U.S. Department of Energy
Advanced Research Projects Agency – Energy

Request for Information (RFI)
DE-FOA-0002703 on

Converting UNF Radioisotopes Into Energy (CURIE)

Objective:
The Advanced Research Projects Agency –Energy (ARPA-E) in the U.S. Department of Energy is seeking comments on the **draft** technical section of a potential future Funding Opportunity Announcement (FOA) for the CURIE program. This new program would focus on innovative technologies and approaches that will significantly improve the economics of commercial nuclear fuel reprocessing facilities, improve reprocessing material accountancy while decreasing materials attractiveness, and drastically reduce the volume of high-level waste (HLW) requiring permanent disposal. An ARPA-E workshop was held in July 2021 to help identify and refine metrics for this contemplated program; presentations can be found here. Such technological advancements would enable a 1¢/kWh fuel cost for a secure 200 MTHM/yr facility that does not generate pure plutonium streams while significantly reducing the volume of high-level waste requiring disposal. ARPA-E seeks input from experts in the fields of separations chemistry (e.g., solvent extraction, pyroprocessing, halide volatility, etc.); head-end processing (e.g., voloxidation, Kr/Xe capture, etc.); process intensification; material accountancy/online monitoring; project engineering; techno-economic analysis; digital engineering; systems analysis and risk assessment; advanced manufacturing and construction (including modular fabrication); artificial intelligence, machine learning, and digital twins; and sensors, instrumentation, autonomous operation, and robotics.

Please carefully review the REQUEST FOR INFORMATION GUIDELINES below and note in particular: the information you provide will be used by ARPA-E solely for program planning, without attribution. **THIS IS A REQUEST FOR INFORMATION ONLY. THIS NOTICE DOES NOT CONSTITUTE A FUNDING OPPORTUNITY ANNOUNCEMENT (FOA). NO FOA EXISTS AT THIS TIME. Respondents shall not include any information in their response to this RFI that might be considered proprietary or confidential.**

Purpose and Need for Information:
The purpose of this RFI is solely to solicit input about the scope of the draft technical section of the CURIE FOA for ARPA-E consideration. ARPA-E will not provide funding or compensation for any information submitted in response to this RFI, and ARPA-E may use information submitted to this RFI without any attribution to the source. This RFI provides the broader research community with an opportunity to contribute views and opinions regarding the technology and economics of reprocessing facilities.

This RFI previews only the **draft** technical section for a possible future program solicitation. If respondents are interested in other sections, including general format and requirements of an ARPA-E FOA, please visit https://arpa-e-foa.energy.gov/. DE-FOA-0002212: BREAKTHROUGHS ENABLING THERMONUCLEAR-FUSION ENERGY (BETHE) is a sample FOA to reference. A few common sections include but are not limited to:

- III.A: ELIGIBLE APPLICANTS (e.g., domestic entities)
- III.B: COST-SHARING
- IV.C: CONTENT AND FORM OF FULL APPLICATIONS
- VI.C: REPORTING (e.g., cost)
- VIII.B: GOVERNMENT RIGHTS IN SUBJECT INVENTIONS
- VIII.C: RIGHTS IN TECHNICAL DATA

REQUEST FOR INFORMATION GUIDELINES:

A summary of RFI responses will be presented by Program Director Jenifer Shafer on February 23-24, 2022, at ARPA-E's CURIE Industry Day. Individuals interested in attending the CURIE Industry Day event should indicate this in the RFI response.

ARPA-E may contact respondents to request clarification or seek additional information relevant to this RFI. All responses provided will be considered, but ARPA-E will not respond to individual submissions. **Respondents shall not include any information in the response to this RFI that might be considered proprietary or confidential.**

Responses to this RFI should be submitted in PDF format to the email address ARPA-E-RFI@hq.doe.gov by **5:00 PM eastern time on February 21, 2022**. Emails should conform to the following guidelines:

- Please insert "Responses for CURIE" in the subject line of your email, and include your name, title, organization, type of organization (e.g., university, non-governmental organization, small business, large business, federally funded research and development center (FFRDC), government-owned/government-operated (GOGO), etc.), email address, telephone number, and area of expertise in the body of your email.
- Responses to this RFI are limited to no more than 5 pages in length (12-point font size).
- Respondents are strongly encouraged to include preliminary results, data, and figures that describe their potential methodologies.

Questions: ARPA-E encourages responses that address any subset of the following questions and encourages the inclusion of references to important supplementary information.

1. For elements/radioisotopes present in used nuclear fuel that could be valuable for recovery, what are the estimated potential demand and prices for these elements/radioisotopes?

2. Are there specific technical research topics being considered that may fall under the “other” category of the draft technical section?
3. What is an envisioned timeline for gaining the requisite approvals and materials access necessary to use actual used nuclear fuel (UNF) for research experiments?
4. What other considerations (e.g., site use or transportation restrictions) should ARPA-E be aware of regarding the use of actual UNF in CURIE project proposals?
5. Any other issues, questions, or feedback regarding the draft FOA.

ATTACHMENT A

Draft of Technical Section for Converting UNF Radioisotopes Into Energy (CURIE)

B. Program Overview

The program goal of CURIE is to enable commercially viable reprocessing of used nuclear fuel (UNF)[1] from the current light water reactor (LWR) fleet by resolving key gaps/barriers in reprocessing ***technologies***, ***process monitoring***, and ***facility design***. The LWR UNF will, ideally, be reprocessed into feedstock that will be used to fuel advanced nuclear reactors (ARs), and to harvest other commercially valuable materials for industrial and medical uses. Projects funded under CURIE will develop innovative separations technologies, process monitoring of special nuclear material (SNM[2]), and/or equipment designs that will significantly improve the *economics* and *process monitoring* (Section I.C below) of reprocessing technologies while dramatically reducing the volume of high-level waste (HLW)[3] from LWR UNF requiring disposal. Specifically, CURIE is interested in separations technologies, process monitoring to enable predictive material accountancy, innovative equipment designs, and systems analyses that satisfy one or more of the ***global program metrics*** without negatively impacting other program metrics:

(1) significantly (i.e., at least an order of magnitude) reduce the volume of LWR HLW requiring permanent disposal,
(2) maintain disposal costs in the range of 0.1¢/kilowatt-hour (kWh)[4],
(3) provide a 1¢/kWh[5] fuel cost for a demonstration 200 metric tons of heavy metal (MTHM)/yr n^{th}-of-a-kind (NOAK) facility,
(4) *in situ* SNM process monitoring approaches that predict, within 1% uncertainty and under representative conditions, the post-process material accountancy, and
(5) development of UNF separations which do not produce pure plutonium streams.

In aggregate, these metrics are envisioned to support a commercially viable reprocessing technology that would provide valuable AR fuel feedstock and the ability to recover fission products of interest (e.g., noble precious metals and medical radioisotopes) while minimizing the Nation's HLW waste impact. CURIE is part of a comprehensive, nearly $90 million ARPA-E strategy to manage and reduce the Nation's HLW waste inventory and is designed to complement the ARPA-E ONWARDS[6] program. While both the ONWARDS and CURIE programs seek to mature innovations that will minimize HLW quantities, CURIE focuses on the development of

[1] UNF is also known as "spent nuclear fuel" (SNF). https://www.energy.gov/ne/articles/5-fast-facts-about-spent-nuclear-fuel.
[2] Special nuclear material is defined as plutonium, uranium-233, or uranium enriched in the isotopes uranium-233 or uranium-235. https://www.nrc.gov/reading-rm/basic-ref/glossary/special-nuclear-material.html.
[3] High Level Waste Definition: https://www.nrc.gov/reading-rm/basic-ref/glossary/high-level-radioactive-waste-hlw.html.
[4] This is consistent with the fee of 1.0 mill per kilowatt-hour ($0.001/kWh, equal to $1.00/MWh) set by the *Nuclear Waste Policy Act of 1982*, as amended, to fund the Nuclear Waste Fund.
[5] Evaluation of fuel costs from a reprocessing facility using proposed technologies will be completed using the Reprocessing Cost Estimator provided in Appendix 1.
[6] https://arpa-e.energy.gov/technologies/programs/onwards.

technologies that will enable UNF from the current LWR fleet to be utilized as feedstock for future nuclear fuel.

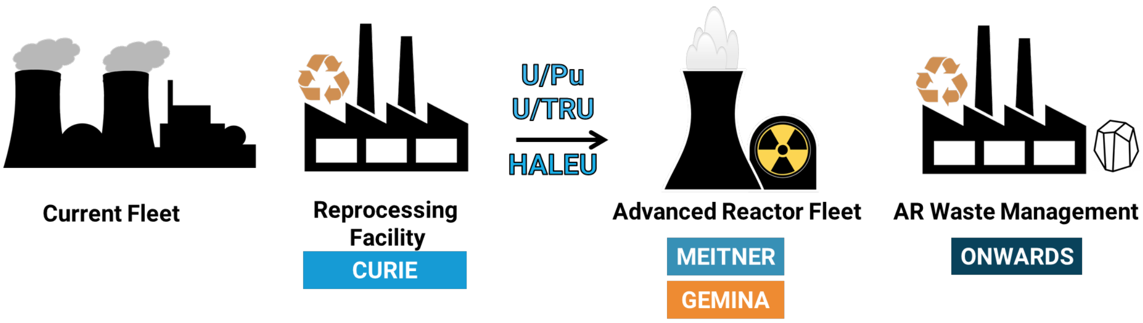

Figure 1. ARPA-E research and development in the advanced reactor technology space.

