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Abstract–*There is an ongoing need to supply energy to small markets and remote locations with limited fossil fuel infrastructures. The Small, Modular, Liquid-Metal-Cooled Reactor, also referred to as SSTAR (Small, Secure, Transportable, Autonomous Reactor), can provide reliable and cost-effective electricity, heat, fresh water, and potentially hydrogen transportation fuels for these markets. An evaluation of a variety of reactor designs indicates that SSTAR, with its secure, long-life core, has many advantages for deployment into a variety of national and international markets. In this paper, we describe the SSTAR concept and its approach to safety, security, environmental and non-proliferation. The system would be design-certified using a new license-by-test approach, and demonstrated for commercial deployment anywhere in the world. The project addresses a technology development need (i.e., a small secure modular system for remote sites) that is not otherwise addressed in other currently planned research programs.*

1. BACKGROUND

This paper describes efforts for the development of a small, secure, transportable liquid-metal-cooled fast reactor to be built and NRC design certified using a new license-by-test approach. The design is targeted for small energy markets (10MWe-100MWe) in remote locations where large-scale energy infrastructures do not exist. Design features related to security, including sealed or cassette cores, long-life fuels and materials, integrated instrumentation and control, and specialized detection and signaling systems will be incorporated to reduce the risk of proliferation of nuclear materials. The system design and R&D, including prototype certification, will be completed to support initiation of demonstration by 2015.

The SSTAR concept is compatible with the existing DOE-NE Gen-IV,[1] AFCI[2] and NP2010[3] programs, and will benefit from and contribute to those programs. The enhanced safety, security, and sustainable advanced fuel cycle of this small liquid-metal-cooled fast reactor (LMR) directly address Gen-IV goals. Small LMRs (lead- or sodium cooled) are one of the development areas of interest for Gen-IV, and the envisioned deployments of the SSTAR as a small, modular reactor system, are a part of the broader Generation IV mission that is not being addressed elsewhere.

The SSTAR concepts that will be considered in this program are primarily focused on lead (or lead-bismuth alloy) cooled reactor systems. Sodium cooled systems are being considered by our colleagues in Japan, and hybrid options may also be possible. Final decisions on the coolant and materials will be based on the results of the work carried out in the initial years of this program. Considerations will include materials compatibility, technology maturity, and the urgency of early deployment.

The fuel cycle for the SSTAR is consistent with Series-II Advanced Fuel Cycle Initiative (AFCI) objectives and plans, with the added uniqueness of very long core lifetimes. The SSTAR project will benefit from (and contribute to) Generation IV (Gen-IV) and AFCI developments in fuels, processing, structural materials, instrumentation and control systems, safety, security, and regulatory processes, and will represent the test bed for proliferation resistant design features.

The SSTAR project will demonstrate features needed to support factory assembly, transportation and deployment of small modular systems. An SSTAR demonstration will provide an early fast-spectrum irradiation facility, of potential benefit to Gen-IV and AFCI. The facility would provide both a prototype demonstration as well as a test facility.

2. SSTAR/SMFR VISION, MISSION, AND GOALS

There is an ongoing need to supply energy to small markets and remote locations with limited fossil fuel infrastructures. The SSTAR/SMFR can provide reliable and cost-effective electricity, heat, fresh water, and potentially hydrogen transportation fuels for these markets. An evaluation of a variety of reactor designs has indicated that a secure-core, long-life SSTAR has many advantages for deployment into a variety of national and international markets.[1]

Lawrence Livermore National Laboratory (LLNL) with Argonne National Laboratory (ANL) and Los Alamos National Laboratory (LANL), the University of California (UCB), and Texas A&M University have worked to develop the concept of a small, transportable, autonomous proliferation-resistant reactor (STAR) since 1997. More recently, with the Central Research Institute for Electric Power Industry (CRIEPI) in Japan, a Joint Preliminary Feasibility Study (JPFS) was initiated to consider a modified 4S (Super Safe, Small, and Simple) small liquid-metal cooled reactor design originated by CRIEPI and Toshiba and to evaluate its potential to meet the desired features of the STAR concept.

Designing a fast-spectrum reactor design to meet U.S. safety, security and economic requirements and with features derived from the 4S concept will be the approach to achieving the final SSTAR design. Japanese collaborators have indicated an interest to cooperate on the SSTAR project, and this cooperation is expected to include full participation in the design, R&D, and demonstration activities in the project, and will entail with cost sharing.

