Engineering Design and Economic Study of Small Modular Molten Salt Breeder Reactor Power Plant

JUNE 4, 2

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MY HEART I OFFER TO YOU LORD PROMPTLY AND SINCERELY

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Outline

- Project Overview
- Systems Designs
  - Reactor
  - Fuel Reprocessing
  - Power Cycle
- Economics
- Conclusion
- Questions

https://inlportal.inl.gov/portal/server.pt?open=514&objID=1269&mode=2&
DA_553053

PROJECT OVERVIEW

Objective

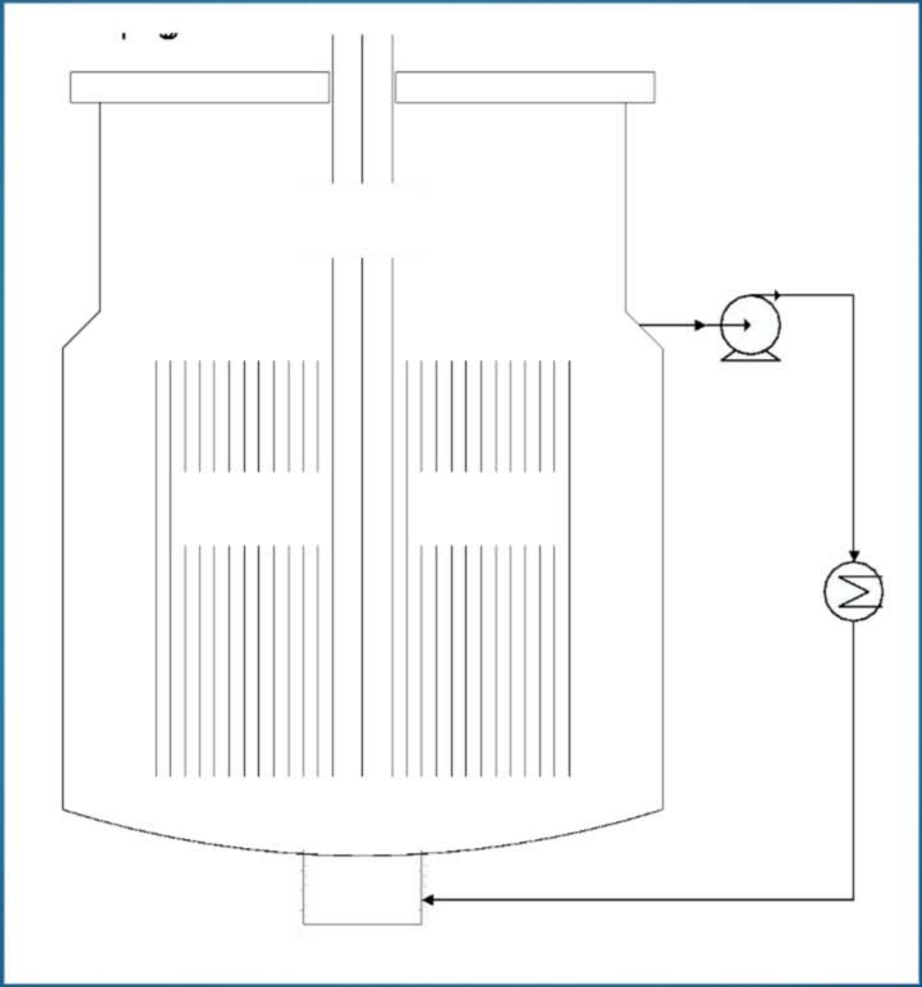
- Develop plant design
  - Nuclear fission reactor
  - Thorium fuel cycle
- Perform economic Analysis

- Problems to address
  1. Negative environmental impact
  2. High cost
  3. Potential human health/safety threat
  4. Low efficiency of fuel and power cy
  5. Decreasing fuel availability

REACTOR SYSTEM

Reactor Specifications

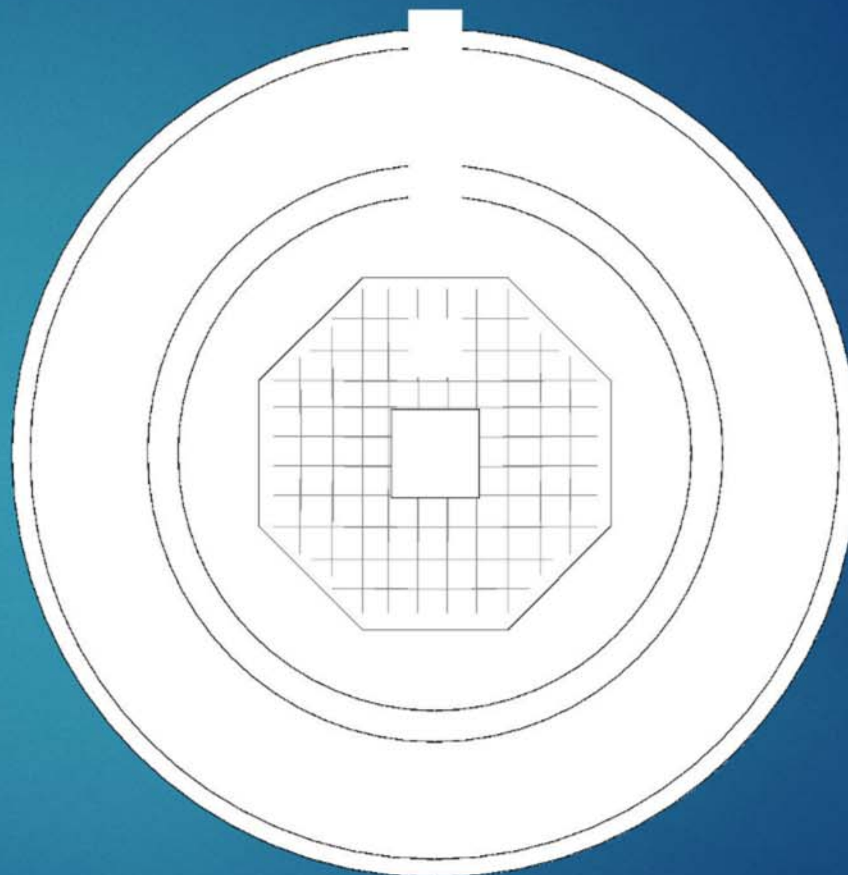
- Size: 200 MWe
- Type: MSBR



Adapted from Robertson, R
ed. Conceptual Design Stud
Single-Fluid Molten-Salt Br
Springfield, VA: Oak Ridge
Laboratory, 1971. 13. Web.

Reactor Core Design

- Materials
  - Moderator: Graphite
  - Solvent: Flibe ($LiF\text{-}BeF_2$)
  - Fuel: UF_4 from ThF_4
  - Vessel/Piping: Hastelloy N
- Single-fluid vs. Two-fluid
- Sizing 2200 ft^3 (60 m^3)
  Height: 14 ft (4.3 m)
  Diam.: 14 ft

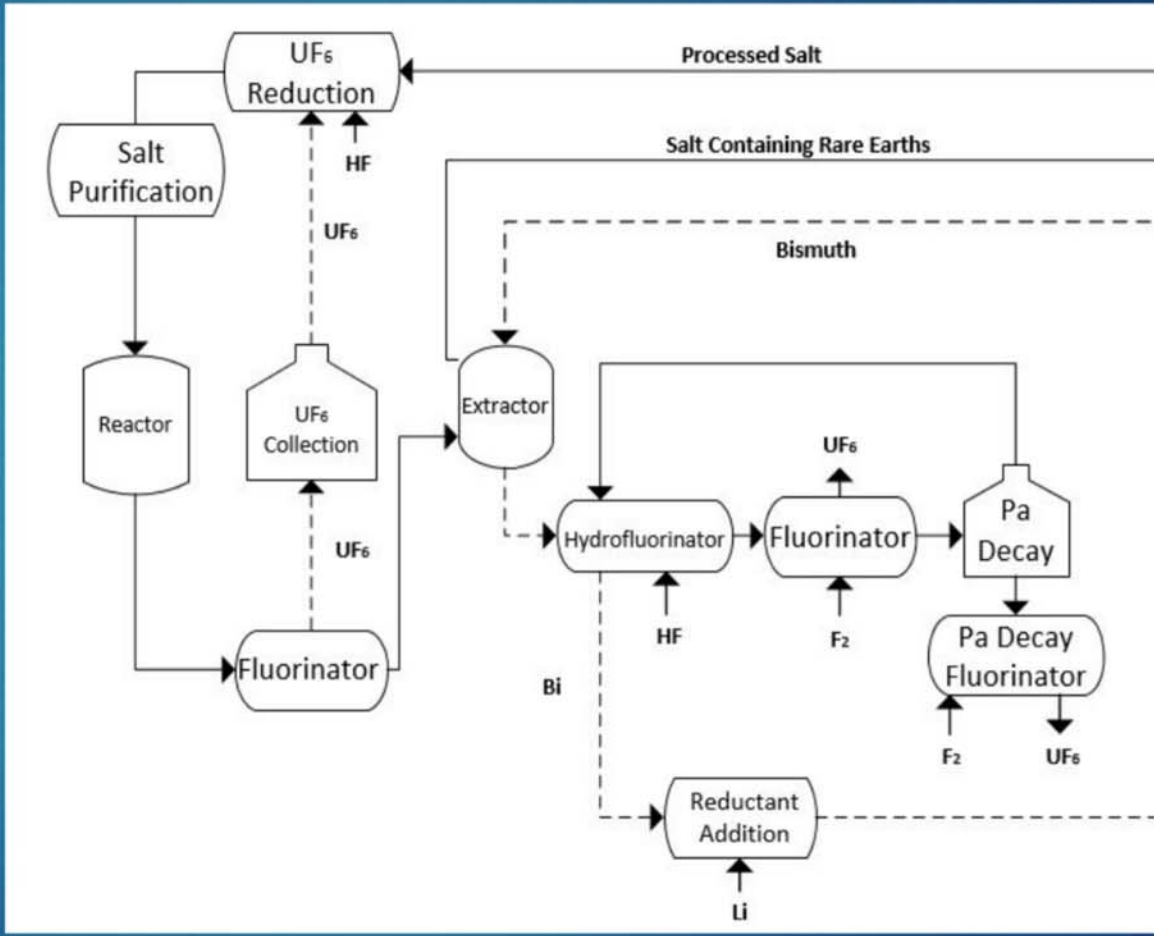


Adapted from Robertson, Roy C., ed. Conceptual Design Study of a Single-Fluid Molten-Salt Breeder Reactor. Springfield, VA: Oak Ridge National Laboratory, 1971. 12. Web. 28 May 2015.

