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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) reactor has been under ongoing development under the U.S. Generation IV Nuclear Energy Systems Initiative. It a system designed to provide energy security to developing nations while incorporating features to achieve nonproliferation aims, 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 U.S. Generation IV Lead-cooled Fast Reactor system.

INTRODUCTION. It is widely known 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 supplky of expanded energy resources ranging from large and highlyt concentrated population centers of countries like China and india to remote and isolated communities (which also may be quite large). In addition, in many cases, existing electric grid capacity is limited and not readily able to accept lthe large increments of generating capacity represented by current central station nuclear power plants. Finally, industrial infrastructures are frequently limited and not able to provide the support needed for large central station plant construction, maintenenace and operation.

Thus, in addition to current central station nuclear power plants, there is a need to provide technology for advanced systems better able to align with the needs of areas with isolated populations, limited grid capacity 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.

The U.S. Lead Cooled 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 the need (and ability for) on-site refueling; (2) transportability: the entire core and reactor vessel 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 observability to permit rapid detection/response to perturbations. These features permit installation and operation in places with minimal industrial infrastructures. Further, they provide a plant characterized by a very small operational (and security) footprint

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. In the U.S., nuclear energy represents about 20% of the electical energy supply, and 103 power plants are currently in operation.

Looking to the future, current U.S. policy, represented by the Global Nuclear Energy partnership, is focused upon domestic deployment of large-scale LWRs and the development of a sodium-cooled fast spectrum Advanced Burner working in symbiotic relationship to burn the existing inventory of fissile material while destroying accumulated actinide material. Internationally, planning for Sodium-Cooled Fast Reactor (SFR) breeders is underway in France, Japan, China, India, and Russia

These future global nuclear deployments could provide a basis for a moderate expansion in the use of nuclear energy, but would be insufficient to stem increasing greenhouse gas emissions as developing nations massively increase in population and per capita energy consumption. Clearly, the world faces a nuclear energy disconnect 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 2001 in order to meet several postulated goals concerning maintenance of market share for nuclear energy, cappiung fossil energy use and provision for substituting nuclear generated hydrogen for fossil energy sources.

Table 1: Selected Nuclear Power Growth Scenarios

Goal	Nuclear Market Share by 2100, %	Nuclear Power by 2100, TWt	100-year Growth Rate, % per year
Maintain current market share*	6**	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 *** for 2/3 of current primary market	144	76.3 (~ factor of 75 increase)	4.34

*** 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)**

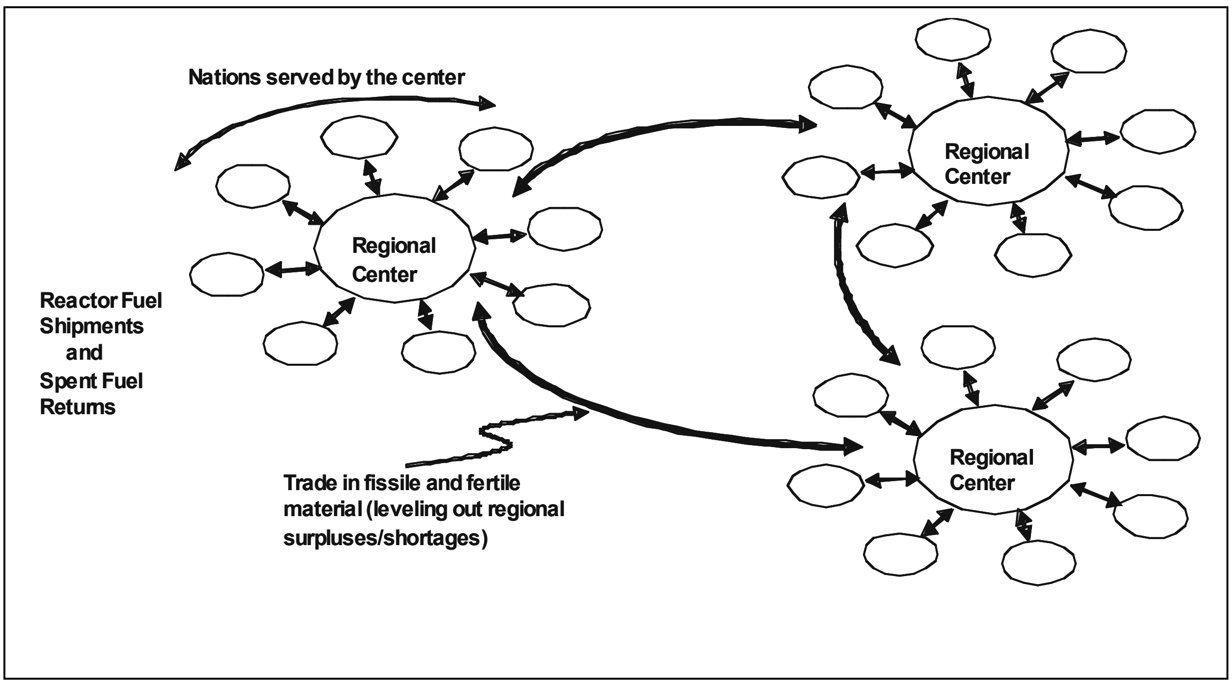
****Current nuclear market share is ~ 6 % of the total primary energy of 16 TWt**

***** At conversion efficiency of 50%**

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 energy the global energy needs while avoiding exacerbating proliferation hazards? The solution to this nergy security/nonproliferation dilemma involves introduction of a fuel cycle architecture based on centralized fuel cycle operations sited at a few locations worldwide. These operations would include facilities for enrichment, recycle, fabrication, and waste management co-sited with high performance fast breeders dedicated to fissile production supporting fleets of long-refueling-interval reactors at distributed customer sites. The Global Nuclear Energy Partnership and Regional Fuel Cycle Center architectures both incorporate features of this institutional structure. Distributed power plants may include variety of reactor types determined by market forces. Figure 1 illustrates the concept.

