Feasibility of Pulsed Current Technology for Removing Bulk Carbon from TRISO-based Fuels

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Abstract

The work described in this report has evaluated the technical feasibility of maturing the pulsed current technology and its full-scale application to processing TRISO used nuclear fuel. No insurmountable technological or safety barriers were identified to successfully maturing the technology to the fourth TRL, which was considered appropriate for a DOE-NE program. The authors recommend DOE-NE's Nuclear Fuel Cycle and Supply Chain Office should pursue the technology on that basis. In the immediate future, the authors recommend DOE-NE's Nuclear Fuel Cycle and Supply Chain Office should acquire non-radioactive surrogate and natural uranium TRISO compacts and pebbles as they become available from commercial vendors. These surrogates could then be used to mature the pulsed current technology.

Summary

The United States Department of Energy Office of Nuclear Energy (DOE-NE), Office of Materials and Chemical Technologies is leading development of technologies for processing Used Nuclear Fuel (UNF) to help inform future decisions regarding the nuclear fuel cycle. While Light Water Reactors have been deployed throughout the world for electricity production for many years, several advanced reactor concepts are currently being progressed with a view to deployment in the next decade. High Temperature Gas-cooled Reactors (HTGRs) hold promise in offering potentially wider applications in addition to electricity generation such as hydrogen production. These reactors achieve their high temperatures in part by the fuel's enhanced integrity in containing fission products and neutron moderation using relatively large quantities of graphite. The fuel's integrity is proffered by coating individual fuel particles in layers of pyrolytic carbon and silicon carbide. Such fuel is known as Tri-structural ISOtropic (TRISO). Breaching these layers, however, to access the used fuel kernel to recover the actinides is not possible with the technologies currently deployed in the nuclear industry. Additionally, separation and separate disposal of the graphite moderator potentially presents benefits for waste management and represents a new technical challenge.

The work described in this report has evaluated the technical feasibility of maturing the pulsed current technology and its full-scale application to processing TRISO UNF either as a head-end means of accessing the actinides or waste volume reduction. The technology works on the principle of applying pulsed high voltage/current discharges on inhomogeneous, nonconducting solids. A high voltage discharge (~400 kV and up to 100 J/cm) is delivered to electrodes separated from the solid by a liquid with a dielectric strength greater than the solid (e.g., water). Pressures of up to 1010 Pa and temperatures of approximately 10,000 K are generated in the solid; the result is a high-pressure impulse that propagates through the solids causing them to be fractured at grain boundaries due to mechanical stress. The technology is proven at industrial scale for fragmenting municipal waste and requires no chemical additions.

No insurmountable technological or safety barriers were identified to successfully maturing the technology to the fourth TRL, which was considered appropriate for a DOE-NE program in previous work, as a means for waste volume reduction or as a head-end process for reprocessing TRISO UNF. Installation of commercially available equipment in either a non-radiological or radiological facility can be accomplished within the safety parameters of existing facilities. The existing commercially available instruments offer enough variable parameters that process maturation can be accomplished. The largest hurdles for maturation of this technology will be the capital cost of the equipment and the availability of either unirradiated or non-radioactive surrogate materials with which to test the equipment. A commercial source of non-radioactive surrogate fuel is likely available by early 2024.

Evaluation of pulsed current technology's full-scale application was limited to conceptual flow diagrams, equipment and nuclear safety considerations given the technology's low TRL. Nonetheless, no insurmountable challenges associated with application of the technology to full-scale were identified at this stage. The likely scale of an industrial plant for processing TRISO UNF is at least an order of magnitude lower than those demonstrated for processing municipal waste, which is an advantage in some respects for a shielded facility where equipment will need to be remotely maintained.

The pulsed current technology is currently judged to be at the second TRL and, therefore, cannot reasonably be compared against other applicable technologies (e.g., acid intercalation

and thermal shock) to form a recommendation on whether DOE-NE should pursue it above others. Instead, the authors evaluated the technology on its own merits and specially to identify any significant challenges to its maturation or full-scale application. In summary, this work has not identified any insurmountable technical challenges to maturing the technology to the fourth TRL or its full-scale application to processing TRISO UNF. Therefore, the authors recommend DOE-NE's Nuclear Fuel Cycle and Supply Chain Office should pursue the further maturation of the pulsed current technology on that basis to the fourth TRL and then perform another evaluation. Additionally, the authors recommend DOE-NE pursue acquisition of unirradiated and non-radioactive surrogate fuel as it becomes available from commercial vendors irrespective of a decision on the pulsed current technology. The authors consider such material represents a strategic technical resource that does not frequently become available. Also in the immediate future, the authors recommend a flowsheet and concept be developed that shows how the technology could be integrated into the head-end of a TRISO UNF actinide recovery plant. The result of this activity would help contextualize maturation of the technology and identify any additional gaps.

Acknowledgments

Acronyms and Abbreviations

DOE-NE	Department of Energy Office of Nuclear Energy
EMF	Electro-Magnetic Field
LLW	Low Level Waste
HTGR	High Temperature Gas-Cooled Reactor
LWR	Light Water Reactor
PWTS	Pre-Weakening Test Station
NRTL	Nationally Recognized Testing Laboratory
TRISO	Tri-structural ISOtropic
TRL	Technology Readiness Level
UNF	Used Nuclear Fuel
MT	Metric Tons, or Tonnes

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1.0 Introduction

Chemical processing of Used Nuclear Fuel (UNF) to recover fissile material for recycle is an integral part of closing the nuclear fuel cycle. However, closing the nuclear fuel cycle presents several political and economic challenges. Notwithstanding the fact the technology is established and has been implemented historically in the United States and currently in France for processing Light Water Reactor (LWR) UNF. Nonetheless, the recent commercial activity in developing advanced nuclear reactors (small modular reactors and microreactors) and their use of advanced nuclear fuels has motivated interest in developing novel means of processing advanced reactor UNF. The work described in this report assesses the feasibility of a pulsed current technology for processing a specific advanced nuclear fuel, Tri-structural ISOtropic (TRISO), and makes a recommendation for its further development.

This report fulfills milestone number M3FT-23PN0304020211, *Evaluate feasibility of pulse current technology for removing bulk carbon from TRISO-based fuels*, in the U.S. Department of Energy Office of Nuclear Energy Nuclear Technology Research and Development Program.

1.1 Background

Separation technologies have been successfully used to recover and recycle uranium and plutonium from irradiated commercial LWR UNF, most notably in Europe. Recycling uranium and plutonium results in increased power production from mined uranium resources and contributes to the national energy security of the country recycling their UNF. In addition, appropriately processing the UNF reduces the volume of high-level waste requiring geologic disposal and there are potential benefits in reducing the radiotoxicity of the disposed material. Processing the UNF to also separate the minor actinides for transmutation results in further improving the utilization of a geologic repository by reducing the long-term heat load. In the United States, the current approach to managing UNF is once-through, with it being stored at the reactor sites while a geological repository is established for its disposal. Nonetheless, the United States Department of Energy Office of Nuclear Energy (DOE-NE), Office of Materials and Chemical Technologies is leading development of technologies for processing UNF to help inform future decisions regarding the nuclear fuel cycle and its potential closure. This is particularly important as power reactor technology shifts from traditional LWRs to novel advanced reactor designs that produce UNF that is significantly different from that of LWRs.

While LWRs have been deployed throughout the world for electricity production for many years, several advanced reactor concepts are currently being progressed with a view to deployment in the next decade. High Temperature Gas-cooled Reactors (HTGRs) hold promise in offering potentially wider applications in addition to electricity generation, such as hydrogen production. These reactors achieve their high temperatures in part by the fuel's enhanced integrity in containing fission products, which also allows for significantly higher burnup than achievable in LWRs, and neutron moderation using relatively large quantities of graphite. The fuel's integrity is greatly enhanced by coating individual fuel particles in layers of pyrolytic carbon and silicon carbide. Such fuel is known as TRISO. Breaching these layers, however, to access the used fuel to recover the actinides is not possible with the reprocessing technologies currently deployed in the nuclear industry because the nitric acid used to dissolve the fuel would be ineffective at breaching the silicon carbide coating.

