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Lawrence Livermore National Laboratory

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SYSM-5620 Final Project: NewLife Nuclear - An environmentally and economically minded solution for fusion energy waste handling

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NewLife Nuclear

AN ENVIRONMENTALLY AND ECONONOMICALLY MINDED SOLUTION FOR FUSION ENERGY WASTE HANDLING

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1. Introduction

1.1. Background

Energy demand is rising as a result of innovative and increasingly more energy intensive processes coming to fruition, particularly through the recent interest in the development of AI data centers as well as manufacturing with the push towards increasing domestic manufacturing interest. Fusion energy can provide virtually limitless energy to support this increase in energy demand. Fusion energy concepts, largely classified as magnetic fusion energy (MFE) and inertial fusion energy (IFE) are being pursued, each having unique challenges to overcome before the successful deployment of electricity to the grid.

Achieving fusion ignition on the National Ignition Facility, first in December 2022, and eight times since, has demonstrated the scientific viability of the IFE approach. Meanwhile, MFE test stands continue to improve confinement times, making meaningful strides in progressing towards experimental scientific viability. In each of these approaches, an emphasis is placed on generating more power out of the system than what is required to power the system. An under-researched area applicable to both IFE and MFE is handling activated waste coming out of fusion energy systems, both in the course of normal daily operations, as well as in intermittent periods as structural materials may need to be replaced.

In the context of an IFE plant system, commonly discussed plant designs suggest targets are ignited within a chamber at a rate of up to one million targets per day. Between each shot, the chamber housing the ignition event will clear a portion of the chamber – resulting in a mixture of vaporized target gas, target debris, and other materials being expelled from the chamber [source]. Additionally, IFE system concepts typically discuss the modularization of plant designs, which are expected to be replaced periodically as the components degrade over time. This would result in the irradiated chamber structure materials, likely metals and alloys, needing to be removed and safely stored. In MFE plant systems, while targets are not ignited at a repetition rate with the frequent chamber clearing as is expected in IFE plant systems, it is anticipated that portions of the confinement area interfacing with the hot plasma will need to be replaced periodically.

In each system, without additional investment and research into alternative processing and recycling methods, the result is storing irradiated materials, and other elements in a safe containment area until they are no longer activated. – resulting in significant waste both economic and environmental.

1.2. Need Statement

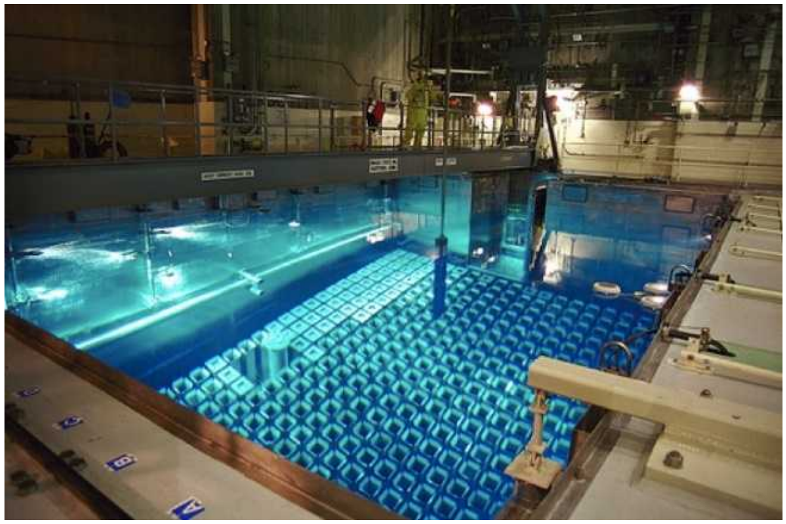
The commercialization of fusion energy will necessitate a long-term, economically and environmentally viable solution for waste handling in the United States. Furthermore, fusion waste will be incurred more often, albeit with a shorter radioactive half-life and less in total quantity, than the 18-month nuclear fission refueling cycle. Fusion energy waste may also generate more varied types of materials irradiated compared to nuclear fission waste, requiring different processing and storage methods. A waste processing/handling system will be necessary for fusion energy to become a reality. A system that supports the fusion energy power plant's economic viability, without adding to the significant nuclear waste storage already accumulating from the traditional nuclear fission power plants will be essential.

1.3. Current equivalent systems and operations

Existing methods of waste storage and removal relevant to the nuclear fission industry current practices are analyzed as surrogates for what one could expect in a fusion energy system.

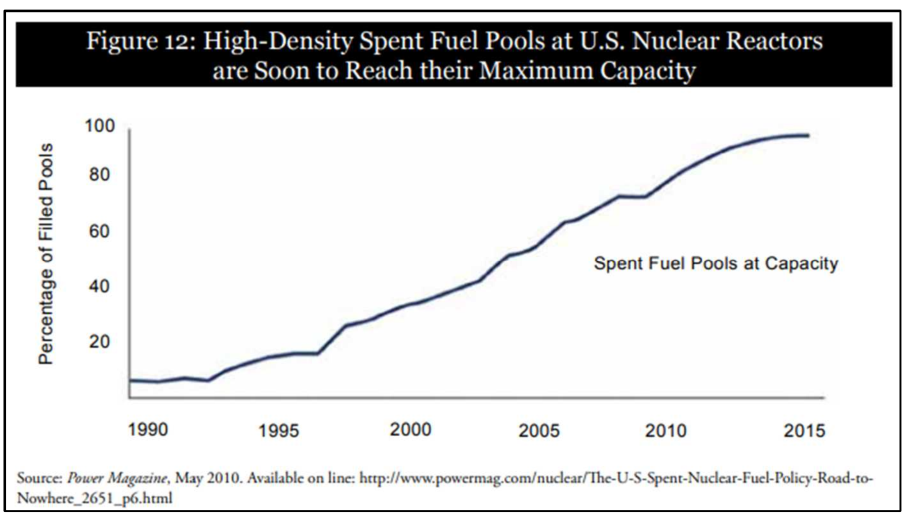
The nuclear fission industry does not have a long-term solution for disposing of nuclear waste. As a result, an increasing number of stored radioactive material is contained in spent fuel pools or dry cask storage[1] throughout the United States.

Spent fuel pools, as shown in the image below[2], are nuclear waste containment areas under at least 20 ft of water, located at nuclear sites. These pools contain the spent fuel, housed in vertical storage racks and may contain both spent fuel and fresh fuel ahead of loading into the reactor core. The pools generally are made of concrete walls with a steel enclosure structure above the stored fuels. Water circulates within the pool, providing cooling of the decay heat from the spent nuclear fuel. This storage method shields workers from radioactive materials and helps to thermally regulate the waste material, which the Nuclear Regulatory Commission (NRC) reported is "…3.9 megawatts (MW) ten days after a one-third core offload." [3]



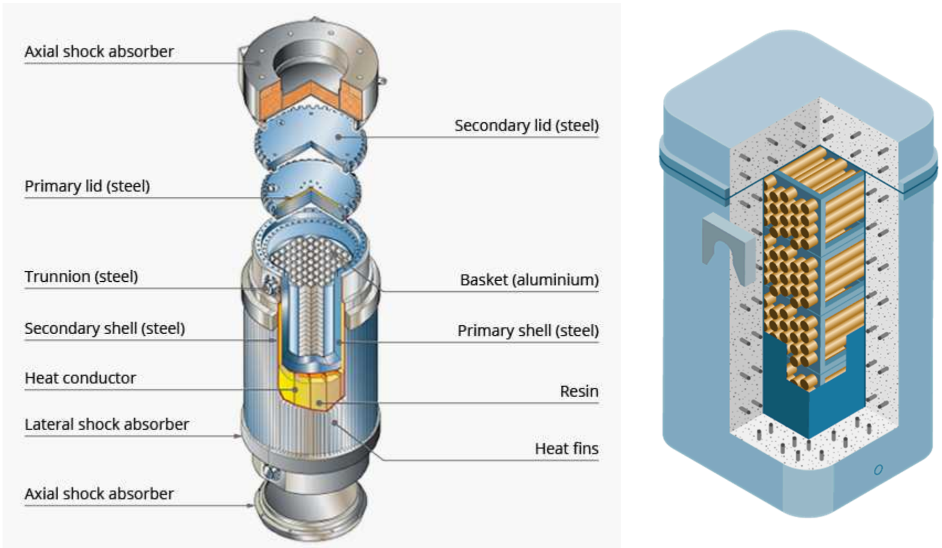
1.3-1 Spent nuclear fuel pool

This method of nuclear waste storage in spent fuel pools was considered a temporary solution until the fuel could be processed. However, a lack of commercial reprocessing in the United States resulted in increasing limited storage capacity in the spent fuel pools as nuclear operations continued[4]. In a 2011 report analyzing the spent nuclear fuel in pools found that spent fuel pools are nearing their maximum capacity, requiring additional storage methods for long-term operations. The graph below represents the percentage of storage capacity since 1990[5].



