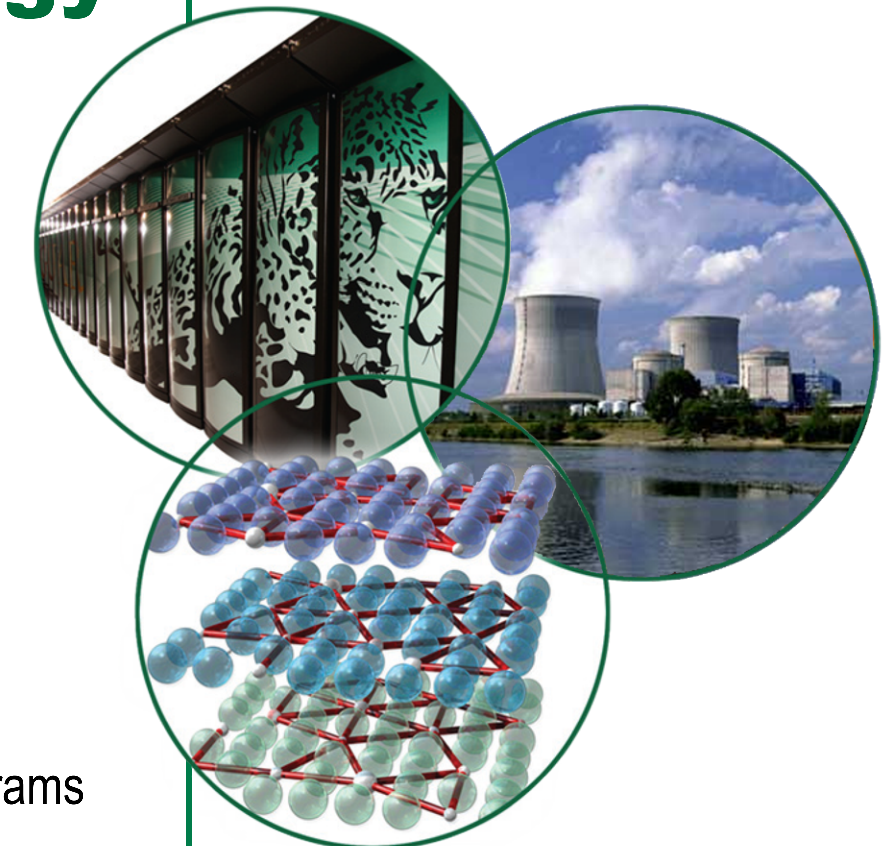
# Fluoride Salt-cooled High Temperature Reactors – Technology Status and Development Strategy



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U.S. DEPARTMENT OF ENERGY

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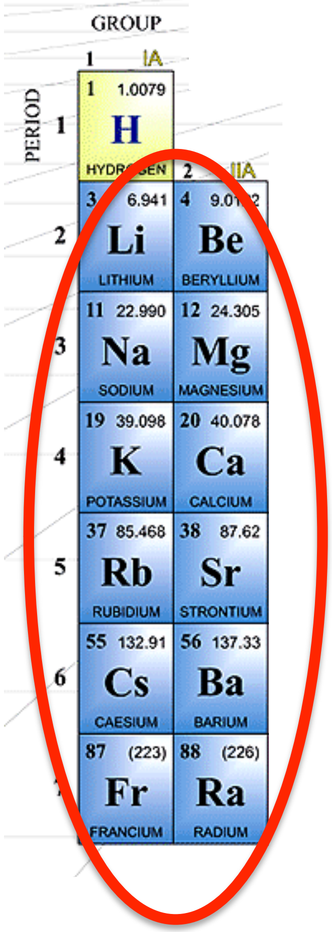
# Presentation overview

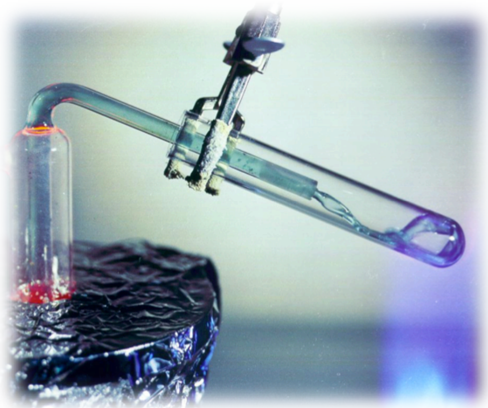
- Fluoride salt
- Fluoride Salt-Cooled High Temperature Reactors (FHRs)
- FHR Technology Suite
- FHR Development Challenges
- FHR Development Strategy

