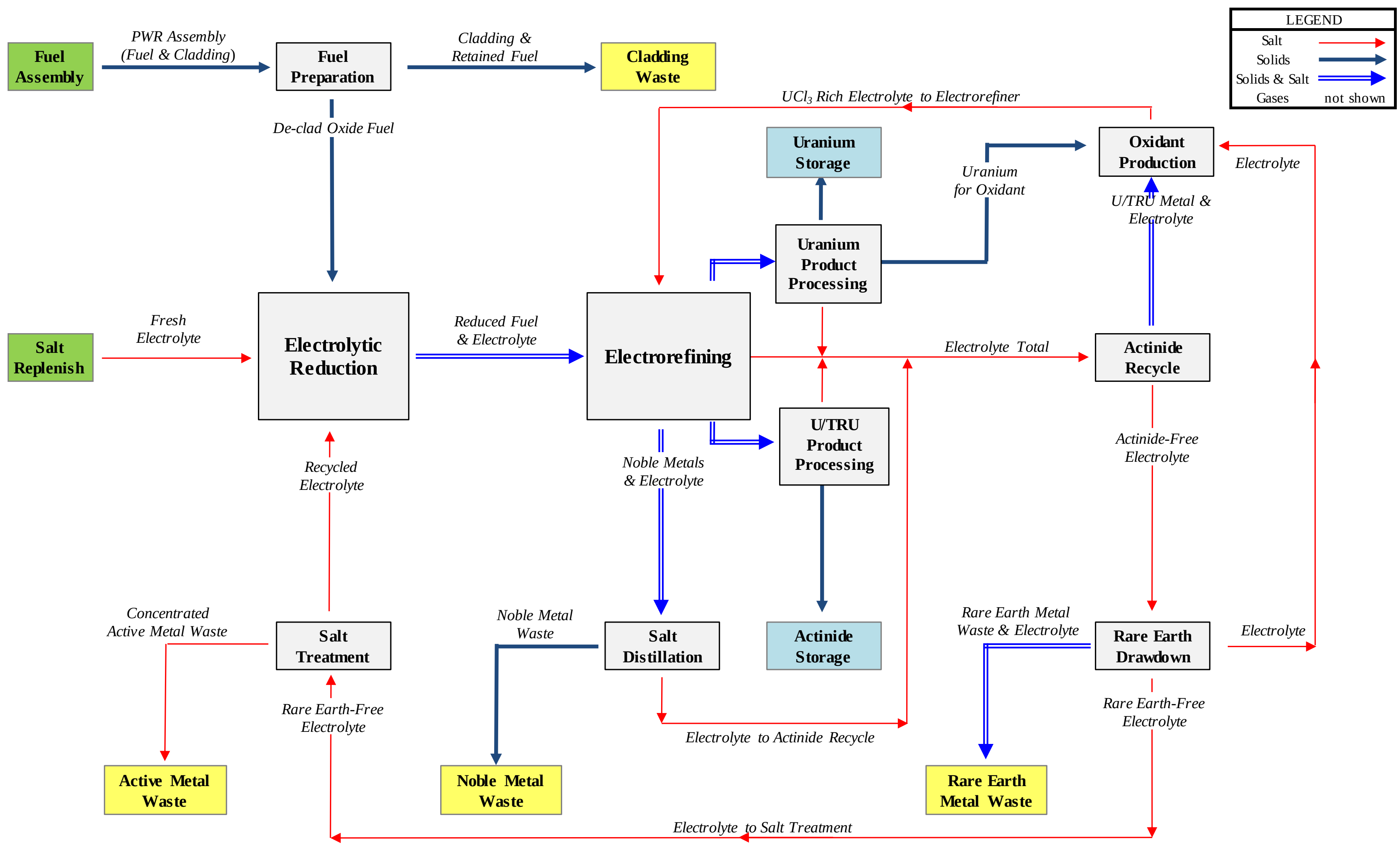

Figure 1 Pyrochemical Process Flowsheet for LWR Used Fuel Treatment

Rare earth (e.g., Gd, Nd, La) fission products partition to the salt phase during the refining process, do not deposit on the uranium or U/TRU cathodes, and are recovered in subsequent operations. Active metal (e.g., Cs, Sr, Rb, Ba), halide (e.g., I) and chalcogenide (e.g., Se, Te) fission products that enter the electrorefining process in the salt adhering to the basket module from the electrolytic reduction process remain in the salt phase during the process. Noble metals (e.g., Zr, Tc, Mo) that remain in the basket module after electrorefining are recovered and treated in a subsequent salt distillation operation that also reclaims any adhering electrolyte salt, which is treated and recycled. The noble metals are converted to an engineered waste form comprised of the noble metals, iron and zirconium.

The U and U/TRU products from the electrorefiner are transferred to their respective product processing operations to recover the adhering electrolyte salt and create consolidated U or U/TRU ingots for storage or fast reactor fuel fabrication. In the case of uranium product processing, the salt is removed via vaporization prior to consolidation of the metal into an ingot. Salt removal from the lower-melting U/TRU alloy is accomplished by melting the product, allowing the metal and salt phases to separate due to the large density difference between the salt and metal (approximately 1.75 g/cm^3 vs. 18 g/cm^3, respectively), and then casting the liquid U/TRU metal into an ingot.

Salt recovered from the U and U/TRU electrorefiner products and the salt distillation operation is treated in the actinide drawdown operation (i.e., electrolysis process) to recycle the residual actinides to the electrorefiner via the oxidant production process. After the actinide drawdown operation, the actinide-free salt is treated in a follow-on drawdown operation (i.e., electrolysis process) to remove the rare earths, except for samarium and europium that remain in the salt as divalent chlorides. The salt then moves forward to the salt treatment process in which the active metal and divalent rare earth (i.e., Sm and Eu) fission products are concentrated in a waste salt.

The process also yields an electrolyte salt that can be recycled to the electrolytic reduction or electrorefining operation. The drawdown operations ensure that the concentration of fission products in the overall fuel treatment system remains low enough to allow recovery of uranium and transuranics at the desired quality, to maximize recycle of process salt, and to minimize loss of TRUs to the waste streams. Ultimately, the waste salt containing the active metal and divalent rare earth fission products is combined with the rare earth metal waste collected in the drawdown process to produce an engineered ceramic waste form.

After the drawdown processes, a fraction of the electrolyte salt is not transferred to the salt treatment process. This salt is used in the oxidant production operation to generate the electrotransport species required for electrorefining (e.g., UCl_3) by chlorinating the uranium and TRU elements recovered during the actinide drawdown process. A quantity of additional uranium metal, transferred from uranium product processing, is chlorinated in the process as required to maintain the desired concentration of actinide chlorides in the electrorefiner salt.

The output from the processing facility consists of uranium and U/TRU ingots in storage for future fast reactor use, cladding waste, hardware waste, noble metal waste, ceramic waste, and off-gas waste. The bulk of the molten salt used in the process is recycled to minimize waste production. Additional lithium chloride can be added as needed to the oxidant salt that is returned to the electrorefiner or to the salt that is recycled to the electrolytic reduction operation to maintain the salt balance in the system. Impurity build-up in the operations is monitored and controlled, through the salt recycle process, to the levels required to meet fuel and waste specifications.

1.7 Hot Cell Design Requirements

- Operations and maintenance in the hot cells use remotely-controlled equipment, which dictates that all active components or modules are remotely repairable in place, remotely removable for repair at a dedicated repair station, remotely removable for remote decontamination followed by hands on repair, or remotely replaceable. This requirement applies to both process and hot cell systems, including remotely operated handling systems (e.g., overhead cranes, robotic cranes and electromechanical manipulators).
- The facilities and hot cells maintain their structural integrity and gas tightness during the design basis seismic event, wind loadings, snow loads and design basis aircraft crash.
- The hot cell interiors are lined with 1/8 inch stainless steel to help with surface decontamination, contamination control and final decommissioning.
- The Fuel Processing Cell structure, penetrations, piping and connected ducting provide the confinement boundary and maintain their structural integrity and gas tightness during the design basis seismic event, wind loadings, and snow loads to prevent the ingress of oxygen and water. Integrated material handling systems move materials between process steps or to storage areas. Use of shielded windows and teleoperated (aka master/slave) manipulators for routine process operations is highly discouraged.
- Process and in-cell support equipment are designed to be installed and maintained by transfers through an equipment transfer lock that maintains the atmosphere purity, shields radiation and controls the spread of radioactive contamination.
- Equipment that is too large to be installed through the equipment transfer locks (e.g. crane bridges, electrorefiner vessel, and electrolytic reducer vessel) are designed for a 40 year life with components replaceable and/or repairable remotely. This equipment is inserted through a special hatch that is seal welded shut before the inert atmosphere is established for operations.
- Passive components of the hot cells are designed to last for 40 years.
- Overhead crane and manipulator bridges, trolleys, and carriages are freewheeling when power is removed from the drive motors to allow moving this equipment by other means to a location where repairs may be more readily accomplished.
- A repair hoist on the roof is provided to remove overhead crane trolleys, bridge drive motors, and electromechanical manipulator carriages from their bridges and lower them to the floor for repair or transfer out of the cell. The hoist is also capable of lifting any overhead bridge off its rails, turning it, and lowering it to the floor for repair or maintenance.
- Shielding windows and teleoperated manipulators are used at an in-cell repair station or specific remote processing stations that require non-routine activities to be performed.
- The hot cell ventilation systems provide pressure and temperature controls during normal operation that maintain the cell pressure below the pressure in adjacent occupied areas and discharge excess cell gas through a HEPA filtered exhaust system. Any recirculation duct work is protected from radioactive contamination with inlet HEPA filters.

1.8 Process Equipment General Design Requirements

- Built modularly as much as practicable with the ability to use the facility transfer locks for systems, modules and/or components;
- Built for remote assembly and disassembly using the remote handling equipment in the cell;
- Operated through the use of programmable logic controllers (PLC) and computer control of built-in mechanisms or stand-alone robots;
- Use no cutting or grinding operations that could cause ignition of the zircaloy used in the assemblies in the cell's air atmosphere;
- Provide instrumentation and control systems that interface with a mass tracking computer and a computer that logs significant process parameters and discrete positions of operationally significant components (e.g., module seating, valve position, etc.)
- Minimize the contribution of heat load to the cell atmosphere.
- Designed and fabricated to comply with appropriate design guides:
    - High temperature process boundaries: to the intent of ASME Boiler and Pressure Vessel Code Section VIII, “Unfired Pressure Vessels”; and
    - Support structures: AISC Specification for Structural Steel for Buildings—Allowable Stress Design and Plastic Design;
- Maintain external surfaces exposed to cell atmosphere below 150°C and minimize transfer of heat to the structural concrete floor beyond limits established by American Concrete Institute standard ACI 349-01;
- Use of externally-pressurized gases in the cells requires flow limiters and automatic shutoff systems;
- Process equipment is restrained using seismic anchors that are designed to be engaged and released remotely, or process equipment will be designed to not need restraint for either tipping or sliding;
- Electrical equipment in inert atmosphere hot cells is designed to operate in a dry inert atmosphere and have radiation resistant, high dielectric insulation;
- Each process area is equipped with shielded feed-throughs that penetrate the cell wall or floor. Normal power, emergency power, process monitoring instrumentation and other utilities are provided as necessary to operate the process from a control room;
- Due to the low-voltage breakdown characteristics of argon, larger-than-normal connectors and spacing of conductors are used in the Fuel Processing Cell. Experience in existing facilities and tests indicate that the standard Type MS connectors per SAE-AS50151 can be used if de-rated;
- Radiation resistant wiring is used in-cell and is remotely replaceable. If radiation-resistant wiring is not available for an electrical component, then the wiring is easily replaceable;
- Material handling systems incorporate remote viewing and lighting systems for operation from a control room. Unique identification and remote viewing of process vessels and storage containers in hot cells provide items surveillance and inventories as prescribed by Safeguards Requirements;
- Back-up remote handling equipment minimizes single failures that can result in shutdown of the cell and vault operations.

1.9 Atmospheres

The process operations in each cell require different atmosphere purity and controls as follows:

- The hot cell ventilation systems provide pressure and temperature controls during normal operation that maintain the cell pressure below the pressure in adjacent occupied areas and discharge excess cell gas through a HEPA filtered exhaust system. Any recirculation duct work is protected from radioactive contamination with inlet HEPA filters.
- The hot cells operate at pressures lower than any adjacent occupied space and ambient cell temperatures are controlled to less than 100^{o}F.
- Gas ventilation systems maintain atmospheres as follows:
    - Fuel Preparation/Storage Cell: Air with H_2O < 500 ppm
    - Fuel Processing Cell: Argon with O_2 = 60 ± 40 ppm; H_2O = 60 ± 40 ppm; N_2 = 100 ± 80 ppm; and CO & CO_2 = 100 ppm
    - Waste Processing Cell: Air with H_2O < 250 ppm
    - Gas Treatment Cell: Air
    - Analytical Hot Cells: Argon with O_2 = 60 ± 40 ppm; H_2O = 60 ± 40 ppm
- The inert atmosphere cells have a pressure-temperature control system capable of maintaining the differential pressure relative to the adjacent occupied area between -1 and -4 inches water gauge and the temperature between 70 and 100°F while removing the heat from operations due to decay heat, process vessel heaters, lighting, etc.

