

# —TRANSACTION—

## Use of Liquid Salt Coolants to Improve Fast-Reactor Economics

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## INTRODUCTION

The central challenge for sodium fast reactors (SFRs) is their high specific capital cost relative to that for light-water reactors (LWRs). While technology improvements are expected to lower the costs of SFRs, technology developments will also continue to lower the costs of LWRs; thus, it is unclear whether the cost differential will close.

One option to improve fast reactor (FR) economics is to change the sodium coolant to a liquid salt coolant [1] in the (1) intermediate heat-transport loop, (2) the reactor, or (3) both. Liquid salt coolants are being considered for a variety of reactor systems [2]. Liquid salts are high-performance heat transfer fluids but with the disadvantage of higher melting points. The coolant in a liquid-salt-cooled fast reactor (LSFR) would be a fluoride salt mixture such as NaF-KF-ZrF<sub>4</sub> or NaF-ZrF<sub>4</sub>. The reactor designs [1, 3] would be similar to those for existing FR designs such as the European Fast Reactor. LSFRs are being examined in the United States (Oak Ridge National Laboratory, Massachusetts Institute of Technology, and the University of California-Berkeley and in France).

## COOLANT OPTIONS

Coolant properties determine many of the engineering properties and thus the economics of alternative reactor concepts. Table I compares the properties of various reactor coolants. Two fluoride salts are chosen to represent a much larger family of salts with somewhat similar properties. The properties of liquid salt coolants imply the potential for lower capital costs for LSFRs than for SFRs.

1. *Equipment size.* Volumetric heat capacities ( $\rho C_p$ ) for liquid salts are 3 to 4 times larger than those for sodium. This reduces the size of pipes, valves, and heat exchangers per unit of energy transferred. The area cross section of a pipe in a LSFR would be one-third to one-fourth the area of a pipe in an SFR carrying the same amount of energy. The high volumetric heat capacity of water and other properties indicate why LWRs have historically had lower capital costs than sodium- or gas-cooled reactors.
2. *Operating pressure.* Like SFRs, but unlike LWRs, salt coolants operate at atmospheric pressure and thus minimize the required thickness for pipes, vessels, and other equipment.
3. *Operating temperature.* FR operating temperatures are determined by materials and reactor physics. Solid-fuel FR cores can have positive void coefficients that can result in power excursions. To avoid this situation, boiling of the coolant must be prevented. Consequently, the maximum coolant temperature in the reactor core must be several hundred degrees below the coolant boiling point. This factor limits SFR coolant temperatures to below 600°C, whereas the high boiling points of liquid salts allow temperatures as high as 1000°C. Higher temperatures imply higher efficiencies, which, in turn, imply lower costs per kilowatt (electric) because of the smaller power conversion equipment, cooling systems to reject heat from the power cycle, and decay-heat-removal systems that are required.
4. *Chemical reactivity.* In SFRs, sodium reacts chemically with water, air, concrete, and other materials. This reactivity generates heat and, if water is present, generates explosive hydrogen. Liquid salts do not react with air and only slowly react with water. Changing coolants (1) eliminates the highly energetic chemical accidents associated with large energy releases and the release of hydrogen and (2) eliminates the associated safety systems and reduces containment costs.
5. *Power cycles.* Many liquid salts do not react with carbon dioxide, thus allowing LSFRs to be coupled to supercritical carbon dioxide cycles. If materials allow coolant temperatures to be increased to 600°C or higher, a LSFR can be coupled to a closed multi-reheat Brayton power

cycle with helium or other working fluids.

These power cycles can increase efficiency to above 50%, compared with 38% for SFRs. With either power cycle, salt freezing is easier to manage than with steam generators and Rankine cycles.

6. *Transparency.* Refueling, inspection, and maintenance (RIM) are major challenges for SFRs because one cannot see through the fluid. Liquid salts are transparent and are compatible with viewing systems currently used for high-temperature furnaces. This enables the use of optical methods for RIM [4].

## CONCLUSIONS

When FRs were initially developed, liquid metals were the only technologically viable FR option. If incremental improvements in SFRs cannot meet the economic challenge, then LSFRs represent a potential option. Various technical viability issues have not yet been answered, and there are massive development needs for an LSFR. However, initial assessments and comparisons of equipment size indicate superior economics if the technology can be successfully developed.

## REFERENCES

1. C. W. FORSBERG, P. F. PETERSON, D. F. WILLIAMS, "Practical Aspects of Liquid-Salt-Cooled Fast-Neutron Reactors," CD-ROM, Paper 5643, *Proc. International Congress on the Advances in Nuclear Power Plants 2005*, May 15–19, Seoul, Korea (2005).
2. C. W. FORSBERG, "Reactors with Molten Salts: Options and Missions," *Proc. Frederic Joliot & Otto Han Summer School on Nuclear Reactors: Physics, Fuels, and Systems, Cadarache, France, August 25–September 3, 2004* (2004).
3. Private communication, Claude Renault, French Atomic Energy Commission (December 2006).
4. C. W. FORSBERG et al., *Refueling Options and Considerations for Liquid-Salt-Cooled Very High-Temperature Reactors*, ORNL/TM-2006/92, Oak Ridge National Laboratory (June 2006).

**TABLE I. Characteristics of Reactor Coolants<sup>a</sup>**

Coolant	NaF-KF-ZrF <sub>4</sub> (0.10-0.48-0.42)	NaF-ZrF <sub>4</sub> (0.58-0.42)	Sodium	Lead	Helium	Water
T <sub>melt</sub> (°C)	385	500	97.8	328		0
T <sub>boil</sub> (°C)		1,290	883	1,750	-269	100
ρ (kg/m <sup>3</sup> )	2770	3,140	790	10,540	3.8	732
C <sub>p</sub> (kJ/kg °C)	1.05	1.17	1.27	0.16	5.2	5.5
ρC <sub>p</sub> (kJ/m <sup>3</sup> °C)	2910	3,670	1,000	1,700	20	4040
k (W/m °C)	~1	~1	62	16	0.29	0.56
v · 10 <sup>6</sup> (m <sup>2</sup> /s)	0.17	0.53	0.25	0.13	11.0	0.13
Reactivity	Low	Low	High	Low	Inert	Low

<sup>a</sup>Nomenclature: ρ is density; C<sub>p</sub> is specific heat; k is thermal conductivity; and v is viscosity. Mole percentages for salt mixtures are provided in parenthesis.