HEER: Liquid Salt Thermal Reactor Concept

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Agenda

- Project Overview (2)
- Material Selection (4)
- Core Design (4)
- Performance (2)

Project Overview

HEER Project Goals

- Develop a High Efficiency and Environmentally-friendly Nuclear Reactor (HEER) to address the needs of electricity, drinkable water, and hydrogen production
- Project supported by Masdar Institute of Science and Technology (Abu Dhabi, UAE) from 2007-2009
- Medium-sized reactor (1000 MWt)
- Ready for deployment worldwide → additional proliferation resistance (infrequent refueling)
- Concepts:
  - Liquid Salt Thermal Reactor
  - Annular-Fueled Superheat BWR
  - High power density IRIS

The Future MIST campus (rendered image)

Liquid Salt Thermal Reactor

- Cool with liquid salt to avoid pressurized primary side
- Self-moderating **hydride fuel** to avoid additional moderator volume, i.e. graphite rods
- Medium enrichment (19.9 wt%) U for ~10 yr cycle length
- Supercritical CO_2 secondary side for high efficiency (45.7%)

Power Rating	1000 MWt (457 MWe)
Cycle Efficiency	45.7%
Peak Fuel Temperature	720ºC
Coolant Outlet Temperature	570ºC
Primary Coolant	Liquid Salt ($NaF\text{-}BeF_2$)
Secondary Coolant	Supercritical CO_2
Fuel Type	Hydride ($U_{0.31}ZrH_{1.6}$)
Flow Type	Integral (Dual-Free Level)

Material Selection

Salt Selection Criteria

- Set up property importance criteria and weighting factors
- Point system based on rankings for each property among fluoride salts from LS-VHTR study [Ingersoll, 2006]
- Chloride salts discounted due to high thermal capture of Cl (30.5 b)

Desired property	Weighting factor
1. low melting temperature	2
2. high heat capacity	1.5
3. low viscosity	1.5
4. high thermal conductivity	1
5. low thermal capture cross section	1
6. high moderation	1
7. low volume expansion coefficient	1

[Forsberg et al., 2003]
[Williams et al., 2006]

Fluoride Salt Properties at 700°C

Scoring (color key): 5 (best), 4, 3, 2, 1

Salt	MP [°C]	ρ*Cp [cal/cm^3°C]	Visc. [cP]	K [W/mK]	n Cap. Ratio[1]	Mod. Ratio[2]	Vol. Exp. Coeff.	total score
$LiF-BeF_2$	460	1.12	5.6	1	8	60	2.52E-04	25.5
$NaF-BeF_2$	340	1.05	7	0.87	28	15	1.84E-04	23
$LiF-NaF-BeF_2$	315	0.98	5	0.97	20	22	2.25E-04	32
$LiF-ZrF_4$	509	0.9	>5.1	0.48	9	29	2.99E-04	9
$NaF-ZrF_4$	500	0.88	5.1	0.49	24	10	2.96E-04	5
$KF-ZrF_4$	390	0.7	<5.1	0.45	67	3	3.17E-04	9
$RbF-ZrF_4$	410	0.64	5.1	0.39	14	13	3.11E-04	9.5
$LiF-NaF-ZrF_4$	436	0.84	6.9	0.53	20	13	3.12E-04	3
LiF-NaF-KF	454	0.91	2.9	0.92	90	2	3.61E-04	12
LiF-NaF-RbF	435	0.63	2.6	0.62	20	8	3.01E-04	12.5
water (300°C)	0	0.986	0.09	0.54	75	246	3.30E-03	

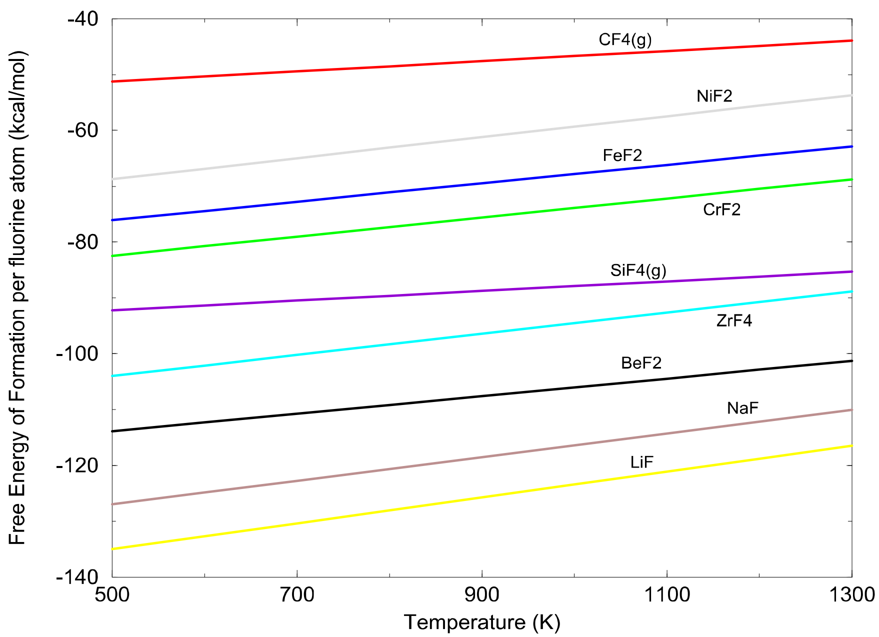
[1] per unit volume, relative to graphite
[2] as calculated in [Williams et al., 2006]

- $LiF-NaF-BeF_2$ winner but $NaF-BeF_2$ much cheaper (avoids Li^7 enr.)

