Molten Salts: Common Nuclear and Concentrated-Solar-Thermal-Power Technologies

Charles Forsberg
Department of Nuclear Science and Engineering (NSE)
Massachusetts Institute of Technology
77 Massachusetts Ave; Bld. 42-207a; Cambridge, MA 02139
Tel: (617) 324-4010; Email: cforsber@mit.edu

November, 2011

American Nuclear Society 2011 Winter Meeting
Washington D.C.

Outline

- Advanced nuclear and solar systems use common high-temperature (700 to 900°C) salt technologies
  - Fluoride salt-cooled high-temperature reactors
  - Concentrated solar power on demand
  - Molten salt reactors
  - High-temperature heat transport and storage
  - Fusion
- Common technologies and incentives for shared programs

Fluoride Salt-Cooled High-Temperature Reactors

High-Efficiency, Better Economics, Eliminate Core Melt Accidents

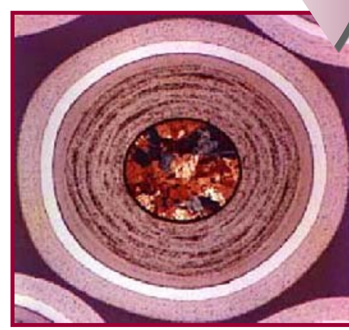
Massachusetts Institute of Technology, University of California at Berkeley, University of Wisconsin Partnership

Oak Ridge National Laboratory, Idaho National Laboratory

Fluoride Salt-Cooled High-Temperature Reactor (FTR)

Passively Safe Pool-Type Reactor Designs

Brayton Power Cycles

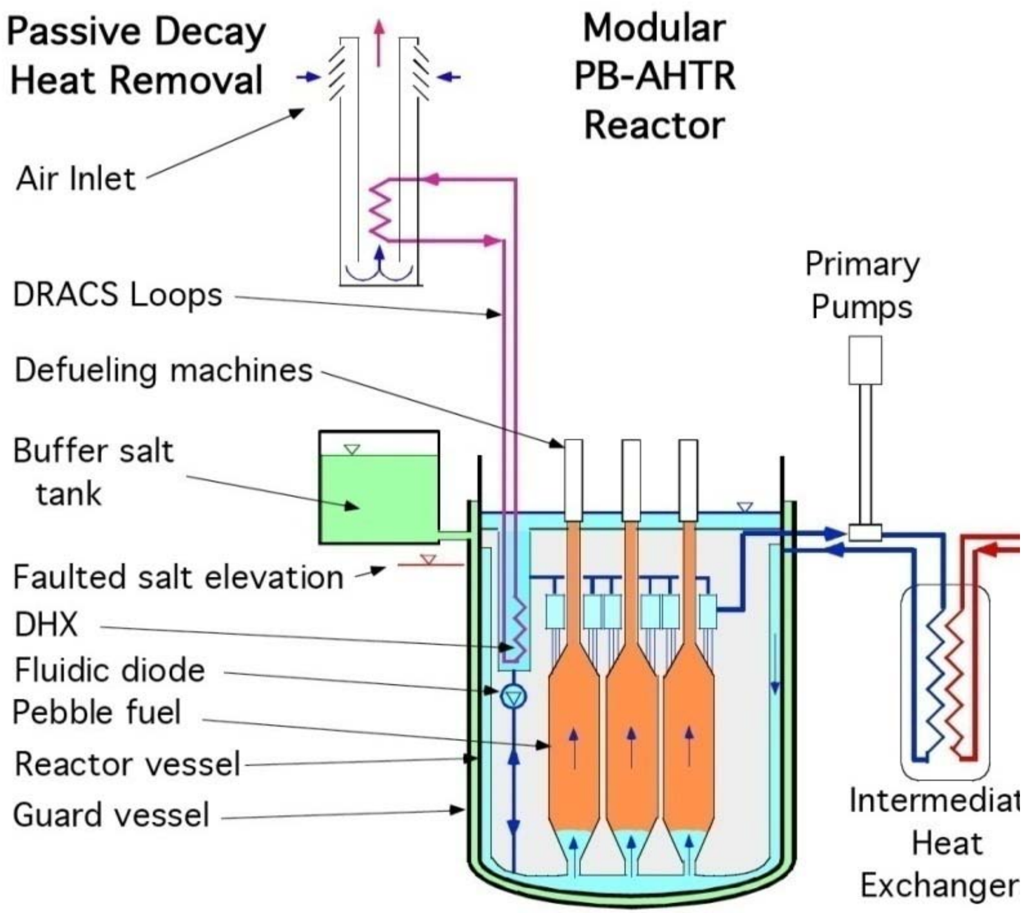


High-Temperature Fuel and Graphite Moderator

High-Temperature, Low-Pressure Transparent Liquid-Salt Coolant

New Concept: No Prototype Ever Built

Studies Underway to Define Preferred Variants



- Coated particle fuels (pebbles, planks, hexagonal blocks)
- Power cycles
- Salt choices for primary and secondary loop

Concentrated Solar Power on Demand (CSPond)

High-Efficiency (>40%) Solar Thermal Power with Storage

Massachusetts Institute of Technology

A. A. Slocum, J. Buongiorno, C. W. Forsberg, T. McKrell, A. Mitsos, J. Nave, D. Codd, A. Ghobeity, C. J. Noone, S. Passerini, F. Rojas, “Concentrated Solar Power on Demand,” Solar Energy