2 Site Plan

The overall site plan is presented in Figure 2. The site covers about 52 acres, and the facilities and buildings are located inside the Secure Area but a few are located in the inner Protected Area as listed below. Originally, the Protected Area Receiving Building and Waste Storage Building were inside the Protected Area but a detailed security assessment recommended placing these buildings outside the Protected Area. The goal was to minimize the Protected Area to minimize the security cost.

- Facilities and Buildings inside the Protected Area
    - Fuel Processing Facility
    - Generator Building
- Facilities and Buildings outside the Protected Area
    - Protected Area Receiving Building
    - Waste Storage Facility
    - Laboratory and Operations Building
    - Maintenance and Mockup Building
    - Utility Building
    - Warehouse and Staging Building
    - Fire Station
    - Utility Electrical Substation
- Offsite Location (not shown in the Site Map)
    - Emergency Operations Center

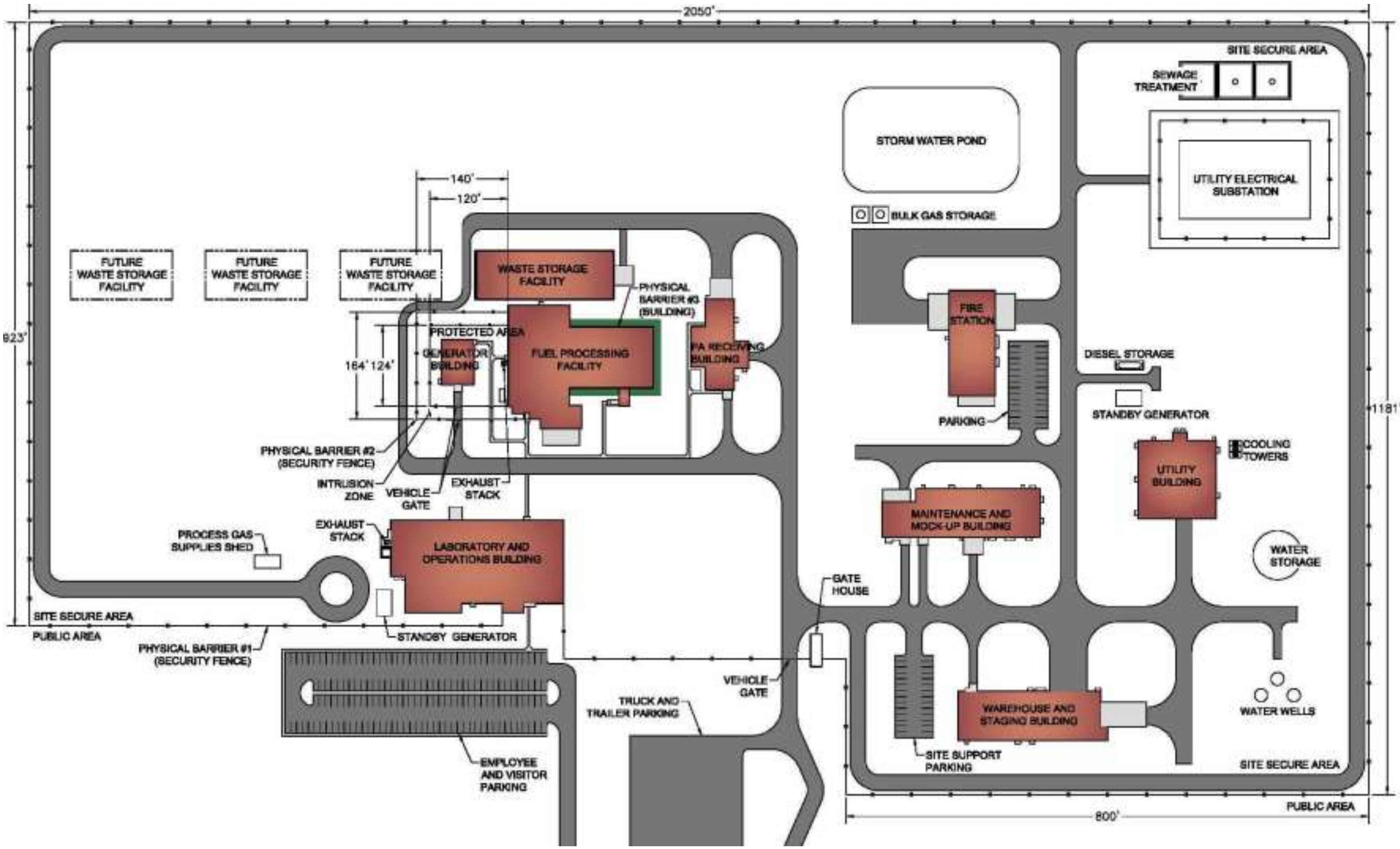

Figure 2 Site Plan

3 Fuel Processing Facility and Storage Facilities

The Processing Facility (Figure 3) 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 ANL'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.

Figure 3 Processing Facility

3.1 Protected Area Receiving Building

The Protected Area Receiving Building is a combination of a conventional metal building and a concrete building. One area is used to receive spent nuclear fuel, and another is used to receive clean materials for use in the Processing Facility.

The Protected Area Receiving Building is manned, supports 24-hour operations, and includes a personnel badge reader system. Protected walkway entrances are located on the west side of the building with access doors located on both the north and south sides.

The Protected Area Receiving Building shown in Figure 4 has three areas: the fuel receiving area, the equipment and clean material receiving area, and the security personnel and access control area.

Figure 4 Protected Area Receiving Building (Roof Removed)

3.2 Process Hot Cells

Four large hot cells in the Processing Facility (Figure 5) provide the necessary shielding, contamination control, and atmospheres for the process operations and necessary process storage locations. Figure 6 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.

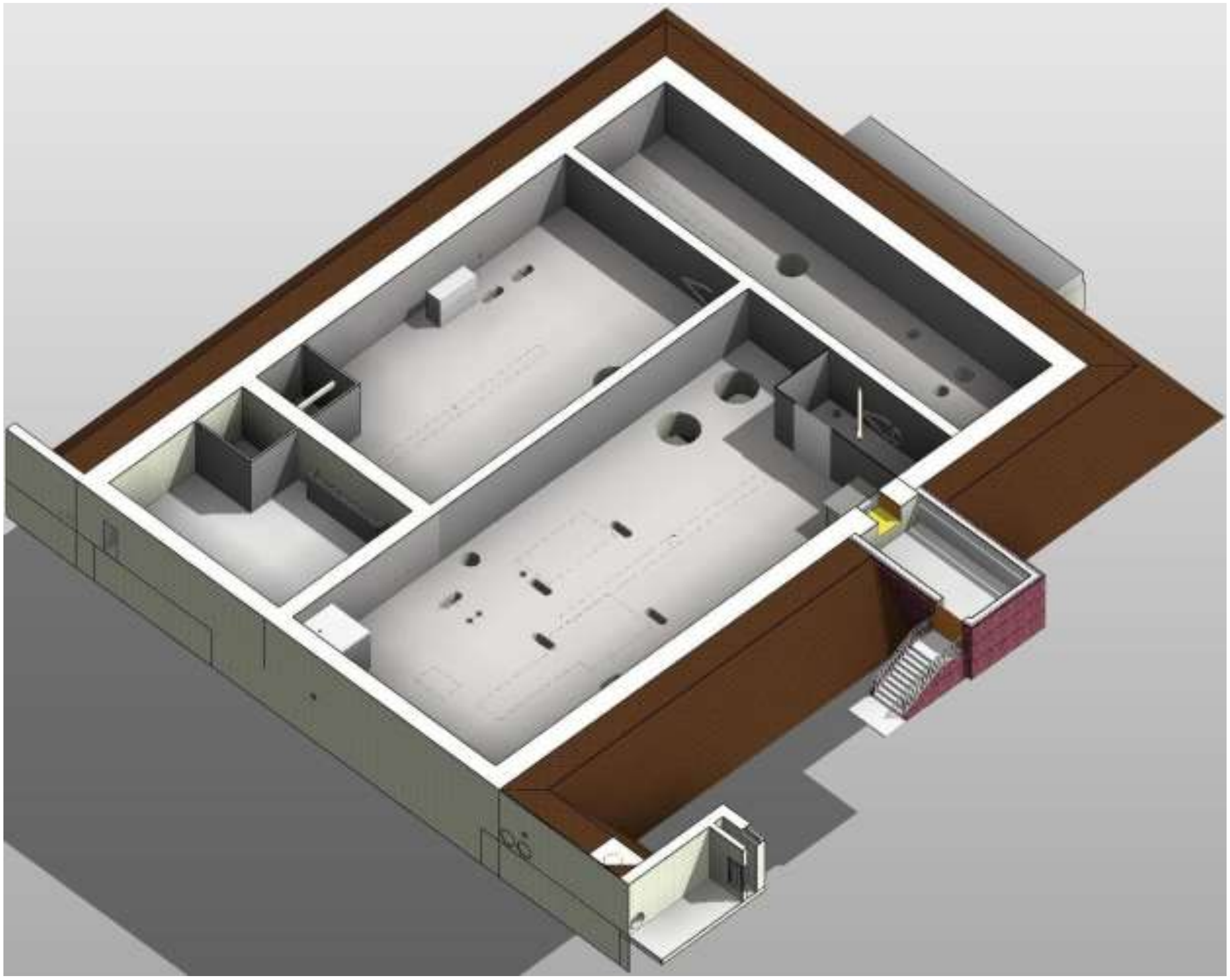

Figure 5 Processing Facility Operating Floor

Fuel Preparation/Storage Cell

The Fuel Preparation/Storage Cell is an air-atmosphere cell that receives the reference fuel assembly in a DOT transfer cask. The cell has two large vertical transfer locks, two small horizontal transfer locks, a fuel assembly nondestructive assay station, two fuel rod slitters and an assembly hardware waste crusher. One vertical equipment transfer lock is used to bring in new equipment and and remove equipment for repairs. The other large lock mates with a commercial cask containing up to four fuel assemblies at the hot cell boundary. A plastic transfer sleeve bagging system, which has been successfully used for over 30 years at HFEF, is used to contain radiological contamination so the commercial cask and other parts of the facility can be kept clean.

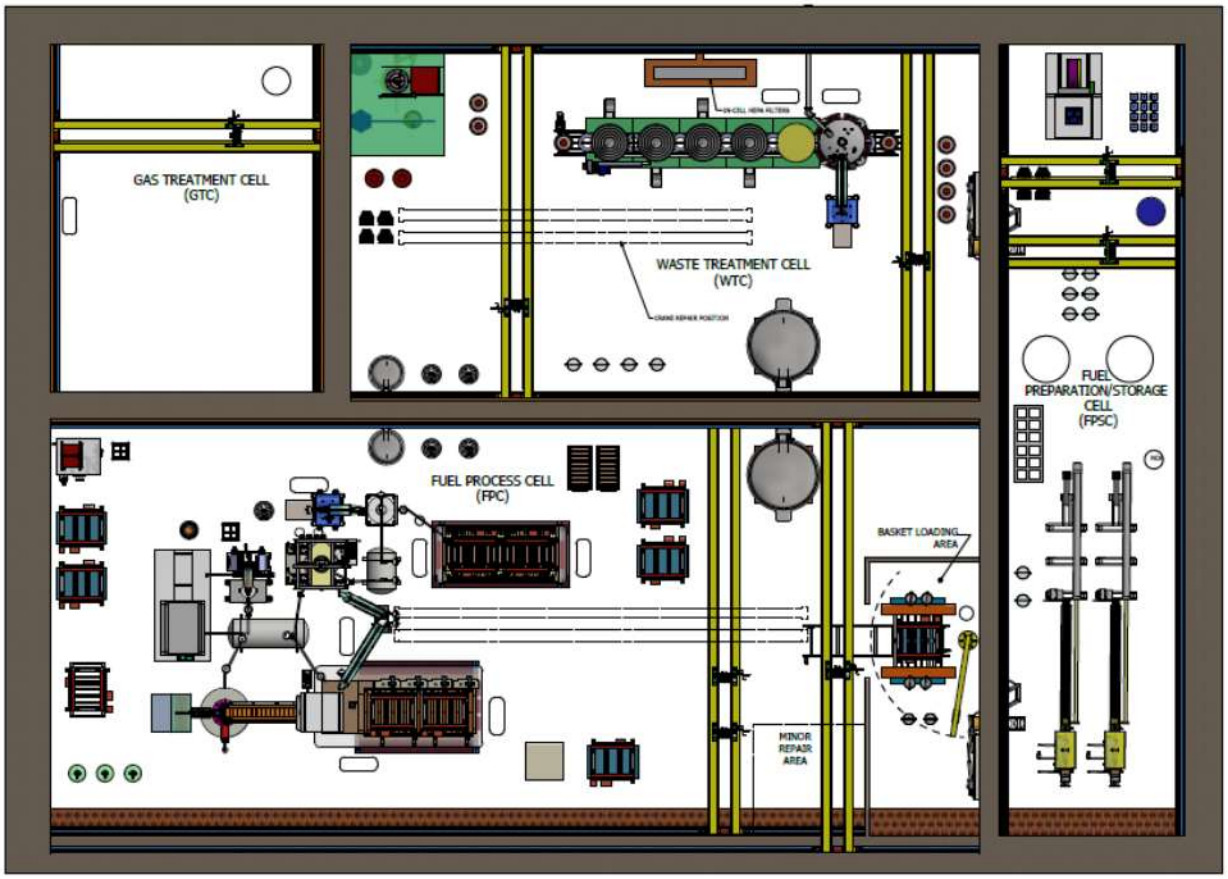

Figure 6 Processing Hot Cells

After the fuel assembly is transferred into the Fuel Preparation/Storage Cell, it is nondestructively assayed to establish a shipper/receiver difference and placed into a storage rack, which is passively cooled. From the storage rack, the fuel assembly is moved to a fuel disassembly machine where the assembly is disassembled, removing the fuel rods from the fuel assembly hardware. The fuel rods are then placed into a module that removes the cladding, and the fuel pellets are collected in fuel transfer containers.