Processing TRISO-based fuel introduces additional challenges due to the configuration of the fuel assembly. The assembly consists of TRISO fuel particles dispersed in a physically robust

graphite monolith. These can take the form of compact rods that are configured into hexagonal graphite blocks, or spherical assemblies referred to as "pebbles." Separation and separate disposal of the graphite moderator potentially presents benefits for waste management and represents a new technical challenge.

Previous work by Arm et al. (2023) established a strategy to help guide DOE-NE in identifying and maturing options for recovery of actinides from TRISO UNF for recycling into the nuclear fuel cycle to produce additional electrical power. The strategy identified several technologies demonstrated for fragmenting the graphite moderator to facilitate separation of the fuel particles, but all were judged at a low readiness level for implementation. One technology identified used pulsed electrical energy of high voltage and current and was considered technically attractive for further evaluation because it does not involve any chemical additions. Therefore, this task was initiated to evaluate the feasibility of the pulsed current technology for fragmenting the graphite as a precursor to separating the fuel particles for either separate disposal or recovery of fissile material.

1.2 Scope

This Plan is directed at providing DOE-NE with an evaluation of the feasibility of the pulsed current technology for fragmenting the bulk graphite of the TRISO fuel as a precursor to separating the fuel particles. Additionally, the evaluation provides DOE-NE with a recommendation as to whether the technology should be pursued to advance its maturity within the context of its Office of Materials and Chemical Technologies. Therefore, the recommendation focuses on maturing the technology to the point when commercial engineering organizations could consider it for industrial application. Maturation beyond that preliminary level of maturity is typically driven by what is needed to underpin design and operations and so is considered unreasonably speculative for the purposes of the recommendation.

The pulsed current technology could be used for reprocessing TRISO fuel in two separate operations. The first operation is the separation of the TRISO fuel particles from the bulk graphite moderator. After fragmentation, the liberated graphite would be separated from the TRISO particles by means that would likely leverage the difference in density between the two (e.g., fluidized bed). The separation itself is also complex but was not evaluated as part of this work except in the context of how the pulsed current technology's maturation could be advanced. The silicon carbide layer coating the separated TRISO particles could then be penetrated by alternative means such as mechanical crushing or chemical penetration or could be subjected to more intense pulsed currents and expose the fuel kernel for chemical dissolution and processing.

2.0 The Technology Maturation Process

The technology maturation process is summarized here to guide the reader in understanding the scope of the maturation strategy for the pulsed current technology presented in this report. The DOE (2015) has established a Guide for maturing technologies and integrating the maturation process into their standard processes for acquiring capital assets. Specifically, the Guide assists individuals and teams involved in conducting Technology Readiness Assessments and developing Technology Maturation Plans. Certain concepts outlined by DOE (2015) have been used by the authors to assess Technology Readiness Levels (TRLs) and then broadly develop strategies for initial maturation.

The readiness or maturity of a technology for a specific project life cycle phase is indicated by its TRL. There are nine TRLs indicative of increasing maturity as described in Table 2-1.

Table 2-1. Technology Readiness Levels

Relative Level of Technology Development	TRL	Definition
System Operations	9	Actual system operated over the full range of expected mission conditions.
System Commissioning	8	Actual system completed and qualified through test and demonstration.
	7	Full-scale, similar (prototypical) system demonstrated in relevant environment.
Technology Demonstration	6	Engineering/pilot-scale, similar (prototypical) system validation in relevant environment.
Technology Development	5	Laboratory scale, similar system validation in relevant environment.
	4	Component and/or system validation in laboratory environment.
Research to Prove Feasibility	3	Analytical and experimental critical function and/or characteristic proof of concept.
	2	Technology concept and/or application formulated.
Basic Technology Research	1	Basic principles observed and reported.

In terms of the capital asset life cycle, a TRL of 4 is required for it to be considered for the first Critical Decision of Alternative Selection. Therefore, maturing technologies to the fourth TRL is considered by the authors as a reasonable target for the types of programs currently funded by DOE-NE. At the fourth TRL, initial technology development, technologies could then be considered sufficiently mature for consideration for commercial or industrial application. At that point, a complete Technology Maturation Plan would be prepared to increase maturity to the sixth TRL, which is recommended for the third critical decision to complete design and start construction.

The descriptions provided by DOE (2015) for each TRL up to 4 are provided in Table 2-2.

Table 2-2. Descriptions of Initial TRLs

Relative Level of Technology Development	TRL	Description
Technology Development	4	The basic technological components are integrated to establish that the pieces will work together. This is relatively "low fidelity" compared with the eventual system. Examples include integration of ad hoc hardware in a laboratory and testing with a range of simulants and small-scale tests on actual feedstock. Supporting information includes the results of the integrated experiments and estimates of how the experimental components and experimental test results differ from the expected system performance goals. TRL 4-6 represent the bridge from scientific research to engineering. TRL 4 is the first step in determining whether the individual components will work together as a system. The laboratory system will probably be a mix of on hand equipment and a few special purpose components that may require special handling, calibration, or alignment to get them to function.
Research to Prove Feasibility	3	Active research and development is initiated. This includes analytical studies and laboratory-scale studies to physically validate the analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representatively tested with simulants. Supporting information includes results of laboratory tests performed to measure parameters of interest and comparison to analytical predictions for critical subsystems. At TRL 3 the work has moved beyond the paper phase to experimental work that verifies that the concept works as expected on simulants. Components of the technology are validated, but there is no attempt to integrate the components into a complete system. Modeling and simulation may be used to complement physical experiments.
	2	Once basic principles are observed, practical applications can be invented. Applications are speculative, and there may be no proof or detailed analysis to support the assumptions. Examples are still limited to analytic studies. Supporting information includes publications or other references that outline the application being considered and that provide analysis to support the concept. The step up from TRL 1 to TRL 2 moves the ideas from pure to applied research. Most of the work is analytical or paper studies with the emphasis on understanding the science better. Experimental work is designed to corroborate the basic scientific observations made during TRL 1 work.
Basic Technology Research	1	This is the lowest level of technology readiness. Scientific research begins to be translated into applied R&D. Examples might include paper studies of a technology's basic properties or experimental work that consists mainly of observations of the physical world. Supporting information includes published research or other references that identify the principles that underlie the technology.

There is considerable subjectivity in assigning TRLs to maturing technologies, which is heavily influenced by a project's risk tolerance, context and objectives. Nonetheless, the target TRL of 4 should be commensurate with the information needed to make informed technology selection decisions and complete initial conceptual design for industrial application.

DOE (2015) also define some of the specific terms used in their descriptions of each TRL. In terms of scale, the DOE (2015) suggest laboratory or bench scale systems, applicable to the lower TRLs, can be anything less than tenth scale but acknowledge engineering judgment should be applied in determining what is most appropriate. The fourth TRL represents the point when a scaled prototype should be demonstrated while lower TRLs use 'pieces' or components of the complete prototype. The fourth TRL also represents the point when the technology receives limited demonstration with actual. Otherwise, tests at lower TRLs use a range of simulants, which may include non-irradiated nuclear fuel for the subject of this report. The selection and formulation of simulants is important because testing, ultimately on a prototype at the fourth level, up to this point should prove the technology 'works' at an engineering level.

What is meant by 'works' is again subjective but typically tests that advance a technology to the fourth TRL should at least inform understanding the technology's capability to absorb process and feedstock variability or, colloquially, its 'robustness'.

This evaluation, therefore, includes identifying the types of tests needed to advance the pulsed current technology to the fourth TRL as part of the recommendation as to whether it should be pursued further by DOE-NE.