[Williams et al., 2006]

SiC Cladding

- Solid monolith surrounded by reinforced SiC fibers to add strength
- CVD carbon coating for salt compatibility [Sridharan, 2008]
- Strength loss saturates quickly below 1000ºC (max fuel temp = 720ºC)
- Thermal conductivity drops to 4 W/mK at high burnup (this was the assumed *K* for conservatism)



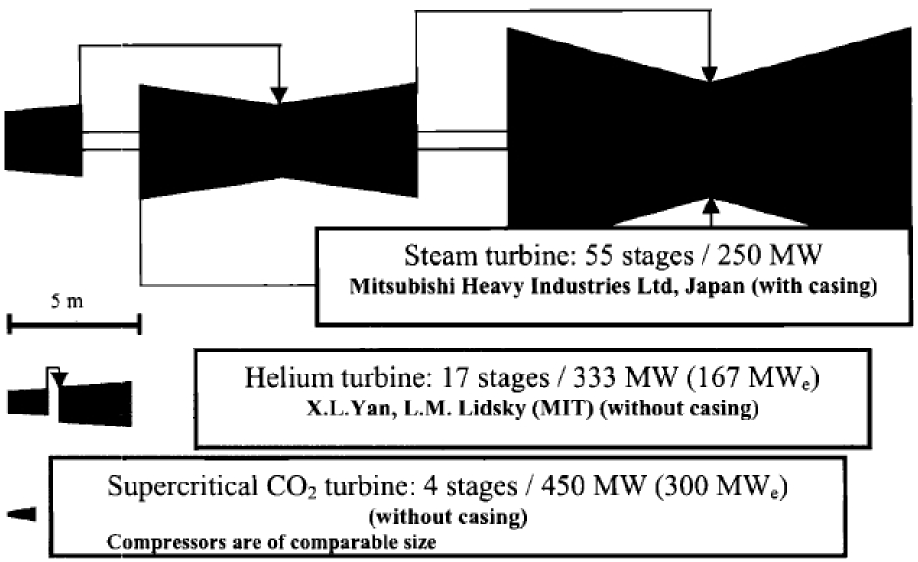
[Peterson, 2003]

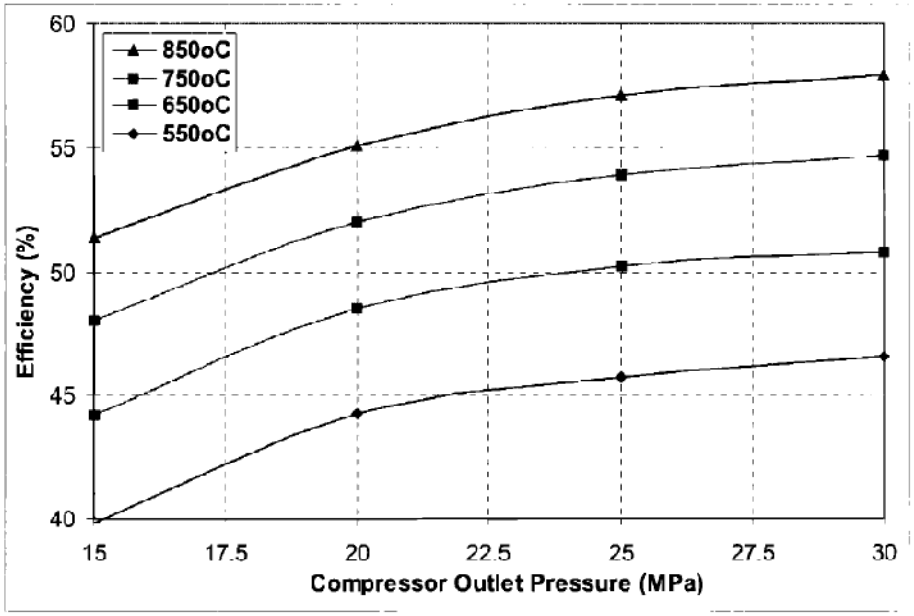
Triplex SiC cladding tube (monolith, fiber composite, and barrier coating are all SiC)

[Carpenter, 2006]

Supercritical CO_2

- Recompressive SCO_2 Brayton cycle
- Core outlet temperature of 570ºC (set to minimize ΔP), 20 MPa compressor outlet pressure → 45.7% cycle efficiency
- Very compact turbine (1.5 m rotor for 300 MWe), lower capital costs





[Dostal, 2004]

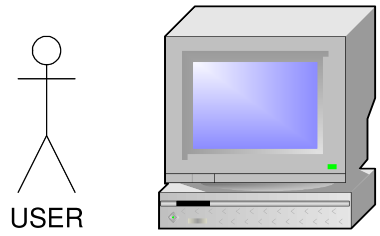
Core Design

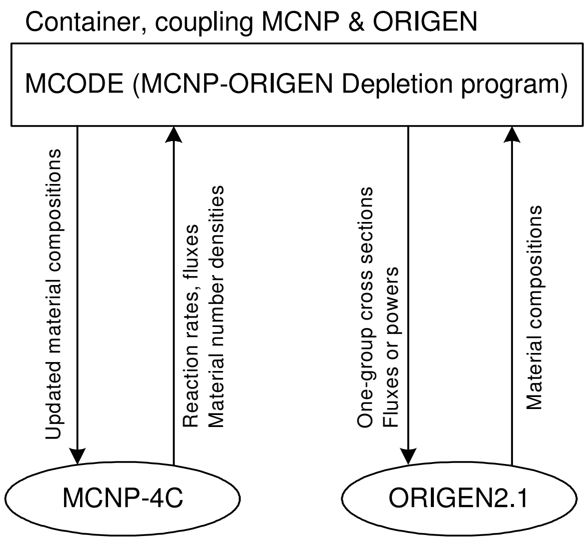
Computational Tools

- Reactivity:
  MCNP + CASMO

- Burnup:
  MCODE (MCNP + ORIGEN)

