Molten Salt Cooled ENHS (Encapsulated Nuclear Heat Source)-Like Reactors

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Background

- At the present state of lead alloy coolant technology, corrosion of structural materials limits the attainable heat source temperature to ~550^{o}C.

- Sodium could be used as a coolant for the ENHS, but its strong chemical reaction with air and water poses safety concerns. Also, due to the relatively low boiling temperature of ~ 890^{o}C coupled with positive coolant void reactivity, the heat source temperature is also limited to ~ 550^{o}C.

- Molten salts can safely operate at the > 550^{o}C temperature range while at nearly atmospheric pressures and are therefore considered a promising working fluid for transferring high-temperature heat.

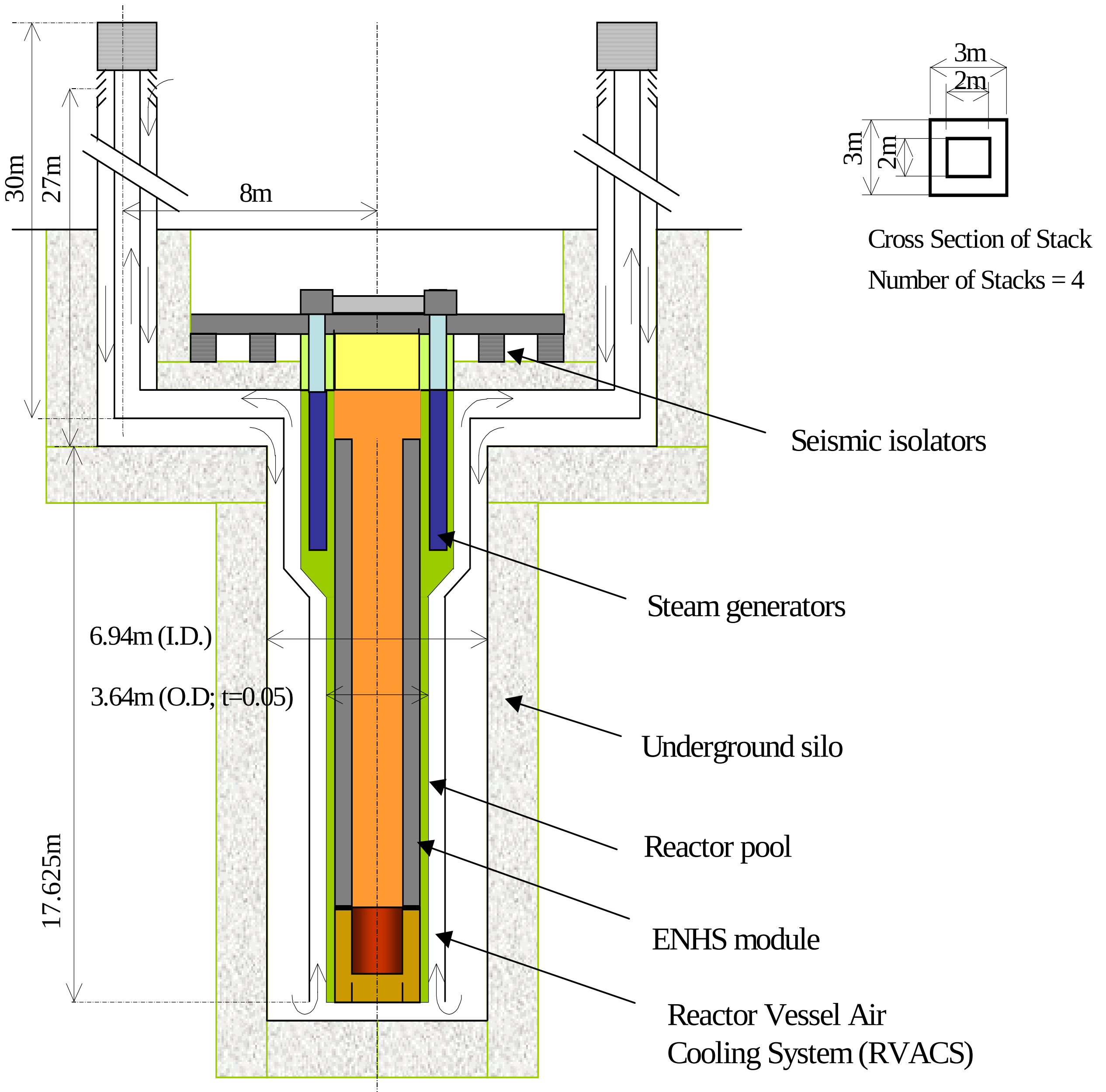
- Molten salts have high boiling temperature (up to ~1400^{o}C), much higher heat capacity so that the required mass flow rate is significantly smaller than that of lead alloy coolants. They also have lower viscosity.

- Molten salts do not react with air and only slowly interact with water.

Objective

- Assess feasibility of using molten-salts as the coolant for an ENHS-like reactor module for developing countries that could provide high-temperature heat for efficient production of electricity and hydrogen while preserving the primary unique features of the ENHS concept:
  - Nearly zero burnup reactivity swing over 20 years of operation
  - Natural circulation
- Scope of feasibility study:
  - Neutronic feasibility -- nearly zero BU reactivity swing for >20 y using uniform composition core with no blanket elements
  - Thermal-hydraulic feasibility – removal of 125 MW_{th} of nominal power by natural circulation using reasonable riser height
  - Examine several combinations of 6 molten salt coolants and 6 structural materials
  - Explore a new core design approach – high MA loading

Schematic vertical cut through the ENHS reactor (125 MW$_{th}$ nominal)



