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SSTAR: The US lead-cooled fast reactor (LFR)

Craig F. Smith [a,*], William G. Halsey [b], Neil W. Brown [b], James J. Sienicki [c], Anton Moisseytsev [c], David C. Wade [c]

[a] Lawrence Livermore National Laboratory, and the US Naval Postgraduate School, 1 University Circle, Monterey, California 93943, USA
[b] Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, California 94550, USA
[c] Argonne National Laboratory, 9700 S. Cass Avenue, Argonne, Illinois 60439, USA

ABSTRACT

It is widely recognized that the developing world is the next area for major energy demand growth, including demand for new and advanced nuclear energy systems. With limited existing industrial and grid infrastructures, there will be an important need for future nuclear energy systems that can provide small or moderate increments of electric power (10–700 MWe) on small or immature grids in developing nations. Most recently, the global nuclear energy partnership (GNEP) has identified, as one of its key objectives, the development and demonstration of concepts for small and medium-sized reactors (SMRs) that can be globally deployed while assuring a high level of proliferation resistance. Lead-cooled systems offer several key advantages in meeting these goals. The small lead-cooled fast reactor concept known as the small secure transportable autonomous reactor (SSTAR) has been under ongoing development as part of the US advanced nuclear energy systems programs. It is a system designed to provide energy security to developing nations while incorporating features to achieve nonproliferation goals, anticipating GNEP objectives. This paper presents the motivation for development of internationally deployable nuclear energy systems as well as a summary of one such system, SSTAR, which is the US Generation IV lead-cooled fast reactor system.

1. Introduction

In considering the trends in global economic development, it is clear that the developing world is the next area for major energy demand growth. This is the part of the world where population growth is high and, furthermore, the gap between the current levels of energy availability and the levels needed to sustain economic growth is also great. There is a diversity of different scenarios for supply of expanded energy resources ranging from large and highly concentrated population centers of countries like China and India to remote and isolated communities (which also may be quite large). In addition, in many countries and locations, existing electric grid capacity is limited and not readily able to accept the large increments of generating capacity represented by current central station nuclear power plants. In many of these same locations, there are also shortages of fresh water presenting an additional need that small nuclear plants can readily fulfill. Finally, industrial infrastructures are frequently limited and not able to provide the support needed for large central station plant construction, maintenance and operation.

Thus, in addition to current central station nuclear power plants, it is appropriate to provide technology for advanced systems that are better aligned with the needs of areas with isolated populations, limited grid capacity, restricted fresh water supplies and limited industrial infrastructures.

For such areas, there is a need for advanced power systems that can provide: small increments of electric power (10–100 MWe) on distributed grids; simple controls; passive safety; low maintenance levels; reliability in power availability over long periods of time; stability in energy prices and low investment risk. A small, lead-cooled reactor concept can satisfy these crucial market needs. Additionally, it is essential to implement enhanced nuclear materials security strategies that reduce concerns about the expanded use of nuclear technology.

The US lead-cooled fast reactor (LFR), being developed under the Generation IV program, is focused on the concept of a small transportable reactor system for international deployment known as the small secure transportable autonomous reactor (SSTAR). SSTAR has the following objectives: (1) a reactor core that is sealed or configured as a cassette core to eliminate or limit the need (and ability for) on-site refueling; (2) transportability: the entire core and reactor vessel is delivered by ship or overland transport; (3) a very long-life core design: 15–30 year core life is the target; (4) the capability for autonomous load following with simple integrated controls allowing minimal operator intervention and enabling minimized maintenance; (5) local and remote monitorability to permit rapid detection/response to operational perturbations. These features

* Corresponding author.
E-mail address: cfsmith@nps.edu (C.F. Smith).

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permit installation and operation in places with minimal industrial infrastructures. Further, they provide a plant characterized by a very small operational (and security) footprint.

2. Background

In the past, nuclear energy development has focused on providing an energy technology alternative for developed countries. By most measures, this has been very successful in stimulating the development of this energy source over the past 50 years. Currently, nuclear energy represents approximately 16% of the world's electrical energy production from a fleet of 439 reactors [1]. In the US, nuclear energy represents about 19% of the electrical energy supply, and 104 power plants are currently in operation [2].

Looking to the future, current US policy, represented by the global nuclear energy partnership [3], is focused upon domestic deployment of large-scale LWRs and the development of a sodium-cooled fast spectrum advanced recycle reactors working in symbiotic relationship with the LWR fleet to manage its used nuclear fuel. Internationally, planning for sodium-cooled fast reactor (SFR) breeders is underway in France, Japan, China, India, South Korea and Russia.