3.0 Description of TRISO Fuel and Challenges to Actinide Recovery

As described by Demkowicz et al. (2019), the development of TRISO fuel was driven by the desire to increase burnup. More extensive fission of fissile plutonium and reducing the downtime for refueling reactors are two reasons to operate to higher burnup. The cladding of conventional LWR fuel is in-service life-limiting component and TRISO fuel looks to improve in-service life by more effective containment of fission products. TRISO fuel was demonstrated at full-scale in the U.S. at the now closed Fort Saint Vrain and Peach Bottom nuclear generating stations. Today, the fuel, with some modifications from its earlier use, is being considered for application in advanced reactors.

As shown in **Error! Reference source not found.**, TRISO fuel consists of particles approximately 1 mm diameter that are formed into 'compacts' of either cylindrical shape (~12 mm diameter and ~25 mm long) or spheres ('pebbles') ~60 mm diameter. Compacts are fabricated by mixing graphite powder with a phenolic resin, then adding the TRISO particles and isostatically pressing the mixture. A heat treatment sometimes is applied. The cylindrical compacts can be considered like the subassemblies of conventional LWR fuel. Thus, they are loaded into prismatic graphite blocks to fuel a HTGR. The pebbles are coated with an outer layer of graphite (approximately 5 mm thick) and intended for use in 'pebble-bed reactors'. In the HTGR, inert gas (e.g., helium) passes through channels in the block or around the pebbles to cool the fuel and provide heat transfer for power conversion.
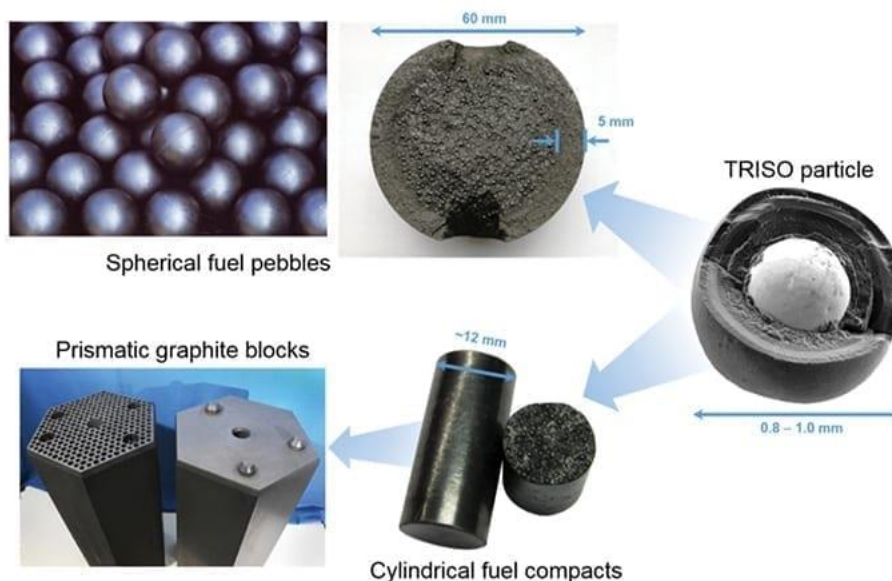
Figure 3-1. TRISO Fuel Assemblies (Source: US Department of Energy. Reproduced inPOWER at https://www.powermag.com/the-allure-of-triso-nuclear-fuel-explained/)

Important to this plan is a consideration of the fuel particles further illustrated in Figure 3-2. The inner core or 'kernel' of the particle consists of uranium dioxide or uranium carbide between 350 and 500 μm in diameter. The kernels are successively coated with layers of silicon carbide and pyrolytic carbon:

- A 'buffer' approximately 100 μm thick of low-density pyrolytic carbon that provides space for gas accumulation.

- Another, more dense layer of pyrolytic carbon approximately 40 µm thick that protects the particle surface from chloride during the subsequent deposition of silicon carbide.

- The main structural layer is silicon carbide, approximately 35 µm thick, which is primarily for retaining non-gaseous fission products.

- A final layer of pyrolytic carbon approximately 40 µm thick that protects the silicon carbide during handling and provides a surface for bonding the particle into the compact or pebble.

Both the inner and outer layers of pyrolytic carbon also contribute to gas retention.

Figure 3-2. The TRISO fuel particle (Source: US Department of Energy)

There are two primary challenges to recovering the actinides from the TRISO fuel that differentiate it from LWR fuel:

- Clearly the superior structure in the successive coatings of the fuel to retain gas and non-gaseous fission products also present significant barriers to accessing the fuel kernel for actinide recovery. Pyrolytic carbon and silicon carbide are chemically inert by design (from the standpoint of in-service fuel performance) that would make industrially mature UNF treatment processes ineffective. That is, the nitric acid normally used to dissolve LWR fuel cannot penetrate through the pyrolytic carbon and silicon carbide layers.

- A relatively considerable quantity of graphite is used in HTGRs and other TRISO-fueled reactors that present a secondary waste challenge. For example, Lotts et al. (1992) have postulated the volume of HTGR UNF dispositioned as a whole block in a geologic repository would be approximately 25 times that of conventional LWR fuel for the same quantity of heavy metal. However, if the fuel can be cleanly separated from the graphite blocks, then the latter could conceivably be dispositioned as low-level waste (LLW). However, notwithstanding the challenges in making a 'clean' separation by mechanical means to minimize contamination, another challenge is the carbon-14 content. Tzelepi et al. (2020) describe how nitrogen and oxygen impurities and the stable carbon, itself, in the graphite can all be neutron-activated to carbon-14, which is a limiting constituent for the LLW classification. Maintaining the carbon-14 concentration low enough for the de-fueled graphite blocks to be disposed of as LLW could be a significant factor in limiting the practical burnup achievable with TRISO fuel.

4.0 Overview of the Pulsed Current Technology

4.1 General Overview of Pulsed Current Technology Applications

Selective fragmentation (fracturing along the interfaces between inhomogenous solids) is based on the principle of applying pulsed high voltage/current discharges on inhomogeneous, nonconducting solids. A high voltage discharge (~400 kV and up to 100 J/cm) is delivered to electrodes separated from the solid by a liquid with a dielectric strength greater than the solid (e.g., water). Under these conditions, the electric current is then delivered to the solid through the liquid. Pressures of up to 10^{10} Pa and temperatures of approximately 10,000 K are generated in the solid; the result is a high-pressure impulse that propagates through the solids causing them to be fractured at grain boundaries due to mechanical stress (Bluhm et al., 2000).

Pulse current technology for fragmentation of solid materials was originally developed to fragment rock samples (Andres 1989) but continues to receive attention as described by Huang and Chen (2021) in their recent review. Within the geology community, the range of application is from laboratory scale (Andres 2001) for the fragmentation and examination of ores and extraction of fossils (Beasley 2020) to geological drilling for oil and gas exploration (Zhu et al, 2020, Li 2021). Further this technology has been examined for removal of metals from slag (Andres 2001) including up to the pilot scale, as well as recapturing valuable minerals from electronics waste (Maurice 2021, Zherlitsyn 2022).

In the context of processing ores, the energy consumption of pulsed current technology has been reviewed by several sources in comparison to the energy consumption for mechanical crushing. Generally, it is concluded that the energy consumption will be of a similar magnitude but whether the pulsed current technology uses less energy differs depends upon the assumptions underlying the study (Huang, 2021).

The size to which particles are being processed will influence the balance of energy consumption between mechanical and pulsed current processing of ores. As the particle size is decreased the energy consumption for pulsed current methods increases at a faster rate than mechanical means. Pulsed current methods are best suited for processing particles down to a particle size of 1-2 mm for ore materials. This is the size regime necessary for liberating TRISO particles from bulk graphite.