underground silo
→ no LOCA

no pumps

no pipes

no valves

factory fueled

weld-sealed

20 years core

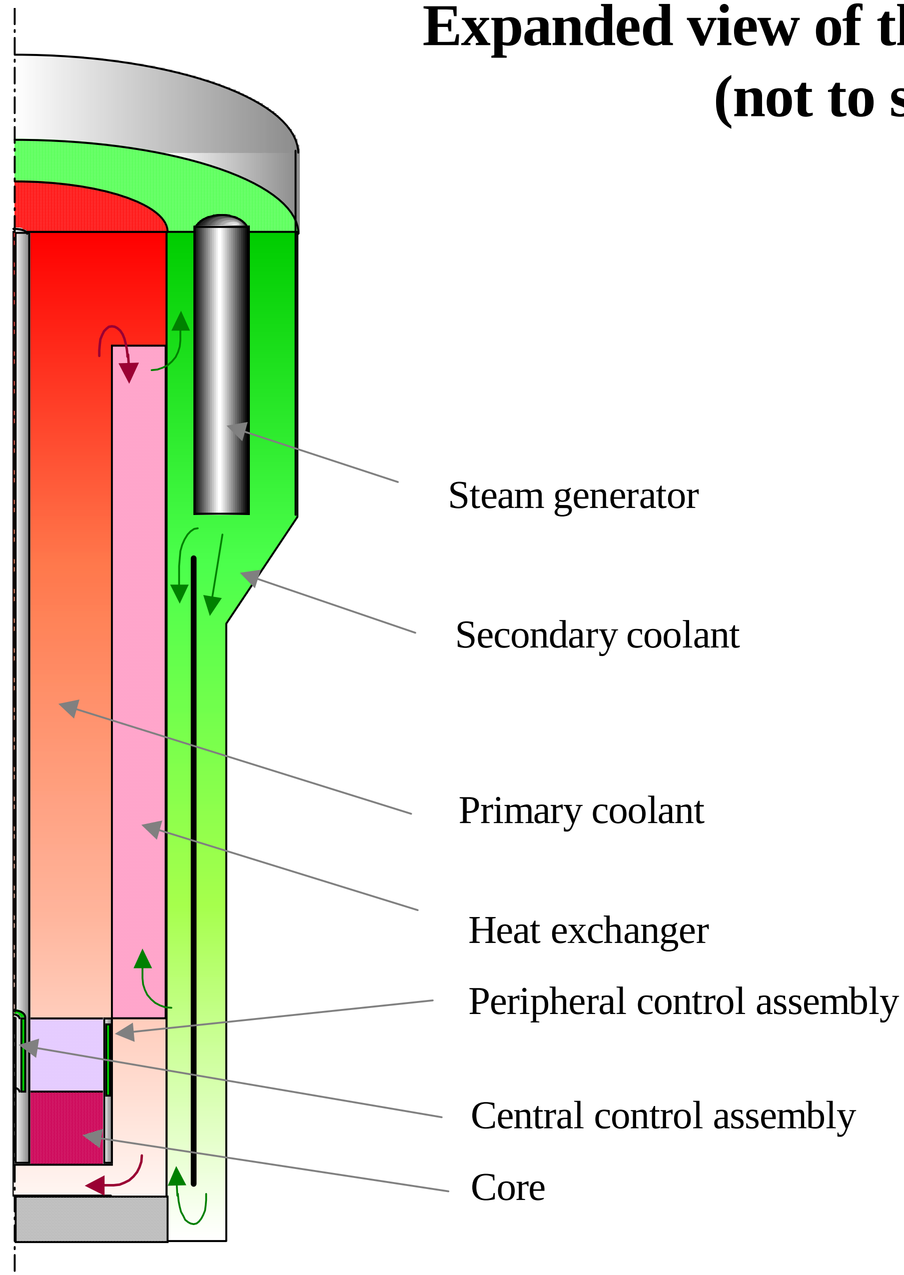
no fueling on site

Module replaced

shipping cask

no DHRS but RVACS

Expanded view of the ENHS reactor (not to scale)



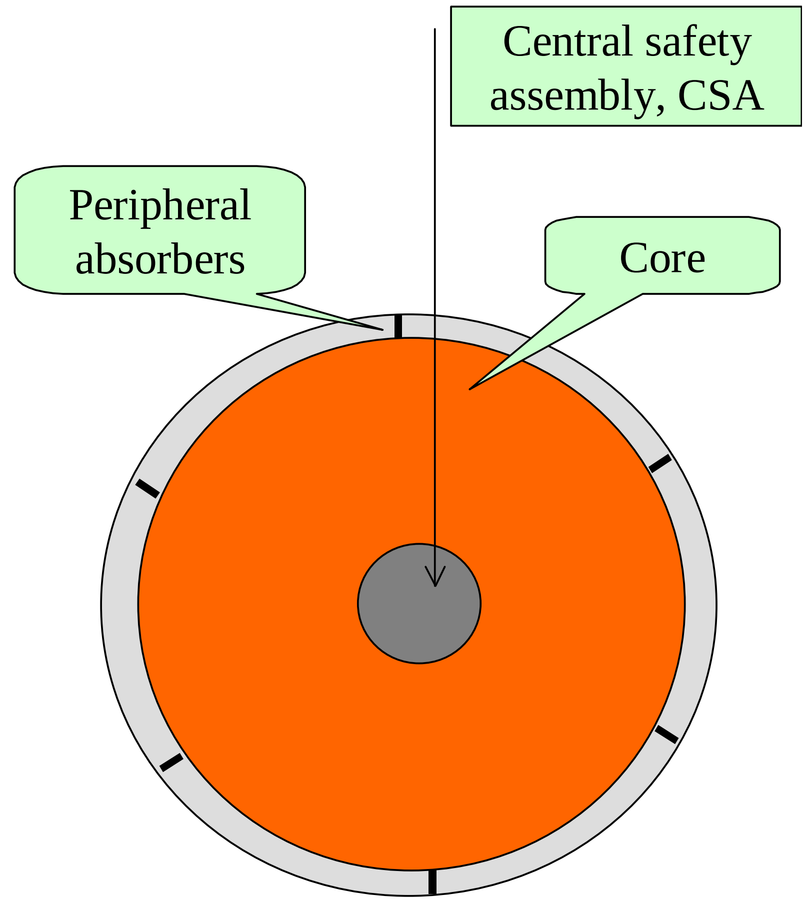
ENHS control (adopted from 4S reactor)

1. **Central absorber for shutdown**

   Latch for withdrawal can be actuated only when T > 350°C

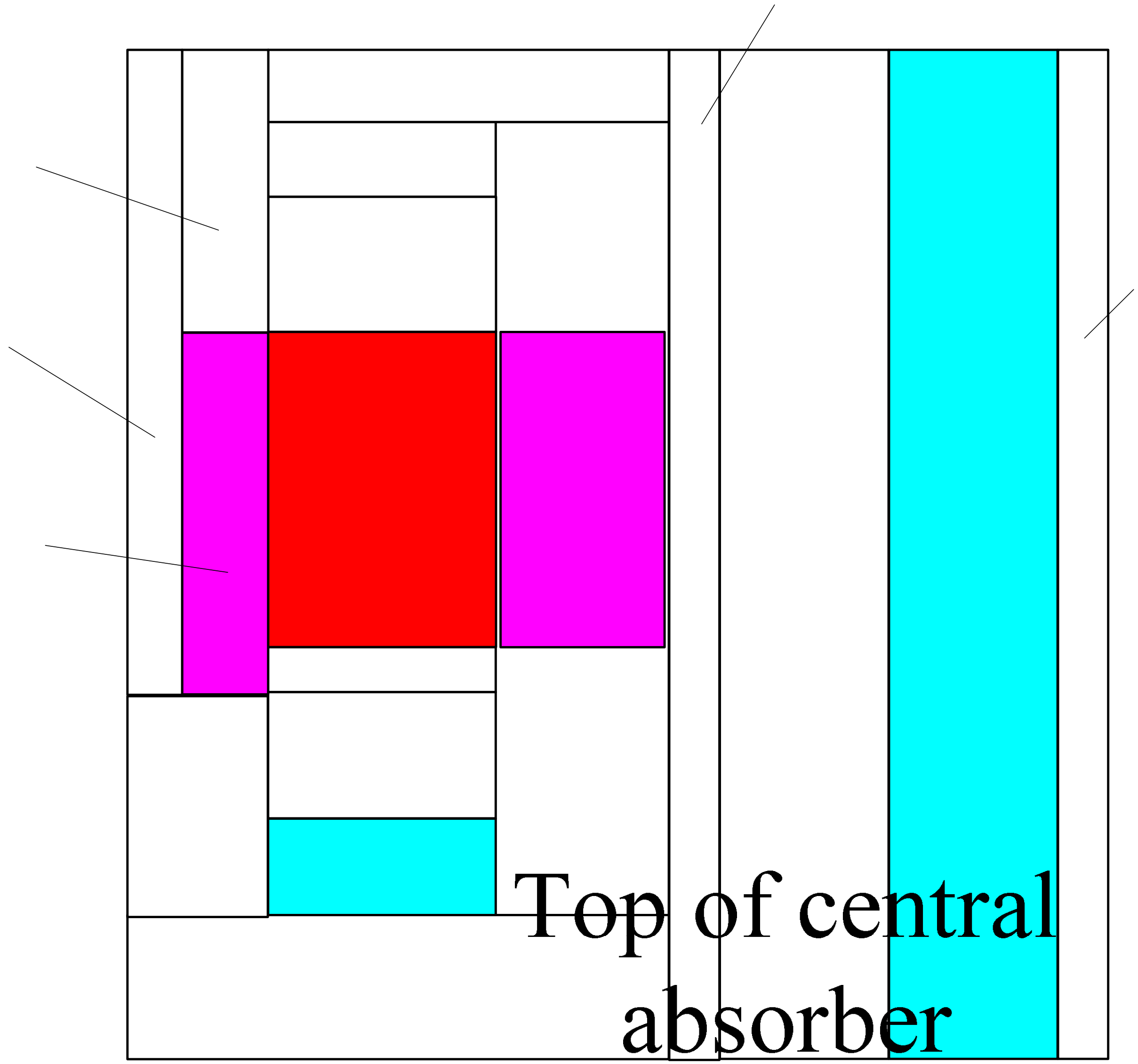
2. **6 segments of peripheral absorbers to**