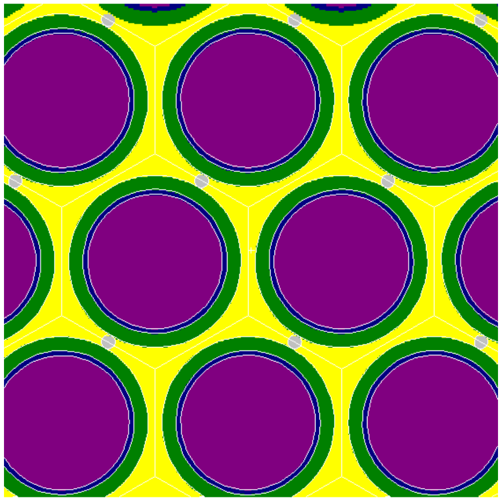
- Thermal Hydraulics:
  iterative MATLAB scripts based on existing correlations

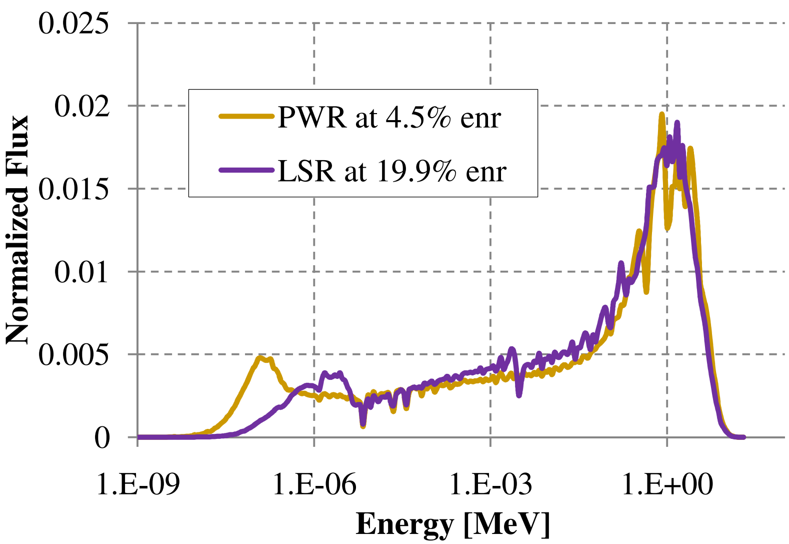




$U_{0.31}ZrH_{1.6}$ Fuel Pins

- TRIGA fuel – large prompt negative T_{fuel} feedback, high thermal conductivity (18 W/mK)
- Hydrogen diffuses out of fuel as T_{fuel} increases beyond limit
- 750ºC recommended T_{CL} design limit [Simnad, 1981], set T_{CL} = 720ºC
- Thin fuel pins (0.7 cm diam) to reduce maximum T_{CL}

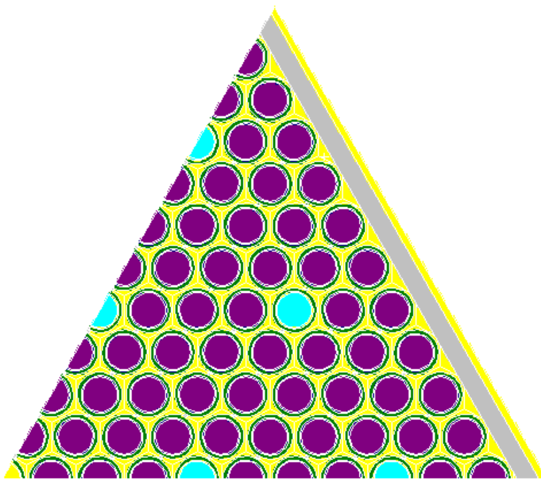


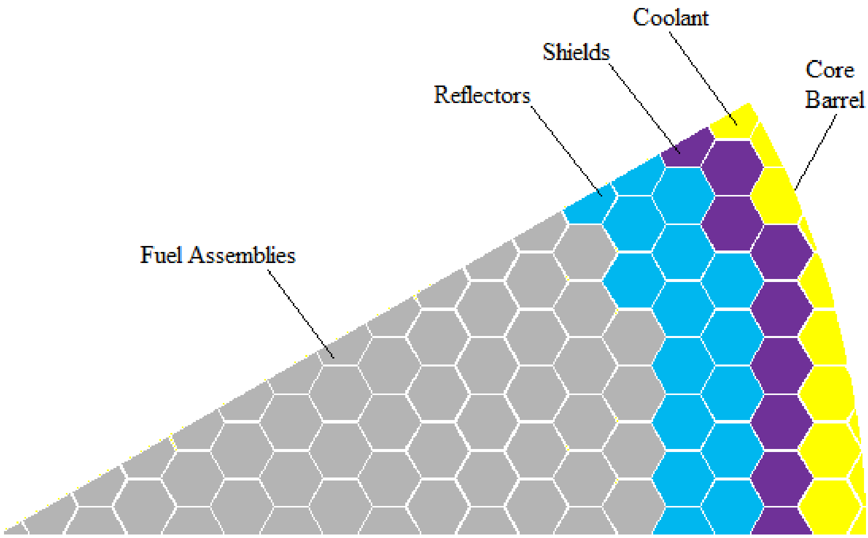


[Olander, 2007]
[Simnad, 1981]