Background

Currently, the U.S. uses a once-through nuclear fuel cycle, in which UNF is ultimately dispositioned as HLW even though more than 90% of the energy remains. However, a *closed* nuclear fuel cycle, which includes reprocessing UNF to recover reusable actinides and *recycling* them in new fuel, has the potential to improve fuel utilization – especially when coupled with advanced reactors – and drastically reduce the volume of HLW requiring disposal. Historically, commercial reprocessing facilities[7] (e.g., La Hague in France) have used the solvent extraction-based Plutonium Uranium Reduction-Extraction process (PUREX), which was developed in the 1950s to recover uranium and plutonium products as uranium trioxide and plutonium dioxide, respectively. The plutonium dioxide product serves a feedstock that is blended with uranium oxide to fabricate mixed oxide (MOX) fuel, which is used by LWRs. Reprocessing facilities generally have large footprints[8] and high throughputs (>1000 MTHM/yr), require numerous unit operations (see Figure 2 below), and generate several waste streams and large volumes of waste.[9] As indicated in the figure below, several material accountancy[10] operations are necessary, including before and after dissolution and for the final uranium and plutonium products. Though a reprocessing facility in the U.S. could enhance fuel utilization and reduce the volume of HLW requiring permanent disposal, current estimates for a similar large-scale PUREX-based reprocessing facility constructed in the U.S. would be approximately $20 billion.[11] Given the advances in separations technologies, material accountancy and online monitoring technologies, and equipment design, opportunities exist to improve reprocessing facility economics by reducing the facility footprint, modularizing unit operations and construction,

[7] https://www.iaea.org/publications/8143/spent-fuel-reprocessing-options.

[8] For example, the original PUREX Plant was a concrete rectangle 1,005 feet long, 104 feet high (with approximately 40 feet below grade), and 61.5 feet wide. https://www.osti.gov/servlets/purl/10115226. Modern facilities are approximately half the size, though still generally large, multi-billion-dollar facilities.

[9] Foare, G., Meze, F., Bader, S., McGee, D., Murray, P. and Prud'homme, P., 2013. Waste Estimates for a Future Recycling Plant in the US Based Upon AREVA Operating Experience–13206. Waste Management.

[10] https://www.nrc.gov/materials/fuel-cycle-fac/nuclear-mat-ctrl-acctng.html.

[11] Idaho National Laboratory, Report No. NTRD-FCO-2017-000265, "Advanced Fuel Cycle Cost Basis – 2017 Edition," Module F1: Spent Nuclear Fuel Aqueous Reprocessing Facility, published September 29, 2017.

reducing waste streams, facilitating regulatory compliance, and enabling timely and accurate nuclear material accounting for unit operations.

In addition, AR fuel feedstocks derived from reprocessing LWR UNF can help stabilize the domestic AR fuel supply chains by providing AR vendors an alternate domestic fuel feedstock source. CURIE seeks to develop multiple reprocessing technologies, including aqueous, pyroprocessing, and fluoride volatility, that can provide feedstocks compatible with the fuel needs of AR designs nearing deployment (e.g., gas-cooled, molten salt, liquid metal-cooled). Any other separations technologies that meet program metrics are also within scope.

Generic PUREX Reprocessing Facility Flowsheet

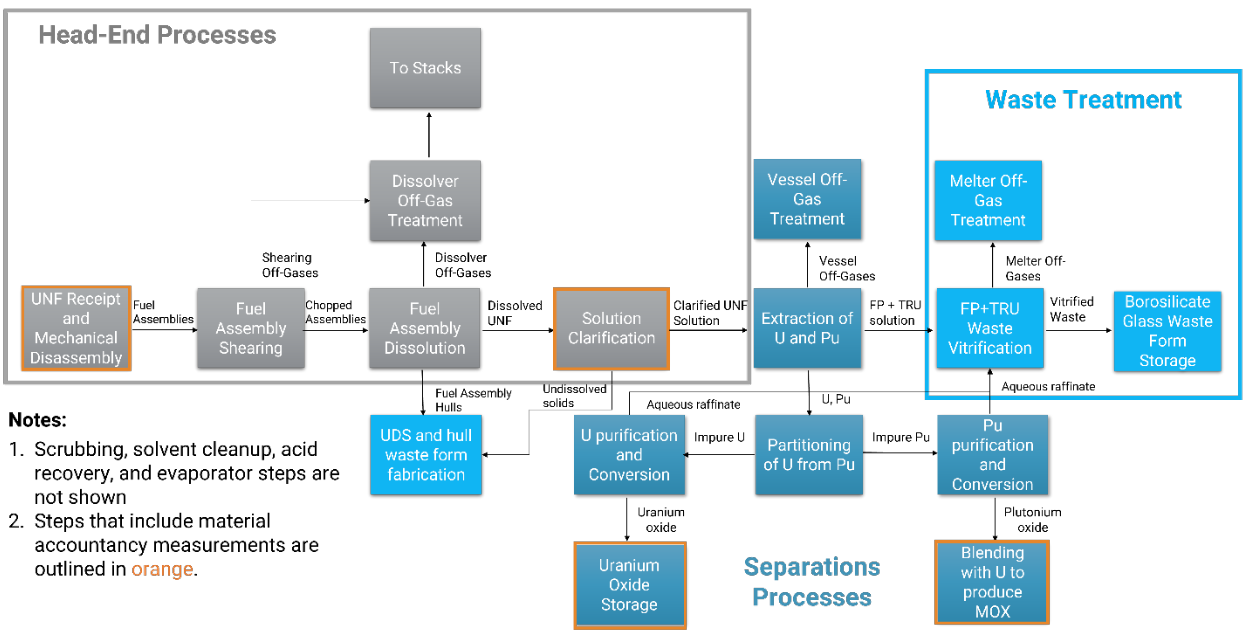

Figure 2. Unit operations associated with the PUREX process, the baseline commercial reprocessing technology.

Program Baselines

To enable applicants to assess the viability of various technologies, including their ability to reach program goals, a general framework that defines process inputs, baseline flowsheets, process outputs, and cost assumptions is provided below. Note that teams can deviate from baseline parameters outlined herein when evaluating their proposed technologies if appropriate justification can be made.

The baseline LWR fuel assumed for technology development is zirconium-clad uranium oxide UNF, which has an average cooling time of 10 years and a burnup of 44 GWd/MTU.[12] The

[12] "US Commercial Spent Nuclear Fuel Assembly Characteristics: 1968-2013", U.S. NRC, NUREG/CR-7227. Appendix A, Table A.14 contains UNF compositions (gram/MT uranium) https://www.nrc.gov/reading-rm/doc-collections/nuregs/contract/cr7227/index.html.

envisioned fuel-stock products arising from a reprocessing facility in support of this program are provided in Table 1. These products could ultimately be sold to a fuel fabricator to produce AR fuel. In addition, fission products of interest (e.g., noble precious metals and medical radioisotopes) could be recovered for industrial or medical uses.

Table 1. Envisioned elemental products arising from potential reprocessing facilities.

Reprocessing Facility Product	Composition (by weight %)
Uranium	100% uranium
U/Pu	70% uranium/30% plutonium
U/TRU	70% uranium/25.5% plutonium/4.5% minor actinides[13]

The presentation of known or baseline technological information is not meant to indicate ARPA-E's preference towards these technologies. ***ARPA-E is interested in significant technological disruptions, brought about by either known or outside-the-box technologies, that would enable achieving the global metrics, and technical sub-metrics, identified in this program.***

Metric Justification, Importance, and Interconnections

1. **Significantly reduce the volume of LWR HLW requiring permanent disposal**: A significant domestic resource of 86,000 metric tons of UNF currently exists.[14] ARPA-E estimates that, if deployed broadly, recycling actinides recovered from LWR UNF could significantly (i.e., by an order of magnitude or more) reduce the quantity of HLW requiring permanent disposal. Such a strategy would be transformational by enabling the expansion of nuclear power while limiting the geological repository[15] burden.

