MOLTEN SALT REACTOR REVIEW

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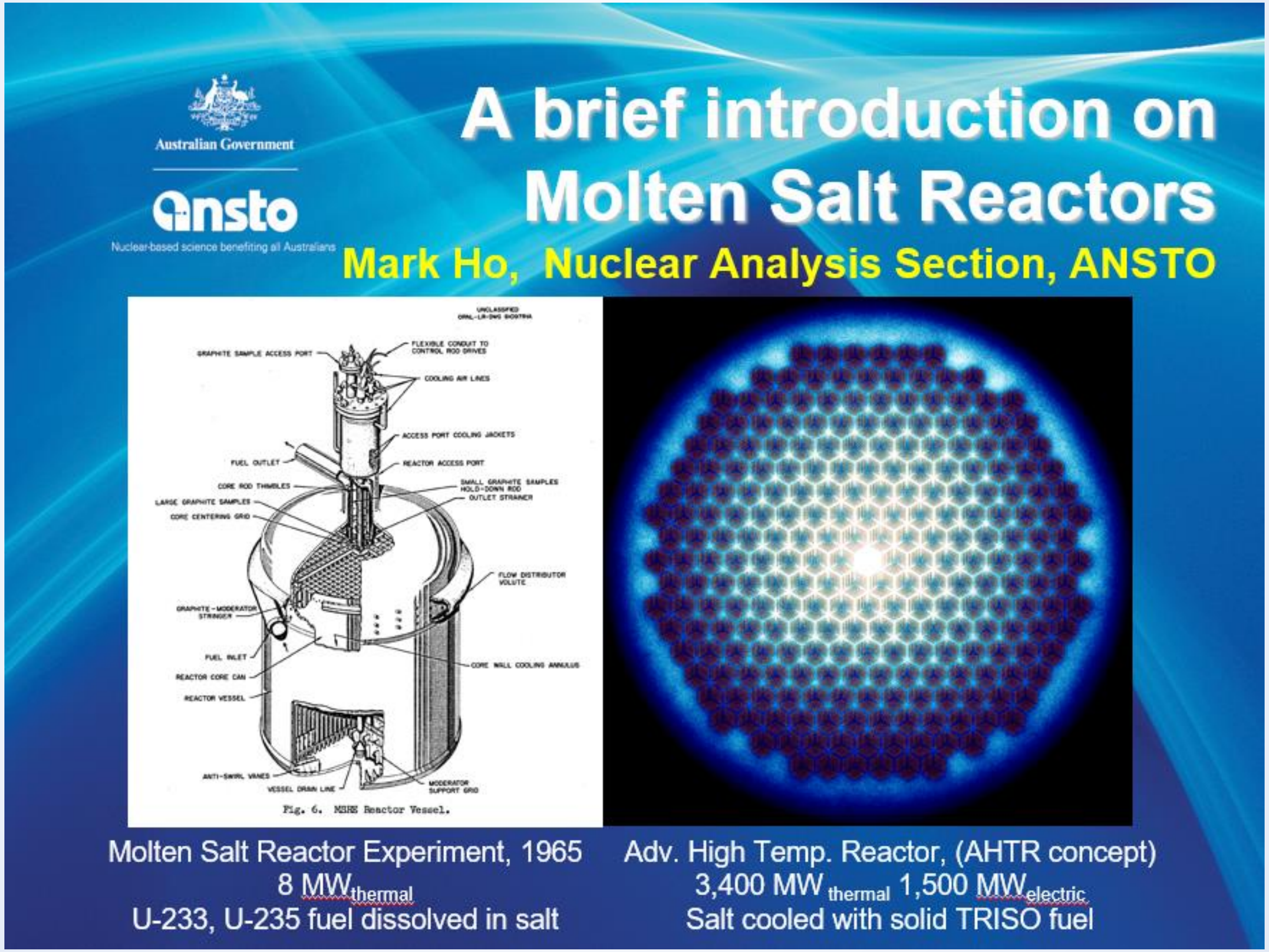
** All views expressed in this presentation are my own and not the official position of the ANA or ANSTO*

Much Progress since 2014



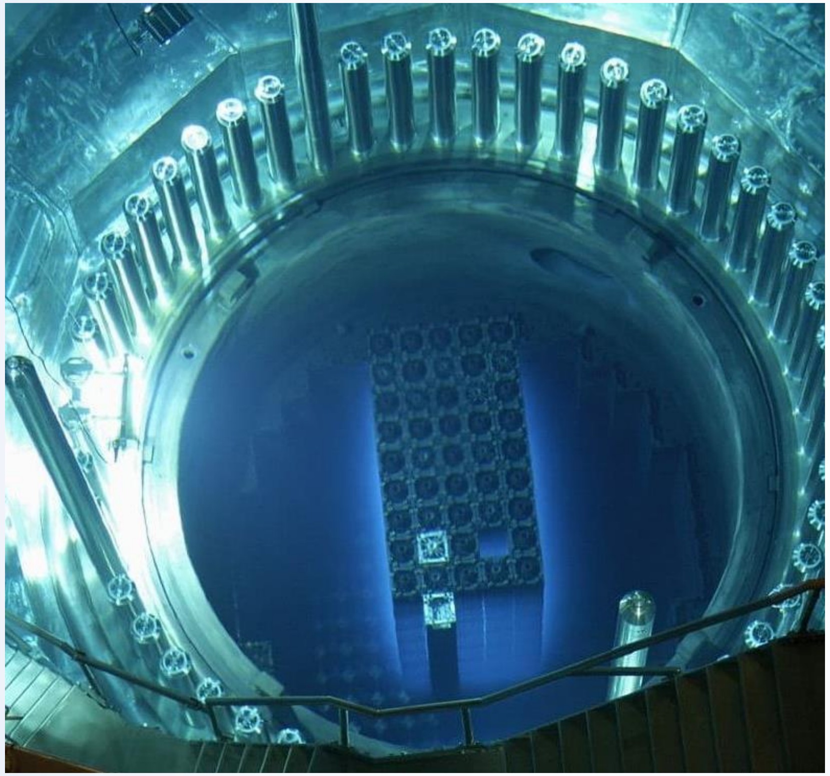
Building a better reactor

Wish-list

Safety	• Meltdown-proof. • Maintain defense-in-depth: Fission product, fuel and TU retainment
Waste	• Burn radioactive 'waste' - close the fuel cycle
Non-proliferation	• Maintain NPT standards – preventing FP, fuel and TU diversion
Economics	• Higher op. temperature and thermal efficiency • Reduce fuel fabrication complexity and cost • Use existing tech. (as much as possible) • Long-lived, lower build cost, lower O/N cost and LCOE • Give the regulator a design they can license.

Typical Pressurised Water Reactor

S	M/D-proof.	✗
	D-in-D	✓
W	Burn TU	✗
NP	No Diversion	✓
E	High temp.	✗
	$ Fuel fab.	✗
	Existing tech	✓
	Low LCOE	✓
	Licensable?	✓



Typical PWR
Top view

Fuel bundles

Coolant – doubles as moderator

In-core control rods

$Temp_{inlet}$ = ~300°C

$Temp_{outlet}$ = ~320°C

Pressure = 150 atm.

Molten Salt Reactor

MSRE (1965)
Top view

Fuel in coolant

Moderator structure - graphite

4

ex-core control rods

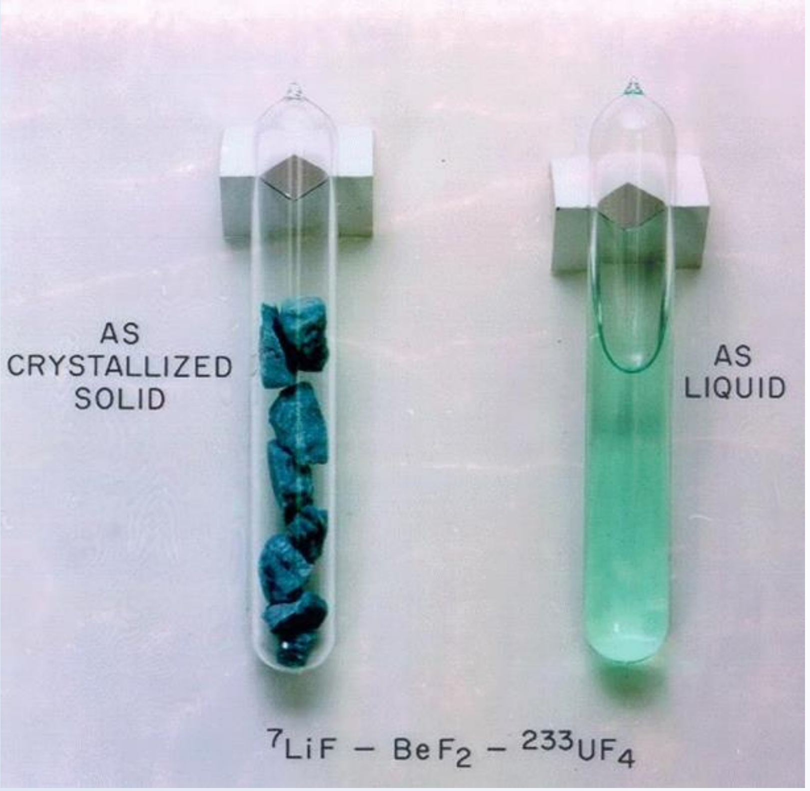
Temp_{inlet} = 600°C

Temp_{outlet} = 610°C

Pressure = ~1 atm.