Assembly and Core

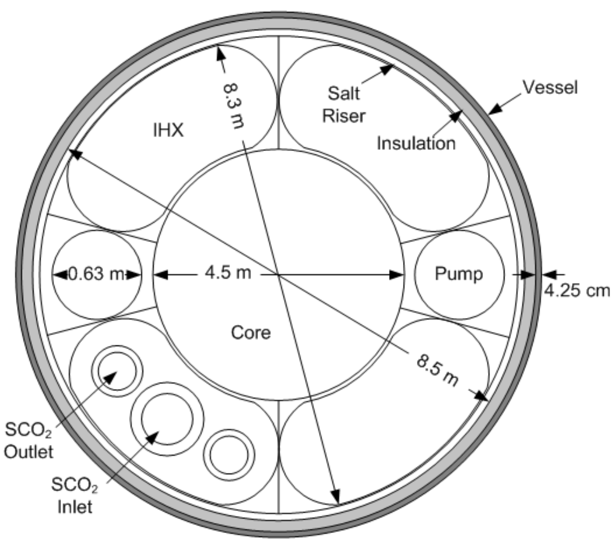
- Pins per assembly limited by assembly mass (500 kg)
- Wire wrap with Hastelloy cans to keep orificing option
- 18 B_4C control rods yield roughly same worth as 24 Ag-In-Cd rods in PWR assembly (1.02 assembly ppf)
- Integral burnable poison to control excess reactivity and core radial power profile – 0.25 wt% Gd had least BU penalty (~3-4 MWd/kg)

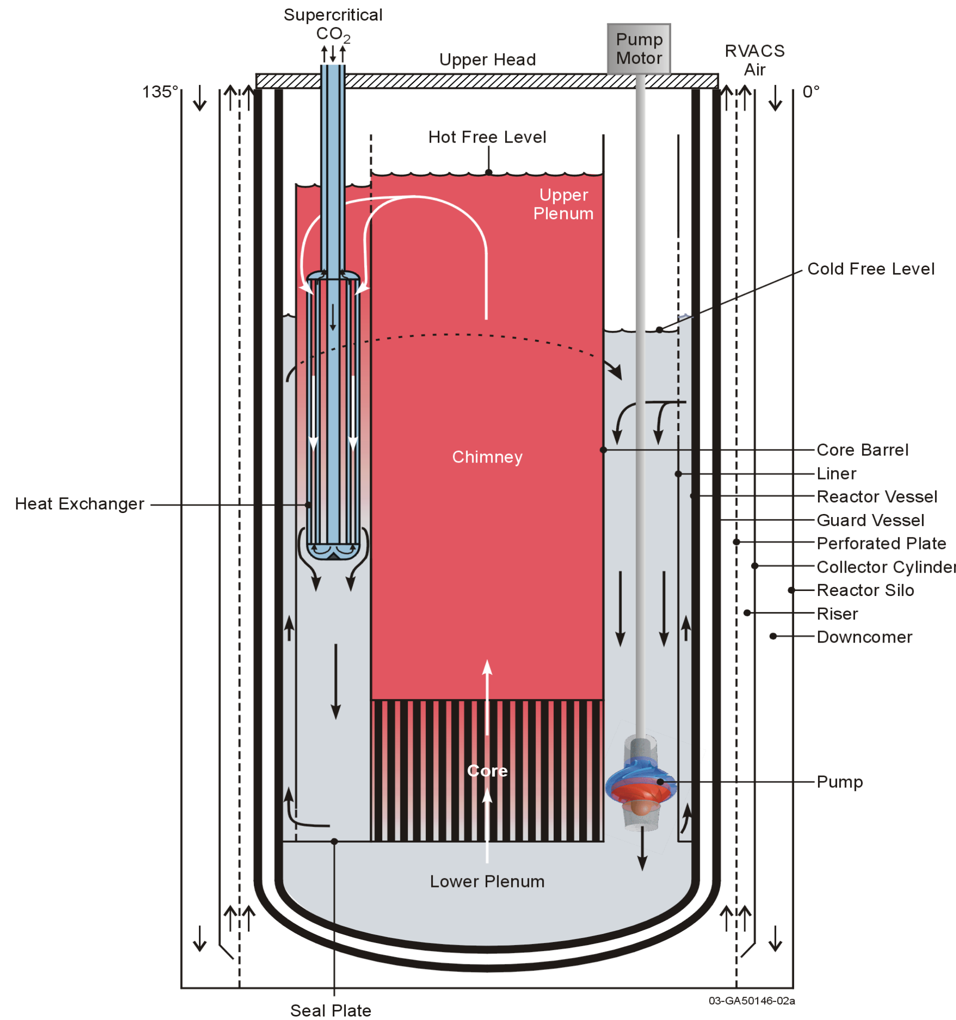




Pool Design

- Integral design to protect against LOCAs
- Vessel diameter small enough to be built off-site and transported via rail or barge
- Dual-free level design allows CO_2 to escape in the event of IHX tube rupture