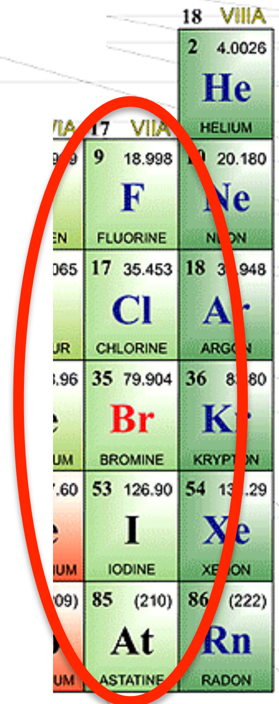
# Presentation overview

- Fluoride salt

# What the heck is “fluoride salt” ?





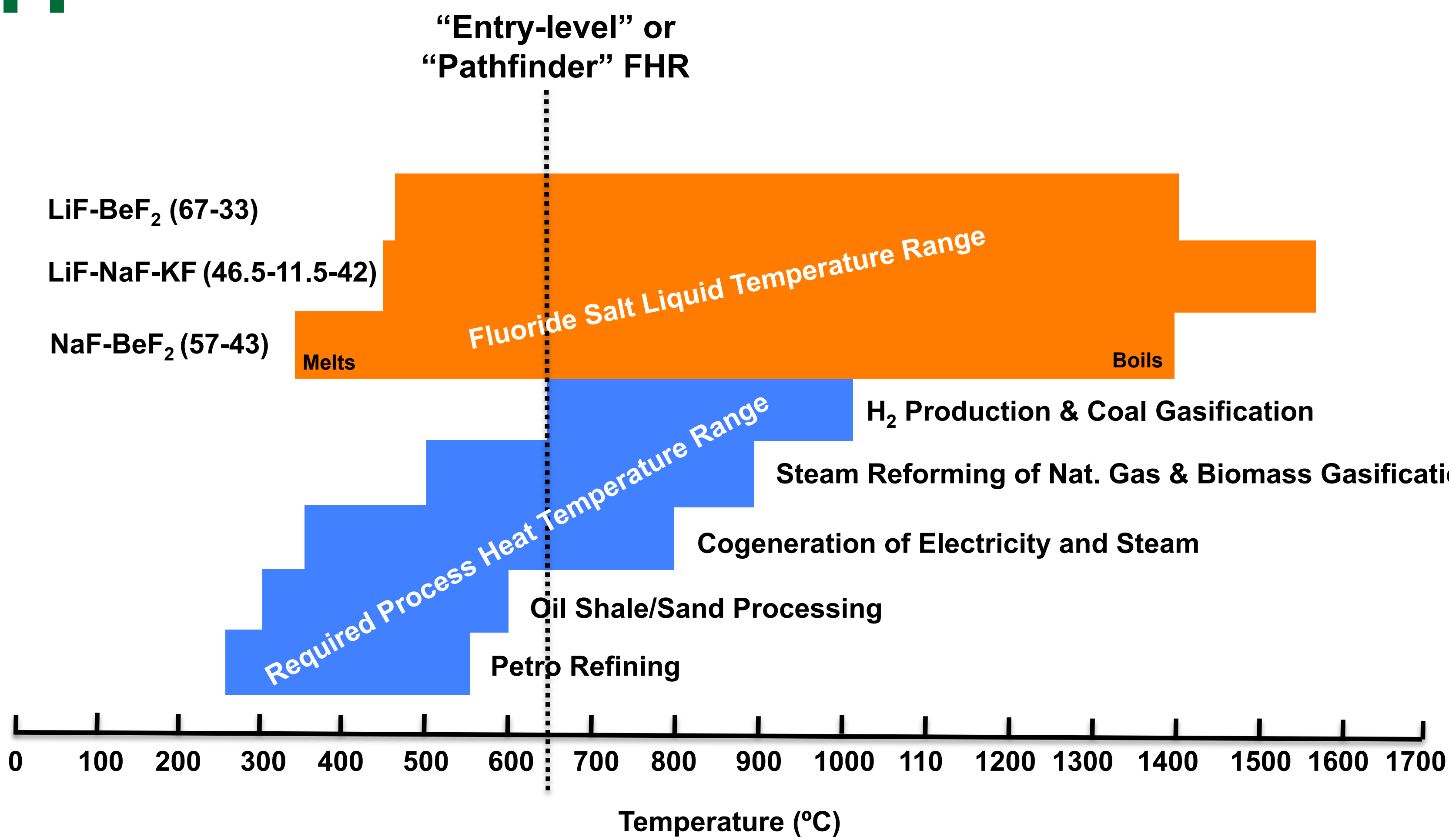

Liquid and “Frozen” $2LiF\text{-}BeF_2$ salt

- ***“Fluoride salt” is a “halide salt”***
- ***Halide salts are ionic compounds formed from the combination of a halogen and another element – commonly, but not exclusively, alkali metals or alkaline earths***
- ***Examples: LiF, $BeF_2$, KF, NaF, $ZrF_4$, RbF, and mixtures of same***

# The potential benefits and challenges of FHRs stem from fundamental coolant properties

| Coolant | Tmelt (°C) | Tboil (°C) | Density ($kg/m^3$) | Specific Heat (kJ/kg °C) | Volumetric Heat Capacity ($kJ/m^3$°C | Thermal Conductivity (W/m °C) | Kinematic Viscosity ($m^2$/s) * $10^6$ |
|---|---|---|---|---|---|---|---|
| **$Li_2BeF_4$ (Flibe)** | 459 | 1430 | 1940 | 2.42 | 4670 | 1.0 | 2.9 |
| **59.5NaF-40.5$ZrF_4$** | 500 | 1290 | 3140 | 1.17 | 3670 | 0.49 | 2.6 |
| **26LiF-37NaF-37$ZrF_4$** | 436 | | 2790 | 1.25 | 3500 | 0.53 | |
| **31LiF-31NaF-38$BeF_2$** | 315 | 1400 | 2000 | 2.04 | 4080 | 1.0 | 2.5 |
| **8NaF-92$NaBF_4$** | 385 | 700 | 1750 | 1.51 | 2640 | 0.5 | 0.5 |
| **Sodium** | 97.8 | 883 | 820 | 1.27 | 1040 | 62 | 0.12 |
| **56Na-44K** | 19 | 826 | 759 | 1.04 | 789 | 28.4 | 0.25 |
| **22Na-78K** | -11 | 784 | 742 | 0.87 | 646 | 26.8 | 0.24 |
| **Lead** | 328 | 1750 | 10540 | 0.16 | 1686 | 16 | 0.13 |
| **44.5Pb-55.5Bi** | 98 | 881 | 10020 | 0.15 | 1503 | 13.9 | 0.12 |
| **Helium, 7.5 MPa** | | | 3.8 | 5.2 | 20 | 0.29 | 11 |
| **Water, 7.5 MPa** | 0 | 290 | 732 | 5.5 | 4040 | 0.56 | 0.13 |

