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Thermal Hydraulics
Laboratory

MSRs for the Future

Workshop on Molten Salt Reactor Technologies—

Commemorating the 50th Anniversary of the Startup of the MSRE

Per F. Peterson
Thermal Hydraulics Research Group, U.C. Berkeley
October 15, 2015

FHR
Fluoride Salt Cooled High Temperature Reactor

NEUP
Nuclear Energy University Programs
U.S. Department of Energy

Overview

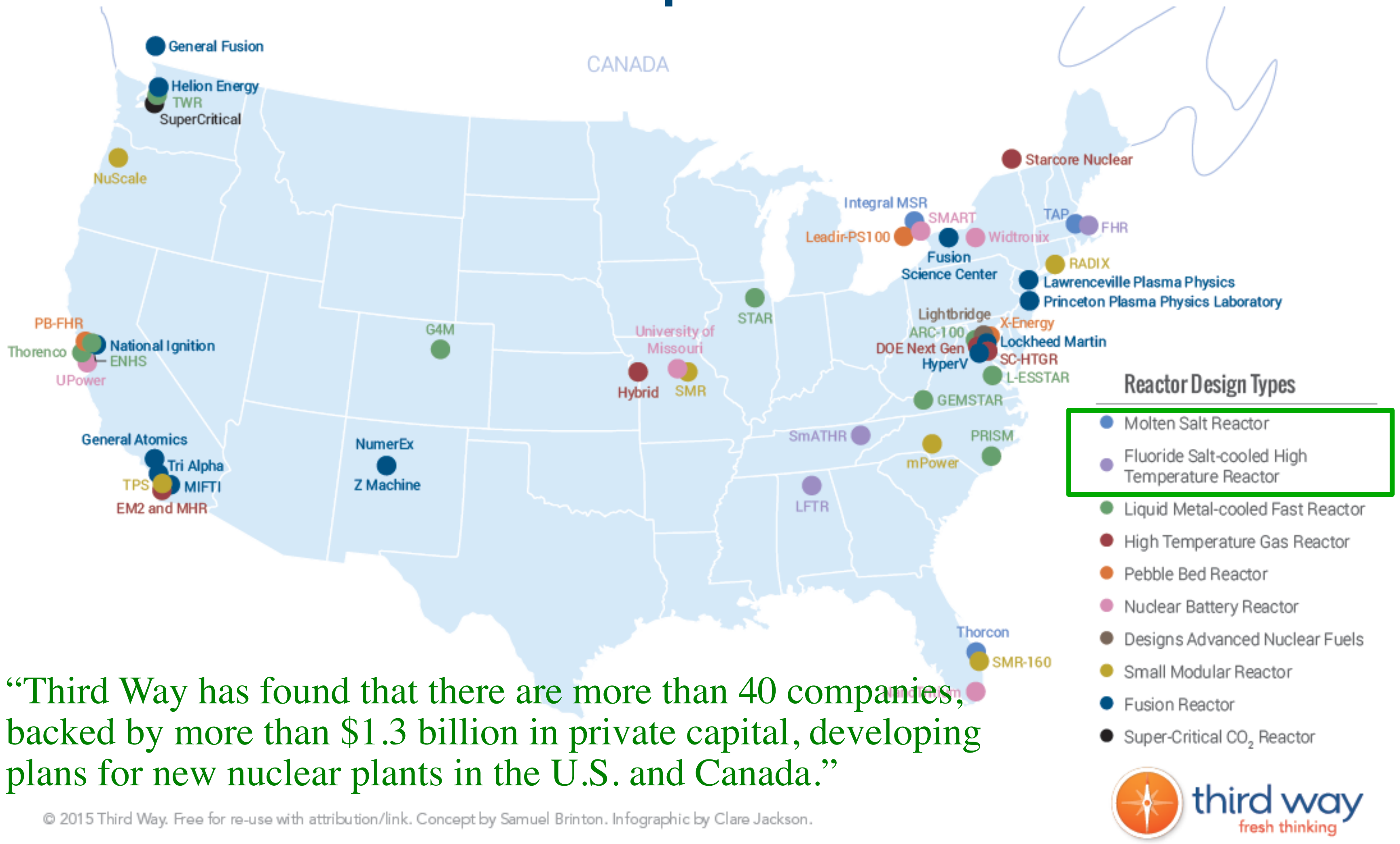
- Context
  - Need for innovation in future nuclear reactor techology
  - Successful innovation in other industries
  - Changing U.S. environment for innovation
- Molten salts: why are they different?
- Molten salts: where are we now?
- Molten salts: what are the next steps?

