U.S. Department of Energy
Advanced Research Projects Agency – Energy (ARPA-E)

Request for Information (RFI)
DE-FOA-0003091
on
Transmutation of Nuclear Waste

Introduction

ARPA-E has as one of its goals the development of energy technologies that improve the management, cleanup, and disposal of radioactive waste and spent nuclear fuel. To meet this goal, ARPA-E has established a suite of programs (GEMINI, MEITNER, ONWARDS, CURIE) that have the potential to reduce the volume of radioactive waste by a factor of 10 or more and the needed time for storage by a comparable amount. Nuclear transmutation of key fission products and actinides in the remaining radioactive waste has the potential to reduce the volume and storage time by additional orders of magnitude. The purpose of this RFI is to solicit input for a potential future ARPA-E program focused on the development of technologies to support advances in nuclear transmutation with the desired goal to reduce the volume, radiotoxicity, and storage time of spent nuclear fuel. Generation of valuable isotopes, semiconductor production, and radioisotopes are also of interest to this RFI.

Consistent with the agency's mission, ARPA-E is seeking novel and disruptive technologies that are early in the R&D cycle. ARPA-E seeks to include input from the developers and end-users of such technologies, including national laboratories, universities, private industry, and the medical community. ARPA-E is particularly interested in transmutation enabling technologies, and it is specifically interested in how such technologies can improve the reliability and duty cycles of transmutation systems while reducing capital and operating costs.

Understanding the economic factors that would lead to a transmutation facility are invaluable to a potential program. Reprocessing of waste may be needed for efficient transmutation. The location of this reprocessing facility, whether located at the waste generating sites, or at the transmutation location will impact the economics. Additionally, depending on the size of the transmutation facility, there may be several facilities constructed in order to reduce quantities of waste to the desired metric. Funds for the decommissioning of reactors as well as the nuclear waste fund may be available for these types of activities.

The questions below are intended to allow relevant stakeholders a mechanism to provide input on:

(i) metrics to gauge the success of transmutation of spent nuclear fuel;
(ii) advancements in transmutation enabling technologies, including accelerator-driven systems and current and advanced generation reactors, and non-neutron sources; and
(iii) economic factors for the operation of transmutation facilities.

Responses to the questions below will help ARPA-E to refine its success metrics for a potential program aimed at the reduction of radiotoxicity, volume, and storage time of spent nuclear fuel through the use of transmutation. ARPA-E does not expect any one respondent to answer all, or even many, of these prompts. Simply indicate the group and question number in your response. Appropriate citations are encouraged. Respondents are also welcome to address other relevant avenues/technologies that are not outlined below.

Areas that are not Considered for this RFI:

- General discourse on nuclear energy and waste disposal strategies
- Transmutation initiated by fusion processes
- Fission-fusion hybrid devices
- Separations of minor actinides from used nuclear fuel
- The use of transmutation to produce medical radioisotopes

Please carefully review the REQUEST FOR INFORMATION GUIDELINES below. Please note, in particular, that 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.**

Purpose and Need for Information

The purpose of this RFI is solely to solicit input for ARPA-E consideration to inform the possible formulation of future research programs. 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 broad research community with an opportunity to contribute views and opinions.

REQUEST FOR INFORMATION GUIDELINES

No material submitted for review will be returned and there will be no formal or informal debriefing concerning the review of any submitted material. 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 or publish publicly a compendium of responses. **Respondents shall not include any information in the response to this RFI that could 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 Monday, June 12.** Emails should conform to the following guidelines:

- Please insert “Response to Transmutation - <your organization name>” in email subject line.
- In the body of your email, 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.
- Responses to this RFI are limited to no more than 10 pages in length (12-point font size).
- Responders are strongly encouraged to include preliminary results, data, and figures that describe their potential materials, designs, or processes.

RFI QUESTIONS

A. Transmutation Enabling Technologies

Nuclear transmutation is the conversion of one chemical element or isotope into another through bombardment with particles (e.g., photons, neutrons, protons, deuterons, other ions) or through radioactive decay. Figure 1 depicts both the natural radioactive decay of I-219 to produce Xe-129, and the neutron transmutation conversion of I-129 to I-130, which is followed by the radioactive decay of I-130 to Xe-130. This demonstrates the large reduction in half-life from ~ 15 million years to ~ 12 hours.