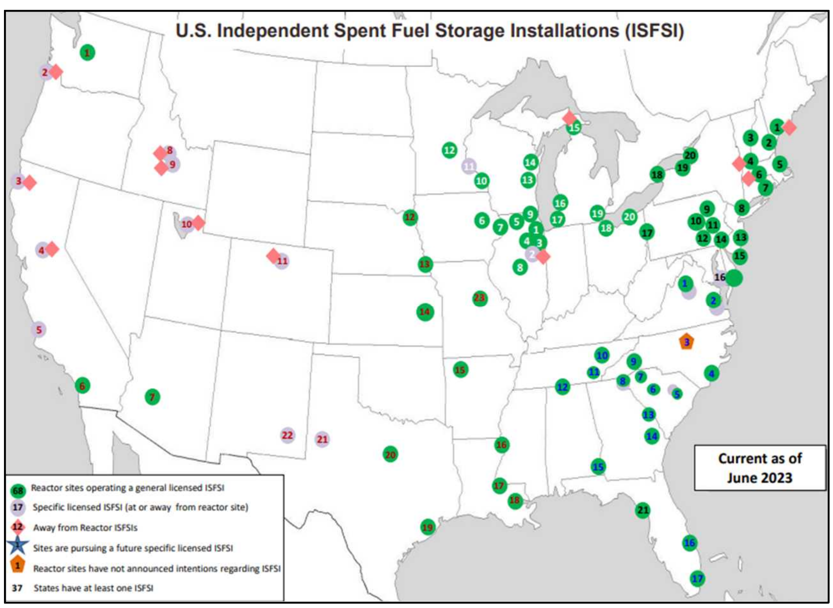
With increasing limited options of storing nuclear material in spent fuel pools, additional storage methods must be utilized such as dry cask storage.

Dry casks are metal or concrete, with metal liner storage, assemblies containing spent nuclear fuel. Nuclear waste material is loaded into the inner dry cask cannister and enclosed via welding the dry cask or bolting it shut. Dry cask storage designs provide neutron shielding of nuclear waste to the external storage facility or environment while optimizing for removal of the nuclear waste decay heat. The images below represent components contained within a metal dry cask (left) and a graphic of a concrete cask (right) [6].



1.3-2 Components of dry cask storage systems (metal dry cask on left; concrete dry cask on right)

The map below highlights U.S. geographical locations where reactor sites have existing storage licenses for dry casks (both onsite in the green circles on the map below, or away from nuclear sites in the red diamonds on map below) as well as sites pursuing a storage license[7].



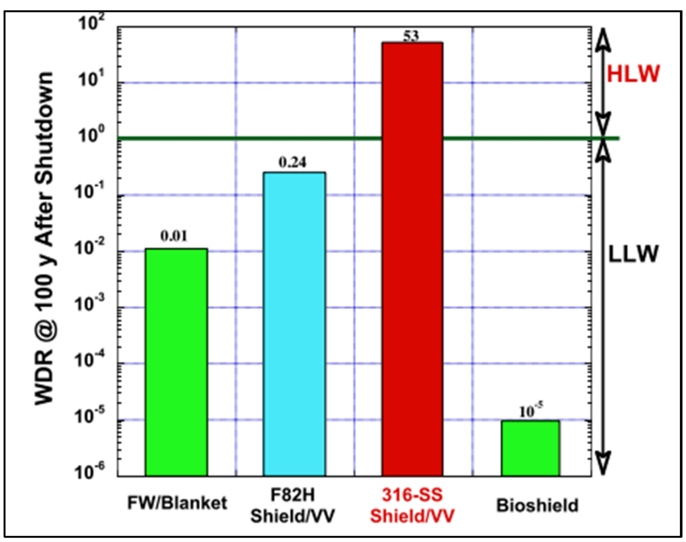
Ohio State News cited a Dept. of Energy, Office of Nuclear Engineering study that noted over 90,000 metric tons of nuclear waste are stored in and around the United States as of 2024[89]. Casks are provided with licensing for forty years, with a possible forty-year renewal, with the expectation that a long-term underground storage solution will be determined in a 25 to 35 years' timeframe[10].

While waste of fusion energy systems will have shorter storage lifetimes, a system should be developed for handling activated waste generated as part of the nuclear fusion energy process.

1.4. Deficiency and Opportunities

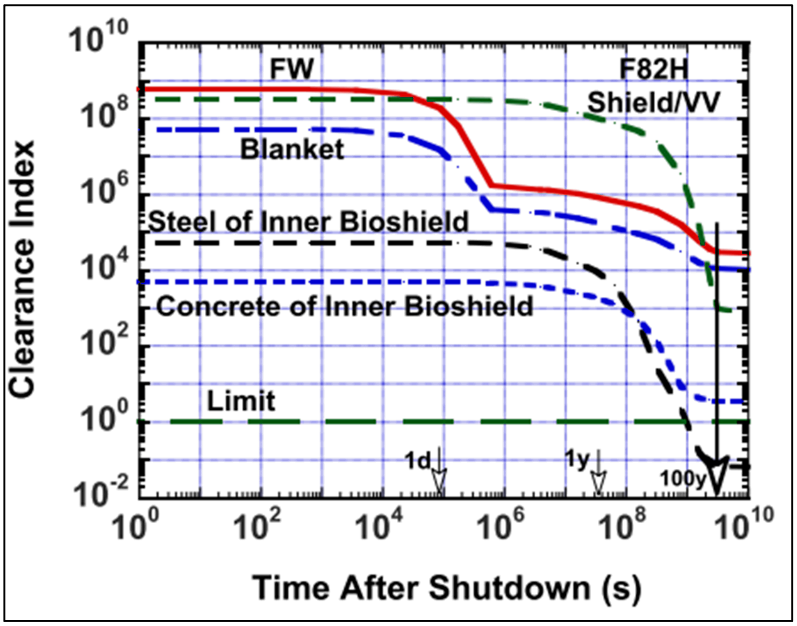
Existing nuclear fission waste storage solutions are primarily focused on the storage of spent nuclear fission fuel. For fusion energy systems the fuel will be recycled, however, components within the fusion chamber including steel alloys used in the first wall (FW) and chamber blanket containment as well as laser optics in the case of IFE systems will degrade over the course of the plant's operations and need to be replaced – particularly, the fusion chamber which could be replaced every five years. Additionally, for IFE systems, debris from targets ignited at a potential 10 Hz pulse repetition frequency within the chamber will be cleared with usable tritium fuel sent back into the plant and the remaining waste will need to be accumulated and processed.

Existing storage methods for nuclear fission are designed for robustness lasting decades and may even withstand corrosion risks for more than 1,800 years[11]. These systems are designed for managing high-level waste (HLW), waste that remains radioactive for tens of thousands of years. Prior studies on potential fusion energy systems found that most waste generated for fusion energy may fall into the low-level waste (LLW) category (shown in the image below)[12], capable of near-surface storage[13].



1.4-1 Low level waste vs high level waste in an analyzed fusion energy system

The low-level waste may not necessitate the storage methods traditionally used in nuclear fission, where the use of these methods for low-level waste may result in more costly, over-engineered storage methods. While low-level waste methods may be used, traditional underground or near-surface storage methods would still require housing the fusion waste for at least 100 years as shown in El-Guebaly's representation of the clearance index after 100 years (clearance applies if the index of the material is less than one) shown in the image below.



1.4-2 Clearance index of primary nuclear fusion system components post shutdown based on the High-Average Power Laser (HAPL) study

Storage of 100 years will add to waste generation over such timeframe and will contribute to long-term environmental waste from the containment devices holding the irradiated materials. These methods are not sufficient for an economically or environmentally viable solution.

2. Stakeholder Analysis

2.1. Active stakeholders and their expectations

Plant operators are those who would directly interact with the system by managing the process steps required for waste handling and processing. This is to include controlling the system through both automated and manual processes, managing how much waste is processed at any given time, tracking post-processed waste material to be recycled back into plant operations or sold to potential material buyers, and monitoring system diagnostics.

Maintenance personnel are those who would make both routine and off-normal repairs to the system. This may include requiring the system to shut down in order to manage and repair both hardware/mechanical components as well as software repairs.

Inspector or watchdog is the regulating entity who will periodically tour the system and will review the waste handled and processed. The inspector or watchdog will ensure waste material is effectively processed with radiative levels lowered to what is deemed safe for either fusion energy power plant system reuse and internal recycle or for external sale. Additional monitoring will include quantities of waste processed vs time to ensure amount of waste generated is within reasonable operations of a nuclear fusion power plant.

The table below outlines the capabilities and characteristics of the persona of each identified stakeholder.

Active Stakeholder	Capability	Characteristic
Plant operators	- Sufficient waste handled per day - Automated controls for monitoring waste - Sensors warning when operations deviate from baseline conditions - Inventory of waste material processed reported at each phase of subsystem - Purity of waste by material is quantified	- Option for specification of size of ingots produced from reprocessed waste
Maintenance personnel	High accuracy radioactivity monitoring	- System should be easy to maintain - System should have backup power to maintain enclosure of radioactive material during processing in the event of system failure - Interlocks associated with hazardous material to prevent accidental exposure - Internal containment vessel where radioactive waste can be manually pumped if hazardous area of system requires maintenance
Regulatory Watchdog/ Inspector	- Reports generated of accumulated waste output - Report generated of radiation level of incoming waste - Report material inventory processed	- Safety shut off mode that can safely secure waste in process of radioactive removal - System data log output with tamper prevention

2.2. Passive stakeholders and their expectations

Target fabrication facility operators receive the recycled waste from the waste handling and processing system. They will use the materials as inputs back into the targets.

Plant managers are responsible for ensuring the fusion energy system operates efficiently and effectively removes radioactive material. They must ensure that the waste is processed and handled quickly enough such that a plant backlog doesn't develop with waste that the plant cannot manage.