Existing Solar Power Towers

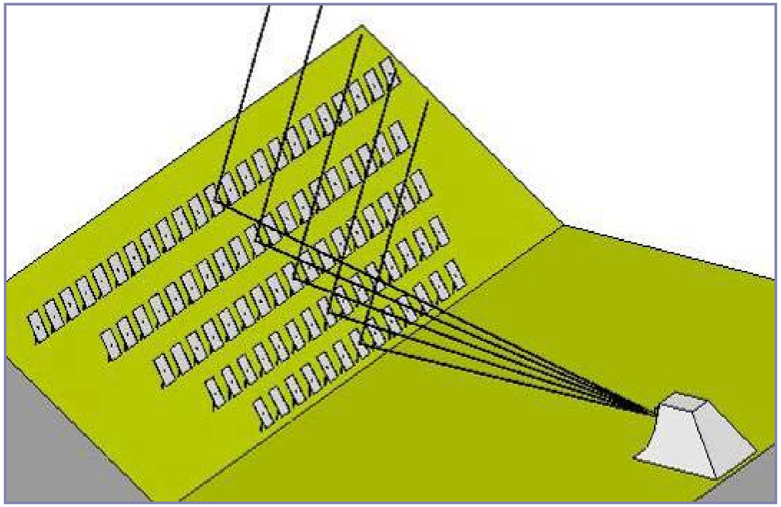
- Mirrors reflect sunlight to boiler
- Boiler tubes on top of tall tower absorb light
- Heat water and convert to steam
- Steam turbine produces electricity
- Poor economics
  - High capital cost
  - Low thermal efficiency

PS-10, 11MWe peak,
Image courtesy of N. Hanumara

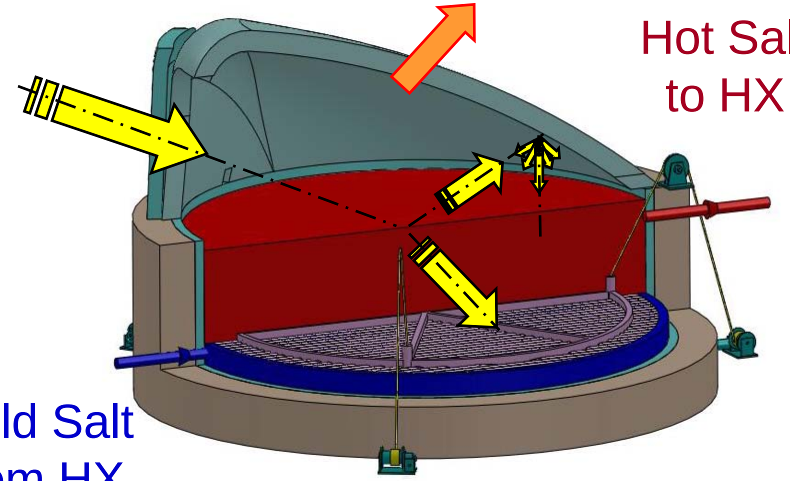
CSPond Description

- Mirrors shine sunlight to receiver
- Receiver is a high-temperature liquid salt bath inside insulated structure with open window for focused light
  - Small open window with very high light fluxes minimizes heat losses to environment
  - Concentrated light fluxes would destroy conventional boiler-tube collectors
  - Light volumetrically absorbed through several meters of liquid salt
  - Enables salt temperatures to 950 C
- Requires high-temperature thermodynamically-stable semi-transparent salt
- Lower temperature version with nitrate salts but nitrate salt decomposition limits temperatures to <~550°C

CSPonD Two Component System



Light Reflected From Hillside Heliostat rows to CSPonD System

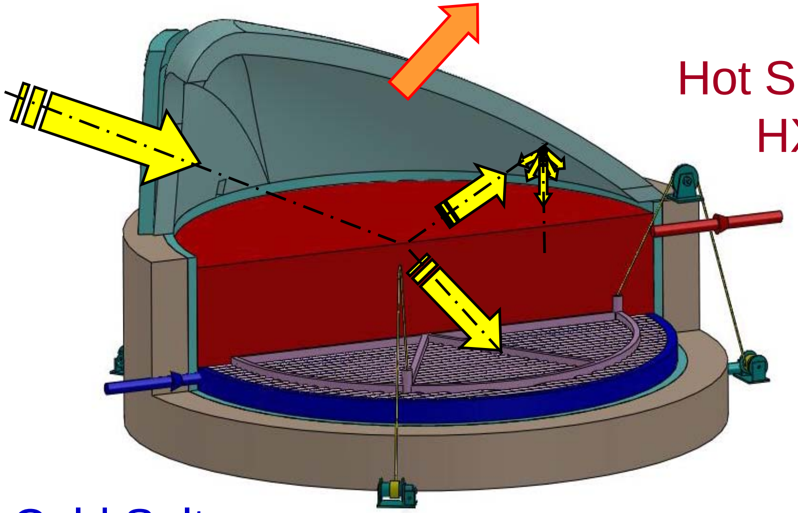


Light Collected Inside Insulated Building With Open Window

(Not to scale!)

CSPond Light Receiver

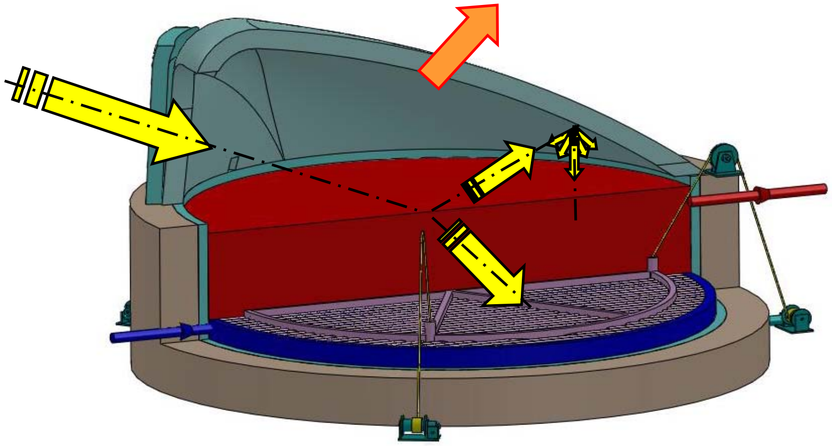
- Efficient light-to-heat collection
  - Concentrate light
  - Focus light through small open window in insulated structure
- Challenge
  - High light energy flux per unit area
  - Will vaporize solid collectors