Source: Oak Ridge National Lab.

Why use molten salt?



Source: Oak Ridge National Lab.

Features

- Best possible HT between fuel and coolant
- Less complicated fuel fabrication
- Use of radioactive spent fuel much easier
- No fuel structural damage, unlike UO_2 pellets
- No fuel bundle improves neutron economy
- No problem with FP_{gas} accumulation
- Little to no pressurisation necessary
- High BP, but want low MP

Drawbacks

- Removal of fuel clad challenges 'defense-in-depth' philosophy
- Primary coolant loop becomes highly radioactive
- Redox control important.

NEPA – Nuclear Energy for Propulsion of Aircraft (1946 – 1961)

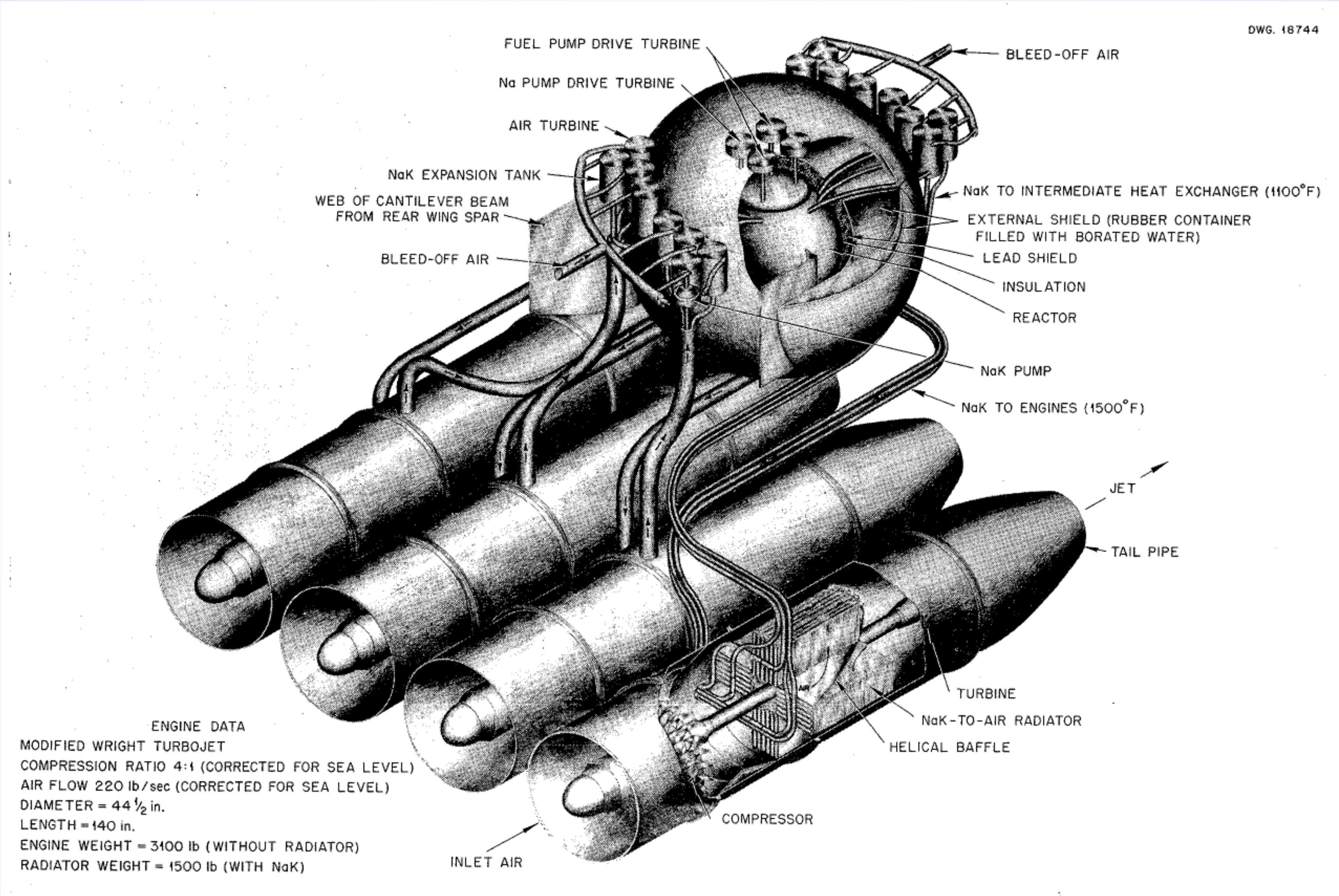
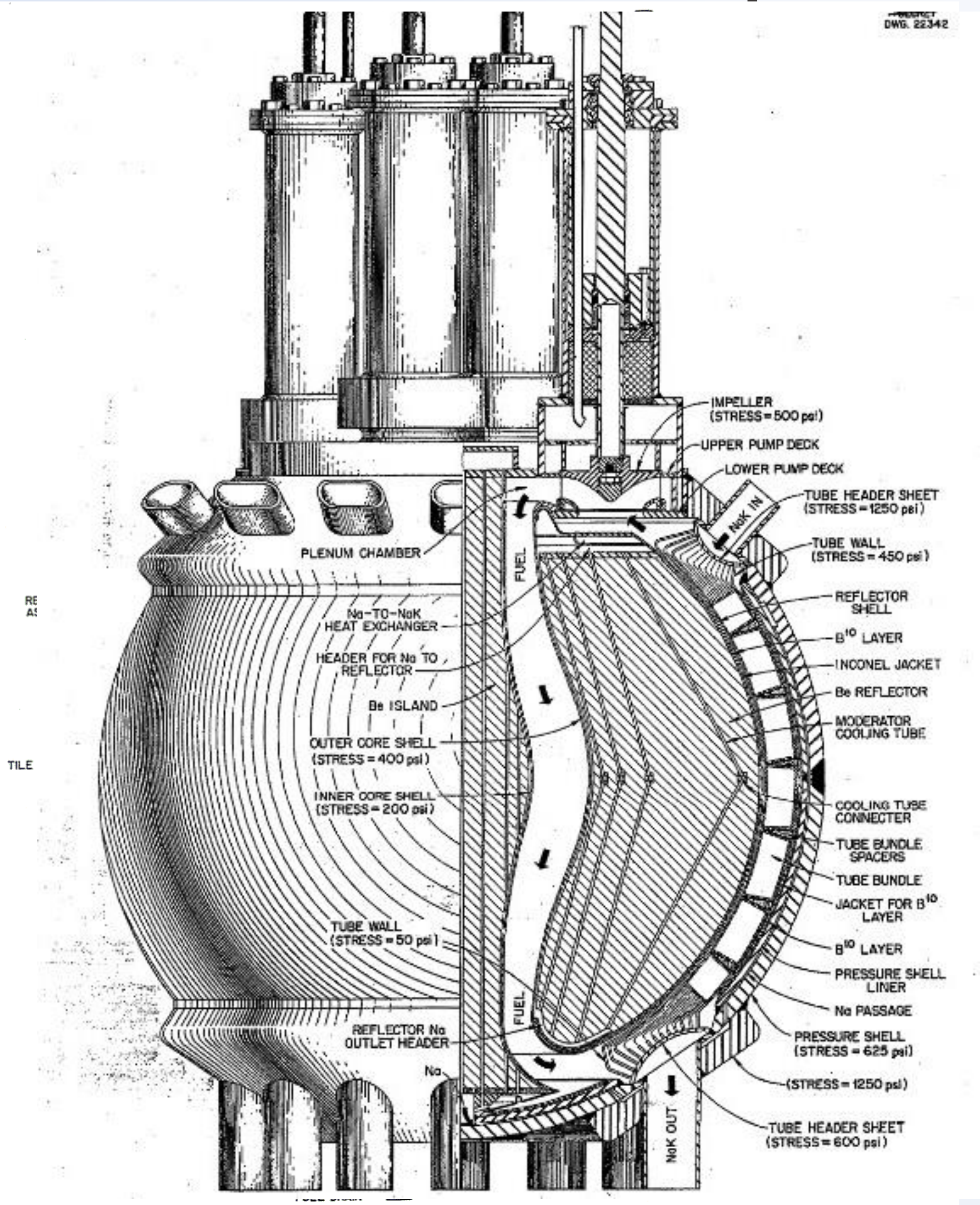


Fig. 4.33. Aircraft Power Plant (200 Megawatt).

