Modeling-Enhanced Innovations Trailblazing Nuclear Energy Reinvigoration (MEITNER) Overview

B. PROGRAM OVERVIEW

1. Summary

Nuclear reactor plants are complex systems where many types and scales of technologies must work together seamlessly. Design choices at each of those scales and for each of those technologies impact the rest of the system in terms of functionality, cost, and constructability.

For nuclear energy to contribute in the coming decades, the next generation of nuclear reactor plants need to simultaneously achieve "walkaway" safe and secure operation, extremely low construction capital costs, and dramatically shorter construction and commissioning times than currently-available plants. To attain these goals, new, innovative, enabling technologies for existing advanced reactor designs are needed. The development of these enabling technologies requires understanding the inter-relatedness of design choices. Thus, ARPA-E encourages a rethinking of how pieces of the nuclear reactor system fit together when developing these enabling technologies.

Through the MEITNER[1] (**M**odeling**-E**nhanced **I**nnovations **T**railblazing **N**uclear **E**nergy **R**einvigoration) program, ARPA-E seeks to identify and develop innovative technologies to enable the advanced nuclear reactor design community to mature their designs for future commercial deployment. These enabling technologies can establish the basis for a modern, domestic supply chain supporting nuclear technology.

As provided in this FOA, ARPA-E will select multiple Awardees (Prime Recipients) to develop innovative technologies using advanced modeling and simulation (M&S) tools and by leveraging expert input to enable advanced reactor systems.[2] The MEITNER Program will establish a set of well-characterized enabling technologies where:

- performance and safety have been studied with multi-physics M&S tools;
- key cost and performance drivers have been identified for critical development and testing;
- key gaps in models or data have been identified, which can be addressed through targeted experimental work;
- costs and construction timelines are well projected; and
- robust techno-economic analysis (TEA) has been performed and a clear technology-to-market (T2M) plan has been created.

MEITNER Awardees will perform key enabling technology development for nuclear reactor systems, components, and structures, moving those technologies toward commercialization. The program will not support development of fundamentally new reactor core concepts[3] nor the design of entire reactor plants. This approach is intended to focus on identifying and developing key enabling technologies for the existing U.S. advanced reactor design community that take advantage of fields adjacent to those that are typically considered nuclear energy research and development (R&D). The MEITNER Program will use modeling and simulation and, optionally, applied science and engineering-based experimental work.

The MEITNER Program will require a system-level approach in describing and quantifying how new and innovative enabling technologies fit into a plant design to make the plant "walkaway" safe, quickly-deployable, safeguardable, cost-competitive, and commercially-viable. To facilitate such a holistic view, ARPA-E will establish a separately-funded Resource Team to work with Awardees, as described in Section 2.3 below. The Resource Team will consist of three coordinated sub-teams: a computational modeling and simulation (M&S) sub-team, a techno-economic analysis (TEA) sub-team, and a subject matter expert (SME) sub-team (see Section I.E of the FOA). Through the Resource Team, Awardees will have access to

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[1] Named in honor of Lise Meitner who, together with Otto Hahn, first discovered nuclear fission of uranium in the 1930s.

[2] Refer to FOA Section I.B.2.3, titled *ARPA-E MEITNER Program Resource Team*, for additional information.

[3] Existing advanced reactor designs include classes of non-light water reactors that are being planned or have been used in the past. This includes designs that use as heat transfer media: gas, lead (or lead-bismuth alloy), molten salt, sodium, supercritical water; and as nuclear fuel types: ceramic oxides, nitride, metal, triso clad, silicon carbide clad, metal clad, liquid eutectic.

SMEs from both the nuclear and non-nuclear disciplines. These resources will allow Awardees to more accurately place their enabling technologies into the larger reactor plant context.

Awardees are encouraged to leverage DOE Office of Nuclear Energy (DOE-NE) programs, such as the GAIN (Gateway for Accelerated Innovation in Nuclear) initiative (https://www.inl.gov/research-program/gain) and the Nuclear Science User Facilities (NSUF) Network (https://nsuf.inl.gov/), to perform strategic experiments–either during or after completion of the Program.