Light Volumetrically Absorbed in Liquid Salt Bath

Light Focused On "Transparent" Salt

- Light volumetrically absorbed through several meters of salt
- Molten salt experience
  - Metal heat treating bath
  - Molten salt nuclear reactor
- Advantages
  - No light-flux limit
  - No thermal fatigue
  - Can go to extreme temperatures



Molten Chloride Salt Metallic Heat Treatment Bath (1100°C)

Molten Salt Reactors

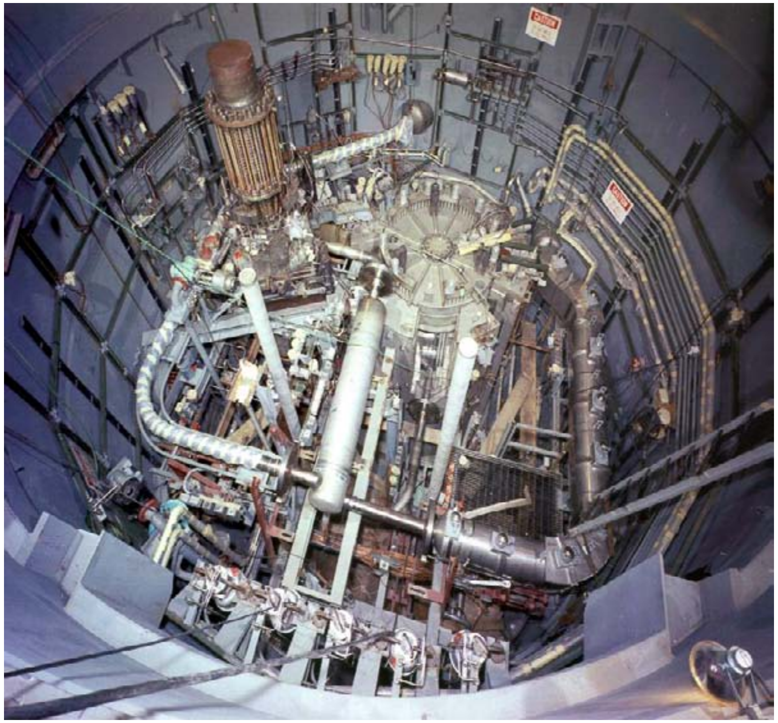
High-Efficiency, Resource Conservation (Breeder), Actinide Burning

Oak Ridge National Laboratory, China, France, Czech Republic, Russia

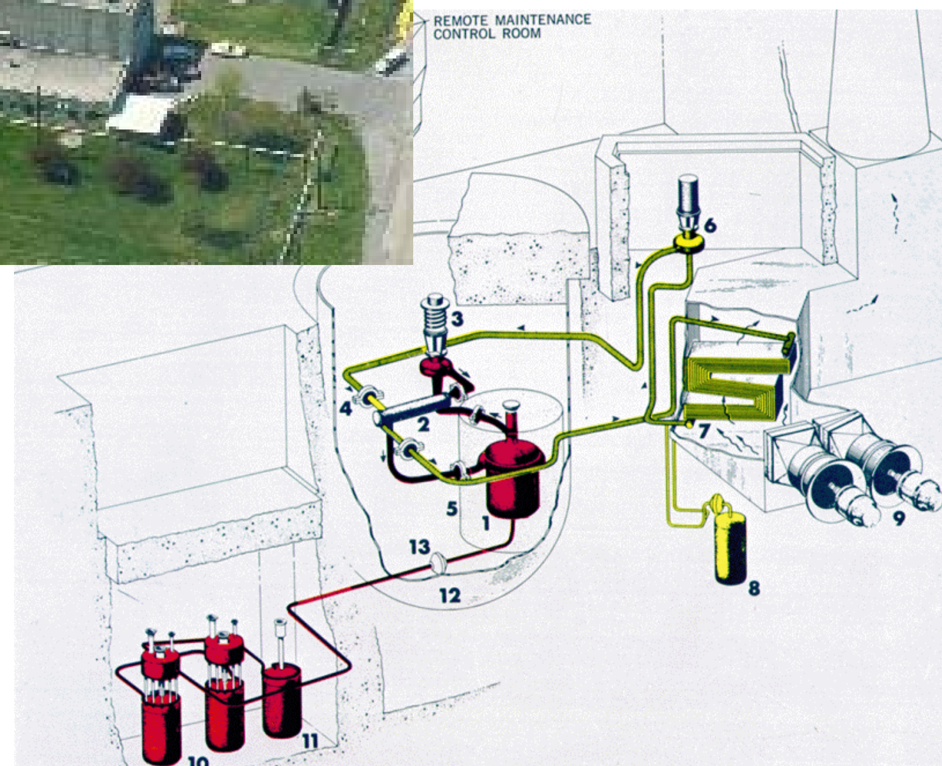
Molten Salt Reactor (MSR)

- Fuel (^{233}U and Th) dissolved in a fluoride salt
  - Fluid-fuel reactor
  - Thermal-spectrum breeder reactor
  - ^{7}Lithium-beryllium fluoride salt
  - Program cancelled when the liquid metal fast breeder reactor chosen
- New interest in MSRs
  - Fast-spectrum MSR
  - Breeding and burning wastes

Molten Salt Reactor Experiment 8 MW(t)



MSRE (1965-69) Is the Reactor-Base Experience with Salt Coolants



1. Reactor Vessel, 2. Heat Exchanger, 3. Fuel Pump, 4. Freeze Flange, 5. Thermal Shield, 6. Coolant Pump, 7. Radiator, 8. Coolant Drain Tank, 9. Fans, 10. Fuel Drain Tanks, 11. Flush Tank, 12. Containment Vessel, 13. Freeze Valve.