Fuel Processing Cell

The Fuel Processing Cell contains the majority of the pyrochemical separation processes and the appropriate storage areas between process steps to provide sufficient buffer for efficient operations. Process equipment includes the electrolytic reducer, electrorefiner, basket module loader, TRU processor, TRU down-blending furnace, uranium processor, drawdown vessel, noble metal processor, salt crystallization vessel and salt storage tank.

The Fuel Processing Cell also contains three specialty work areas: basket loading area, TRU packaging area, and remote repair area. The basket loading area has a removable secondary confinement enclosure that operates at a lower pressure than the rest of the cell to minimize radioactive dust contamination of other parts of the cell. The TRU packaging area also has a removable secondary confinement enclosure but operates at a positive pressure relative to the main cell so loose contamination on TRU ingot cans is minimized when they are transferred to TRU vault.

A viewing window with two mechanical master-slave operators is provided for small equipment repair and special operations such as preparation of samples to be transferred to the analytical laboratory. The important cell features include an inert atmosphere, an overhead crane, two overhead robotic cranes, space for in-process storage; and five transfer locks. The process cell has an important to safety confinement boundary, transfer lock monitoring to support safeguards and security criteria, and piping that is used to remove inert atmosphere impurities and capture radioactive fission gases (krypton).

The off-gas collection piping collects the radioactive gases that are released as fuel is reduced from an oxide to metal and gases produced by the electrolytic reduction process. The fuel processing cell requires several ancillary systems to maintain atmosphere purity and heat removal from this tightly sealed area.

Waste Treatment Cell

The waste treatment cell contains the process equipment (ceramic waste blender and ceramic waste processor) to convert the radio-nuclides into a stable ceramic waste form for final disposal, plus a waste packaging area and temporary in-process storage spaces. The primary features include an overhead crane, a robotic crane and four transfer locks: a horizontal transfer lock from the fuel preparation/storage cell, a vertical lock and tunnel from the fuel processing cell and decontamination cell, a vertical material transfer lock from the material transfer tunnel and vertical waste transfer lock to the waste transfer tunnel. This hot cell has a pass through air atmosphere and several storage areas for waste cans. These waste cans are inserted into waste canisters that are transferred to the waste storage facility.

Gas Treatment Cell

The gas treatment cell receives gases directly from the electrolytic reduction vessel and a side stream of the argon gas recirculation loop that maintains the Fuel Processing Cell atmosphere. These gases go through a system that converts oxygen to water and carbon monoxide to carbon dioxide. After removing the water and carbon dioxide in molecular sieves, the gas stream is sent to the cryogenic system that first removes argon, xenon and krypton. The argon is recycled back to the fuel process cell while the xenon is vented to the facility exhaust stack. The krypton is concentrated in standard pressurized gas bottles that are packaged in waste canisters and transferred to the waste storage facility. Since the gas treatment cell only handles gases that can be vented or transferred out, equipment maintenance uses special radiological procedures that enable hands on maintenance. The cell walls between the waste treatment cell and the fuel processing cell are 3 feet thick rather than the 2 foot thick interior walls between other hot cells to provide shielding for limited hands-on operations.

Penetrations

Each process hot cell is equipped with transfer locks that allow for transferring equipment, containers, chemicals and other process needs while maintaining atmosphere purity, contamination control and shielding. Normal power, emergency power, process monitoring instrumentation and other utilities are provided by shielded feed-throughs that penetrate the cell wall or floor. Design requirements for transfer lock and feed-through locations are as follows:

- Systems for transferring materials in, out and between the hot cells provide shielding for and containment of the radioactive materials expected to be handled.
- Penetrations to the containment boundary of hot cells that contain a dry inert atmosphere, including those penetrations used for transferring materials between cells, are designed to minimize the introduction of air and are capable of being replaced while maintaining the cell atmosphere and minimizing contamination of occupied areas.

The decontamination area and hot repair area are two shielded cells that are connected to the main cells by operations and maintenance systems. The decontamination area uses a high pressure wash to lower the radiological sources to support maintenance in either shielded glove boxes or two stations that have lead shielded windows with two mechanical master-slave manipulators.

Operations and Maintenance

Integrated material handling systems move materials and equipment between process steps or to storage areas. These and other in-cell materials handling systems also install process equipment systems into the hot cells, support maintenance operations on process equipment, and transfer equipment from the hot cells to the decontamination and hot repair area. The process related cells are connected to the decontamination cell by shielded, contained and safeguarded equipment transfer systems to allow the movement of process and support equipment to the decontamination cell for decontamination. Use of shielded windows and tele-operated manipulators for routine process operations is highly discouraged.

The various types of in-cell remote handling systems are illustrated in Figure 7.

Operations and maintenance in the hot cells are performed using remotely-controlled equipment, which dictates that active components or modules have to be remotely repairable in place, remotely removable for repair at a dedicated repair station, remotely removable for remote decontamination followed by hands on repair, or remotely replaceable. This requirement applies to both process and hot cell systems, including the remotely-operated handling systems (e.g., overhead cranes and electromechanical manipulators).

Process and in-cell support equipment are installed and maintained by transfers through equipment transfer locks that maintain the atmospheric purity, shield radiation, and control the spread of radioactive contamination. Equipment that is too large to be moved through the equipment transfer locks (e.g., crane bridges and some process vessels) are designed for a 40-year life with components replaceable and/or repairable remotely. This equipment is inserted through a special hatch that is seal-welded shut before the inert atmosphere is established for operations.

Process materials are transferred through smaller ports that incorporate safeguards interrogations systems that verify the composition of declared material that is being transferred.

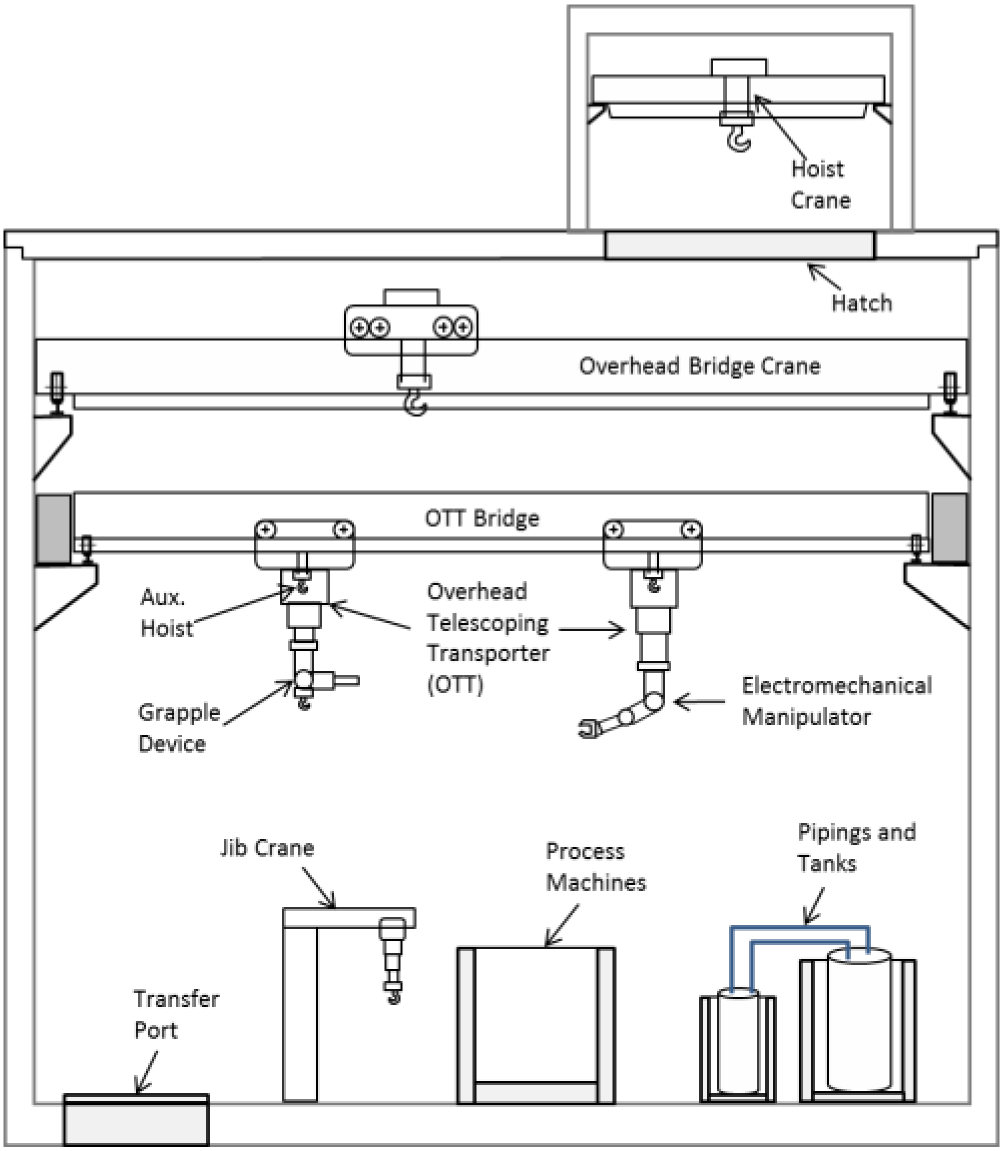

Figure 7 In-cell Remote Handling Systems Configuration

Although the basic overhead handling system design varies for different hot cells, the fuel preparation, fuel processing and waste treatment cells have material handling systems with interchangeable parts and remote maintainability. These overhead handling systems have modular design like the process equipment to enable remote maintenance. Also, these overhead crane and manipulator bridges, trolleys, and carriages are freewheeling when power is removed from the drive motors to allow moving this equipment by other means to locations where repairs may be more readily accomplished.

Monitoring and Control System

The Process Facility has a central control room that is used to monitor and control process equipment in the hot cells, facility systems, and material handling equipment. A distributed control system is used so data from different systems can be shared where necessary. The overall system can be divided into seven areas: operation and control of remotely operated processes, material tracking, in-cell material handling and robotics control systems, the facility monitoring, facility support system monitoring and control, out-of-cell material handling monitoring and control systems, and security systems. These seven systems are integrated and consist of plant operation computers, programmable logic controllers, user interfaces; and control and operational logic software.

The remotely-operated processes are groups of processes that are located inside the hot cells which have typical process monitoring and controls that need to be closely integrated and interlocked with the in-cell material handling and robotics control system. These two systems are closely tied to the material tracking systems that keep an ongoing special nuclear material inventory, item inventory and records data from nondestructive analysis devices. These three systems operate primarily with inputs and outputs from equipment and processes in the four major cells. The facility monitoring system collects data primarily from the Processing Facility but also collects data from important supporting systems around the site. The other facility support systems primarily provide the necessary functions for the monitoring and control of ventilation systems and cooling systems that keep the hot cells within operating parameters. The security system has primarily responsibility to provide information to the security organization and monitors and controls access throughout the whole complex.

Although the major systems provide monitoring and control to specific areas, redundancy, local controllers, signal isolation and data sharing are integrated to ensure one set of systems does not adversely impact the other system operations.

Analytical Laboratory

In support of process operations, an analytical chemistry laboratory is located in the Laboratory and Operations building. In the laboratory portion of this building, six small hot cells are connected by a pneumatic transport system to the Processing Facility so radioactive samples can be directly received from the processes. These hot cells have an argon atmosphere. Nitrogen control is not necessary in these cells since the chemistry is done at lower temperatures and nitride formation is not an issue. After receipt, the samples are typically dissolved and diluted so that small samples can be analyzed in one of the six adjacent laboratories.

3.3 Storage Facilities

The Pilot-Scale Pyroprocessing Facility provides adequate storage for the uranium and transuranic products, metal and ceramic high level wastes, radioactive krypton gas, assembly hardware wastes, and routine low level wastes. These items are stored in the TRU Vault, Waste Storage Facility, and Warehouse and Staging Building depending on their security, shielding and operational requirements.

