SSTAR Lead-Cooled, Small Modular Fast Reactor with Nitride Fuel

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Research and development is in progress to determine the viability of a small modular Lead-Cooled Fast Reactor (LFR) concept known as the Small Secure Transportable Autonomous Reactor (SSTAR). One mission of SSTAR is to provide electricity generation in small increments to match the needs of developing nations and remote communities without major electrical grid connections such as those that exist in the states of Alaska or Hawaii, island nations of the Pacific Basin (e.g., Indonesia), and elsewhere. The reference fuel form consists of nitride pellets bonded by molten Pb to silicon-enhanced ferritic-martensitic stainless steel cladding. Nitride fuel has been selected for several reasons. First, it has a high melting temperature (e.g., 2630 °C for UN) and is compatible with the cladding as well as the Pb bond and coolant at high temperatures. It has a high atom density which makes feasible a compact fast spectrum core. The nitrogen is enriched to near 100% N$_{15}$ to eliminate parasitic captures as well as the formation of long-lived C$^{14}$. Recent investigations at Argonne National Laboratory indicate that a reactor with an active core diameter/height of ~1.2 m/0.8 m can provide 20 MWe (45 MWt) of power over a 20-year long core lifetime (for enhanced proliferation resistance) with a maximum burnup reactivity swing less than one dollar, and an average discharge burnup of 72 MWd/Kg HM (i.e., fuel utilization comparable to current LWRs). Transuranic fuel feed from LWR spent fuel is utilized following a 25-year cooldown time. A closed fuel cycle can be realized using electrometallurgical reprocessing. The conversion ratio is near unity (for fissile self-sufficiency) over the 20-year lifetime. Nitride has a low volumetric swelling such that assuming a smeared density of 85%, the active core fuel volume fraction is equal to 0.55 at which the core power can be removed to in-reactor heat exchangers solely by single-phase natural circulation of the Pb coolant (i.e., main coolant pumps are eliminated).

An analysis of high temperature thermal decomposition of both mononitride (UN) and mixed nitride ($U_{0.8}P_{0.2}N$) was carried out. The analysis results indicate that thermal decomposition of mixed nitride would not result in the creation of any significant amount of metallic species that could potentially interact with the cladding below about 1400 °C. This temperature significantly exceeds those anticipated for normal reactor operation or during transient and accident conditions.

The fast spectrum core with transuranic nitride fuel and Pb coolant has a strong reactivity feedback with temperature enabling autonomous load following without the deliberate operation of control rods and provides passive power reduction, in the event of loss-of-normal heat removal from the reactor system. The nitride fuel pellets have a high thermal conductivity which, together with Pb bonding, results in a low peak fuel temperature during normal operation.
The high fuel melting temperature, high thermal decomposition temperature, and high thermal conductivity together with the high Pb boiling temperature (1740 °C) and Pb coolant natural circulation provide for enhanced passive safety whereby the core and in-reactor heat exchangers remain covered by ambient pressure single-phase primary coolant inside the reactor vessel and single-phase natural circulation removes the core power under all operational and postulated accident conditions. The reactor system is coupled to a supercritical carbon dioxide gas turbine Brayton cycle power converter that enables potential improvements over the traditional Rankine saturated steam cycle including higher cycle efficiency at temperatures attainable with Pb primary coolant and nitride fuel (650 °C peak cladding temperature and 561 °C core outlet temperature for a 405 °C inlet temperature) as well as a smaller plant footprint with simpler secondary side components. Application of swelling correlations for nitride indicates that the smeared density might be further increased to as much as 92 % at an assumed 13.5 at % peak burnup; this could facilitate a decrease in the fuel volume fraction and enhance natural circulation heat transport. Research and development needs that have been identified for the SSTAR concept include nitride fuel steady state irradiations to burnups (e.g., 12 at %) significantly beyond the existing database as well as transient fuel testing.