2. Background and Motivation

2.1 Opportunities and Challenges of Nuclear Energy

Nuclear electricity generation accounts for about 63% of the total low-emissions electricity generation worldwide.[4] In the U.S., nearly 20% of the total electricity generation, or about 800 billion kW-hr per annum, comes from 99 operating nuclear reactors that have a total installed capacity of 98.7 gigawatts of electricity (GW_e) operating with a fleet-average capacity factor of 95%.[5] These nuclear plants are all conventional light water reactors (LWRs), which have been the workhorse of the nuclear industry since its inception. Most reactors currently in operation around the world are classified as second- or third-generation systems, with the first-generation systems having been retired some time ago. New LWRs (Generation III+) with simplified physical plants, optimized control systems, significantly enhanced passive safety systems,[6] and standardized designs that may reduce maintenance and capital costs[7] are commercially available today (e.g., Westinghouse AP1000™).

However, the future of nuclear energy in the U.S. is unclear. Existing nuclear power plants are facing the significant challenge of having comparatively high operational and maintenance (O&M) costs.[8] Many of the Generation III+ reactors under construction have been plagued by escalating capital costs and unpredictable construction schedules. Today, only two such Gen III+ LWRs are scheduled to come online in the U.S. by 2021.[9] The low volume of new plant construction combined with expected retirements of the existing U.S. nuclear fleet is projected to reduce nuclear electricity capacity by 20.8 GW by 2050, even with planned license extensions and power uprates to enable some plants to reach 60- or 80-year operations or increase their electrical output.[10]

For nuclear energy to be more attractive and competitive, both the overnight construction cost and the O&M cost need to be significantly reduced—these are the two major contributors to the levelized cost of electricity (LCOE).[11] Construction of large-scale LWRs, similar to the construction of other megastructures,[12,13] is prone to delays and cost-overruns,[14,15] which

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[4] Nuclear Energy Institute (NEI), http://www.nei.org/Knowledge-Center/Nuclear-Statistics/Environment-Emissions-Prevented. Calculated from U.S. EPA and EIA data for 2014. Nuclear power amounted to some 595 million metric tons of avoided carbon dioxide emissions.

[5] U.S. Energy Information Administration (EIA), Nuclear Energy Overview (1957-2015), http://www.eia.gov/totalenergy/data/monthly/pdf/sec8.pdf

[6] Passive safety systems rely almost exclusively on natural forces, such as density differences, gravity, and stored energy, to supply safety injection water and provide core and containment cooling. These passive systems do not include pumps. However, they do include some active valves, but all the safety-related active valves require either dc safety-related electric power (supplied by batteries), are air operated (and fail safe on loss of air), or are of the check valve type. U.S. Nuclear Regulatory Commission (NRC), http://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr1793/initial/chapter22.pdf.

[7] https://www.iaea.org/NuclearPower/Downloads/Technology/meetings/2011-Jul-4-8-ANRT-WS/2_USA_UK_AP1000_Westinghouse_Pfister.pdf

[8] Nuclear Energy Institute. *Nuclear Costs in Context*. April 2016.

[9] http://www.world-nuclear.org/information-library/country-profiles/countries-t-z/usa-nuclear-power.aspx, https://www.scana.com/investors/nuclear/questions-answers

[10] https://www.eia.gov/todayinenergy/detail.php?id=31192

[11] B. Vegel and J.C. Quinn, Economic evaluation of small modular nuclear reactors and the complications of regulatory fee structures, Energy Policy, 104 (2017) 395-403; and communications with the authors.

[12] B. Flyvbjerg, M. Garbuio, and D. Lovallo, Delusion and deception in large infrastructure projects: two models for explaining and preventing executive disaster, California Management Review, 51 (2) (2009) 170-193.

[13] B. Flyvbjerg, What you should know about megaprojects and why: an overview, Project Management Journal, 45 (2) (2014) 6–19.

[14] J.R. Lovering, A.Yip, and T. Nordhaus, Historical construction costs of global nuclear power reactors, Energy Policy, 91 (2016) 371–382.

[15] A. Gilbert, B.K. Sovacool, P. Johnstone, and A. Stirling, Cost overruns and financial risk in the construction of nuclear power reactors: a critical appraisal, Energy Policy, 102 (2017) 644–649.

can lead to a significant increase in LCOE due to the increased capital involved and additional interest payments on the construction loans. The uncertainties associated with the construction time and cost make it more difficult for utilities to commit to new, large LWRs.