Today's fission reactors are remarkably expensive to build !!

Commodity Input	Com-modity Price (1)	1000-MW Gen II Pressurized Water Reactor (2)		2-MW Vestas V90 wind turbine in 50-MW field (3)		0.15-MW (196-Hp) Chevy Malibu automobile (4)	
	(\$/kg)	kg/kW	$\$/\text{kW}_{\text{peak}}$	kg/kW	$\$/\text{kW}_{\text{peak}}$	kg/kW	$\$/\text{kW}_{\text{peak}}$
Concrete	\$0.03	180.06	\$5.85	375.44	\$12.20		
Carbon steel	\$0.64	33.99	\$21.75	110.56	\$70.76	7.547	\$4.83
Copper/brass	\$5.13	0.73	\$3.74	3.32	\$17.02	0.197	\$1.01
Aluminum	\$1.60	0.02	\$0.03	3.20	\$5.12	0.715	\$1.14
Inconel	\$10.50	0.12	\$1.30				
High-alloy steel	\$1.79			12.22	\$21.87		
Nickel	\$10.50	0.00	\$0.01				
Lead	\$1.74	0.05	\$0.08				
Magnesium	\$4.59					0.021	\$0.10
Platinum	\$31,800					0.000	\$1.65
Plastic/paint	\$1.52	0.05	\$0.08	26.78	\$40.65	1.161	\$1.76
Rubber	\$1.63					0.249	\$0.41
Glass/ceramic	\$2.00			9.56	\$19.12	0.301	\$0.60
Thermal insulation	\$1.00	0.92	\$0.92				
Electronics	\$5.13			1.20	\$6.15		
Totals		216	**\$33.76**	542	**\$192.89**	10.19	**\$11.50**
Purchase price (\$/peak kW) (5)			**\$5,000**		**\$1,750**		**\$154**
Commodity % of peak kW price			**0.68%**		**11.0%**		**7.46%**
Ratio nuclear com. % of price vs. ot			**1.0**		**16.3**		**11.0**

Nuclear commodity cost is $\$37.51/\text{kW}_{\text{ave}}$, vs. wind $\$539/\text{kW}_{\text{ave}}$

Third Way study identified 7 current molten salt development efforts



“Third Way has found that there are more than 40 companies, backed by more than $1.3 billion in private capital, developing plans for new nuclear plants in the U.S. and Canada.”

© 2015 Third Way. Free for re-use with attribution/link. Concept by Samuel Brinton. Infographic by Clare Jackson.

http://www.thirdway.org/infographic/nuclears-continuing-evolution

New technologies for space launch provide interesting analogies for advanced nuclear

Space Shuttle, 1984

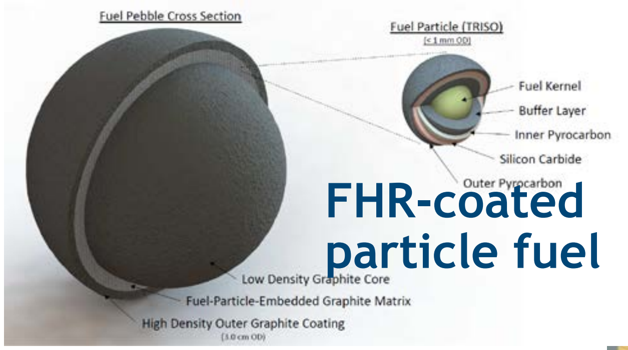
SpaceX Falcon 9, 2015

- Designed for reusability
- Two major accidents (astronauts perished)
- Liquid hydrogen/oxygen and solid rocket boosters
- Lifetime launch cost: $60,000/kg