- **establish criticality;**
  Max. speed 1mm/s → < ¢0.006/s
- **Compensate for BU reactivity swing;**
  Once every 2 to 5 years



B_4C + W are used for absorber of CSA as well as of AC

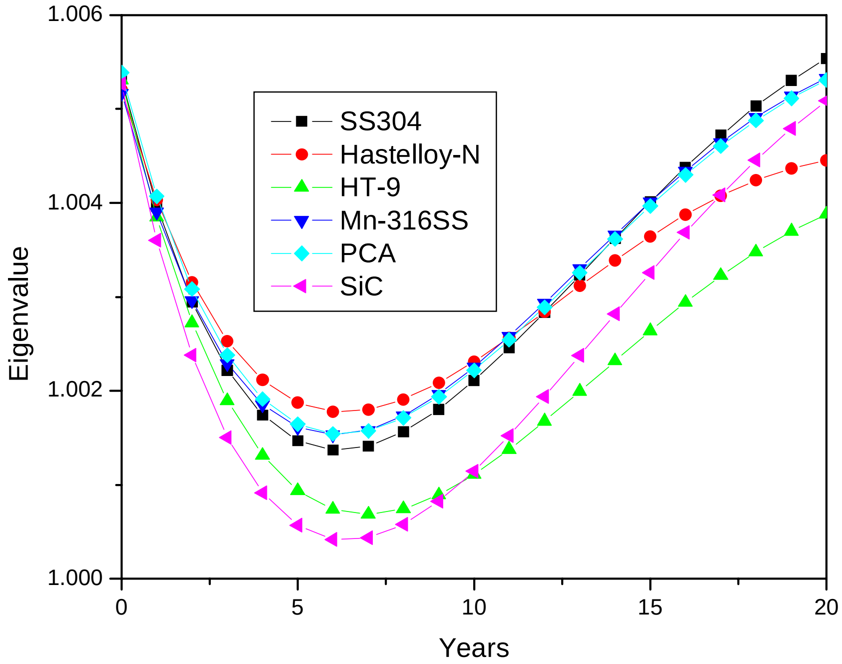
Reactor Model for Neutronic Analysis (not to scale)



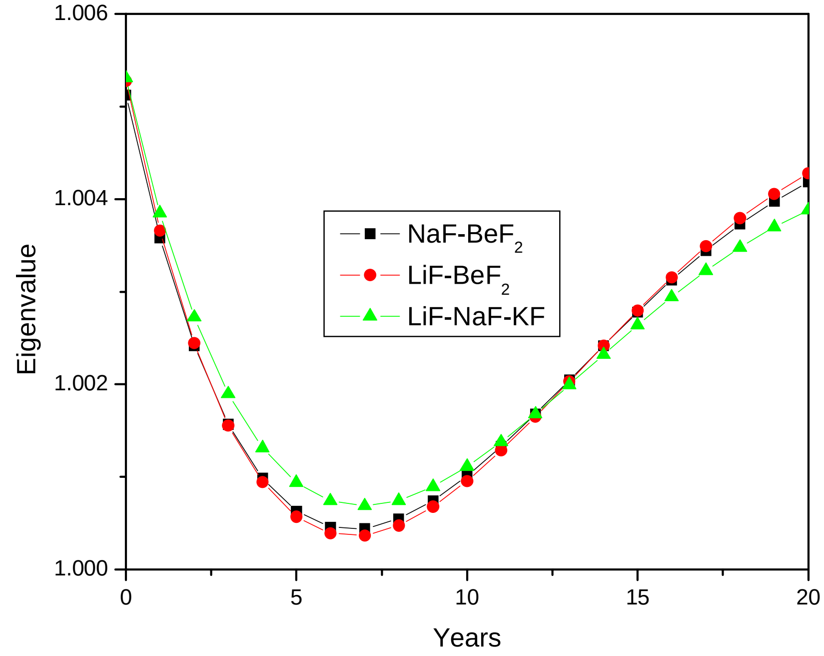
Assumptions for Neutronic Analysis

- Mono nitride fuel ($Pu^{15}N$-$U^{15}N$) for high temperature applications
  - Pu is taken from LWR spent fuel (50GWD/tHM,10years cooling)
  - 85% smear density
- The fuel rod dimensions are of the reference ENHS core: 1.56 cm O.D.
- Six structural materials are considered : SS304, HT-9, Mn-316SS, PCA, Hastelloy-N, SiC
- Three molten salts are considered: NaF(57%)-BeF_2(43%), LiF(66%)-BeF_2(34%), LiF(46.5%)-NaF(11.5%)-KF(42%)
- The core is homogenized into a cylindrical annulus. In comparison with reference ENHS:
  - Peripheral absorber is located closer to the core to enhance its reactivity worth.
  - A structural material region and void region are introduced at the center of central absorber region to reduce the power peaking in the inner-most region of the core.
  - For depletion analysis, the core is divided into 9 zones (3 radial, 3 axial zones)
  - REBUS-3/DIF3D(80group, R-Z) is used for depletion analysis.

Core Design Results - Eigenvalue Evolution



LiF-NaF-KF cooled cores



Optimal cores with HT-9

- The optimal cores with the same structural material have a similar eigenvalue evolution.
- But the eigenvalue evolution of optimal cores with the same coolant depends on the structural material.

Summary of Core Physics Parameters

$NaF-BeF_2$ cooled cores

Parameters	SS304	Hastelloy-N	HT-9	Mn-316 SS	PCA
P/D ratio	1.14	1.06	1.15	1.14	1.13
Pu weight %	13.45	13.376	13.62	13.69	13.51
Burnup swing (%dk)	0.471	0.372	0.468	0.441	0.452
Initial conversion ratio	1.0583	1.0336	1.0515	1.0514	1.0544
3-D peaking factor (BOL/EOL)	1.967/2.187	2.013/2.192	1.899/2.118	1.955/2.165	1.992/2.200
BOL peak linear heat (W/cm)	198	202	191	197	200
Average discharge burnup (MWD/kg)	45.9	45.8	46.0	46.0	45.9
Peak discharge burnup (MWD/kg)	102.7	103.7	99.4	101.9	103.5
Peak fast neutron fluence (n/cm^2)	2.046E+23	2.518E+23	2.009E+23	2.084E+23	2.120E+23

$LiF-BeF_2$ cooled cores

Parameters	SS304	Hastelloy-N	HT-9	Mn-316 SS	PCA
P/D ratio	1.12	1.05	1.13	1.12	1.12
Pu weight %	13.61	13.54	13.80	13.85	13.80
Burnup swing (%dk)	0.520	0.401	0.490	0.457	0.493
Initial conversion ratio	1.0611	1.0332	1.0525	1.0527	1.0483
3-D peaking factor (BOL/EOL)	1.946/2.180	2.017/2.206	1.906/2.140	1.963/2.189	1.983/2.20
BOL peak linear heat (W/cm)	196	203	192	197	199
Average discharge burnup (MWD/kg)	45.9	45.8	45.9	45.9	45.9
Peak discharge burnup (MWD/kg)	102.0	104.1	100.0	102.7	103.3
Peak fast neutron fluence (n/cm^2)	2.023E+23	2.448E+23	1.948E+23	2.030E+23	2.014E+23