TRU Vault

The metal transuranic ingot products have a high security attractiveness level and require reliable heat removal for long term storage. These products are stored in a special vault that is located in the lower level of the Processing Facility with a direct transfer lock from the Fuel Processing Cell. For 10 years storage, this vault will hold a minimum of 1865 storage cans. This inventory requires heat removal of 430 kilowatts, shielding for 137 million curies with an unshielded neutron field of 5.46×10^{14} neutrons per second. The cans are lowered through the TRU Transfer Lock to the material transfer room and placed in a storage container for transfer into the vault.

Waste Storage Facility

The Waste Storage Facility stores high level waste streams, assembly hardware waste and radioactive krypton gas. This facility initially will store 10 years of waste production and is designed to accommodate expansion with 3 more modules to hold up to 40 years of waste production. The initial module also provides a transfer path for uranium product and low level waste boxes that will be temporarily stored in the Warehouse and Staging Building for offsite shipment.

The ceramic waste, metal waste, krypton cylinders and assembly waste have shielding, heat removal and security sabotage requirements which have led to a building design that is attached to the Processing Facility by the Waste to Storage Tunnel. The exterior waste canister has been designed to provide an interface similar to the Department of Energy High Level Waste Canister. The waste canisters contain either two inner ceramic waste cans, twelve compacted fuel assembly hardware cans, three noble metal waste cans, or two krypton gas cylinders.

These canisters are transferred to Waste Storage Facility via a transfer tunnel. The facility which is shown in Figure 8 has two main areas: storage area and staging area. The storage area has 644 storage silos which hold 2 canisters each for total storage of 1288 canisters.

Warehouse and Staging Building

The uranium product and low level waste boxes are transferred from the Processing Facility through the Waste Storage Facility to a Warehouse and Staging Building. The uranium is stored in uranium storage cans containing 1950 kg uranium per can. The process produces 47 cans per year. The staging area allows for the storage of ten years uranium product and 32 boxes of low level waste.

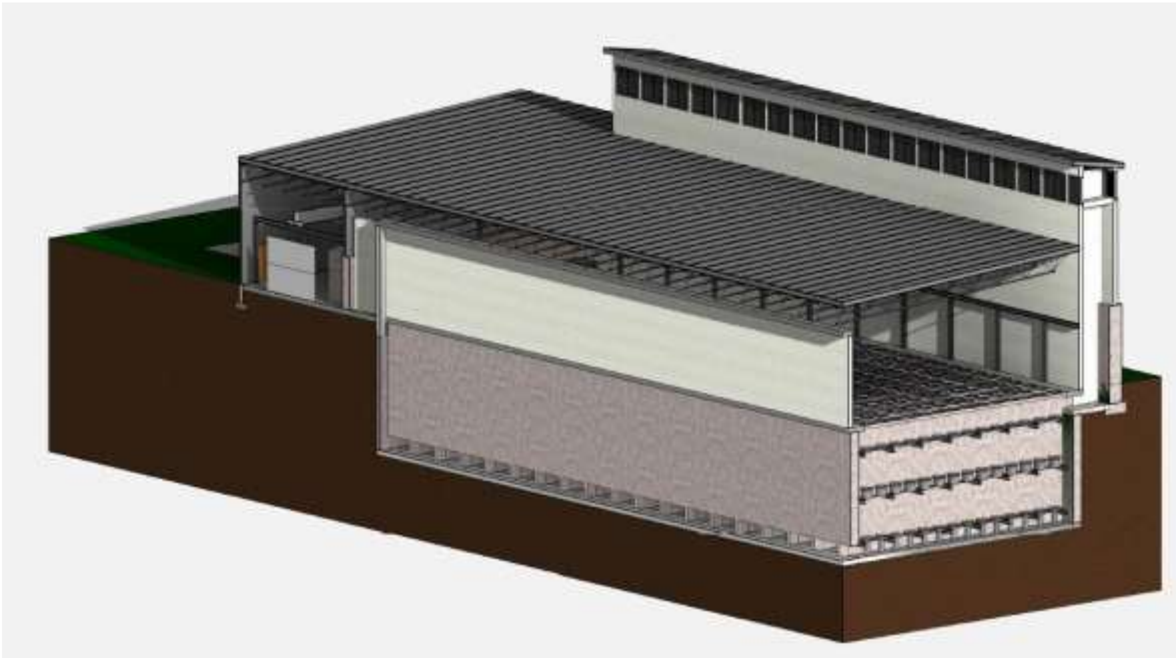

Figure 8 Waste Facility Isometric View

4 Safety Assessment

4.1 Metal Fire in Fuel Processing Cell

The most severe accident scenario in the Fuel Processing Cell is the breach of the cell boundary, leading to loss of inert argon atmosphere and ingress of air causing metal fire. The total mass of potentially pyrophoric material in the FPC at any time is approximately 1,000 - 2,000 kg.

If the atmospheric integrity in the FPC is lost, air will enter. If the oxygen content exceeds the 4% ignition threshold, the pyrophoric materials will begin to oxidize rapidly, releasing heat and radioactive particles into the cell atmosphere. The heat will raise the cell pressure, which may force radioactive particles into the ventilation system or into adjacent areas.

To evaluate the consequences of loss of the FPC atmospheric integrity, computational tools developed to analyze cell breach scenarios at FCF and HFEF were obtained from Idaho National Laboratory. These tools were modified to evaluate the current design of the Fuel Processing Cell.

Various breach sizes were assumed ranging from 0.75 in. to 7 ft. in diameter. During each scenario, it was assumed that power was lost to the equipment and ventilation system. The only method of control over the cell atmospheric temperature and pressure was through the pressure relief system.

If the pressure relief system is assumed not operating, then for all breach size cases, the air flows into the cell, but the cell atmosphere temperature continues to rise due to both decay heat and residual heat sources, which results in a positive relative cell pressure. While the relative cell pressure is positive, cell atmosphere (both argon and air) flow from the Fuel Processing Cell into the adjacent cell through the breach. The air ingress never reaches 4% and hence no metal fire occurs. The maximum cell atmosphere temperature reaches about 140^{o}C.

If the passive pressure relief system remains functional, the cell pressure is maintained at slightly negative allowing air ingress into the cell and the oxygen mole faction reaches a value of 4% in about 125 minutes for the selected breach scenario. At this time, the metal oxygen reaction occurs which rapidly increases the relative cell pressure and the entire metal inventory is consumed in about 30 minutes. At this point, the relative pressure of the Fuel Processing Cell atmosphere rapidly decreases due to the flow of cooler air into the cell through the breach. Shortly after this negative relative pressure spike, the cell temperatures and relative pressure leveling off to a constant value. During the transient the maximum temperatures of the cell atmosphere, steel liner, and concrete wall surface were about 620°C, 250°C, and 60°C respectively. The cell pressure, oxygen content and temperature during the metal fire are plotted in Figures 9 and 10.

Based on the preliminary analyses, we concluded that a safety grade cell exhaust system would be required to minimize unfiltered release to atmosphere.

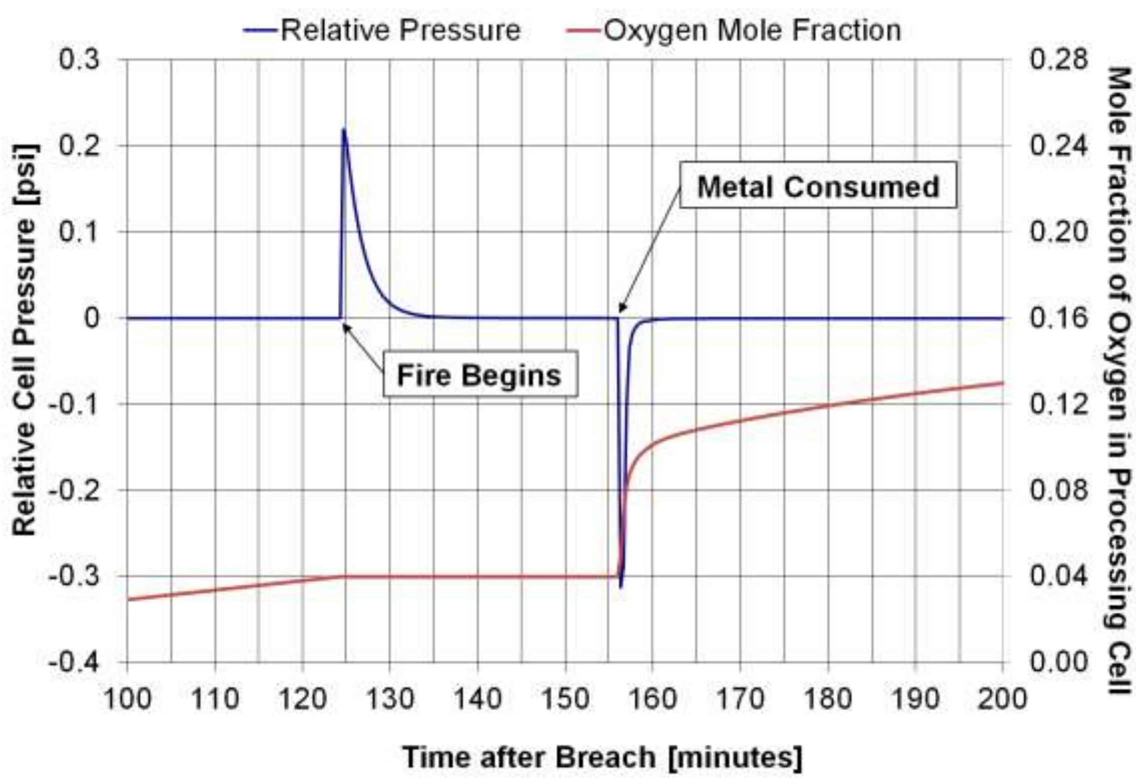

Figure 9 Cell Pressure and Oxygen Content during the Metal Fire

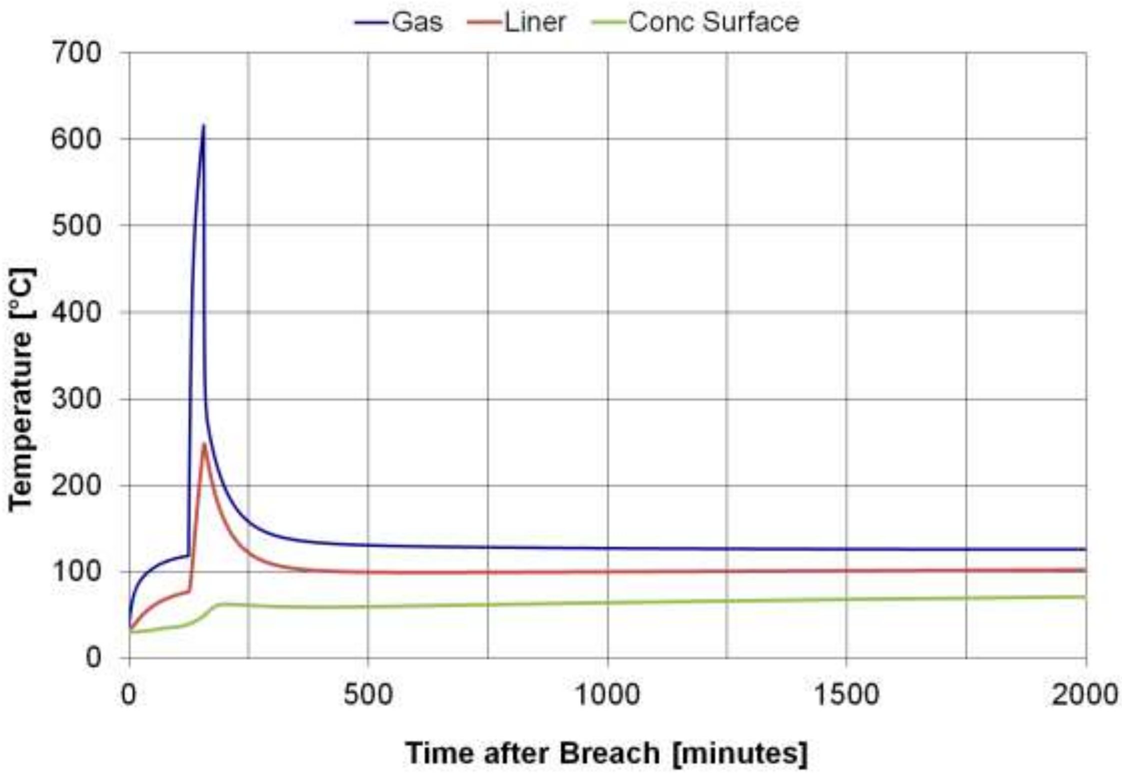

Figure 10 Cell Temperatures during and after the Metal Fire

4.2 Active and Passive Cooling in the TRU Vault

During storage, the TRU ingots generate heat that must be removed in a controlled manner to ensure safe storage conditions. During normal operation, it is assumed that an active cooling system will be used to remove heat generated by the ingots and maintain air temperatures in the 21°C to 38°C range. During certain accident scenarios, it is assumed that the active system is nonfunctional and that the heat generated by the TRU ingots will be passively removed via natural convection and rejected to the environment.