4.2 Application of the Pulsed Current Technology to Processing TRISO Fuel

For TRISO applications, the single work by Fütterer et al. (2009) sponsored by CARBOWASTE examined the fragmentation of surrogate TRISO pebbles. In the study, the energy consumption from the commercially available SELFRAG laboratory unit would equate to 0.125 – 0.25% of the energy which was produced by the fuel during its time in the reactor, with the possibility of the proportional energy consumption decreasing upon system scale up and optimization. Importantly, the CARBOWASTE experiment also demonstrated surrogate coated particles were liberated intact from their matrix. In a subsequent fragmentation, the silicon carbide layers were breached to sub-millimeter dimensions. This is a promising result, but further tests need to be performed with non-irradiated radioactive material followed by radioactive material to ensure the silicon carbide layer will remain intact during graphite fragmentation. The important conclusions of this work include:

- The 2009 CARBOWASTE tests used surrogate TRISO pebbles and demonstrated the feasibility of the technology for processing TRISO fuel. Based on this work, the technology can be considered at the second TRL. Full separation of the coatings and matrix material from irradiated kernels needs to be confirmed.

- Chemically dissolving the fuel was mentioned as a typical step in its recovery. Coating fracture was sufficient for this purpose after separation of the particles from the fuel element matrix (i.e., pebbles or compacts).

- Development of processes that further fragment the graphite (matrix or moderator) to facilitate decontamination and to obtain a powder as the starting product for possible re-fabrication of reactor graphite should be studied.

- The CARBOWASTE study suggests that high speed, high yield, controllable process suitable for fuel element matrix material streams (tons per hour) could be developed that have the capability to transition from batch to continuous operation. The potential for concentration of fissionable material in a limited space that exceeds criticality limits should be considered as well as potential release of gaseous fission products in system design. Operational and post-process water treatment must be integrated into the system design as water conductivity requirements were not evaluated.

- There is mention of incorporating mechanical sieves into the process flow to control the distance between the HV electrode and the pebble. The report suggests that 3 mm sieves are used to hold the pebbles and fragmented material passes through the sieve matrix. The design should be closely evaluated to ensure fragmented pebbles do not raise a radiological safety (criticality) concern.

4.3 Application of Commercial Units to Technology Maturation

Two vendors of pulsed current equipment were identified in the process of this work:

- SELFRAG AG are based in Switzerland and offer laboratory-scale batch (Lab) and continuous pilot equipment (known as the Pre-Weakening Test Station, PWTS) as well as technical services for large-scale applications (e.g., processing slag at ~100 MT/day).

- ImpulsTec GmbH are based in Germany and similarly offer a range of equipment and technical services.

The research community has employed devices from these vendors to complete studies on a variety of materials as earlier described and presented in the examples shown in Table 4-1. The SELFRAG units Lab and PWTS) appear to be the more widely used and are currently used across the world. However, as described by Zuo et al. (2015), the PWTS offers greater flexibility over the Lab and a continuous processing capability. In particular, the voltage and capacitance of the pulse generator can be adjusted independently to allow the tests at the same pulse energy, but different voltages and the electrodes' polarity is reversible. Bru et al. (2018) compared results from the Lab and PWTS and showed the latter performed with greater efficiency probably due to its generator being designed for energy-efficient industrial operations.

Table 4-1. Vendor Pulsed Current Equipment Research Application

Unit	Material	Reference
SelFrag Lab	Waste printed circuit boards	Duan et al. (2015)
	Glass fiber thermoset composite	Mativenga et al. (2016)
	Various rocks	Van der Wielen et al. (2013)
SelFrag Lab and PWTS	Ultra-high performance fiber-reinforced concrete	Bru et al. (2018)
SELFRAG PWTS	Three ores	Zuo et al. (2015)
ImpulsTec batch	Galvanized plastic, carbon-fiber composite, coated electrode foils from lithium-ion battery production	Leissner et al. (2018)

5.0 Evaluation of the Pulsed Current Technology for Industrial Implementation

5.1 Comparison of the Pulsed Current Technology to Alternates

Arm et al. (2022) has described several technologies applicable to fragmentation of the graphite moderator of TRISO fuel. However, all the technologies were judged to be at a very low TRL and certainly less than the fourth level considered by DOE (2015) acceptable for evaluating alternates. Therefore, Arm et al. (2022) did not identify any preferred technologies but did provide several criteria valuable for assessing proposed new technologies. The pulsed current technology is considered in the context of these criteria in the following list. However, the discussion should not be considered conclusive given the very low technical maturity of the technology.

- Technology 'robustness'. This attribute is associated with ease of control and the extent performance varies with varying process conditions. The pulsed current technology appears robust in the sense that performance described in the literature does not appear to be significantly dependent on temperature, pressure or any chemical conditions that could fluctuate.

- Technology Adaptability. This attribute refers to a technology's ability to adapt to developments in TRISO fuel. The technology appears adaptable to the extent it needs to be for fragmenting the graphite. However, performance needs to be demonstrated across ranges of the important process variables.

- Integration with Technologies for Actinide Recovery. Application of the pulsed current technology appears not to add any additional chemical reagents or generate any significant off-gas. It operates at ambient conditions. Therefore, there does not appear to be any significant issues as far as integrating the technology with actinide recovery.

- Hazard Control. This is likely one of the main areas of uncertainty for the pulsed current technology given no process requiring such high electrical energy has ever been attempted in a nuclear processing facility. Nuclear safety is the subject of section 5.3 below.

- Waste Management. Electrically or mechanically assisted processes are generally advantageous because they typically generate less process waste than their chemical counterparts. Key for this technology's application will be to ensure the separated graphite is sufficiently free of contamination that it can be classified as LLW. This aspect would include ensuring the process parameters are so selected to avoid breaching the fuel particles while ensuring adequate fragmentation of the graphite. This consideration is germane to fragmentation technologies in general. The single liquid waste stream is the water used in the fragmenter which will likely be contaminated at least with solid material but potentially also with dissolved fission products. Integrating the fragmentation operation into a complete flowsheet will likely yield opportunities to recycle or use the water elsewhere.

- Technology maturation beyond the fourth TRL. Given the available information, the technology appears readily scale-able so that most of the maturation could likely be accomplished at laboratory scale. The technology has been implemented at very large scale while laboratory-scale fragmentation has equally been successful on a range of heterogenous materials. Importantly, the availability of large quantities of actual TRISO UNF may not be very significant given the physical means by which the graphite moderator and, optionally, silicon carbide is breached. Nonetheless, understanding the effects of radiation on the

graphite and its susceptibility to fragmentation will be important for confidence in the maturation.

- Engineering for remote operations. This is another area of relatively significant concern again because the electrical equipment the technology relies upon have never before deployed in a nuclear processing facility. This aspect is considered further in the sections below.

5.2 Process Concept

A preliminary process concept for treating TRISO UNF based on the pulsed current technology was developed by extending information contained in the patent submitted by Fütterer (2006). The preliminary concept is illustrated in Figure 5-1. Intact TRISO UNF in either the pebble or block form is retrieved from storage. The blocks need to be reduced in size to approximately that of pebbles (~6 cm) for subsequent fragmentation using the pulsed current technology. The graphite is fragmented to allow the fuel particles to be separated from it. This is considered a gross separation and further decontamination of the graphite is achieved in a further step likely employing either a fluidized bed or hydrocyclone that exploits the density difference between the graphite and fuel particles. The graphite is disposed once sufficiently decontaminated. If the objective of treatment is volume reduction, then the TRISO particles can then be directly dispositioned.