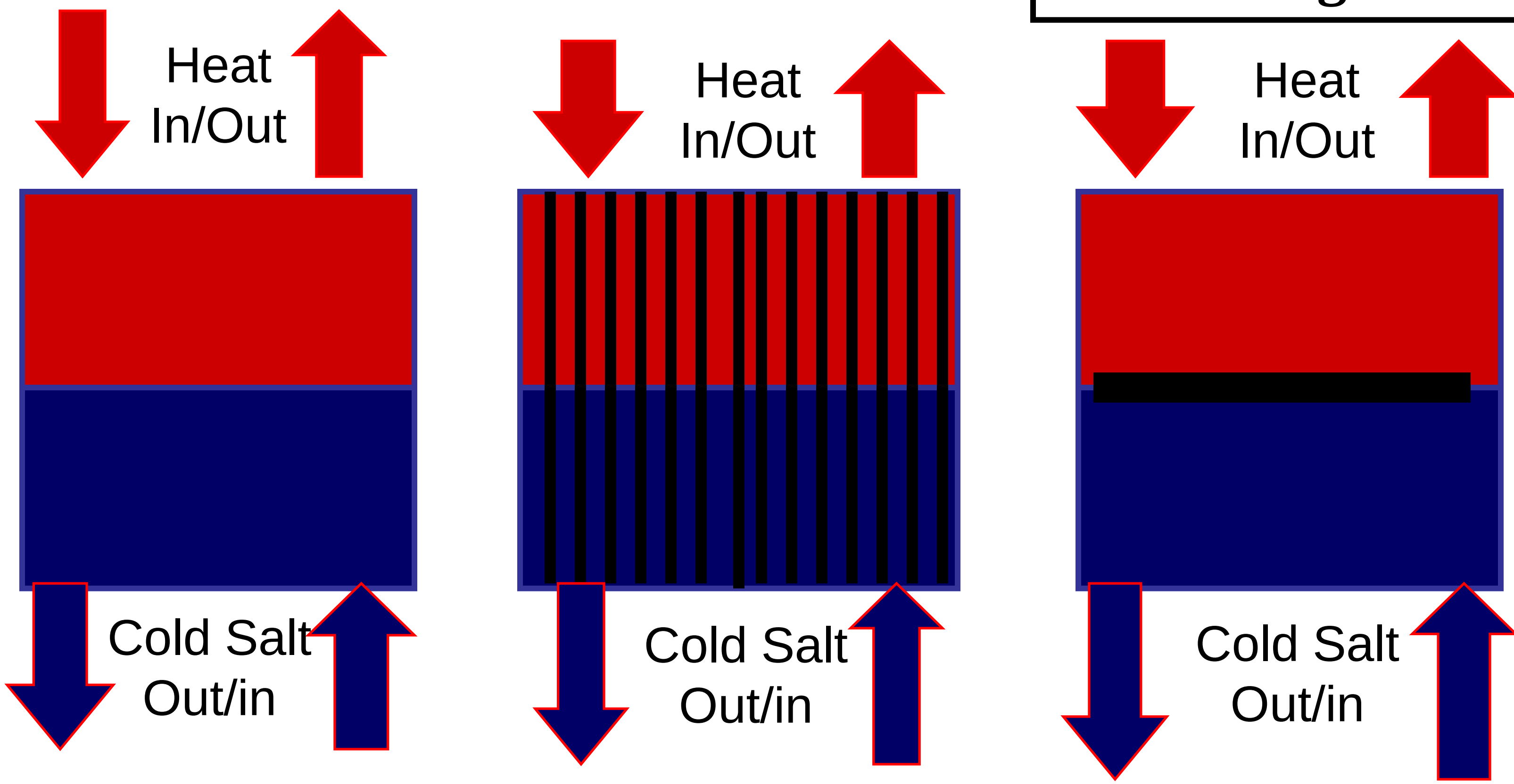
Heat Storage for High-Temperature Reactors

Match Energy Production with Energy Demand

Massachusetts Institute of Technology

Three Single-Tank Heat Storage Systems

Hot Salt on Top of Cold Salt	Hot Salt on Top of Cold Salt with Solid Fill	Hot Salt on Top of Cold Salt Separated With Insulated Floating Plate



Need To Understand Radiation Heat Transfer for Storage System Designs

Salt Variable Optical Path Length Transmission Apparatus (850°C)