FUEL REPROCESSING

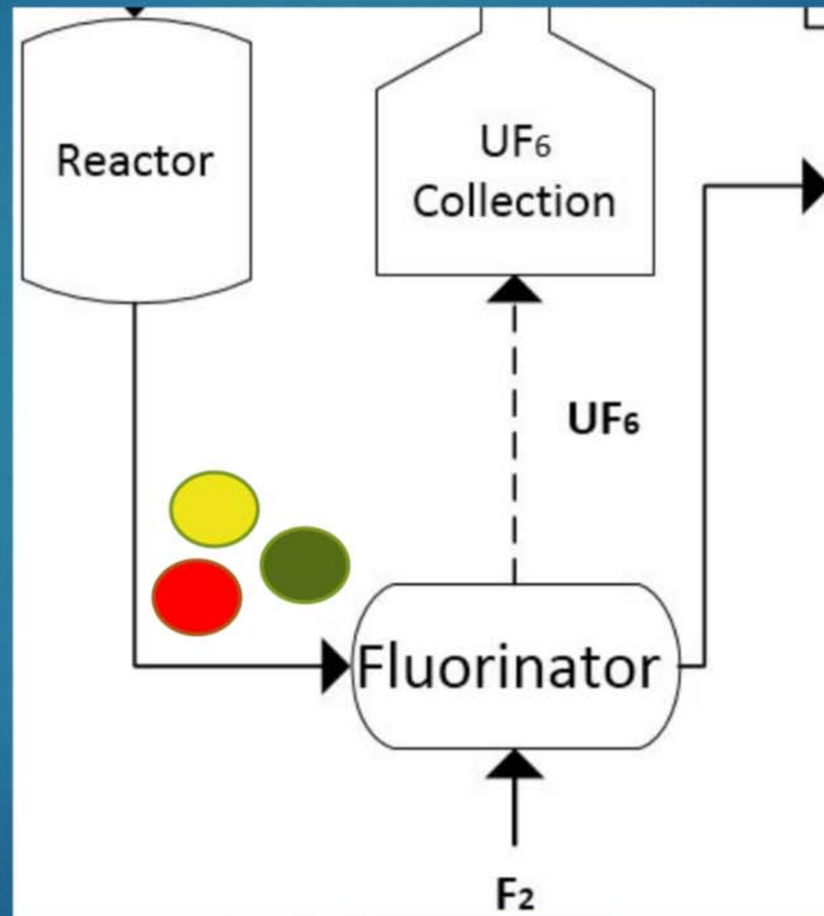
Fuel Reprocessing Overview

- Objective: Remove feed poisons and fission products from fuel
- Advantages
  - Maintain high reactor performance
  - Decrease fuel inventory



Fluorination

- Main Components
  - Uranium
  - Thorium
  - Fission Products
- Fluorinator
  - T=550-600˚C
  - P = 1 atm
  - 95% of uranium removed



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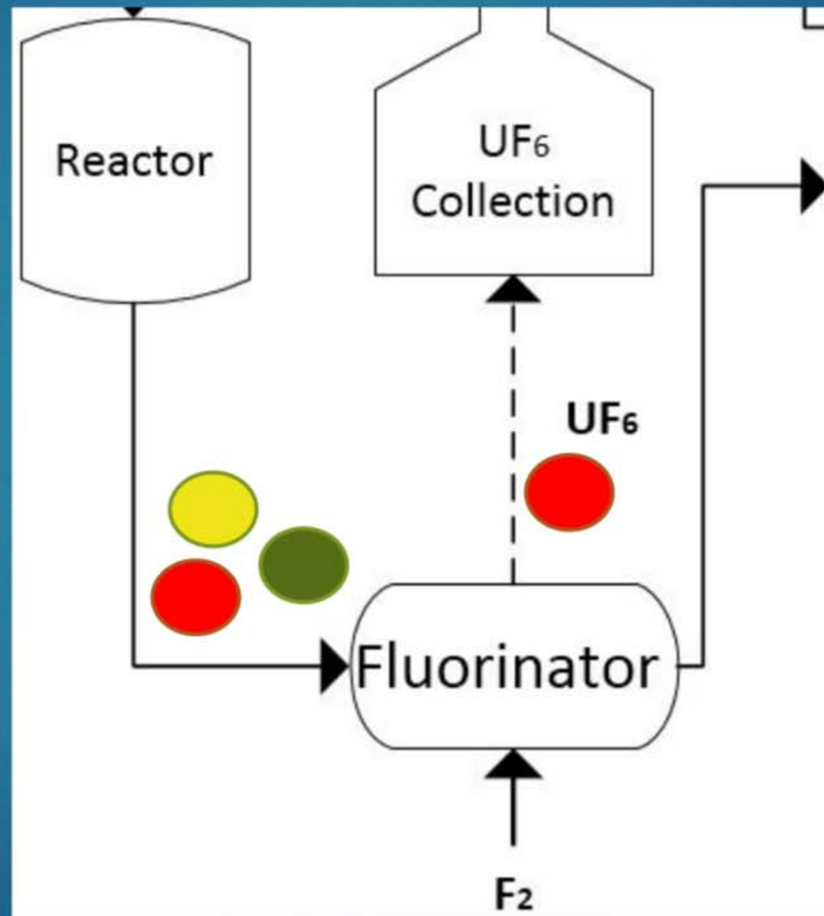

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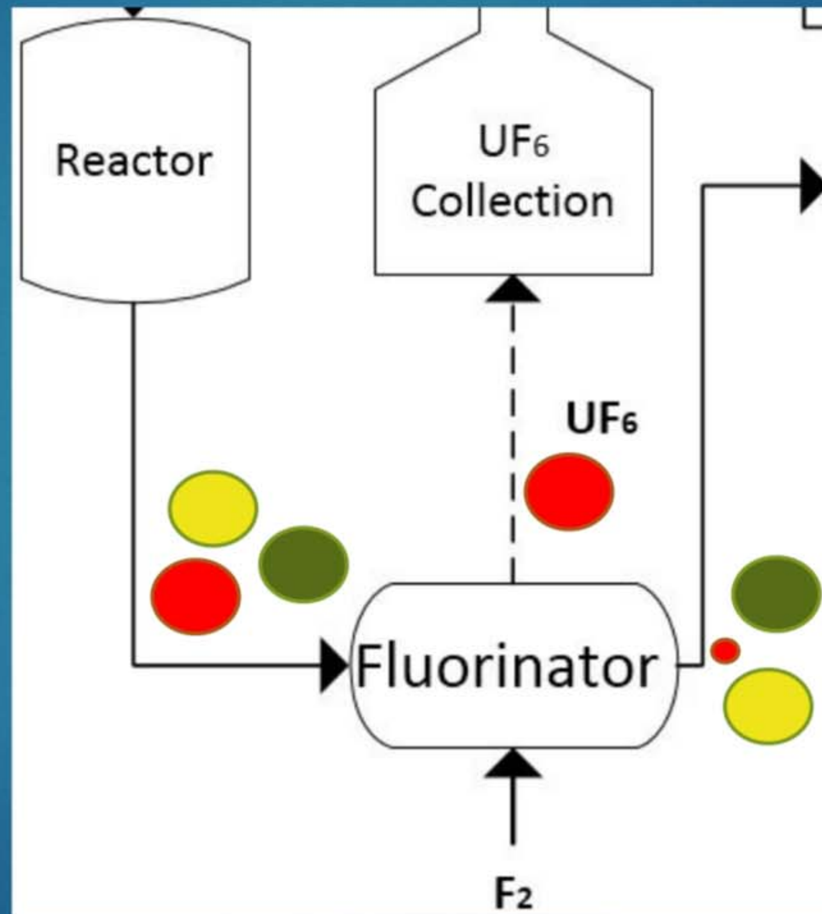
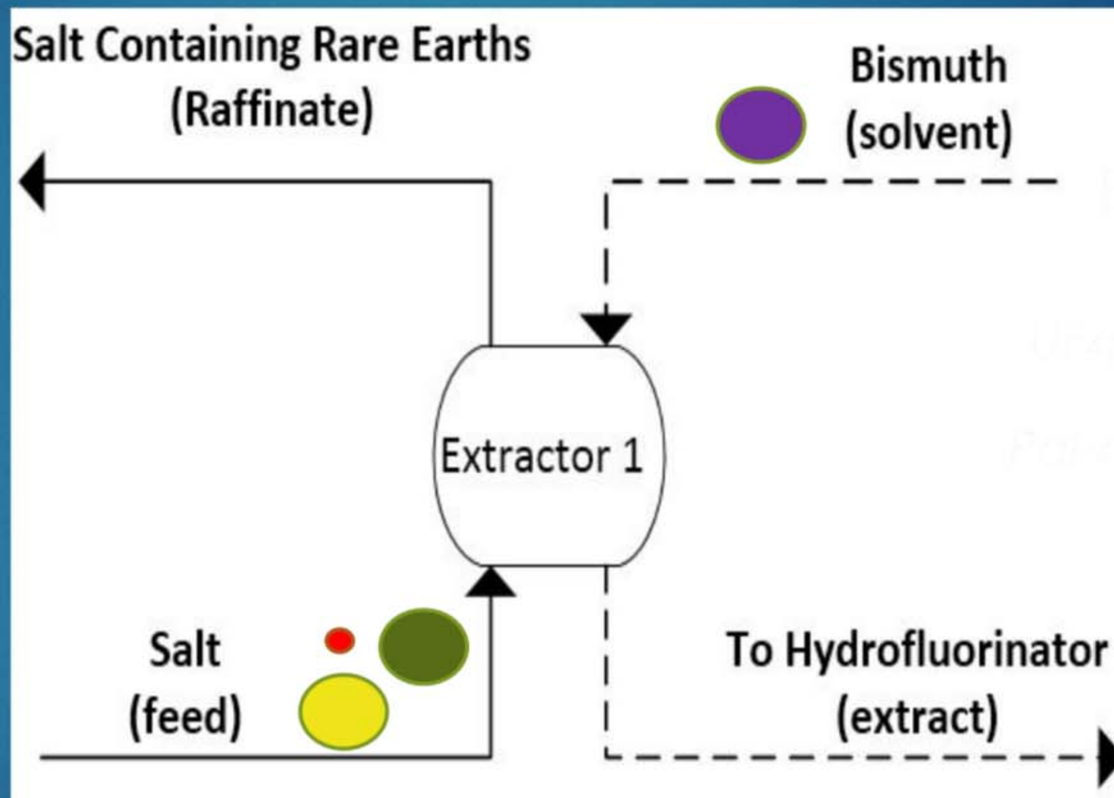