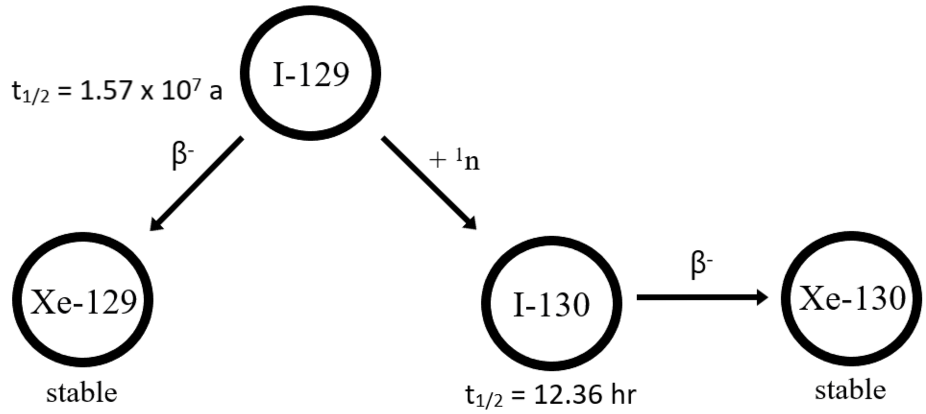

Figure 1. Neutron transmutation chain of ^{129}I which results in the formation of ^{130}Xe. This is compared to the natural beta decay of ^{129}I which results in the formation of ^{129}Xe.

Several different strategies have been used to initiate nuclear transmutation. For example, accelerator-driven systems (ADS) use a high-powered proton beam that can generate neutrons through spallation. Spallation occurs when the proton beam causes excitation of the atoms in the spallation target (e.g., mercury, lead, lead-bismuth eutectic), when the atoms undergo relaxation, they expel neutrons. These neutrons can be used to transmute isotopes or generate electricity through the initiation of fission reactions. ADS can be run in both sub-critical and critical modes, which offer different advantages. Sub-critical systems are inherently safe as there is no sustained nuclear reaction, and turning the proton beam off results in no power being produced from the reactor. Additionally, the fuel requirements for sub-critical systems are less stringent than critical systems.[1] Critical systems sacrifice inherent safety and lower costs for increased power generation.

Current generation reactors have also been demonstrated to be able to transmute minor actinides (MA) and long-lived fission products (LLFP), although the rates of transmutation in these systems are low. As these types of reactors currently make up nearly all the nuclear power sources in the United States, optimizing current generation reactor technology to allow for effective transmutation of nuclear waste is desirable.

Advanced reactor designs have also shown to be effective at transmuting MAs and LLFPs from spent nuclear fuel. Lead cooled fast reactors are capable of transmuting both LLFPs and MAs simultaneously through mixing the LLFPs with a neutron moderator which softens the neutron energy spectrum in the vicinity of the LLFPs, allowing transmutation without affecting the neutron flux in the rest of the reactor.[2]

A 2012 Nuclear Energy Agency (NEA) report discussed the possibility of homogeneous and heterogeneous recycling in fast reactors.[3] Homogenous recycling involves the multi-recycle of grouped transuranic (TRU) fuels. Heterogeneous recycling involves the separation of the less radioactive

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[1] Aït Adberrahim, H.; Galambos, J; Gohar, Y.; Henderson, S.; Lawrence, G.; McManamy, T.; Mueller, A.C.; Nagaitsev, S.; Nolen, J.; Pitcher, E.; Rimmer, R.; Sheffield, R.; Todosow, M. Accelerator and Target Technology for Accelerator Driven Transmutation and Energy Production. **2010.** DOE sponsored White Paper on technology for accelerator driven systems. FERMILAB-FN-0907-DI, LA-UR-10-06754.
[2] Sun, X.Y.; Han, L.H.; Li, X.X.; Hu, B.L.; Luo, W.; Liu, L. Transmutation of MAs and LLFPs with a lead-cooled fast reactor. *Nature Scientific Reports*. **2022**. 13, 1693.
[3] Nuclear Energy Agency. Homogeneous versus Heterogeneous Recycling of Transuranics in Fast Nuclear Reactors. **2012**.

components of light water reactor (LWR) used nuclear fuel transuranics (TRUs) (Pu and Np) to make fuels and use the remaining MAs (Am and Cm) as targets for transmutation. Both methods of target introduction were determined to be feasible, with both having advantages and disadvantages.