- Designed for reliability and low cost (reusability available soon)
- One major accident June 2015 (Dragon capsule survived)
- Kerosene/liquid oxygen (LNG longer-term option)
- Current launch cost: $4,600/kg

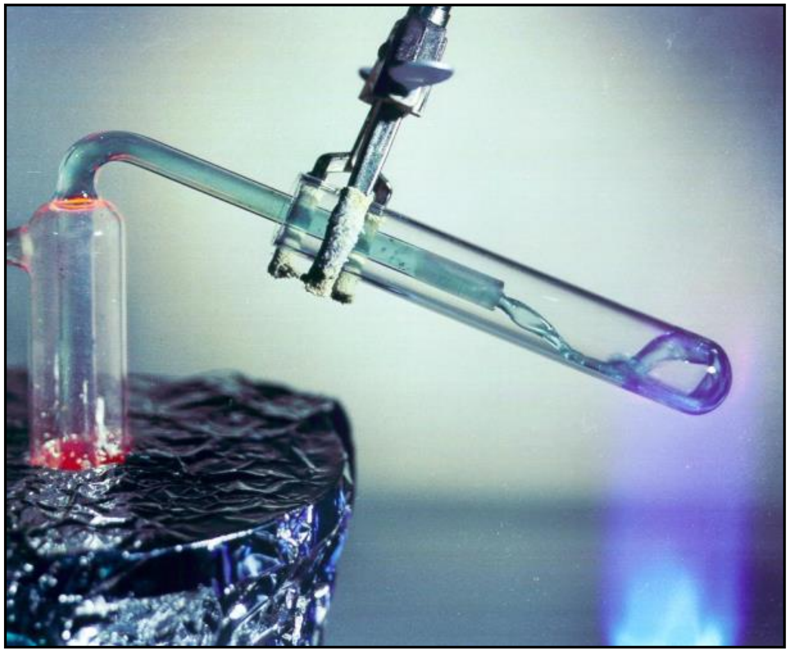
Molten salts: why are they different?

FHRs and MSRs combine three key technologies that enable delivery of heat at high temperature