2. **Maintenance of 0.1¢/kWh disposal costs**: The current Nuclear Waste Fund was established to fund the development and operation of a geological repository for commercial HLW. This fund collected resources at the rate of 0.1¢/kWh to support the permanent disposal of UNF. Proposed UNF disposal solutions need to fit within the resources of the collective funds. [16] Reprocessing the existing (and future) LWR UNF could significantly reduce the quantities of HLW requiring permanent disposal and could significantly simplify waste management strategies and cost. Reprocessing UNF to facilitate complete consumption of long-lived

[13] Minor actinides (MA) are defined as neptunium, americium and non-U or Pu actinides present in UNF. The approximate transuranic composition of UNF is 1% Pu and 0.1% minor actinides. The minor actinide composition proposed for U/TRU fuel maintains the 10:1 Pu:MA ratio present in UNF.

[14] Government Accountability Office, Report No. GAO-21-603, "Commercial Spent Nuclear Fuel: Congressional Action Needed to Break Impasse and Develop a Permanent Disposal Solution," published September 2021, available online at https://www.gao.gov/products/gao-21-603. Accessed November 12, 2021.

[15] A geological repository is defined as an excavated, underground facility that is designed, constructed, and operated for safe and secure permanent disposal of high-level radioactive waste. See https://www.nrc.gov/reading-rm/basic-ref/glossary/geological-repository.html for more information.

[16] As of 2020, the current balance in the Nuclear Waste Fund is approximately $43 billion. More information is available at https://www.energy.gov/sites/prod/files/2020/12/f81/FY20%20-%20NWF%20Annual%20Financial%20Report%20Summary.pdf, accessed November 12, 2021.

actinides could also potentially obviate the need for a repository if the NRC classifies remaining shorter-lived fission products (<500 years) as something other than HLW.

3. **A 1¢/kWh fuel cost for a 200 MTHM/yr facility:** This cost metric is defined in the context of a hypothetical advanced reactor with a 200 MWe capacity and 100,000 MWd_t burnup. ARPA-E estimates, for this hypothetical reactor, the HALEU fuel cost would be approximately 1.2¢/kWh. Developing a cost competitive reprocessing technology would minimize the production of further HLW by developing a commercial market for reprocessed materials, while stabilizing AR fueling with a domestic material source. The 1¢/kWh cost metric is also in line with LWR fuel costs, which are estimated at 0.65¢/kWh. Therefore, reprocessed fuel at 1¢/kWh could enable backwards compatibility with the existing LWR fleet.

   The scale metric of 200 MTHM/yr is defined in such a way to support the modular deployment of reprocessing technologies. Modular deployment would be enabling for reprocessing in many ways, including potential supply chain development, benefits of NOAK deployment (including enhanced learning effects), increased access to capital resources, and flexibility to match reprocessing product outputs with advanced reactor needs by monitoring AR deployment plans.[17] A 200 MTHM/yr facility throughput is also anticipated to provide a sufficient U/Pu or U/TRU feedstock to meet AR fuel needs in the 2030 timeframe.[18]

   Viable costing scenarios for the capital and operational expenditures of a reprocessing facility are shown in Table 2. These solutions are provided as an example, as a 1¢/kWh fuel cost could be provided by multiple capital expenditure[19] (CapEx) and operational expenditure[20] (OpEx) combinations. These values have been assessed using the Reprocessing Cost Estimator[21] in Appendix 1. Preliminary findings from such analysis suggest a 2-fold and >10-fold reduction is required in Aqueous facility OpEx and CapEx costs, respectively. Pyroprocessing solutions would require less significant decreases in facility OpEx and CapEx relative to an aqueous facility, though advances are still required to reach the 1¢/kWh fuel cost goal. The cost target of a $500-$600 million CapEx would also be less than the up to $800 million in legal fees the

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[17] Pyroprocessing technology can be used to produce a metallic product that is suitable for metallic fuel fabrication for sodium fast reactors. Aqueous reprocessing is anticipated to be most compatible with thermal-spectrum reactors due to the decontamination requirements of thermal-spectrum technologies. Fluoride volatility yields actinide fluoride products that can be used to fabricate fluoride or metallic fuels or could be re-enriched.

[18] A July 23, 2020, letter from the Nuclear Energy Institute (NEI) President and CEO Maria Korsnick to U.S. Secretary of Energy Dan Brouillette, NEI estimates that, by 2032, approximately 220 MT HALEU per year would be needed to supply AR needs. Letter accessed online on November 14, 2021. U/TRU or U/Pu fuel would provide the feedstock equivalent to the same amount of HALEU, and reprocessed material could serve as a HALEU feedstock.

[19] Capital Expenditures - money spent by a business or organization on acquiring or maintaining fixed assets, such as land, buildings, and equipment.

[20] Operational Expenditures - money spent on the ongoing costs of running a business or organization, such as wages and rent on premises.

[21] The Reprocessing Cost Estimator Tool provided from ARPA-E in Appendix 1 will be used by teams to assess the cost impact of their technologies. This will be discussed in more detail below.

U.S. government is currently paying annually due to lack of progress associated with UNF disposal.[22]

Table 2. Demonstration of fuel costs derived from State-of-the-Art (SOTA) aqueous and pyroprocessing technologies, as well as potential CapEx and OpEx solutions that would be consistent with program goals.

	Aqueous SOTA	Aqueous Potential Solution	Pyroprocessing SOTA[a]	Pyroprocessing Potential Solution
Capital Expenditure	$20,000,000,000	$600,000,000	$600,000,000	$500,000,000
Operational Expenditure (as % of CapEx)	5%	2.5%	10%	4%
Throughput (MTHM)	800	200	200	200
Fuel Cost (¢/kWh)	6.4	1.0	1.5	1.0

[a]Derived from the LANDMARK study: Pilot_Scale_Pyroprocessing_Facility.pdf (anl.gov)

Regardless of reprocessing facility type, construction costs (e.g., concrete & rebar) constitute a significant fraction[23,24] (>50%) of the overall facility CapEx. Therefore, minimizing foundations, structures, waste and associated tankage, and facility footprint through process and hardware design can have a significant impact on overall cost. Other ways of minimizing cost could include, but are not limited to, innovative designs, construction technology, and management or changes to the separations process that decrease the overall footprint. Cost breakdowns can be assessed using the Reprocessing Cost Estimator. In general, HLW, off-gas, and low-level waste (LLW)[25] waste management can be a significant cost driver for both reprocessing CapEx and OpEx, so approaches that minimize these wastes are expected to reduce these costs by minimizing both the amount of facility footprint (e.g., concrete and rebar) dedicated to these operations and the staffing needed to support waste management.

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[22] https://www.nei.org/advocacy/make-regulations-smarter/used-nuclear-fuel.

[23] LANDMARK Foundation & Argonne National Laboratory, 2018 “Summary Report Conceptual Design of a Pilot-Scale Pyroprocessing Facility”, April 2018.

[24] Washington Savannah River Company, 2007, “Engineering Alternative Studies for Separations Summary Report,” EAS-G-ESR-G-00049, June 2007. (This document has a restricted distribution, may be proprietary, or both, and is not publicly releasable.)

[25] See the NRC’s definition of low-level waste and the waste classification tables promulgated in 10 CFR 61.55 for more information.

4. **Accurate, *in situ* UNF process monitoring:** ARPA-E is seeking technologies which enable the accurate, in process monitoring of SNM during UNF reprocessing. A program target is the development of approaches that would enable accurate prediction (within 1% uncertainty) of the post-process accountancy value assessed *ex situ*. Such technologies would be transformative in their ability to mitigate in-process diversion of UNF, enable off-site monitoring, provide substantially improved process control, and benefit future safeguards/monitoring. Process monitoring could also show early detection of potential process upsets, increase overall facility safety, and improve predictive maintenance of reprocessing facilities. For these reasons, ARPA-E anticipates joint-use technologies[26] could provide an overall cost benefit to the facility and would thus naturally incentivize participation in safeguards efforts.

5. **Development of UNF separations which do not produce pure plutonium streams:** The currently used commercial UNF separations process, PUREX, produces a pure plutonium stream. Separations that develop a co-recovered actinide product, either U/Pu or U/TRU, would represent a lower proliferation risk and are consistent with CURIE program goals of increasing the overall proliferation resistance of reprocessing technologies and products.

These metrics provide a path forward for commercially viable, safe, and secure reprocessing technologies.

General Information

This FOA is focused on supporting the development of viable technologies to achieve the global program metrics. Technical categories of interest are identified in Section I.D of the FOA.[27] Performance targets for the technical categories of interest are provided in Section I.E of the FOA. ARPA-E strongly encourages formation of multidisciplinary teams from various sectors to address multiple program metrics, such as having a team composed of individuals or organizations representing the chemical industry, major construction, and sensor development.