Homogenous introduction results in easier fabrication of the fuel but has no flexibility between the production of electricity and long-lived waste mission. Heterogeneous introduction involves more complex fuel fabrication methods and higher thermal load of the used fuel but allows a degree of flexibility in operation of the reactor.

A1. What elements and isotopes should be the target of nuclear transmutation?

A2. Do the results from this NEA report hold true to this day? What loading strategies for transmutation of MAs and LLFPs in advanced reactors result in the optimization of transmutation rates and reactor operation?

Questions that are specific to the possible reactor systems are as follows.

B. <u>Accelerator-Driven Systems (ADS)</u>

ADS will require more reliable operations than current proton accelerators. Figure 2 illustrates the duration and number of beam trips at four different accelerator facilities: Paul Scherrer Institute (PSI), ISIS Neutron and Muon Source (ISIS), Los Alamos Neutron Science Center (LANSCE), and the Spallation Neutron Source at Oak Ridge National Laboratory (SNS). These facilities are primarily for research applications, and do not typically invest in redundant hardware systems that would be required to achieve the high reliability performance expected for an industrial-scale installation.[4] Orders of magnitude reductions in the frequency and duration of these beam trips is necessary for successful implementation of ADS transmutation.[5]

Lead-Bismuth Eutectic (LBE) is used as a coolant in fast reactors, as well as a spallation target in ADS. While lead is essentially invisible to neutrons, Bi-209 can be activated to produce Bi-210 which then undergoes beta decay ($t_{1/2}$ = 5.012 d) to produce Po-210, which is a highly radioactive isotope ($t_{1/2}$ = 138.376 d).[6]

B1. What materials could be used as spallation targets that do not produce highly radioactive isotopes?

Beam availability is related to the number of beam trips, but also includes time lost for beam studies. Current accelerator and synchrotron facilities have large amounts of time (up to 25%) allocated to beam studies and maintenance.

B2. What specific components are responsible for the frequency of these beam trips? Can the beam be monitored in real-time such that minimal time is lost for beam studies? Are built-in redundancies sufficient to minimize time lost for maintenance?

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[4] Abderrahim, H.A.; Galambos, J.; Gohar, Y.; Henderson, S.; Lawrence, G.; McManamy, T.; Mueller, A.C.; Nagaitsev, s.; Nolen, J.; Pitcher, E.; Rimmer, R.; Sheffield, R.; Todosow, M. Accelerator and Target Technology for Accelerator Driven Transmutation and Energy Production.

[5] Wangler, T.P. Reliable-Linac Design for Accelerator-Driven Subcritical Reactor Systems. **2002**. Los Alamos National Laboratory. Los Alamos, NM. LA-UR-02-6684.

[6] Fiorito, L.; Stankovskiy, A.; Hernandez-Solis, A.; Van den Eynde, G.; Zerovnik, G. Nuclear data uncertainty analysis for the Po-210 production in MYRRHA. *EPJ Nuclear Sci. Technol.* **2018**. 4, 48.