Additional steps to facilitate reprocessing of the fuel particles are outlined in the dashed lines in Figure 5-1. The separated TRISO particles are further fragmented to expose the fuel kernels. The fuel kernels are then dissolved (likely in nitric acid consistent with established reprocessing practices) while the TRISO coating pieces remain as solid particulates. The coating pieces and dissolved fuel are separated to facilitate disposal of the former and reprocessing of the latter.
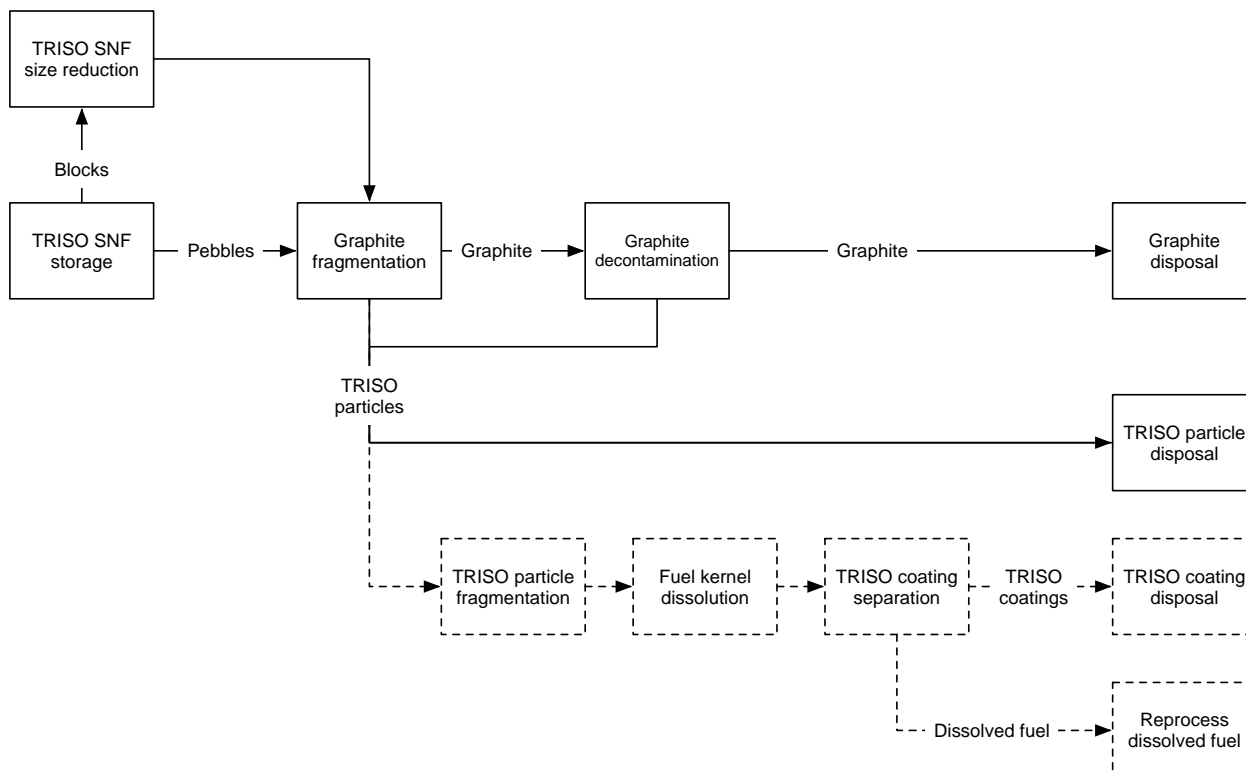
Figure 5-1. Outline Concept of a TRISO UNF Pulsed Current Treatment Process

The fragmentation vessel concept described by Fütterer (2006) and reproduced in Figure 5-2 is fabricated from steel and lined with an electric insulator such as plastic. The vessel is filled with water and the pebbles or size-reduced blocks added to it before a steel electrode (arranged in an electrically insulated cover block) is lowered into the water. A second electrode is arranged at the bottom of the vessel and is also electrically insulated from it. The fuel is placed on a sieve in the vessel. The size of the holes of the sieve would need to be optimized but are likely ~3 mm to allow fuel particles through and collect in the base. A pulse generator periodically charges the top electrode with voltages between 40 and 400 kV relative to the bottom electrode. For cracking the particle coatings, the sieve hole diameter should be slightly smaller than the kernels (0.4 mm) so the silicon carbide and pyrolytic carbon fragments drop through. Alternatively, the sieve need not be used at all since the subsequent dissolution step essentially performs the separation of fuel from coating fragments.
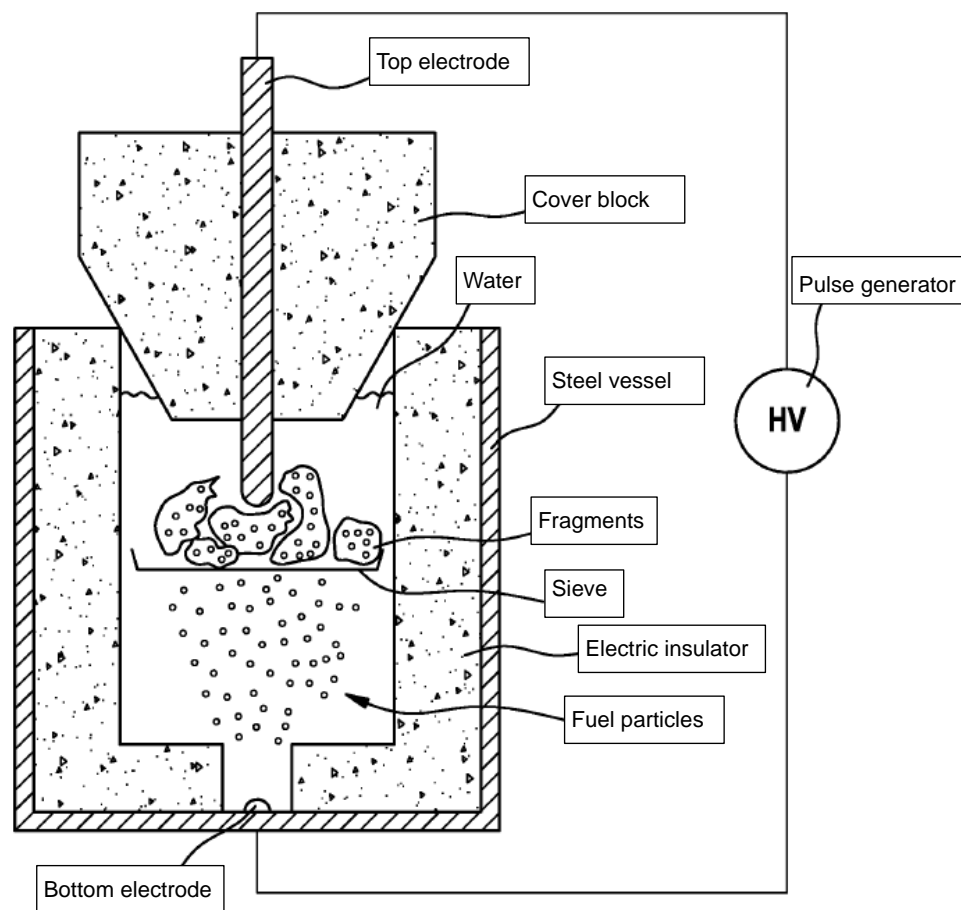
Figure 5-2. Conceptual Fragmentation Vessel (reproduced from the patent of Fütterer (2006))

Generation of electrical discharge shockwaves causes erosion of electrodes and other spark formation components (McWilliams, 2015). The erosion is estimated to be ~2mm (~50,000 pulses) (Kovalchuk, 2013). The number of pulses needed to fragment a pebble was stated to be 300 by Fütterer et al. (2009) for a typical 222.5 g pebble used in their tests. This results in 165 pebbles (37kg) processed per electrode maintenance period. The electrodes may be

inexpensive, but they are physically located in the water solution with the fragmented fuel. Therefore, the system design must allow for routine replacement of these components.