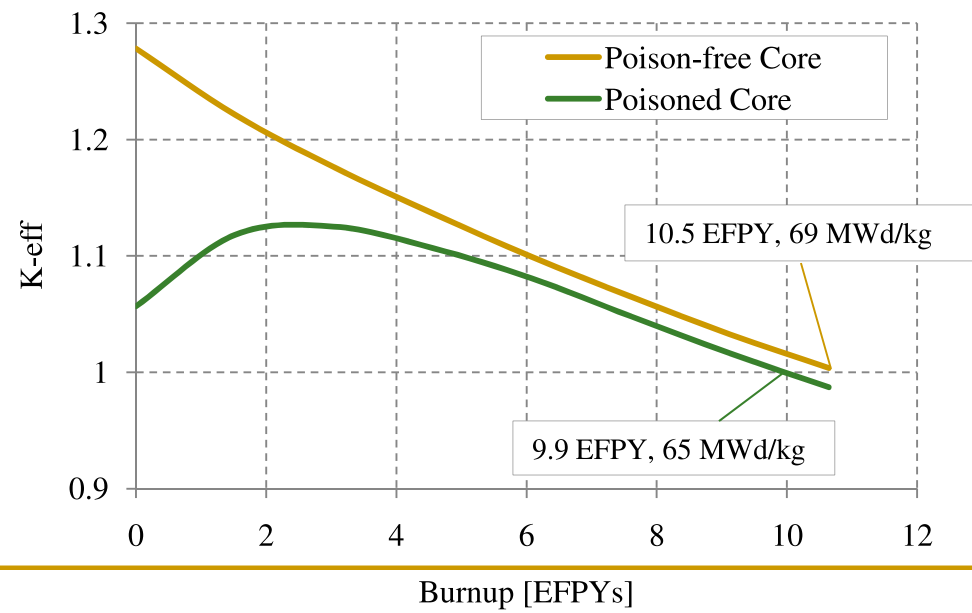




Performance

Burnup Performance

- Single batch → less frequent refueling (fixed 10 EFPYs)
- Infinite pin lattice (poison-free) → BU_d = 98.5 MWd/kg, Q''' = 47 kW/L
- For 1000 MWt core, BU_d ~ 70 MWd/kg, Q''' = 26.4 kW/L mainly due to highly-absorptive Hastelloy cans
- Using spacers (no cans) or SiC cans yields BU_d ~ 95 MWd/kg, Q'''~ 36 kW/L → smaller core diameter (8.5 m → 7.2 m)



Conclusions

- **Proposal of a more traditional design with fluoride salt using hydride fuel rods**
- Spectrum similar to low enriched PWR (can use similar reactivity control methods)
- 10 year single batch cycle feasible with power density ~36 kW/L and ~20 wt% enrichment
- With traditional fuel pin design, Hastelloy cans are a huge neutronic penalty, should consider spacers (which precludes orificing) or inert can material (SiC)
- More data is needed on salt/cladding corrosion, multilayer cladding performance, materials for SCO_2, fabrication feasibility of SiC cans, high burnup hydride fuel performance modeling
- **<u>Bottom line</u>: one of many options for high temperature salt application**

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Backup Slides

Geometry

Pin

P/D	1.08
Pitch [cm]	0.756
Pin Diameter [cm]	0.700
Clad Thickness [cm]	0.057
Gap [cm]	0.020
Fuel Diameter [cm]	0.546
Wire Wrap Diameter [cm]	0.056

Assembly

Rings per Asse.	11
Pins per Asse.	331
Can Thickness [cm]	0.3
Inter-Assembly Gap [cm]	0.1
Active Fuel Height [cm]	400
Inner Duct Flat-to-flat [cm]	13.85
Outer Duct Flat-to-flat [cm]	14.45
Inter-Assembly pitch [cm]	14.65
Assembly Area (incl. duct) [cm^2]	180.84

Core

Fuel Assemblies per Core	511
Linear Power [kW/m]	1.57
Volumetric Power [kW/L]	26.35
Specific Power [kW/kgHM]	18.01
1/12 Core Fuel Volume [L]	1244.3
Power (1/12 core) [MWt]	83.44
Power (full core) [MWt]	1001.23
Discharge Burnup [MWd/kg]	69
Cycle Length [EFPY]	10.49

Backup Slides (2/8)