Aircraft Reactor Experiment (ARE)



Aircraft Reactor Tests (ORNL)

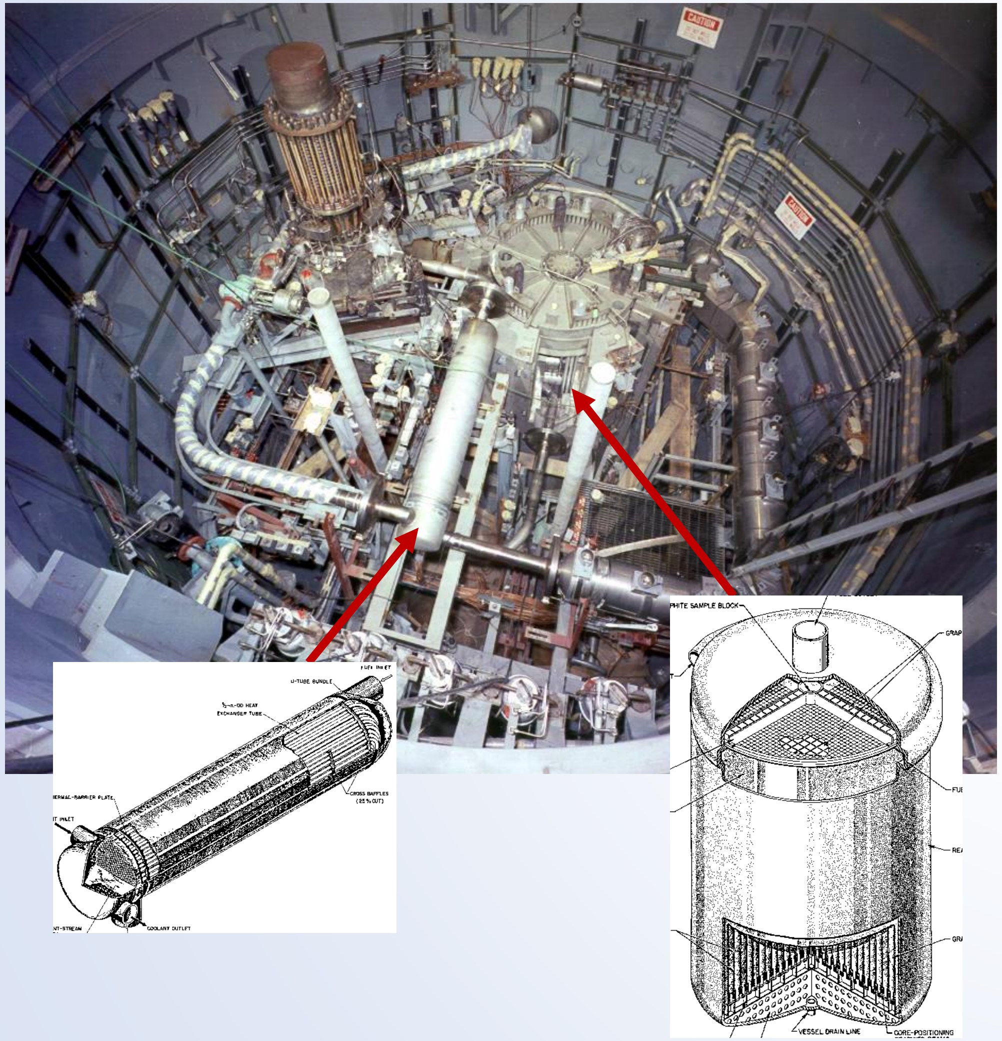
- Primary Coolant & Fuel: NaF - ZF_4 - UF_4 (53 - 41 - 6 mol %)
- Secondary Coolant: NaK @ 1150 K (~880°C)
- Power: 60 MW_{th}
- Dia. 1.4 m outer pressure shell
- Core Power density: 1.3 MW/L (Primary coolant)

- Design life: 1500 hours, 62.5 days
- 500 hrs at maximum power
- Zero power mock up built.
- ANP project cancelled before PWAR-1* was built

* Pratt & Whitney Aircraft Reactor – 1

Source: Oak Ridge National Lab. Gehin J., Sorensen K.

Molten Salt Reactor Experiment (MSRE) 1965-1969

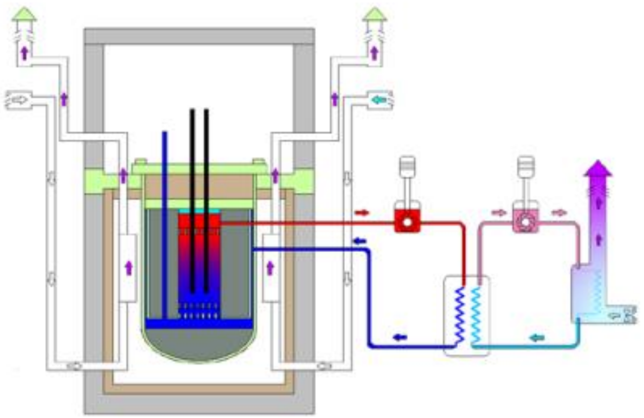


- Primary Coolant: FLiBe (^{7}Lithium-beryllium-fluoride)
- Secondary Coolant: FLiNaK
- Fuel: UF_4 (35% enriched HEU)
- Moderator: graphite
- Neutron reflector: graphite
- Vessel: Hastelloy-N

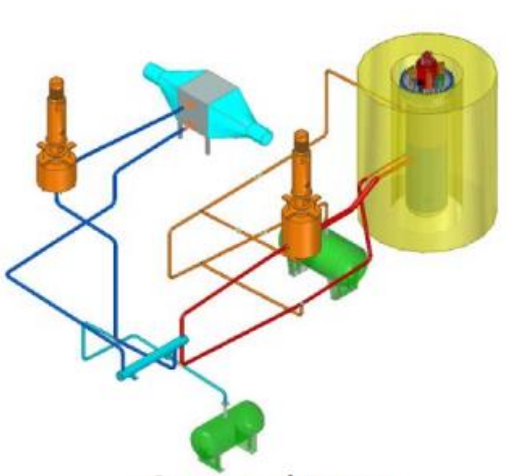
- Operating temperature: 600 – 610 °C
- Operating temperature: ~1 atm
- Power: 8 MW_{th}
- ~10,000 hrs operation using both ^{235}U and ^{233}U
- Plan was to construct a MSBRs for breeding ^{233}U from thorium
- However, project was discontinued

Intermission
(1975 - 2010)

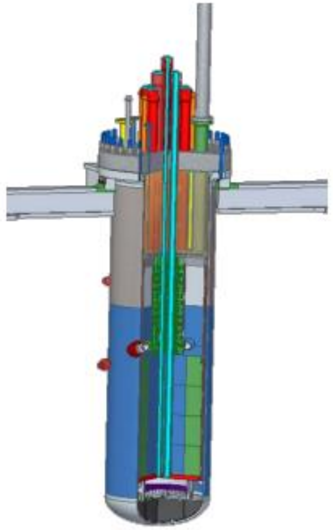
TMSR SF-0, SINAP Shanghai Inst. of Applied Physics