# Potential FHR operating temperatures match many important process heat applications



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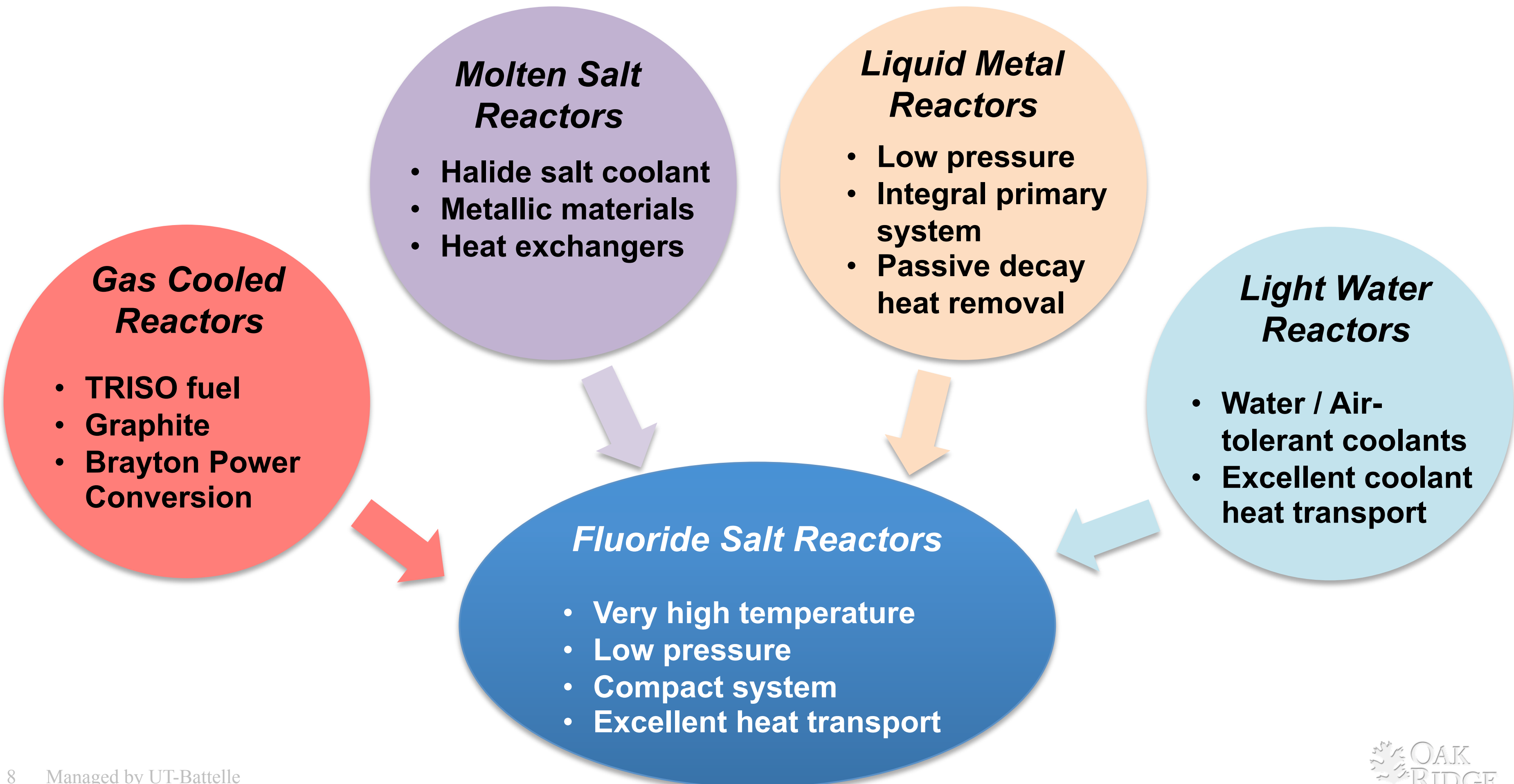
# FHRs combine the best attributes of other reactor types to provide unique performance benefits









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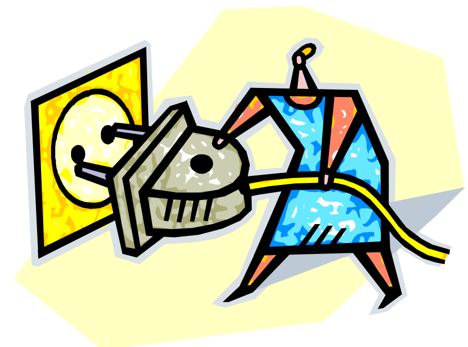
# FHRs are promising candidates for traditional and non-traditional applications

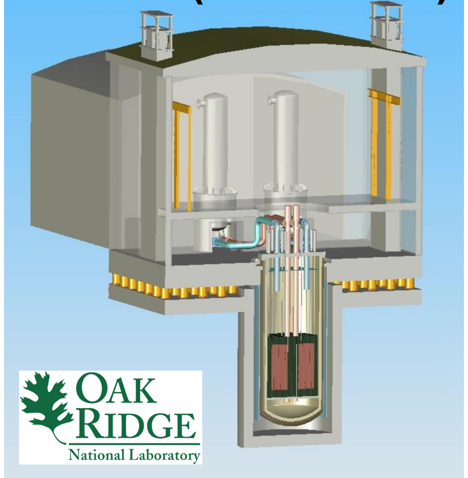


- Electricity production
  - Large centralized
  - Small remote site
- High and Very High-Temperature Process Heat production
  - Large centralized
  - Small remote site