The relatively high O&M cost of the current nuclear fleet stems largely from the high staffing level required for the nuclear power plant operation, maintenance, safety, and security. A staffing level of more than 450 full time staff equivalents (FTE) per GW_e is typically required.[16] In contrast, as few as eight staff members are required to run a 300 MW_e natural gas power plant. The high O&M cost is a major reason some utilities are, or are considering, closing some existing operational nuclear plants before the conclusion of their licensed operational lifetimes in some highly competitive markets/states.[17,18]

2.2 Call for Innovative Technologies for Advanced Nuclear Power Plants

It is clear that a substantial reduction of construction cost, O&M cost, and construction time, in combination with targeting reactor plant operation for commercial viability, is required to fundamentally enhance the competitiveness and attractiveness of nuclear energy so that it can be available for affordable, low-emissions future energy scenarios.[19] Thus, ARPA-E seeks applications for research funding for transformative technologies to enable advanced nuclear reactor plant designs that simultaneously achieve:

1) Low overnight construction cost.
2) Substantially autonomous operations to reduce the total (onsite and offsite) staffing level.
3) "Walkaway" safety when considering
    a. the amount of time before human intervention or backup power are required in an accident scenario; and
    b. potential for public exposure to radiation.
4) Very short on-site construction time.
5) Proliferation resistance through safeguards by design.[20]
6) The ability to achieve either or both:
    a. operate in a manner that facilitates easy electrical grid integration with intermittent sources such as wind and solar; or
    b. be available to provide economical industrial process heat.[21]

To achieve these goals, ARPA-E seeks applications for research funding for identification and development of transformative technologies that can assist the U.S. advanced reactor design community in maturing their conceptual designs into commercially-deployable products, establishing the basis for a modern, domestic supply chain supporting nuclear technology. These technologies should be considered within the context of an integrated reactor plant system. There are a variety of strategies that could be adopted and combined to work towards the stated goals, some of which are described in the following subsections. It should be noted that current regulatory constraints should not restrict proposed innovations.

2.2.1 System Simplification

Past and current reactor plant construction, and large construction projects in general, have demonstrated that large, complex construction projects are frequently fraught with construction management challenges, cost overruns, and

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[16] https://www.eucg.org/pub/3ff048c1-f842-57dd-f625-bc35440aa9c4

[17] https://www.everycrsreport.com/files/20161214_R44715_e13f9da7116c0368451dd56ac6f1c729b593d21c.pdf

[18] http://faculty.haas.berkeley.edu/ldavis/Davis%20and%20Hausman%20AEJ%202016.pdf

[19] J. Jenkins and S. Thernstrom, Deep decarbonization of the electric power sector: Insights from recent literature. *Energy Innovation Reform Project*. March 2017.

[20] https://nnsa.energy.gov/aboutus/ourprograms/dnn/nis/safeguards/sbd.

[21] C. McMillan, R. Boardman, M. McKellar, P. Sabharwall, M. Ruth, and S. Bragg-Sitton, (2016). *Generation and Use of Thermal Energy in the U.S. Industrial Sector and Opportunities to Reduce its Carbon Emissions.* (Report No. NREL/TP-6A50-66763). The Joint Institute for Strategic Energy Analysis.

schedule delays.[22] Significant simplification of plant design,[23] reduction in plant size, and manufacturing standardization could all bring large cost reductions.

Nuclear reactor plants are some of the heaviest structures on earth, requiring expensive site preparation. The concrete basemats and containment structures are very complicated to pour. Direct materials, labor, and equipment costs are high. Therefore, reducing the weight and complexity of the entire power plant through advanced construction techniques, or choosing plant designs that are safer or have lower operating pressures that require significantly smaller containments, are all strategies that could lower the capital and construction cost.

Further, many LWR construction projects are plagued by inefficiencies and challenges to construction management caused by the complexity of installing very large systems with many requirements. The project complexity is often compounded by the fact that many components of nuclear power plants are customized to a specific site. The combination of these effects can lead to design changes, re-engineering, and unanticipated costs or delays. These costs and delays can be avoided by designing reactors with simple systems that are easy to construct and that do not require customization for any particular site with respect to requirements such as water availability and seismic preparation.

Both the quality assurance (QA) requirements and the procurement of nuclear-grade components can also lead to high costs. The QA process for components such as pipes or processes such as welding can increase the cost compared to a non-nuclear counterpart by a factor of 10 or more. A potential cost-reduction strategy is to simplify plant design such that fewer overall components and processes need NQA-1[24] certification per plant. Further, since reactor construction stalled in the U.S. for approximately 30 years, the supply chain for nuclear reactor components and availability of craft workers such as nuclear-trained welders and construction experts is currently underdeveloped. All of this can lead to higher costs, uncertainty in supply chain, and delays. Any reduction in the number and volume of nuclear-grade components per MW_e could translate into cost savings.