Fluorinator

Extraction

- Main Components
  - Uranium
  - Thorium
  - Fission Products
  - Bismuth
- Bismuth stream composition
  - 0.2 at% Li metal
  - 0.25 at% Th metal



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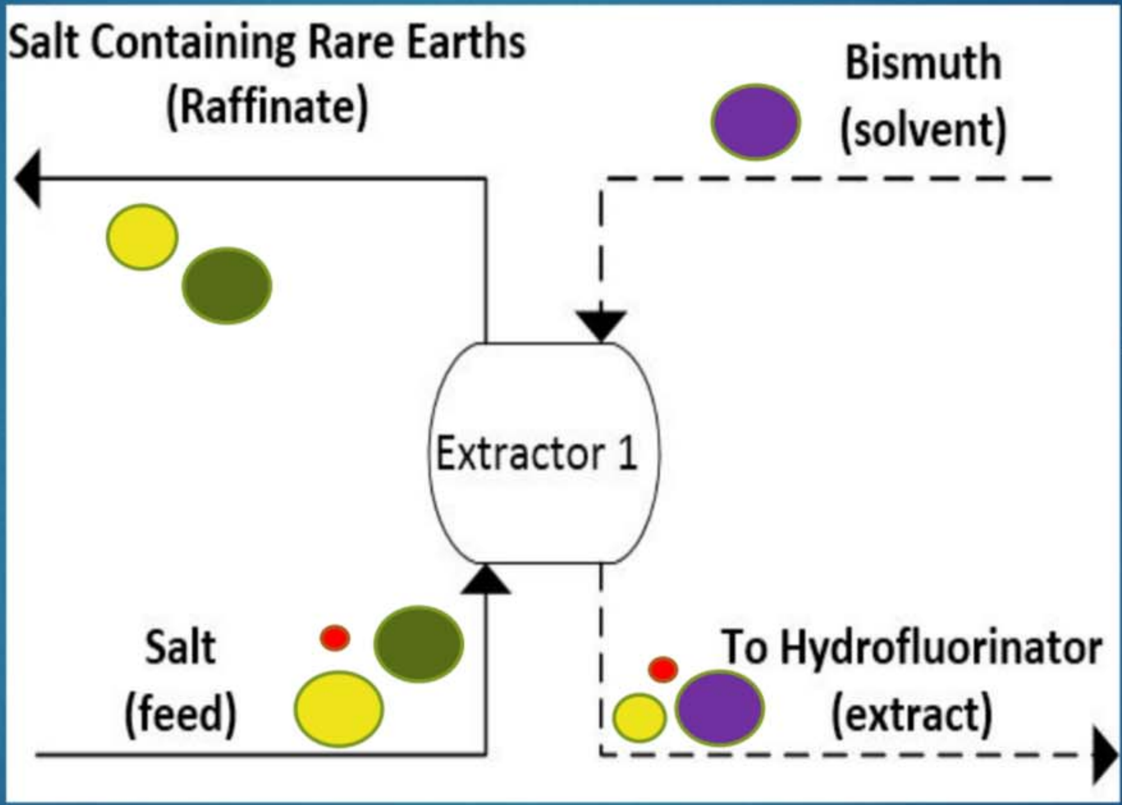