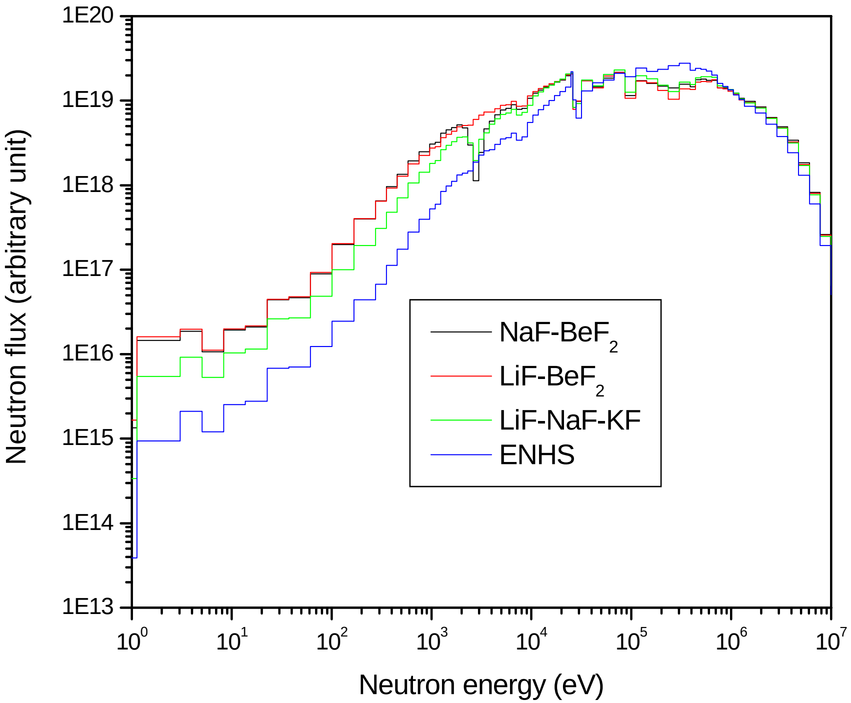
Summary of Core Physics Parameters

LiF–NaF–KF cooled cores

Parameters	Hastelloy-N	HT-9	Mn-316 SS	PCA	SiC
P/D ratio	1.07	1.17	1.16	1.15	1.17
Pu weight %	13.34	13.83	13.84	13.68	13.10
Burnup swing (%dk)	0.342	0.462	0.379	0.384	0.484
Initial conversion ratio	1.0310	1.0388	1.0418	1.0424	1.0671
3-D peaking factor (BOL/EOL)	2.027/2.176	1.929/2.098	1.981/2.139	2.010/2.164	1.819/2.050
BOL peak linear heat (W/cm)	204	194	200	202	184.21
Peak power density (W/cc,BOL/EOL)	84.53/90.74	67.41/73.33	70.40/76.04	72.51/78.26	63.85/71.94
Average discharge burnup (MWD/kg)	45.9	46.1	46.1	46.1	46.3
Peak discharge burnup (MWD/kg)	103.6	99.6	101.8	102.9	96.4
HM inventory at BOL (kg)	19210.0	19212.7	19213.6	19210.4	19213.0
TRU inventory at BOL (kg)	2563	2657	2659	2618	2517
Peak fast neutron fluence (n/cm^2)	2.643E+23	2.155E+23	2.217E+23	2.249E+23	1.902E+23

- LiF-NaF-KF cooled cores have the largest P/D ratio while LiF-BeF_2 cooled cores have the smallest P/D ratio.
- LiF-NaF_2 cooled cores have lowest value of fast neutron fluence (due to its softest spectrum).
- For a given coolant, the optimal core with SiC has the largest P/D ratio, lowest peak linear power, largest initial CR, and smallest Pu inventory while the optimal core with Hastelloy-N has tightest lattice because of the relatively high neutron absorption by Ni.

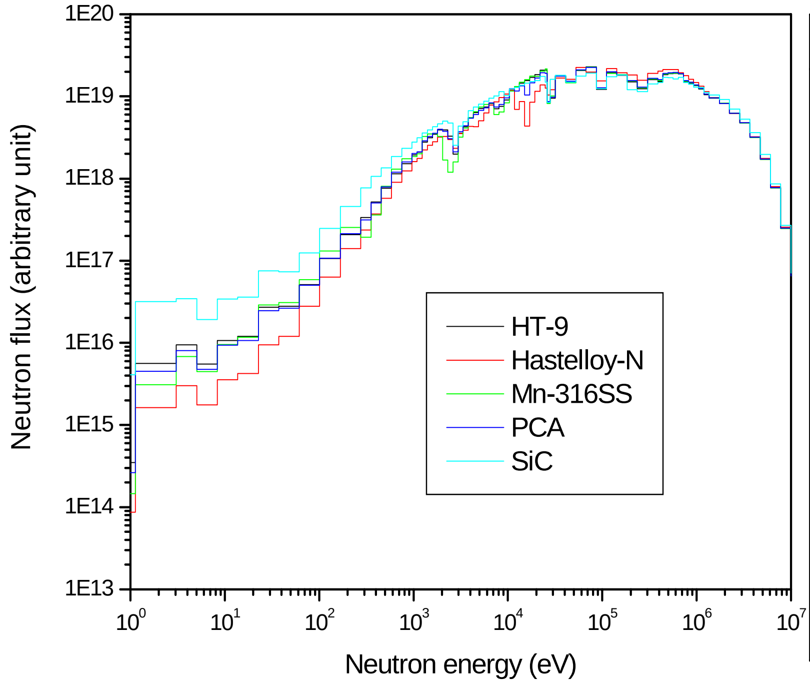
Core Spectra and Neutron Balance
Fixed P/D, Pu wt%, HT-9 structural material



Characteristic	$NaF-BeF_2$	$LiF-BeF_2$	LiF-NaF-KF	ENHS ($Pu^{15}N-U^{15}N$)
p/d	1.15	1.15	1.15	1.15
Pu wt %	13.62	13.62	13.62	13.62
k_{eff}	1.00512	0.986445	1.008626	1.122795
Leakage	0.095	0.089	0.109	0.120
Absorption				
in HM	0.875/0.533[a]	0.883/0.546[a]	0.855/0.510[a]	0.854/0.470[a]
in coolant	0.007	0.005	0.015	0.005
in N	0.000	0.000	0.000	0.001
in HT-9	0.023	0.023	0.021	0.020
Total	0.905	0.911	0.891	0.880
Fission	0.342	0.337	0.345	0.384
ν	2.914	2.913	2.916	2.918
η	1.1389	1.1118	1.1766	1.3121
ICR	1.0515	1.0737	1.0509	0.94804

- ENHS reference core has much harder spectrum.
- Of three molten-salt cooled cores, the LiF-NaF-KF core has the hardest spectrum.
- LiF-NaF-KF cooled core gives the largest k_{eff} even though its leakage probability and the parasitic capture are the largest. This is due to its hardest spectrum (largest value of η).
- The $LiF-BeF_2$ cooled core has the lowest leakage probability but also the lowest k_{eff} (due to its softest spectrum).
- The reference ENHS core has much larger k_{eff} while it has the lowest CR. This is due to its harder spectrum.

Core Spectra and Neutron Balances
Fixed P/D, Pu wt%, LiF-NaF-KF molten-salt coolant



Characteristic	Hastelloy-N	HT-9	Mn-316SS	PCA	SiC
p/d	1.17	1.17	1.17	1.17	**1.17**
Pu wt %	13.83	13.83	13.83	13.83	13.83
k_{eff}	0.962776	1.00531	0.998802	0.999713	1.03404
Leakage	0.100	0.110	0.107	0.104	0.097
Absorption					
in HM	0.813/0.484	0.853/0.509	0.848/0.506	0.849/0.507	0.883/0.529
in coolant	0.015	0.016	0.015	0.016	0.016
in N	0.000	0.000	0.000	0.000	0.000
in structure	0.072	0.021	0.028	0.031	0.004
Total	0.900	0.890	0.891	0.896	0.903
Fission	0.329	0.344	0.342	0.342	0.354
ν	2.917	2.916	2.916	2.916	2.915
η	1.1804	1.1760	1.1760	1.1746	1.1686
ICR	1.0301	1.0388	1.0456	1.0358	1.0043

- The core with SiC has the softest spectrum while the core with Hastelloy-N has the hardest spectrum.
- The core with SiC has the largest eigenvalue despite of its softest spectrum (i.e., lowest η). This is due to the low fraction of neutrons absorbed in structural materials.
- The core with Hastelloy-N has the lowest eigenvalue despite of its hardest spectrum (i.e., highest η). This is due to the high fraction of neutrons absorbed in structural materials (in particular, by Ni) and small leakage fraction.
- The cores with HT-9, Mn-316SS, PCA have very similar neutron balance.