The scale of the process was developed by considering the published operating characteristics of the X-Energy Xe-100 reactor described by Chapman (2023). The initial operating concept for the Xe-100 involves discharging 179 pebbles from the core of 220,000 every full-power day. The power plant has an assumed operational life of 60 years. Therefore, a treatment plant should be capable of treating 179 pebbles per day assuming the same operational life. For conceptual purposes only, we considered an Xe-100 fleet of 100 reactors (representing approximately 10% of the current nuclear electricity generating capacity in the US) for the treatment plant to treat approximately 18,000 pebbles per day. A single pebble weighs approximately 200 g and so the capacity of the plant becomes approximately 3.6 MT UNF/day. This capacity is quite small compared to the size of plant designed by SELFRAG for processing slag waste (~100 MT/day). Furthermore, the PWTS described by Bru et al. (2018) has a nominal capacity of up to 1 MT/hour or approximately 7 times larger than required for the conceptual full-scale case. Therefore, a shielded chemical process plant with remote maintenance appears feasible based purely scale.

5.3 Nuclear Safety Considerations

Processing of actual TRISO UNF, at either research or industrial scale, will necessarily be performed in a Hazard Category 2 or 3 nuclear facility and be subject to nuclear safety analysis and inclusion in the facility's safety basis consistent with DOE-STD-3009, *Preparation of Nonreactor Nuclear Facility Documented Safety Analysis*. The amount of nuclear/fissionable material and energy involved in pulsed current processing includes a number of considerations in the areas of hazard and accident analysis.

This list does not represent a complete list of potential hazards that would be identified in a formal hazard analysis of a system design but does identify the primary areas for consideration and further evaluation.

5.3.1   Criticality Hazards

The pulsed current separation process will affect moderation and spacing of the fuel particles as they are separated from the graphite into the process fluid (likely water). The mass of fissionable material will also be increasing if a continuous flow process is implemented where multiple compacts or spheres of material are supplied to the system.

Control of mass, geometry, and other criticality safety parameters are not unique challenges in nuclear facilities. However, consideration of criticality safety throughout the technology readiness development process will need to be taken into account. Criticality safety evaluations will be a necessary part of any system processing non-simulant fuel and may result in process limitations; administrative requirements; and, potentially, engineered controls.

Active engineered controls to maintain a system critically safe (e.g., continuous sluicing to remove liberated fuel pellets) are candidates for designation as Safety Significant (SS). While SS engineered controls are regularly implemented throughout the DOE complex, this designation comes with increased design and operability requirements that can significantly affect cost, approvals to operate, and down time. Conceptual system designs at scale should aim to include passive features to address criticality safety concerns.

5.3.2   Processing Fluids

Spills, sprays, and boil-off of contaminated fluids are common hazards at nuclear facilities. As fuel particles are liberated, contamination from the graphite matrix or trapped radioactive gasses, for example, are likely to cause the working fluid (likely water) to become contaminated. Analysis of accident consequences involving the working fluid will require an understanding of the potential source term. Past research and other industry materials do not address potential contamination of the working fluid within the pulsed current system resulting in a knowledge gap for nuclear safety analysis. The technology maturation process will need to consider this gap and develop tests to establish the effect of contamination on the working fluid such that it can be translated into a source term for accident analysis. Depending on the degree of contamination of the working fluid, controls may be necessary to limit the concentration of dissolved radioactive materials in the fluid (e.g., regular disposal of the working fluid, continuous concentration reduction through fluid removal/replacement).

Consideration for alternate working fluids if water is not used may also be relevant to nuclear safety analysis. The use of corrosive chemicals as the working fluid would need to be evaluated for interaction with connected systems (i.e., the facility ventilation system). If connected systems are credited features in the existing facility safety basis, then the protection method for those systems by using an abatement technology for evaporated fluid would likely be elevated to the same level as the system being protected (e.g., SS or defense in depth).

5.3.3   Electro-Magnetic Fields

The production of the high-energy electrical pulses will create EMF which require shielding to prevent interaction with nearby electronics (e.g., a Faraday cage). Depending on the facility's existing safety basis credited controls and their location within the facility, the EMF shield may become a credited support system and be required to be elevated to the same level system(s) being protected (e.g., SS or defense in depth). The selection of the facility and location within the facility for the deployment of a pulsed current system should consider these interactions to limit the impact of EMF on credited safety basis, as well as other general service, electrical systems.

5.3.4   Maintenance Requirements

Maintenance requirements, including regular replacement of the system's electrode, will need to be evaluated via the nuclear safety hazard analysis process. The development of this report did not identify any significant hazards associated with system maintenance but depending on the direct radiation hazards and other physical realities of a permanent installation, handling of maintainable components may introduce additional hazards that rise to the level of requiring safety basis controls. Consideration of maintenance requirements should be given to the system design to minimize the hazards to workers and the facility to eliminate the need for additional controls.

5.3.5   Inadvertent Breach of Fuel Pellets

The process described in this report focuses on the liberation of fuel particles from the graphite matrix. However, previous research by Fütterer et al. (2009) shows the capability of the pulsed current technology to separate the fuel kernel from the protective coating. The fuel kernels are robust solids and are not likely to produce an unexpected sludge. However, if the particle is breached, release of additional fission gasses is likely, and the presence of the smaller fuel

kernels may introduce an alternate variation of the criticality hazards described previously. Additional development of this technology should evaluate the likelihood of the inadvertent breach of the fuel particles and further understanding of how the system hazards change if this occurs. If system parameters, such as the power setting, can eliminate this as a potential scenario, then that should be clearly established and is a likely candidate for a process control within the facility safety basis.

6.0 Evaluation of the Pulsed Current Technology for Experimental Implementation

6.1 Pulsed Current Technology Maturation Strategy

A strategy for maturing the pulsed current technology was presented by Arm et al. (2022). At that time, a TRL of unity was applied to the technology but the limited work by Fütterer et al. (2009) on surrogate pebbles was not known to the authors. Given that work, a TRL of two is more appropriate, albeit low in that range.

While application of this technology to processing TRISO fuel will result in different process parameters, the technology progression in the mining and geology space can serve as a partial roadmap to technology maturation, particularly with respect to what variables should be probed to augment fragmentation of TRISO compacts. Advancing through the second level requires the fragmentation be characterized as a function of the major operational parameters, including:

- Capacitance (Zhang and Nie (2023))

- Electrode geometry or spacing (Yan et al. (2023) and van der Wielen et al. (2013))

- Polarity (Yan et al. (2023))

- Pulse rate (van der Wielen et al. (2013))

Characterization would take the form of fragment size measurement and any disruption to the coatings of the simulated fuel particles. Early tests could use simple graphite pieces to provide some initial data and a broad envelope of conditions for subsequent tests with simulant. The SELFRAG Lab unit appears to be the established platform to perform these tests.

At the third TRL, the ability to handle multiple pebbles or compacts within the same equipment should be demonstrated. An experimental prototypic unit could be designed and fabricated, likely in collaboration with SELFRAG, to accomplish these tests. Indeed, a small-scale version of the equipment envisioned by Fütterer (2006) in his patent for TRISO application (further details are provided in section 5.1) is conceivable. Tests at this TRL should evaluate the effects of high voltage discharge effectiveness changing as the water ion content (conductivity) increases through both plasma formation and dissolution of fuel and matrix fragments. Potential solutions to mitigate resulting performance degradation could include alternative fluids, ion exchange, fragmentation waste stream filtration, or separation methods (McWilliams, 2015).

Additionally at the third level, the ability to physically separate TRISO particles from electrolytically generated rubble needs to be developed. Gross separation is achieved by the sieve intrinsic to the equipment, but further decontamination of the rubble is likely needed to facilitate disposal of it as LLW. In general, technologies such as fluidized beds and hydrocyclones that would separate the particles by exploiting their size and density difference from the graphite are well developed but will need to be demonstrated in this application.