It is recognized that R&D to support the development and testing of separations and online monitoring technologies to support CURIE's goals may necessitate access to research resources (e.g., materials, facilities, software, computing resources, subject matter experts). These types of facilities include items such as, but not limited to, actinide isotopes and other radioactive materials; licenses and processes to support material handling, storage, and disposal; hot-cells and gloveboxes; and high-performance or field-specific computing codes and facilities. Applicants without existing access to such research resources are encouraged to establish teaming

[26] For the purpose of this FOA, joint-use safeguards technology is defined as technology used both for safeguards monitoring and facility operations.
[27] Since this draft technical section of the FOA only includes a portion of section I of the full FOA, Sections "I.X" (e.g., "I.D., Technical Categories of Interest") are analogous to sections "X" (e.g., "D. Technical Categories of Interest") found throughout this document.

relationships with commercial entities, national laboratories, universities, etc., with such research resources to successfully complete their proposed R&D activities. Applicants without access to such research resources or teaming relationships **will not be disqualified,** nor will they be deemed nonresponsive at the Concept Paper stage for that reason alone; however, applicants at the Full Application stage will need to be able to demonstrate that they have access to the research resources needed to successfully complete R&D activities under the subsequent full-application FOA. The resources and teaming relationships for separations and monitoring testing with actual UNF will be evaluated during the program (following the selection of award recipients) and are not a significant evaluation criterion during the evaluation stage. Additional information regarding research resources and teaming relationships can be found in Section I.E of the FOA.

C. Program Objectives

The program goal of CURIE is to enable commercially viable reprocessing of UNF from the current LWR fleet by resolving key gaps/barriers in reprocessing ***technologies***, ***process monitoring***, and ***facility design***. Specifically, CURIE seeks to support development of technologies that enable

- a significant reduction of the volume of LWR HLW requiring permanent disposal;
- global system disposal costs in the range of 0.1¢/ kWh;
- separations technologies supporting a 1¢/kWh fuel cost for a 200 MTHM/yr NOAK facility;
- *in situ* SNM process monitoring approaches that predict, within 1% uncertainty under representative conditions, the post-process material accountancy; and
- development of UNF separations that do not produce pure plutonium streams.

D. Technical Categories of Interest

Four technological categories have been identified as offering the most likely avenues to achieving substantial improvements in affordability and process monitoring to support predictive materials accountancy. While technologies discussed below are of interest, new technologies not considered for reprocessing are encouraged, as well as significant disruptions to more established technologies.

i) Category 1 – Reprocessing Technologies: This technology area includes process improvements that minimize waste volumes, compress unit operations (e.g., combine dissolution with solvent extraction), improve intrinsic proliferation resistance of actinide separations (including the prevention of creating pure plutonium streams), increase resource utilization efficiency, simplify off-gas management, enable repurposing and recovery of valuable fission products (e.g., noble metals, medical radioisotopes), equipment design optimization, and bolster commercialization supporting the 1¢/kWh fuel cost target.

ii) Category 2 – Integrated Monitoring & Materials Accountancy: This technology area includes pathways to support online monitoring of fissile materials during LWR UNF reprocessing. This could include improved sensor fusion, instrumentation to support automated collection of process monitoring training sets, or novel sensors. The ability to use online monitoring under relevant process conditions (i.e., high radiation fields, complex process matrix) to predict post-process materials accountancy within 1% uncertainty is sought by ARPA-E. The post-process materials accountancy must be established using validated and established methodologies (e.g., mass spectroscopy, alpha counting, etc.).

iii) Category 3 – System Design & Assessment: A reprocessing facility is a complex chemical and radiological facility with many opportunities for design optimization that could reduce a reprocessing facility's footprint, optimize throughput, facilitate efficiencies in construction and deployment that reduce CapEx and/or OpEx, and ensure adequate safeguards are maintained in a cost-effective manner. This category is intended for proposals that focus on lowering construction costs for reprocessing facilities via approaches such as (but not limited to) modularization of unit operations, automation, development of digital twins, and the use of advanced manufacturing and construction techniques. Moreover, systems analysis proposals that enable optimization of the facility footprint and throughput of reprocessing facilities; evaluate risks associated with a reprocessing facility; and otherwise explore ways of dramatically improving the economics of reprocessing facilities are encouraged in this category. This category will focus on identifying optimization opportunities in design and construction of a reprocessing facility, while being significantly integrated with Category 1 & 2 efforts.

iv) Category 4 – Other: This category is provided for submissions which do not cleanly fall into the above three categories but can potentially meet overall programmatic objectives (detailed in Section I.C). Submissions must make a compelling case for inclusion based on delivering a significant improvement to reprocessing affordability or safeguards.

Each applicant is required to indicate their primary technological area(s) of focus, as well as any secondary area(s), if appropriate.

ARPA-E **strongly** encourages proposals spanning two or more technical categories. For example, online monitoring associated with materials accountancy may provide significant benefit in the development of new separations technologies. Proposals that consider the economic impacts on diverse areas (e.g., head-end operations, off-gas, separations, waste management, safeguards) are also encouraged.

Coordination between teams with complementary technologies or proposals is also possible. For example, a proposal focusing on a head-end dissolution technology may benefit from generally coordinating this effort with a separate proposal focusing on the subsequent actinide/fission product separations.
As a reminder, applicants without access to such research resources or teaming relationships **will not be disqualified,** nor will they be deemed nonresponsive at the Concept Paper stage for that reason alone; however, applicants at the Full Application stage will need to be able to demonstrate that they have access to the research resources needed to successfully complete R&D activities under the subsequent full-application FOA.

For a proposed technology in Category I or II, the submission must clearly articulate the following:

- How the proposed technology leads to cost savings for the impacted unit operation.
- The technology's impacts on the capital and operating costs of other parts of the reprocessing facility. For example, a separation may minimize process waste and, consequentially, decrease the downstream cost of waste treatment at the facility.
- Which technological adjustments to the broader facility and fuel cycle are required to support the proposed technology. For example, a proposed separation technology may require a more selective headend process, which is upstream of separations.
- The number and volume of waste streams generated relative to the SOTA.

When evaluating impacts to CapEx, OpEx, and anticipated ¢/kWh fuel cost, all applicants should use the Reprocessing Cost Estimator provided in Appendix 1.

Category	Upstream Impact	Proposed Technology Impact	Downstream Impact
Capital Expenditure (% savings)			
Operational Expenditure (%savings)			
Anticipated total ¢/kWh fuel cost			

<u>Scaled UNF Separation and Monitoring Testing</u>

ARPA-E is interested in testing potential technologies with actual UNF, although lack of access to UNF or facilities appropriate for UNF handling is not a requisite for a successful application. During the award, ARPA-E will evaluate whether technologies are viable for UNF testing and, if appropriate technologies exist, funds may be available for additional studies. Preliminary goals of such testing could include achieving the following sub-metrics:

- Complete actinide co-recovery (>99% by weight).
- Product within 1% of proposed product composition (selected from Table 1).
- Sufficient fission product decontamination from product (<0.1% by weight).
- Assessment of separation reproducibility (e.g., execution of multiple extraction/stripping cycles).
- Throughput of 2 kg / hour for eight hours and three testing runs (Rate is ~10% scale of 200 MTHM/year facility, assuming 100% capacity factor).
- *in situ* SNM process monitoring approaches that predict, within 1% uncertainty and under representative conditions, the post-process material accountancy.

- Off-gas capture efficacy (>99% by weight).

The actual goals of UNF testing with developed separations and monitoring technology, as well as the physical and program resources, will be assessed during the program. The product produced during such an evaluation should be one of the products identified in Table 1 unless sufficient justification for an alternative product can be provided.

I. Category I – Reprocessing Technologies

Reprocessing technological solutions must address the affordability and complexity of facility head-end, off-gas, separations, and/or waste management operations. In all aspects of technical or facility development, the potential interfaces a given technology has with online monitoring, materials accountancy, or safeguards-by-design principles should be addressed. Reprocessing technologies responsive to this technical category will aim to achieve the following sub-metrics:

- reduce by at least an order of magnitude the volume of LWR HLW requiring permanent disposal,
- provide appropriate nuclear fuel feedstock (see Table 1),
- have an actinide content in waste streams of <0.1% by weight,
- have a fission product content in product streams of <0.1% by weight,
- have compatibility or potential compatibility with online monitoring technologies,
- support a 1¢/kWh fuel cost and throughput needs for a 200 MTHM facility, and
- be compatible with at least one existing licensed waste form or is co-developed with a compatible waste form suitable for final geological disposal[28].

While online monitoring is relevant to enabling challenging separations and supporting separations development, for the purposes of this FOA, online monitoring will be discussed in Category 2. Again, project coordination between categories and technologies is highly recommended in CURIE applications.

Separations Technologies

Separations of LWR UNF represents an opportunity to support AR fueling and minimize waste from U.S. nuclear energy production. The separation of long- and short-lived radionuclides can reduce the volume of radioactive waste that requires long-term storage[29]; however, the production of new high-volume waste streams (e.g., added solvents, equipment) must be minimal relative to a once-through fuel cycle. Further, an economically viable reprocessing facility must have market-appropriate capital and operating costs. To help performers evaluate the benefits their technology confers on capital and operational costs, ARPA-E has provided the

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[28] If neither criterion is met, the case must be made that the technology could potentially provide a significant disruption to reprocessing cost and safeguards SOA, such that separate investment in a novel waste form would be justified.