Recycled waste purchasers are those external to the facility who have an interest in using the previously irradiated materials. These can be fission companies or bulk material procurers.

Passive Stakeholder	Capability	Characteristic
Target fabrication operators	Impurities of target fabrication recycled material recovered from waste must be low	Recycled waste returned in a way that's easy to incorporate back into targets
Plant managers	- Onsite storage of waste must be capable of handling the plant maximum capacity - Roughly operating in equilibrium of waste inflow and processed waste outflows	Cost of handling, processing, and recycling waste material maintains plant economic viability
Recycled waste purchasers		Radioactive waste must be removed to naturally occurring environmental levels Processed waste is in a usable form

2.3. Stakeholder requirements

Expectations from both active and passive stakeholders were reviewed and consolidated into the below set of stakeholder requirements.

2.3.1. Stakeholder Requirements – Normal Operating Scenarios

- SR1) The system shall be capable of processing 1 MT of material per day.
- SR2) The system shall have automation controls with monitoring for each function within the waste processing system.
- SR3) The system shall have diagnostic reports and indicators when the system deviates greater than 5% of normal operating parameters.
- SR4) The system shall remove radiation of material recycled for new IFE target fabrication to 1 Bq/g.

- SR5) The system shall remove radiation of material for external sale to below background radiation levels, less than 0.1 Bq/g
- SR6) The system should allow the user to specify the size of the processed waste for intra-plant recycling or for external sale.
- SR7) Power requirements of the system should be less than 0.1% of total power plant net electricity output.

2.3.2. Stakeholder Requirements – Diagnostics and Tracking

- SR8) The system shall have mass-basis inventory tracking through each phase of the system's operations.
- SR9) The system shall report the composition of processed materials to within 5 ppm accuracy.
- SR10) The system shall report material radioactivity levels at system input and output.
- SR11) The system shall report the mass of waste generated in hourly intervals for regulatory compliance.
- SR12) The system shall report the radioactivity level of incoming waste for processing to 1 Curie/gram accuracy.
- SR13) The system shall report a tamper-preventive output log of data for regulatory compliance.

2.3.3. Stakeholder Requirements – Workplace Safety

- SR14) The system shall have dosimeters with accuracy of 0.1 mRem in each area of operation for workplace safety.
- SR15) The system shall alarm when system location comes within 10% of workplace safety radiation exposure limits.

2.3.4. Stakeholder Requirements – Maintenance and off-normal operational scenarios

- SR16) The system shall contain a redundant equipment where radioactive waste can be pumped to in off-normal scenarios.
- SR17) The system's materials and components shall require replacement on the same frequency, and no more than that of the fusion chamber.
- SR18) The system should have readily accessible access locations for conducting repairs.
- SR19) The system shall have interlocks to protect maintenance workers or operators from accidental exposure.
- SR20) The system shall have a back-up power source to avoid accidental spills in unintended shut-down scenarios.

- SR21) The system shall have a backup containment vessel where hazardous material can be stored if maintenance is required on radioactive handling systems.

2.4. Acceptance criteria

Based on the list of stakeholder requirements generated, a select number of requirements were determined as essential for the waste processing and handling system. These criteria were considered those essential to the success of the system and fulfill the need required.

Requirements identified and converted into key acceptance criteria are:

AC1) The system shall be capable of processing 1 MT of waste per day.

AC2) The system shall remove radiation of material recycled for new IFE target fabrication to 1 Bq/g

AC3) The system shall remove radiation of material for external sale to below background radiation levels, less than 0.1 Bq/g

AC4) The system shall require replacement no more frequently than that of the fusion chamber lifetime 5 years, (timeframe for purposes of this analysis).

AC5) The system shall report the composition of processed materials to within 5 ppm accuracy.

3. Concepts for proposed waste handling system

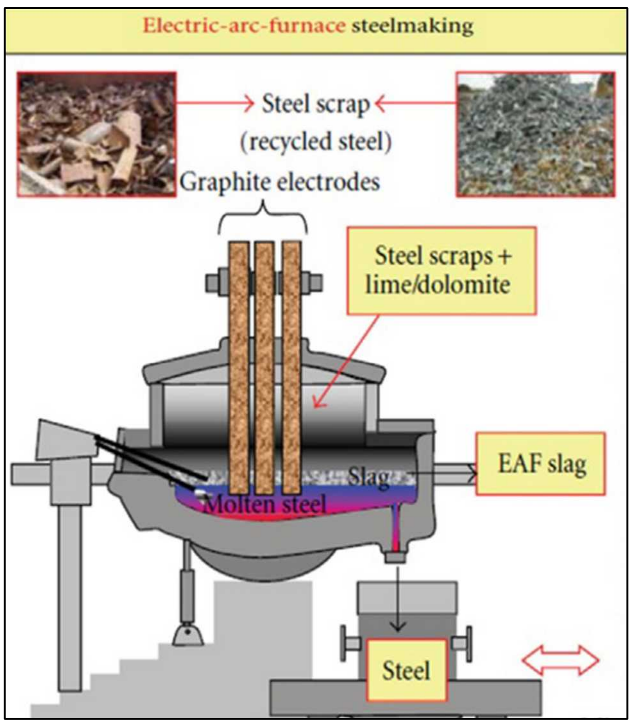
3.1. Concepts generation

3.1.1. High-temperature molten slag radiation removal

A method of removal of radiation material involves heating the irradiated waste components retrieved to high temperatures to remove radioactive materials– skimming the radioactive products from the top of the melt while the non-radioactive materials are separated and remain in the bulk material. Slimák and Necas propose this process for decommissioning of nuclear power plants, noting elements similar to iron may remain in the melt while volatile chemicals – tritium of note – may be removed from the melt[14]. The removal of tritium makes this method particularly promising as that is the primary radioactive material generated in a fusion energy power plant. Tritium may ingress from the first wall and the blanket into structural materials, which will degrade over several years requiring replacement.

Within this melting and molten-slag radiation removal process, a particular method that could be used to heat the material to remove the contaminated material was discussed by Schlienger et al using electric arc melting. Using this method, waste material is melted via an electric current applied across electrodes submerged in a melt. The electricity melts the waste material to a high enough temperature where radiative material separates. Schlienger[15] sites the challenges with this method including contaminated dust and fume present as well as difficulties in slowly cooling the melt from 1400C to maintain remaining material composition.

This method could be considered analogous to use of an electric arc-furnace used as a method in the production of steel as shown in the image below[16]. In this depiction, rather than "EAF slag" as shown in the image, radioactive material would be removed while remaining uncontaminated materials are released, representative by "steel", in the image below[17].



3.1-1 Electric arc furnace steel production method

3.1.2. Electrorefining material separation

Electrorefining relies on applying a current across electrodes to plate radioactive material out of the bulk contaminated waste material through the process of oxidation and reduction. As a result, the radioactive materials are plated onto an electrode with the bulk melt containing the non-radioactive materials. Galashev studied this method in the case of fission reactors for separating Pu and U from spent nuclear fuel. The image below shows the setup of the proposed method by Galashev[18].

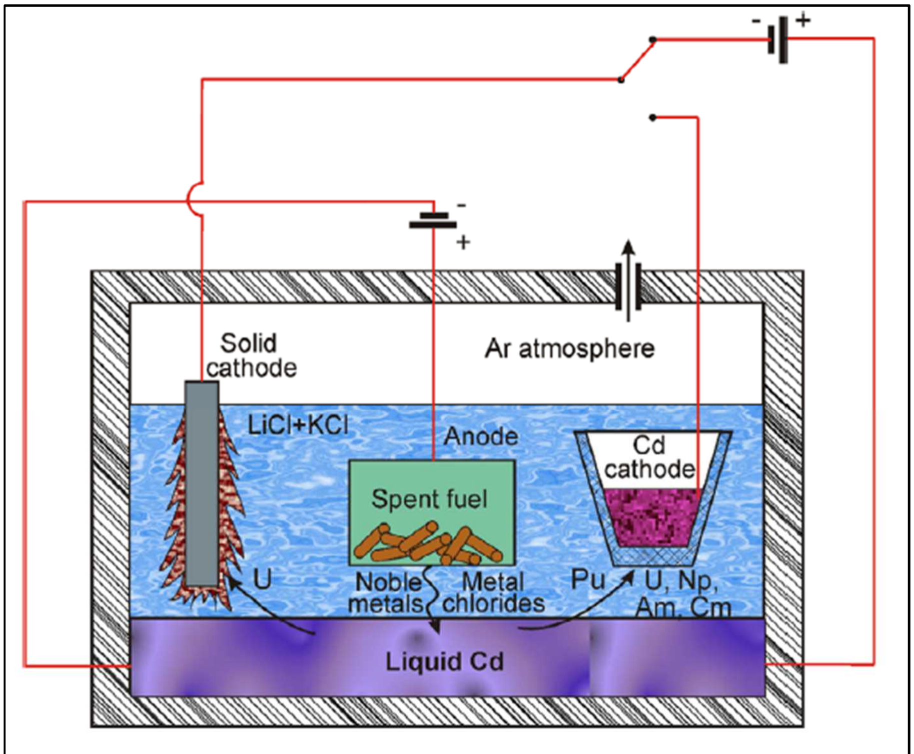


FIGURE 3 Schematic diagram of the electrorefining process[15]

Figure 3.1-2 Galashev representation of separation of spent nuclear fuel materials

While this method is focused on separating lanthanides from actinides, variations of this method have been used by Ito, Aratani, et al., to analyze extraction of tritium from liquid Li[19]. The experimentation setup used by Ito, Aratani, et al. is shown in the image below[20].