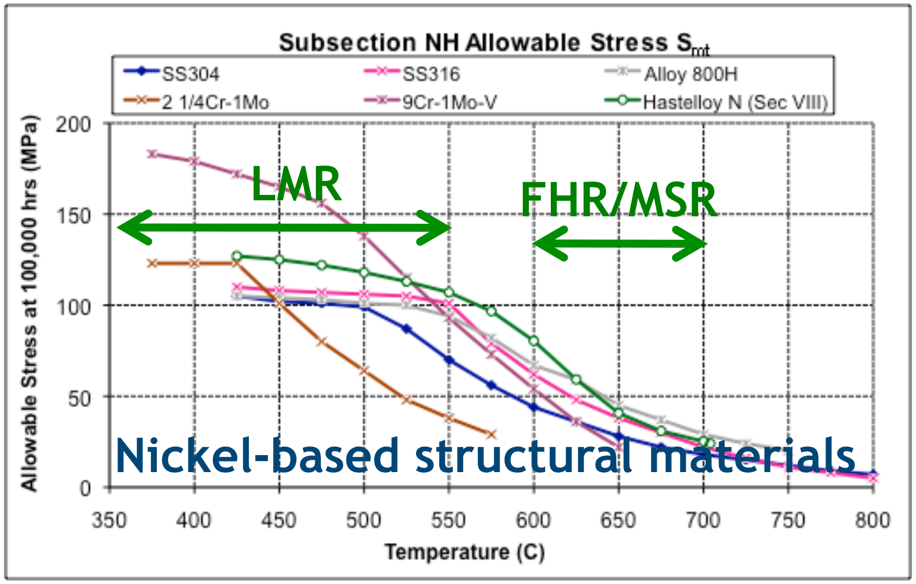


FHR-coated particle fuel

MSR-graphite moderator structures



Liquid fluoride salt coolants



Nickel-based structural materials

Molten salts have substantial different properties than other reactor coolants

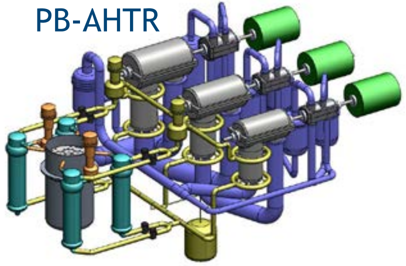
Material Properties at 700°C	T_{melt} (°C)	T_{boil} (°C)	ρ (kg/m^3)	C_p (kJ/kg°C)	ρC_p (kJ/m^3°C)	k W/m°C	ν x 10^6 m^2/s
$^7Li_2BeF_4$ (Flibe)	459	1,430	1,940	2.34	**4,540**	1.0	2.9
Sodium	97.8	883	790	1.27	**1,000**	62	0.25
Lead	328	1,750	10,540	0.16	**1,700**	16	0.13
Helium (7.5 MPa)			3.8	5.2	**20**	0.29	11.0
Water (7.5 MPa) †	0	100	732	5.5	**4,040**	0.56	0.13

† Water properties at 290°C for comparison

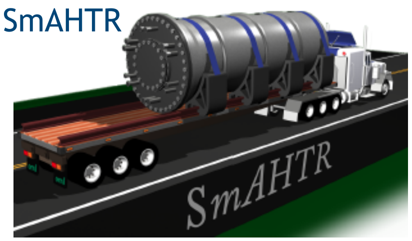
- High volumetric heat capacity
  - Results in compact reactor primary system, low circulating power
- High boiling temperature
  - Intrinsically low pressure, thin-walled primary coolant boundary
- Chemically stable coolant compatible with graphite
  - Core internal structures have very large thermal margins

U.S. university and laboratory R&D has focused on understanding FHRs

2008 900 MWt PB-AHTR

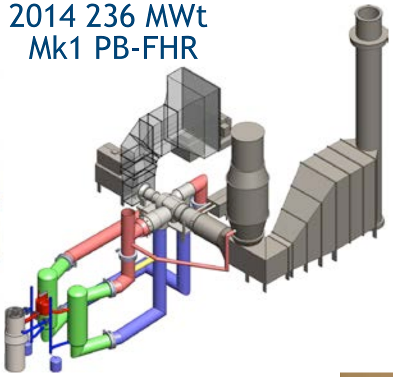


2010 125 MWt SmAHTR



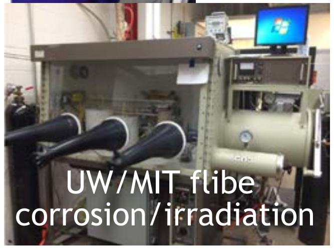
2012 3600 MWt ORNL AHTR

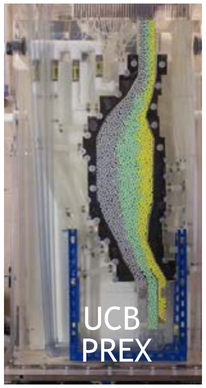
2014 236 MWt Mk1 PB-FHR

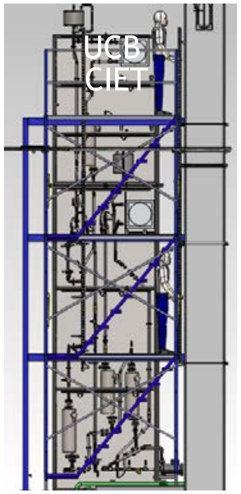


Multiple FHR Conceptual Design Studies


NGNP AGR


UW/MIT flibe corrosion/irradiation


UCB PREX


UCB CIET

Experiments and Simulation


4th FHR Workshop, MIT, Oct. 2012

Preliminary FHR Subsystems Definition, Functional Requirement Definition, and LBE Identification White Paper