[29] Baptista, Annibal; Parker, Joshua; Park, Jung-Ho. "Advantages and disadvantages of nuclear fuel reprocessing". *Energia Nucleara*; v. 19(1-2); p. 32-35. https://inis.iaea.org/search/search.aspx?orig_q=RN:39071523

Reprocessing Cost Estimator tool (Appendix 1) that applicants should utilize for estimating technology cost benefits.

A variety of approaches currently exist that have been, or could be, used for the separations of UNF, including aqueous processing (e.g., solvent extraction), pyroprocessing, fluoride or chloride volatility, supercritical CO_2, and chromatography.[30] Of interest to this FOA are separation technologies that would significantly improve the economic viability of commercial reprocessing and decrease the proliferation-risk of material produced from a reprocessing facility. This could include the design of new chemistries, engineering, or equipment design. While not the only way of achieving the cost targets, ARPA-E anticipates proposals in this area will incorporate advancements that result in the facility's separation processes producing minimal process and secondary waste streams, significantly reducing the overall facility footprint and number of facility operations, thus reducing the overall facility CapEx, OpEx, and ultimately, fuel cost.

Each of the abovementioned separations technologies will require head-end treatment to prepare the UNF for separations and off-gas capture systems to recover volatile fission products. Commercial PUREX-based reprocessing facilities (see Figure 2) employ off-gas treatment systems throughout the facility to capture volatile and semi-volatile radionuclides such as ^{3}H, ^{85}Kr, ^{14}C, ^{106}Ru, and ^{129}I. More selective head-end processing could also limit the presence of challenging matrix elements (e.g. ^{3}H, Zr, and Ru) present during separations – minimizing the number and volume of waste streams and, ultimately, facility cost. Head-end operations (including off-gas capture) that significantly simplify downstream chemistry, improve valuable product recovery, and improve the overall cost attractiveness of a reprocessing facility are encouraged under this FOA.

Chemical and radiological HLW and LLW generated from reprocessing can add significant cost to the OpEx and CapEx of a facility. The HLW streams emerging from a reprocessing facility are those primarily containing fission products. The LLW streams would include process wastes, such as metal- (i.e., assembly hardware- and/or hull-) and off-gas- (^{85}Kr-, ^{14}C-, and ^{3}H-) containing wastes, and secondary wastes such as nitrate effluents, spent resins, and solvent residues. Notably, for the SOTA commercial PUREX process, more than 90% of the initial radioactivity is contained in the small volume of HLW generated, while approximately 96% of the total volume of waste generated is LLW.[31] Table 3 illustrates key process wastes, estimated volumes, and their waste classifications for wastes generated from a hypothetical large reprocessing facility licensed and constructed in the U.S. using existing NRC regulations. Proposed separations technologies that are associated with substantially less waste production or have effective strategies for post-separation waste management are viewed by ARPA-E as a promising approach to managing reprocessing facility costs.

[30] World Nuclear Association. "Processing of Used Nuclear Fuel" (Updated December 2020). https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/fuel-recycling/processing-of-used-nuclear-fuel.aspx.
[31] HLW volume and radioactivity estimate taken from Orano's reprocessing website describing radioactive waste generated from reprocessing. Last accessed 12/16/2021.

Table 3. Estimated Forms, Volumes, and Waste Classification of Process Wastes Generated in an 800 MT/yr Reprocessing Facility*

Process Waste Form	Volume (per MTIHM)†	Waste Classification‡
Vitrified FPs	0.91 m^3	HLW
Compacted Metal Process Wastes	0.85 m^3	GTCC§
Iodine-129 Waste (as Synthetic Rock)	6.25×10^{-4} m^3	GTCC
Kr-85 (in 50 L Cylinders)	0.005 m^3	A
C-14 Waste (in Cement)	0.075 m^3	A
Tritiated Wastes (in Cement)	5 m^3	B
Salt-Bearing Wastes (in Cement)	1.4 m^3	A

*Excerpted from G. Foare et al., "Waste Estimates for a Future Recycling Plant in the US Based Upon AREVA Operating Experience," paper #13206, WM 2013 Conference, February 24-28, 2013, Phoenix, AZ, USA.
†MTIHM = Metric Tons of Initial Heavy Metal. Volumes listed assume 5-year cooled UNF and do not include secondary waste stream (e.g., spent resins) volumes. For 50-year-old UNF, Kr-85 capture is unnecessary, and the volume of tritiated waste is expected to be lower because of its decay.
‡ Waste classifications were made based on existing NRC regulations. See the NRC waste classification tables promulgated in 10 CFR 61.55 for more information.
§GTCC=Greater Than Class C; GTCC waste is currently deemed unsuitable for near-surface disposal.

While Category 2 specifically discusses the development of sensors, monitoring, and other enabling technologies relevant to monitoring and safeguarding a UNF reprocessing *facility*, the role of safeguards and security-by-design must also be considered in separations technologies development, and any technology solution proposed shall not make safeguarding more challenging. Technologies that improve proliferation-resistance and/or intrinsically limit, at the chemical level, production of pure plutonium streams are of specific interest. ARPA-E is interested in process and production designs that would improve economics and security, and provide enhanced opportunities for safeguarding. Online monitoring technology which integrates with process control is considered an important design principle.

Predominant examples of separations technologies include aqueous processing (e.g., solvent extraction), pyroprocessing, and fluoride volatility. These technologies will be discussed in more detail below and the technical viability of these processes in various subcategories are presented in illustrative radar charts in Figure 2 that represent ARPA-E's general assessment of technology risks and competencies. Further discussion of the radar charts in Figure 3 are provided in the sub-section below. While not explicitly discussed below, ***novel technologies beyond aqueous, pyroprocessing, and fluoride volatility that enable other processing approaches are also of interest and encouraged.***

Aqueous **Pyroprocessing** **Fluoride Volatility**

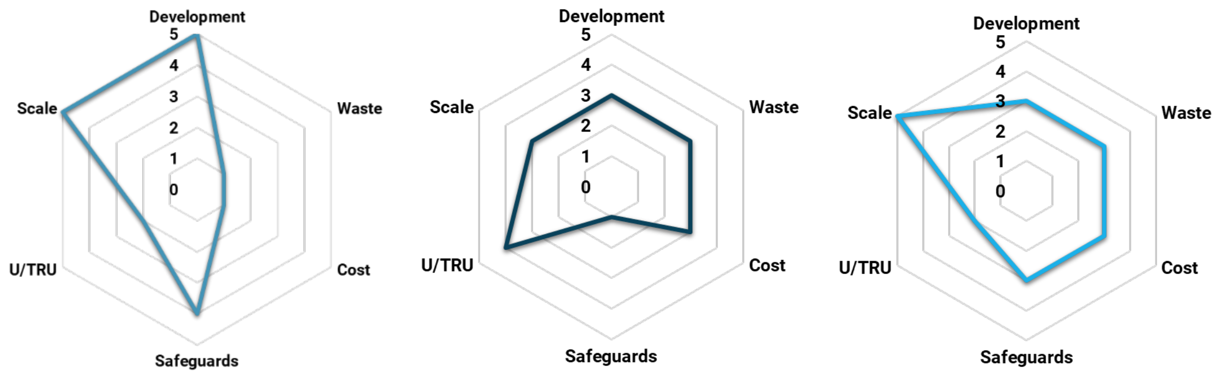

Figure 3. ARPA-E's general assessment of various demonstrated technologies for reprocessing UNF. A *5* is considered a technology strength, whereas a *0* is considered a technology weakness.

<u>Aqueous (Solvent Extraction)</u>

The standard method for separation of UNF, and the only method presently practiced on a commercial, industrial scale, is the PUREX[32]. Derivatives include technologies like CoDCon[33] (co-decontamination) or COEX (co-extraction of actinides).[34] These technologies are generally recognized to scale well and have a high level of development. However, there is no demonstrated pathway for a U/TRU fuel from a solvent extraction technology, and safeguards are largely established but are associated with significant cost. As discussed above, HLW and LLW management with aqueous separations is a significant challenge for this technology.

In general, many opportunities exist for the development of alternative solvent extraction technologies that would disrupt the processing landscape. Technologies that would enable the co-recovery of the AR fuel cycle-relevant actinides (i.e., uranium through americium) in a single separation step could improve both the economics and potentially proliferation resistance. Other technologies that could improve the group separations of the actinides or minimize third phase formation, thus allowing a higher solvent loading and minimizing LLW, are also of interest. Significant advancements in technology and facility layout would necessitate new facility designs, and Category 3 provides a mechanism to evaluate studies considering how various factors (e.g., the reprocessing of fuel cooled more than 30 years, safeguards-by-design, adjustment of unit operations) would impact the overall facility cost and actual facility designs.

<u>Pyroprocessing</u>

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[32] Ibid.