Well-conceived systems integration of simple technologies may greatly reduce plant construction complexity, avoiding expensive site preparation and customization, and reducing or avoiding large-size components that are difficult to procure.

2.2.2 Substantially-Autonomous and "Walkaway"-Safe Systems

Unlike fossil electricity sources, wherein the fuel cost is the primary component of the electricity cost, the cost of electricity production from current-fleet LWRs is dominated by non-fuel O&M costs, which are driven by the high staffing levels (≥ 450 FTE/GW_e) needed to operate, maintain, and secure the LWR plants.[25,6] Thus, reduced staffing levels are essential for the economically-sustainable operation of nuclear power plants.

Advanced technologies such as robotics, thorough and sophisticated sensing, model-based fault detection, and secure networks may be leveraged to design substantially-autonomous operations for nuclear reactors to significantly reduce the staffing level. Here, substantially-autonomous operations are defined as those that are free from operator interventions during normal operations, and only requiring supervised autonomy or autonomous shut-down in abnormal or accident scenarios.

Approaches in sensors, data analytics, and advanced controls (including autonomy and integration of machine learning) that limit or eliminate the need for humans to conduct regular monitoring and maintenance and enable early corrective action for abnormal conditions are encouraged. A simulated system allows exploration of a full range of potential data streams, and can help identify the most relevant sensor needs. This could help set the stage for radically new control approaches and substantial autonomy in nuclear power plants. With the advent of modern machine learning approaches, nuclear plant operators can better understand plant operations, anticipate equipment maintenance, and predict equipment replacement. Machine learning and predictive modeling could also allow nuclear units to communicate with and learn from one another and to operate in an optimal manner to respond to grid variations in energy load demand. Applicants are encouraged to explore novel control schemes and predict responses to a wide range of operating conditions and demands

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[22] http://www.mckinsey.com/industries/capital-projects-and-infrastructure/our-insights/the-construction-productivity-imperative.

[23] I.N. Kessides, The future of the nuclear industry reconsidered: Risks, uncertainties, and continued promise. Energy Policy, 48 (2012) 185–208.

[24] https://www.nrc.gov/reading-rm/doc-collections/cfr/part050/part050-appb.html

[25] http://instituteforenergyresearch.org/wp-content/uploads/2015/06/ier_lcoe_2015.pdf

that would be impractical and expensive to explore in a physical prototype. Well-designed experiments may derisk the most uncertain aspects of some of these control schemes.

Inherent safety is characterized by the lowest potential consequences of an accident. In the worst scenarios, there should be no radioactive nuclide releases that could have measurable public health impacts (defined as 0.25 millisieverts/month above background radiation levels). This can be achieved by strategies such as having a reactor with fail-proof systems (with no reliance on electrical power) that provide accident protection, and/or a small nuclear source term. [26]

"Walkaway" safe reactor plant designs may not have accidents that require human intervention or any backup electricity for an extended period of time. This reduces the need for emergency response teams to be on-site and in nearby communities, reduces the complexity of emergency planning, and alleviates the uneasiness of having a reactor near a community.

Designs that are "walkaway" safe also need to protect against sabotage and include safeguards by design. Inherent safety is often linked with increased physical security of nuclear materials. Reactor plants are very physically secure when it is difficult to sabotage the plant, purposefully cause an accident, or divert nuclear materials for nefarious purposes. Very physically secure reactor plants with substantially-autonomous operations may enable the reduction of on-site security staff since the consequence of a reactor breach is minimal and the time to respond is much extended.

Applicants are encouraged to develop other innovative means for reduction of the staffing and overall O&M cost.

2.2.3 Materials and Chemistry

Nuclear materials integration, chemical interactions, and corrosion (including coolant chemistry control) are areas that contain some of the largest uncertainties and may have some of the biggest impacts on new reactor plant potential. With the integration of multi-physics models to support the modeling and simulation of integrated power plant systems, plant designers can identify materials challenges in advance of any hardware development, and develop solutions to mitigate or avoid interactions that will limit the safety, performance, or lifetime of components or sub-systems. Identifying the highest-risk or most uncertain areas can inform targeted experimental work to move this area forward.