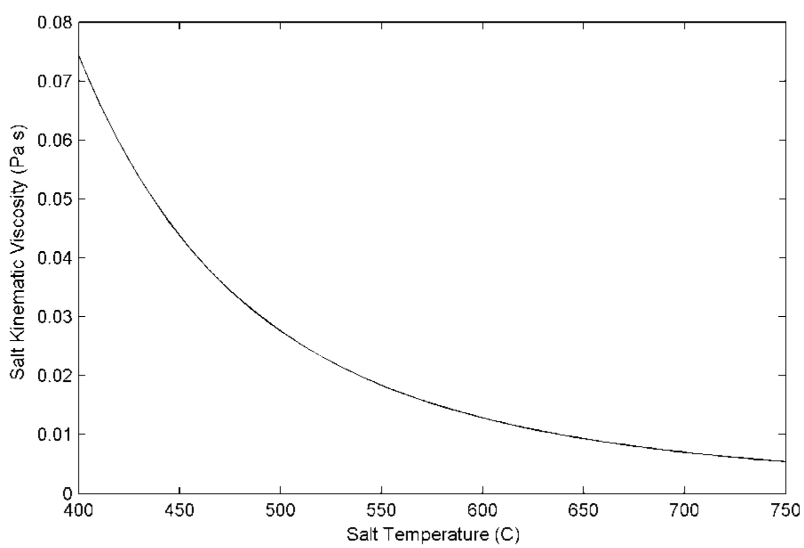
Core Thermal Hydraulics

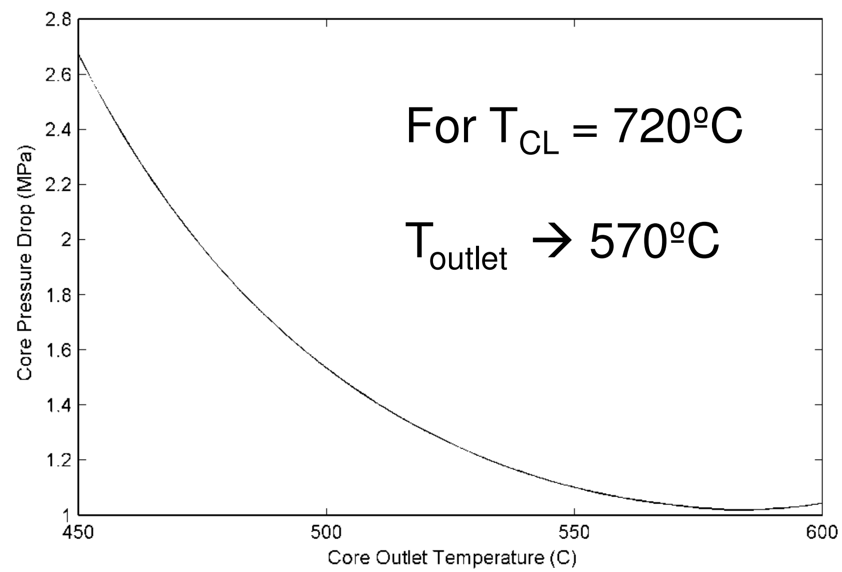
- Core geometry, T_{CL}, and q'(z) fixed
- Varied outlet temperature (T_o) and to minimize ΔP

Competing effects:

- For a fixed q'(z) and T_{CL}, a higher T_o → ΔP increases
- But salt viscosity decreases with T_o → ΔP decreases

$$q'(z) = \frac{T_{CL} - T_{bulk}}{R}$$

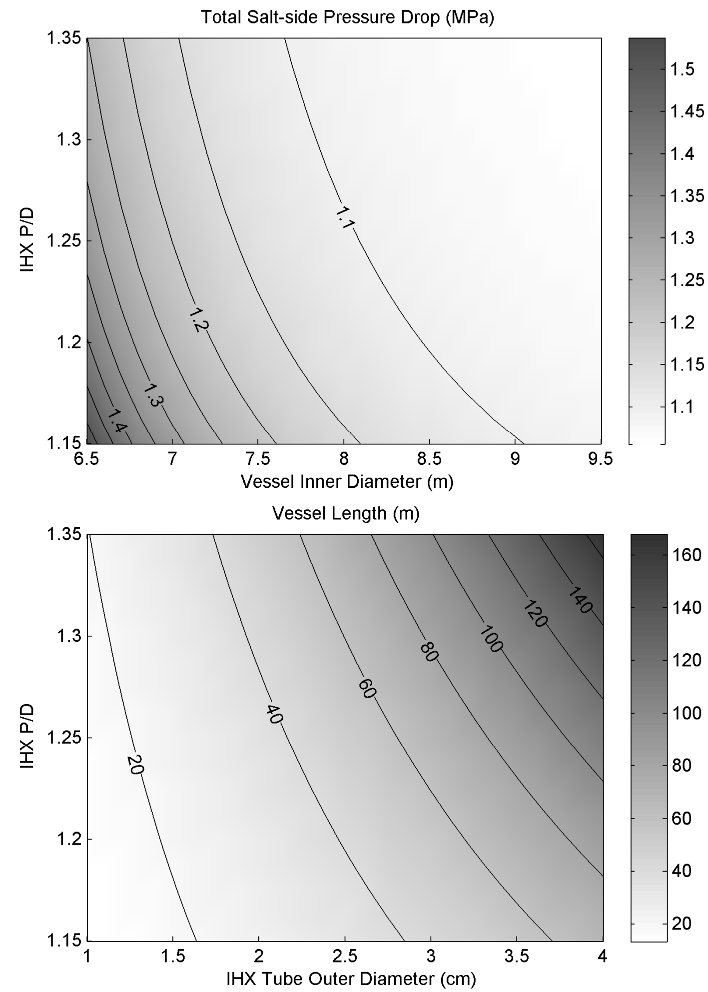




Backup Slides (3/8)

IHX and Vessel Diam. Optimization

- For this optimization, the core inlet and outlet temperature and salt mass flow rate were held constant at the values determined by the core optimization
- Vessel Diameter was varied, as was the IHX tube outer diameter and pitch to diameter ratio (P/D)
- Tube thickness in the IHX was adjusted to maintain safe material stress limits
- Heat exchanger length was determined using ε -NTU method
- This length was used to determine many important parameters such as:
  - Total pressure drop
  - Pump diameter
  - Vessel Length
  - Power Cycle Efficiency
  - SCO_2 pressure drop through IHX
- Using these techniques, a design was selected, described on next slide