UCBTH-12-001

Preliminary Fluoride-Salt-Cooled, High-Temperature Reactor (FHR) Subsystems Definition, Functional Requirement Definition, and Licensing Basis Event (LBE) Identification White Paper

March 2012
Revision 3

Integrated Research Project Workshop 1
Department of Nuclear Engineering
University of California, Berkeley

Panel Members

UC Berkeley Facilitators

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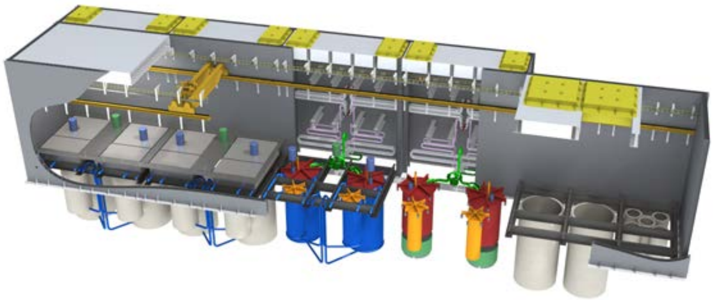
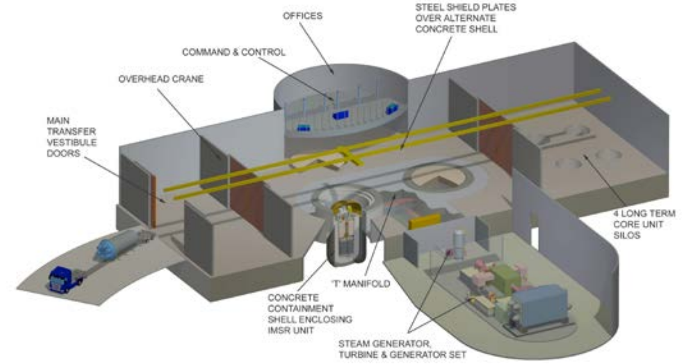
This research is being performed using funding received from the U.S. Department of Energy Office of Nuclear Energy's Nuclear Energy University Programs.

Expert Workshops and White Papers

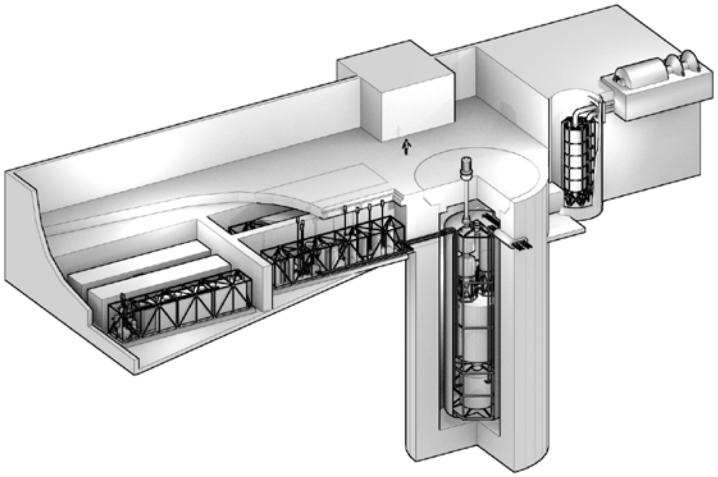
Multiple start-up companies are now developing liquid-fueled MSRs