Figure 1: Regional Fuel Cycle Center Architecture



Desired Attributes for International Deployment. The reactor systems needed to meet this deployment concept while also meeting the constraints of many host countries are that the reactors should be small (i.e., < 300 MWe) or medium (300 to 700 MWe) in size. 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 the energy security and proliferation concerns that could arise from widespread use of nuclear energy technology, restricted access to fuel would be an additional desitred attribute. The design of a system with a very long core lifetime would enable the further restriction of access to fuel by reducing or eliminating need for refueling. 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 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).

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 number of accident initiators and the need for safety systems, it is possible to dramattically reduce the size of exclusion and emergency planning zones.

SSTAR. The Secure Transportable Autonomous Reactor (SSTAR) fast lead-cooled reactor is a concept designed to achieve the major desired attributes for the international deployment marketdescribed above. The SSTAR reactors are “right sized” for initially small but fast growing electric grids; they provide energy security for nations not wanting expense of indigenous fuel cycle and waste repository infrastructure but willing to accept guarantee of services from regional fuel cycle center by virtue of long (15- to 30-year) refueling interval. The SSTAR initial fissile inventory is relatively large; nevertheless. the one-time initial fissile loading is substantially less than lifetime ^{235}U consumption of LWR for same energy delivery.

Once loaded, SSTARs are fissile self-sufficient with a Conversion Ratio fo about 1.0.As such, they provide an alternative approach to actinide management in which actinides are “stored” in long core lifetime power reactors instead of being transmuted in advanced burner reactors.

The current design concept for the SSTAR, under development in the U.S. Generation IV Program, 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 and 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.

Current U.S. 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 international deployment consistent with both Generation IV and GNEP goals.

In addition, the U.S. LFR program has been recently realigned to focus upon a concept for a near-term deployable demonstration test reactor to demonstrate successful reactor operation with a lead coolant at realistic system temperatures, provide a capability to irradiate advanced fuels and materials, and incorporating innovative engineering that will help show 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 Figure 2.. This pre-conceptual design is a small shippable reactor (12 m X 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 20MWe (45MWt) 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 strong proliferation resistance. If these technical innovations can be realized, the LFR will provide a unique and attractive nuclear energy system that meets both GNEP and Generation IV goals. Table 2 provides core performance characteristics that correspond with this design.

Figure 2   Conceptual 20 MWe (45 MWt) SSTAR system.

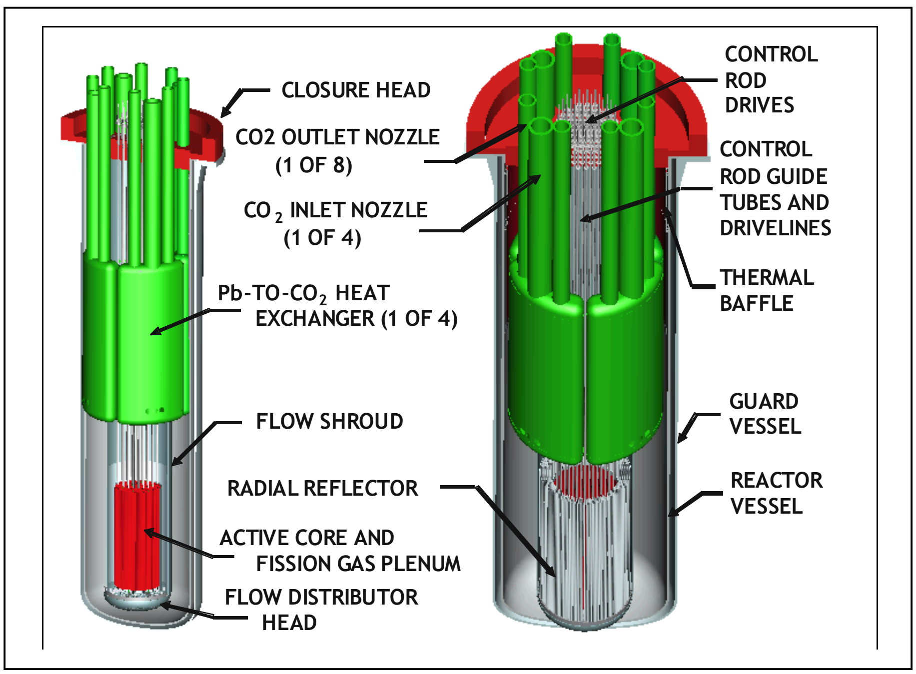


Table 2. SSTAR Core Performance

Coolant	**Pb**
Fuel	**Transuranic Nitride (TRUN) Enriched to 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**

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 an LFR demonstration plant. Viability will be established through focused R&D tasks and with formulation of a technically defensible pre-conceptual design.

- 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 start-up/shutdown control rod strategy, and calculating reactivity feedback coefficients.

- Fuel and Fuel Cycle. Viability of both nitride fuel and whole-core cassette refuelling 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 turbo-machinery 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.

Summary. Dynamic scenario simulations show that with technically feasible deployments, nuclear energy can provide 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 needs to be recognized as the legitimate successor to fossil energy, and the world energy supply will need to be re-optimized to exploit the potential of nuclear energy. In addition, judicious use must be made of fissile resources and massive international deployments of fast reactors will be required.

Small- and medium-sized LFRs such as SSTAR have the neceaarsy attributes for international 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 SSTARs with long core lifetimes (up to 30 years) present the means of providing energy security to partner nations and customers while meeting nonproliferation aims.

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 development of LFR systems is essential.

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