These future global nuclear deployments in industrial nations could provide a basis for an expansion in the use of nuclear energy in countries such as China, India and Russia and in other countries with well developed electrical grids, but such expansion would not necessarily directly benefit the large populations in less developed countries; further, it would not be sufficient to stem increasing greenhouse gas emissions as developing nations massively increase in population and per capita energy consumption. Clearly, the world should address the potential issues that could arise as the developed nations expand their reliance on nuclear energy while the developing nations dominate future growth in energy demand.

Table 1 presents the results of an analysis of the demand for nuclear energy capacity by 2100 in order to meet several postulated goals concerning maintenance of market share for nuclear energy, capping of fossil energy use and providing for the substitution of nuclear generated hydrogen for fossil energy sources. These scenarios further emphasize the expanding need for nuclear power and it is only realistic to recognize that small reactors will be needed for a portion of this growth. It is recognized that renewables should also play a key role in meeting a portion of the future demand growth anticipated in these scenarios. However, renewables, being intermittent, require the emplacement of associated base load capacity for those periods where they are unavailable – thus, they are better suited for adding incremental capacity on well established grids than they are for developing grids.

2.1. The need for fast reactors

For nuclear energy generation to significantly contribute to greenhouse gas mitigation, very large growth rates in the nuclear market share would be required. To achieve such levels, the available fissile mass becomes a limiting factor. Thus, the use of fast reactors with moderate to high conversion ratios must become a significant factor in the introduction of advanced nuclear energy sources.

This raises a significant institutional challenge – how can we simultaneously meet global energy needs while avoiding exacerbating proliferation hazards? The solution to this energy security/nonproliferation dilemma involves introduction of a fuel cycle architecture based on recycling and fuel cycle service centers sited at a few locations worldwide. These service centers would include facilities for enrichment, fuel recycle and fabrication, and waste management. Establishing these few service centers is a major challenge but is necessary to assure equitable world access to safe secure growth in nuclear energy.

Selected sites would include high performance fast breeders dedicated to fissile fuel production to provide continued supplies of economic fuel. This strategy could support fleets of long-refueling-interval reactors at distributed customer sites not otherwise served by large light water or advanced recycle reactors. The global nuclear energy partnership and Regional Fuel Cycle Center architectures both incorporate features of this institutional structure. Distributed power plants may include a variety of reactor types determined by market forces. Fig. 1 illustrates the concept.

2.2. Desired attributes for worldwide deployment

The additional reactor systems needed to complete nuclear deployment to all potential users, including those in remote locations on small grids, while also meeting the constraints and limitations of the host countries can be envisioned to be reactors that are small (i.e., <300 MWe) or medium (300–700 MWe) in size [4]. Such reactors are better suited to growing economies and infrastructures of partner states and developing nations than classical economy-of-scale plants.

To further address both the energy security and proliferation concerns that could arise from widespread use of nuclear energy technology, and the limited infrastructure in developing countries, it is desirable for the reactors to employ very long core lifetimes, approaching 30-years. Such core designs would permit restriction of access to fuel and the neutron environment while alleviating the need for the users to develop infrastructures to address the fuel cycle, including enrichment, reprocessing and waste disposal. The supplier would also provide the infrastructure for fuel handling at the end of core life and would return the used fuel to a central recycling center. Restriction of access to the reactor core would additionally reduce the potential for misuse of the system in a breeding mode.

Additional desired attributes include the incorporation of fuel forms that are unattractive in a safeguards sense; and the implementation of a design with a conversion ratio (CR) near unity to self-generate as much fissile material as is consumed (also enabling the very long core life mentioned earlier).

Table 1
Selected nuclear power growth scenarios

Goal	Nuclear market share of primary energy by 2100, %	Nuclear power by 2100, TWt	100-year growth rate, % per year
Maintain current market share[a]	6[b]	3.18 (~factor of 3 increase)	1.2
Cap fossil energy at current absolute level	75	39.8 (~factor of 40 increase)	3.68
Reduce fossil energy to ½ current absolute level by manufacturing H_2[c] for 2/3 of primary energy market	144	76.3 (~factor of 75 increase)	4.34

[a] Assumes world primary energy growth at 1.2% per year from 16 TWt to 53 TWt over a 100-year period (53 TWt would support 10 billion people at 4 tonnes of oil equivalent per capita).
[b] Current nuclear market share is ~6% of the total primary energy of 16 TWt.
[c] At conversion efficiency of 50%.