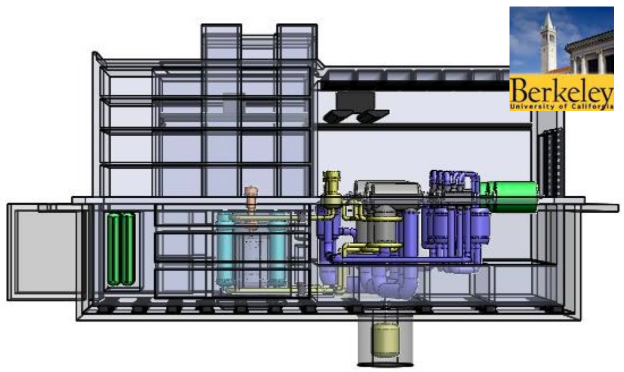
- Incremental energy demand growth scenarios
- Compact power applications

# FHR concepts are being developed for diverse applications

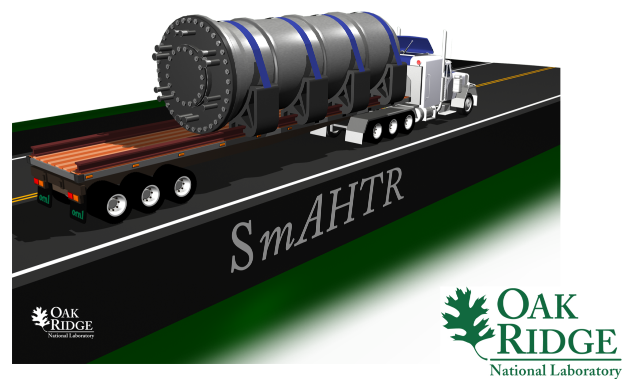
**AHTR* (1500 MWe)**




**PB-AHTR* (410 MWe)**

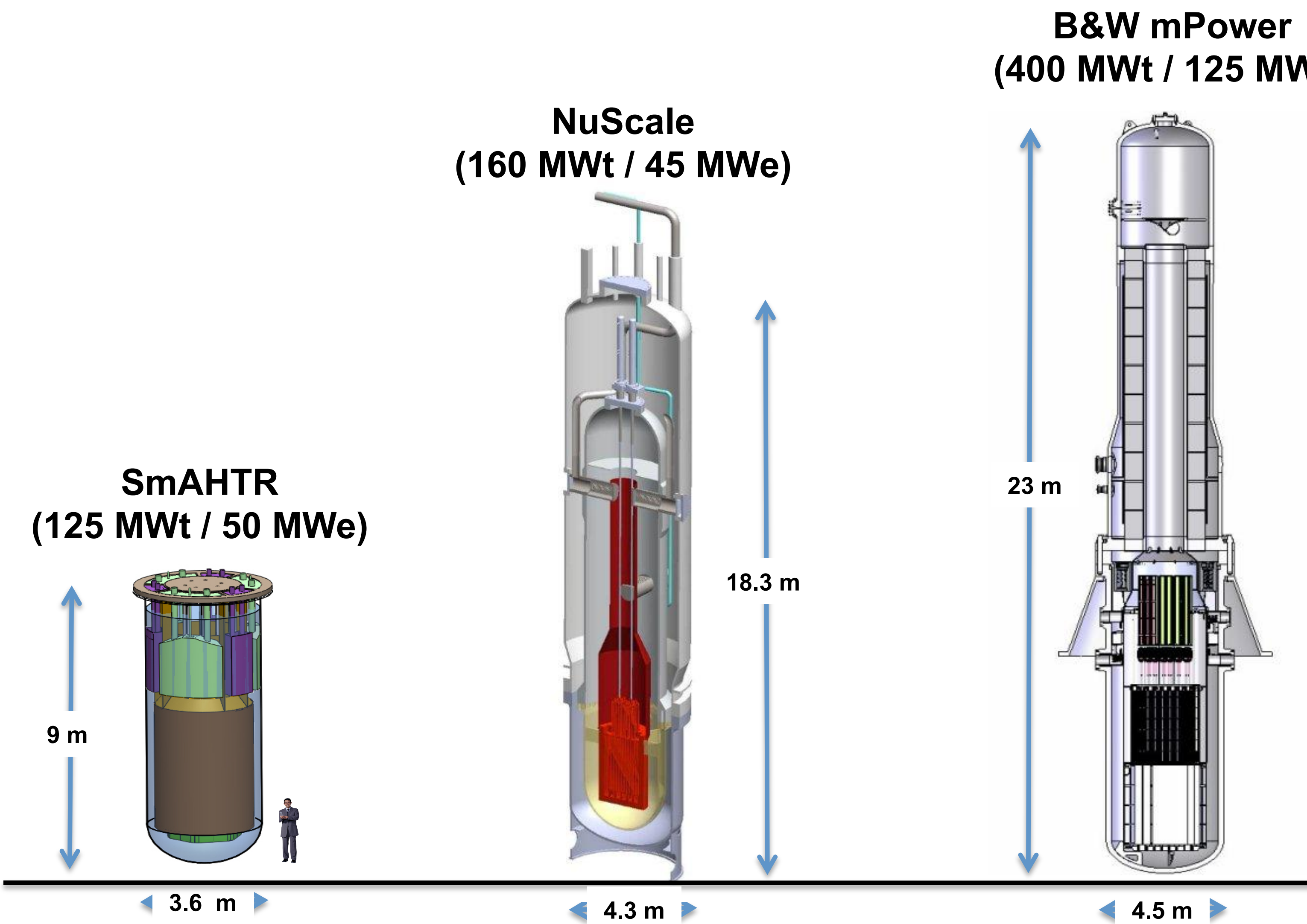



**SmAHTR* (125 MWt/50 Mwe)**




*** AHTR = Advanced High Temperature Reactor**
**PB-AHTR = Pebble Bed Advanced High Temperature Reactor**
**SmAHTR = Small Modular Advanced High Temperature Reactor**