Active cooling of the TRU vault is maintained by a combination of two refrigeration units and three blowers. Each refrigeration unit can handle the entire heat load of the TRU vault, and only two of the three blowers are required to provide the necessary air flow rate. Each blower provides a cooling air flow rate of 31,000 cfm at 13ºC, and each refrigeration unit can remove up to 600 kW of heat load.

The current design of the TRU vault (at the rated capacity of 431.2 kW) contains 1865 storage modules in vertical stacks with each stack made up of 5 storage modules (373 total stacks). Each storage module is assumed to have a heat load of 231 W. At rated flow (62,000 cfm, which assumes two of the three blowers are operating) and assuming the flow is distributed equally to each stack, the velocity of air through a single stack is 3.7 m/s and the outlet air temperature of each stack is 25°C. These values are utilized to perform the heat transfer analysis for the active cooling scenario.

The passive air flow rate through the storage module stacks is calculated by solving the one-dimensional Bernoulli equation. The equation states that the form and friction losses across the storage module stack are equal to the buoyancy (driving) head. It should be noted that additional form and friction losses should be accounted for from the remaining elements in the air flow pathway (chimneys, headers, ductwork, etc.), however, those components have yet to be designed. Instead, in this analysis, it is assumed that 85% of the form and friction losses occur in the storage module stacks.

The goal of the thermal analyses is to determine maximum temperatures of the TRU ingots and TRU ingot storage cans. Currently, it is assumed that the TRU ingots are annular ingots with an outer radius of 3.5 cm, an inner radius of 1.59 cm, and a thickness of 2.5 cm. The storage cans are assumed to be constructed from 316 S.S. tube with outer diameter of 8.89 cm and a wall thickness of 0.549 cm. The storage cans are assumed to be sealed and have an inner argon gas environment. These storage cans are fixed into place inside storage modules, and the storage modules are stacked in the TRU vault where they remain until the TRU ingots are transferred out of the facility. The airflow pathways through the storage modules allow cooling air to pass over the outside wall of the storage cans to remove heat. From the steady-state active and passive flow analyses, the storage module stack air outlet temperatures and the air velocities through the storage module stacks are known for both scenarios.

The results for both the active and passive cooling scenarios are provided in Table 1. As expected, due to the significantly higher cooling air velocity and lower inlet air temperature of the active cooling scenario, the steady-state storage can and ingot temperatures are significantly lower than in the passive cooling scenario (147°C vs. 415°C and 320°C vs. 496°C, respectively). The higher temperature results of the passive cooling scenario are still below thresholds where eutectic formation between the TRU ingot and the storage can become a concern. Both the maximum storage can wall temperature and the maximum TRU ingot temperature are still below thresholds where eutectic formation is a concern. It is important to note, all of the temperature results provided in this section are maximum values calculated at the top of the storage module stack.

Table 1 Steady-State Results for Active and Passive Cooling Analyses

Parameter	Active Cooling	Passive Cooling
Air Inlet Temp	13°C	20°C
Air Outlet Temp	25°C	67°C
Rad. Fraction	0.58	0.76
Conv. Fraction	0.42	0.24
Max Storage Can Temp	147°C	415°C
Ingot Surface Temp	313°C	489°C
Max Ingot Temperature	320°C	496°C

5 Safeguards Assessment

The process flowsheet, equipment, and material accountancy were developed in parallel for the conceptual design so the safeguards assessment focused on the changes and an independent review of the proposed materials control and accountancy approach. The conceptual design flowsheet has improvements from previously developed pyroprocessing flowsheets. These small changes dictate specific safeguards design requirements for individual process equipment that need to be stated for future design phases.

Sandia National Laboratories has been actively involved in developing a pyroprocessing Separation and Safeguards Model as part of the Department of Energy's Materials Protection Accounting and Control Technologies for Fuel Cycle Technologies Program. Sandia modified their existing model to reflect the process steps in the conceptual design flowsheet. This new model was used to test and improve our safeguards strategy.

The safeguards assessment tasks were divided between Argonne and Sandia to efficiently utilize their resources. Sandia scope included the following items:

- Review conceptual safeguards approach.
- Modify Separation and Safeguards Performance Model.
- Examine timing and different measurement uncertainties.
- Recommend measurement methods and material balance frequency.
- Propose alternative approaches.

Argonne integrated known differences between the conceptual process flowsheet and equipment and the information used to develop the original strategy. Also, new information from the safety assessment such as a TRU Down-Blending Furnace was included to provide a current compilation of the materials. Argonne's responsibility included:

- Update inventory and process values.
- Compare hazard matrix versus standard approach.
- Evaluate overall material balance approach.
- Determine process configuration and monitoring.
- Update safeguards description.

Sandia and Argonne personnel discussed specific approaches to ensure the new safeguards model captures our plans. The use of Nondestructive Analysis rather than traditional sampling and destructive analysis is discussed. The current pyroprocessing facility incorporates nondestructive analysis and a full analytical laboratory. The conceptual design safeguards plan recognizes that any technique would have to be shown to give comparable and reliable numbers, especially for formal material balances. Locations, conceptual designs and costs for nondestructive methods are incorporated into the facility design because adequate shielding, facility space and remote operations capability are important to identify early since they are difficult to add in later design and construction phases. The project team recognizes that many improvements are still necessary in nondestructive equipment; however, enough different designs have been proposed for the conceptual layout to provide for both passive and active interrogation equipment. The analytical laboratory was sized to have modern analytical chemistry instrumentation and incorporated lessons learned from operating the existing pyroprocess demonstration at the Idaho National Laboratory. The challenges of input measurements and inventory verification are well recognized.

The “in-process” inventory is dominated by the inventory in the electrorefiner, and different measurement methods and limitations were discussed. For the other pieces of equipment, ways to minimize the special nuclear material inventory are described. Specific equipment configurations for formal material balances and necessary steps to resume processing operations are detailed. One suggestion that is being pursued is to adjust equipment sizes so they hold integer quantities of material. For example, the oxide transport can and basket modules could be modified to hold one entire Pressurized Water Assembly of fuel rather than fractional quantities. Also, the Transuranic Recovery Cathodes could be adjusted so two cups contain the transuranic product from one assembly and possibly one cup would equal one final transuranic ingot. These changes would help resolve any discrepancies that are found during a formal material balance and help to assign any process equipment hold-up to the appropriate piece of equipment.

Sandia National Laboratories summarizes their study with the following abstract:

> “A preliminary material control and accountancy strategy was developed in the original study, which was the focus of the safeguards review. The general approach was reviewed against current regulations. NRC regulations are difficult to compare against since the rules would need to be re-written for reprocessing, but IAEA goals were also considered. An independent safeguards model of the facility was developed as part of this review to determine the ability to meet regulatory requirements. The model was used to determine that a Standard Error of the Inventory Difference (SEID) of 3.2 kg of Pu could be achieved for a monthly material balance if low measurement uncertainties (0.5%) are feasible for the key measurement points. The SEID value calculated here differed quite a bit from those presented in the original Landmark study. This SEID is slightly higher than the IAEA goal of 2.42 kg of Pu, which likely means that additional measures (such as process monitoring) will be required to support international safeguards. Examples of additional measures and general recommendations were developed and are presented.”

Although Nuclear Regulatory Commission regulations would need to be re-written for reprocessing, Sandia considered 10CFR74 Material Control and Accounting of Special Nuclear Material. This regulation specifically excludes reprocessing but can be used for general terms and expectations for smaller throughput facilities. The requirement for a shutdown and flush out plus strict inventory difference goals and detection requirements would be unrealistic and likely impossible to achieve. These challenges support the need to rewrite the regulations for a large throughput facility.

International Atomic Energy Agency (IAEA) requirements are written for large reprocessing facilities and provide a better basis to design and evaluate the Pyroprocessing Facility proposed safeguards approach. The standard error of the inventory difference (SEID) should be at or below 2.42 kg plutonium. The IAEA goal of expected accountancy capability should be 1% throughput. Although a specific balance period is not specified, Sandia expects timeliness requirements between one and three months for material balances. The differences in regulatory requirements are summarized in Table 2.

Table 2 Existing Regulatory Comparison.

Description	Nuclear Regulatory Commission	International Atomic Energy Agency
Standard Error of Inventory Difference	< 0.1% active inventory	< 1.0% mass balance
	Plant flush out required	2.4 kg plutonium per balance period
Timeliness detection goal for abrupt loss	2 kg plutonium within 3 days	8 kg non-pure plutonium < 3 months
		8 kg pure plutonium < 1 month
Physical Inventory	Every 6 months	Once per year

Sandia reviewed the original concept safeguards approach which was based on a new proposed safeguards hazards matrix. This matrix was based on a risk-informed and graded approach that is used for nuclear safety analysis. Its description did not specify the material balance period or sufficiently explain how the inventory difference numbers were mapped onto the proposed matrix. A known deficiency was the estimates for process inventory, especially the electrorefiner, since the equipment designs were being developed at the same time as the safeguards strategy. Sandia found the description was not sufficiently clear and thought that the approach was not sufficiently transparent for a regulator. The new safeguards approach is similar to traditional materials and control accountancy for existing international facilities.

6 Security Assessment

Since security systems are an important part of the overall facility costs and impacts, Argonne National Laboratory contracted with International Nuclear Security Engineering Department of Sandia National Laboratories to review the initial conceptual design for security systems. Four major tasks were included in their work:

- Determine how well the Physical Protection System (PPS) concept could meet Nuclear Regulatory Commission (NRC) regulations (given the level of detail available). Given that no specific requirements exist for pyroprocessing, this work focused on the existing NRC regulations for nuclear power plants (10 CFR 73.55).
- Determine if it is a workable concept. If not, suggest how it might be constrained or modified so that it is. If it is, determine its main strengths and weaknesses for further development.
- Review the cost estimate for the Physical Protection System. Offer an opinion on the reasonableness of the estimate and suggestions for reducing it if warranted.
- Cooperatively develop a more substantial, performance based security conceptual design and installation budget. This is based on first characterizing the target, threat, facility, and response; then performing path and scenario analysis to determine the most vulnerable path for a most likely scenario; then performing neutralization analysis through modeling and simulation. The result is the requirements for the detailed design of the site's Physical Protection System.

These tasks were integrated with Argonne and Merrick & Company's work so the drawings and specifications could be updated.

Sandia has identified six specific areas for more detailed design and assessment for the conceptual design:

- Protect against Design Basis Threat (DBT).
- Analyze how barriers protect against Design Basis Threat.
- Determine location of Central Alarm Station and Secondary Alarm Station.
- Develop target sets.
- Evaluate detection and assessment systems.
- Determine response requirements for protective force.

Regardless of what PPS concept the project adopts, the Sandia reviewers have several 'best practice' recommendations:

- Minimize the footprint of the Protected Area in order to minimize locations to respond to, and the amount of real estate (doors, surfaces, etc.) that must have sensors and assessment equipment. It is especially important to minimize the length of the Perimeter Intrusion Detection and Assessment System (PIDAS), since it is difficult and expensive to install, operate, and maintain.
- Entry Control Points should be inside the area that they protect so that they are less vulnerable to the threats they are protecting against. The number of entry control points should be minimized.
- The Central Alarm Station (CAS) and Secondary Alarm Station (SAS) should also be inside the area that they protect. Siting them in a less secure location leaves the entire PPS vulnerable to attack or unauthorized access.
- Emergency electrical power to the CAS & SAS is an important part of the PPS's ability to respond to an attack by the DBT and should be protected to that level. How this is done is affected by the CAS's electrical loads, duration of attack, and by how many other loads the emergency power supply serves (lighting, cameras, & sensors at a PIDAS being the largest). The backup power requirement for 'safety' systems is very large (and so call for a generator), so it seems more practical for safety and security systems to share emergency backup and then protect it against the DBT.
- The response force should be protected from a pre-emptive attack by the DBT. If an adversary can extend the timeline by removing the primary armed responders at the start of their attack, it would be an advantageous tactic for them. The ready responders should be located as close as practical to the target material (inside the Fuel Processing Facility) and to protect them from an initial attack.

Sandia's approach in the conceptual design for this project has been to try to take advantage of the delay and protection built into the very robust construction of the Fuel Processing Facility and Waste Storage Facility. Siting both underground is a significant security advantage. The very thick concrete walls around the hot cells and the nearly self-protecting nature of the Fuel Processing Cell's argon atmosphere, high temperature, and limited accessibility made them good candidates for this approach. Seeing this possibility, an approach was examined to replace a PIDAS around the entire area with intrusion detection on the Fuel Processing Facility exterior walls.

The evaluation of an existing or proposed PPS requires a methodical approach in which the ability of the security system to meet defined protection objectives is measured. Without this kind of careful assessment, valuable resources might be wasted on unnecessary protection or, worse yet, fail to provide adequate protection of materials against a theft attack by the defined threat. The Vulnerability Assessment methodology was developed to implement performance-based physical security concepts at nuclear sites and facilities.