[33] G.J. Lumetta et al. (2019), "Simulant Testing of a Codecontamination (CoDCon) Flowsheet for a Product with a Controlled Uranium-to-Plutonium Ratio," *Separation Science and Technology*, 54:12, 1977-1984, DOI: 10.1080/01496395.2019.1594899.

[34] U.S. Nuclear Regulatory Commission, "Background, Status, and Issues Related to the Regulation of Advanced Spent Nuclear Fuel Recycle Facilities, NUREG-1909, June 2008, Agencywide Document Access and Management System (ADAMS) Accession No. ML081550505.

Pyroprocessing is a high-temperature, non-aqueous, batch electrochemical separation of UNF into different streams for re-use and/or disposal.[35] It is potentially attractive for production of fuel for some fast-spectrum AR fuel cycles from LWR UNF because the TRU elements, including plutonium, are not well separated from each other, providing a level of proliferation defense-in-depth.[36] In addition, such facilities have fewer unit operations, smaller footprint, fewer waste streams, are amenable to reprocessing short-cooled LWR UNF, and can potentially be co-located with other fuel cycle facilities or even reactors. For example, pyroprocessing of Experimental Breeder Reactor-II fuel was successfully demonstrated in a co-located Fuel Conditioning Facility.[37]

ARPA-E's assessment of pyroprocessing technology (cf. Figure 2) is that, compared to the reference PUREX-based reprocessing technologies, pyroprocessing has only been demonstrated on a small scale in a research and development setting. However, its current estimated costs are closer to program goals, and in general, though research on more robust pyroprocessing waste forms is actively being pursued, it is estimated that fewer waste streams and smaller volumes of HLW will be produced. Technologies that enable co-recovery of U/TRU have also been developed, but not demonstrated with UNF, but there are material accountancy challenges that need to be addressed. For example, online monitoring of pyroprocessing separations is considered a *significant* impediment to deployment. Technologies addressing these and other challenges will be considered in Category 2.

Technologies supportive of the fuel cost metric include, but are not limited to, those that enable reduction and/or synergistic combinations of unit operations, enable continuous operations, and simplify the handling and disposition of waste streams for current pyroprocessing flowsheets. Proposals outlining new and innovative processes should improve the cost-effectiveness, safety, and/or security of the pyroprocessing. Any technology solutions proposed must not increase the presence of actinides in waste streams relative to SOA capabilities and shall not make safeguarding more challenging.

Fluoride Volatility

Fluoride volatility is a high-temperature process that exploits the volatility of high-oxidation-state fluorides (e.g., UF_6) to achieve separation. It was used to recover more than 100,000 MT of uranium from irradiated non-commercial fuel and to reprocess Molten Salt Reactor Experiment fuel[38] in the 1960s. Of the actinides useful as AR fuel feedstock, uranium, plutonium, and neptunium can form hexafluorides, and flowsheets have been designed that target these actinides. However, americium and curium, along with most of the fission products, form nonvolatile fluorides that require disposal. Fluoride volatility has not been demonstrated as a

[35] Michael F. Simpson. "Developments of Spent Nuclear Fuel Pyroprocessing Technology at Idaho National Laboratory" (INL/EXT-12-25124). March 2012. https://inldigitallibrary.inl.gov/sites/sti/sti/5411188.pdf.
[36] Argonne National Laboratory. "Recycling Used Nuclear Fuel for a Sustainable Energy Future". 2018. https://www.anl.gov/sites/www/files/2018-10/Pyroprocessing_brochure_2018.pdf.
[37] https://factsheets.inl.gov/FactSheets/Fuel%20Conditioning%20Facility.pdf.
[38] Oak Ridge National Laboratory, ORNL-TM-2578, "Processing of the MSRE Flush and Fuel Salts," 1969.

means of directly processing LWR UNF, but the smaller potential facility footprint, lower HLW volumes, ability to process high-burnup and/or short-cooled fuel, potential for actinide co-recovery, and ability to recover fission products of interest (e.g., noble precious metals and medical radioisotopes) could make fluoride volatility a commercially viable technology.

The radar chart in Figure 2 indicates that fluoride volatility can be readily scaled to meet throughput needs, and while significant technical demonstration of the technology exists, there is no demonstration of the technology with UNF directly from an LWR. While the volume of waste generated from fluoride volatility is expected to be small, it is highly radioactive, and a clear pathway for the management of these HLW fluorides (or off-gases) has not been developed. The cost for a fluoride-volatility based separation is anticipated to be comparable to a pyroprocessing facility because of its smaller footprint and simple flowsheet, but no cost estimates have been reported. Materials accountancy has been established for enrichment facilities generally, but not those handling UNF nor has online material monitoring been established. A pathway to producing a U/TRU product could exist through the co-oxidation of U, Np, and Pu to volatile hexafluorides, but this has not been demonstrated and co-recovery of americium through this route is not currently deemed possible.

R&D opportunities for fluoride volatility flowsheets include evaluation of less corrosive fluorination reagents (e.g., NF_3), actinide co-recovery (via fluorination or from processing fluorination ashes), head-end process technology development, and adaptation or development of online monitoring and materials accountancy technologies for fluorination flowsheets (that latter of which should be addressed in Category 2).

<u>Fission Products</u>

There is also an interest in economically recovering and repurposing fission products for stakeholders other than AR vendors, such as for industrial or medical radioisotope usage. Isotopes and elements of interest include those listed in Table 2. Such isotopes and elements could serve as an additional revenue stream to help reduce the cost of the nuclear fuel cycle back-end. Technologies developed in support of fission product recovery should clearly describe the general technology-to-market case and where (or if) the fission product separations technology is anticipated to directly interface with the reprocessing facility. Any technologies considering the repurposing of fission products as a potential product stream should not include the potential revenue for this as an offset to the cost of fuel. Potential isotopes of value include ^{14}C, ^{63}Ni, ^{85}Kr, ^{90}Sr, ^{129}I, ^{133}Xe, ^{147}Pm, ^{166m}Ho, ^{241}Am, and ^{244}Cm.

II. <u>Category II – Integrated Monitoring & Materials Accountancy</u>

Nuclear materials accountancy, and the associated verification activities, is a key element of safeguards implementation, and is the primary reason that the detection of attempts to divert SNM is paramount. Currently, accountancy sampling occurs at specific unit operation areas, material balance areas (MBAs)[39], usually before and after the separation. The accountancy is verified by federal regulators (or IAEA) by several means, including conducting physical inventories of the materials, performing non-destructive assays locally or taking samples for destructive analysis in off-site laboratories, and reviewing surveillance system records. Each of the existing methods for validating control over the SNM is laborious and time-consuming, and can involve protracted facility shutdowns to resolve discrepancies. Accurate monitoring of SNM, as well as other chemistry and other process aspects, *in situ* could serve as an opportunity to improve the operational costs of a reprocessing facility and improve alignment with pre- and post-separation materials accountancy assays. Projects supporting this category should meet the following sub-metrics:

- provide *in situ* SNM process monitoring approaches that predict, within 1% uncertainty and under representative conditions[40], the post-process material accountancy;
- support development of UNF separations which do not produce pure plutonium streams; and
- provide an overall cost benefit to the facility (e.g., added capital or operational expenditures to the technology must be offset by other decreases in capital or operational expenditures).

Such technology could potentially minimize the number, frequency or type of post-process *ex situ* materials accountancy assays, therefore minimizing material handling needs, aiding in reducing scheduled maintenance, or improving general in-process knowledge and control. Significant synergies exist between online monitoring and decreasing costs throughout the facility. For instance, improvements in monitoring capabilities could allow for more precise controls, or perhaps integrated control, of the various reprocessing stages, while ensuring improved security of materials of concern. Analysis of the cost impacts associated with in-process monitoring can and should be indicated as a part of a response using this technology. While not a requirement, integration of Category 2 efforts with novel separations efforts in Category 1 is highly encouraged.

A general goal of online monitoring technologies/systems proposed in CURIE is to provide an overall cost benefit to the facility (e.g., added capital or operational expenditures to the technology must be offset by other decreases in capital or operational expenditures). Many technologies that support such a metric will fall under the general description of providing online monitoring, digital twinning, or integrating monitoring with process control, but this is not the requirement of a successful application. Any technology that supports CURIE's program metrics would be viewed as responsive.

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[39] An MBA is an area where (a) the quantity of nuclear material transferred into or out of can be determined, and (b) a physical inventory of nuclear material can be performed.
IAEA (2019) International Safeguards in the Design of Reprocessing Plants; https://www.iaea.org/publications/13454/international-safeguards-in-the-design-of-reprocessing-plants.

[40] Examples of representative conditions include relevant separations matrices and radiation fields (most likely gamma doses ~1000 R/hr or neutron emission rates ~ 10^4 – 10^5 neutron/sec).