BOL Core Performance (HT-9)

Performance Parameter	$NaF\text{-}BeF_2$	$LiF\text{-}BeF_2$	LiF-NaF-KF	ENHS
P/D ratio	1.15	1.13	1.17	1.45
Pu wt%	13.62	13.80	13.83	13.08
Burnup reactivity swing (%dk)	0.468	0.490	0.462	0.221
Peak burnup after 20 EFPY (GWD/tHM)	99.4	100.0	99.6	92.5
Average burnup after 20 EFPY (GWD/tHM)	46.0	45.9	46.1	46.2
Peak fast (E>0.1 MeV) fluence at 20 EFPY (n/cm^2)	2.009E+23	1.948E+23	2.155E+23	2.904E+23
Conversion ratio	1.0515	1.0525	1.0388	1.0399
Doppler effect (dk/kk'-^{o}C)	-1.6939E-05	-1.6618E-05	-1.2786E-05	-8.9799E-06
Axial fuel expansion (dk/kk'-^{o}C)	-2.3872E-06	-2.3757E-06	-3.3965E-06	-2.7625E-06
Coolant expansion (dk/kk'-^{o}C)				
Density change in active core	+1.1536E-05	+1.6094E-05	+2.6529E-05	+3.1767E-06
Density change in active core/gas plenum	+1.1287E-05	+1.5822E-05	+2.5969E-05	+1.6747E-06
Grid-plate radial expansion (dk/kk'-^{o}C)	-5.9775E-06	-6.0738E-06	-6.9664E-06	-7.2268E-06
Void reactivity effect (%dk)				
Voiding inner 1/3 core/+gas plenum	+6.953/+6.653	+7.869/+7.592	+7.146/+6.862	+3.114/+1.905
Voiding middle 1/3 core/+gas plenum	+2.933/+2.772	+3.368/+3.223	+3.089/+2.936	+0.978/+0.224
Voiding outer 1/3 core/+gas plenum	+0.418/+0.349	+0.579/+0.516	+0.474/+0.405	-0.508/-0.839
Voiding whole core/+gas plenum	+11.046/+10.610	+12.53/+12.14	+11.08/+10.65	+3.462/+1.374
Peripheral absorber reactivity worth (%dk)	1.463	1.291	1.390	2.070
Central absorber reactivity worth (%dk)	2.341	2.287	2.728	3.600
Peripheral absorber+central absorber worth (%dk)	4.349	4.282	4.807	6.320
Total plutonium mass (kg)	2616	2651	2657	2513

BOL Core Performance (HT-9)

- **The molten-salt cooled cores have much lower value of peak fast neutron fluence than LM cooled cores. This enables the molten-salt cooled cores to have significantly longer core life.**
- **The molten-salt cooled cores have an order of magnitude more positive reactivity coefficient of coolant expansion and of coolant voiding than ENHS. This is due to the fact that the molten-salt cooled cores have much softer neutron spectra so that the relative spectral change resulting from coolant expansion or voiding is much larger than in LM cooled cores.**
- **However, the larger positive coolant expansion reactivity is compensated by the significant enhancement of Doppler effect.**
- **The LiF-NaF-KF cooled core has the most positive reactivity coefficient of coolant expansion because of its largest thermal expansion coefficient.**
- **Of the three molten-salt cooled cores, the $LiF\text{-}BeF_2$ cooled core has the most positive void reactivity because of its softest neutron spectrum.**
- **However, it is impossible for large scale voiding of molten-salts to occur because their boiling temperature is high (~1400ºC) : this is at least 500ºC higher than peak coolant temperature.**
- **The molten-salt cooled cores have smaller reactivity worth of peripheral absorber of $90^{v}/_{o}B_4C+10^{v}/_{o}$structure than ENHS ($40^{v}/_{o}W+40^{v}/_{o}B_4C+20^{v}/_{o}$structure). However, the peripheral absorbers give sufficient reactivity worth to compensate for the reactivity deficiency resulting from cold-to-hot reactivity swing and burnup reactivity swing.**
- **The reactivity worth of central absorbers of $90^{v}/_{o}B_4C+10^{v}/_{o}$structure is much smaller than that of the LM-cooled ENHS ($40^{v}/_{o}W+40^{v}/_{o}B_4C+20^{v}/_{o}$structure).**

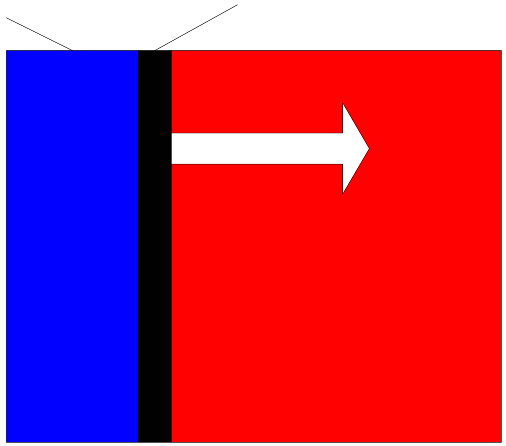
BOL Core Performance (LiF-NaF-KF)

Performance Parameter	Hastelloy-N	SiC	HT-9
P/D ratio	1.07	1.17	1.17
Pu wt%	13.34	13.10	13.83
Burnup swing (%dk)	0.342	0.484	0.462
Peak burnup after 20 EFPY (GWD/tHM)	103.6	96.4	99.6
Average burnup after 20 EFPY (GWD/tHM)	45.9	46.4	46.1
Peak fast (E>0.1 MeV) fluence at 20 EFPY (n/cm²)	2.643E+23	1.902E+23	2.155E+23
Conversion ratio	1.0310	1.0671	1.0388
Doppler effect (dk/kk'-ºC)	-1.0061E-05	-1.8117E-05	-1.2786E-05
Axial fuel expansion (dk/kk'-ºC)	-2.8182E-06	-2.0395E-06	-3.3965E-06
Coolant expansion (dk/kk'-ºC)			
Density change in active core	+1.9362E-05	+2.2518E-05	+2.6529E-05
Density change in active core/gas plenum	+1.9253E-05	+2.1980E-05	+2.5969E-05
Grid-plate radial expansion (dk/kk'-ºC)	-4.5178E-06	-1.44755E-06	-6.9664E-06
Void reactivity effect (%dk)			
Voiding inner 1/3 core/+gas plenum	+4.626/+4.597	+5.606/+5.386	+7.146/+6.862
Voiding middle 1/3 core/+gas plenum	+2.054/+2.030	+2.695/+2.567	+3.089/+2.936
Voiding outer 1/3 core/+gas plenum	+0.353/+0.342	+0.597/+0.527	+0.474/+0.405
Voiding whole core/+gas plenum	+7.110/+7.075	+9.031/+8.675	+11.08/+10.65
Peripheral absorber reactivity worth (%dk)	1.037	1.549	1.390
Central absorber reactivity worth (%dk)	2.306	2.635	2.728
Peripheral absorber+central absorber worth (%dk)	3.806	5.462	4.807
Total plutonium mass (kg)	2563	2517	2657

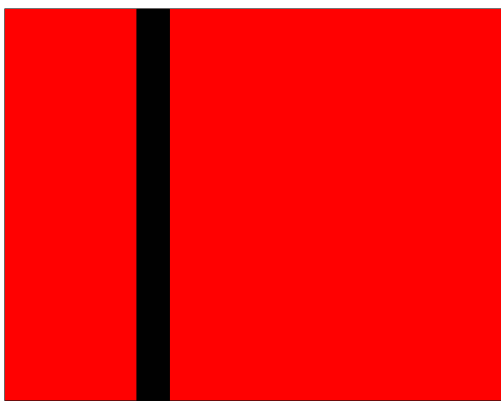
BOL Core Performance (LiF-NaF-KF)

- The core with SiC uses SS-304 rather than SiC for structural material at the central region because use of SiC doen't reduce the central power peaking.
- The core with SiC has lowest peak fast fluence due to its softest neutron spectrum. This core has also the most negative Doppler coefficient.
- Of the three cores, the core with Hastelloy-N has the least positive reactivity coefficient of coolant expansion and of coolant voiding. This is due to its hardest neutron spectrum. However, this core has still much more positive coolant void reactivity worth than the reference ENHS core.
- The core with SiC has the largest reactivity worth of peripheral absorber and of the combination of peripheral and central absorbers.