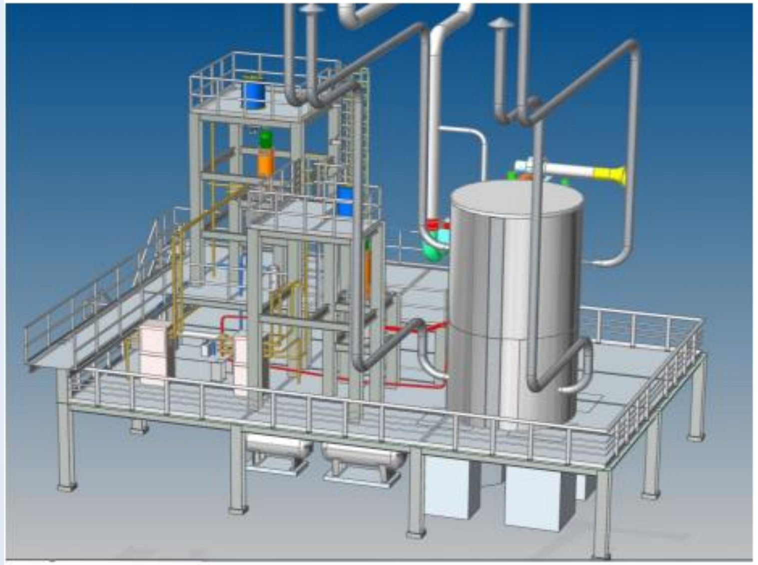


Schematics of principle



System layout



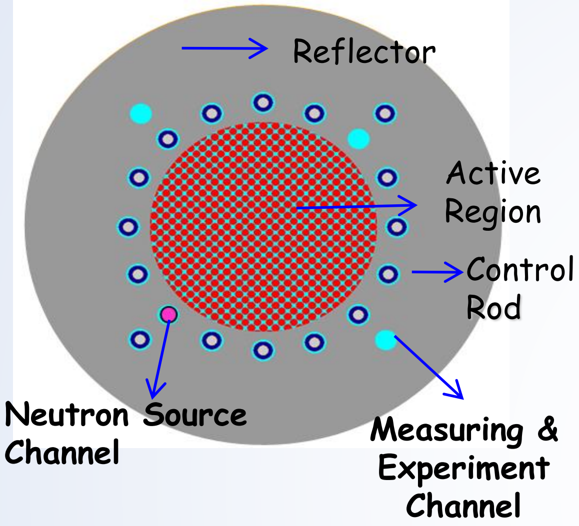


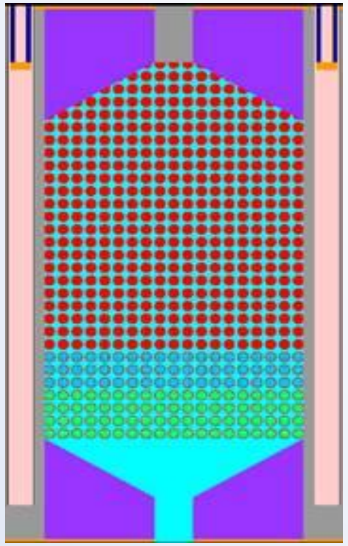
Overall installation drawing

TMSR- SF0 Design Parameters			
Electric Heating Rated Power @ Core	370kW	Design Temperature @ Main Vessel	700℃
Temperature of Molten Salt @Reactor Inlet	600℃	Design Pressure @ Main Vessel	0.5MPa
Temperature of Molten Salt @Reactor Outlet	650℃	Design life	10 year
Mass Flow of Molten Salt @ Primary Loop	0-10.0 kg/s	Mass Flow of Molten Salt @ Second Loop	0-12.2 kg/s
Cover Gas @ Primary Loop	Ar	Rated Power of Passive Exhaust System	12.8 kW
Molten Salt @ Primary Loop	FLiNaK	Molten Salt @ Second Loop	FLiNaK

Source: SINAP – ORNL MSR workshop 2016

TMSR SF-1



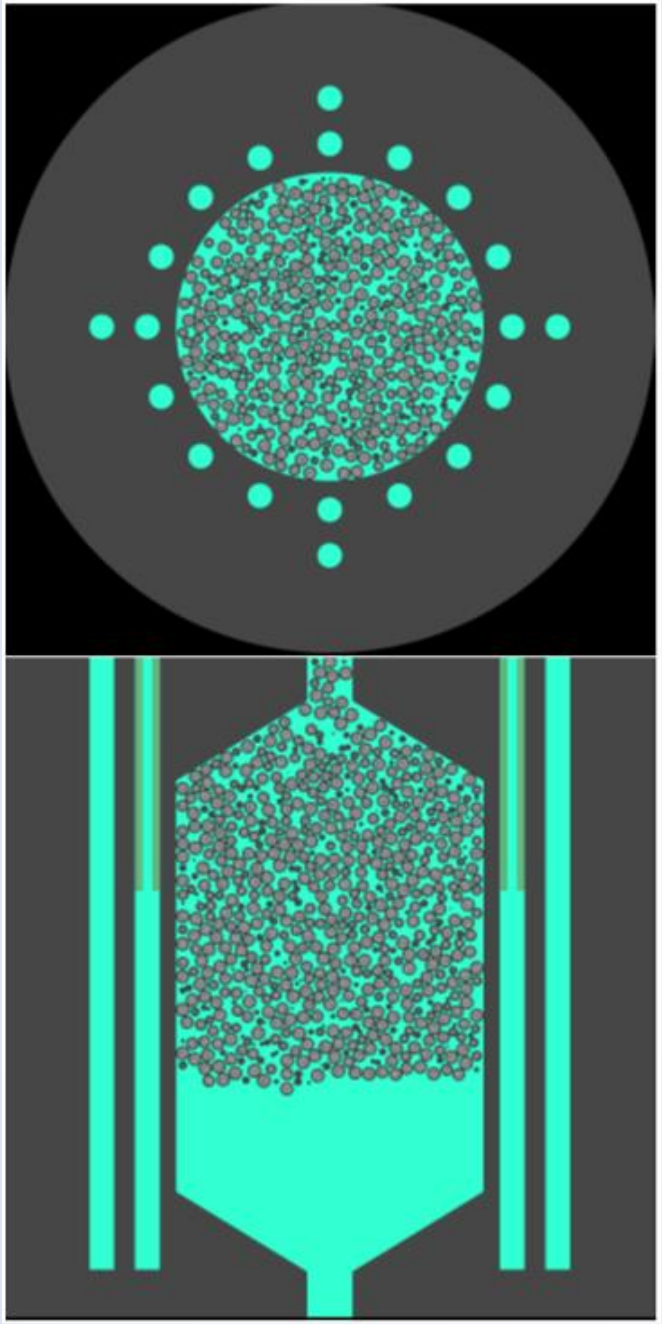


- 10 MW thermal
- 14,650 x 6cm dia. TRISO pebble fuel
- U-235 enrichment: 17.08 % (13.1 kg)
- Primary coolant: 2LiF-BeF2
- Secondary coolant: FLiNaK
- Operating Temperature: 628°C
- Design discontinued

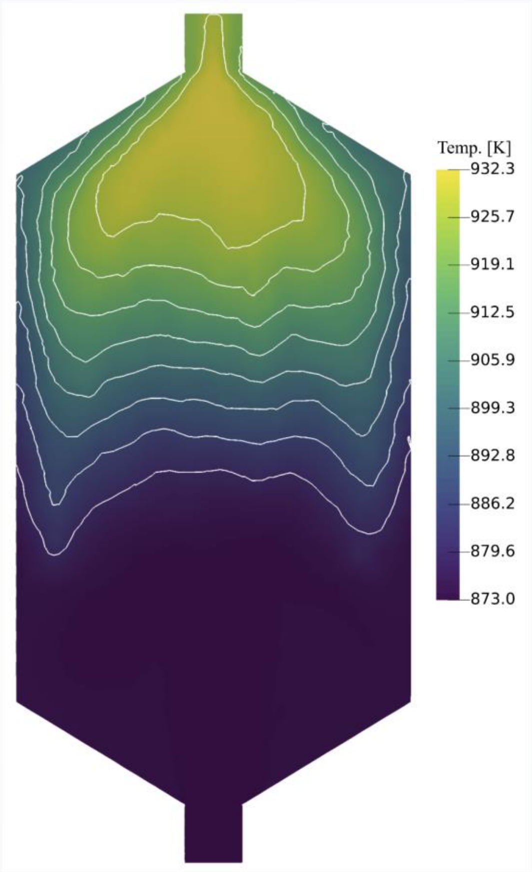
Source: SINAP

TMSR-SF1

Multiphysics simulation of a molten salt cooled, pebble bed fuelled reactor

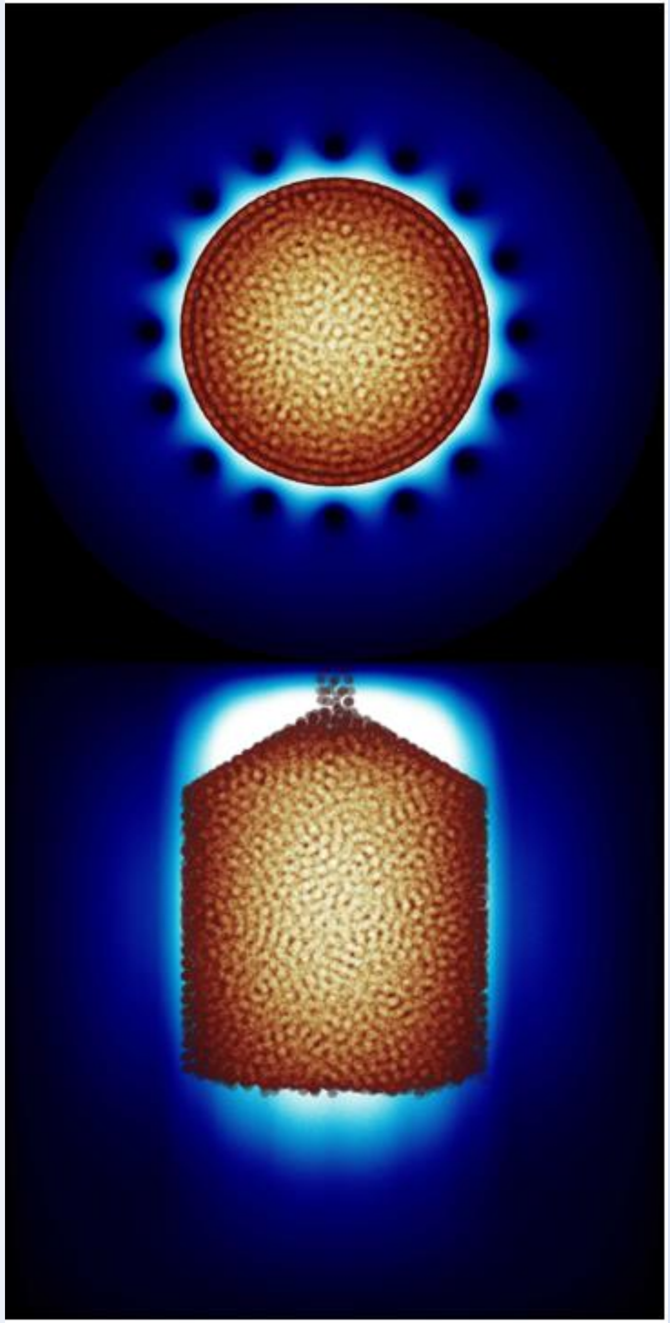


Geometry and location of pebbles for the TMSR-SF1 containing 11 000 fuel pebbles with a flat-shaped base.