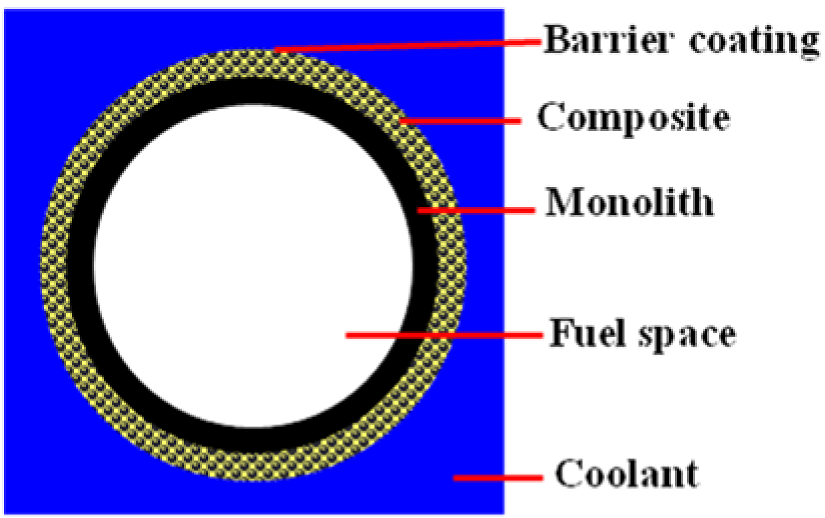
Optimized System Properties

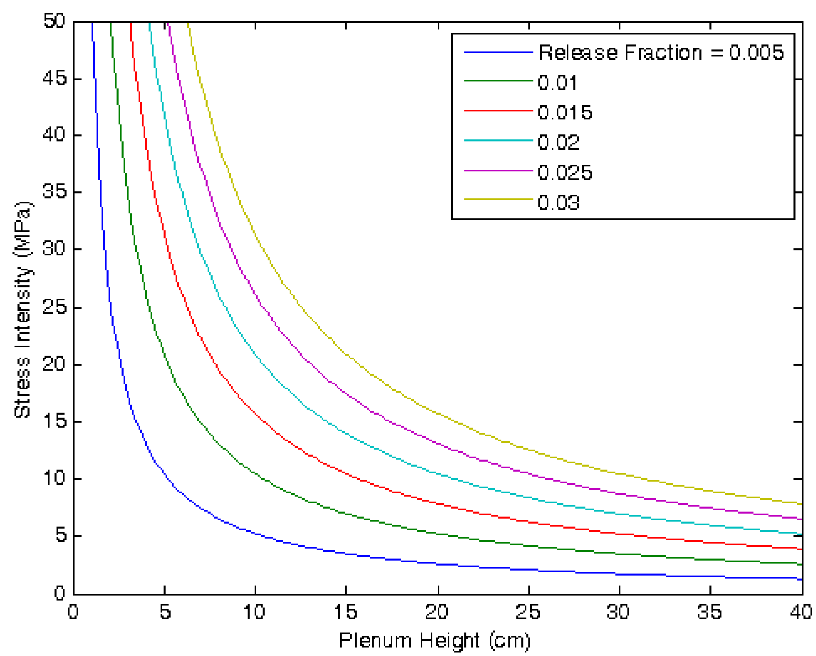
System Optimization Results

Parameter	Value
Optimized Parameters:	
Vessel inner diameter	8.5 m
IHX P/D	1.2
IHX tube outer diameter	1 cm
Code Outputs:	
Vessel length	15.31 m
Margin to IHX voiding	4.1 m
Net Power Output	456.5 MW
SCO_2 pressure drop in IHX	19.6 kPa
Total salt-side pressure drop	1.10 MPa
Reactor vessel thickness	5.5 cm
Pump diameter (for 2 pumps)	0.63 m
IHX tube length	6.89 m
IHX tube thickness	1.7 mm
Net Cycle Efficiency	45.65%
Salt heat transfer coefficient in IHX	645.3 W/m^2K
Salt velocity in IHX	0.26 m/s
Salt Reynolds number in IHX	140
SCO_2 heat transfer coefficient in IHX	2881 W/m^2K
SCO_2 velocity in IHX	4.92 m/s
SCO_2 Reynolds number in IHX	1.31E5

SiC Cladding Performance

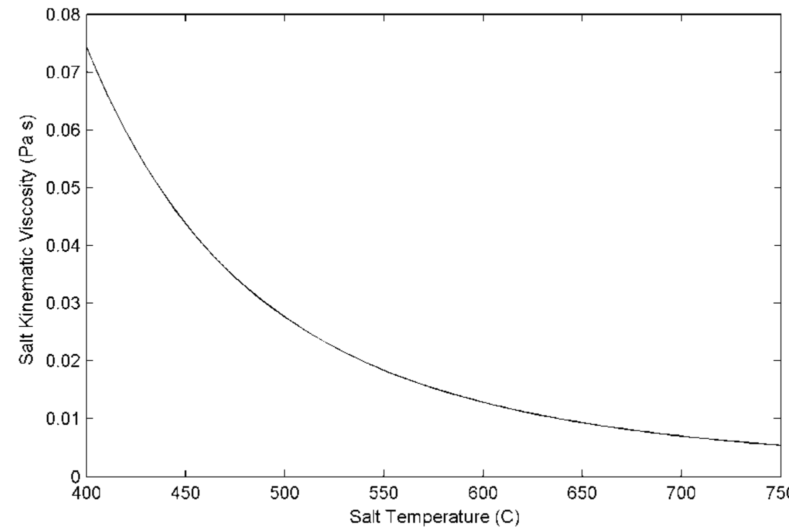
- Pb-Sn-Bi gap wide enough to prevent FCMI at desired burnups [Olander-UC Berkeley]
- FG release main cause of internal stress, unknown for high burnups
- With careful manufacturing tensile strength should be 2-300 MPa minimum; enough to withstand stress intensities of 15-20 MPa