This project will provide a new generation reactor and fuel cycle technology meeting U.S. safety, security, environmental and non-proliferation requirements, demonstrated in the U.S. and deployable commercially in the U.S. and abroad, while sharing the development and demonstration costs. The project capitalizes on a unique opportunity for a highly leveraged approach to deploy a modular system for remote areas. In addition it fills a gap (i.e., a small secure modular system for remote sites) while otherwise complimenting and harmonizing with current plans for the Gen IV and AFCI programs. Figure 1 provides a sketch of the SSTAR transportation concept and a summary of SSTAR attributes.

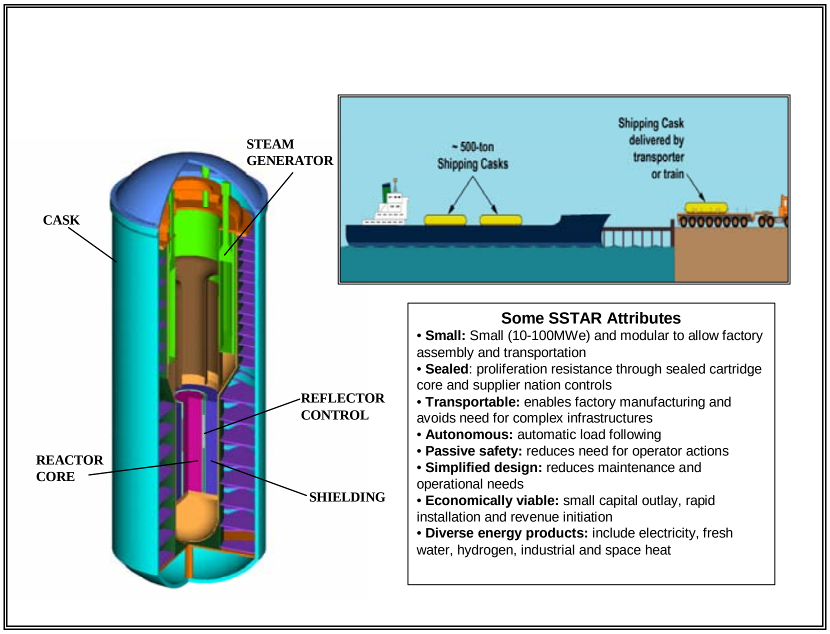

Figure 1. The Small Secure Transportable Autonomous Reactor (SSTAR)

2.1 Vision

The vision of the SSTAR/SMFR program is the future commercial deployment of advanced small reactors (10-100MWe), which are highly proliferation resistant (including no on site storage of fuel), employ secure reactor cores with lifetimes of up to 30 years, are economic and simple to operate, and are deployable virtually anywhere in the world.

2.2 Mission

The mission of the SSTAR/SMFR program is to research, design, develop and initiate demonstration of an advanced small reactor, which is safe, secure, transportable and highly proliferation resistant, by the year 2015.

2.3 Goals and Objectives

The overall goal of SSTAR/SFMR program is the successful demonstration (leading to commercial deployment) of a small, proliferation resistant reactor. The goal of the SSTAR/SFMR program under this Six Year Program Plan is to complete the formal project activities leading to the decision to go forward with the design and construction of a Demonstration Facility for the SSTAR/SFMR reactor concept(s).

To achieve these goals, the following objectives will be pursued:

- Complete preliminary project activities related to mission need in FY-04
- Continue with pre-conceptual planning activities in FY-05
- Submit pre-conceptual planning package by the end of FY-05
- Complete conceptual planning activities leading to the alternative selection and cost range definition by 2010 (FY-09)
- Conduct international collaborative activities to support joint US-Japan project participation

- Complete needed technical R&D to support design development (including fuels, materials, design and deployment)

- Develop basis for demonstration activities to enable the commercial deployment (with related manufacturing and support infrastructures) in the 2015 to 2025 time frame.

3. R&D ACTIVITIES

The R&D activities envisioned for this project include those related to reactor design, fuels, materials and deployment. In addition, the anticipated collaboration and coordination with ongoing related activities in Japan can be considered to be an important adjunct to these efforts. A summary of planned activities in each area follow. Because the program is not yet fully established, emphasis has been placed on determining the near-term (i.e., the next six years, or so) activities, and those activities are discussed here.