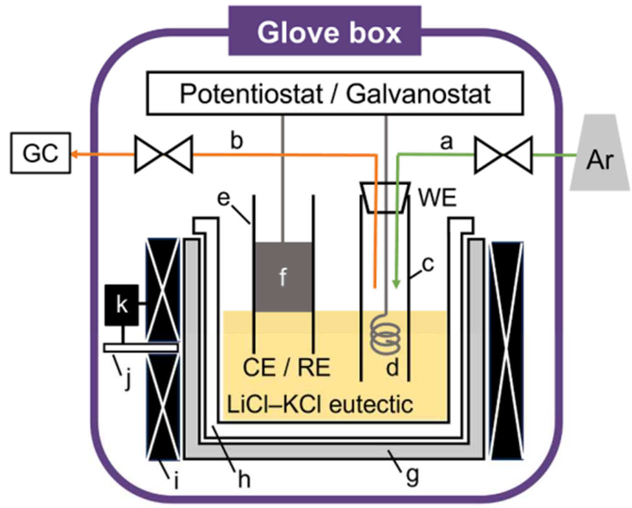


Fig. 1. Schematic diagram of experimental apparatus: (a) gas inlet, (b) gas outlet, (c) glass tube, (d) coil-like nickel wire, (e) stainless tube, (f) liquid lithium, (g) stainless crucible, (h) glass beaker, (i) heater, (j) thermocouple, and (k) temperature controller. WE, CE, RE, and GC denote working electrode, counter electrode, reference electrode, and gas chromatography, respectively.

Figure 3.1-3 Experimental setup for Li-H separation by Ito, Aratani, et. al

Argonne National Laboratory is also testing out this research and has had success in showing the separation of actinides from metals. An image of ANL's results is shown below where uranium is plated onto an electrode[21].

Figure 3.1-4 Image from Argonne National Laboratory experimental results of Uranium plated onto an electrode

In the case of incorporating this system into a fusion energy system, this electrode would instead, for example, plate Pb in the case of IFE target debris, separating it from tritium in the exhaust mixture exiting the fusion chamber.

3.1.3. Transmutation of waste

The final method considered is removal of waste by transmutation of nuclear waste. This method involves reducing the radioactivity of a material by dilution – adding particles to create a less radioactive isotope with a shorter half-life. One method of doing this is through the use of lasers. Mourou discussed this in the Polytechnique insights review where he proposed using lasers to detach protons and electrons from materials to change the chemical composition and thus the radioactivity lifetime of materials[22]. This method was shown experimentally viable as discussed by Maddox in 2003 where she reported on scientists who transmutated iodine-129, which has a half-life of 15.7 million years to iodine-128, a half-life of 25 minutes[23].

Tajima, Brocklesby and Mourou reviewed research done by an international collaboration of researchers under the ICAN project, International Coherent Amplification Network, who sought to develop a high-repetition rate laser with one potential purpose – treating nuclear waste[24]. In the project review, the researchers discussed how, via the process of spallation, a neutron could be generated and be absorbed by the irradiated material to transmutate the material into a lower half-life isotope. This is illustrated in the figure below that the authors published in Optica in 2013[25].

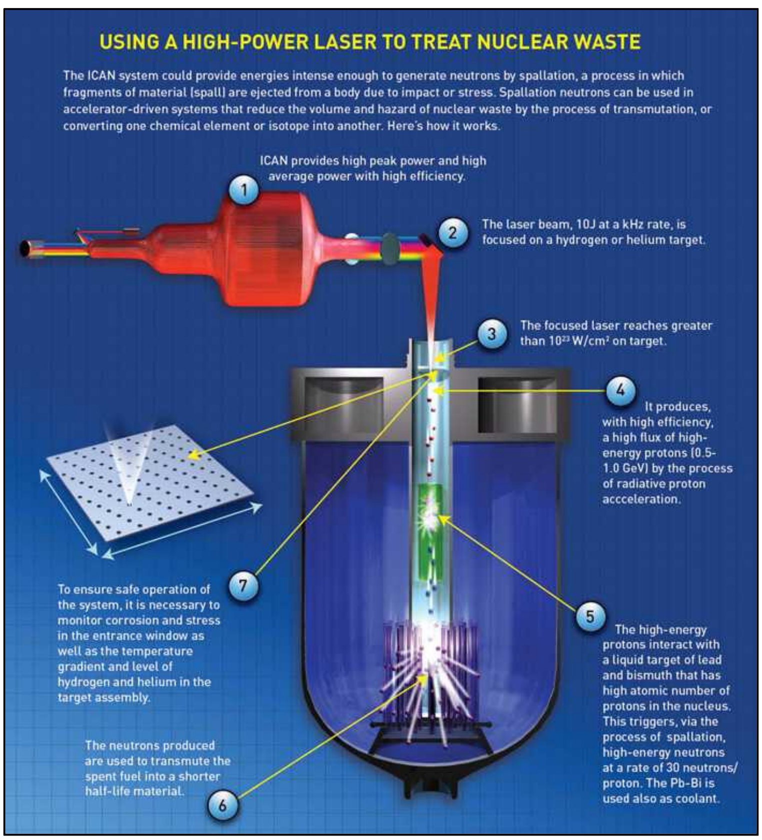


Figure 3.1-5 Illustration of laser transmutation as presented by Tajima, Brocklesby, and Mourou

3.2. Concept Selection

3.2.1. Concept Selection Discussion

Challenges with the **molten slag** method may include the amount of electricity required to operate the electric-arc furnace, which would decrease the power available for net electricity sent to the grid. Additionally, maintenance within the furnace would result in exposure to radioactive material, requiring robotics or a process of adequately cleaning the furnace prior to completing required maintenance. Lastly, this method may not be effective for separating waste material in the vapor form or in the gas phase.

One benefit of the molten slag method is the amount of material that can be processed. According to Nucor, a steel production company, this method can produce 130 to 180 tons of steel in 40 minutes[26], keeping up with the daily demand of waste material processing, with enough space available for melting that the furnace could melt fusion structural components without significant handling required before melting and separation.

The **electrorefining method** has been well established for assessing the impurities within a melt by using cyclic voltammetry measurements. This system could have the added benefit of quantifying radioactive materials that remain in the mixture, without requiring additional diagnostics. While this method may be helpful for processing of daily radioactive waste, this would not be a feasible solution for periodic chamber structural replacement. This concept may also add significant complexity for full system integration given the electrical isolation requirements and removal of electrodes overtime that are no longer effective at separating waste radioactive material.

In the final considered concept, the **transmutation method** via a laser, mixtures of materials may prove problematic where attempting to transmutate multiple different chemical compounds and isotopes into new isotopes at once, which may not be feasible. This may require additional separation systems by isotope before the transmutation process can occur. Incorporating this system into a fusion power plant may draw too much power from the plant’s electricity production, possibly diverting far too much power away from the power plant’s electricity production for the grid.

3.2.2. Pugh Matrix

	Molten Slag	*Electrorefining*	*Transmutation*
Processing rate (mass flow rate)	+	-	+
Radioactive removed waste is in an easy to reuse form	+	0	0
Complexity of system incorporation	0	-	-
Power requirements	-	0	-
Process of daily waste material	0	+	0
Processing of cyclical structural replacement	+	-	-
Economical	+	+	-
Totals	***2***	***-2***	***-3***

4. Proposed System

4.1. Context Diagram

The below context diagram outlines the relationship between active stakeholders, which are interacting with the nuclear waste processing system as both receiving input or information, and providing input, information, or performing a service. The diagram also highlights the passive stakeholders which present the relationships that are either prescribing inputs to the system, such as the plant manager dictating performance requirements, which may include setting maximum limits on tritium stored after waste is processed at any point in time or setting requirements for how processed waste should be packaged (i.e., ingots or large bulk material), or in the case of both the target fabrication operator and the purchaser of processed waste, those entities who are receiving material from the system but who do not provide any feedback or system directives.