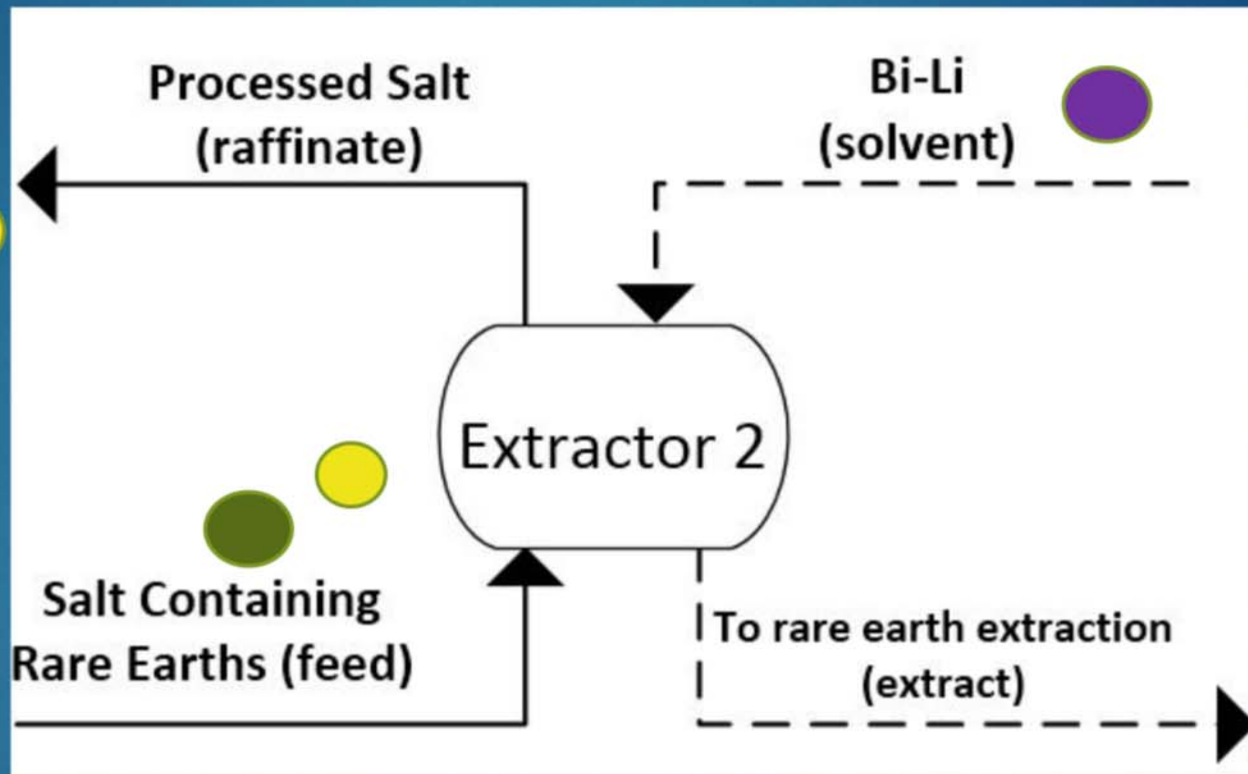
Extrac

$UF_{4(salt)}$+4L

$PaF_{4(salt)}$+4L

Fission Product Removal

- Main Components
  - Thorium
  - Fission Products
  - Bismuth



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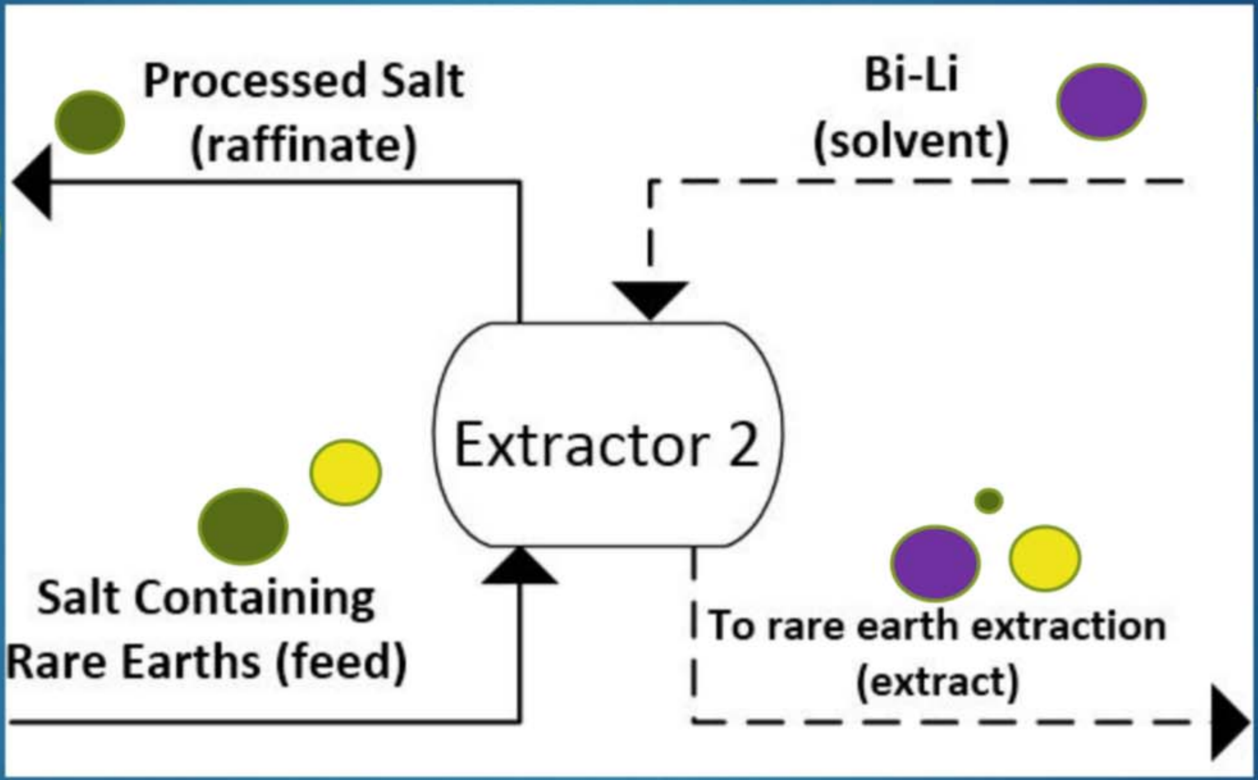
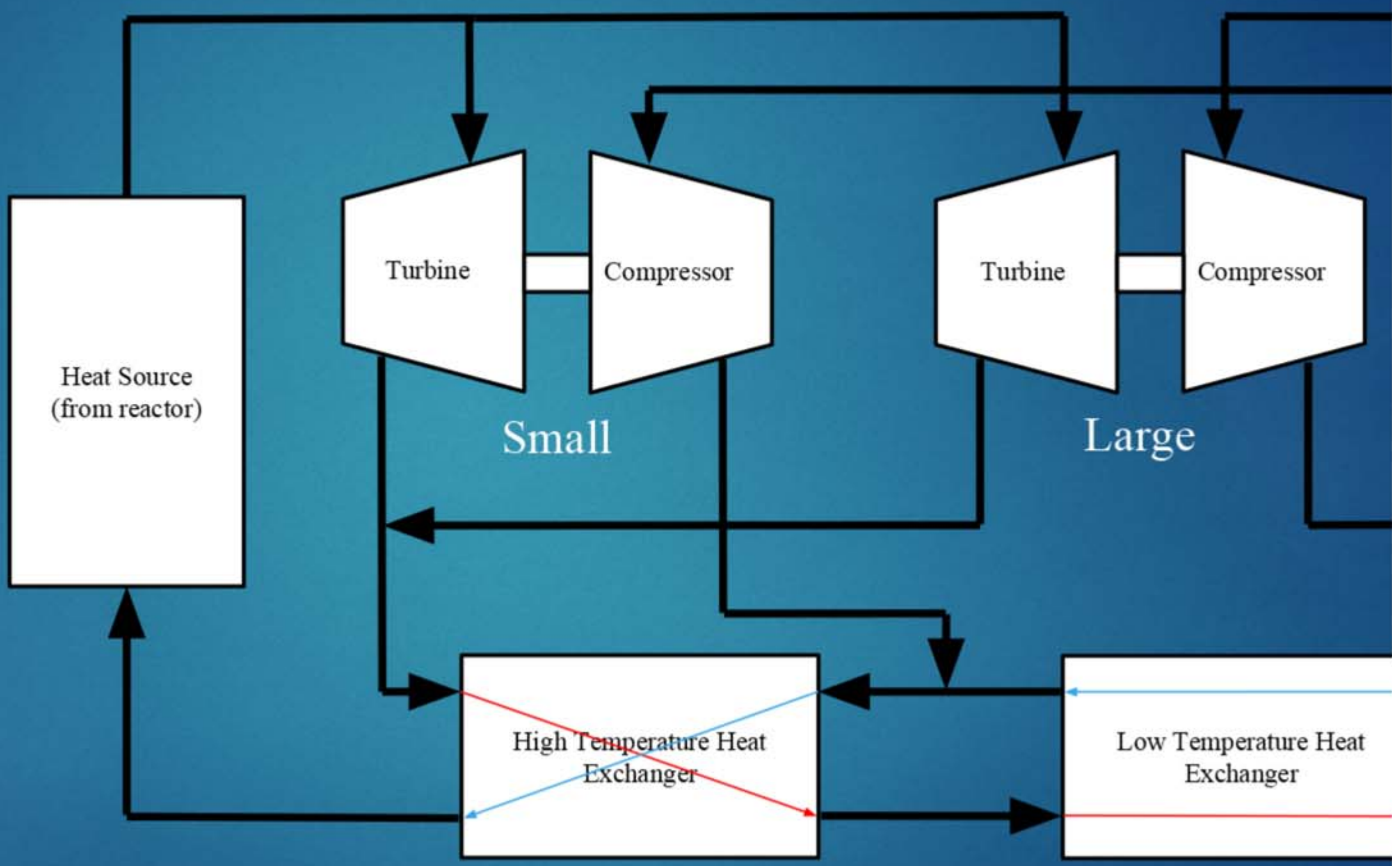


- Fiss

POWER CYCLE

Thermal System Design

- Working Fluids
  - Supercritical CO2
  - Steam
  - Helium
- System: Sandia National Laboratories
- Materials issues
  - Corrosion



Optimization

- System solved in EES
- Goal: Reduce Cost

Turbines	Compressors	Heat Exchangers
Increase		
Outlet pressure	Inlet pressure	Heat transfer coefficient
Isentropic efficiency	Isentropic efficiency	
Decrease		
Mass flow rate	Mass flow rate	Heat transfer
Inlet temperature	Outlet pressure	
Inlet pressure		

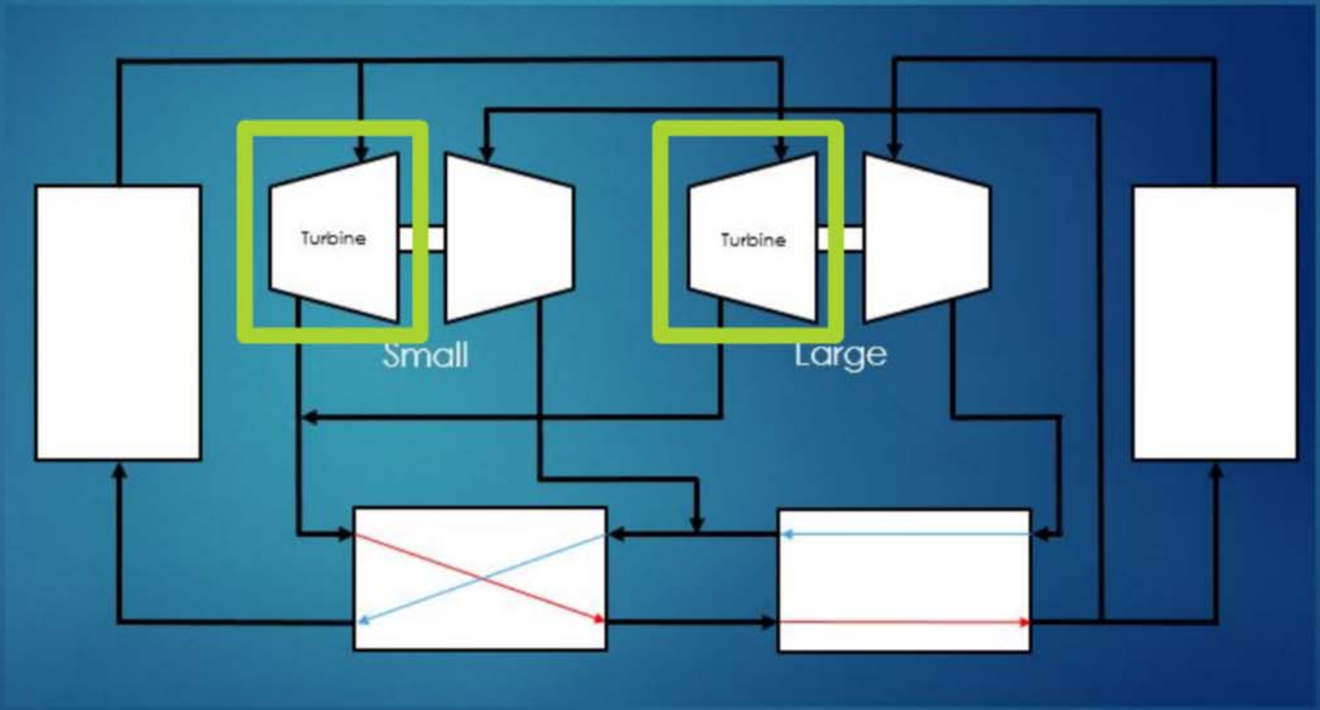
Fluid Dynamics and Power Calculations

- Set Variables
  - Small Turbine: 80 MWe
  - Large Turbine: 200 MWe
  - Reactor Outlet Temperature: 675°C
  - Reactor Outlet Pressure: 11.9 MPa
- Flownex Analysis