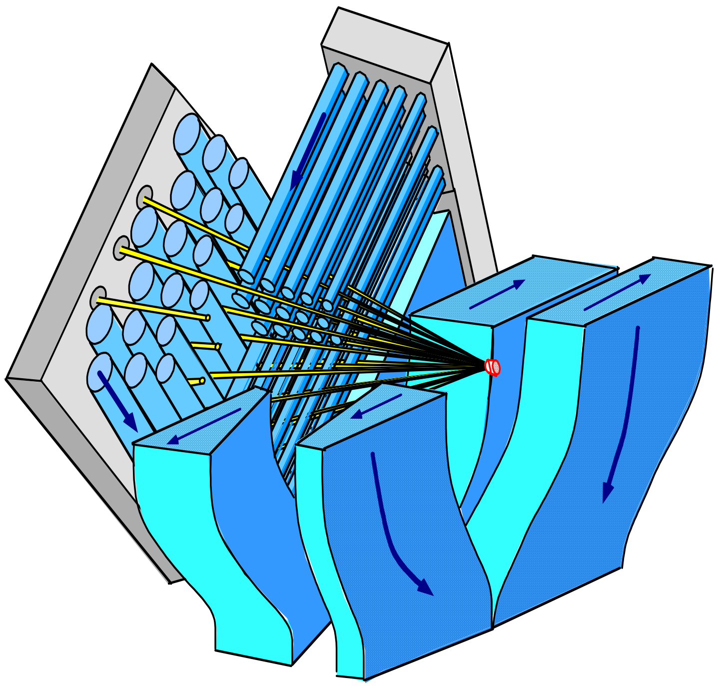
- Radiation heat transfer important > 700°C
- Need optical properties as function of frequency and temperature
- Limited measurements have been made
- Needed for all high-temperature salt systems

Salt-Cooled Fusion Reactor

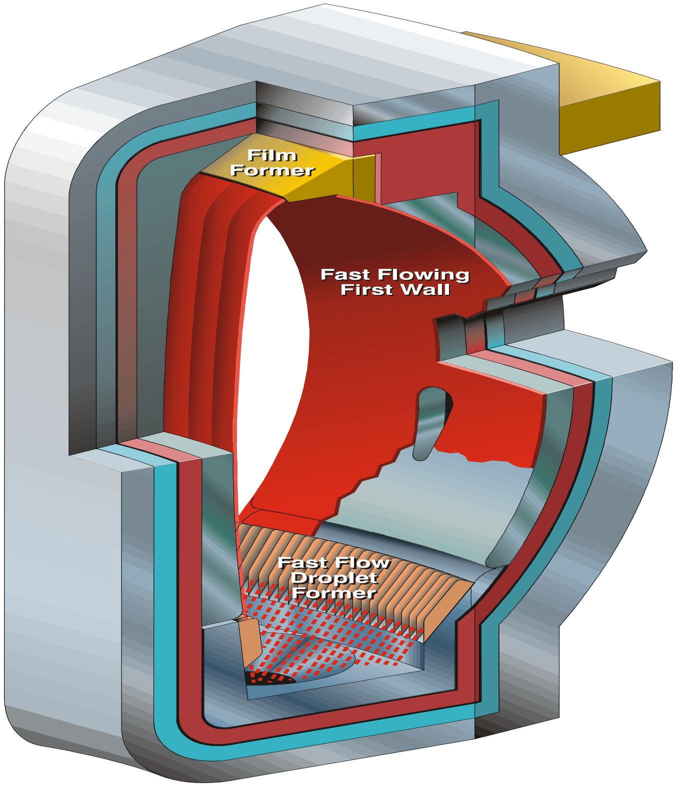
Liquid Inner-Wall Radiation Shield, Heat Transfer, Tritium Blanket

Liquid-Salt-Wall Fusion Machines

Higher-Power Densities and Less Radiation Damage



Heavy-Ion Inertial Fusion



Magnet Fusion Tokamak

Incentives for Cooperative Programs to Develop / Demonstrate Common High-Temperature Industrial Systems

Large Fission, Solar, and Fusion Incentives for Joint Programs

- Measuring and understanding liquid salts as coolants
- Heat exchangers, piping, valves, etc.
- Power cycles
  - Air-cooled Brayton power cycles with no cooling water requirements
  - Supercritical CO_2 cycles
  - Helium and mixed gas cycles