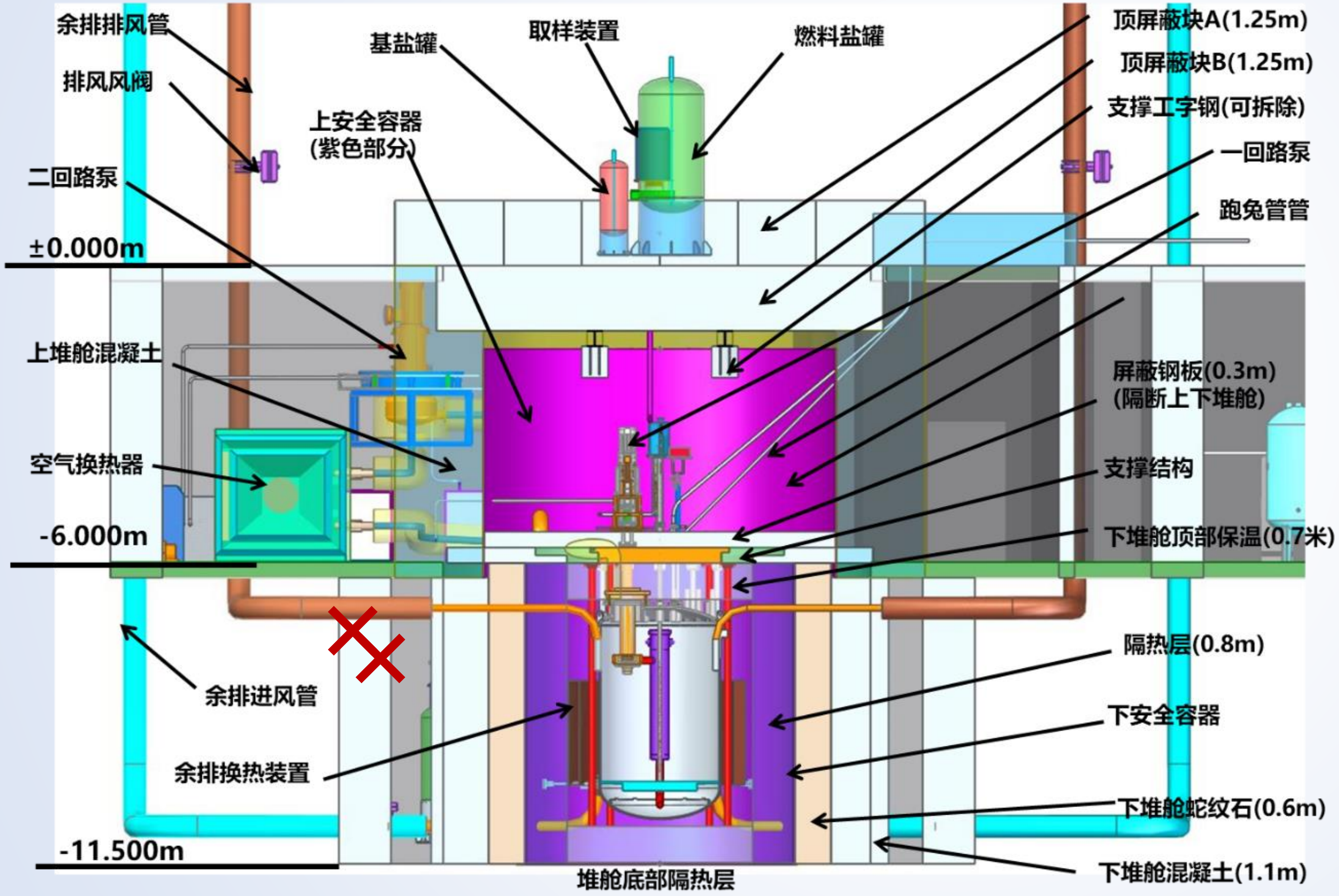
Temperature distribution of molten salt coolant for the TMSR-SF1 containing 11 000 fuel pebbles with a flat-shaped base at a power of 10 MW_{th}.

Source: Mardus-Hall, et al.



Relative thermal neutron flux (cool blues) and relative fission rate (hot reds) for TMSR-SF1 containing 11 000 fuel pebbles with a flat-shaped base, control rods fully inserted.

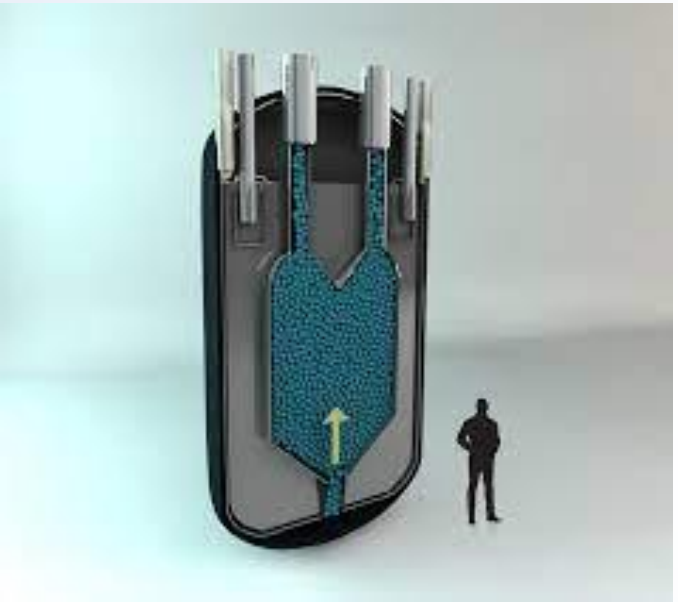
LF-1 (2MW$_{th}$) construction in Wu Wei, Gansu

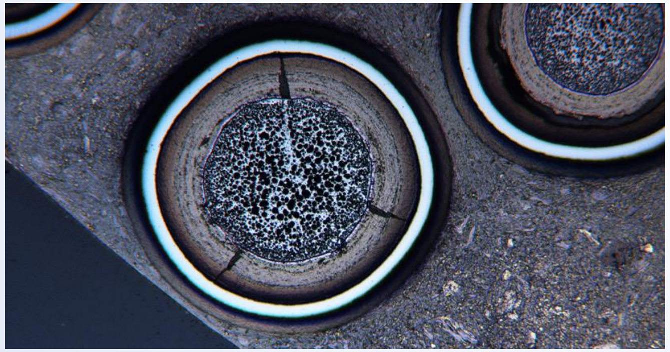


Source: Shanghai Institute of Nuclear Applied Science

Kairos Power – Pebble fuel, FLiBe coolant

S	M/D-proof.	✓
	D-in-D	✓
W	Burn TU	✗
NP	No Diversion	✓
E	High temp.	✓
	$ Fuel fab.	✗
	Existing tech	✓
	Low LCOE	?
	Licensable?	✓