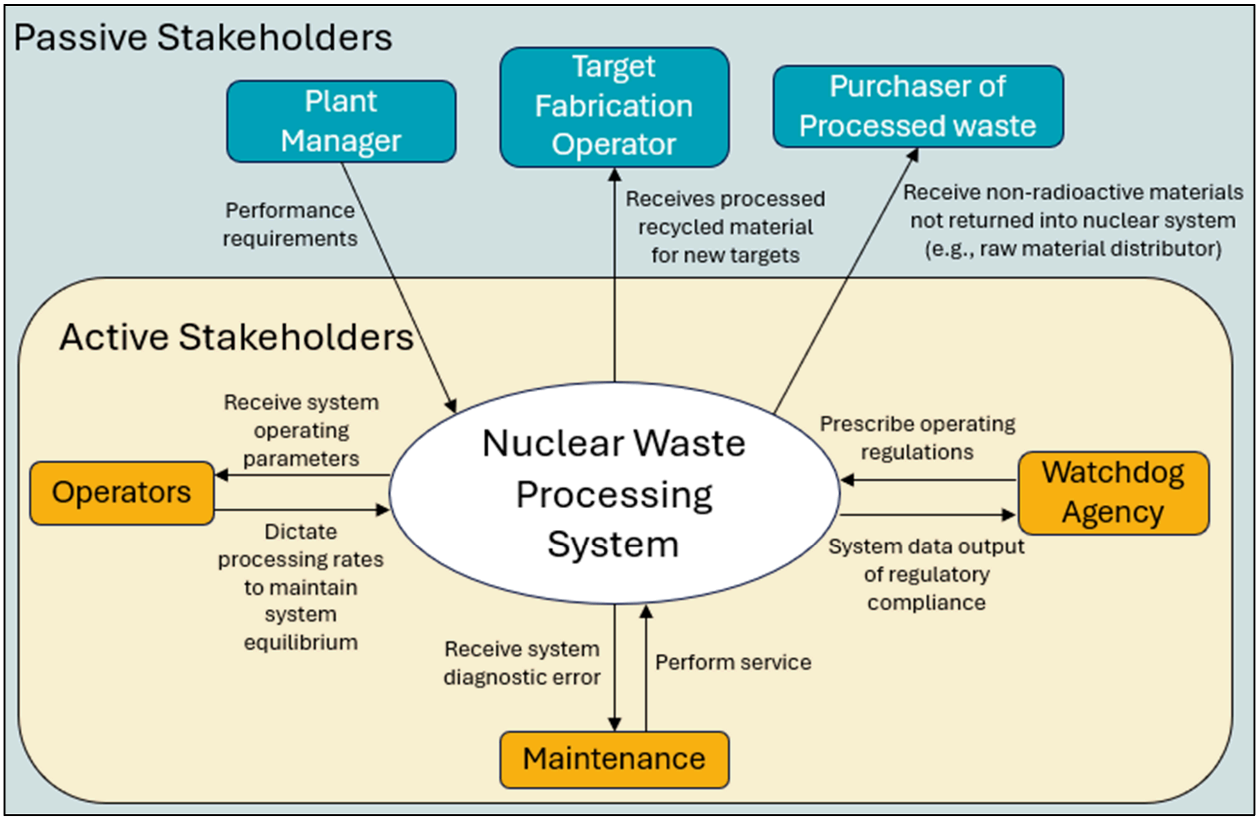


Figure 4.1-1 Context diagram of the nuclear waste processing system

4.2. Concept of Operations

4.2.1. Operational Scenarios

The image below highlights the operational flow of how the nuclear waste will be processed. This flow diagram considers the operation where daily waste will be generated in the fusion chamber and will be pumped to a containment vessel for secondary storage ahead of radioactive vs. non-radioactive material separation using the furnace. The non-radioactive material settles to the bottom of the furnace where it is extracted and poured into ingots while molten in preparation for external sale and shipment or returned to the target fabrication facility for use in new IFE targets.

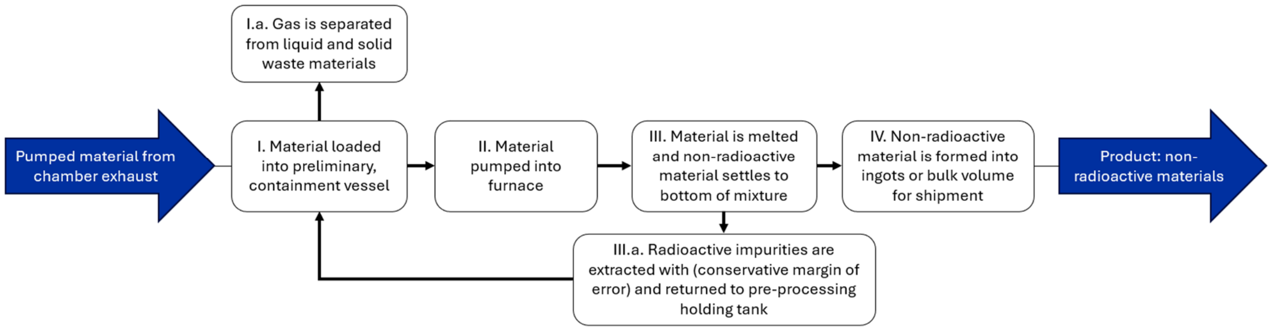


Figure 4.2-1 Flow diagram of nuclear waste processing system operations

4.2.1.1. Plant operator interacting with the waste processing system

The operator must manage flow of material to ensure that the power plant operates efficiently and in equilibrium, requiring no backlog of a processes in one subsystem while another subsystem waits idle. In this scenario, the operator is notified that accumulated radioactive waste is ready for processing. The operator submits a waste processing request through the system, specifying the processing parameters. The manager approves the processing request within the system. The operator is notified when the waste processing is complete. The operator receives detailed output data such as trace radioactivity levels of processed, non-radioactive bulk material and inventory of radioactive material removed, and material compositions of each. The operator can accept the processed waste output or choose to re-process the waste (step IIIa) through the furnace once more, repeating the cycle, numbers I through III in the graphic above. Once the waste is processed, the system stores the separated non-radioactive material and preps it for shipment for external use or notifies the target fabrication facility that the material is processed and ready to be re-used in the IFE targets.

4.2.1.2. Maintenance personnel interacting with the waste processing system

In a maintenance scenario, a system error is sent to the plant operator, informing the workers of a system inefficiency or failure. The preliminary containment vessel coming from the chamber exhaust is full, but the furnace to process the radioactive and non-radioactive waste mixture is empty. The preliminary containment vessel is not correctly filling the emptied furnace with the contaminated material. The operator flags this issue and, via the system, notifies the maintenance personnel. Maintenance personnel receive the error and from the system are given the last day of operating data summarized in graphical outputs. Using this data the maintenance finds that the pump is operating as expected with no deviations. However, maintenance uncovers a lag time between when the system reports the furnace is empty and is ready to be refilled, and the opening of the valve of the chamber waste containment vessel which should let the contaminated material into the furnace.

As a result, the maintenance team runs diagnostics and finds that the valve is faulty and the electrical wiring needs replacement. The system also reports that the radiation level in that area of the plant is not safe for human intervention and robotic support is directed to perform the wire replacement. Once completed, the maintenance personnel log the event, including the cause and the solution, and returns the system to operational mode.

4.2.1.3. Regulatory watchdog inspection of waste processing system

In order to maintain compliance, the regulatory watchdog must be enabled access to conduct randomized inspection of the waste processing system. As part of this use, the watchdog will enter an access code and the system will provide a report including data such as radioactivity levels by waste processing step, mass flow rate of waste processed, and material composition of waste processed. The watchdog will sign off on the data logs and flag any issues directly in the system for the operators to address.

4.3. Use case model

The Use Case diagram below describes the uses of the system and the active stakeholders who are associated with such uses. Operators use the system for requesting waste to be processed, receiving system performance parameters, and specification of waste processing parameters. The maintenance personnel interact with the system by conducting maintenance. Lastly, the regulatory watchdog uses the system for printing a data log of events to ensure the system is within regulatory compliance.

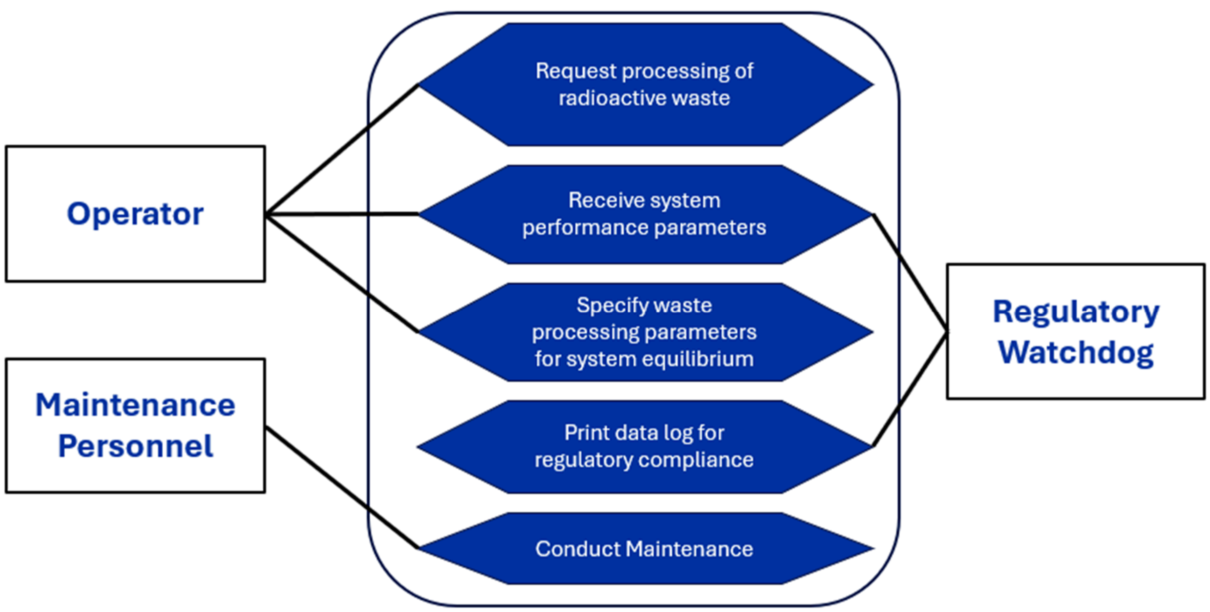


Figure 4.3-1 Use case diagram of the nuclear waste processing system

4.4. Sequence [Interaction] Diagrams

4.4.1. Operator requests waste processing

The sequence diagram below outlines the interactions to occur for the use case of the operator requesting waste to be processed. Once the operator requests waste to be processed, the system returns a status report to ensure no system faults prior to processing the waste. The operator submits the desired waste processing parameters to the plant manager for approval. The manager approves the waste process parameters, and the system begins the steps to process nuclear waste, separating the non-radioactive material from the radioactive material.