Need Better Engineering Understanding of High-Temperature Salts

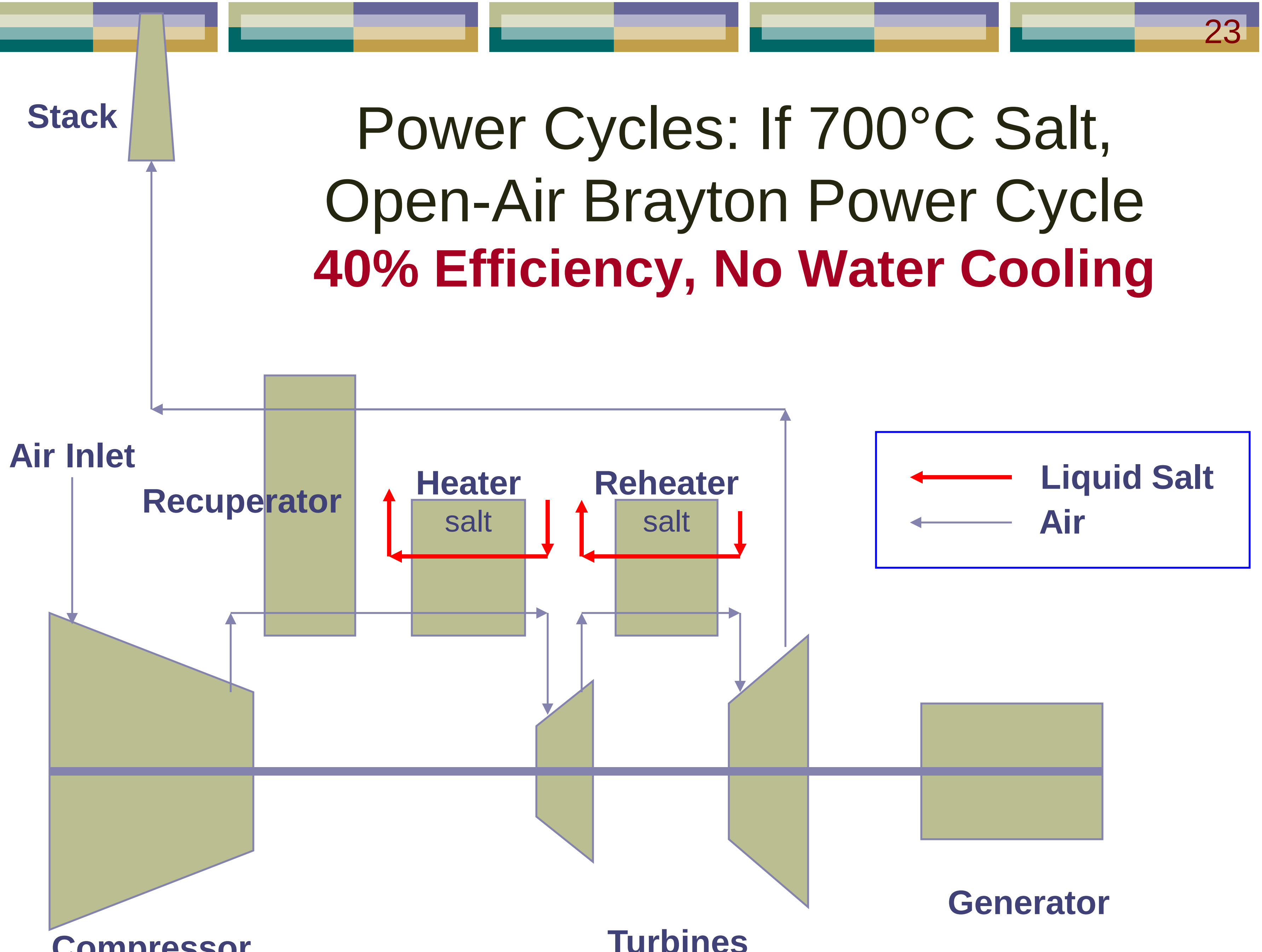
Appearance of molten

NaCl-KCl salt at 850°C

- Corrosion in different systems
- Salt cleanup to control impurities
- Optical properties as a function of temperature and frequency: radiation heat transfer can control coolant behavior

Power Cycles: If 700°C Salt, Open-Air Brayton Power Cycle

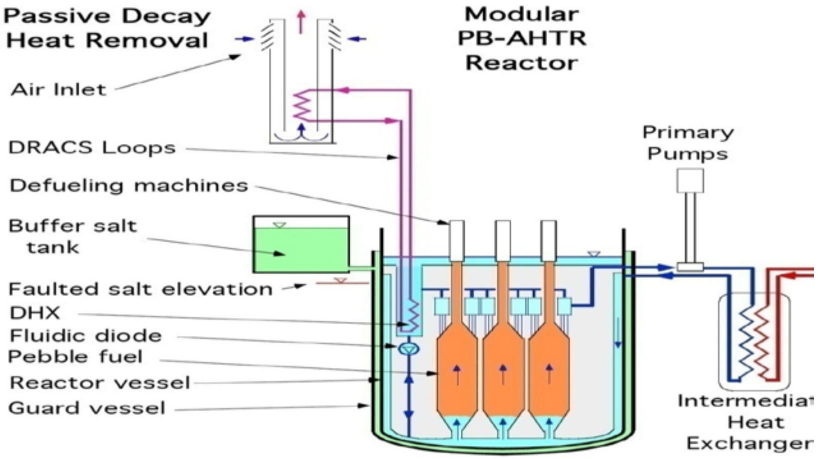
40% Efficiency, No Water Cooling



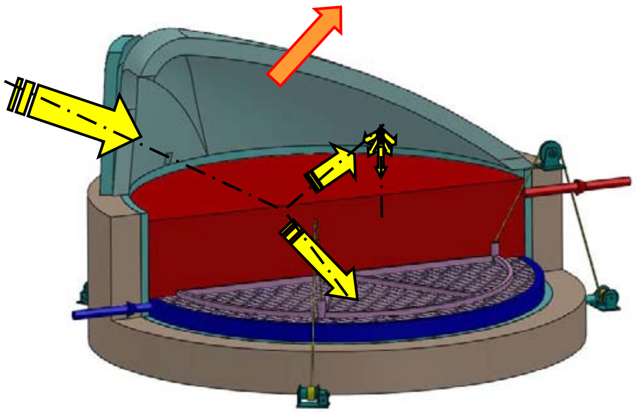
Conclusions

- Multiple salt-cooled power technologies are being developed (Fission, Solar, Fusion)
- Schedule and financial incentives for joint efforts to commercialize shared technologies
  - Salt Technologies
  - Power Cycles at >700°C
  - Associated equipment

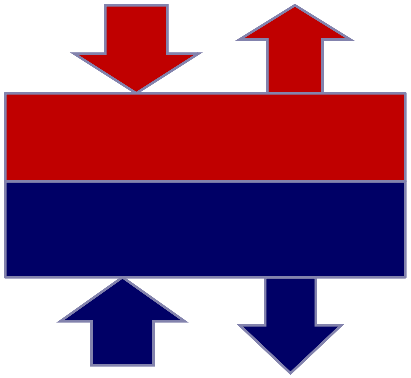
Questions?