# FHRs can be attractive Small Modular Reactors (SMRs)



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# FHRs incorporate many attractive attributes

| Coolant (Reactor Concept) | High Working Temp[a] | High Volumetric Heat Capacity[b] | Low Primary Pressure[c] | Low Reactivity With Air & Water[d] | Coolant & Materials Cost |
|---|---|---|---|---|---|
| Water (PWR) | ☹ | ☺ | ☹ | ☺ | ☺ |
| Sodium (SFR) | 😐 | 😐 | ☺ | ☹ | 😐 |
| Helium (GCR) | ☺ | ☹ | ☹ | ☺ | 😐 |
| Salt (AHTR) | ☺ | ☺ | ☺ | ☺ | ☹ |

[a] High system working temperature desirable for high efficiency power conversion and process heat applications

[b] High coolant volumetric heat capacity enables ~constant temperature heat addition / removal ($\eta_C = 1 - T_C/T_H$ ~ Carnot cycles), compact system architectures, and reduces pumping power requirements

[c] Low primary system pressure reduces cost of primary vessel and piping, and reduces energetics of pipe break accidents

[d] Low reactivity with air and water reduces energetics of pipe break accidents





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# FHR critical technology maturity varies

**SmAHTR FHR Energy System**

- **Reactor Subsystem**
  - Coolant Salt
  - Fuel
  - Core Structures
  - Control Rods
  - Reflector
  - I & C
  - Core Barrel
  - Reactor Vessel
  - Trace Heaters
- **Decay Heat Removal Subsystem**
  - Working Salt
  - Salt-to-Salt Heat Exchanger
  - Vortex Diode
  - Piping
  - Trace Heaters
  - I & C
  - Salt-to-Air Radiator
- **Heat Transport Subsystem**
  - Working Salt
  - Salt-to-Salt Heat Exchanger
  - Piping
  - Trace Heaters
  - Pumps
  - Valves
  - I & C
  - Salt-to-Gas OR Salt-to-Salt Heat Exchanger
- **Brayton PC Subsystem**
  - Gas
  - Salt-to-Gas Heat Exchanger
  - Turbines
  - Compressors
  - Recuperators (Gas-to-Gas Heat Exchanger)
  - Valves
  - I & C
  - Gas-to-? Heat Exchanger
- **Heat Rejection Subsystem**
  - Working Fluid
  - Gas-to-? Heat Exchanger
  - Piping
  - Pumps
  - Valves
  - I & C
  - ?-to-? Radiator or Heat Exchanger
- **Energy Storage Subsystem**
  - Working Salt
  - Salt-to-Salt Heat Exchanger
  - Tank
  - Insulation
  - Piping
  - Trace Heaters
  - Pumps
  - Valves
  - Salt-to-? Heat Exchanger



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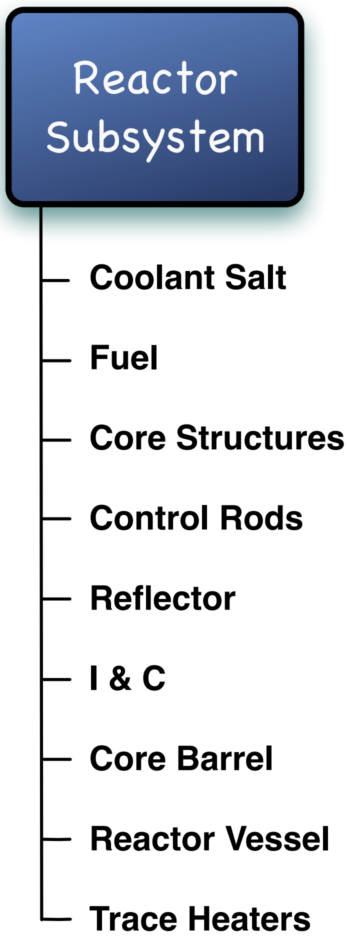
# Reactor subsystem technology development focuses on materials




- **Fluoride salt** – $LiF$-$BeF_2$ is coolant of choice
  - Requires 99.993% $^{7}Li$ enrichment to maintain negative void coefficient and avoid unacceptable tritium production in reactor coolant
  - Has Be occupational health concerns
  - Expensive
- **Fuel** – NGNP / AGR TRISO fuel
  - Solid and annular pellets, plates, or pebbles are possible
- **Core Structures**
  - C-C and SiC-SiC composites
- **Control Rods**
  - C-C guides
  - Boron carbide or molybdenum hafnium carbide
- **Reflector** – Nuclear grade graphite
- **Core Barrel** – C-C composite
- **Reactor Vessel** – Alloy N

# Li / Be / F compounds are very good (but expensive) coolants from nuclear perspective

| Salt Constituent | Moderating Ratio | Short-lived Activation | Long-lived Activation |
|---|---|---|---|
| Lithium-7 | Good | Very Good | Very Good |
| Beryllium | Very Good | Very Good | Good |
| Fluorine | Very Good | Very Good | Very Good |
| Sodium | Acceptable | Acceptable | Good |
| Potassium | Poor | Acceptable | Poor |
| Rubidium | Acceptable | Poor | Good |
| Zirconium | Good | Poor | Acceptable |