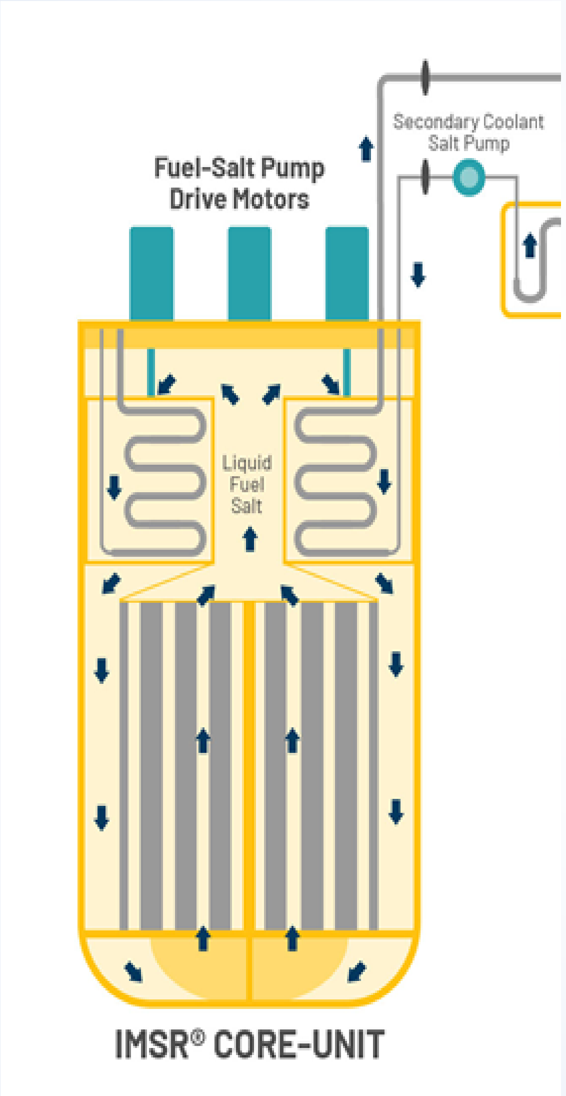


- Power: 320 MW_{th} / 140_e
- Reactor Vessel H / Dia (m): 15 / 3
- Primary coolant: Li_2BeF_4 (^{7}Lithium-beryllium-fluoride)
- Secondary: Nitrate salt; Tertiary: SH Steam
- Moderator: FLiBe + graphite
- Core T_{in} / T_{Out}: 550 / 650°C
- Fuel: TRISO Pebble fuel, 19.75% (HALEU)
- Online refueling
- Control Rod – B_4C in SS316H Clad, in reflector
- Passive shutdown and heat removal
- Longer than 72-hour coping time
- Design status: Conceptual
- Awarded USD 303 M (Adv. Reactor Demo. Program)
- Collaborating with TVA to deploy low power HERMES

Source: IAEA, Advances in SMR Technology Developments, 2020

Terrestrial Energy – IMSR Integral Molten Salt Reactor

S	M/D-proof.	✓
	D-in-D	?
W	Burn TU	✗
NP	No Diversion	✓
E	High temp.	✓
	\$ Fuel fab.	✓
	Existing tech	✓
	Low LCOE	?
	Licensable?	✓

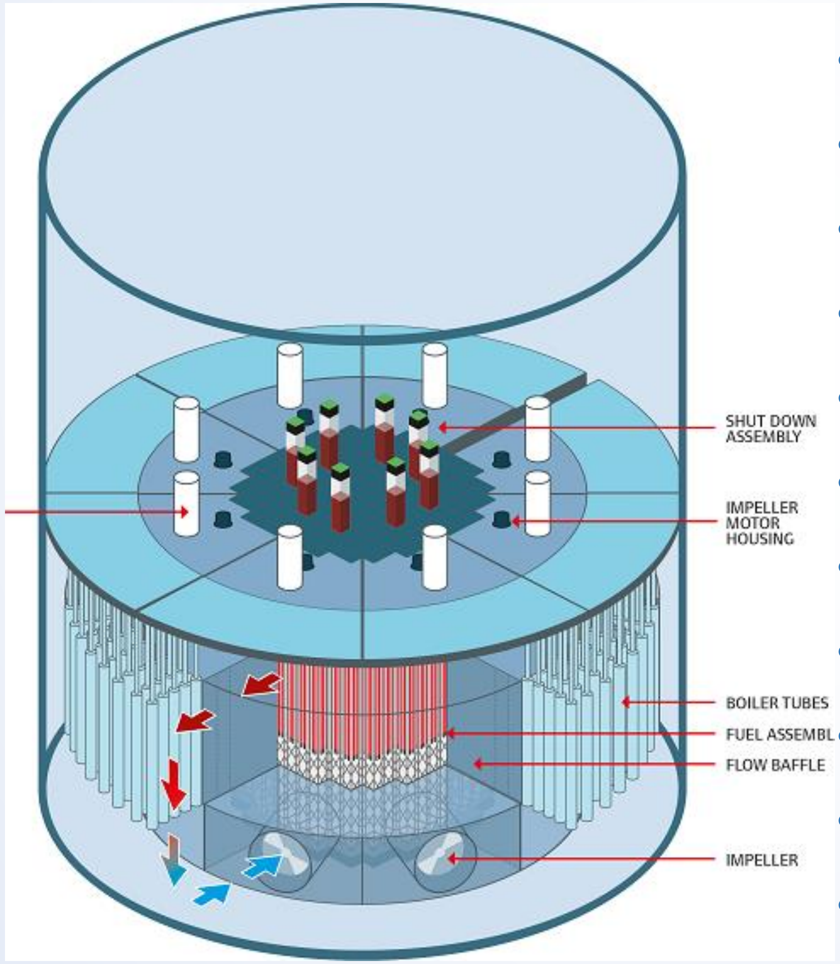


- Power: 440 MW_{th} / 195 MW_e
- Reactor Vessel H / Dia (m): 10 / 3.7
- Primary coolant: Fluoride salt (No ^7Li or Be)
- Secondary: Solar salt; Tertiary: SH Steam
- Moderator: fluoride salt + graphite
- Core T_{in} / T_{Out}: 620 / 700°C
- Fuel: Molten Fuel salt, < 5% enriched. Also Pu, U-233 etc
- Fuel Cycle: 7 years (core content swap out)
- Control Rod – B_4C in SS316H Clad, in reflector
- Passive shutdown and heat removal
- Design status: Conceptual
- Working with ANL to test fuel salt as part of DOE's Gateway for Accelerated Innovation in Nuclear (GAIN) program

Source: IAEA, Advances in SMR Technology Developments, 2020

Moltex Energy SSR - fuel stringers, ZrF_4 - KF salt

S	M/D-proof.	✓
	D-in-D	✓
W	Burn TU	✓
NP	No Diversion	?
E	High temp.	✓
	$ Fuel fab.	?
	Existing tech	✓
	Low LCOE	?
	Licensable?	✓

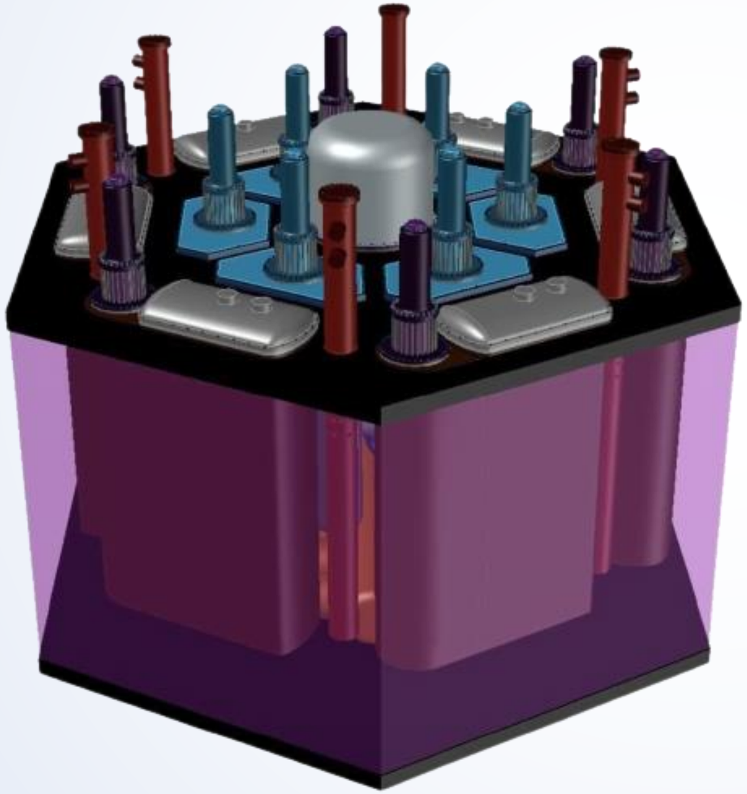


- Power: 750 MW_{th} / 300_e , 900_e peaking plant
- Reactor Vessel H / Dia (m): 10 / 6
- Primary coolant: 42% ZrF_4 / 58% KF
- Secondary coolant – nitrate salt buffer
- Moderator: none – fast spectrum
- Core T_{in} / T_{Out}: 525 / 590°C
- Fuel: 45% KCl, 25% RG $PuCl_3$, 30% UCl_3
- Molten salt fuel in 451 FAs in hexagonal array
- Fuel Stringer – Alloy-91 steel
- Redox control – Zr sacrificial metal
- Core Burn up: 120 – 200 GWd/tHM
- Design status: Conceptual
- UK / Canadian collaboration
- Awarded $50.5 M from Canada, $2.5 M from DOE