Applications are encouraged that propose innovative approaches to resolving materials and chemistry issues for advanced reactor plants.

2.2.4 Modular and Advanced Manufacturing

Advanced manufacturing (including additive manufacturing) of nuclear-relevant metals and materials may enable less expensive manufacturing of plant equipment and components, up to and including large components. The ability of additively-manufactured components to withstand the harsh temperature and radiation environments of nuclear reactors needs to be demonstrated to support the commercial use of the technology for nuclear power plant applications. Applicants should consider how work piloted here can rapidly explore component and subsystem designs to bound materials and component requirements, and help guide hardware development with advanced manufacturing.

Beyond advanced manufacturing at the component level, modular manufacturing of systems and sub-systems may be a key enabler to achieving fast on-site construction time. Applicants should consider the factory manufacturing experience of large gas turbines and other similar systems that are made modularly in factories and then assembled on site. In this way, the long-lead-time components can be planned and made according to manufacturing schedules. The reactor plant systems can be made-to-order in factories, which allows the construction of an entire nuclear power plant on site very quickly.

A modular approach may also enable rigorous testing of the reactor core modules in various extremes, such as seismic shaking or system flooding. Nuclear reactor plant designers may be able to leverage the safety design and testing practices used in other industries that use modular manufacturing, such as jet engines and gas turbines, to improve designs and enhance safety. Applicants may also consider the inclusion of other innovative manufacturing and construction processes,

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[26] https://www.nrc.gov/reading-rm/basic-ref/glossary/source-term.html

such as use of high performance concrete or advanced robotics, as long as fast on-site and overall (on-site + factory time) construction can be achieved.

2.3 ARPA-E MEITNER Program Resource Team

As part of the MEITNER Program, ARPA-E will task and fund the Oak Ridge National Laboratory (ORNL) to establish a Resource Team to provide relevant assistance to Awardees for their efforts. The Resource Team will consist of three coordinated sub-teams: a computational M&S sub-team, a TEA sub-team, and a SME sub-team. (For details, see Section I.E below, "TECHNICAL SUPPLEMENT: ADDITIONAL INFORMATION ON THE CAPABILITIES OF THE RESOURCE TEAM"). Through the Resource Team, Awardees will have access to SMEs from both the nuclear and non-nuclear disciplines needed for developing the enabling technologies needed by the U.S. advanced reactor design community. As outlined in Section I.E below, Awardees are expected to draw upon Resource Team expertise, and will be required to cooperate with the TEA sub-team, which will ensure that uniform assumptions are applied across all Awardee technologies.

Specifically:

- The M&S sub-team will leverage existing federal DOE investments, primarily embodied in the DOE-NE Nuclear Energy Advanced Modeling and Simulation (NEAMS) program[27] and Consortium for Advanced Simulation of Light water reactors (CASL) Energy Innovation Hub,[28] to perform M&S for and with the Awardees upon request using the best available software. Computing resources will also be provided to the Awardees for this purpose.

- The SME sub-team will provide advice and information to the Awardees to ensure their technologies contribute substantially to safety, security, manufacturability, feasibility, and other design technologies and considerations for advanced reactor designs. Examples include seismic considerations, autonomous operations, advanced manufacturing, sensing and data analytics, component procurement, etc. The SME sub-team will also assist Awardees in placing their technologies into the larger system context.

- The TEA sub-team will be comprised of experts in energy system cost modeling and will work with each Awardee to ensure consistency and quality of TEA of the selected enabling technologies funded through this FOA.

ARPA-E will approve ORNL's proposed members of the Resource Team, including review for potential personal or organization conflicts of interest. MEITNER Awardee and Sub-Awardee personnel and consultants will be excluded from the Resource Team. No Resource Team members or their employers will obtain data rights or other intellectual property rights in any MEITNER Awardee's work products submitted to the Resource Team for evaluation. The Resource Team members will be required, via agreements with MEITNER Awardees (CRADAs or otherwise), to maintain strict confidentiality regarding:

a) The proprietary technical details of the MEITNER Awardee's work products provided to the Resource Team members for evaluation, and

b) Results that are generated by the Resource Team, to the fullest extent allowable by statute and regulation. In addition, data generated by the Resource Team members about individual MEITNER work products under the agreements (CRADAs or otherwise) will only be provided to the specific MEITNER Awardee whose work products are being evaluated, and to ARPA-E.