- **All fluoride salts are good coolants**

- **Lighter (low-Z) salts**
  - **Better heat transfer and nuclear performance**
  - **Have larger moderating ratios, yielding more negative (better) coolant void coefficients (FLiBe is best)**

- **Heavy (high-Z) salts**
  - **Lower heat capacities and thermal conductivities**
  - **More activation and transmutation products**

Reference: D. F. Williams, et al., *Assessment of Candidate Molten Salt Coolants for the Advanced high-Temperature Reactor*, ORNL/TM-2006-12, March 2006

# Salt optimization (value engineering) for heat transport and storage applications is needed

Decay Heat Removal Subsystem

Heat Transport Subsystem

Energy Storage Subsystem

| Salt | Formula Weight (g/mole) | Melting Point (°C) | 900 °C Vapor Pressure (mm Hg) | *P* Density (g/cm³) | *PC*$_p$ Volumetric Heat Capacity (cal/cm³-°C) | *μ* Viscosity (cP) | *k* Thermal Conductivity (W/m-K) |
|---|---|---|---|---|---|---|---|
| **LiF-NaF-KF** | 41.3 | 454 | ~0.7 | 2.02 | 0.91 | 2.9 | 0.92 |
| **$NaF-ZrF_4$** | 92.7 | 500 | 5 | 3.14 | 0.88 | 5.1 | 0.49 |
| **KF-ZrF4** | 103.9 | 390 | 1.2 | 2.80 | 0.70 | <5.1 | 0.45 |
| **$LiF-NaF-ZrF_4$** | 84.2 | 436 | ~5 | 2.92 | 0.86 | 6.9 | 0.53 |
| **LiCl-KCl** | 55.5 | 355 | 5.8 | 1.52 | 0.435 | 1.15 | 0.42 |
| **LiCl-RbCl** | 75.4 | 313 | _ | 1.88 | 0.40 | 1.30 | 0.36 |
| **$NaCl-MgCl_2$** | 73.7 | 445 | <2.5 | 1.68 | 0.44 | 1.36 | 0.59 |
| **KCl-MgCl2** | 81.4 | 426 | <2.0 | 1.66 | 0.46 | 1.40 | 0.40 |
| **$NaF-NaBF_4$** | 104.4 | 385 | 9500 | 1.75 | 0.63 | 0.90 | 0.40 |
| **$KF-KBF_4$** | 109.0 | 460 | 100 | 1.70 | 0.53 | 0.90 | 0.38 |
| **$RbF-RbF_4$** | 151.3 | 442 | <100 | 2.21 | 0.48 | 0.90 | 0.28 |

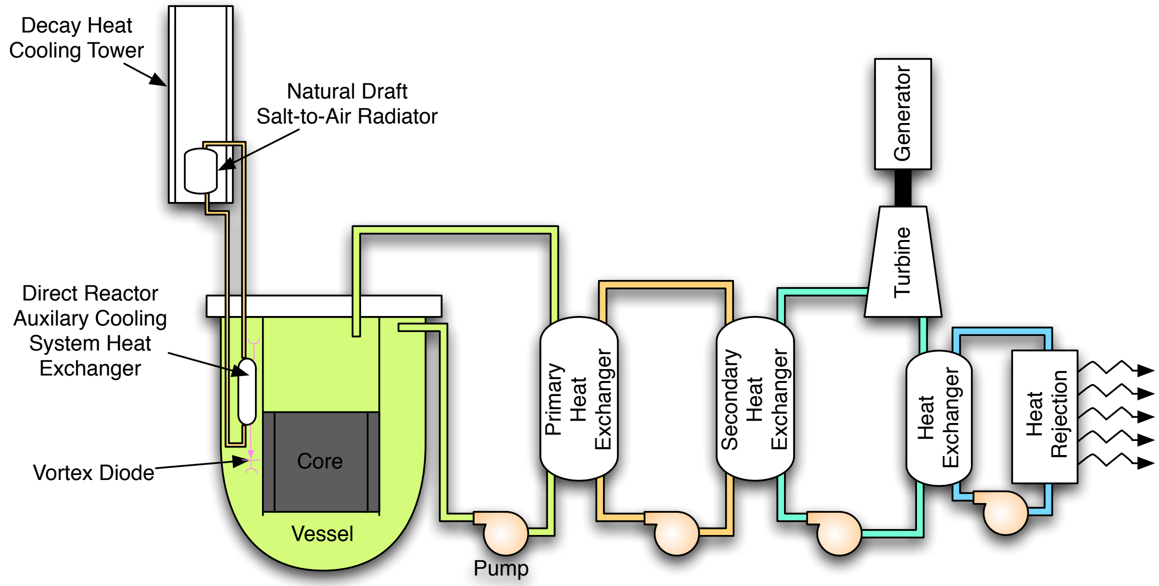
## Very little R&D to optimize fluoride salt properties and salt production processes has been conducted since 1960's

Reference: D. F. Williams, Assessment of Candidate Molten Salt Coolants for the NGNP/NHI Heat-Transfer Loop, ORNL/TM-2006/69, June 2006

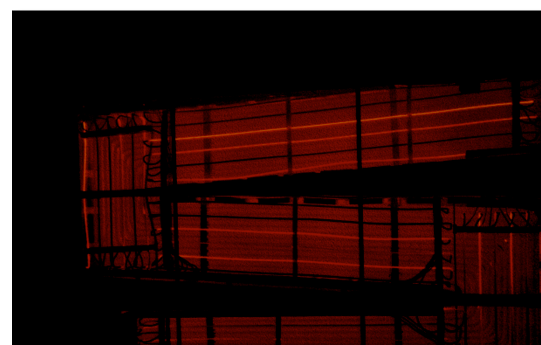
# Heat exchangers and vortex diodes are principal passive decay heat removal subsystem technology development needs