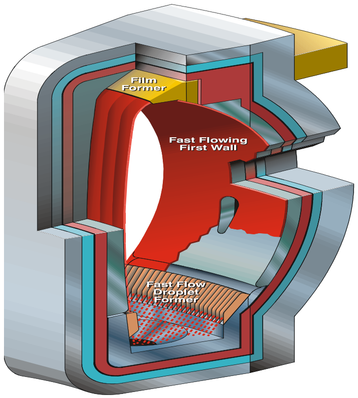
Fluoride Salt-Cooled High-Temperature Reactor (FTR)



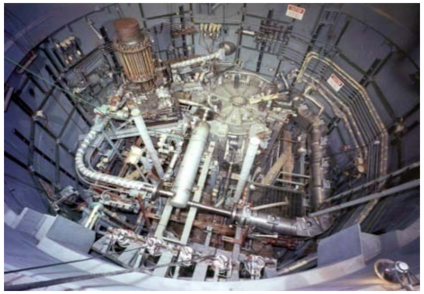
Concentrated Solar Power On Demand (CSponD)



High-Temperature Heat Storage



Salt Cooled Fusion Reactor



Molten Salt Reactor

Biography: Charles Forsberg

Dr. Charles Forsberg is the Executive Director of the Massachusetts Institute of Technology Nuclear Fuel Cycle Study, Director and principle investigator of the High-Temperature Salt-Cooled Reactor Project, and University Lead for Idaho National Laboratory Institute for Nuclear Energy and Science (INEST) Nuclear Hybrid Energy Systems program. Before joining MIT, he was a Corporate Fellow at Oak Ridge National Laboratory. He is a Fellow of the American Nuclear Society, a Fellow of the American Association for the Advancement of Science, and recipient of the 2005 Robert E. Wilson Award from the American Institute of Chemical Engineers for outstanding chemical engineering contributions to nuclear energy, including his work in hydrogen production and nuclear-renewable energy futures. He received the American Nuclear Society special award for innovative nuclear reactor design on salt-cooled reactors. Dr. Forsberg earned his bachelor's degree in chemical engineering from the University of Minnesota and his doctorate in Nuclear Engineering from MIT. He has been awarded 11 patents and has published over 200 papers.

Incentives for Better Technology

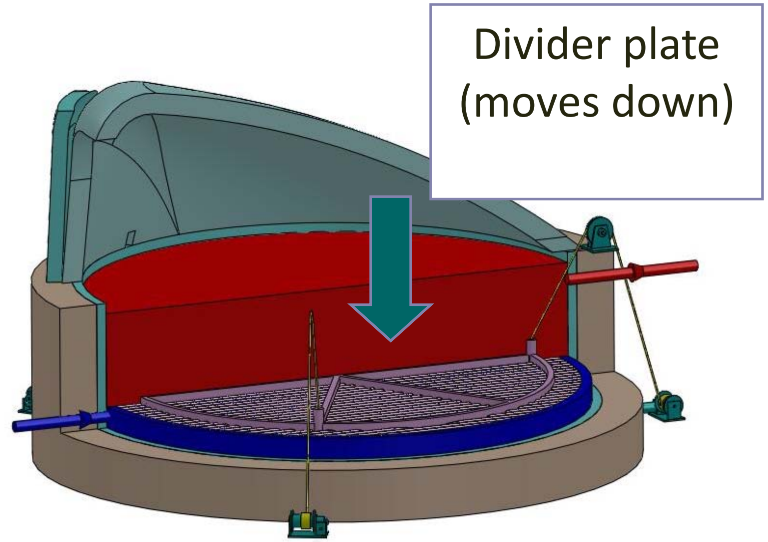
- Low efficiency system
  - Steam temperatures limited to avoid boiler-tube thermal fatigue from variable light (wind effect on mirrors)
  - High heat loses from exposed boiler tubes
- High Costs
  - Need efficient light to electricity system
  - Storage to avoid selling electricity at times of low prices

PS-10, 11MWe peak,
Image courtesy of N. Hanumara

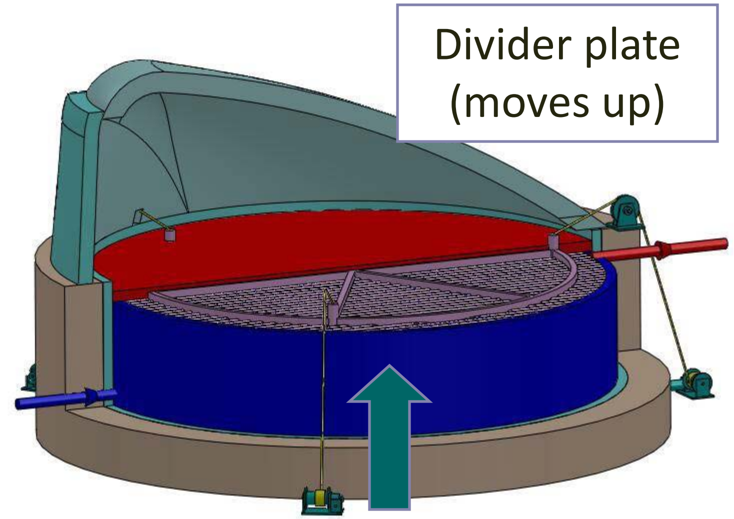
CSPond Integral Heat Storage

- Salt tank has insulated separator plate
- Plate functions
  - Separates hot and cold salt
  - Bottom light absorber
- Storage role
  - If excess heat input, plate sinks to provide hot salt storage volume
  - If power demand high, plate raised with cold salt storage under plate