Virtual simulation software modeled the facility and its PPS under adversary attack. The model uses artificial intelligence along with detailed information about a facility's buildings, utilities, and landscape; PPS performance characteristics; and tactics and weapons for both the adversary and response force. The 314 simulations concentrated on an adversary sabotage scenario, which takes into account the varying tactics and configuration of response forces. For the parameters modeled, the security system performs very well. The security system contains adequate detection and delay, and features a sizable onsite response force to provide interruption and neutralization. In just under 90% of runs, the adversary is defeated before acquiring target material in the TRU vault, and in just over 1% of scenarios, they acquire the material and get it outside the building; however, the two exterior patrols are able to prevent the adversary from escaping the site with the material. Overall, the original design contained many of the typical security elements but benefitted from some optimization. Reduction in the PIDAS size and changes to the locations of key security elements would produce a much more robust and cost-effective design.

The most significant facility change resulted from the security assessment was minimization of the protected area by moving the Protected Area Receiving Building (PARB) and Waste Storage Facility outside of the protected area. These facilities can be in less secure areas because they handle and store lower value target material. This change minimizes the length of the Perimeter Intrusion and Detection System. An embedded detection system in the Process Facility walls and outside structure will be considered early in the preliminary design phase for the possibility to lower initial capital costs and operating costs. The Generator Building is also a candidate to move outside of the protected area. This change will be determined as the safety/security assessments are completed. The analyses should specify the emergency power safety function and length of time that the facility can be operated without emergency power with no safety events. The transfer tunnels to and from the Protected Area Receiving Building and Waste Storage Facility will have security doors that minimize potential attacks and increased intrusion detection through these entry points. For the receiving building, credit can be taken for the extra guard force that will accompany the offsite shipments.

Although security concerns would like to see one entrance, the operational needs are better met with two secure entrances. The main personnel entrance is located in the southwest corner of the vital area of the Processing Facility. For transfers from the Protected Area Receiving Building, a new security entrance was moved from the PARB ground level to the service level (20 feet below grade) and connected to the Processing Facility.

This security post will be used to facilitate transfers into the facility plus provide a secondary alarm station and location for one response force team. The location also meets the security suggestion that teams and staging areas should provide paths from opposing directions to the highest value target (TRU vault). This change also eliminated a third path for personnel to enter the protected area, thus minimizing entrances.

Both the Central Alarm Station and Secondary Alarm Station are moved inside the Processing Facility. The two stations will be physically separated and hardened to minimize the possibility of a simultaneous attack and unauthorized access. The central alarm station is located near the control room and the second one at the service floor where the TRU Vault is located. The security offices and entry points in the Laboratory and Office Building will be used to support administrative security personnel and control access into the owner-controlled area where the other buildings are located.

7 Cost and Construction Schedule Estimates

7.1 Capital Cost

Methodology for Facility Capital Cost

The facility cost estimate is based on the floor plans, roof plans, sections and elevations for the following buildings plus structure, systems and components (SSC) list for the primary support systems:

1. Emergency Operations Center
2. Fire Station
3. Generator Building
4. Laboratory and Operations Building
5. Maintenance and Mock-up Building
6. Protected Area Receiving Building
7. Fuel Processing Facility
8. Utility Building
9. Warehouse and Staging Building
10. Waste Storage Facility
11. Proposed Site Breakdown Plan and Proposed Site Utility Plan
12. Pilot Scale Pyroprocessing Facility Item List (SSC List)

Detailed measurements of quantities are used, where possible, and reasonable allowances for items not clearly defined by the information are provided. These detailed estimates were divided into the following categories for each building:

- Foundations
- Vertical Structure
- Floor and Roof Structures
- Exterior Cladding
- Roofing
- Interior Construction
- Conveying
- Mechanical
- Electrical
- Equipment

Each of these categories is divided into elements where the estimates were based on square footage, cubic yards, or linear feet with applicable costs for these units of measures. Based on the SSC list, equipment and specific systems such as heating, ventilation and air conditioning are priced based on informal quotes or previous experience.

The ten different categories are summed to give direct building costs, and 10% general conditions and construction management costs is added to the direct costs. In addition, a contingency was 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 following items were excluded from this estimate:

- Professional fees
- Building permits and fees
- Inspections and tests except as noted in the estimate
- Furniture, fixtures and equipment
- Construction change order contingency
- Contractor bonding, and
- Hazardous material abatement/removal.

As the facility design progresses, the detailed estimates can be refined with construction quotes and more details on individual systems.

The facility capital cost estimate did not include the design cost. A bottom-up design cost estimate was developed rather than taking a percentage of the overall construction costs. Since this report constitutes the conceptual design effort, the design cost estimate deals with the phases of the engineering design effort required after completion of the conceptual design through start-up. The engineering design costs associated with the support of construction/startup shown in the estimate only deal with completion of the as-designed condition and do not include contingency for changes to the facility designs that require redesigns of the facility or associated buildings. Labor rates utilized in the design cost estimate are average values typical of the resource being used during the specific portion of the design phase where that resource is utilized.

Methodology for Process Equipment and Support System Capital Cost

Costs were estimated for each equipment system or component (if not a part of a specific system) in four general categories: Engineering design and analysis (hereafter referred merely as Engineering), Fabrication, Purchased Parts, and Qualification. Detailed estimates of cost subcategories (especially in the Engineering category) and individual items were made.

Engineering

The design and engineering efforts were estimated from concept to fabrication drawings (See Figure 11). Where appropriate this may include electrical engineering or other support personnel.

Engineering complies with the applicable Quality Assurance requirements. Each design review is documented to meet these requirements and project objectives. The design reviews document the engineering process and include engineering analyses required to fulfill the scope of work and fabrication drawings.

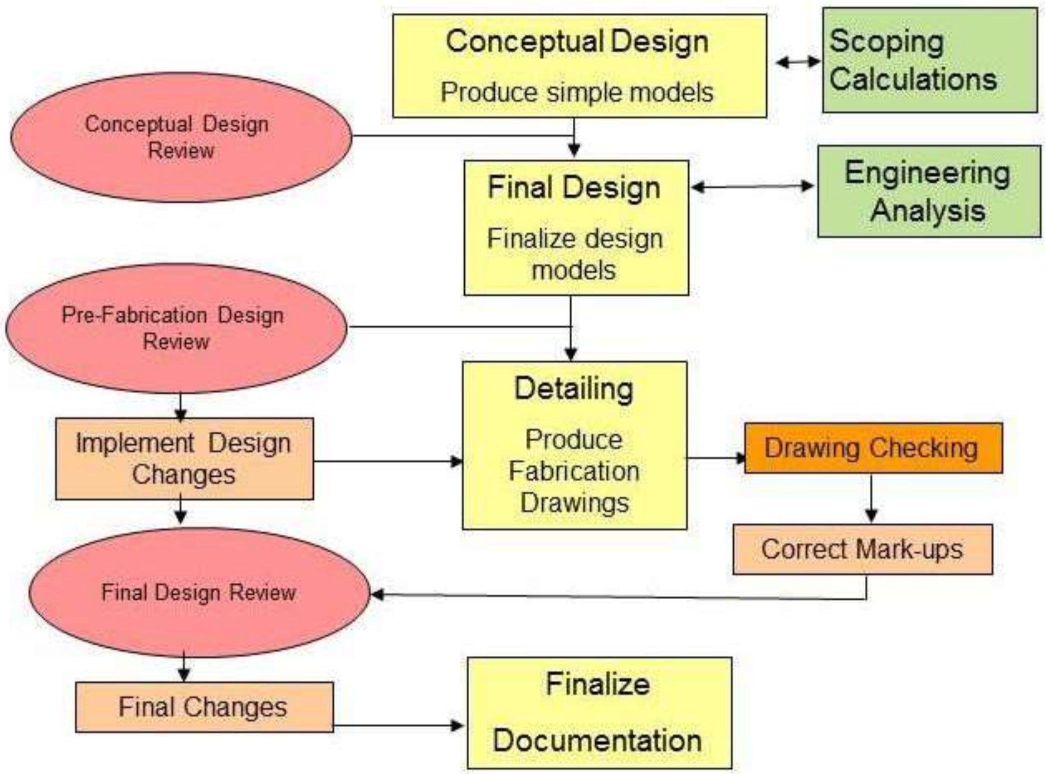

Figure 11 Design/Engineering Work Flow

The estimates include the cost for preparation of a Design Description document describing the equipment in detail, an Operation and Maintenance Manual for each system, and all equipment Qualification Plans including acceptance criteria.

Fabrication

Due to the scope and complexity of the many systems, many fabricators will be involved in parallel. The mechanical cost estimates for custom made parts are based on the current price per pound of the materials in the fabricated item (approximated by 3-D CAD models) and labor estimates are developed in consultation with ANL Central Shops. The labor estimates include time for the fabricator to assemble matching components to ensure proper fit-up. In general, specially fabricated parts, sub-assemblies, or assemblies will be manufactured by single providers if all the parts fall within that provider's normal capabilities with no special training or equipment required to complete the task. In most instances, these pieces are not expected to be remotely broken into smaller units for maintenance, but to be replaced as units are taken to the Decontamination Cell and/or the Hot Repair Area for further disassembly and maintenance. One obvious exception is the case involving motors/actuators, which are replaceable independent of the component which is being driven; another is the case of the most critical heating elements.

Cost of purchased parts was estimated using vendor catalogs or informal estimates from sales engineers. Due to the conceptual nature of the current work, no formal binding quotes were obtained. Since specific instrumentation needs can be determined only after detailed design of the various systems, an arbitrary amount according to system complexity was added to the purchased parts account for each system.

The estimates include allowances for rework discovered to be necessary during the qualification process stemming from engineering/fabrication shortcomings. They do not include shipping costs or additional labor required to meet delivery dates or from labor disputes.

Integration/Qualification

Qualification consists of three distinct phases:

- *Phase I - Fit-up, integration, and outfitting.* Parts and subassemblies from different sources are put together for the first time and integrated with any other pieces to form the assembly that is intended to be operated as a unit or system in the cell. Outfitting includes installation of parts requiring special techniques or operations for which special training is required on the part of technicians for their performance. Examples of this might be the application of heating elements to components and wiring them to each other or to connectors, the latter requiring special qualifications for those performing soldering/splicing for in-cell applications. All motors, actuators and heaters are tested for proper operation using convenient, but appropriate, power sources. The amount of labor required for instrumentation installation is based on system complexity. Most design and/or manufacturing errors are uncovered and corrected in this phase of qualification.

- *Phase II - Out-of-cell qualification including remote operations.* The system configured in Phase I tests operational and any anticipated maintenance sequences that will be encountered in the cell using the exact remote handling tools and techniques that are intended for actual operations and maintenance. When problems are found from which recovery using remote operating techniques is not possible, hands-on recovery is undertaken and the appropriate design and fabrication changes are made and tested until resolution is achieved. Electrical equipment operations (e.g., heaters, motors, actuators, etc.) are verified using the actual electrical cabinets, cabling (including feed-throughs) and junction boxes that will be used in actual operation. This phase of qualification should require relatively few revisions, but is still quite time consuming because of the necessity of verifying anticipated operational and maintenance sequences.

- *Phase III - Final in-cell installation and remote qualification.* The systems are installed in the cell and the operations and maintenance sequences conducted in Phase II are repeated with the cell remote handling systems under the actual environmental conditions of the cell, except that perhaps all the other systems may not yet be in place and operating at temperature. This qualification verifies only that each given system can indeed be operated and maintained using the handling systems, with appropriate fixtures and end- effectors in place, but only in a manual mode controlled by human operators. Robotic operations, programming of the trajectories for them, and verification of their adequacy are included in the support systems.

Manpower cost estimates for all three phases were made by assuming a mix of engineers and technicians with an average cost $98.60/hr, the same as shop rates. This allows any necessary equipment modifications to be taken into account in the qualification effort cost estimates.

Support Systems

In addition to the process equipment, cost estimates for the following systems that support the process operations were made:

1. Transfer Locks and Feed-Throughs
2. Overhead Handling and Robotics
3. Electrical Systems
4. Process Monitoring and Control Systems
5. Materials Control and Accountancy Equipment
6. Safeguards and Security Equipment
7. Analytical Laboratory Equipment

The same methodology described above for the process equipment is utilized for most of the support systems. However, the overhead lifting and robotics cost estimates were based on the vendor quotations.

The cost estimates for overhead bridge cranes, overhead telescoping transporters and jib cranes used in the Fuel Preparation/Storage Cell, Fuel Processing Cell, and Waste Treatment Cell are included here. The cost estimates for the overhead cranes, overhead telescoping transporters and jib cranes used elsewhere in the facility are included in the facility capital cost.

Summary of Capital Cost

The project total capital cost estimate is summarized in Table 3. 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.

The capital cost in Table 3 reflects the facility updates resulted from the security assessment. The protected area footprint has been reduced drastically and the security system cost was reduced from $68.5 million to $25.1 million. The process equipment cost has also been updated: the original vertical disassembly silo was replaced with a simpler horizontal disassembly and a new TRU down-blending furnace was added.