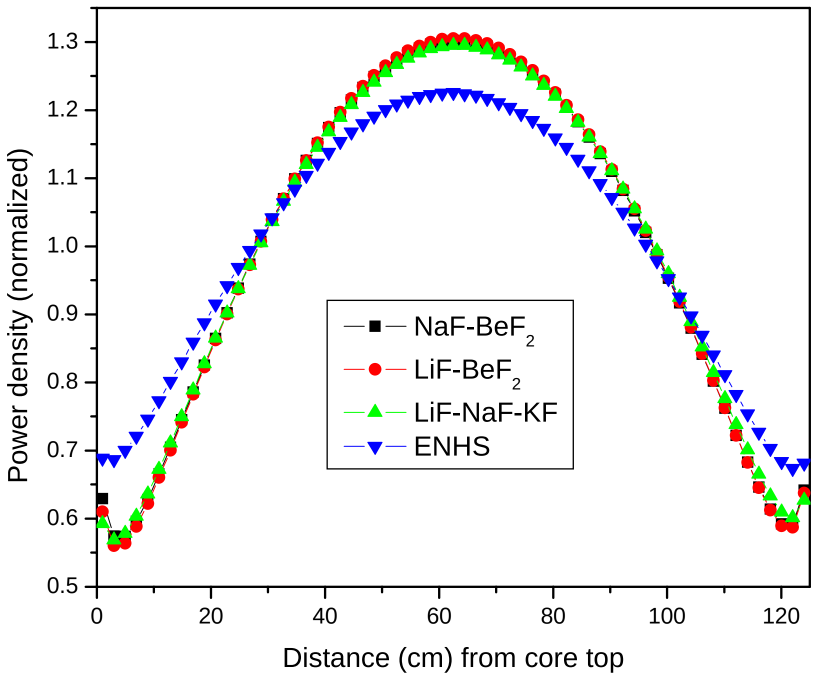
Improvement of Central Absorber Reactivity Worth (LiF-NaF-KF coolant, SiC structural material)

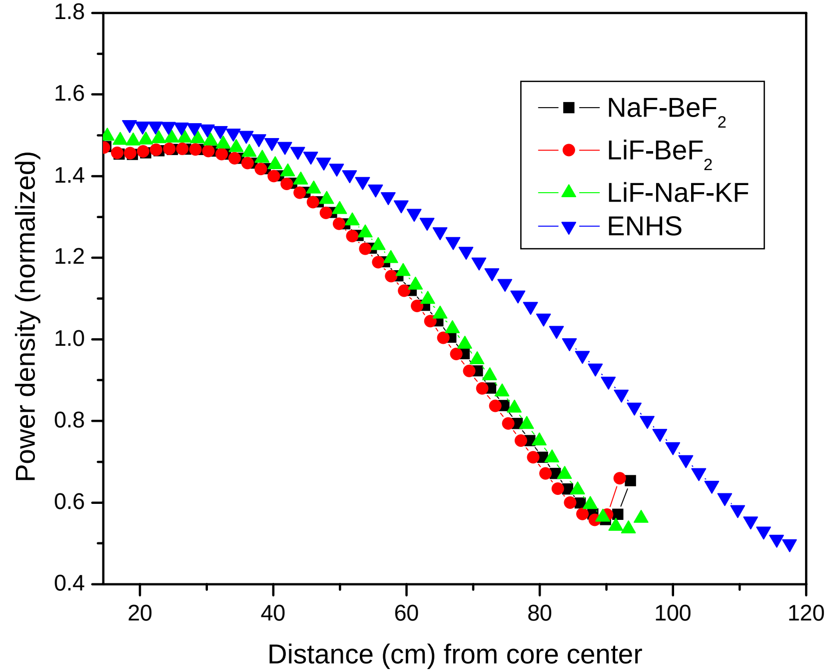


- Approach-I : increase absorber thickness and B-10 content
  - Did not give acceptable increase
- Approach-II : increase the central absorber region
  - Its outer radius is increased from 14.12cm to 20cm.
  - P/D ratio is reduced from 1.17 to 1.14 so as to reduce burnup swing.
  - The resulting central, peripheral, and their combined absorber worth are 3.13%dk, 1.35%dk, and 6.45%dk, respectively.
- Approach-III : use an annular type absorber in core internal
  - The outer and inner radius of the annular absorber are 20cm and 25cm, respectively.
  - P/D ratio is reduced from 1.17 to 1.14 so as to reduce burnup swing.
  - The resulting central, peripheral, and their combined absorber worth are 4.587%dk, 1.464%dk, and 7.367%dk, respectively.



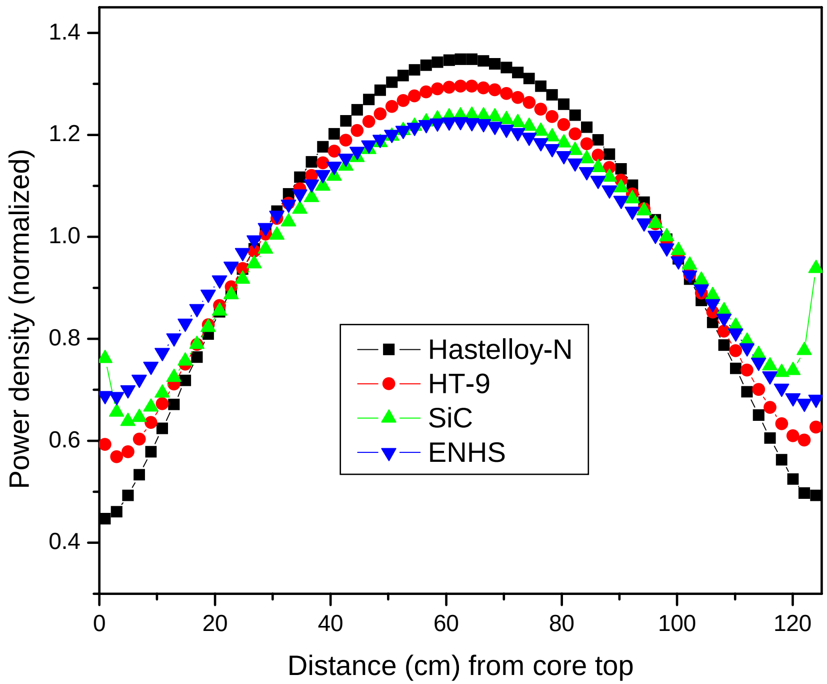
Power Distribution (HT-9)