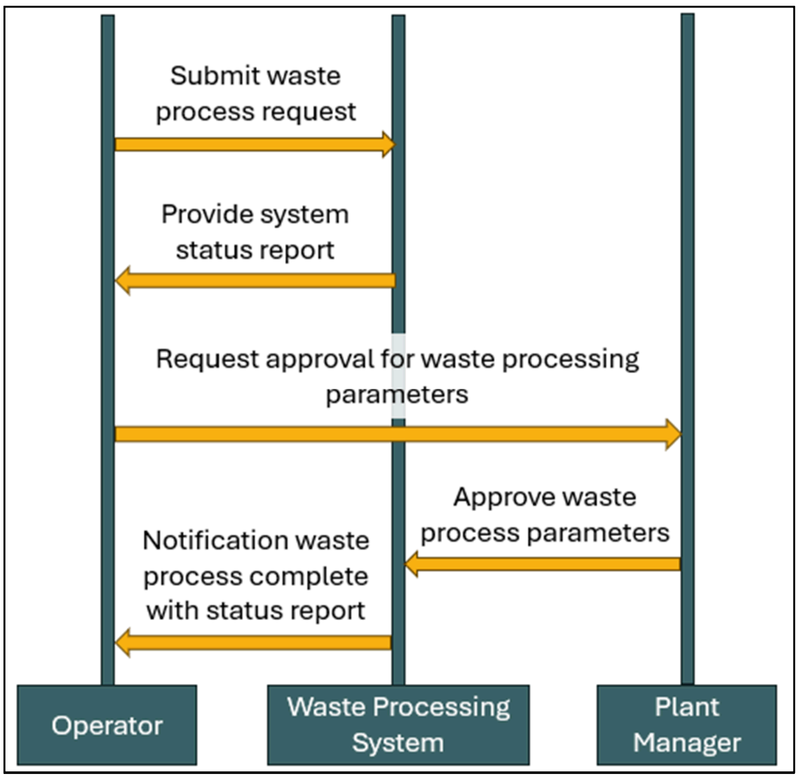


Figure 4.4-1 Sequence diagram of the request processing of radioactive waste use case

4.4.2. Maintenance personnel conduct serving on the system

In the below sequence diagram, the operator receives a warning signal from the system, flagging plant operations outside of usual operating bounds. The operator requests the system to report a diagnostics log. The system reports the status of operating subsystems to maintenance personnel. The maintenance personnel conduct system maintenance. Once complete, the system notifies the operator that system warning signals have been cleared.

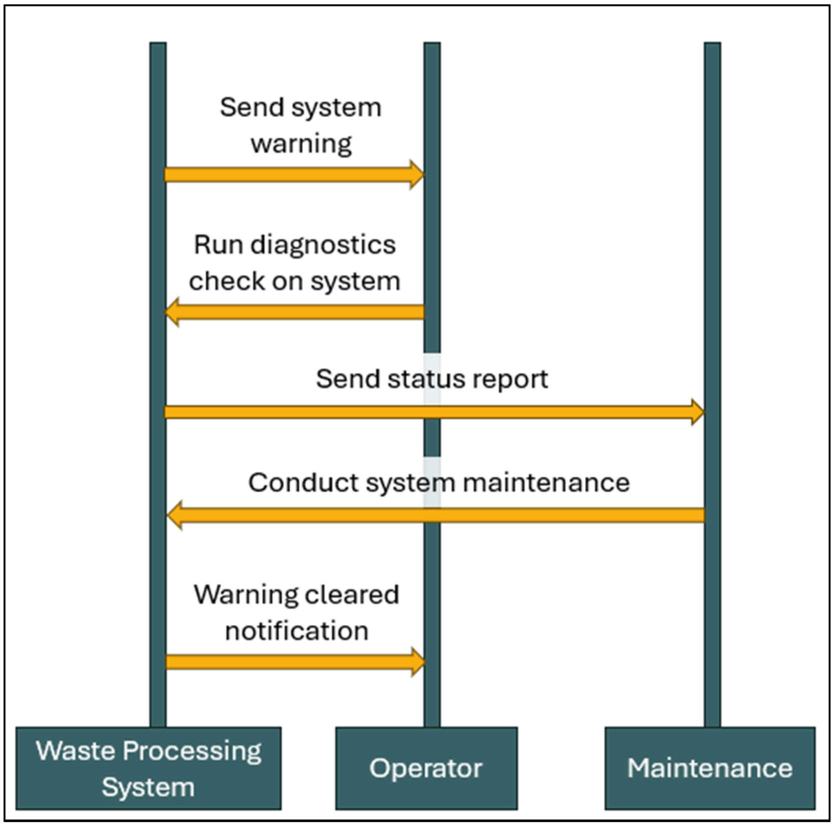


Figure 4.4-2 Sequence diagram of the conduct maintenance use case

4.4.3. Regulatory watchdog requests a data log of system operations

In the final sequence diagram shown below, regulatory watchdogs are requesting a report of data and log of activity of the nuclear waste processing system. The regulatory watchdog first enters pin into system, and the system responds by asking which report data the watchdog would like to see. The regulatory watchdog selects the desired report, and the system retrieves the desired report. Once the report is received, the watchdog will add compliance comments to the report. This report is submitted through the system, and the plant manager is notified of the compliance notes and status of the system.

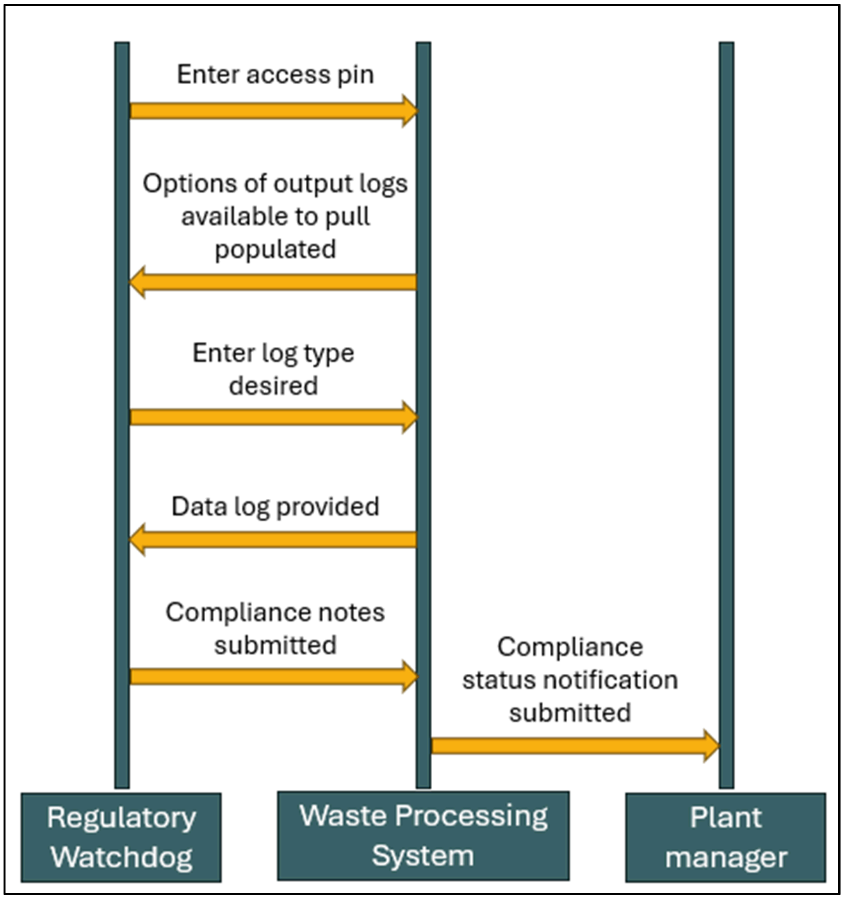
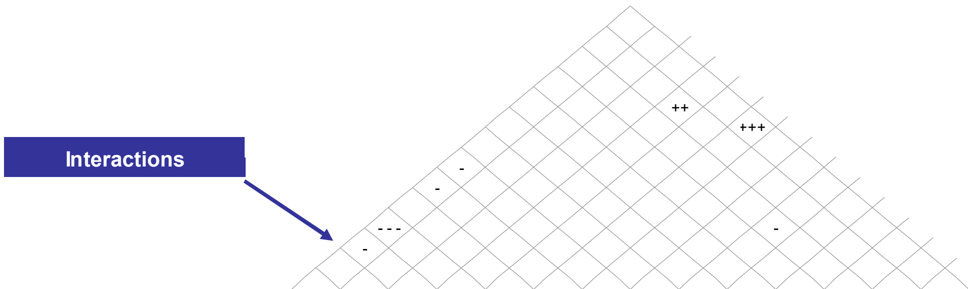


Figure 4.4-3 Sequence diagram of the print data log for regulatory compliance use case