The sophistication of monitoring solutions studied depends on the type of reprocessing technology utilized. Aqueous technologies have the highest sophistication, but outstanding questions exist regarding technology robustness, potential improvements afforded by sensor fusion and multi-block modeling, and the ability to predict post-process accountancy.[41] Fluoride volatility does not have any demonstrated solutions for actinide co-recovery or online monitoring, but current technologies may translate to monitoring solutions. SNM monitoring challenges are particularly acute for pyroprocessing, where the SOA is greater than the 1% uncertainty necessary to meet materials accountancy standards. A clear pathway for pyroprocessing to meet the 1% uncertainty standard, either during process monitoring or during material accountancy, does not exist currently. For technologies without an acceptable (i.e., within 1% uncertainty) means of materials accountancy, projects can propose both online monitoring and materials accountancy approaches, but online monitoring of SNM must be a part of the proposed effort. **Teams applying to Category 2 need to define the separations technology/process being targeted.**

Examples of technologies that are in scope of this category, and generally supportive of online/*in situ* process monitoring include, but are not limited to

- Non-destructive analysis (NDA) of fissile material, with an emphasis on unambiguous signatures, low latency, and functionality in representative environments and capable of determining
    - Radiation signatures: gamma[42] , neutron and alpha spectroscopy and characteristic X-rays, nuclear resonance fluorescence, neutron interrogation including induced fission, neutron multiplicity[43]
    - Chemical/Electronic Signatures: UV-Vis-NIR, Raman, excitation of characteristic X-rays, k-edge densitometry laser-induced spectroscopy[44], electrochemistry
- Analysis of non-fissile material is also of value if monitoring produces an overall cost-benefit to the facility, but SNM monitoring must be a part of the proposed technology
- Process modifications and sampling technologies that significantly improve NDA accuracy and volumetric sampling

[41] Multi-block modeling – where multiple sensors are fused to provide a single material accountancy value for a given element or isotope.

[42] Fensin, Michael L., Steven J. Tobin, Howard O. Menlove, and Martyn T. Swinhoe. "Quantifying the passive gamma signal from spent nuclear fuel in support of determining the plutonium content in spent nuclear fuel with nondestructive assay" No. LA-UR-09-03900; LA-UR-09-3900. Los Alamos National Lab. (LANL). 2009. https://www.osti.gov/servlets/purl/990302.

[43] Tiitta, Antero. "NDA verification of spent fuel, monitoring of disposal canisters, interaction of safeguards and safety issues in the final disposal." In Safeguards for final disposal of spent nuclear fuel: Methods and technologies for the Olkiluoto site, pp. A1-A16. Radiation and Nuclear Safety Authority STUK, 2003. http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.568.2123&rep=rep1&type=pdf

[44] Cook, Matthew Tyler. "Hybrid K-edge densitometry as a method for materials accountancy measurements in pyrochemical reprocessing." (2015). https://trace.tennessee.edu/cgi/viewcontent.cgi?article=4694&context=utk_graddiss.

- Modeling, to include sensor processing and data fusion, volumetric sampling analysis, and/or artificial intelligence/machine learning (AI/ML) techniques to improve "signal"
- Data fusion of multiple signatures and process control variables, AI/ML and other data analysis tools that enable achievement of mass accountancy metrics, possibly through improvement in signal processing, pulse shape analysis, data fusion of complimentary isotopic signatures, or spatial and temporal correlation of measurements
- Off-gas monitoring, bulk properties measurements, or other inferential technologies are appropriate if applicant provides a clear, quantitative description of how such measurements contribute to improved and unambiguous fissile mass accountancy
- Increasingly, online monitoring systems are developed on a framework of more complex statistical approaches (e.g., chemometrics, machine learning, etc.). Model training for these systems can be cumbersome and a slow step in deployment. Automated instrumentation that significantly expedites the experimental data collection process by >10x is also considered in scope

Simulation and modeling of the safeguards-by-design be considered only if a reasonable case can be made that it significantly expands upon prior detailed studies or offers a fundamentally different and beneficial operation and measurement protocol from currently accepted practices. Such modeling should be completed as a part of broader facility design studies completed in Category III (see below) if proposed.

III. Category III – Facility Design & Systems Analysis

PUREX-based commercial reprocessing facilities were generally constructed over 20 to 50 years ago, with additional equipment added to the facility as demand evolved. A new reprocessing facility constructed in the U.S. should leverage lessons learned from decades of PUREX reprocessing experience while exploiting the numerous advancements in equipment design, advanced manufacturing techniques, and modularization that have been made in similar non-nuclear industries (e.g., the oil & gas (O&G) industry) since the first reprocessing facilities were constructed decades ago. Over the past few decades, the O&G and chemical industries have developed valuable expertise in process intensification and successfully transitioned to modularized construction of key unit processes that have led to substantial reductions in construction and operations & management (O&M) costs. Such approaches might lead to similar reductions for new reprocessing facilities. Examples of equipment designs within scope of this category include, but are not limited to, those that compress unit operations, reduce a facility's overall construction costs, and enable modularized operation to meet the 200 MTHM/yr UNF throughput target outlined in this FOA.

While the approaches to designing and building reprocessing equipment mentioned above, along with the technologies proposed in Categories I and II, can potentially enable construction of reprocessing facilities that provide a cost-competitive feedstock for ARs, the full impact of such design approaches on cost needs to be evaluated and optimized. In addition, siting, licensing, constructing, and operating a modern reprocessing facility in the U.S. needs to be done in a streamlined, cost-effective manner. Lastly, and perhaps most critically, the U.S. has not constructed a commercial reprocessing facility in nearly five decades and, consequently, would functionally be building a first-of-a-kind (FOAK) facility.

To address these challenges, full systems analyses that evaluate variables with respect to the CURIE global metrics should include, but are not limited to, the following topics:

- Economic impact of reprocessing on federal waste disposal burden
- Evaluation of the supply chain, construction, and flexibility afforded from a modular vs. “stick-built” approach to constructing reprocessing facilities
- Impacts of using shorter-cooled (i.e., <10 years) vs longer-cooled (i.e., >30 years) fuels on facility design
- Economics of fluoride volatility facilities co-located with enrichment facilities
- Siting considerations of reprocessing facilities (e.g., regional vs centralized facilities)
- Economic benefits of safeguards-by-design approaches, including the benefits of integrating online monitoring with automated systems control

Facility design efforts relevant to CURIE could include

- Use of advanced digital twins to support design and construction
- Development of project engineering best practices for FOAK reprocessing facilities
- Civil and structural cost analysis tools designed to support evaluation of Category 1 and 2 technologies against the CURIE global cost metric

When appropriate, studies that integrate with Category 1 and/or 2 efforts are highly encouraged. For example, project engineering efforts from Category 3 could be integrated with Category 1 separations efforts to specifically screen their process and/or facility designs, and ultimately civil/structural costs, while the process is being developed.

Understanding the cost benefits of these and other relevant areas could significantly inform design and future R&D needs. As such, the outcomes of proposed systems analyses should evaluate the most effective means to meet the CURIE global metrics. The analyses can be performed using the applicant’s reprocessing technology of choice (e.g., pyroprocessing, aqueous separations, etc.) as long as they meet the program metrics outlined herein. Systems analysis proposals submitted under this category should also reflect an understanding of the regulatory needs for siting, constructing, and operating a reprocessing facility and the implications of reprocessing UNF that has been stored in spent fuel pools or in stranded or co-located independent spent fuel storage installations. Design of tools capable of such analyses would support future design optimization efforts and are especially encouraged. As with the proposals submitted under Categories I and II, ARPA-E strongly encourages forming diverse teams where possible.

IV. <u>Category IV – Other</u>

This category is provided for submissions that do not cleanly fall into the above three categories but can potentially meet overall programmatic objectives detailed in Section I.C of this FOA.

Submissions must make a compelling case for inclusion based on its ability to meet the stated program metrics.

E. Technical Performance Targets

Submissions must discuss how their technologies support the global program metrics described in Section I.C of the FOA. While addressing at least one program metric would constitute a responsive application, applicants should indicate which metrics are being targeted and the impact their technology would have on other metrics perhaps not being addressed.

Metric	Effect relative to SOA (positive/negative/neutral)	Description or Justification
>10x HLW waste reduction		
Predictive process monitoring within 1% uncertainty		
Separations technology with no pure plutonium streams		
Global system disposal in the range of 0.1¢/kWh		
Separation technology supporting a 1¢/kWh fuel cost for a 200 MTHM facility		

Estimation of the cost metric (1¢/kWh fuel cost for a 200 MTHM facility), will be completed using the Reprocessing Cost Estimator Tool provided in Appendix 1. The Reprocessing Cost Estimator Tool should help potential performers complete a general assessment of their technology and the impact the technology would have on the CURIE global cost metric. ARPA-E appreciates that such a tool will perhaps not have the resolution to assess the finer benefits of a given technology, though the tool should be able to provide a first approximation of technology cost impact. Applicants are encouraged to use the tool in their technological assessments and submit their findings, as well as the justifications for adjustments made to the tool, as a part of their full applications. Applicants should be attentive to the significant construction/civil engineering costs associated with a particular unit operation and justifications should include some consideration facility design impacts arising from a new technology.