http://concentrating.sun.ac.za/flownex-3-day-trainin

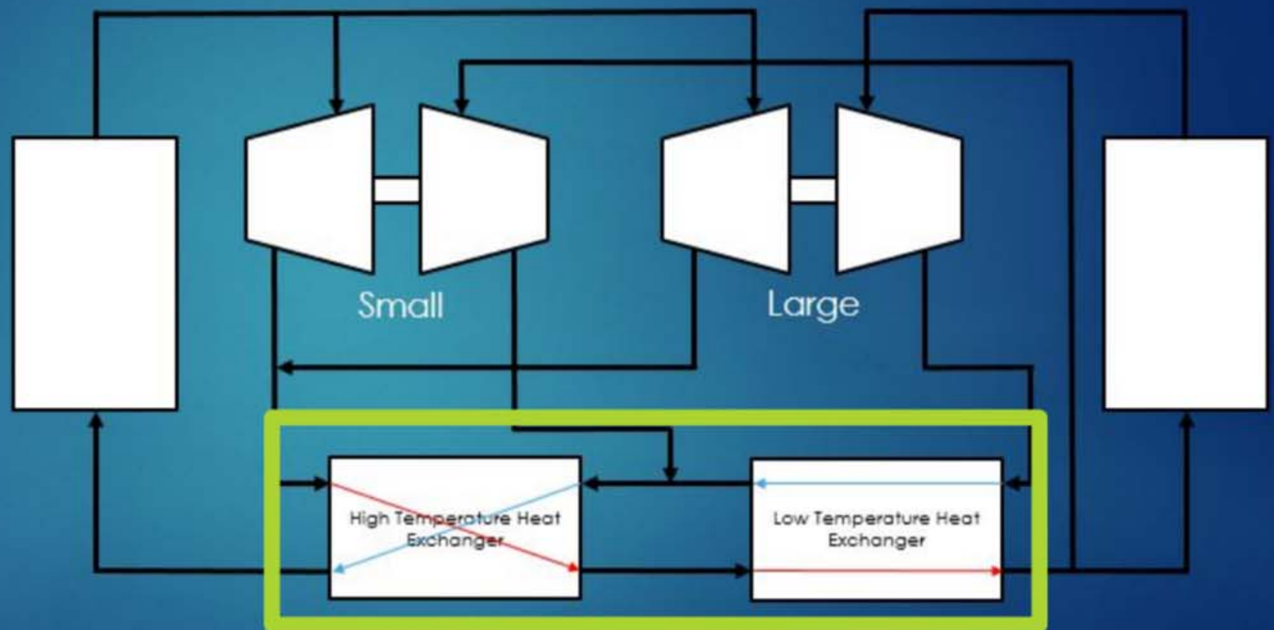
Turbine Sizing

Set Value	Variable	Equation
Power Out	Discharge Coefficient	
Outlet Pressure	Flow Admittance	



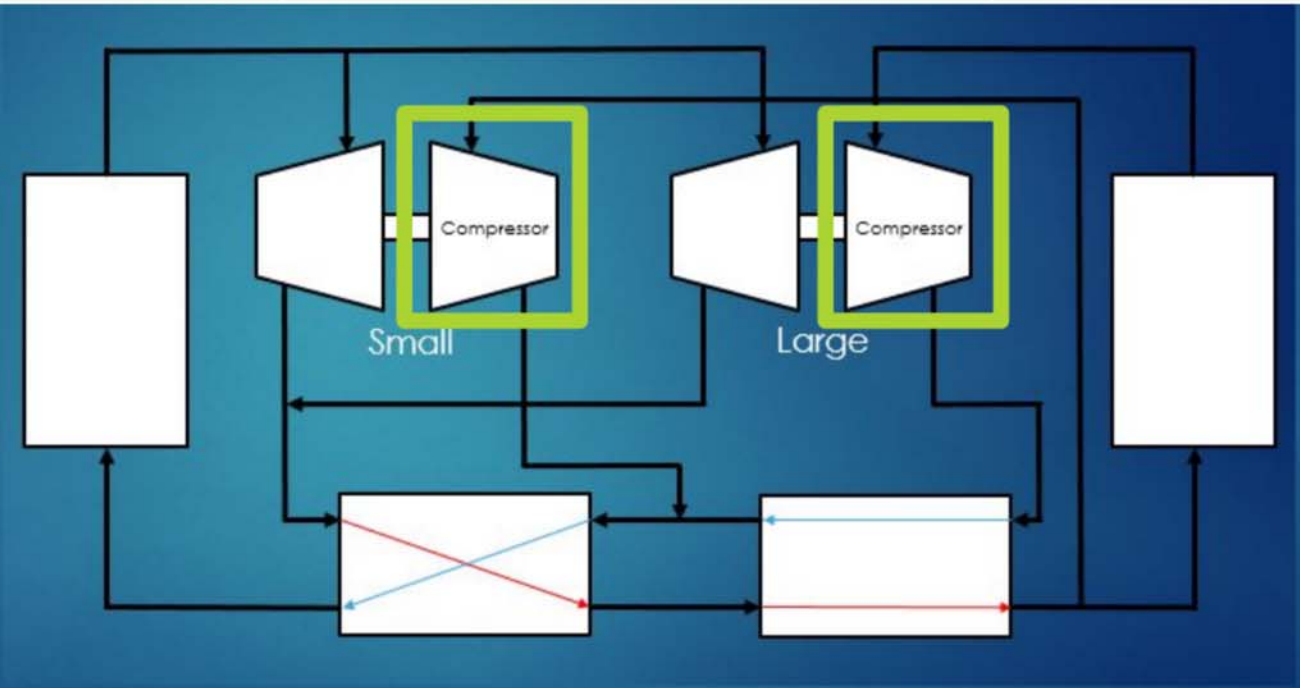
Heat Exchanger Sizing

Set Value	Variable	Equation
Mass Flow Rate	Discharge Coefficient	
Cold Outlet Temperature	Heat Transfer Coefficient	



Compressor Sizing

Set Value	Variable	Equation
Mass Flow Rate	Swept Volume	
Outlet Temperature	Intercooling Temperature	



Thermal System Overview

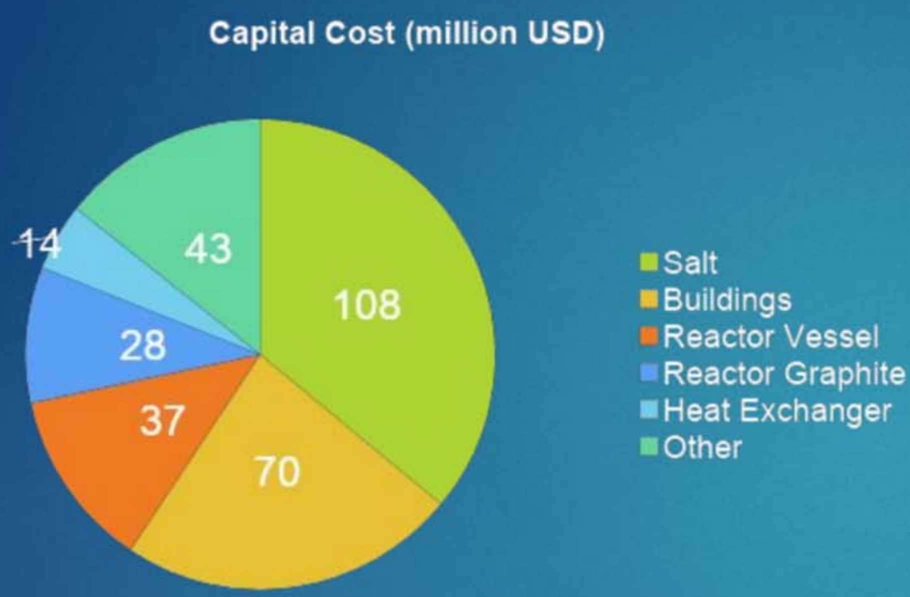
Parameter	Value
Power Out	200 MWe
Heat Required from Reactor	480 MWt
Thermal Efficiency	41%
System Mass Flow Rate	2825 kg/s
Minimum Pipe Thickness	40 mm

ECONOMIC ANALYSIS

Economic Assumptions

- 30-year loan
- 12% interest rate
- 90% capacity factor

Reactor Economics



Total Capital: $240 million
Total Capital Annual: $39 million

Total Operating Annual: $54 million

Total Annual: $93 million

Fuel Reprocessing Economics

Capital Costs

Total Equipment Cost: $2.16million
Total Building Cost: $12.8 million
Total Building Annual: $2 million

Annual Operating C

Annual Materials Cost: $0.5 mil
Total Operating Annual Cost: $

Total Annual Cost: $3 million

Thermal Cycle Economic Analysis

Total Equipment Cost: $33.2 million
Total Building Cost: $209 million
Total Building Annual: $34 million

Economic Analysis

System	Annualized Capital Costs	Operation & Maintenance Costs	Overall Annual Cost
Thermal Loop	$28 million	$6 million	$34 million
Reactor Loop	$33 million	$60 million	$93 million
Fuel Reprocessing	$2 million	$1 million	$3 million
Total Annual Cost		$148 million	
Cost of Electricity		8.7 ¢/kW-hr	