4.5. Quality Function Deployment (QFD) Analysis



WHATs - Stakeholder Characteristics	HOWs - System Objectives	Power use of furnace <1MW	Material limit of interfacing components >100 DPA/year	Pump flow rate 0.5 to 1.0 m^3/s	Furnace temperature maintained at 500C	Mass spec resolution of 50,000 FWHM	At least 2 backup holding tanks	Dosimeters placed every 1 m	Accessible controls within 2 clicks of main plant control panel	Waste contained within at least two outer vessel liners	Measurement of waste components every 30 seconds	Mold capacity of processed waste < 5 kg	Size of waste processing facility < 3,000 sq ft	Waste process system completion < 1 hour	Waste storage vessel capacity per tank 2 m^3	Importance: 5 High, 1 Low
Performance	Low power requirements			- -	- -											2
	Good reliability		+				+									5
	Fast waste processing			+++	+++									+++		4
	Good accuracy of removal					+++					++					5
	Waste processed in a format easy for new uses											+++				3
Efficiency	Affordable system	+++			-		-			-			++		-	4
	Little "good" material lost in the process					++					+					3
	Seamless integration into overall plant controls								+++		+					3
Maintenance	Safe off-normal material handling						++	++		++					+	5
	Easy to maintain		+													2
	Feature Raw Score	36	7	30	26	54	16	15	27	11	21	27	12	36	1	
	Feature Rank	2	13	4	7	1	9	10	5	12	8	5	11	2	14	

Figure 4.5-1 Quality function deployment analysis

The QFD analysis identified quantitative performance criteria to meet the characteristics desired by the stakeholders. After analyzing the proposed system solutions, many of the safety and maintenance system solutions did not appear to interfere with meeting performance metrics.

However, balancing system reliability and performance with cost and system affordability proved challenging. Particularly balancing low power requirements with operating the system efficiently via fast pump flow rates or maintaining a base level furnace temperature to avoid re-heating from RT or lower each time material should be melted, factors in support of enabling the waste material to be quickly processed. The ranking of the scores demonstrated that despite conflicting resolutions in attempting to resolve solutions for each of the stakeholder characteristics, those surrounding performance, accuracy, and efficiency parameters for the system still maintained the highest feature rank – largely due to the high importance the customer gave to such parameters.

4.6. System requirements

Based on the analysis through studying and completing the QFD exercise, and system capabilities outlined from the stakeholder expectations and requirements, the below list of system requirements were determined.

Reference	Requirement Type	System Requirement
SysR1	Operation	The power of the furnace shall be less than 1MW.
SysR2	Operation	The system shall pump waste material between 0.5 to 1.0 m^3/s.
SysR3	Operation	The furnace shall maintain temperature of 500˚C during operation.
SysR4	Operation	The waste storage vessel shall have a capacity per tank of 2 m^3.
SysR5	Operation	The system should be capable of processing 1 MT of materials per day.
SysR6	Operation	The system shall report the composition of processed materials to within 5 ppm accuracy.
SysR7	Performance	The material limit of interfacing components shall withstand at least 100 displacements per atom (DPA)/year.
SysR8	Performance	The entire waste process system shall be completed within 1 hour.
SysR9	Performance	The system shall remove radiation of material to below background radiation levels, less than 0.1 Bq/g.
SysR10	Performance	The system's materials and components shall require replacement on the same frequency, and no more than that of the fusion chamber.
SysR11	Diagnostics	The resolution of the mass spec shall be at least 50,000 FWHM.
SysR12	Diagnostics	The radiation level of the waste shall be measured at a rate of at least 0.5 Hz.
SysR13	Diagnostics	Controls shall be accessed within 2 clicks of main plant control panel.
SysR14	Diagnostics	The system shall report the of waste processed at any subsystem stage in thirty-minute intervals.
SysR15	Diagnostics	The system shall have diagnostic reports and indicators when the system deviates greater than 5% from normal operating conditions.
SysR16	Usability	The capacity of the molds for recycled post-processed material shall have a capacity of no more than 5 kg.
SysR17	Economics	The size of waste processing facility shall fit within a 3,000 sq ft building.
SysR18	Maintenance	There shall be at least 2 backup holding tanks for waste material pre separation.
SysR19	Safety	Dosimeters shall be placed every 1 m along the system.

SysR20	Safety	The system shall have at least two outer material liners for containment vessels.
SysR21	Safety	The system shall have dosimeters with accuracy of 0.1 mRem in each area of operation for workplace safety.
SysR22	Safety	The system shall have interlocks to protect maintenance workers or operators from accidental exposure.
SysR23	Safety	The system shall alarm when system location comes within 10% of workplace safety radiation exposure limits.
SysR24	Compliance	The system shall report the radioactivity level of incoming waste for processing to 1 Curie/gram accuracy.

4.7. Functional Architecture

4.7.1. Functional Decomposition

I identified the primary functions of the system as shown in the functional decomposition figure below.

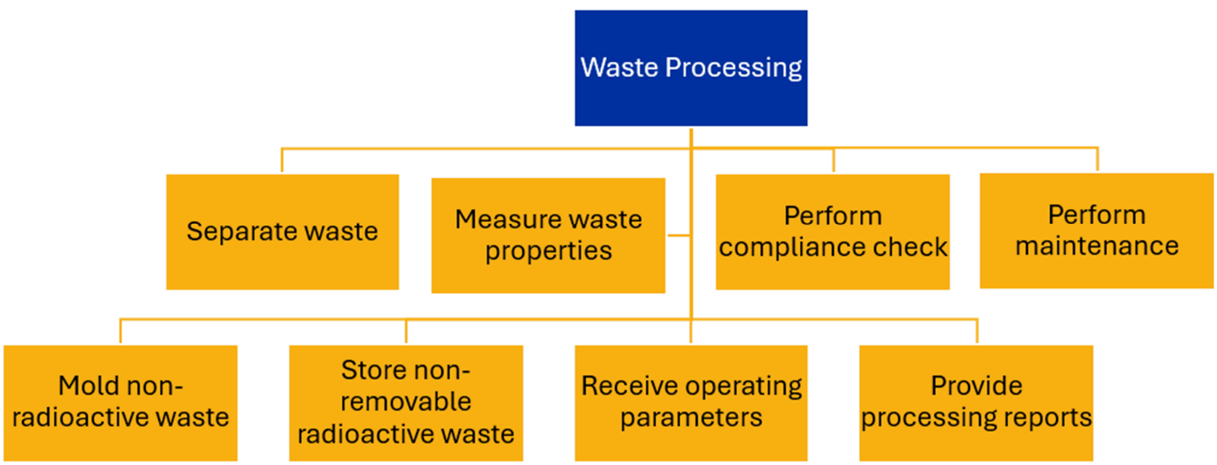


Figure 4.7-1 Functional decomposition of waste processing system

4.7.2. Functional Architecture

The functional architecture of the system for separating waste is shown in the image below.

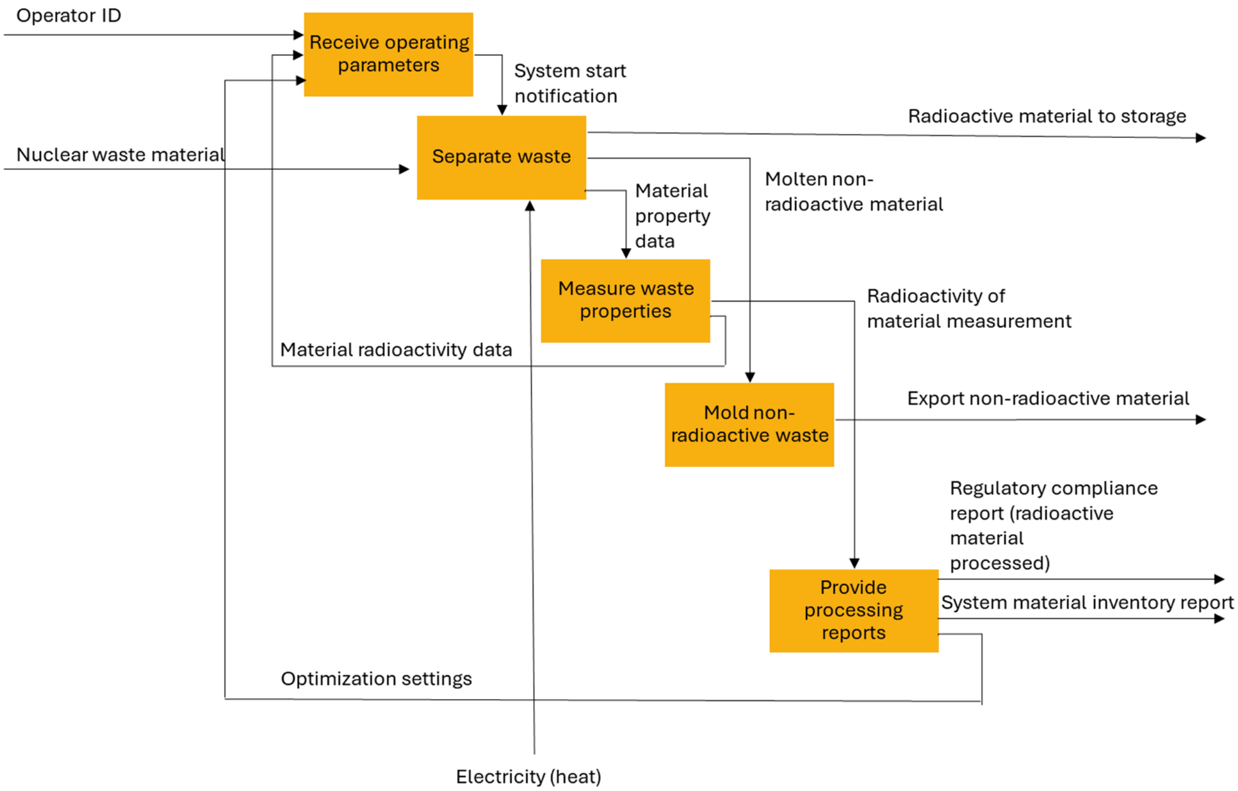


Figure 4.7-2 Functional architecture of separating nuclear waste into radioactive and non-radioactive material