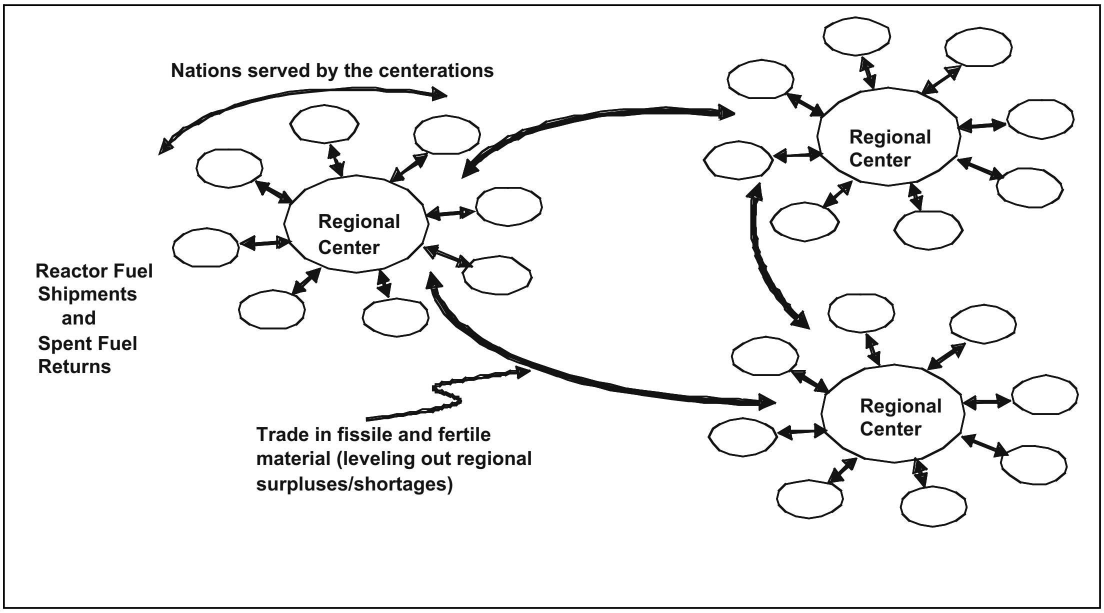

Fig. 1. Regional fuel cycle center architecture.

For international deployment in developing nations and at remote or isolated sites, it would be valuable to offer systems with small power levels matching the smaller demand of towns or sites that are off-grid or on immature local grids; sufficiently low cost to be economically competitive with alternative energy sources (e.g., diesel generators in remote locations); the ability to be readily transported and assembled from transportable modules; simplicity in operation resulting in limited requirements for operating staff; high system reliability and a high level of passive safety. By reducing the possibility for and consequences of severe accidents and the need for engineered safety systems through plant simplification, it is possible to dramatically reduce the size of exclusion and emergency planning zones or possibly to limit the emergency response planning to the exclusion area itself.

2.3. SSTAR

The secure transportable autonomous reactor (SSTAR) fast neutron spectrum lead-cooled reactor is a concept designed to achieve the major desired attributes for the worldwide deployment market described above [5]. The SSTAR reactors are 'right sized' for initially small but fast growing electric grids; they provide energy security for nations not wanting the expense of an indigenous fuel cycle and waste repository infrastructure but willing to accept the guarantee of services from regional fuel cycle centers by virtue of a long (15- to 30-year) refueling interval [6]. The SSTAR initial fissile inventory is relatively large; nevertheless, the one-time initial fissile loading is substantially less than the lifetime ^{235}U consumption of a LWR for same the energy delivery.

Once loaded, SSTARs are fissile self-sufficient as they operate with a conversion ratio of about 1.0. As such, they provide an alternative approach to actinide management in which these nuclear materials are securely 'stored' in long core lifetime power reactors instead of being transmuted in advanced recycle reactors.

The current design concept for the SSTAR, under development in the US is a 20 MWe natural circulation pool-type reactor with a small shippable reactor vessel. Specific features of the lead coolant, transuranic nitride fuel, fast spectrum core, and small size have been incorporated to achieve proliferation resistance, fissile self-sufficiency, autonomous load following, simplicity of operation, reliability, transportability, as well as a high degree of passive safety. Conversion of the core thermal power into electricity at a high plant efficiency of 44% is accomplished by utilizing a supercritical carbon dioxide Brayton cycle power converter.

2.4. Current US LFR program thrust

The current system development activities are being directed toward a pre-conceptual design and viability assessment for a SSTAR 20 MWe (45 MWt) natural circulation LFR for worldwide deployment consistent with both Generation IV and GNEP goals.