Table 3 Project Total Capital Cost (in thousands dollars)

Category	Cost ($K)	Contingency Factor, %	Cost with Contingency
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 System	25,100	20	30,120
Design Engineering	38,253	20	45,904
Subtotal	249,587		298,649
Process Equipment & Support			
Process Equipment	21,905	25	27,381
Transfer Locks & Feed-Throughs	10,109	25	12,636
Overhead Lifting & Robotics	26,599	10	29,259
Electrical Systems	2,251	25	2,814
Monitoring & Control Systems	4,480	25	5,600
Materials Control & Accountancy	1,030	25	1,288
Safeguards & Security Equipment	4,645	25	5,806
Analytical Laboratory Equipment	3,800	25	4,750
Subtotal	75,239		89,534
Licensing Support	5,000	20	6,000
Start-up Materials	2,859	20	3,431
Total	324,308		397,614

7.2 Operating Cost

Staffing Levels and Cost

Staffing levels are established based on the different required functions for typical nuclear operations including the necessary security, radiological control, safety and emergency management personnel. The following assumptions were made to estimate the staffing levels:

- The facility and processes are staffed for 24 hours per day and 365 days per year.
- Training for most staff is held during scheduled facility system maintenance (28 days), process equipment maintenance (52 days), and inventory operations (30 days).
- Four crews (12 hours per shift) cover around-the-clock-operations.
- Analytical Laboratory is staffed for 12 hours per day and 365 days per year so 2 crews are required.

- Staffing levels are assigned locations and numbers adjusted to recognize the extra time that is needed to work within a protected area and remote operations.
- Expertise provides engineering and design for minor modifications, safety evaluations and repairs for process equipment, facility systems, and security systems. Major modifications and repairs are performed by outside organizations.
- Information Technology personnel are included in different functions to provide 24 hour per day coverage for the control systems, mass tracking systems, security systems, and general site computers and networks.
- Specialty expertise is provided for radiological control, material control and accountancy, training, analytical chemistry; and security.

A brief description of each of the site functions with some of the special skills and assumptions is described below:

Process Operations: These personnel operate the process systems and ancillary equipment in the four Processing Facility hot cells, transuranic vault, decontamination cell, hot repair area and Protected Area Receiving Building. System engineers provide the necessary technical support for all the remote equipment, control systems, and process operations. Equipment operators operate the equipment remotely and perform material transfers. Maintenance operators work on equipment in the hot repair area and remote repair area. The transfer operators perform the physical transfer into and out of the cells including fuel casks, transfers between cells, transfers to the vault and transfers to the waste storage facility. Instrumentation technicians maintain and calibrate instrument and control systems associated with process equipment. Material control personnel are responsible for nondestructive assay operations, item inventories, and technical support for the mass tracking system, as necessary.

Facility Operations: These personnel are responsible for the systems in every building on the site to ensure safe operations and maintenance.

Analytical Laboratory: These personnel include both analytical laboratory and small hot cell operations. They perform chemical analysis including sample receipt through analysis and necessary quality assurance.

Mock-up: These personnel make minor modifications for remote process operations. They also prepare process chemicals before transfer into to the protected area.

Health Physics: Radiological control and monitoring are provided by this organization.

Administrative and Technical Support: Typical support functions for an operating nuclear facility are provided by this group.

Security: Access control, physical protection, and special response forces are provided. The reduced security system cost resulted in increased response force team, and the cost increase is included in Table 4.

Fire/Emergency Response: This on-site group allows quick response while maintaining personnel access control before outside help is required.

The payroll plus fringe costs were based on average costs for groups based on similar positions that support operating nuclear plants. The necessary support costs including office supplies, computers, miscellaneous chemicals, radiation control items, guns, ammunition, training supplies, etc. were accounted for by adding ten percent of the average personnel costs. This money would be used in different ways for the different functional areas. Table 4 shows the staffing costs for each of the functional areas.

Table 4 Annual Operating Costs by Functional Areas, $K/yr

Functional Area	Personnel Annual Costs	Support Annual Costs
Process Operations	12,095	1,200
Facility Operations	4,585	460
Analytical Laboratory	4,305	430
Mock-up	440	40
Health Physics	2,200	220
Administrative	2,885	290
Technical Support	5,155	520
Security	8,265	830
Fire/Emergency Response	1,860	190
Total	41,790	4,180

Start-up Operations

After the process equipment is installed and facility systems are operational, processing cell and analytical laboratory hot cells will be filled with argon gas to establish inert atmospheres, and the other hot cells will be brought to their operating parameters. After operating conditions are established, the process chemicals are placed into the process vessels that are brought to operating temperatures. The start-up operations are estimated to take approximately one year to complete a thorough equipment check out, training and initial modifications needed before radioactive operations begin. Limited testing is assumed to occur with 10 metric tons of used nuclear fuel being processed. Since the fission products will be accumulating in the process vessels, no waste containers will be filled with radioactive material, but limited testing will be done to ensure the waste treatment equipment is ready for operations.

7.3 Start-up Materials

The start-up materials include the initial charge of process vessel chemicals, some storage containers, and the necessary argon gas to establish cell purity. During these operations, the primary electricity costs will be for heaters for the process equipment, facility system operations, and limited testing (three batches assumed for electrochemical processes). Argon usage is based

on the volumes of the inert hot cells plus 100% to purge additional air. The cell atmosphere purification systems operate to bring the cells to their final specifications. The cryogenic system for krypton recovery is tested when the initial 10 metric tons of spent nuclear fuel are processed. The start-up materials costs (Table 5) are divided into process chemicals, containers, argon gas, process electricity costs, facility electricity costs and spare parts inventory.

Table 5 Start-up Materials

Description	Quantity	Units	$K
Process Chemicals	8,900	Kilograms	118
Containers	99	Items	550
Argon	450,000	Cubic Feet	26
Process Electricity	1,600	Megawatt-hours	80
Facility Electricity	11,300	Megawatt-hours	565
Spare Parts	129	Items	1,520
Total			2,859

The process chemicals fill each of the vessels with their initial inventory of materials plus supply the chemicals for processing 10 metric tons of spent nuclear fuel.

The containers are used for initial testing of equipment and the initial processing.

The argon amounts assume one truckload to fill the initial bulk storage system and another truckload to cover initial operations and purge the inert hot cells. The prices are based on a budgetary quote from an argon gas provider.

The electricity assumes that the process electricity is only 50% of annual operations because the processes are not operated at usual capacity; however, the initial vessel heating will require extra power to bring items to their operating temperatures. The facility electricity is the same as annual operations with adjustments made for Fuel Processing Cell and Transuranic Vault cooling since the heat loads will be considerably lower. The assumption for both process and facility electricity are described under annual costs.

The spare parts are based on engineer and designer experience and are planned to be purchased after initial testing verifies operational readiness and any necessary modifications.

The start-up materials are included as part of the initial capital cost presented in Table 3.

7.4 Staffing

During start-up operations, the full staffing is provided except for the security guards and health physics during the first six months when the Protected Area is an open but limited access area. Also, the health physics organization is not completely staffed until radioactive materials are present. These two functional areas are estimated to have half the annual costs as people are added as required and allowing for operational procedure development and training.

Annual Consumables

The annual consumable costs were based on the process mass balance and operational model plus estimates to keep the facilities running.

Process Chemicals: Process chemicals are dominated by the salts and graphite electrodes for electrochemical processes and the ceramic waste operations. Other chemical usage was estimated but lumped together as miscellaneous.

Process/Storage Containers: The process and storage containers were divided between uranium and transuranic product storage, waste containers, and process containers that can't be reused.

Replacement of Spare Parts: Since equipment breakage cannot be predicted, an estimate for replacement process parts was based on ten percent of the identified spare parts that would be built. The budgeted costs for this item would be $120K.

Utilities

The primary annual utility costs are based on the process equipment and facility electrical loads and the argon gas that is used in routine operations for the inert atmosphere in the fuel processing cell and analytical laboratory small hot cells. The facility electrical loads were based on the connected loads for the facilities and buildings on site. The Fuel Processing Facility dominates the electrical use (10,900 of 14,700 MWh). This result is expected because of the necessary removal of large heat loads from high temperature processes and stored transuranic product. Also, the ventilation systems for contamination control and a central control room with ability to monitor the entire complex are located in this facility.

Other utilities such as water and sewer are included in the site infrastructure so the primary utility costs are electricity and operating personnel to operate these systems. These costs are already included in the annual staffing and electrical costs.

Summary of Annual Operating Cost

The annual operating cost is summarized in Table 6.

Table 6 Annual Operating Cost (in thousands dollars)

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

7.5 Project Schedule

The project schedule incorporates an approach that integrates the facility and process equipment design efforts with the licensing efforts. The conceptual design effort is expected to be complete

enough to interact with the NRC on the specific issues associated with licensing a pyroprocessing facility.

A precise licensing regime has not yet been established by the NRC for a pyroprocessing facility license application. In preparing these milestones and the schedule, certain assumptions regarding NRC licensing requirements were made that may change once a specific licensing regime is established.

The project sequence is summarized below:

- Licensing Process: As stated above, a precise licensing regime has not been established, so the licensing process will begin with the development of a licensing strategy document to form the basis for interaction with NRC. Among other things, a safety assessment, a NEPA process, and license applications will be required. These activities will be integrated with the design team to ensure timely input occurs to the facility and process equipment design. The reference regulatory approach is based on preparing a two part NRC license application. Part 1 would provide sufficient information to obtain authorization to construct the facility. Part 2 would provide sufficient information to obtain authorization to operate the facility. It is also possible that an adjudicatory hearing before an NRC Atomic Safety and Licensing Board may be required. The length of time needed to complete a full NRC licensing process will vary depending upon a number of factors including the precise regulatory regime selected and the hearing process, if any. The licensing schedule shown in Figure 10 is an ideal schedule as required to support the design, fabrication, and construction schedules. In reality the licensing process may take longer.

- Process Equipment Design: These design activities affect the facilities located inside the Protected Area of the site and the potential, credible accidents that need to be analyzed. As such, the continuation of this portion of the design/development effort will start as early as possible. The preliminary design will focus on structural and thermal analysis plus possible changes that can lower the overall costs as safety and security issues are raised. The final design will include detailed fabrication drawings and specifications for formal bids. The more complex equipment designs including the electrorefiner, electrolytic reducer and drawdown vessel will be completed first, so that their fabrication can start before other equipment design is completed.

- Equipment Fabrication: Equipment fabrication is planned to be done in specialty shops where the equipment will be assembled to verify fit. This initial assembly and testing will be followed by two additional qualification steps that verify functionality and remote operations for assembly, operations and maintenance.

- Facility Design: Preliminary designs of each facility and the ancillary systems will be integrated with the process equipment designs and transferred to the safety analysts and security specialists. This will include updated facility models, process and instrument

  diagrams, preliminary structural analysis, ventilation calculations, electrical calculations and specification lists for key components. Final design will use two different approaches where specialty buildings such as the Processing Facility, Protected Area Receiving Building, Waste Storage Facility, and Laboratory and Operations Building are designed with detailed specifications and construction drawings. Other standard site buildings will be designed by developing a design-build specification where a company will be responsible for developing the construction drawings and constructing the buildings.

- Facility Construction: The Maintenance and Mock-up Building, and Warehouse and Staging Building will be constructed first and used to support ongoing construction and operational support activities associated with the other site structures. Construction of the Processing Facility, Protected Area Receiving Building, and Waste Storage Facility will follow. The other site buildings will follow as logistics allow. Each building will have a facility commissioning phase where performance tests will verify their functionality and completeness.

- Key Decisions: Several decision points have been established to ensure the project progresses and continually assesses the viability of the overall project. After preliminary design activities have provided updated capital and operating costs, the decision will be made on submitting the application for authorization to construct. An estimated five and a half years into the project an operating organization will be established and key operations personnel hiring will occur. An operational readiness review in parallel with facility commissioning and remote qualification of process equipment will likely be required for the issuance of the authorization to operate.

The overview schedule is shown in Figure 12.