3.1 Design

System design activities are planned to address issues related to reactor design, energy conversion, instrumentation and control, and modular manufacturing and transportation. The design work will include pre-conceptual and conceptual design, trade studies to refine the reference concept, research and development of necessary technology, and design of a demonstration prototype unit.

The objectives of the pre-conceptual studies are to obtain a simplified design for a commercial plant to be deployed after the reactor concepts are demonstrated. These design studies will consist of preliminary trade-off and simplified design studies, incorporating past experience from development of SSTAR and other related reactor concepts. A major objective will be to obtain data to allow for incorporation of fuels and materials considerations into the pre-conceptual design used as a basis for the mission needs analysis. Another major objective is to define the functions and requirements for a demonstration plant to verify the novel features that can be later incorporated into a commercial plant design.

The objective of the pre-conceptual design activities is to perform core physics design, thermal hydraulic design, and reactor/systems design to develop a pre-conceptual design for a Demonstration Test Facility that will meet functions and requirements identified in the pre-conceptual studies. Core reactor physics design studies will determine core dimensions, fuel composition and loadings, and a reactivity control strategy for startup and autonomous load following. Thermal hydraulic design studies will determine the reactor system configuration and dimensions to achieve full natural circulation heat transport of the core heat rating together with autonomous load following and passive safety. Reactor and system design concepts will be developed for refueling/reload and logistics, balance of plant (i.e., Rankine steam cycle, or supercritical CO2 Brayton cycle), mechanical design of key components including identification of materials for the components, seismic accommodation, design to achieve the core radial expansion behavior required for autonomous load following and strategies for decay heat removal. Either steam, or in the case of a Brayton cycle energy conversion system, other appropriate working fluid will be connected by coolant flow piping to the energy conversion equipment external to the reactor vessel.

The objective of the conceptual design effort is to perform the core design, safety evaluation, and reactor and plant conceptual design activities necessary to develop a design for the Demonstration Test Facility. Core design activities will include core reactivity control concepts, operational evaluation, core mechanical design, core thermal hydraulic design, and assessment of core reactor physics performance and reactivity feedbacks. Safety evaluation will address implications of the reactivity feedback coefficients, system response to off-normal events, and seismic response evaluation. Reactor and plant conceptual design will encompass mechanical design of key components, design for radial expansion to achieve autonomous load following and passive safety, refueling/reload schemes and logistics, structural design features, decay heat removal schemes, containment approval, and the plant layout including power conversion.

3.2 Fuels

Key to this program is the identification of fuel and cladding materials and the design of the fuel system for the very long lifetime demanded by the SSTAR concept. Therefore, the SSTAR/SMFR program will address fuel development and testing as well as the back end of the fuel cycle. The near-term research in this effort will include defining fuel performance requirements, fuels design and definition, compatibility testing of fuel and cladding and their compatibility with Pb and Pb-Bi coolant, selection of a reference fuel form and cladding material, cladding and coolant materials testing, and fuel design for long life. Established fuel concepts (or minor variants thereof), such as ceramic or metallic rod-type fuel, will be considered first, but innovative fuel concepts will be considered as necessary.

Initial fuels work will be directed toward developing detailed fuel performance requirements based on the needs identified in the initial reactor design. These requirements will be updated as the design evolves from pre-conceptual to conceptual stages. In addition, a fuel qualification plan will be developed to address the needs of the reactor design and its safety and licensing approach. This plan will be complicated by limited availability of fast-spectrum testing facilities, so the start-up strategy for a demonstration plant will likely include provision for fuel performance verification and surveillance. Research and development work in the laboratory will focus on assessing the compatibility of fuel and cladding candidates with Pb and Pb-Bi coolant. Any incompatibilities will be assessed to determine if such are reasons to eliminate a particular fuel or cladding candidate from consideration.

In addition to fuel design for reactor performance, fuel cycle issues will also be addressed in this program. It is important to ensure that the reference fuel design is compatible with the front and back end of the fuel cycle. Studies and analyses are planned to address availability of fuel material and enrichment and to ensure fuel type compatibility with the reprocessing, partitioning and waste disposal options for final disposition.