**Decay Heat Removal Subsystem**

- **Working Salt**
- **Salt-to-Salt Heat Exchanger**
- **Vortex Diode**
- **Piping**
- **Trace Heaters**
- **I & C**
- **Salt-to-Air Radiator**




MSRE Salt-to-Salt Shell-in-Tube Heat Exchanger



600 °C LiF-$BeF_2$ / Air Blast Radiator (operated > 26,000 hrs in MSRE, 1965-1969)



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# Heat exchangers, pumps, and valves are primary heat transport subsystem technology development challenges

**Heat Transport Subsystem**

- Working Salt
- Salt-to-Salt Heat Exchanger
- Piping
- Trace Heaters
- Pumps
- Valves
- I & C
- Salt-to-Gas OR Salt-to-Salt Heat Exchanger

- Pumps
  - Long-shafted centrifugal pumps
  - Ceramic bearings and dry gas seals
  - Ti-modified Alloy N material
- Piping
  - Alloy N for temperatures < 700 ºC
  - C-C composites for higher temperatures
- Valves
  - No experience base for active valving
  - “Freeze plugs” used in MSRE
  - Salt-compatible valve seats and seals
- Trace Heaters & Insulation
  - No major challenges



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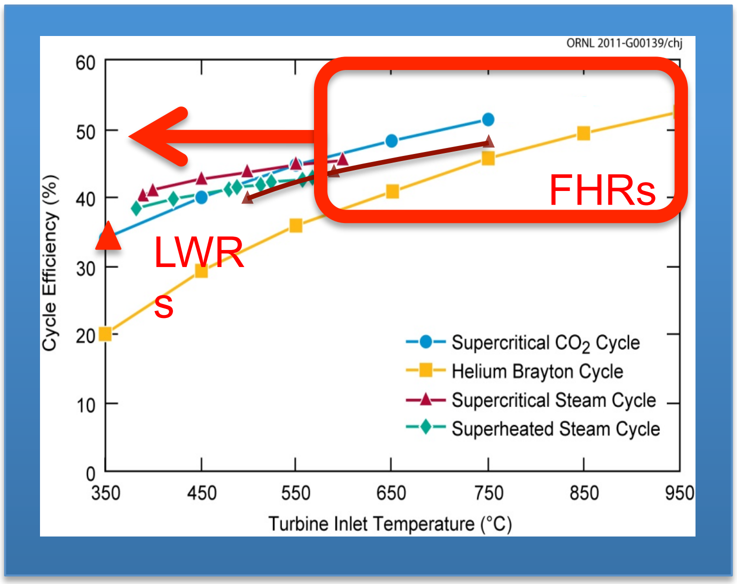
# Optimal Brayton power conversion technology is not obvious…

**Brayton PC Subsystem**

- **Gas**
- **Salt-to-Gas Heat Exchanger**
- **Turbines**
- **Compressors**
- **Recuperators (Gas-to-Gas Heat Exchanger)**
- **Valves**
- **I & C**
- **Gas-to-? Heat Exchanger**




Data from: W. S. Jeong et al., *Potential Improvements of Supercritical $CO_2$*, Korea Advanced Institute of Science and Technology; and I. Satyanarayana et al., *Second Law Analysis of Super Critical Cycle*, International Journal of Engineering (IJE), Volume (4): Issue (1)

- **Closed-cycle Brayton:**
  - He: High-temp capability, bulky, complicated
  - Super-critical $CO_2$:, compact, temp-limited
- **Open direct-cycle air**
  - Very high temperature capability, simple
- **Supercritical steam Rankine is mature**



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# Heat rejection subsystem technology needs are coupled to power conversion technology selection

**Heat Rejection Subsystem**

- Working Fluid
- Gas-to-? Heat Exchanger
- Piping
- Pumps
- Valves
- I & C
- ?-to-? Radiator or Heat Exchanger

- Almost no FHR-specific work done to date.
- Coupled to power conversion selection
- "Dry" heat rejection to air should be attractive due to high temperatures
- Hybrid wet/dry systems may be 1st step
- Opportunity to leverage concentrating solar power plant technologies?