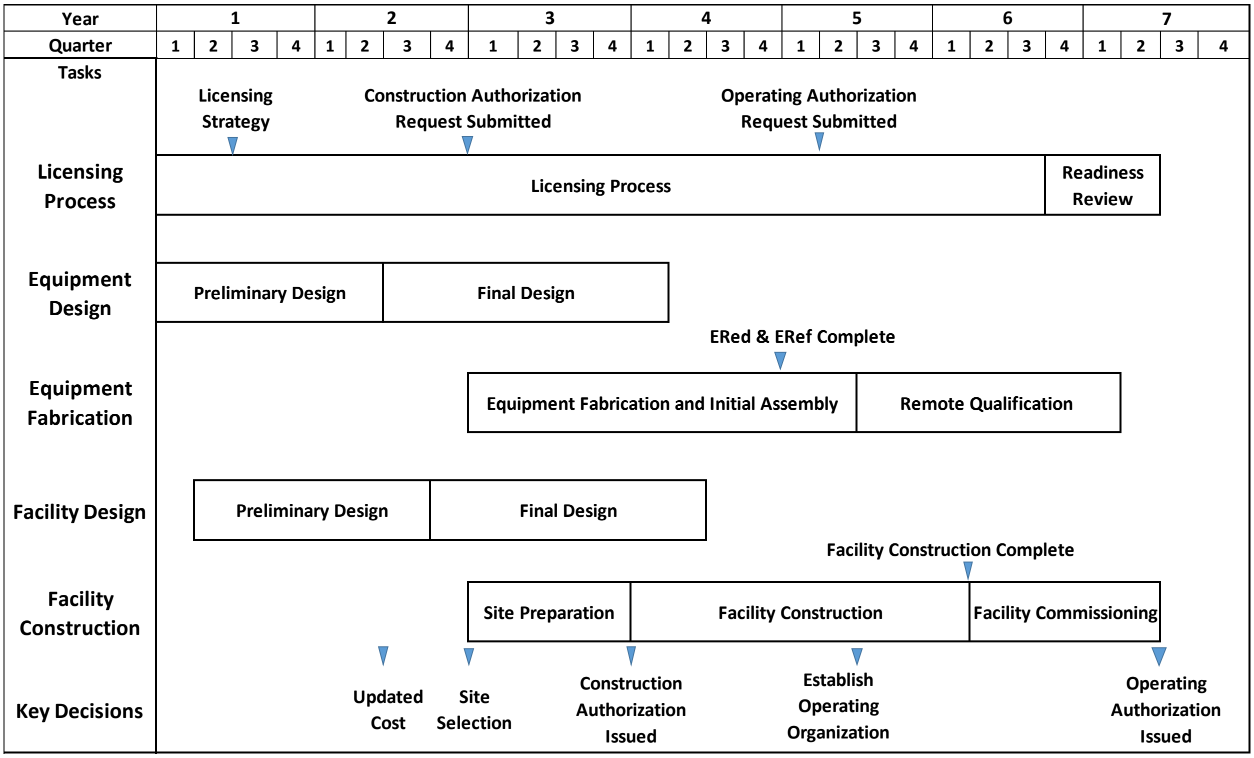

Figure 12. Project Overview Schedule

8 Potential for Scaling up to Commercial-Scale Facility

A common perception 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.

This section presents a potential approach for scaling the current pilot-scale design up to a commercial-scale facility. We have chosen 400 T/yr facility as an example, but a similar approach can used to scale up to whatever throughput rate is needed.

In our example, there are significant economies of scale achieved at 400 T/yr throughput rate and further economies of scale are expected as scale-up continues.

8.1 Scale-up of the Electrorefiner

The evolution of the electrorefiner designs for the EBR-II spent fuel treatment indicates that the throughput scale-up in fact is reasonably straightforward. The first electrorefiner installed in the Fuel Conditioning Facility (FCF), Mark-IV, has a 40 in. diameter vessel and four electrode ports, each with 10 in. diameter. The Mark-IV was intended to operate with two anode baskets and two cathodes in parallel. Each anode basket can contain about 10 kg of chopped pins, limited by the criticality constraints, and the throughput rate of Mark-IV electrorefiner was limited to about 10 kg/day.

But to process the large inventory of the EBR-II blanket assemblies, this throughput rate was not adequate, and the Mark-V electrorefiner was designed, constructed and installed in the FCF. It utilized concentric anode-cathode modules in a spare electrorefiner vessel identical to Mark-IV electrorefiner. With the concentric anode-cathode arrangement, the heavy metal loading in the anode baskets is increased to 100 kg total for four electrode modules and the throughput rate has increased by a factor of 5 in the same size electrorefiner vessel and the same size and number of electrode ports.

For LWR spent fuel processing, where the criticality constraint is considerably lessened, a much higher throughput rate is possible, and indeed is required for commercial viability. The annular anode-cathode module can be scaled up in radius by adding additional rows of concentric rings as well as increasing the height. However, a new approach has been developed that is more amenable to large batches and higher throughput rates. Parallel planar design incorporates thin rectangular anode baskets stacked vertically, sandwiched with cathode plate or multiple rods. The planar design allows simplified basket geometry, and hence, simplified scale-up.

The parallel planar electrode design concept has been adopted for the pilot-scale design. A single electrorefiner can achieve about 400 kg/day throughput rate. The rectangular vessel size is 5’-9” wide, 12’-7” long, and 6’-5” high. A further scale-up in size might be possible, but the current size is near optimum. Hence, we decided to duplicate the main process equipment for the 400 T/yr facility.

8.2 Fuel Processing Facility Layout for 400 T/yr Facility

As discussed above, the main processing equipment, electrorefiner and electrolytic reducer are duplicated four times. Similarly, the TRU processor, uranium processor, drawdown vessel, and ceramic waste processor are duplicated four times. Some equipment, such as the TRU processor is constrained in size by the criticality safety consideration. Others can be consolidated, but in order to make the materials control and accountancy easier, they are duplicated as the electrorefiner is duplicated.

For the front-end operations in the Fuel Preparation/Storage Cell, there was flexibility in the equipment utilization, and hence the fuel disassembly station, fuel rod slitter, hardware waste packaging were replicated three times. Other equipment that can be scaled up easily has been duplicated twice. This category includes basket module loader, salt tank, noble metal processor, salt crystallization vessel, waste salt transfer system, and waste packaging.

Having decided on the number of equipment systems, we considered various ways of configuring the processing cells, and adopted the layout presented in Figure 13 as most promising.

This layout option has the additional advantage in that further scale-up can be achieved by simply adding additional north-south oriented processing lines, both in the Fuel Processing Cell and the Waste Treatment Cell.

As compared to the 100 T/yr facility, the hot cell floor area is 1.8 times larger, hence significant economies of scale are achieved.

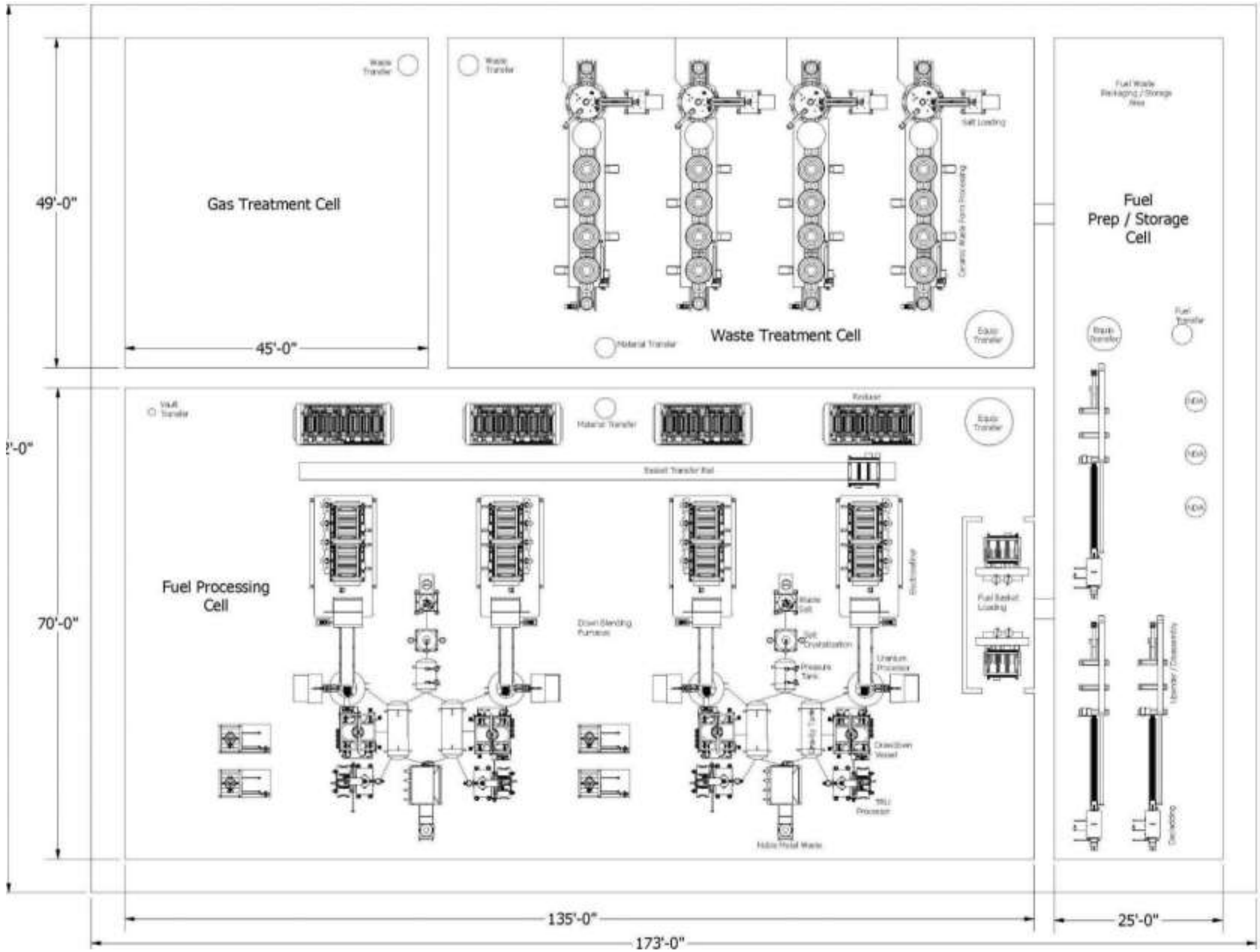

Figure 13 Layout of Pyroprocessing Cell for a 400 T/yr Facility

8.3 Facility Capital Cost for 400 T/yr Facility

The floor area of the Fuel Processing Facility is increased by a factor of 1.8, but the construction commodities would be increased by a lesser factor. However, the TRU vault capacity is increased by a factor of 4, and HVAC and argon circulation system capacity would have to be increased by a similar factor. Therefore, we assumed a multiplier of 2.5 for the Fuel Processing Facility going from 100 T/yr to 400 T/yr. The physical protection system also assumed a multiplier of 2.5, due to the complexity associated with the TRU vault capacity increase.

The Waste Storage Facility capacity is increased by a factor of 4, so we assumed a multiplier of 4. The Generator Building is assumed a multiplier of 3 due to increased emergency power requirements. We assumed a multiplier of 2 for the Protected Area Receiving Building, Laboratory and Operations Building, Maintenance and Mockup Building, Utility Building, and Warehouse and Staging Building. For the remaining buildings, we assumed a multiplier of one: Utility Building, Emergency Operation Center, Fire Station, and the Site Work.

A multiplier of 2 was assumed for the Design Engineering cost and Licensing Support cost. A multiplier of 4 was assumed for the Start-up Materials.

The process equipment cost consists of the following four components:

- Engineering
- Fabrication
- Purchased Parts
- Integration/Qualification

The equipment engineering cost would remain the same whether one or multiple units of the same design are manufactured. However, the fabrication, purchased parts, and integration/qualification costs have to be, to a first order, multiplied by the number of units.

For the process equipment constrained by criticality or materials control and accountancy considerations, the original size will be maintained and four units will be required for the 400 T/yr facility. Equipment systems in this category are electrolytic reducer, electrorefiner, uranium processor, TRU processor, TRU down-blending furnace, drawdown vessel, salt transfer lines, and ceramic waste processor. Fuel disassembly station, hardware waste packaging, fuel rod slitter have some slack time in their utilization and three units can handle the 400 T/yr throughput. For basket module loader, salt tanks, noble metal processor, salt crystallization vessel, waste salt transfer system, TRU can sealing station, waste packaging, only two units are required.

For other support systems, such as overhead lifting and robotics, electrical systems, feedthroughs, monitoring, MC&A, and safeguards/security, appropriate multipliers have been applied on a case-by-case basis.

The resulting project total capital cost and the annual operating cost are summarized in Tables 7 and 8 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.

Table 7 Total Project Capital Cost for a 400 T/yr Facility

Category	400 T/yr ($K)	Contingency Factor, %	Cost with Contingency
Facility			
Fuel Processing Facility	211,360	25	264,200
Protected Area Receiving	7,960	15	9,150
Waste Storage Facility	31,830	15	36,600
Lab & Operations Bldg	38,940	15	44,780
Maintenance & Mockup	19,630	15	22,570
Utility Building	27,170	15	31,250
Warehouse & Staging	8,600	15	9,890
Generator Bldg	8,330	15	9,580
Emergency Op Center	6,780	15	7,800
Fire Station	3,440	15	3,960
Site Work	59,190	15	68,070
Physical Protection System	62,750	20	75,300
Design Engineering	76,510	20	91,810
Subtotal	562,490		674,960
Process Equipment & Support			
Process Equipment	43,130	25	53,910
Transfer Locks & F-T	21,990	25	27,490
Overhead Lifting & Robotics	54,630	10	60,090
Electrical Systems	9,010	25	11,260
Monitoring & Control Sys.	17,920	25	22,400
MC&A	4,120	25	5,150
Safeguards & Security Eq.	9,180	25	11,480
Analytical Laboratory Eq.	15,200	25	19,000
Subtotal	175,180		210,780
Licensing Support	10,000	20	12,000
Start-up Materials	11,440	20	13,730
Total	759,110		911,470

Table 8 Annual Operating Cost for 400 T/yr Facility

Category	Cost ($K)
Staffing	56,460
Materials and Services	4,910
Process Chemicals	2,320
Spare Parts	480
Product & Waste Containers	21,890
Utilities	3,940
Total	90,000

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Nuclear Engineering Division
Argonne National Laboratory
9700 South Cass Avenue, Bldg. 208
Argonne, IL 60439

www.anl.gov

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