Acknowledgements

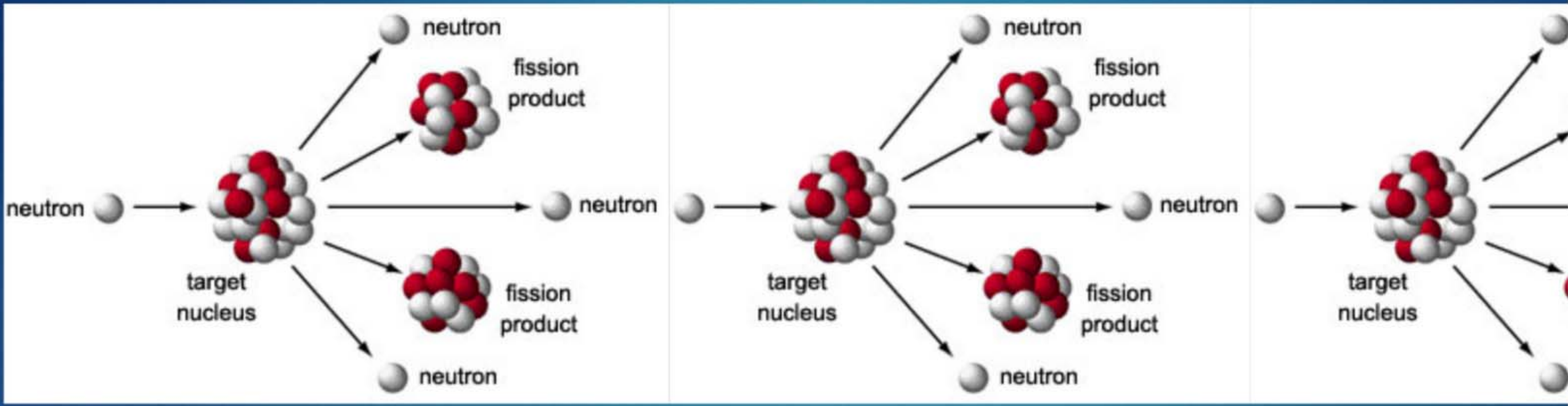
- Sigval Berg, US Navy, UniStar Nuclear Energy, INPO, WANO
- Profs. VanAntwerp and Heun, Calvin College
- Profs. Skutnik and Chvala, University of Tennessee
- Stephen Theron, Flownex
- John Kutsch, Thorium Energy Alliance