Source: IAEA, Advances in SMR Technology Developments, 2020

Elysium Industries – Molten Chloride Fast Reactors

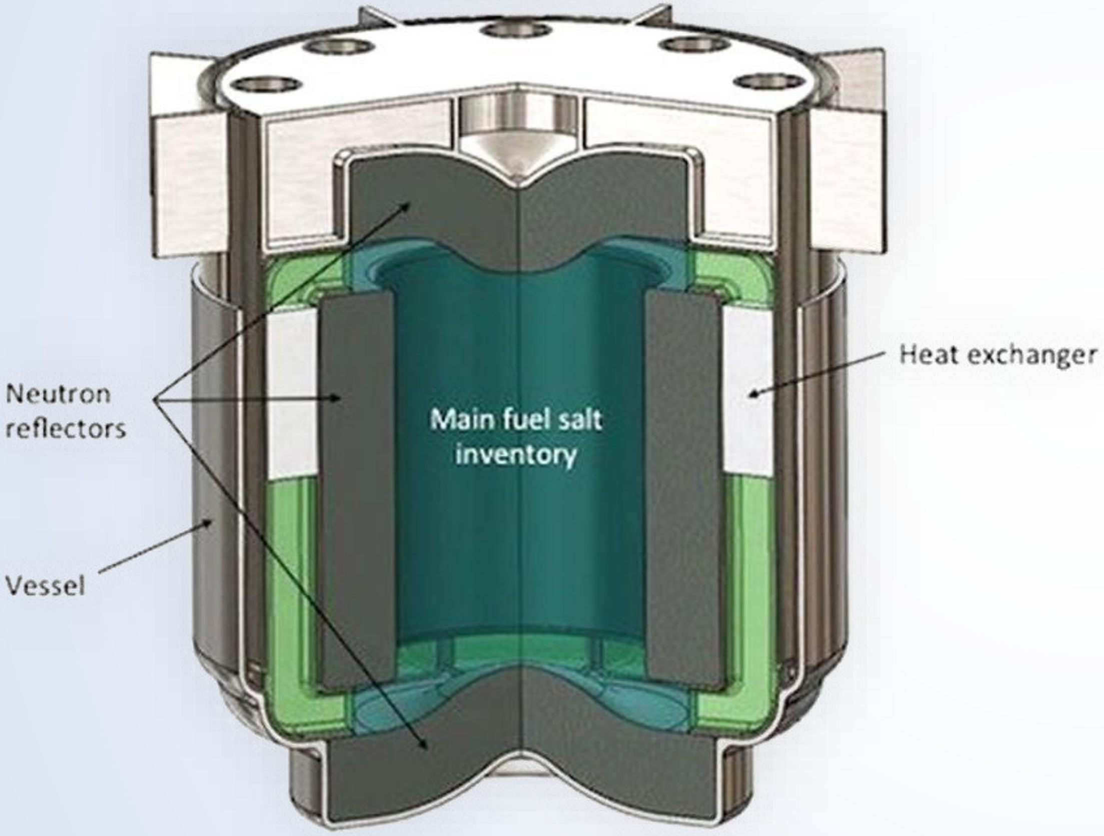
S	M/D-proof.	✓
	D-in-D	?
W	Burn TU	✓
NP	No Diversion	✓
E	High temp.	✓
	$ Fuel fab.	✓
	Existing tech	✓
	Low LCOE	?
	Licensable?	✓



- Power: 125 MW_{th} / 50_e , 3000 MW_{th} / 1200_e
- Reactor Vessel H / Dia (m): 9 / 4
- Primary coolant: $NaCl\text{-}XCl_v\text{-}YCl_z\text{-}UCl_{3/4}$
- Secondary coolant – Primary w/o Fuel salt
- Tertiary loop – SH Steam
- Moderator: none – fast spectrum
- Core T_{in} / T_{Out}: 650 / 750°C (Goal 950°C)
- Fuel: $PuCl_3\text{-}FPCl_y$ fuel salt
- Enrichment: 10% Pu fissile/(Pu+U total)
  or 15% HALEU
- Core Burn up: SNF/DU/NU (1tHM/GWe-yr)
- Design status: Conceptual
- Working with ORNL to convert SNF into fuel salt as part of DOE's Gateway for Accelerated Innovation in Nuclear (GAIN) program