Awardees will be required to establish an Intellectual Property (IP) Management Plan with the Resource Team upon award. Details on the IP Management Plan can be found in Section VIII.H of the FOA, "RIGHTS IN TECHNICAL DATA." Note: <u>MEITNER Awardee and sub-awardee personnel and consultants will be excluded from the Resource Team.</u> Resource Team members will not obtain data rights or other IP rights in any MEITNER Awardee's designs submitted to the Resource Team for evaluation.

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[27] http://www.ne.anl.gov/NEAMS/, Advanced Modeling & Simulation Office (NE-41), Nuclear Energy Advanced Modeling & Simulation (NEAMS) Program Overview.

[28] http://www.casl.gov/, J. Turner, K. Clarno, M. Sieger, R. Bartlett, B. Collins, R. Pawlowski, R. Schmidt, and R. Summers, The virtual environment for reactor Applications (VERA) design and architecture, Journal of Computational Physics, 326 (2016) 544–568.

No data rights or IP Management needs to be addressed during the Concept Paper or Full Application stages.

C. PROGRAM OBJECTIVES

The objective of the MEITNER Program is to identify, characterize, and develop enabling technologies that support moving existing advanced reactor designs from concept to products that are “walkaway” safe, quickly-deployable, safeguardable, cost-competitive, and commercially-viable. ARPA-E anticipates that most work will be based in M&S, but welcomes targeted experiments that substantially contribute to technology development. It is expected that the improvements and modeling validation in Awardee technologies will reduce the perceived risks, providing more complete and certain information for future development and commercialization.

It is expected that at the end of the MEITNER Program, each Awardee will have established a well-characterized enabling technology or set of technologies where:

- performance and safety have been studied with multi-physics M&S tools;
- key cost and performance drivers have been identified for critical development and testing;
- key gaps in models or data have been identified, which can be addressed through targeted experimental work;
- costs and construction timelines are well projected; and
- robust techno-economic analysis (TEA) has been performed and a clear technology-to-market (T2M) plan has been created.

Further, a successful outcome of the MEITNER Program will be for the Awardees to perform or be ready to perform essential experiments, or to build prototypes or demonstration systems, and to garner follow-on funding at the completion of this Program.

D. TECHNICAL DESIGN TARGETS

Applicants are required to describe and quantify in detail how their technologies will enable nuclear power plant designs to perform significantly better than the state of the art. Table 1 summarizes the metrics of interest, and Applicants must specify how they will perform in each area. Each Applicant must include quantitative analysis, with supporting calculations and references, that demonstrate how the envisioned technology will improve nuclear plant performance in these target areas. This must include estimations of uncertainty associated with each target area. Applications must include the approach used for cost projections.

Applicants are also required to quantify and justify how and how much they anticipate their technologies would improve during this Program. This discussion should include an explicit assessment of technical gaps and critical areas that are to be de-risked and a plan to reduce uncertainties in safety and cost. Specifically, Applicants must discuss what would be accomplished with both the requested financial assistance through this FOA and through access to the Resource Team (funded separately by ARPA-E). Applicants must include what M&S is needed and an estimate of the amount of computing resources they might need to use the software tools as well as what areas of subject matter expertise will be most impactful. Applicants must explain how cost modeling will be implemented in their work strategy. Further, Applicants must outline any experiments they would like to conduct and how the results of those experiments will improve or validate their technology.

Each Applicant must provide a technical description of the work to be performed and discuss how participating in the ARPA-E MEITNER Program will substantially enhance their ability to more rapidly, safely, and cost-effectively develop state-of-the-art technologies that support the licensing and deployment of existing advanced reactor concepts. Each Applicant must propose specific and well-defined deliverables that quantify, to the fullest extent possible, the anticipated improvements in reactor and power plant performance that would be achieved by the end of the Program and explain how those deliverables will enable the Applicant to move to the next stages of development.

1. Primary Design Target Areas

Table 1 lists the design target areas for the MEITNER Program and provides an assessment of the current state-of-the-art. Applicants are to provide their own targets for the entries left blank. Note that only one of 7a, ability to grid-integrate with intermittent resources, and 7b, ability to produce heat for industrial processes, needs to be targeted. For overnight construction cost and total staffing level, Applicants **must** detail either (1) how their technology enables the performance specified, or, (2) in the case that this performance is not yet obtainable, a realistic pathway such that the performance may be obtained in a relevant timeframe. Note that the TEA workbook described below may be used to demonstrate overnight construction cost.