The primary objective at the fourth level will be testing with unirradiated TRISO fuel compacts or pebbles while monitoring the solution and off-gas for escape of fission products and integrated with TRISO particle separation from the graphite fragments. Some preliminary tests with irradiated TRISO fuel compacts or pebbles would help to prove or calibrate the results from

simulated material. The separated particles should be examined to determine relative proportions of exposed layers (pyrolytic carbon versus silicon carbide).

Some results from tests at each level will inevitably be unexpected and necessarily lead to adjustments in the program moving forward. This is more likely at the higher TRLs and the program will need to be designed to accommodate modifications.

6.2   Surrogate and Unirradiated TRISO Fuel Availability

The availability of surrogate material is an important consideration for a maturation strategy particularly at the lower TRLs. Zirconium dioxide is an established non-radioactive surrogate for uranium in TRISO fuel. For example, Kim et al. (2020) selected zirconium dioxide for the fuel kernel for TRISO particle coating process development as they note it has "similar physical and thermal properties" to a uranium dioxide fuel kernel. Additionally, Jolly et al. (2016) likewise selected zirconium dioxide for the fuel kernel simulant for use in separate effects testing and for consolidation process development. They noted that characterization of the produced TRISO particles met the desired coating property specifications. PNNL is collaborating with BWX Technologies on the provision of zirconium dioxide-based surrogate material. At the time of writing this report, BWX Technologies are within a few months of being able to provide PNNL with surrogate TRISO compacts for testing. These surrogate compacts will be manufactured using the same equipment used to manufacture actual TRISO fuel and, therefore, must be treated as though they are radiologically contaminated.

Tests with unirradiated TRISO fuel are also important early in the maturation process in that the zirconium is replaced with uranium, which constitutes most of the mass in the kernel of TRISO UNF. Unirradiated TRISO fuel will be especially important for tests of the technology if applied as a head-end to reprocessing TRISO UNF. Like zirconium oxide TRISO compacts, PNNL has initiated discussions with BWX Technologies on the possible provision of unirradiated TRISO compacts containing natural uranium, which could be available this year at the time of writing this report. Custody of the natural uranium will need to be transferred but otherwise there should be no obstacle to acquiring the material for NE-4.3 purposes.

While there are good prospects for acquiring compacts for tests, the authors did not identify an immediate source of surrogate or unirradiated TRISO pebbles. The company X-Energy is pursuing a reactor (Xe-100), which is fueled with TRISO pebbles and are known to be constructing a fuel fabrication plant. Non-radioactive surrogate and then natural uranium TRISO pebbles are likely to be produced as the plant is commissioned and potentially available for NE-4.3 purposes.

6.3   Description of SELFRAG Laboratory Fragmenter

As mentioned, a commercially available laboratory scale pulsed current fragmenting unit is manufactured by SELFRAG AG in Switzerland. Intended customers include academic laboratories which focus on fragmentation of ores and electronic wastes. The unit is designed to operate as a batch processing unit with individual batch sizes of 1 kg, which would allow for the processing of up to five unirradiated or surrogate TRISO pebbles. A representation of the unit is shown in Figure 6-1 and an overall schematic of the system's three sub-systems in Figure 6-2. A video description of the SELFRAG Lab Fragmenter is presented at https://www.youtube.com/watch?v=EL7IGCEkZY4. After material is loaded into the fragmenter, doors are closed to prevent accidental touching of electrical leads and provide electro-magnetic

field (EMF) shielding to the surrounding area. With respect to the latter, the manufacturer advertises that the device can be operated by individuals with pacemakers with no ill effects.

Figure 6-1. SELFRAG Laboratory Fragmenter. The unit is entirely self-contained and operated by a remote touchscreen.

The system has several adjustable parameters. The number of discharge pulses can be set to a desired number and adjusted from 90 to 200 kV at frequencies from 1 to 5 Hz. The working electrode gap (distance between the discharge electrode and the grounding plate at the bottom of the sample vessel) can be adjusted from 10 to 40mm depending on size of the sample material and desired gap.
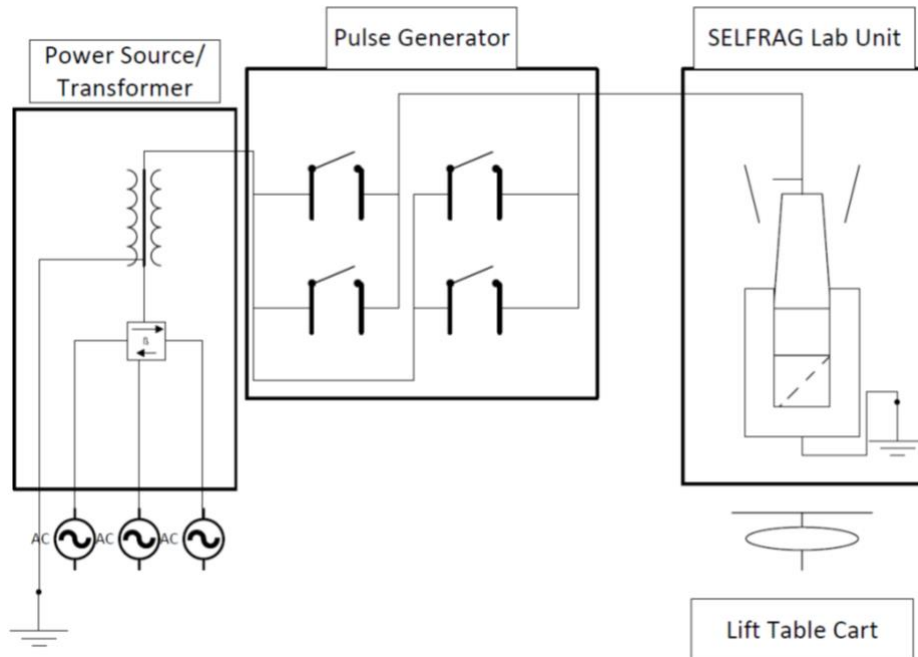
Figure 6-2: Schematic of working components of pulsed current fracture system

The dimensions of the unit are 2.4 x 0.9 x 2.1 meters and weighs 2,250 kg. The system draws 400V 3-phase power (10% or less phase variance at 50-60Hz) with a standby power consumption of 0.2 kW and a maximum power draw of 6 kW. The pressure of high purity nitrogen gas (class 4.5 or approximately 99.995%) in a Marx generator is used to control the delivered voltages. When operating, the environment the system is in should be kept between 12 and 32 °C and humidity kept below 75%.

6.4   Laboratory Electrical Safety Considerations

A wide variety of research and development is undertaken in the national laboratory complex, with varying infrastructure needs and hazards. Acquisition of the SELFRAG Lab Fragmenter is not anticipated to present any major problems in a national laboratory, but does require planning for infrastructure needs, for safety of the operators, and safety during maintenance activities.

One important way that staff are protected during the normal use of electrical equipment is through the requirement of Nationally Recognized Testing Laboratory (NRTL) listing of such equipment. While many common pieces of electrical equipment are sold in a listed condition, some specialty equipment is not. In this case, the SELFRAG system is not listed. Nevertheless, unlisted equipment can be accepted through the process of Field Evaluation. Either the vendor or national laboratory staff can contact an NRTL (or a Washington State acceptable engineering firm) to perform a Field Evaluation prior to shipment, or upon receipt. This evaluation ensures that staff will be able to perform safe operation of the equipment.

Since this is European equipment, a transformer will be required to supply the 3-phase 400 VAC necessary, but the power needs of 6kW (7kVA) are easily met. It has a physical footprint of 237 x 87 x 206 cm, so is not unreasonably large. It does not require any water or other coolant but does need to have a nitrogen gas supply. A national laboratory engineering organization would provide the design requirements for any facility modification necessary.