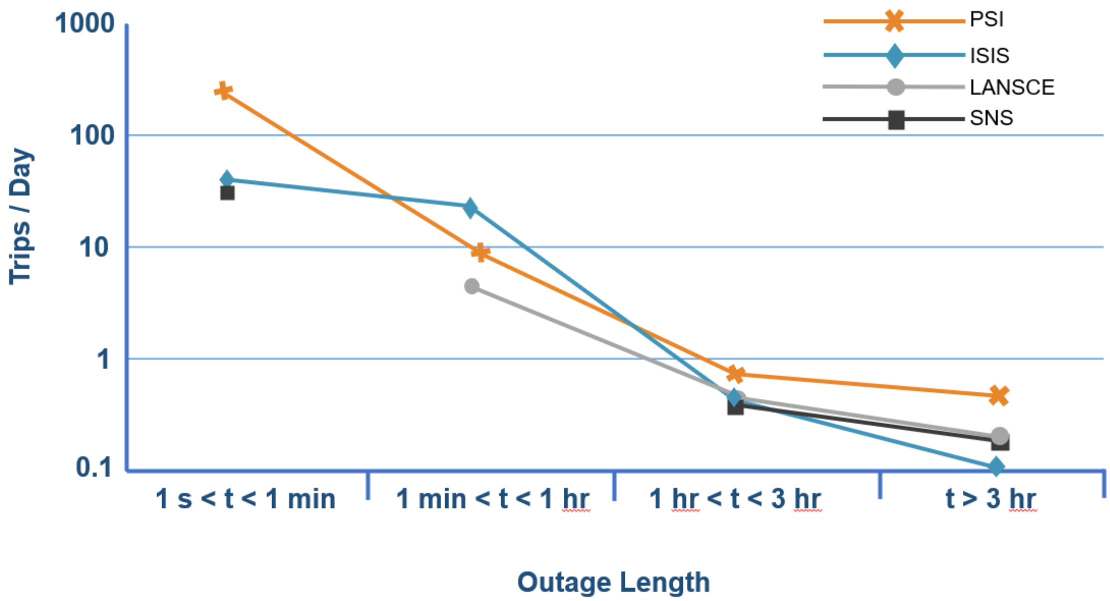

Figure 2. Average number and length of outages in four proton accelerator facilities.[7]

The Japan Atomic Energy Agency (JAEA) uses the strategy of local compensation to reduce beam trips and failures.[8] This directly contrasts with the Belgian Nuclear Research Centre (SCK CEN) Multi-purpose hYbrid Research Reactor for High-tech Applications (MYRRHA) approach of global compensation. While global compensation allows for simultaneously compensating several superconducting radio frequency (SRF) cavities, it is much more complex than local compensation.

B3. What are the other pros and cons of each type of compensation? Is it possible to simplify a global compensation strategy?

C. <u>Current Generation Reactors</u>

Current generation reactors, including LWR, pressurized water reactors (PWR), and boiling water reactors (BWR) are capable of burning multiple fuel types, including uranium dioxide, mixed uranium-thorium dioxide, and mixed oxide (MOX) fuel. Transmutation of minor actinides in these types of reactors is difficult due to the lower neutron fluxes and the higher absorption cross sections of the minor actinides. In some cases, boric acid used as a moderator in the coolant must be removed to maintain criticality when minor actinides are introduced into the reactor.[9] A study including 1% MA loading into UO_2, $(U, Th)O_2$, and MOX fuel assemblies indicated that $(Th,U)O_2$ was the most promising fuel type in a PWR for transmuting MA with the goal of reducing the radioactivity of the fuel. After around one year of running, the radioactivity in $(Th,U)O_2$ was expected to be reduced by 2 orders of magnitude.[10]

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[7] Galambos, J.; Koseki, T.; Seidel, M. Commissioning Strategies, Operations and Performance, Beam Loss Management, Activation, Machine Protection. *Proceedings of Hadron Beam 2008, Nashville, TN, USA.* **2008**. 489-492.

[8] Yee-Rendon, B.; Kondo, Y.; Tamura, J.; Nakano, K.; Maekawa, F.; Meigo, S.-I. Beam dynamics studies for fast beam trip recovert of the Japan Atomic Energy Agency accelerator-driven subcritical system. *Physical Review Accelerators and Beam*. **2022**. 25, 080101.

[9] Heidet, F.; Kim, T.K.; Taiwo, T.A. Impact of minor actinide recycling on sustainable fuel cycle options. *Nucl. Eng. Des.* **2017**. 323, 434-462.