Table 1. Enabling technologies sought by ARPA-E must improve reactor performance in these target areas.

ID	Metric	Units	State-of-the-Art	Performance to be achieved by using the new technology*
1	Overnight construction cost	$\$/W_e$	2-7 [29]	< 2
2	On-site construction time	Months	> 60 [30]	
3	Total staffing level (on-site & off-site)	FTE/GW_e	450-750 [31]	< 50
4	Emergency planning zone (EPZ)$^+$	Miles	10 and 50 [32]	
5	Time before human response required for an accident	Days	3 [33]	
6	Onsite backup power	kW_e	> 0 kW [34]	
7a	Ramp rate without steam bypass	power capacity/min	5% [35]	
7b	Process heat temperature	ºC	N/A	

* Applicants are required to provide the projected performance based on the inclusion of their new technology into advanced reactors.

$^+$ As measured from the center of the nuclear reactor core to the boundary: location where, during an accident, radiation levels are 0.25 millisieverts/month or less above the background level.

ARPA-E recognizes that suitable high-fidelity analysis tools or data may not exist by the deadline for submission of the application to this FOA to conclusively prove that a new technology will cause a plant design to perform in the manner asserted in each application. To mitigate this issue, each Applicant is required to provide the following information, termed “Associated Indicators”, about the system their technology will fit in to.

2. Associated Indicators

For each item in Table 2, Applicants must indicate

1. An impact:
    - “Improved” for items specifically affected by their technology.
    - “Not Impacted” for areas unaffected by their technology that are still relevant to their technology (e.g., a heat exchanger design may not change technical readiness level of fuel and the heat exchanger may only be applicable to a certain reactor type, so technical rediness level of fuel is still relevant information).

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[29] http://www.world-nuclear.org/information-library/country-profiles/countries-o-s/south-korea.aspx, http://www.world-nuclear-news.org/NN-Flamanville-EPR-timetable-and-costs-revised-0309154.html

[30] http://www.world-nuclear-news.org/NN-Key-commissioning-test-completed-at-Korean-unit-1711165.html, http://www.world-nuclear-news.org/NN-Flamanville-EPR-timetable-and-costs-revised-0309154.html

[31] https://www.eucg.org/pub/3ff048c1-f842-57dd-f625-bc35440aa9c4

[32] https://www.nrc.gov/about-nrc/emerg-preparedness/about-emerg-preparedness/planning-zones.html

[33] http://www.nuscalepower.com/images/our_technology/nuscale-safety-nucl-tech-may12-pre.pdf, https://www.iaea.org/NuclearPower/Downloads/Technology/meetings/2011-Jul-4-8-ANRT-WS/2_USA_UK_AP1000_Westinghouse_Pfister.pdf

[34] https://www.nrc.gov/docs/ML1122/ML11229A062.pdf

[35] http://nuclear-economics.com/12-nuclear-flexibility/

- "Not Related" for items that are not relevant to their technology (e.g., a new construction technique may be applicable to many designs and could have no relationship to refueling frequency).

2. A "Base Case" value or description for a system that does not include the new technology. Include for improved and not impacted items.
3. A "New" value or description for a system that does include the new technology. Include for improved items.

Applicants may add and describe areas improved by their technologies that are not listed below.

Table 2. Applicants must indicate the impact of their technology on these associated indicators.

Item	**Impact**	**Base Case**	**New**
Cost			
Power conversion efficiency and/or co-product generation details			
% of construction/fabrication materials by number of components requiring an NQA-1 program			
% of construction by weight that needs to be site-customized			
% of plant by weight that can be manufactured and delivered as modules (by truck, rail, or boat)			
Technical readiness level of fuel			
Cost of fuel in $/MW$_e$			
Core power density			
Safety			
Core damage frequency (or equivalent measure)			
Core melt frequency (or equivalent measure)			
Size of nuclear source term in Curies (Ci) or megawatt thermal (MW$_t$)			
Ability to test/demonstrate new safety characteristics			
Market Appeal and Viability			
Refueling frequency and duration			
Core and plant design life			
Reliability and availability			
Electrical output			
Water requirements			
Waste generation and/or ability to consume used fuel			
Target market or markets of the plant			
Justification of how plant characteristics fit that market			
Safeguards by Design			
Refueling strategy in terms of potential for material diversion			
Breeding ratio (if applicable)			
Enrichment level (if applicable)			
Fuel form			
Strategy for materials control and accountability and associated uncertainty quantification			
Refueling strategy in terms of potential for material diversion			

If new technologies important to safety are being introduced and these technologies have not yet been tested or demonstrated, Applicants will need to detail the feasibility and timeline of testing and demonstrating such safety features, e.g., the use of a new material or the use of robotics to conduct maintenance activities will require a certain number of hours of testing in specific environments.