3.3 Materials and coolant technology

The objectives of the SSTAR materials and coolant technology research are to address significant materials and coolant technology challenges, both for a demonstration prototype reactor and for a commercially deployable design. These issues include:

- Corrosion challenges related to the use of Pb or Pb-Bi eutectic (LBE) coolants
- The need for a simple, low-maintenance design with high inherent safety to achieve high component reliability requirements
- High radiation damage performance requirements related to the fast neutron spectrum and the very long life time requirements
- Long cladding lifetime required for the long core life of the reactor
- High-temperature materials performance requirements

These issues, combined with the desire for an early demonstration prototype, result in significant materials science challenges. A systematic program of materials evaluation, research, development, and demonstration is planned to address these challenges in parallel with reactor and fuel development and demonstration. The approach includes early identification of leading candidate materials for critical applications, performing material testing and model development to provide a basis for construction of the prototype reactor where material performance can be confirmed, while pursuing one or more material options as a backup in the event the candidate fails to perform as needed.

3.4 Deployment and infrastructure

The deployment and infrastructure activities needed to demonstrate the SSTAR concept will entail assessment of economic and proliferation resistance requirements, systems studies and other similar activities in support of the USDOE project decision process, and related safety and licensing activities to meet USNRC requirements. Work in this area will include specific activities needed to meet Critical Decision-0 (i.e., mission needs analysis) and Critical Decision-1 (i.e., conceptual design) requirements. As part of this, the technical functions and requirements will be determined and refined. Another important element is the performance of economic and market analyses. The safety and licensing approach will rely on a license-by-test strategy. Issues related to siting, manufacturing, installation and unit replacement will also be addressed.

International collaboration is also recognized as an important consideration. This involves potential technical collaboration with other national programs addressing small, fast spectrum reactors, including activities coordinated through the Generation IV International Forum. In addition, the joint US-Japan collaboration on small, fast reactors is and will be a continuing cornerstone of this program.

Japanese programs, especially those related to the CRIEPI/Toshiba Super Safe Small and Simple (4S) reactor concept,[5] have demonstrated a long-standing interest and commitment to small, fast reactors. During the past year, a joint project entitled the Joint Preliminary Feasibility Study (JPFS) has been carried out with participants from CRIEPI, LLNL and ANL. The purpose of JPFS is to evaluate the 4-S concept in three major areas: International Security, Market and Economics and Safety. The study suggests R&D and potential design modifications needed to make the program suitable as a joint U.S.-Japan effort and it evaluates possible design certification by the U.S.-NRC.

At the present, the Japanese program is considering two reactor designs, both with sodium coolant, at 10Mwe and 50Mwe outputs. The former is a loop type reactor with an integrated intermediate heat exchanger and steam generator, and the later is a pool type system. Both reactors maintain negative coolant void reactivities during a 30-year design life.

4. NON-PROLIFERATION IMPLICATIONS

The development of SSTAR to provide small reactors suitable for remote regions and countries with limited or developing energy infrastructures is linked to the non-proliferation advantages that the concept embodies. The concept is intended to reduce the complexity and expense of eliminating concerns about nuclear proliferation and severe nuclear accidents, even when the user country is in the initial phase of developing an energy infrastructure. A fundamental feature of the SSTAR is that the nuclear fuel is contained within the sealed reactor vessel when shipped to the user; the spent fuel is then returned to the supplier without being removed from the reactor vessel. As fresh fuel is provided as part of the reactor system and spent fuel is removed from the plant site within the sealed vessel, and no on-site refueling is needed during the reactor operation, there is neither access to, nor long-term storage of nuclear materials on-site. Small reactors with very long life nuclear cores are key to the SSTAR concept and its economic competitiveness.

5. SUMMARY AND CONCLUSIONS

In the SSTAR program, a new small, secure, transportable liquid-metal-cooled fast reactor will be built and NRC design certified using a new license-by-test approach. The design is targeted as a small energy generator (10Kwe-100Kwe) for remote locations where fully developed energy infrastructures do not exist. Design features related to security, such as sealed core, long-life fuel, and specialized detection and signaling systems will be incorporated to reduce the risk of proliferation of nuclear materials. This project will provide a new generation reactor technology meeting U.S. safety, security, environmental and non-proliferation requirements, demonstrated in the U.S. and deployable commercially in the U.S. and abroad.

ACKNOWLEDGMENTS

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