Small- and Medium-Sized Reactors

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In recent years, great interest has developed in Small- and Medium-Sized Reactors (SMRs). This is also the acronym for Small Modular Reactors (SMRs) which refers to essentially the same concept. As defined by the IAEA, a small reactor has an output electrical power of 300 MWe or less while a medium-sized reactor has an electrical power between 300 and 700 MWe. A number of arguments have been advanced as part of the rationale for SMRs. In the U.S., construction of a large economy-of-scale LWR requires significant investment (several Billion dollars) that is difficult to secure. Thus, an argument is that SMRs have lower financial investment requirements and can be deployed incrementally with shorter construction times enabling planning and financing to be spread out over time. SMRs can provide improved baseload flexibility. Another argument is that at sufficiently small scale the designer can take advantage of simplifications in the design that are not feasible at large scale to break the economy-of-scale penalty of an increase in plant cost per unit electrical power as the plant power level decreases. A number of LWR SMR designs are being developed with the goal of achieving design certification by the U.S. NRC (e.g., IRIS, NuScale, mPower). SMRs have also been identified as filling the needs of niche markets such as a need for power in remote regions that are off of major electrical grids. An example is provided by planning for deployment of a Toshiba 4S Sodium-Cooled Fast Reactor (SFR) to provide electricity for the town of Galena, Alaska. For remote deployments, the financial case for SMRs may be bolstered by the fact that the competitive generation technology may be costly or involve high operating costs (e.g., diesel generators for which fuel must be transported in perhaps by air). It must be recognized, however, that the arguments for SMRs remain to be validated with actual plant orders and deployments.

Although the wider interest in SMRs is a relatively recent phenomenon, Argonne National Laboratory (ANL) has been developing SMR concepts for Lead-Cooled Fast Reactors (LFRs) and SFRs since 1997. A number of LFR concepts have been developed that are referred to a Secure Transportable Autonomous Reactors (STARs). STARs have been developed for international deployment in developing nations, deployment on initially small but fast growing electrical grids on which small changes in load demand can have a significant impact, and remote deployments. They are fast neutron spectrum reactors providing the benefits of a closed fuel cycle. Once loaded, the core can be fissile self-sufficient with a conversion ratio of about unity. The core lifetime can be made very long (e.g., twenty to thirty years). STARs can provide energy security for nations not wanting the expense of indigenous fuel cycle and waste repository infrastructures but willing to accept the guarantee of services from a regional fuel cycle center by virtue of the long reactor refueling interval (twenty to thirty years). The long lifetime core also provides proliferation resistance in reducing or eliminating the need for refueling operations. Access to fuel or neutrons can be further restricted by having no refueling equipment onsite except during refueling when it is brought onsite and removed when refueling is completed. STARs are readily transported to the site as transportable modules fabricated in factories where manufacturing economies of scale and greater quality control can be exercised.

An example of a STAR is the ≈ 120 MWe (300 MWt) Pb-cooled, pool-type, small modular fast reactor named the SUstainable Proliferation-resistance Enhanced Refined Secure Transportable Autonomous Reactor (SUPERSTAR) being developed at ANL. Efforts are focused on a SUPERSTAR demonstrator (demo). SUPERSTAR provides a thermal power limited by primary Pb coolant natural circulation heat transport at greater than 100 % nominal power inside of a reactor vessel and guard vessel having dimensions limited by the requirement of transportability by rail. The Pb coolant has a high boiling temperature exceeding the temperatures at which steels lose their strength or melt. Thus, the primary Pb coolant is a low pressure coolant that does not flash upon failure of the primary coolant system boundary. Natural circulation is a simplification that eliminates the capital cost of primary coolant pumps and the need to deal with erosion by Pb of the pump impellers. It is a passive safety feature that eliminates loss-of-flow initiators from pump coastdown (e.g., due to loss-of-electric power) and downtime due to pump failures. The SUPERSTAR demo utilizes an innovative particulate metallic fuel form that does not require a sodium bond to facilitate near term deployment of a demo by seeking regulatory approval for the use of the metallic fuel taking advantage of the existing experience and database for metallic fuel. The peak cladding temperature exposed to Pb coolant is limited to 550 °C with the goal of enabling the use of existing materials in the near term such as T91 ferritic-martensitic steel for cladding and structures (T91 is an ASME codified structural material) exposed to higher Pb temperatures; the core inlet temperature is 400 °C. Corrosion by the Pb coolant is controlled by maintaining dissolved oxygen in the coolant at a high enough level that protective magnetite (Fe_3O_4) layers form upon the steel structure reducing the dissolution rate of steel constituents but remaining low enough to avoid the formation of solid PbO in the coolant. SUPERSTAR incorporates an intermediate heat transport circuit utilizing Pb intermediate coolant to exclude the CO_2 working fluid from inside of the containment. This eliminates the need to include a CO_2 line break in the containment design basis such that the containment does not need to have a significant pressure retention capability simplifying the containment structural design and reducing the cost associated with the containment. Lead-to-lead intermediate heat exchangers (IHXs) consisting of Formed Plate Heat Exchanger (FPHE, Heatric Divison of Meggitt (UK), Ltd.) compact diffusion-bonded heat exchangers providing a large surface area for interfacial heat transfer are installed inside of the reactor vessel to cool down the primary Pb coolant as it flows outward from the hot pool inside of the cylindrical shroud above the core into the cold pool in the annulus between the shroud and reactor vessel. This feature enables the reactor vessel to be exposed to only the cold Pb inside of the cold pool during normal operation and eliminates heatup and cooldown transients and thermal stresses in the portion of the reactor vessel that would otherwise be exposed to hotter primary coolant during startup and shutdown operations. Consequently, the reactor vessel can be fabricated of austenitic stainless steel such as Type 316 stainless steel for which no corrosion protection measures are needed for temperatures below about 425 °C. The fast neutron spectrum core with metallic fuel and Pb coolant has strong reactivity feedbacks whereby the core thermal power adjusts itself to the heat removal from the reactor system without the need for the deliberate motion of control rods. SUPERSTAR incorporates the supercritical carbon dioxide (S-CO_2) Brayton cycle advanced power converter with an automatic control system that adjusts the heat removal from the intermediate Pb coolant such that the generator power equals the load demand from the electrical grid. This enables autonomous load following by SUPERSTAR which is an important capability for a plant operating on a small electrical grid.