3. Technoeconomic Analysis Workbook

Full Applications must include a detailed estimation of costs of their technology and the associated reactor plant. Applicants must provide the information identified in the TEA Workbook Template, available on ARPA-E eXCHANGE at https://arpa-e-foa.energy.gov.

4. Technical Categories

Applicants must select the most relevant Technical Category and Applicable Reactor Type

Technical Category:
- Analytics / Controls / Sensors
- Construction / Fabrication
- Grid Integration
- Heat Exchangers / Power Conversion
- Materials / Chemistry
- Plant Component Design

Applicable Reactor Type:
- Multiple Types / General
- Gas Cooled
- Heat Pipe
- Lead Cooled
- Molten Salt Cooled
- Sodium Cooled
- Supercritical Water Cooled

E. TECHNICAL SUPPLEMENT: ADDITIONAL INFORMATION ON THE CAPABILITIES OF THE RESOURCE TEAM

The M&S sub-team will support the M&S needs of the MEITNER Awardees. The areas required for M&S support will depend on the technology being developed. Table 3 lists the codes in both the CASL and NEAMS programs, as well as other DOE National Laboratory-developed tools, that can be made available to Awardees through license agreements with the developing organizations. Awardees may need other software, such as MCNP, Serpent, and SCALE, that are commonly used for nuclear reactor plant design. Note this list and Table 3 are not exclusive, and that the software does not need to be developed at DOE National Laboratories.

Table 3. List of potential M&S codes.

Category	Activities	Preliminary list of codes to be leveraged
Software Integration	Physics coupling	SIGMA, DTK, MOOSE
	Usability	VERAin/VERAout/VERAview, NEAMS Workbench
	Neutronics	MC2-3, DIF3D/VARIANT, REBUS, ORIGEN, PROTEUS, PERSENT, MPACT, Shift
	Thermal fluids	SE2-ANL, Nek5000, COBRA-TF

Physics Tool	Fuel performance	LIFE-METAL, BISON
	Structural mechanics	NUBOW-3D, DIABLO
	Chemistry/corrosion	MAMBA
Systems and Controls	Integrated system modeling	RELAP53D, SAM
	Safety analysis	SAS4A/SASSYS-1, CONTAIN-LMR, RELAP53D
	Dynamic PRA	ADAPT

The TEA sub-team of the Resource Team will be available to assist awardees to evaluate the overnight construction cost, the O&M cost, the LCOE, and the effects of various design trade-offs on the costs. The TEA sub-team members will have established experience in performing TEA for the nuclear industry. The TEA sub-team will leverage software packages and analysis procedures such as EON's model [36] to perform TEA for various innovative Awardee designs.

The SME sub-team will consist of experts from both nuclear and non-nuclear sectors to provide advice and information to Awardees to improve their technologies as they impact safety, security, manufacturability, feasibility, and other design technologies and considerations. Examples of areas of expertise that could be leveraged include:

- Factory manufacturing of safety-grade and/or large components
- Electricity markets
- Load following and grid integration
- Generation of co-products such as industrial process heat
- Advanced construction techniques
- Reactor physics, neutronics, nuclear data, and shielding
- Structural and functional materials
- Chemistry, chemical interactions, corrosion, and coolant chemistry control
- Nuclear fuel design, fabrication, and performance
- Power conversion and heat transport
- Sensors, instrumentation, controls, autonomous operation, and robotics
- Diagnostics and prognostics
- Safety, severe accidents, and environmental impacts
- Nuclear security and safeguards
- Used fuel and waste management
- Advanced/emerging technologies (such as advanced manufacturing)

The SME sub-team experts will be selected and invited based on the collective needs of expertise expressed post-award to the MEITNER Program Director by Awardees.

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[36] http://innovationreform.org/wp-content/uploads/2017/07/Advanced-Nuclear-Reactors-Cost-Study.pdf