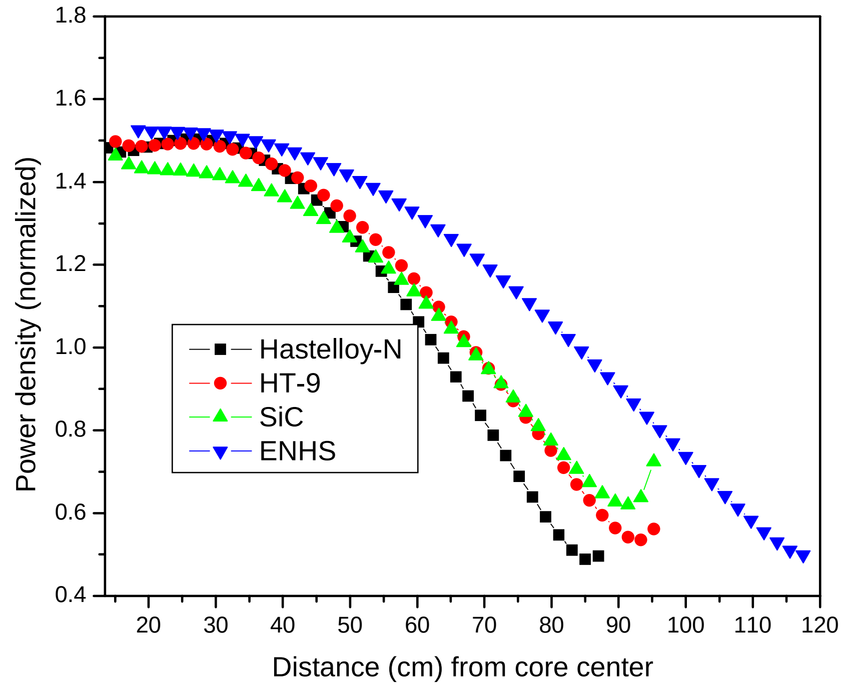




- The three molten-salt cooled cores have nearly same axial power distribution; it peaks more than that of the reference lead-alloy cooled ENHS core.
- Three molten-salt cooled cores has nearly similar radial power peaking factor as the reference ENHS.

Power Distribution (LiF-NaF-KF)





- The axial power peaking is quite sensitive to the structural material ; the Hastelloy-N core has the largest while the SiC core has the smallest axial power peaking (it is nearly the same as of the reference ENHS core.).
- The combination of softer spectrum of the reflected neutrons and low neutron capture probability of SiC amplifies the power peaking near the boundary between core and reflector.
- The SiC core has also the flattest radial power distribution; it is even somewhat flatter than of the reference ENHS core.

Feasibility of Natural Circulation

- **Goal:**

  Removal of 125 MW_{th} of nominal power by natural circulation using reasonable riser height

- **Approach:**

  One dimensional flow model that searches for riser length necessary for natural circulation cooling. Fixed core deign.

- **Molten Salts Considered:**

Molten Salts Considered and Their Selected Properties*

Molten Salt	$T_{melting}$ °C	Density(b) Kg/m^3	$\Delta\rho$(a) Kg/m^3	C_p(b) KJ/Kg-C	C_v(b) KJ/m^3-C	K W/m-C	ν(b) m^2/s
0.465LiF-0.115NaF-0.42KF	454	2019	73	1.88	3798	1.0	1.44
0.43LiF-0.57RbF	475	2817	69	1.19	3344	6.0	0.91
0.66LiF-0.34BeF_2	458	1938	49	2.38	4618	1.1	2.84
0.57NaF-0.43BeF_2	360	2011	37	2.17	4371	1.0	3.41
0.50NaF-0.50ZrF_4	510	3139	93	1.17	3674	1.0	1.64
0.42LiF-0.29NaF-0.29ZrF_4	460	2789	83	1.46	4080	1.0	2.49
Lead bismuth	125	9774	138	0.15	1432	16.7(b)	0.11

(a) Assuming temperature difference from 700°C to 600°C (b) At 700°C

* Provided by David Williams of ORNL

Screening of Molten Salts - Assumptions

- Fixed geometry core of given power shape; no attempt to optimize
- Using simple 1-D model to account foe friction losses of primary coolant through core, IHX and all other components (developed by Tsuyoshi Okawa on the basis of Sienicki's model – published)
- Peak clad/fuel temperature is 850/2777 ^{o}C
- Design variables are riser height and number of IHX channels

Parameter	Unit	Value
Core height	m	1.25
Gas plenum height	m	1.25
Fuel rod outer diameter	m	0.0156
Pitch-to-diameter ratio		1.06
Clad thickness	m	0.0013
Radial shield height	m	3.35
Width of IHX channel	m	0.025
2nd coolant hydraulic diameter in IHX	m	0.047
Hydraulic diameter in radial shield section	m	0.500
Primary coolant core inlet temperature	^{o}C	610
Secondary coolant IHX inlet temperature	^{o}C	560

Hastelloy!!

Screening of Molten Salts by IHX Length

Molten Salt	$T_{core\ outlet}$ °C	$\Delta T_{primary}$ °C	$LMTD_{IHX}$ °C	$W_{primary}$ Kg/s	$W_{secondary}$ Kg/s	$\Delta P_{primary}$ Kg/ms^2	H_{IHX} m
0.465LiF-0.115NaF-0.42KF	712	102	61	649	860	10387	23
0.43LiF-0.57RbF	723	114	26	921	692	13850	30
0.66LiF-0.34BeF$_2$	712	103	46	510	481	8535	29
0.57NaF-0.43BeF$_2$	711	102	25	563	406	11364	56
0.50NaF-0.50ZrF$_4$	711	102	41	1044	907	18253	34
0.42LiF-0.29NaF-0.29ZrF$_4$	711	102	46	835	778	14966	30
Lead bismuth	450	100	47	8557	5986	11808	12

- LiF-NaF-KF requires the shortest IHX; it is ~double that required with Pb-Bi coolant
- Next in order of preference: LiF-BeF$_2$, LiF-NaF-ZrF$_4$, LiF-RbF, NaF-ZrF$_4$, NaF-BeF$_2$

Sensitivity of IHX Length to Coolant ΔT

Parameter	Unit	Primary coolant ΔT (°C)		
		75	100	125
Riser height	m	47.87	24.95	18.43
Active IHX height	m	**45.87**	**22.95**	**16.43**
Number of IHX channels	-	122	170	200
Primary coolant flow area in IHX	m^2	2.12627	1.50535	1.11727
Secondary coolant flow area in IHX	m^2	1.19560	1.66600	1.96000
Primary coolant hydraulic diameter in IHX	m	0.062	0.035	0.023
Primary coolant core outlet temperature	°C	659.9	676.5	693.1
Secondary coolant IHX outlet T	°C	650.2	650.8	651.9
Coolant ΔT in core	°C	50.2	66.9	83.6
IHX log-mean temperature difference	°C	24.5	36.5	45.5
Primary coolant flow rate	Kg/s	1324.1	993.5	794.6
Secondary coolant flow rate	Kg/s	736.7	732.2	723.3
Coolant velocity in core	m/s	0.70	0.53	0.42
Coolant velocity in riser	m/s	0.18	0.14	0.11
Primary coolant velocity in IHX	m/s	0.30	0.32	0.34
Secondary coolant velocity in IHX	m/s	0.30	0.21	0.18
Coolant velocity in radiation shield section	m/s	0.33	0.25	0.20
Coolant velocity in flow distributor	m/s	0.28	0.21	0.17