The system functions by receiving an operator ID and nuclear waste material. Once the operating parameters are received by the operator, the system starts the separation process, and outputs both non-radioactive material and material data associated with the radioactive material to determine if it should be sent back to the system and repeat the separation process. The confirmed non-radioactive material is sent to the molding subsystem, where ingots of the now non-radioactive material are produced. These materials are exported to other areas of the plant or to external purchasers of the material. The data from the radioactivity measurement is recorded and used for providing processing reports. These reports inform and optimize settings based on material composition of waste material processed and can be used for determining improved operating parameters. This data also gets sent to the regulatory compliance watchdog with specific information related to the radioactive material processed and the inventory of material onsite. A general system progress report is also completed and stored for data tracking.

4.8. Risk Assessment

4.8.1. Technical Risks Identification

System risks and associated mitigation strategies were identified below.

Index	Risk	Risk to System Success	Likelihood of Risk Occurrence	Mitigation
R1	System may draw too much power from the plant.	5 – High	4 – High / Medium	Utilize an extra storage vessel such that waste can be processed in larger quantities but less power needs for fast pump flow rates or maintaining high furnace temperature for long periods of time
R2	System failure in radioactive material area too dangerous for maintenance personnel to intervene.	4 – High / Medium	3 – Medium	Robotics equipment developed for handling areas of high potential failure points.
R3	Operating requirements may result in too much radioactive storage on site flagging regulatory compliance concern.	5 – High	4 – High / Medium	Store radioactive material waiting to be processed at a separate, underground storage location as a reserve until system can process the waste fast enough to maintain compliance.
R4	Social acceptance of using previously radioactive materials for use in other industries (i.e., issues with securing offtake agreement of processed waste).	2 - Low	4 – High / Medium	Conduct informational presentations to potential buyers of material or set up agreements with nuclear fission companies, which may be more open to utilizing previously irradiated material.
R5	System disposes of too much non-radioactive material in radioactive containment.	2 - Low	5 – High	Implement a multi-step process of repeating stages of melting and skimming radiation method such that material is not conservatively discarded after the first pass.
R6	System requires frequent shutdown for radioactive materials damaging processing components.	5 - High	4 – High / Medium	Implement planned downtime during remaining plant scheduled downtime for pre-emptive maintenance, replacing commonly deteriorated parts before operational issues result.

Based on the mitigation measures above, new risk ratings were assigned. Risks associated with the highest risk to system success were analyzed using the stoplight matrix. These risks include the following:

- R1) System may draw too much power from the plant.
- R3) Operating requirements may result in too much radioactive storage on site flagging regulatory compliance concern.
- R6) System requires frequent shutdown for radioactive materials damaging processing components.

After implementing the risk mitigation methods, the new expected risk ratings are reflected in the stoplight matrix below with new risk ratings for R1, R3, and R6 followed by M (mitigated).

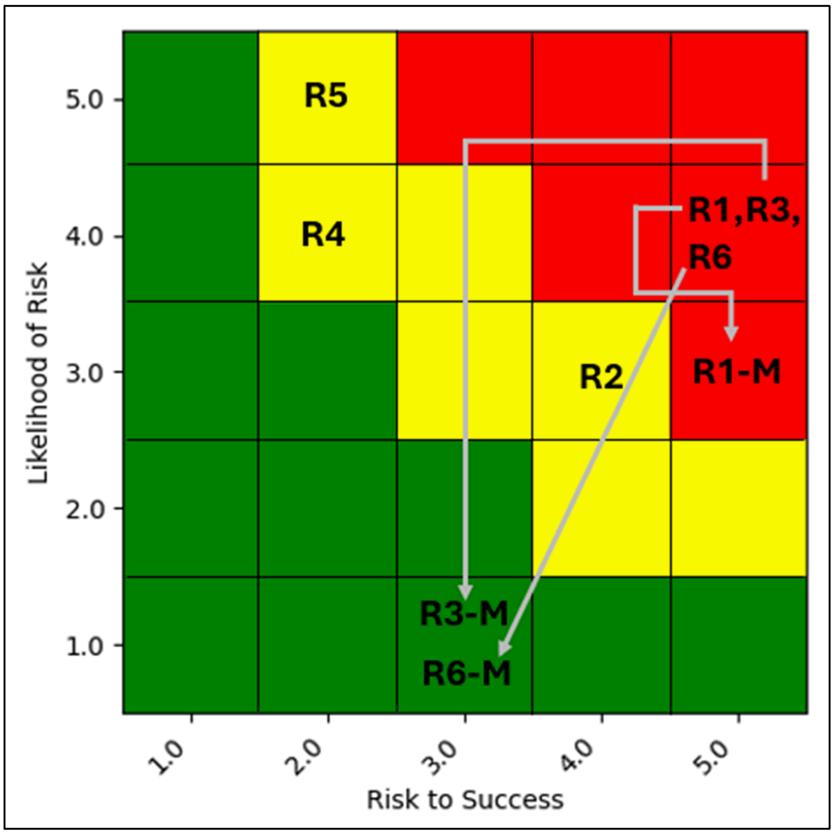


Figure 4.8-1 Stoplight matrix of risk and risk post mitigation strategies

The risk of the waste processing system drawing too much power from the plant remains at a high-risk level for risk to the system's success. However, by including an extra storage vessel and reducing the aggressive processing requirements, less power draw may be necessary – reducing the risk of the occurrence.

By siting a location as a viable option for storing extra waste in an underground facility until it can be processed in the plant as part of the waste processing system directly, it may drastically reduce the likelihood of a compliance issue for plant operations. An underground storage facility has its own risks and so while this may mitigate the risk of the system's success, it will remain at a medium risk level.

The final risk and mitigation plan considered is expected to reduce the frequency of unplanned plant outages as a result of preemptive maintenance that aligns with planned plant shut down. While this may reduce the useful life of material and increase costs, it is expected this will be offset by the expense avoided associated with a plant shutdown. Therefore, the risk to the system's success decreases, while the likelihood of the risk is significantly reduced.

4.8.2. Technical Performance Measure(s) (TPM)

Risk	Technical Performance Measure(s) (TPM)
System may draw too much power from the plant.	• Measure power draw of proposed pumps and heaters. • Total power draw should be at least 15% below expected power draw. • If total power draw of components approaches the maximum for economic feasibility, replace with higher efficiency, more costly replacements.
Operating requirements may result in too much radioactive storage on site flagging regulatory compliance concern.	• Measure flow rate of inlet of waste material > 0.75 m^3/s and flow rate of outlet of waste material > 0.75 m^3/s • Radioactivity level after 2 times material is re-processed in system
System requires frequent shutdown for radioactive materials damaging processing components.	• Material degradation testing of displacements per atom (DPA) of material per day of interfacing components • Thermophysical property measurement of radiation interfacing components weekly (density, brittleness, electrical resistivity, thermal conductivity) – indicators to assess changes in material composition

5. Reflection

I started this analysis by considering the proposed system need that I identified, what is currently used, and what may be implemented for use in the proposed fusion energy system. I then identified broadly what active and passive stakeholders would be interfacing with such a system. I outlined the system more generally in considering the concept of operations that would need to be applied for any of the selected concepts – considering what needs to be done in order to consider the system a success in terms of meeting the need defined. I then assigned expected characteristics and capabilities that the stakeholders would want from the system. This list was quantified and summarized for the stakeholder requirements.

As I continued in the exercises of developing the Pugh matrix, the concept of operations and the context diagram, I iterated on the list of stakeholder expectations that I would anticipate the active stakeholders would desire, which weren't previously listed during the first iteration of outlining the stakeholder expectations. After developing the use case and sequence diagrams, I laid out the basis of the QFD analysis. In conducting this analysis, I added additional items that the stakeholders may want for outlining the list of the "What's" that the stakeholders want the system to accomplish. This required re-considering the list of stakeholder expectation characteristics.

In conducting the risk analysis, technical performance measures, and mitigation plan for highlighted risks, I felt this was a very useful exercise to consider what system choices were selected that could diminish the viability of the system. Additionally, I found that in trying to mitigate for one risk, it was challenging to think of resolutions that do not generate a new risk. I re-visited the QFD after conducting the risk assessment, however, I did not make any adjustments. For implementing this project, this is where I would go back to stakeholders and conduct follow-up interviews to better understand areas stakeholder system requirements and determine which needs or expectations may be of lower importance which were originally thought to be of higher more critical importance. This process is truly iterative, and it is clear the refinement and improvement that results from circling through these steps multiple times.

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