Source: IAEA, Advances in SMR Technology Developments, 2020

Other notable designs



Terrapower
Molten Chloride Fast Reactor

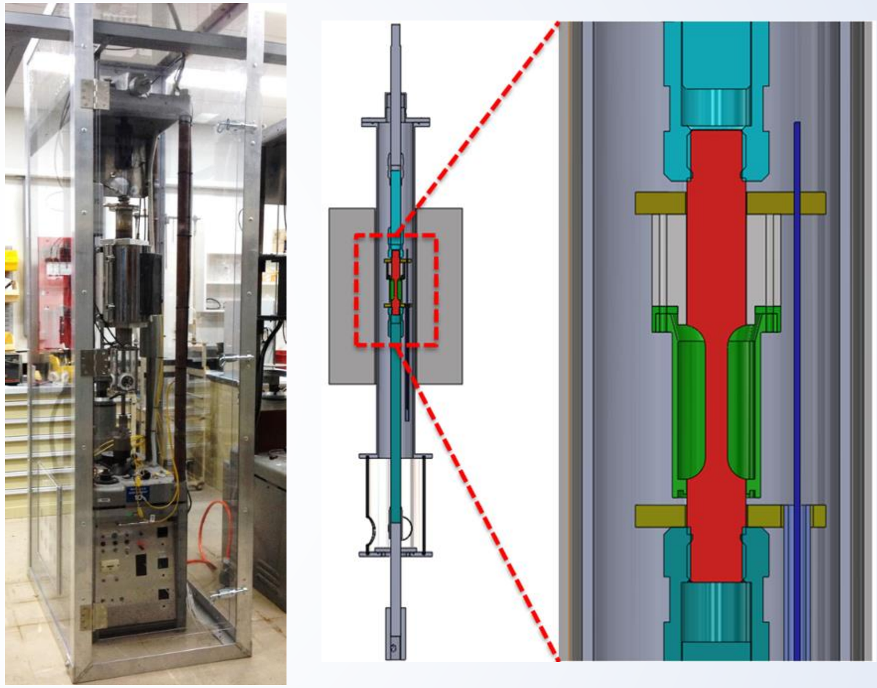
Thorcon
FNPP Molten Salt Reactor

Molten Corrosion Testing Facility @ANSTO

Static Corrosion Rig

- FLiNaK salt composition
- Temperatures: 500°C - 750°C
- Argon Atmosphere

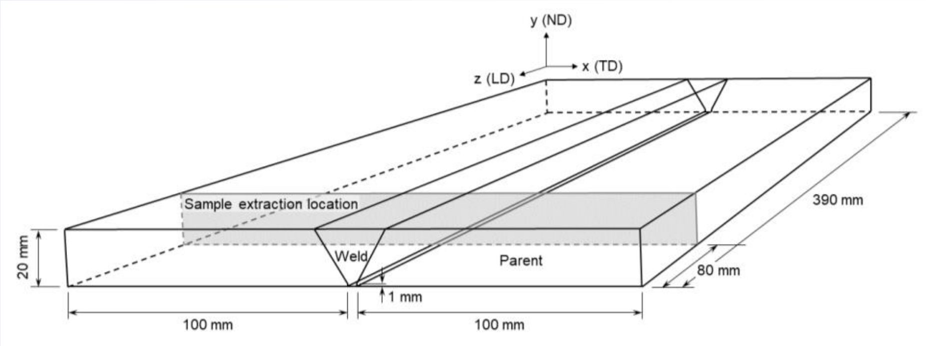
Creep - Molten Salt Testing

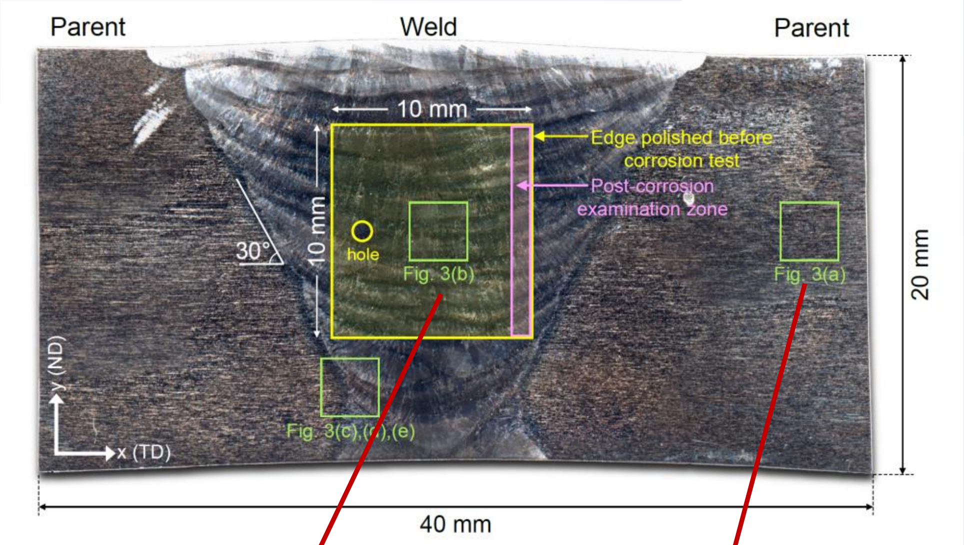


- FLiNaK salt composition
- Temperatures: 550°C - 850°C
- Argon Atmosphere

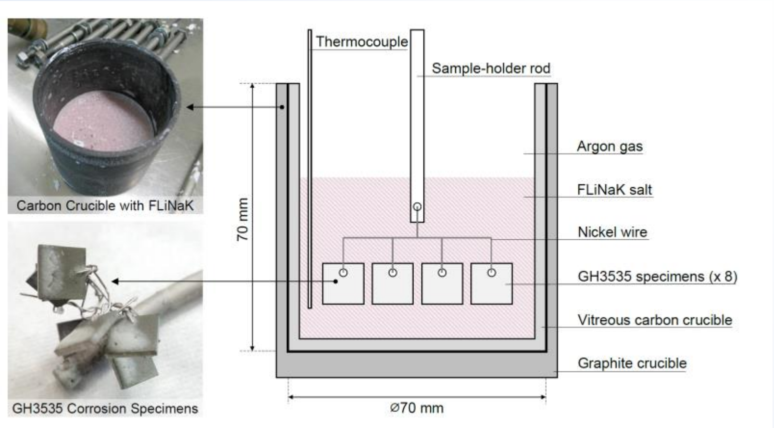
NiMoCr Parent/Weld - FLiNaK Corrosion

GH3535 Welded Plate



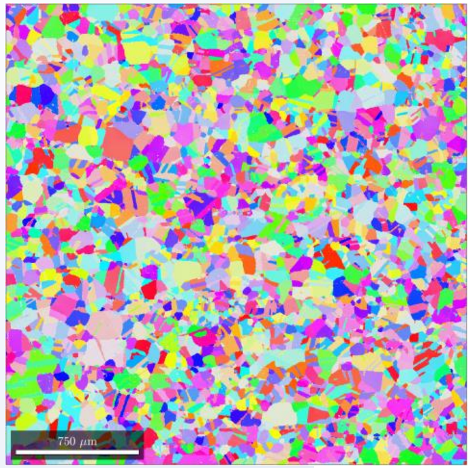


Molten Salt Testing



Weld Metal

Parent Metal



A. Danon, O. Muránsky, H. Zhu, I. Karatchevtseva, L. Edwards, et al., Corrosion Science, 164, 2020.

Closing Thoughts

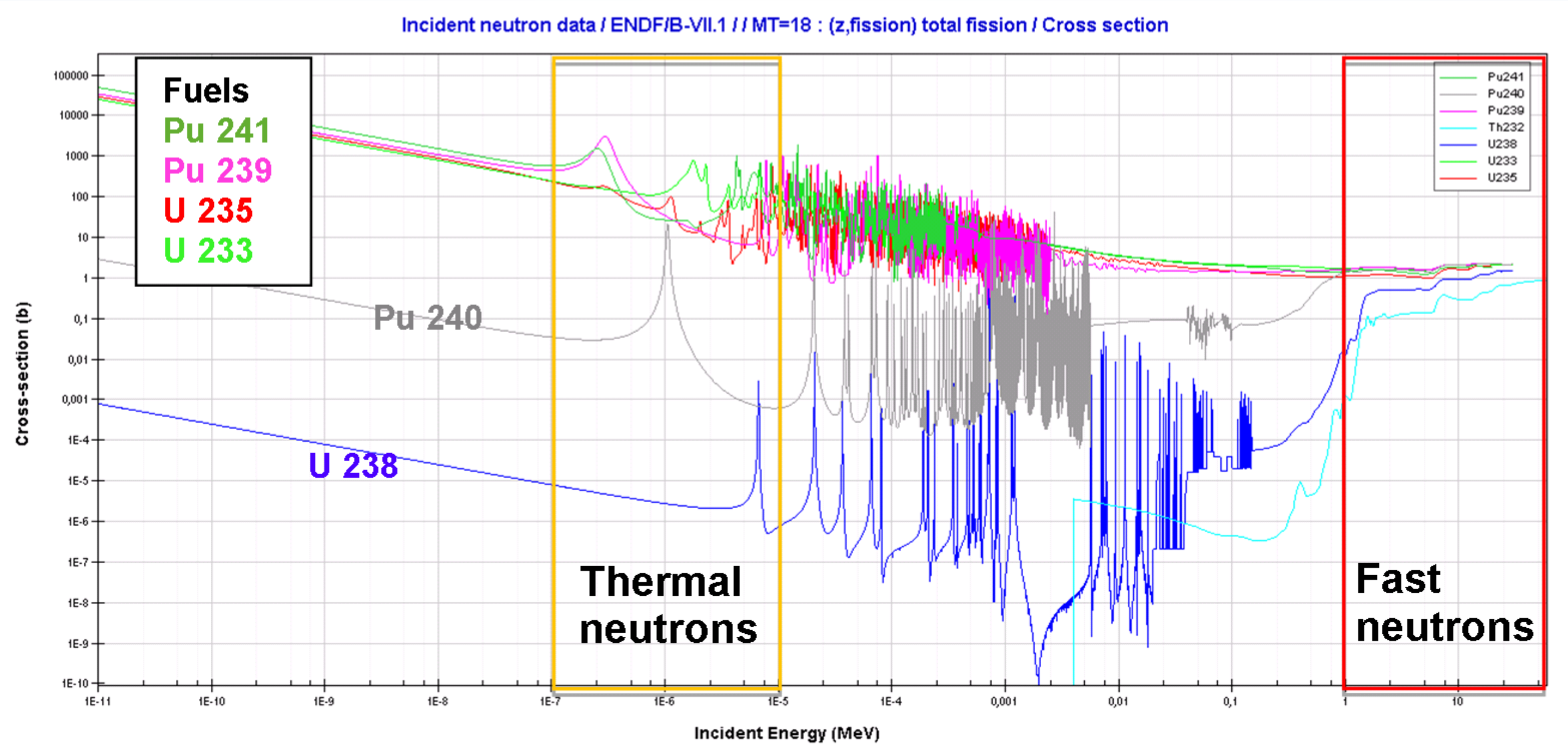
Wish-list

S	M/D-proof.	✓
	D-in-D	✓
W	Burn TU	✓
NP	No Diversion	✓
E	High temp.	✓
	$ Fuel fab.	✓
	Existing tech	✓
	Low LCOE	✓
	Licensable?	✓

- Passive safety designs
- Non-proliferation consideration still v. important
- There is a business case for TU burning
- Onus on dispatchable power.
- Use of 3 loops common
- Intermediate salt serves as a heat-bank
- Not waiting on next-gen tech.
- Use of SH Steam cycle and existing alloys
- Strong Gov. funding for a wide range of ideas
- Drive to increase competition in the nuclear sector while building capability with National Nuclear Labs.

Thanks.
Questions?

Capture Cross Section



Coolant Comparison

Salt [a]	Formula weight (g/mol)	Melting point (ºC)	900ºC vapor pressure (mm Hg)	Heat transfer properties at 700°C: ρ Density (g/cm^3)	ρ*Cp Volumetric heat capacity (cal/cm^3-ºC)	Viscosity (cP)	Thermal conductivity (W/m-K)	Neutron capture relative to graphite[b]	Moderating ratio[c]
LiF-BeF$_2$	33.0	460	1.2	1.94	1.12	5.6	1.0	8	60
NaF-BeF$_2$	44.1	340	1.4	2.01	1.05	7	0.87	28	15
LiF-NaF-BeF$_2$	38.9	315	1.7	2.00	0.98	5	0.97	20	22
H_2O (1 atm)	18.0	0.0	N/A	1.0	1.00	1.0	0.58	75	246
LiF-ZrF$_4$	95.2	509	77	3.09	0.90	> 5.1	0.48	9	29
NaF-ZrF$_4$	92.71	500	5	3.14	0.88	5.1	0.49	24	10
KF-ZrF$_4$	103.9	390	--	2.80	0.70	< 5.1	0.45	67	3
Rb-ZrF$_4$	132.9	410	1.3	3.22	0.64	5.1	0.39	14	13
LiF-NaF-ZrF$_4$	84.2	436	~ 5	2.79	0.84	6.9	0.53	20	13
LiF-NaF-KF	41.3	454	~ 0.7	2.02	0.91	2.9	0.92	90	2
LiF-NaF-RbF	67.7	435	~ 0.8	2.69	0.63	2.6	0.62	20	8

[a] Salt compositions are given in Table 2; nuclear calculations used 99.995% ^{7}Li.
[b] Computations based on energy range 0.1 to 10 eV (Sect. 4.1)
[c] As defined in textbooks and in Sect. 4.1.

Source: ORNL Report: TM-2006 -12 Assessment of Candidate Molten Salt Coolants for the AHTR