QUESTIONS

http://www.theenergycollective.com

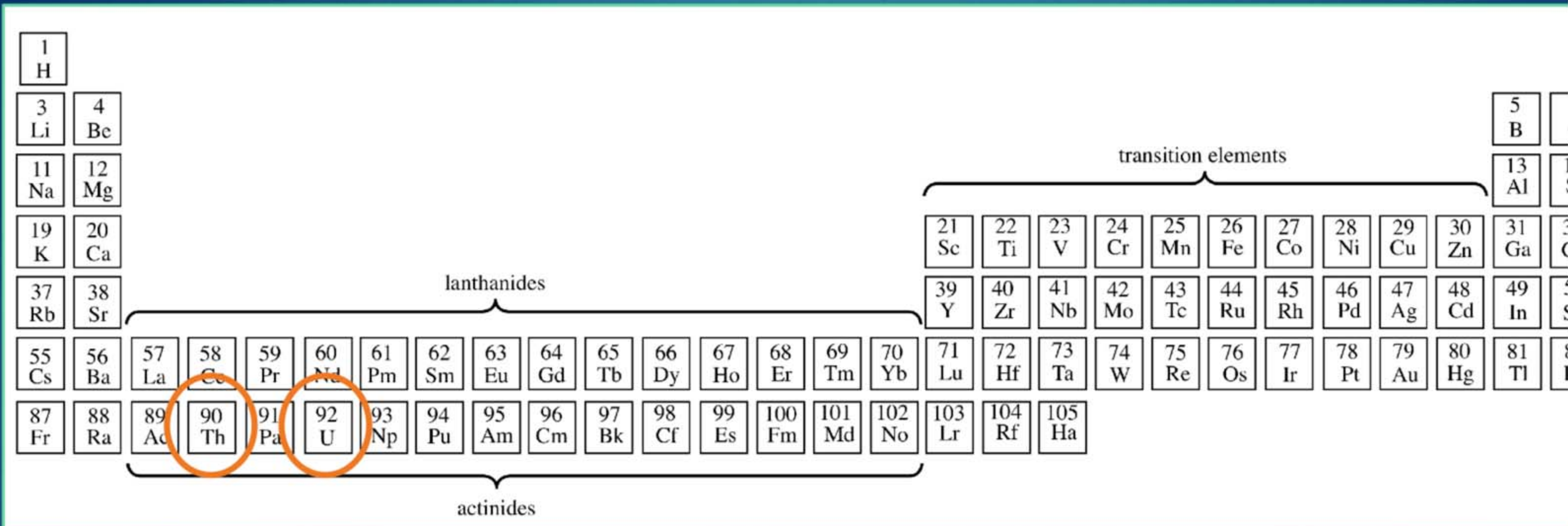
APPENDIX

Appendix: Nuclear Fission



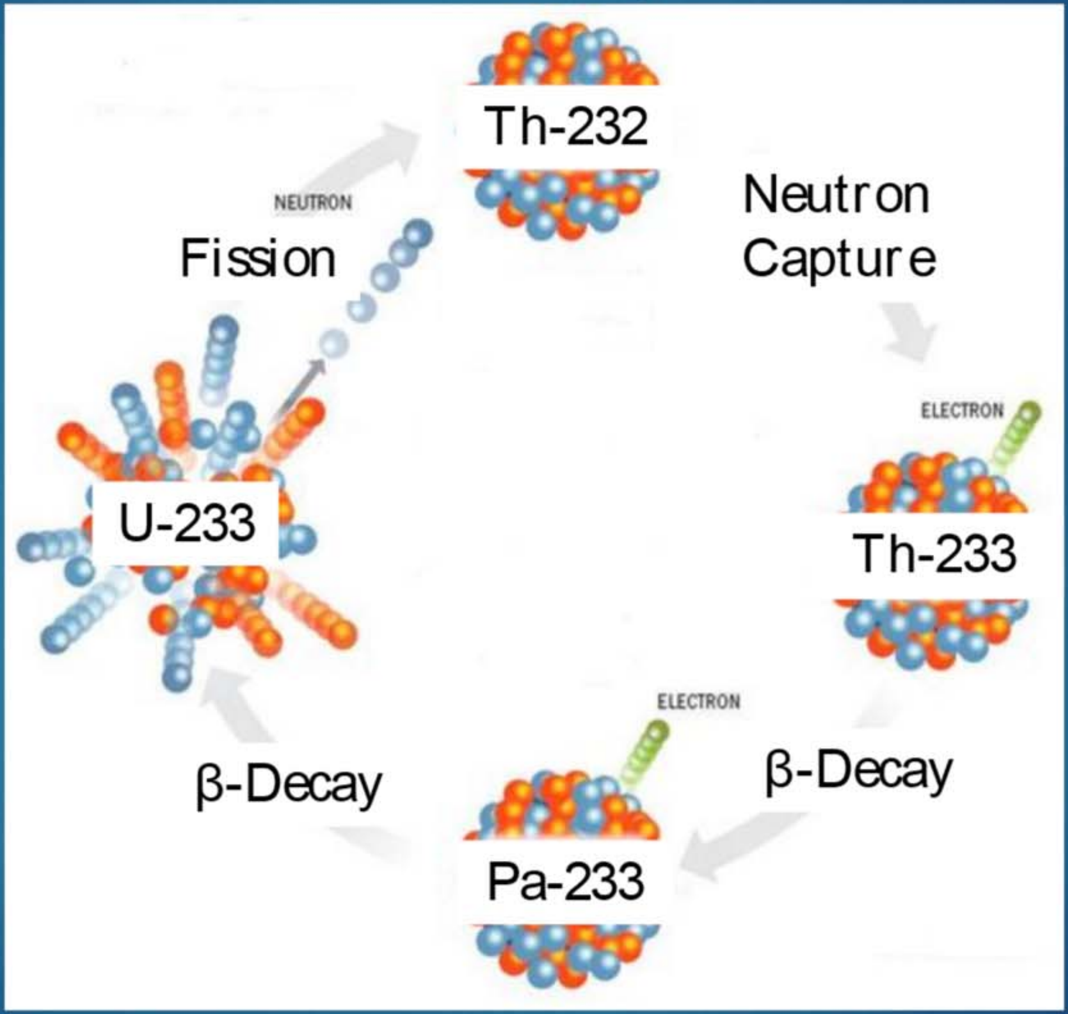
http://www.atomicarchive.com

Appendix: Nuclear Fuels



http://www.met.reading.ac.uk

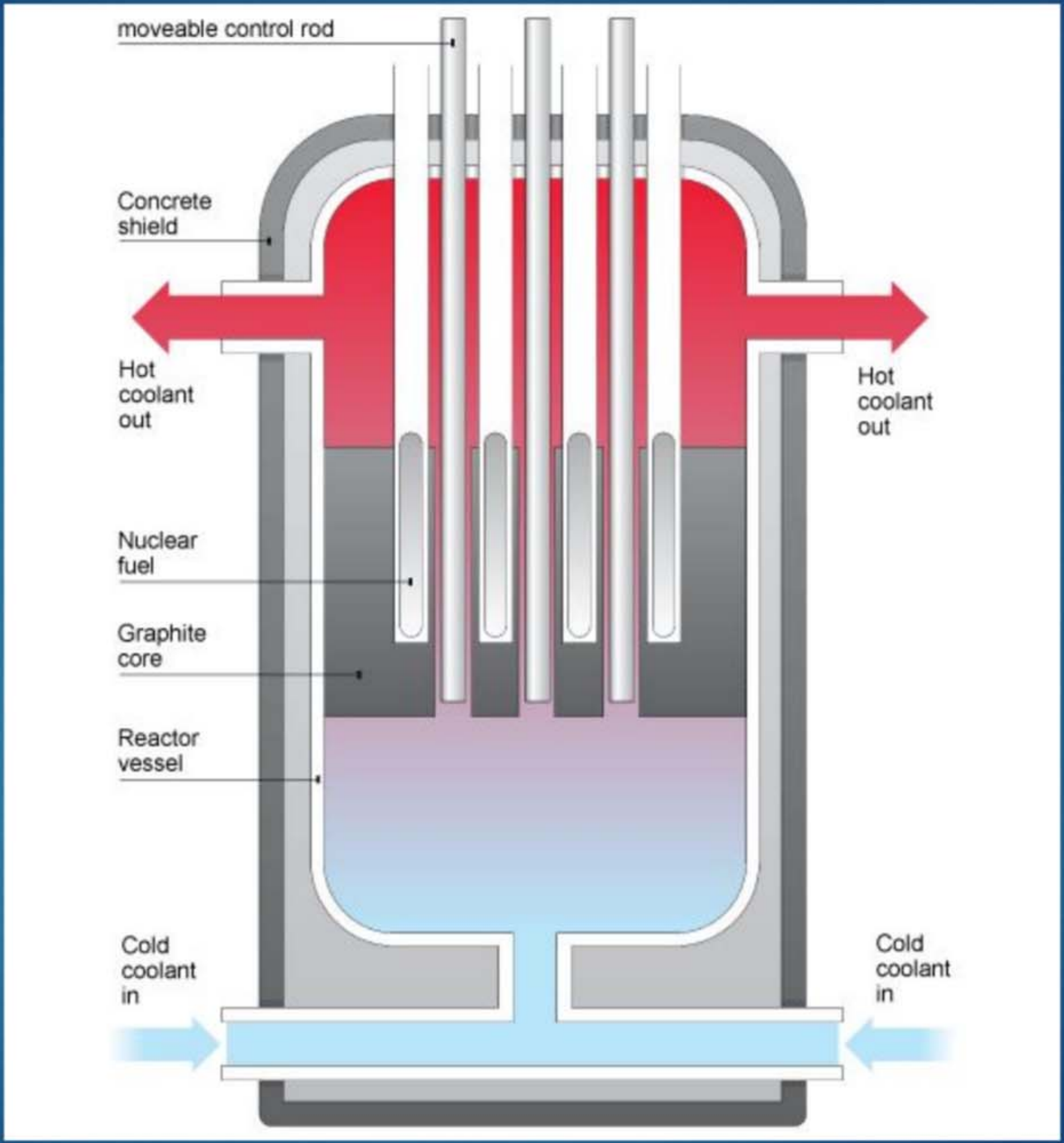
Appendix: Thorium Fuel Cycle



http://www.energyfromthorium.com

Appendix: Nuclear Reactors

- Fuel
- Moderator
- Control rods
- Coolant
- Containment



http://www.bbc

Appendix: Fuel Reprocessing

Notes:

- Flow rate is approximately 1 m^3/day or 1000 L/day
- Total volume recycle in 10 days
- Drain tank provides safe storage of the salt during maintenance operations
- The estimated plant capital costs for a fully developed MSBR are about the same as those for light-water nuclear power station (ORNL)
- Side stream of the primary salt is continuously processed to remove Pa, to recover the bred U, and to adjust the fissile content
- Tritium, xenon, and krypton are sparged from the circulating primary salt by helium introduced in a side stream by a bubble generator and subsequently removed by a gas separator.

Appendix: Fuel Reprocessing

<u>Advantages of single fuel over two fuel:</u>

- Higher conversion ratio
- Only need to replace graphite from core due to exposure limitations instead of entire reactor assembly
- Does not depend on the integrity of the graphite "plumbing" of the reactor vessel
- Radiation damage to graphite during reactor exposure leads to dimensional changes in graphite which is easier to accommodate in single fluid reaction

Appendix: Fuel Reprocessing

Two-Fluid MSBR

Blanket

- Contains salt and Thorium

Core

- Contains salt and uranium

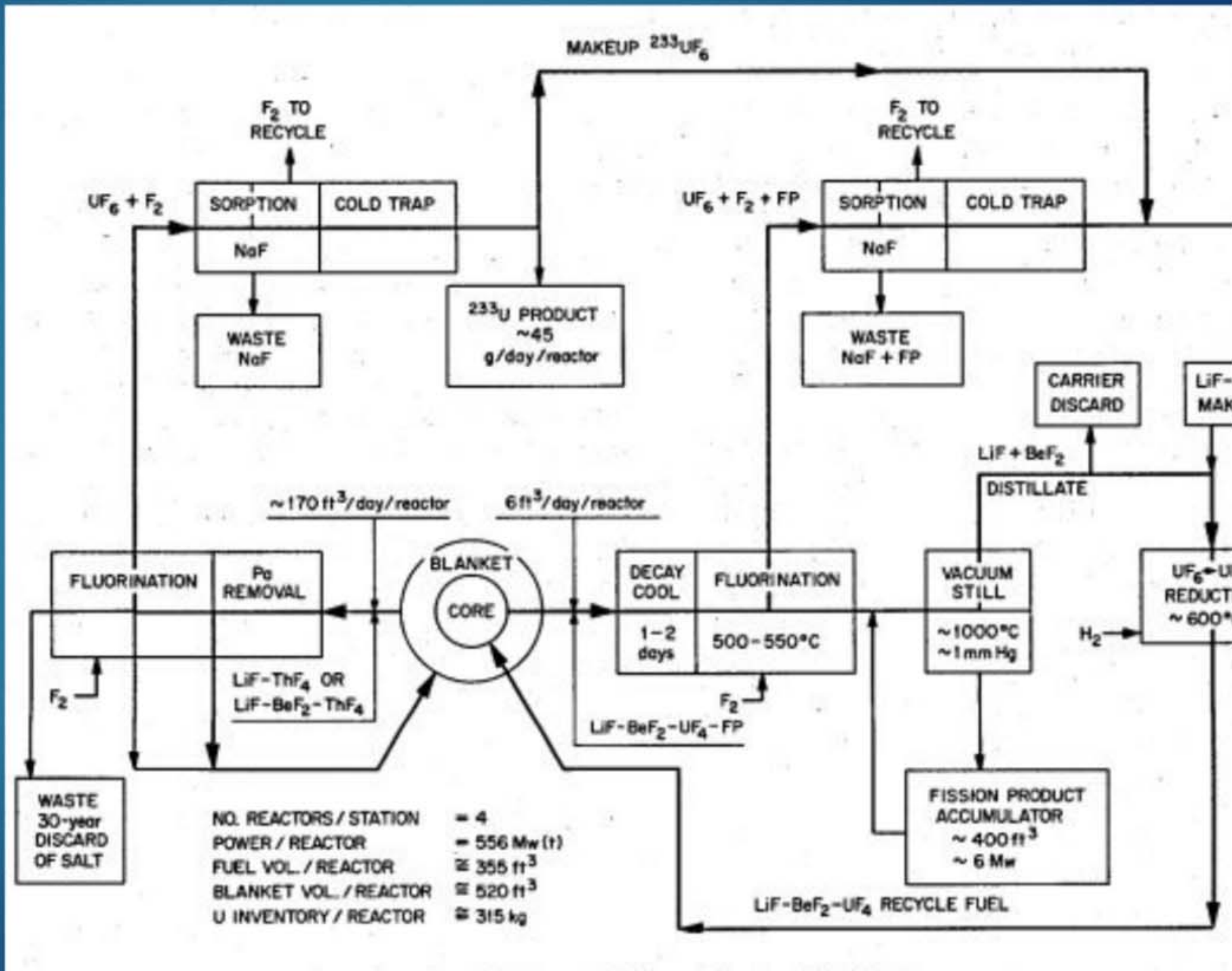
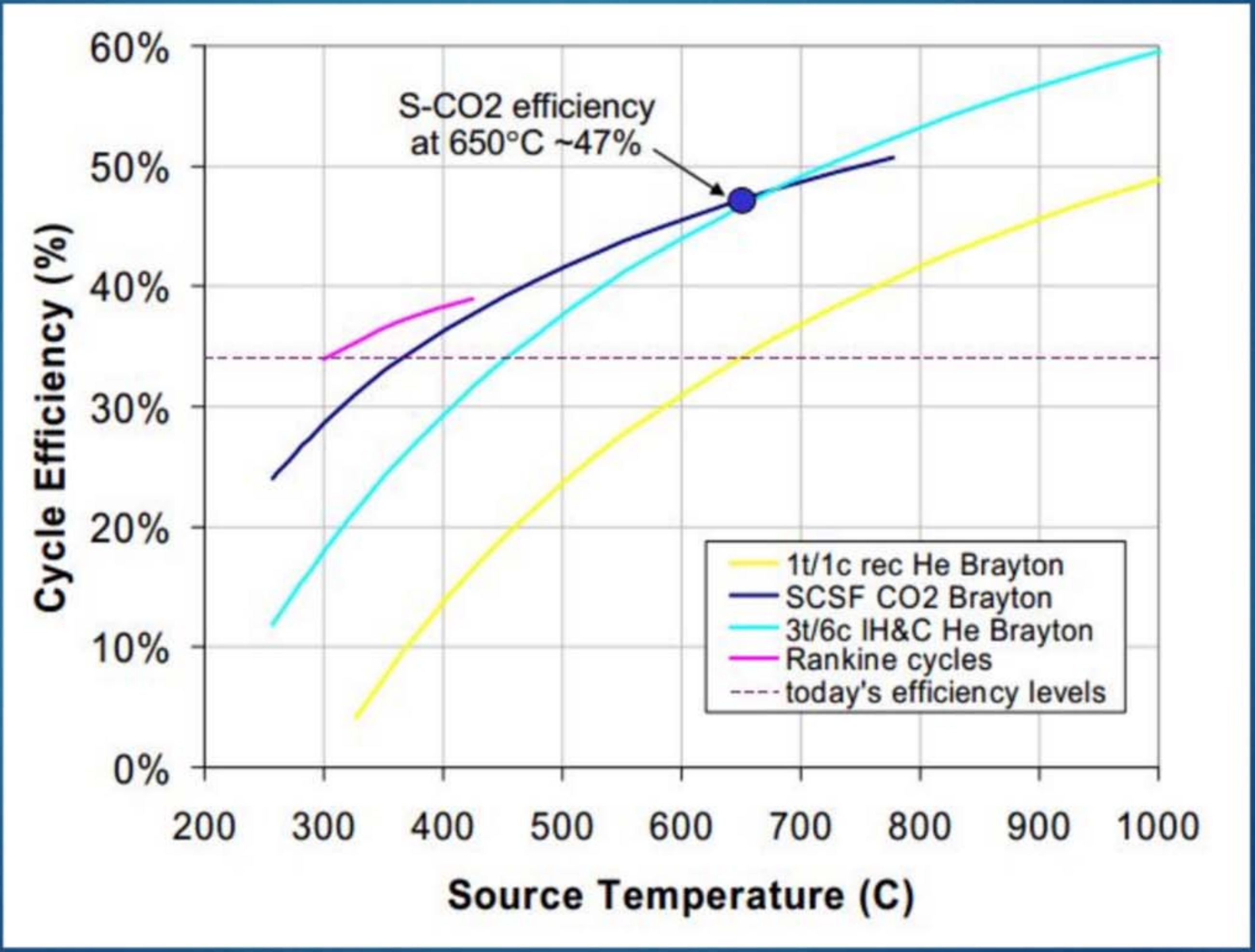