Normal operation of the SELFRAG system does not pose any risk. Use of the equipment will be done in accordance with the manufacturer's instructions. The one regular user operation which will need further evaluation is the occasional replacement of the discharge electrode. This is connected to a high-voltage capacitor bank, with the potential for stored energy. A procedure would be required to ensure that, while replacing the electrode, the capacitor bank has been sufficiently discharged and the system locked out to prevent recharging.

Any repair work beyond electrode replacement will need to be done by SELFRAG service engineers, in accordance with the specific national laboratory and DOE standards. The national laboratory's Electrical Safety organization would work with SELFRAG to develop a safe procedure for any repair work necessary.

6.5   Concept of Implementation in a Non-Radiological Laboratory

A round of testing fuel surrogate is conceptualized to study the efficacy of pulsed current fragmentation on separating graphite from the silicon carbide coating of the fuel particles. In summary, the tests are aimed at optimizing liberation of the silicon carbide-coated particles with minimal damage to the silicon carbide layer, separation of the particles from the bulk graphite, followed by potentially further fragmentation to breach the silicon carbide layer. Variables that could be adjusted using the SELFRAG Lab fragmenter are: the discharge voltage, frequency of pulses, total number of pulses, and working electrode gap. A conceptual experimental matrix is presented in Table 6-1.

Variable	# Pulses	Discharge Voltage [kV]	Pulse Frequency [Hz]	Electrode Gap [mm]
Number of pulses	10 – 600	140	3	18
Discharge voltage	300	90 – 200	3	18
Pulse frequency	300	140	1 – 5	18
Electrode gap	300	140	3	6 – 40

Table 6-1: Example test matrix for non-radiological fracturing of TRISO fuel surrogates

Following processing, the bulk graphite would be sieved from the TRISO particles with subsequent characterization of each fraction. Several steps will be used to assess the separation. Further mechanical sieving will be used to generate a rough particle size distribution with more refined particle size analysis (e.g., laser scattering) as needed. Optical microscopy will be used to assess the integrity of the silicon carbide layer as well as the degree to which the silicon carbide was completely liberated of graphite. A chemical analytical technique could be developed such that samples of the TRISO particles will be leached followed by analysis of the leachate by Inductively Coupled Plasma Optical Emission Spectroscopy to determine the exposure of kernel material. If fracturing of the silicon carbide layer is identified, scanning electron microscopy with energy dispersive x-ray analysis will be used to map extent of silicon carbide destruction and distribution of internal fuel surrogate (likely zirconium).

In conjunction with the fracturing tests, feasibility testing to separate the fuel particles from the fractured graphite are envisioned. In addition to the mechanical sieving that will be used to characterize the particle distribution, fluidized bed and aqueous separations could be

investigated to advance the TRL. Fluidized bed separations have been proposed as potentially effective as the density of the fuel kernel will be roughly five times denser than the fractured graphite, ~10 g/cm^3 for fuel kernel and ~2 g/cm^2 for graphite. For this separation, the combined fractured materials will be loaded into a glass tube and fluidized via air flow for a few seconds to a few minutes and separate naturally by density via entrainment. To potentially reduce downstream processing steps, aqueous separations will also be investigated. Using the same density principle from the fluidized bed, it may be possible to separate the fractured graphite from the fuel kernels in the same water medium that is used for the fracturing process by simply allowing time to separate or applying mild agitation (e.g., ultrasonic vibrations).

6.6 Concept of Implementation in a Radiological Laboratory

This section describes conceptual limits and considerations for processing simulated TRISO UNF in a radiological laboratory. Additional considerations may be necessary if the research is to take place in a Hazard Category 2 or 3 facility, see Section 5.3.

Promising results from non-radiological testing would be used in initial studies utilizing compacts or pebbles which are not irradiated but have a kernel composed of either depleted or natural uranium. The instrument pulse chamber of the fragmenter would be posted as a benchtop contamination area which would allow testing with 2-3 kg of natural uranium from a radiological safety standpoint; likely in excess of the maximum capacity of the fragmenter. Three kilograms of natural uranium in particulate form would utilize 0.05 % of a less than Hazard Category 3 annual air permit threshold, and thus would not be expected to negatively impact other activities performed within the building. Presently greater than 500 g of natural uranium is treated as accountable nuclear material by safeguards and thus requires greater scrutiny with respect to tracking and security. The capability to implement the security necessary from a safeguards and security perspective exist at multiple radiological facilities within the US-DOE national laboratory complex.

Four primary objectives would be achieved for radiological tests:

- Confirmation of the fragmentation of the graphite matrix while leaving the silicon carbide layer intact.

- Sieving of the TRISO particles from the bulk graphite followed by leaching of the TRISO particles with nitric acid to ensure no breaches allowing access to the fuel kernel have occurred.

- Return of the fuel particles to the fragmenter for intentional breaching of the silicon carbide layer.

- Leaching of the fuel kernel with nitric acid and determination of the extent of recovery of the actinide elements.

Fragmentation may create dispersible radioactive material. Therefore, the apparatus should be situated next to a radiological fume hood where sieving and leaching can be conducted safely. The general evaluation of the interplay between pulse parameters, size analysis, and separation studies would follow the same principles as outline in Section 6.5.

Studies conducted on irradiated TRISO compacts or pebbles would need to be performed in a Hazard Category 2 or 3 nuclear facility depending on the quantity of material being processed.

At this time there is no apparent reason why this could not be accomplished but implementation in such a facility is currently considered to be beyond the scope of this study.

7.0 Conclusions

The work described in this report has evaluated the technical feasibility of maturing the pulsed current technology and its full-scale application to processing TRISO UNF.

Evaluation of the technology's full-scale application was limited to conceptual flow diagrams, equipment and nuclear safety considerations given the technology's low TRL. Nonetheless, no insurmountable challenges associated with application of the technology to full-scale were identified at this stage. The likely scale of an industrial plant for processing TRISO UNF is at least an order of magnitude lower than those demonstrated for processing municipal waste, which is advantageous in some respects for a shielded facility where equipment will need to be remotely maintained.

No insurmountable technological or safety barriers were identified to successfully maturing the technology to the fourth TRL, which was considered appropriate for a DOE-NE program, as a means for waste volume reduction or as a head-end process for reprocessing TRISO UNF. Installation of commercially available equipment in either a non-radiological or radiological facility can be accomplished within the safety parameters of existing facilities. The existing commercially available instruments offer enough variable parameters that process maturation can be accomplished. The largest hurdles for maturation of this technology will be the capital cost of the equipment and the availability of either radioactive or non-radioactive surrogate materials with which to test the equipment. A commercial source of surrogate fuel is likely available within a few months of this report's publication.

8.0 Recommendations

The pulsed current technology is judged to be at the second TRL and, therefore, cannot reasonably be compared against other applicable technologies to form a recommendation on whether DOE-NE should pursue it above others. Instead, the authors evaluated the technology on its own merits and specially to identify any significant challenges to its maturation or full-scale application.

In summary, this work has not identified any insurmountable technical challenges to maturing the pulsed current technology to the fourth TRL or its full-scale application to processing TRISO UNF. Therefore, the authors recommend DOE-NE's Nuclear Fuel Cycle and Supply Chain Office should pursue the technology on that basis and then perform another evaluation. This would provide sufficient knowledge concerning the technology to compare it against alternatives.

In the immediate future, the authors recommend DOE-NE's Nuclear Fuel Cycle and Supply Chain Office should acquire non-radioactive surrogate and natural uranium TRISO compacts and pebbles as they become available from commercial vendors. Sufficient quantities should be acquired for planned tests as well as for potential future programs given such material does not frequently become available. Also in the immediate future, the authors recommend a flowsheet and concept be developed that shows how the technology could be integrated into the head-end of a TRISO UNF actinide recovery plant. The result of this activity would help contextualize maturation of the technology and identify any additional gaps.

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