I. Category I – Reprocessing Solutions

Applicants proposing development of a technology for separating the components of UNF should describe how their innovation will accomplish one or more of the following targets of

- Significantly reduce the volume of LWR HLW requiring permanent disposal,
- Provide appropriate fuel feedstock (70/30 U:Pu; 50/50 U/TRU by weight),
- have an actinide content in waste streams of <0.1% by weight,
- have a fission product content in product streams of <0.1%,
- have compatibility or potential compatibility with online monitoring technologies, and
- support a 1¢/kWh fuel cost and throughput needs for a 200 MTHM facility.

All proposed technologies must have the following characteristics:

- The proposed technology does not at any point create a pure plutonium product (i.e., it produces a co-recovered actinide stream),
- It would have an equivalent throughput processing rate of 2 kg/h for 8 h (~10% scale of 200 MTHM/year facility, assuming 100% capacity factor) without any loss of selectivity
  - Applicants may use non-radiological surrogates and minimize the use of hazardous materials during appropriate stages of process development;
  - It would enable a 1¢/kWh fuel cost for a 200 MTHM/year facility, and
- The proposed technology is either compatible with at least one existing licensed waste form or is codeveloped with a compatible waste form suitable for final geological disposal. If neither criterion is met, the case must be made that the technology could potentially provide a significant disruption to reprocessing cost and safeguards SOA, such that separate investment in a novel waste form would be justified.

An applicant to this Category shall provide an overview description of their proposed technology that includes

- A comparison of the proposed technology's performance and cost to SOA technologies applied under proposed conditions,
- The expected maturity (e.g., lab-scale, pilot-demonstration, commercialization) of the proposed technology at the completion of the project as demonstrated by process' equivalent throughput (2 kg/h), and
- Any relevant synergies with Category 2 or 3 efforts

In addition, each Applicant to this Category must provide the information in Table 4, in summary form.

Property	**Description**
Improvements in proliferation resistance	
Describe the composition of each waste stream, the associated waste forms expected from the proposed technology, and the need (if any) for the waste form to be co-developed?	
Provide the composition (e.g., 70/30 U/Pu) and form (e.g., oxide, metal) of the actinide	

feedstock that would be produced from the proposed technology.	
Estimated commercial scale processing facility capital expenditure (CapEx) and annual Operating and Maintenance (O&M) costs	

II. Category II – Integrated Monitoring & Materials Accountancy

In situ SNM process monitoring approaches that predict, within 1% uncertainty and under representative conditions, the post-process material accountancy, is an important CURIE global program metric. Proposed technical solutions under this category must support the program metric and address these facets of the proposed technology (if relevant):

- If an inferential signature is proposed, validation data must be provided to demonstrate the accuracy of fissile mass determination.
- If a full volume of UNF is not sampled, an extrapolation methodology must be specified and a validation procedure defined.
- The solution must be compatible with the anticipated radiation backgrounds the system would experience during UNF reprocessing.
- Technology should enable process monitoring.
- Maintenance and service schedules must be consistent with the overall system and cost goals of the program.

Each applicant to this category shall provide a schematic with all major system components identified, including required ancillary equipment, and provide the information below to the best of the applicant's ability.

The separations process and technology design-basis	
Process location(s) where sensor is located	
Estimate of material uncertainty & accuracy (including how this was determined)	
Anticipated capital and operational costs and savings of the proposed system	
Latency and/or throughput of measurement	
Scale of technology demonstration relative to actual operating conditions.	
Comparison to State-of-the-Art	
Mean Time Before Failure (include basis)	
Schedule for, and cost estimates of, maintenance (include all types of maintenance required, time required for	

actual servicing, operational or chronological time periods between required maintenance, and any replacement components or consumables needed)	
Description of mass accountancy validation (must include realistic sensor data rates, for both signal and backgrounds both from target mass and external sources)	
Number of sensors and sensor types required to support program metrics	
Sampling methodology (include approach, units of measurement, fraction of volume sampled, and scale)	
Experimental Validation Methodology for accuracy determination (including recalibration schedule)	
Software Validation Methodology for accuracy determination (including recalibration schedule)	

III. Category III – System Design and/or Analysis

System Design and Analysis approaches must provide a clear description of what reprocessing technology(ies) and variables are considered, the justification for their selection, and/or basis for design approach with a clear indication of how these efforts support the CURIE program metrics and goals.

IV. Category IV – Other

The target values for this category must be directly tied to the global program goals and specific targets from categories I, II and/or III. Comparison must be made to the state-of-the-art relative to the proposed solution. It is important to provide a clear description of why the proposed solution does not fit cleanly into categories I, II or III and how the selected targets from the other categories satisfy the global requirements of the program. All relevant information requested in the tables must be completed, where applicable.

C. Other

1. Compliant Criteria

Concept Papers are deemed compliant if

- The Applicant meets the eligibility requirements in Section III.A of the FOA;

- The Concept Paper complies with the content and form requirements in Section IV.C of the FOA; and
- The Applicant entered all required information, successfully uploaded all required documents, and clicked the "Submit" button in ARPA-E eXCHANGE by the deadline stated in the FOA.

Concept Papers found to be noncompliant may not be merit reviewed or considered for award. ARPA-E will not review or consider noncompliant Concept Papers, including Concept Papers submitted through other means, Concept Papers submitted after the applicable deadline, and incomplete Concept Papers. A Concept Paper is incomplete if it does not include required information. ARPA-E will not extend the submission deadline for Applicants that fail to submit required information and documents due to server/connection congestion.

Full Applications are deemed compliant if

- The Applicant submitted a compliant and responsive Concept Paper;
- The Applicant meets the eligibility requirements in Section III.A of the FOA;
- The Full Application complies with the content and form requirements in Section IV.D of the FOA; and
- The Applicant entered all required information, successfully uploaded all required documents, and clicked the "Submit" button in ARPA-E eXCHANGE by the deadline stated in the FOA.

Full Applications found to be noncompliant may not be merit reviewed or considered for award. ARPA-E will not review or consider noncompliant Full Applications, including Full Applications submitted through other means, Full Applications submitted after the applicable deadline, and incomplete Full Applications. A Full Application is incomplete if it does not include required information and documents, such as Forms SF-424 and SF-424A. ARPA-E will not extend the submission deadline for Applicants that fail to submit required information and documents due to server/connection congestion.

Replies to Reviewer Comments are deemed compliant if

- The Applicant successfully uploads its response to ARPA-E eXCHANGE by the deadline stated in the FOA.
- The Replies to Reviewer Comments comply with the content and form requirements of Section IV.E of the FOA.

ARPA-E will not review or consider noncompliant Replies to Reviewer Comments, including Replies submitted through other means and Replies submitted after the applicable deadline. ARPA-E will not extend the submission deadline for Applicants that fail to submit required information due to server/connection congestion. ARPA-E will review and consider each compliant and responsive Full Application, even if no Reply is submitted or if the Reply is found to be noncompliant.

2. Responsiveness Criteria

ARPA-E performs a preliminary technical review of Concept Papers and Full Applications. The following types of submissions may be deemed nonresponsive and may not be reviewed or considered:

- Submissions that fall outside the technical parameters specified in this FOA.
- Submissions that do not address the required technical information (i.e., information that "must" be included), as specified in Sections I.D and I.E of the FOA.
- Submissions that have been submitted in response to other currently issued ARPA-E FOAs.
- Submissions that are not scientifically distinct from applications submitted in response to other currently issued ARPA-E FOAs.
- Submissions for basic research aimed solely at discovery and/or fundamental knowledge generation.
- Submissions for large-scale demonstration projects of existing technologies.
- Submissions for proposed technologies that represent incremental improvements to existing technologies.
- Submissions for proposed technologies that are not based on sound scientific principles (e.g., violates a law of thermodynamics).
- Submissions for proposed technologies that are not transformational, as described in Section I.A of the FOA.
- Submissions for proposed technologies that do not have the potential to become disruptive in nature, as described in Section I.A of the FOA. Technologies must be scalable such that they could be disruptive with sufficient technical progress.
- Submissions that are not scientifically distinct from existing funded activities supported elsewhere, including within the Department of Energy. Submissions that describe a technology but do not propose a R&D plan that allows ARPA-E to evaluate the submission under the applicable merit review criteria provided in Section V.A of the FOA.

3. Submissions Specifically not of Interest

Submissions that propose the following will be deemed nonresponsive and will not be merit-reviewed or considered:

- Submissions explicitly targeting reprocessing to support the currently deployed LWR fleet. While backwards compatibility is permissible, the technology must have a clear connection to supporting ARs.
- Marketing solutions
- Discourse or policy papers about reprocessing technologies