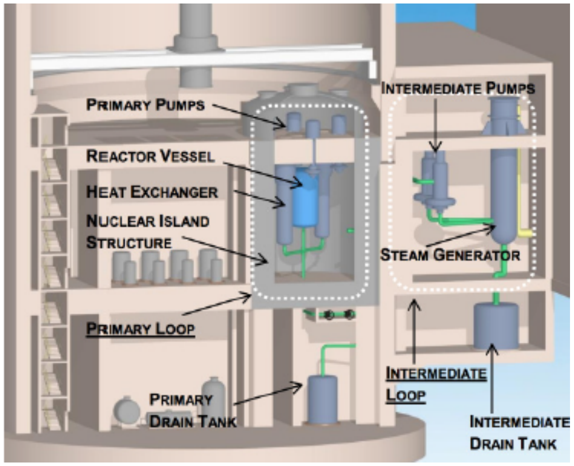
Thorcon



Terrestrial Energy



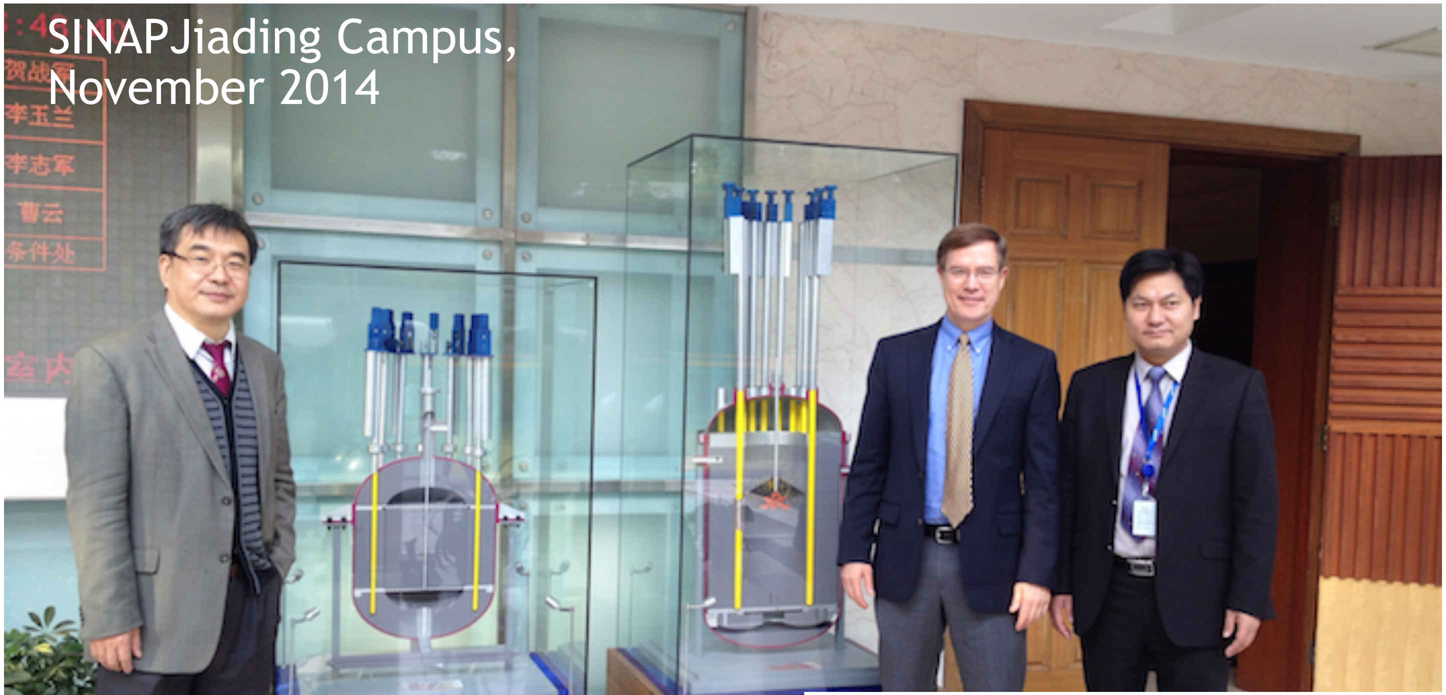
Flibe Energy



Transatomic

Europeans are also studying fast-spectrum MSRs

The Chinese Academy of Sciences is pursuing development of both solid and liquid fueled molten salt reactors



SINAPJiading Campus, November 2014

SINAP Shanghai Synchrotron Radiation Facility

Molten salts: what are the next steps?