Alternative Core Design Approach – High Loading of MA

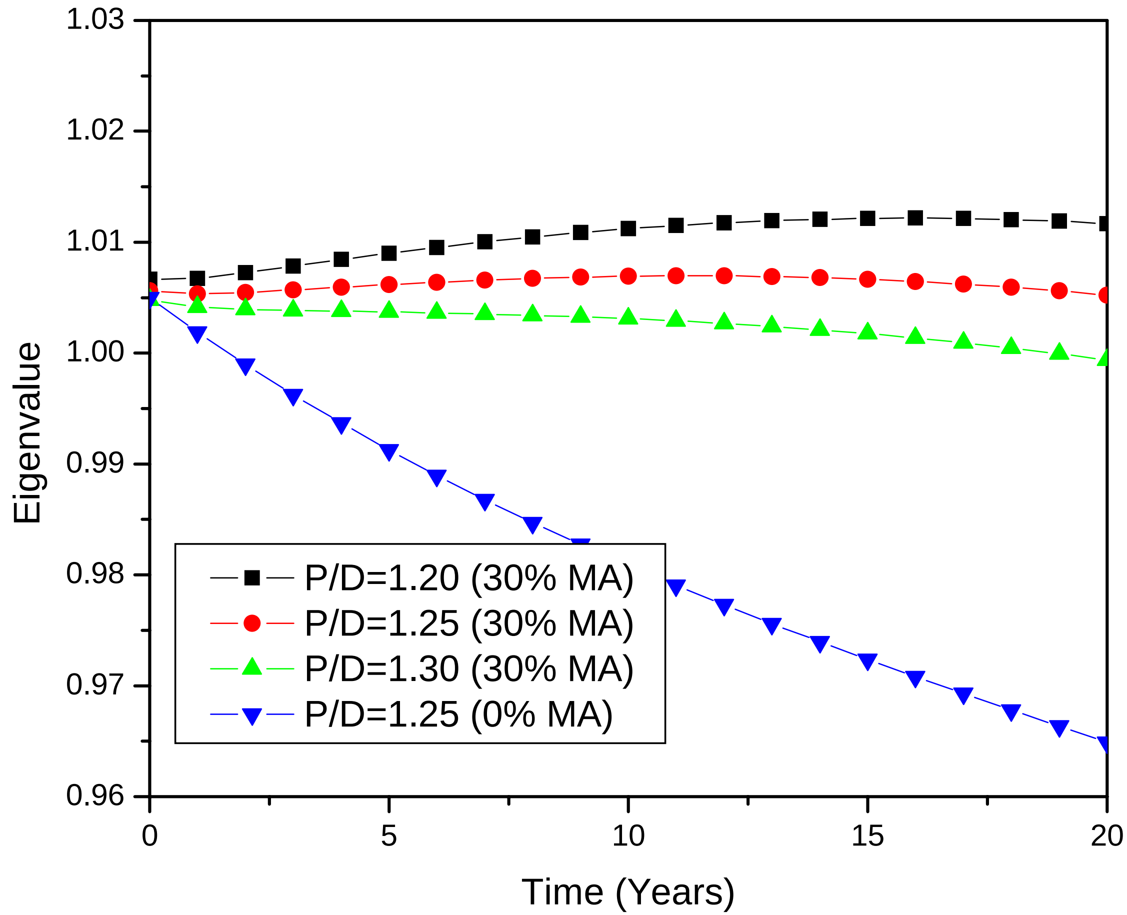
- Incentive – Our observation that with MA, larger P/D is required in order to get nearly zero burnup reactivity swing

- Systems compared:
  - DESIGN-I : NaF-BeF2 coolant, initial TRU composition of 100%Pu
  - DESIGN-II: NaF-BeF2 coolant, initial TRU composition of 70%Pu + 30%MA
  - ENHS : lead coolant, initial TRU composition of 100%Pu

- DESIGN-I and II use Hastelloy !

- So far did neutronic analysis only

Alternative Core Design Approach – k_{eff} evolution



- Using TRU with 30% MA, required P/D increases from 1.06 to 1.25 !!!
- K_{eff} evolution with BU is very flat

Alternative Core Design Approach – Physics characteristics

Performance Parameter	DESIGN-I	DESIGN-II	ENHS
P/D ratio	1.06	1.25	1.45
Core inner/outer radius (cm)	12.79/87.16	25.0/98.77	17.49/119.23
TRU wt%	13.376	25.88	13.08
Burnup reactivity swing (%dk)	0.372	0.174	0.221
Peak-to-average power density	2.013	1.842	1.856
Peak linear heat rate (W/cm)	202	185	187
Peak burnup after 20 EFPY (GWd/tHM)	103.7	90.9	92.5
Average burnup after 20 EFPY (GWd/tHM)	45.8	45.9	46.2
Peak fast (E>0.1MeV) neutron flux (n/cm^2-s)	3.7119E+14	2.1651E+14	4.4334E+14
Peak fast (E>0.1 MeV) fluence at 20 EFPY (n/cm^2)	2.518E+23	1.419E+23	2.904E+23
Conversion ratio	1.0336	0.7338	1.0399
Reactivity coefficients			
Doppler effect (dk/kk'-^{o}C)	-1.1224E-05	-6.3602E-06	-8.9799E-06
Axial fuel expansion (dk/kk'-^{o}C)	-2.5469E-06	-2.9963E-06	-2.7625E-06
Coolant expansion (dk/kk'-^{o}C)	+1.0196E-05	+2.0723E-05	+1.6747E-06
Grid-plate radial expansion (dk/kk'-^{o}C)	-4.0682E-06	-5.6837E-06	-7.2268E-06
Voiding whole core (%dk)	+7.550	+18.626	+3.462
+gas plenum	+7.511	+18.430	+1.374
Peripheral absorber reactivity worth (%dk)	0.834	0.823	2.070
Central absorber reactivity worth (%dk)	2.065	1.234	3.600
Peripheral absorber+central absorber worth (%dk)	3.543	2.407	6.320
Total plutonium mass (kg)	2570	3479.4	2513
Total minor actinide mass (kg)	0.0	1491.2	0.0
Total HM inventory (kg)	19211	19206	19212

Alternative Core Design Approach – DESIGN-II Isotopics

Nuclides	BOL	EOL	EOL-BOL
U-234	0.0	22.97	22.98
U-235	28.47	19.96	-8.51
U-236	0.0	2.21	2.21
U-238	14207.0	13429.0	-778.0
PU238	52.39	242.42	190.0
NP237	497.8	362.22	-135.59
PU239	2191.2	2083.13	-108.07
PU240	887.0	958.96	71.96
PU241	155.78	82.85	-72.93
PU242	192.98	209.25	16.27
AM241	888.69	716.26	-172.43
AM242M	1.39	32.4	31.0
AM243	91.77	83.52	-8.25
CM242	0.0	4.55	4.55
CM243	0.198	0.298	0.100
CM244	10.31	18.59	8.28
CM245	0.892	2.48	1.58
CM246	0.099	0.181	0.082

Conclusions

- It is possible to design uniform composition, blanket free molten-salt cooled cores for ENHS-like reactors that feature
  - nearly zero burnup reactivity swing
  - Removal of 125 MW_{th} using natural circulation
- Use of MA in addition to Pu will enable to achieve the ENHS design goals using even the strongly absorbing Hastelloy for the structure. Large HM inventory is required.
- However, the MS cores have a large positive coolant temperature coefficient and void coefficient

Conclusions (cont.)

- Relative to the reference ENHS core, the molten-salt cores feature a somewhat softer spectrum, significantly more negative Doppler reactivity effect but more positive coolant expansion reactivity and void reactivity coefficient and smaller reactivity worth of control elements.
- Approaches giving sufficient reactivity worth of control elements were devised.
- Of the molten salts considered, LiF-NaF-KF is the best both from neutronics and from thermal-hydraulics considerations – it offers the best neutron balance and, hence, the largest P/D ratio and, for a given P/D ratio, requires the shortest IHX. The drawback of this salt is a relatively large positive coolant expansion reactivity and relatively small negative Doppler coefficient.
- Of the structural materials considered, SiC gives the largest P/D ratio, lowest Pu loading, flattest power distribution and largest reactivity worth of the control elements.

Conclusions (cont.)

Before continuing with the study of feasibility of using MS for the coolant of solid fuel fast reactors it is necessary to find a solution to the positive coolant temperature coefficient and positive void reactivity effect.