Fig. 4.13. Processing Diagram for Two-Fluid MSBR.

http://moltensalt.org/references/static/downloads/pdf/ORNL-4528.pdf

Appendix: Thermal Efficiencies of Heat Transfer Fluids

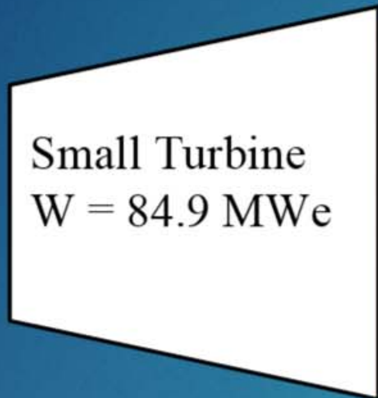


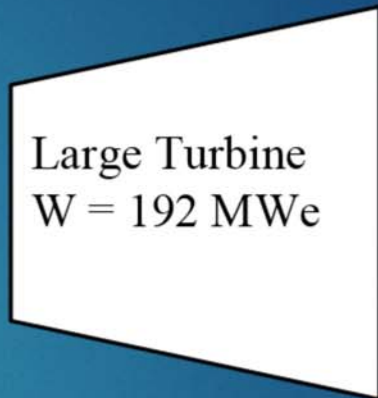
http://prod.sandia.gov/techlib/access-control.cgi/2011/112525.pdf

Appendix: Flownex Sizing Variables

Set Value	Optimized Variable
Turbine Power Out	Discharge Coefficient
Reactor Outlet Pressure	Flow Admittance
Heat Exchanger Mass Flow Rate	Discharge Coefficient
Heat Exchanger Cold Stream Outlet Temperature	Heat Transfer Coefficien
Compressor Mass Flow Rate	Swept Volume
Compressor Outlet Temperature	Intercooling Temperatur

Appendix: Turbine Sizing Values





Inlet pressure	11.9 MPa
Outlet pressure	5.62 MPa
Inlet temperature	675℃
Mass flow rate	825 kg/s
Isentropic efficiency	80%

Inlet pressure	11.9
Outlet pressure	5.62
Inlet temperature	675
Mass flow rate	199
Isentropic efficiency	70%

Appendix: Heat Exchanger Sizing Values

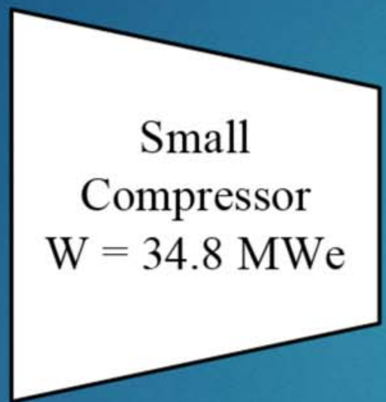
High Temp Heat Exchanger

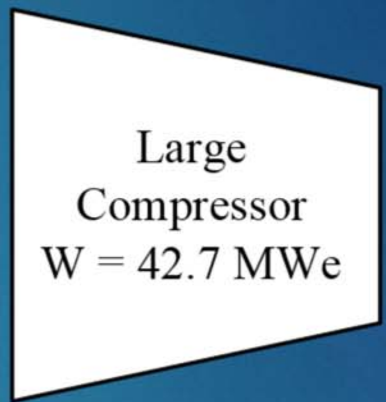
Heat Transfer Coefficient	3760 W/m^2-K
Heat Transfer	1420 MWt

Low Temp Heat Exchanger

Heat Transfer Coefficient	18
Heat Transfer	6

Appendix: Compressor Sizing Values





Inlet pressure	5.10 MPa
Outlet pressure	4.84 MPa
Mass flow rate	485 kg/s
Isentropic efficiency	80%

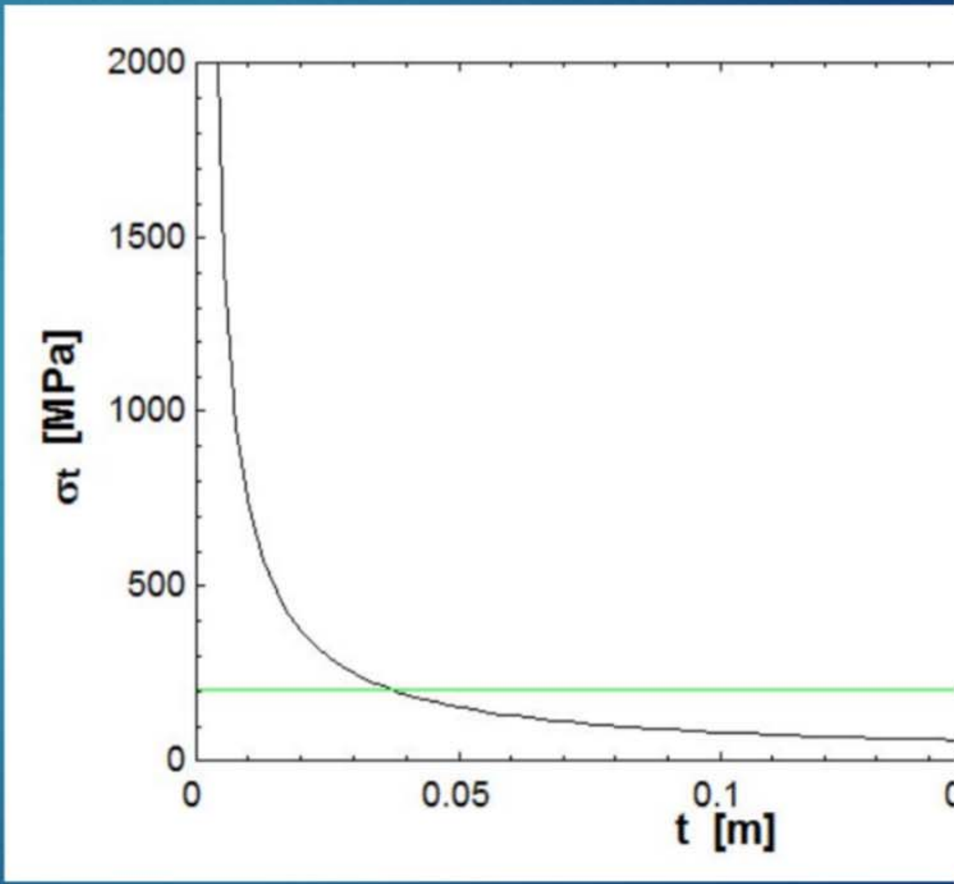
Inlet pressure	4.86 MPa
Outlet pressure	14.2 MPa
Mass flow rate	2330 kg/s
Isentropic efficiency	70%

Appendix: Pipe thickness

- Max Allowable Pressure = 200 MPa
  - Yield Strength of material
  - Approximately after 10 years at 675℃

$$\sigma_t = \frac{a^2 p_i}{b^2 - a^2}\left(1 + \frac{b^2}{\rho^2}\right)$$

- a = inner diameter
- b = outer diameter
- ρ = boundary condition
  - = a with only internal pressure



Appendix: Thermal Loop Cost Models

Component	Cost Model
Turbine	
Compressor	
Heat Exchanger	

Appendix: Thermal Cycle Detailed Cost

Component	Capital Cost
Small Turbine	$2.85 million
Large Turbine	$4.53 million
Small Compressor	$1.17 million
Large Compressor	$9.04 million
Heat Recovery 1	$3.89 million
Heat Recovery 2	$2.63 million
Heat Rejection	$9.10 million
Purchased Equipment Cost	$33.2 million
Total Building Cost	$ 209 million