Minimizing Core Pressure Drop

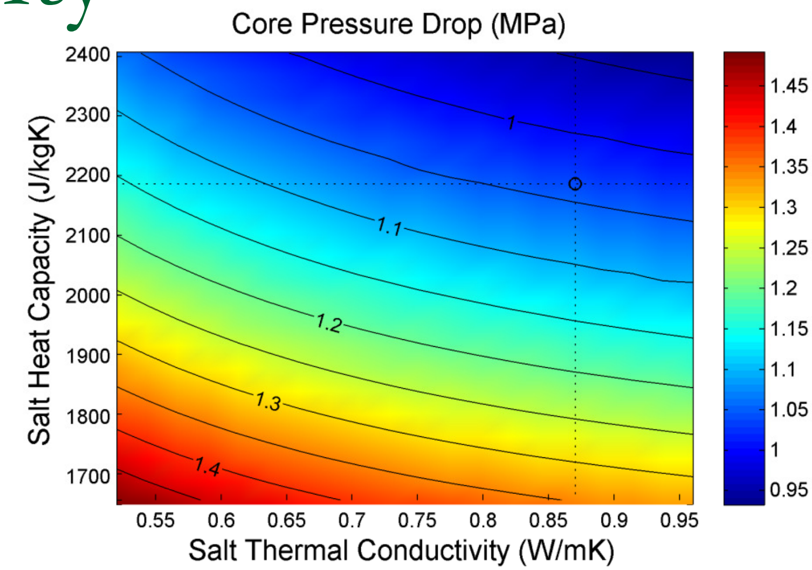
- Given assembly dimensions and linear heat rate, core flow rate is set
- To select the flow rate, core *outlet* temperature and fuel temperature limit were varied.
- Coolant velocity was increased until the peak fuel temperature was below the limit during normal operation.
- Coolant inlet temperature was simultaneously varied to maintain desired core outlet temperature.
- Results for core pressure drop is shown at top right. Given a fuel temperature limit, there is a core outlet temperature that minimizes pressure drop. The plot for 720° C fuel temperature limit is shown at bottom-right.
- Pressure drop is minimized due to temperature dependence of salt viscosity. Higher outlet temperature means higher flow rates but also reduced viscosity. These factors compete.
- For the HEER LSR, 720° C was selected as the maximum fuel temperature, and 570° C as the core outlet temperature.

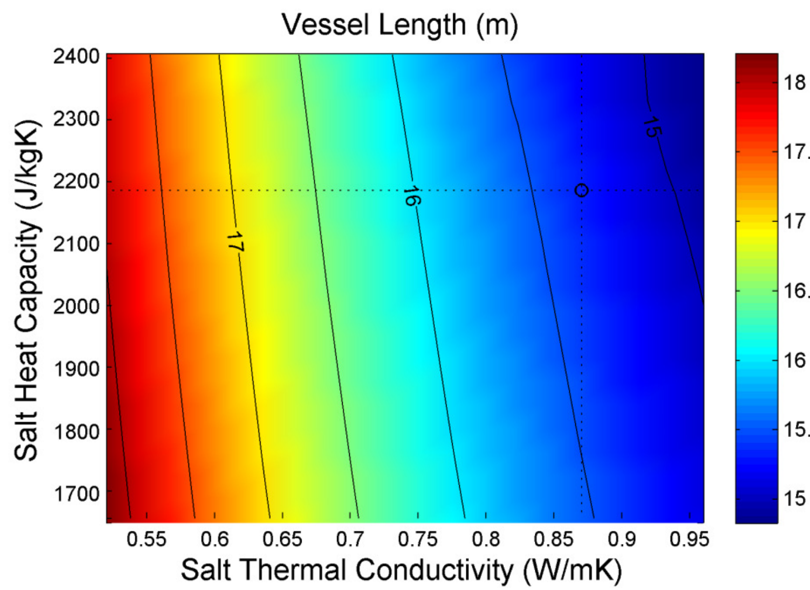


$$q'(z) = \frac{T_{CL} - T_{bulk}}{R}$$

Salt Property Sensitivity

- Since salt properties have not been extensively studied, sensitivity tests were performed.
- Thermal Conductivity was assumed in the previous design to be 0.51 W/mK. Now it is varied between 0.52 and 0.96 W/mK
- Heat Capacity was assumed to be 2186 J/kgK. For the sensitivity study it is varied between 1650 and 2400 J/kgK
- The plots on the right show the effect on core pressure drop and vessel length.
- Vessel length is still within the goals of the design. Worst case is about 18.2m
- Core Pressure Drop suffers more drastically. Worst case is just under 1.5 MPa, 50% greater than the design goal.
- This points to the need for further study of the salt in order to determine the actual values of these properties.





Correlations Used

$NaF\text{-}BeF_2$	
property	correlation
k	Kokhlov
Nu	4.36 for Re < 2300 Gnielinsky for Re > 2300
Nu interpolation	VDI-Warmeatlas
f	Cheng and Todreas
SCO_2	
property	correlation
Nu	Gnielinsky for smooth wall Bergles et al. for ribbed design
f	Todreas and Kazimi