In addition, the US LFR program has been recently realigned to focus upon a concept for a near-term technology pilot plant reactor to demonstrate successful reactor operation with a lead coolant at system temperatures compatible with readily available materials, provide a capability for irradiation testing of advanced fuels and structural materials, and incorporating innovative engineering that will help demonstrate and confirm the economic benefits and industrial attractiveness of Pb as a primary coolant.

A sketch of the current reference concept for the SSTAR small, modular, fast reactor is shown in Fig. 2. This pre-conceptual design comprises a small shippable reactor (12 m × 3.2 m vessel), with a 30-year life open-lattice cassette core and large-diameter (2.5 cm) fuel pins held by spacer grids welded to control rod guide tubes. The design integrates three major features: primary cooling by natural circulation heat transport; lead (Pb) as the coolant; and transuranic nitride fuel in a pool vessel configuration. The main mission of the 20 MWe (45 MWt) SSTAR is to provide incremental energy generation to match the needs of developing nations and remote communities without electrical grid connections, such as those that exist in Alaska or Hawaii, island nations of the Pacific Basin, and elsewhere. This may be a niche market within which costs that are higher than those for large-scale nuclear power plants are competitive. Design features of the reference SSTAR in addition to the lead coolant, 30-year cassette core and natural circulation cooling, include autonomous load following without control rod motion, and use of a supercritical CO_2 (S-CO_2) Brayton cycle energy conversion system. The incorporation of inherent thermo-structural feedbacks imparts walk-away passive safety, while the long-life cartridge core life imparts both energy security and strong proliferation resistance. If these technical innovations can be realized, the LFR will provide a unique and attractive

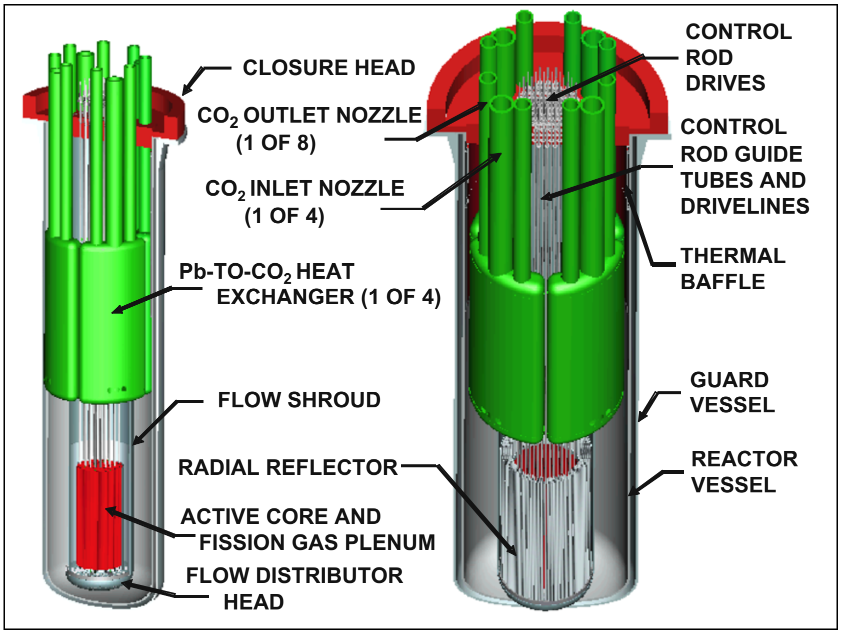

Fig. 2. Pre-conceptual 20 MWe (45 MWt) SSTAR reactor.

nuclear energy system that meets both GNEP and Generation IV goals. Table 2 provides core performance characteristics that correspond with this design [7].

2.5. Research directions

The ongoing and planned R&D in the US is intended to address viability issues associated with the LFR leading to the design and construction of a LFR technology pilot plant. Viability will be established through focused R&D tasks and with formulation of a technically defensible pre-conceptual design [8].

- *System design and evaluation.* R&D tasks for system design and evaluation address the areas of core neutronics, system thermal hydraulics, passive safety evaluation, containment and building structures, in-service inspection, and assessing cost impacts. Core design is essential to establishing the necessary features of a 15- to 30-year-life core and determining core parameters that impact feedback coefficients. R&D tasks associated with this work include further optimization of the core configuration, establishing a startup/shutdown control rod strategy, and calculating reactivity feedback coefficients.
- *Fuel and fuel cycle.* Viability of both nitride fuel and whole-core cassette refueling are to be addressed in the fuel and fuel cycle R&D.
- *Energy conversion.* Use of a S-CO_2 Brayton cycle for energy conversion offers the prospect of higher thermal efficiencies with lower Pb coolant outlet temperatures and small turbomachinery reducing the footprint and cost of the power converter.
- *Materials.* Viability of long core lifetime, passive safety, and economic performance (both capital and operating costs) of the LFR concept will depend on identifying materials with the potential to meet service requirements.