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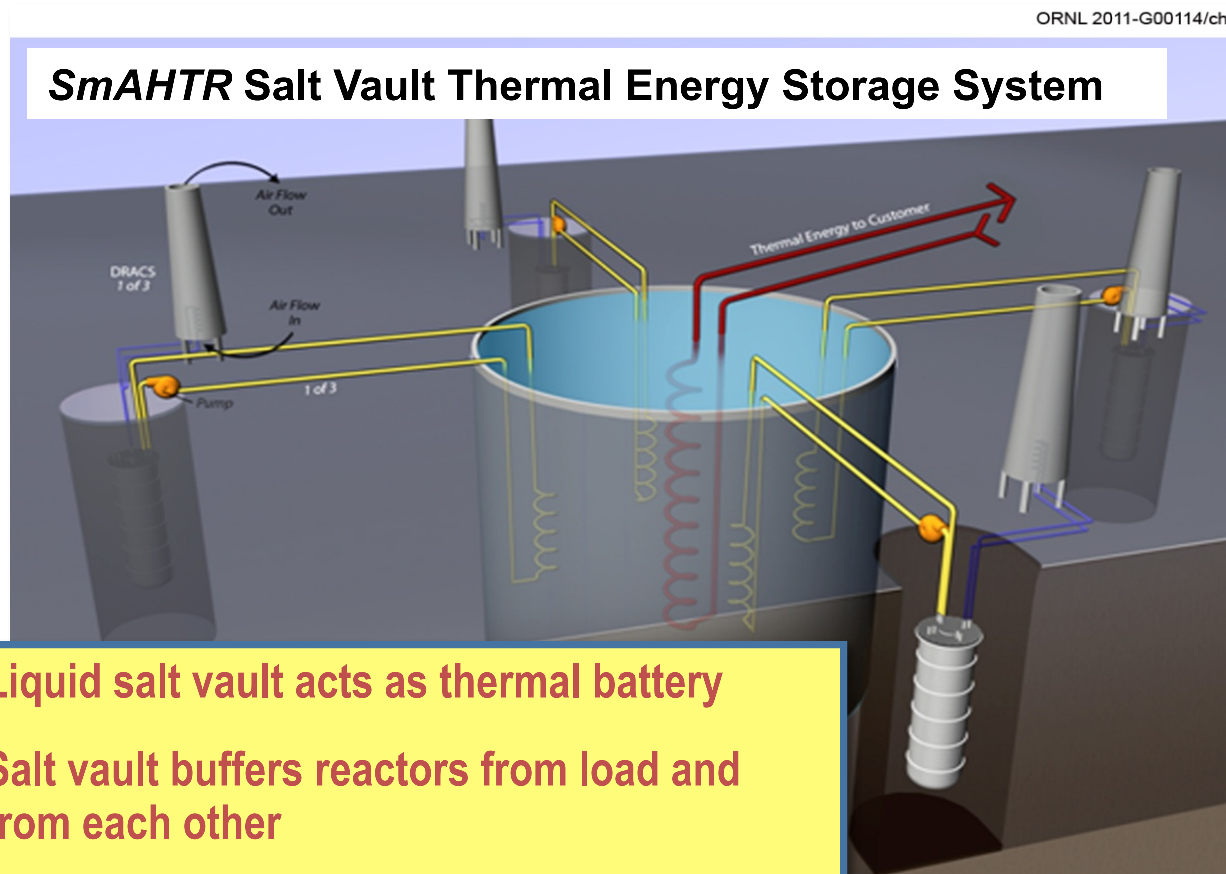
# Feasibility of FHR thermal energy storage system hinges on cost of salt

**Energy Storage Subsystem**

- Working Salt
- Salt-to-Salt Heat Exchanger
- Tank
- Insulation
- Piping
- Trace Heaters
- Pumps
- Valves
- Salt-to-? Heat Exchanger




- Liquid salt vault acts as thermal battery
- Salt vault buffers reactors from load and from each other
- Salt selection and salt vault size can be optimized for differing applications
  - 125 MWt-hr storage @ 500 –600 ºC requires ~ 13 meter cubic salt tank



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# Near-term technical feasibility of FHRs is dominated by four considerations

- "Cost" of salt coolants (especially LiF-$BeF_2$) and heat-transport working salts
  - Li-7 isotopic purity is major cost driver
  - Be ES&H considerations
  - Bulk heat transport/storage compounds
- Tritium management technology for systems employing Li-based reactor coolants
- Alloy N code qualification (in-vessel) *and supply chain*
- Heat exchanger and radiator technology
  - High temperature
  - Salt-to-salt, salt-to-gas, salt-to-air
  - Feasibility of high pressure differential designs





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# An integrated FHR development strategy would focus on

- System concept development
- Base technology development
  - Optimized salts
  - Salt cleanup and tritium management
  - TRISO fuels (leverage on-going gas reactor fuels work)
  - High-temperature materials (especially advanced composites)
- Component development
  - Heat exchangers (salt-to-salt, salt-to-gas)
  - Pumps
  - Valves
  - Fluidic diodes
- High temperature power conversion technology
- Infrastructure
  - Salt synthesis laboratories
  - Electrically heated loops for materials, component, power conversion, and heat rejection technology development
- Small demonstration FHR

# Materials R&D will pace evolution to higher operating temperatures

| System Element | @ 700 ºC | @ 850 ºC | @ 1000 ºC |
|---|---|---|---|
| Graphite Internals | Toyo Tanso IG110 or 430 | Toyo Tanso IG110 or 430 | Toyo Tanso IG110 or 430 |
| Reactor Vessel | Alloy N | •Ni-weld overlay on 800H<br>•Insulated low-alloy steel<br>•New Ni-based alloy | • Interior-insulated low-alloy steel |
| Core barrel & other internals | Alloy N | •C-C composite<br>•New Ni-based alloy | •C-C composite<br>•SiC-SiC composite<br>•New refractory metal |
| Control rods and internal drives | •Alloy N<br>•C-C composites<br>•Nb-1Zr or MHC | •C-C composites<br>•Nb-1Zr<br>•MHC | •C-C composites<br>•Nb-1Zr<br>•MHC |
| PHX & DRACS | Alloy N | •New Ni-based alloy<br>•Double-sided Ni cladding on 617 or 230 | •C-C composite<br>•SiC-SiC composite<br>•Monolithic SiC |
| Secondary (salt-to-gas) HX | Coaxial extruded 800H tubes with Ni-based layer | •New Ni-based alloy<br>•Coaxial extruded 800H tubes with Ni-based layer | ? |

# Summary

- FHRs are a new class of high- to very-high-temperature reactor that leverages best features of traditional reactors
- FHR designs target :
  - process heat production and electricity generation
  - ease of transport and deployment
  - long-term evolvability to higher efficiency electric generation and higher temperature process heat applications
- A 650ºC FHR is a reasonable “pathfinder” objective
- Current technology status benefits from molten salt reactor, gas-cooled, and liquid metal-cooled reactor technology development over many decades
- Key challenges are salt economics, high-temperature materials, and high-temperature heat exchanger technologies
- Reason for technical optimism
- Promise is significant