[10] Galahom, A.A.; Sharaf, I.M. Finding a suitable fuel type for the disposal of the accumulated minor actinides in the spent nuclear fuel in PWR. *Progress in Nuclear Energy*. **2021**. 156, 103749.

C1. The location, form, composition, fuel type, and mass loading of the waste and the reactor coolant have varying levels of effect on the rate of transmutation in PWR. How do these variables interact to determine the overall transmutation efficiency?

C2. The performance of the reactor includes several metrics (e.g., k_{eff}, safety considerations, burn-up of the fuel, and neutron flux). How does the inclusion of transmutable material into the reactor affect these metrics?

C3. Transmutation rates of long-lived fission products are very low in LWR and PWR environments. Is this an inherent limitation or the reactor technology, or can this be improved?

D. Advanced Reactors (AR)

Advanced reactor designs including molten salt reactors and gas-, sodium-, and lead-cooled fast reactors have a high potential for the transmutation of nuclear waste due to their high neutron fluxes.[11] Loadings of up to 5% MA can result in transmutation rates of up to 10% per year.[12] This involves the separation of transmutation targets in the reactor based on their neutron absorption cross sections.

D1. The location, form, composition, fuel type, and mass loading of the waste and the reactor coolant have varying levels of effect on the rate of transmutation in advanced reactors. How do these variables interact to determine the overall transmutation efficiency?

D2. The performance of the reactor includes several metrics (e.g., k_{eff}, safety considerations, burn-up of the fuel, and neutron flux). How does the inclusion of transmutable material into advanced reactors effect these metrics?

D3. Pure burner systems would require significant infrastructure to transmute all available LWR used fuel.[13] Do burner systems have the flexibility to switch focus between transmutation and electricity generation given different loads? What transmutation rates are necessary for both MAs and LLFPs for a pure burner reactor to be economically viable?

E. Economic Factors

The United States' Nuclear Waste Fund was established in 1983 and was funded through a 0.1¢ per kWh fee on all net electricity generated and sold by civilian nuclear power reactors starting on April 7, 1983 and ended May 16, 2014. The nuclear waste fund (NWF) currently has a balance of $45B USD, with roughly $1.5B in interest earned every year. This money is earmarked for the development of a permanent geological disposal repository for the high-level nuclear waste in the country and eventual disposal of stored waste at the site.

In addition to the NWF, the Nuclear Regulatory Commission (NRC) requires a decommissioning fund be established for every reactor facility. This fund includes money to store used fuel and radioactive waste disposal costs. Estimates for the cost of decommissioning of a nuclear facility are between $280 and $612 million and are dependent on the type of reactor or facility, the location, and the timing and sequence of the program (https://www.nrc.gov/waste/decommissioning/cost-estimates-dla.html, Cost

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[11] Abram, T.; Ion, S. Generation-IV nuclear power: A review of the state of the science. *Energy Policy*. **2008**. 36, 4323-4330.
[12] Wakabayashi, T. Concept of a fast breeder reactor to transmute MAs and LLFPs. *Nature Scientific Reports*. **2021**. 11, 22443.
[13] Taiwo, T.A.; Hill, R.N. Summary of Generation-IV Transmutation Impacts. *Argonne National Laboratory Report*. **2005**. ANL-AFCI-150.

Estimates For Decommissioning Licensing Actions | NRC.gov).

E1. Targeted goals of transmutation of used nuclear fuel include reduction in radiotoxicity, heat load, storage time, and storage volume. Which of these metrics is the biggest driver for transmutation? Are there additional metrics that should be included in this list?

E2. Is it economical to transmute used nuclear fuel, or is reprocessing needed prior to transmute a specific target? Is extraction of the transmuted target needed prior to disposal? If necessary, are these processes currently scalable?

E3. What lessons from industry can be applied to a transmutation facility?

E4. A transmutation facility could either be centrally located or co-located at waste generation sites. The operation of these facilities could fall under several models: (a) government-owned, government-operated (GOGO), (b) government-owned, contractor-operated (GOCO), (c) privately-owned, or (d) public-private partnership. Which of these models would be the best option from a cost, safeguards, and/or any other perspective, and why?