Table 2
SSTAR core parameters, features and performance

Coolant	Pb
Fuel	Transuranic nitride (TRUN) using nitrogen enriched in N^{15}
Enrichment, %	1.7/3.5/17.2/19.0/20.7 TRU/HM, 5 radial zones
Core lifetime, years	30
Core inlet/outlet temperatures, °C	420/567
Coolant flow rate, kg/s	2107
Power density, W/cm^3	42
Average (peak) discharge burnup, MWd/kg HM	81 (131)
Burnup reactivity swing, $	<1
Peak fuel temperature, °C	841
Cladding	Si-enhanced ferritic/martensitic stainless steel bonded to fuel pellets by Pb
Peak cladding temperature, °C	650
Fuel/coolant volume fractions	0.45/0.35
Core lifetime, years	30
Fuel pin diameter, cm	2.50
Fuel pin triangular pitch-to-diameter ratio	1.185
Active core dimensions height/diameter, m	0.976/1.22
Core hydraulic diameter, cm	1.371

3. Summary

Dynamic scenario simulations show that with technically feasible deployments, nuclear energy can provide the means to cap or reduce greenhouse gas emissions below current levels by replacing a significant fraction of fossil energy generation over a one hundred year transition. For this to take place, nuclear energy should be recognized as the legitimate successor to fossil energy, and the world energy supply should be re-optimized to exploit the potential of nuclear energy. In addition, judicious use should be made of fissile resources if significant worldwide deployments of fast reactors are to be realized.

Small- and medium-sized LFRs such as SSTAR have the necessary attributes for worldwide deployment while providing proliferation resistance, fissile self-sufficiency, autonomous load following, simplicity of operation and reliability, transportability, high degree of passive safety, and high plant efficiency. Economically competitive distributed small- and medium-sized fast reactors with long core lifetimes (up to 30-years) such as SSTAR present the means of providing energy security to partner nations and customers while meeting nonproliferation aims.

4. Concluding comment

On a worldwide basis, LFR technology is experiencing broad attention. Systems being considered include subcritical systems, central station critical systems and concepts for small transportable reactors for international deployment. These three types of systems are different in both mission and design, but there is a substantial overlap in the research and technology needed for their development. For this reason, international cooperation and collaboration in the pre-commercial development of LFR systems is essential to economical development.

References

[1] 'Nuclear Power in the World Today', World Nuclear Association Information Paper, <http://www.world-nuclear.org/info/inf01.html>, August 2007.
[2] US Nuclear Power Industry, World Nuclear Association Information Paper, <http://www.world-nuclear.org/info/inf41.html>, August 2007.
[3] US Department of Energy, 'The Global Nuclear Energy Partnership', GNEP Overview Fact Sheet, 07-GA50575-01.
[4] G. Rennie, Sci. Technol. Rev. (July/August) (2004).
[5] C. Smith, D. Crawford, M. Cappiello, A. Minato, J. Herczeg, The Small Modular Liquid Metal Cooled Reactor: A New Approach to Proliferation Risk Management, Pacific Basin Nuclear Conference, Honolulu, HI, March 2004.
[6] J.J. Sienicki, D.C. Wade, A. Moisseytsev, Role of Small Lead-Cooled Fast Reactors for International Deployment in Worldwide Sustainable Nuclear Energy Supply, Paper 7228, 2007 International Congress on Advances in Nuclear Power Plants (ICAPP 2007), Nice, France, May 13–18, 2007.
[7] J.J. Sienicki, A. Moisseytsev, D.C. Wade, A. Nikiforova, Status of Development of the Small Secure Transportable Autonomous Reactor (SSTAR) for Worldwide Sustainable Nuclear Energy Supply, Paper 7218, 2007 International Congress on Advances in Nuclear Power Plants (ICAPP 2007), Nice, France, May 13–18, 2007.
[8] L. Cinotti, C.F. Smith, J.J. Sienicki, H. Alt Abderrahim, G. Benamati, G. Locatelli, S. Monti, H. Wider, D. Struwe, A. Orden, I.S. Hwang, The Potential of the LFR and the ELSY Project, Paper 7585, 2007 International Congress on Advances in Nuclear Power Plants (ICAPP 2007), Nice, France, May 13–18, 2007.