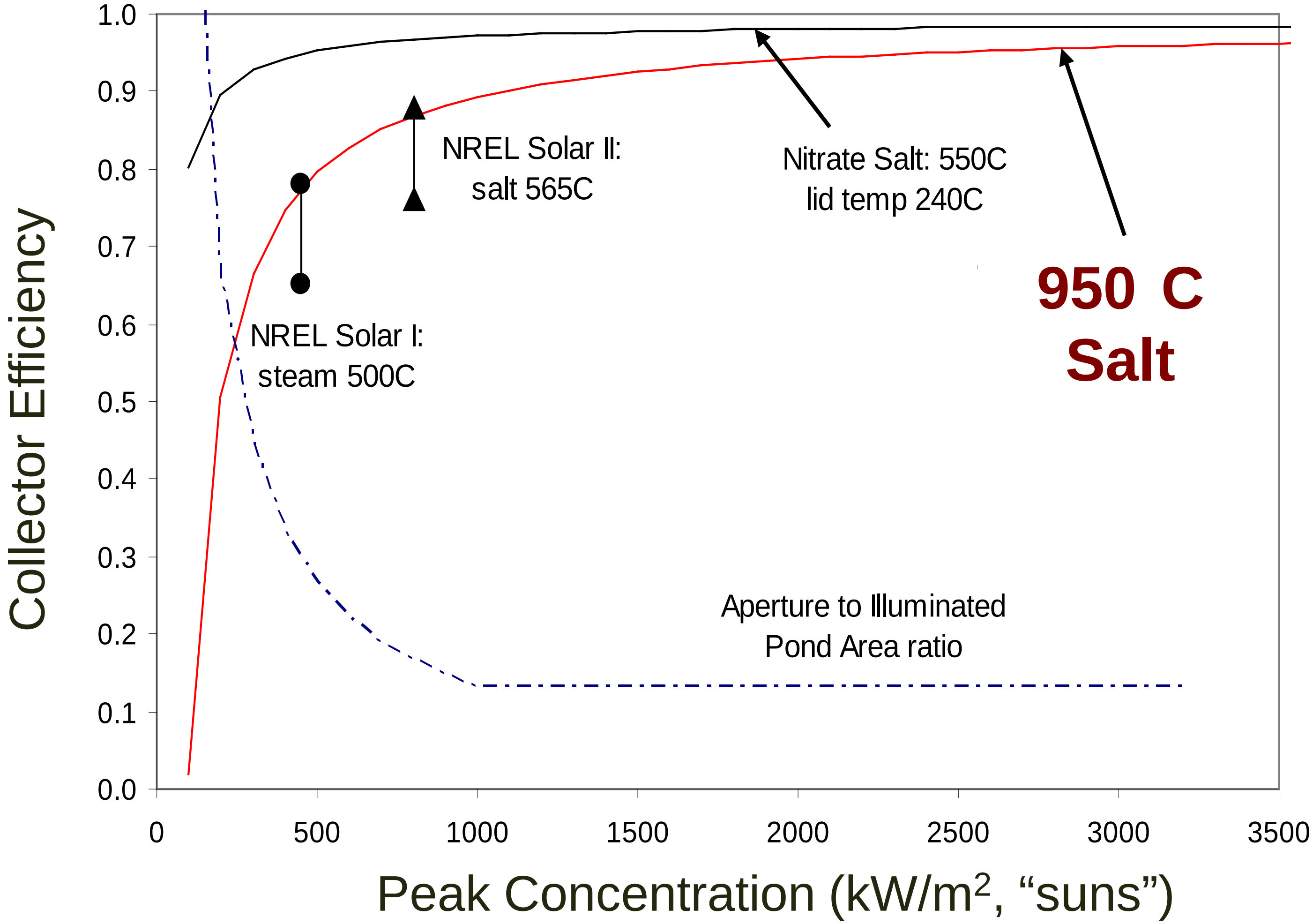
Daytime



Nighttime



Volumetric Light Absorption: Low-Loss High-Temperature Solar-Thermal System



50-100% Increase in Light to Electricity Efficiency

CSPond Leading Candidate Salts

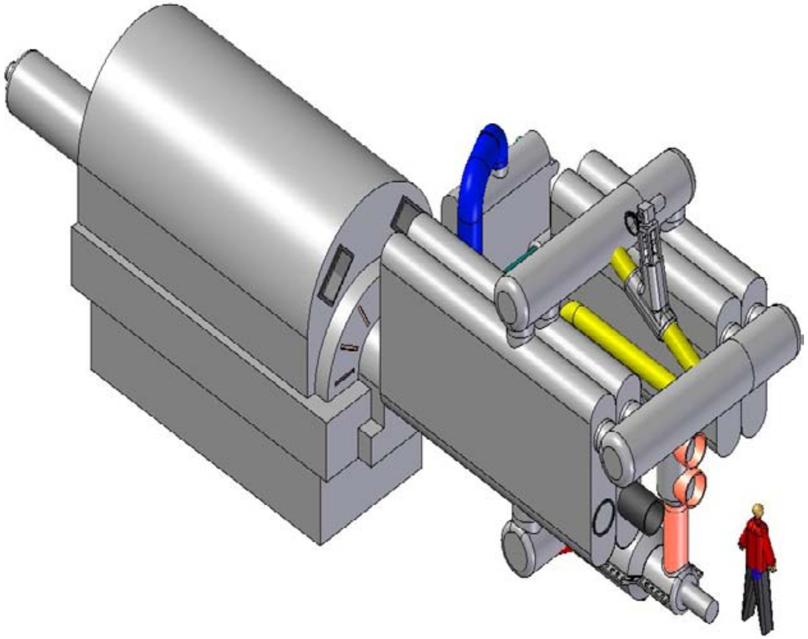
	NaCl-KCl at 800°C	Li_2CO_3-Na_2CO_3-K_2CO_3 at 800°C	KNO_3-$NaNO_2$-$NaNO_3$ at 350°C
Density kg/m^3	1520	1902	1850
Viscosity mPa·s	1.2	4.3	2.360
Thermal conductivity W/m-K	0.45	0.822	0.61
Specific heat J/kg-K	1090	1560	1560

Nitrates limited to lower temperature systems because decompose if overheated. Decompose at ~550°C

Example High-Temperature R&D Applicable to Nuclear and Solar

Work at MIT Nuclear Science and Engineering Department

Salt Variable Optical Path Length Transmission Apparatus (850°C)



50-MWe Super-Critical Carbon Dioxide Power Conversion Unit