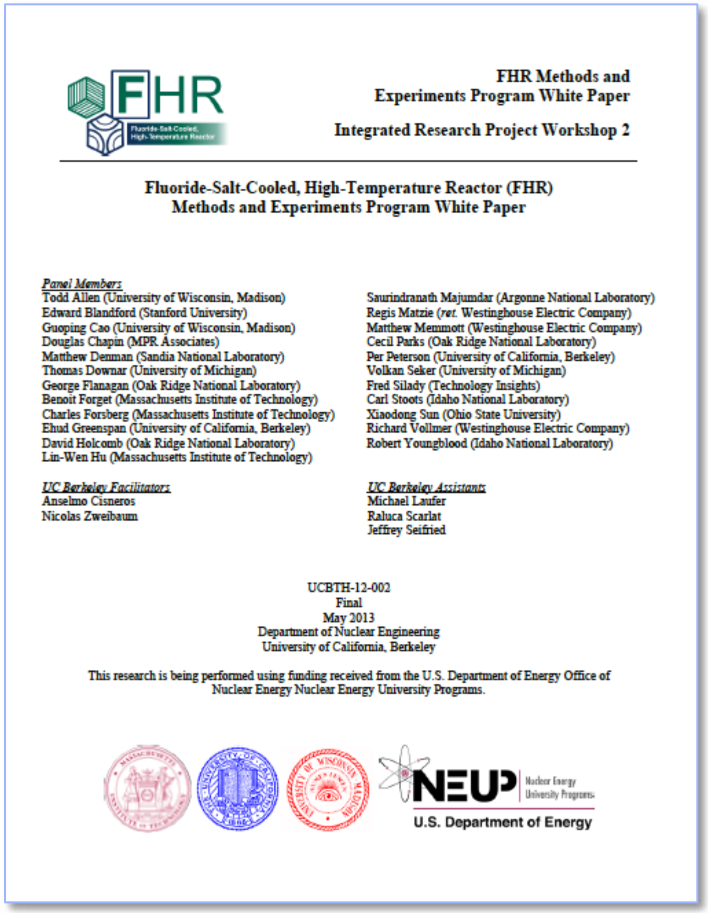
FHRs and MSRs have remarkably compact reactor vessels compared to HTGRs and SFRs

			Reactor Vessel		
	Type	Power (MWe)	Diameter (m)	Height (m)	**Specific power** (MWe/m3)
Mk1 PB-FHR	FHR	100	3.5	12.0	**0.87**
2012 ORNL AHTR	FHR	1530	10.5	19.1	**0.93**
Thorcon	MSR	250	5.0	5.7	**2.26**
1966 Molten Salt Breeder Reactor	MSR	1000	5.0	5.8	**8.93**
Westinghouse 4-loop	PWR	1092	6.0	13.6	**2.84**
PBMR	HTGR	175	6.2	24.0	**0.24**
S-PRISM	SFR	380	9.2	19.6	**0.29**

- **Compact size and low mass of FHR and MSR reactor vessels makes periodic replacement practical and economic**
- **Replacibility enables a "limited warrantee" on components that must operate at high temperature**

LWR thermal hydraulics codes work well for FHRs, but FHRs have key differences

- LWR thermal hydraulics codes appear to work well for FHRs
- FHRs have large thermal margin to fuel damage during design-basis accidents
  - LWR operating limits established by fuel-damage limits
  - FHR operating limits established by primary coolant boundary limits
- FHRs operate with low coolant volumetric flow rates
  - Low pumping power
  - Flow regimes commonly in transition or laminar regime
  - Single-phase flow unless gas entrainment occurs



FHR Methods and
Experiments Program White Paper

Integrated Research Project Workshop 2

Fluoride-Salt-Cooled, High-Temperature Reactor (FHR)
Methods and Experiments Program White Paper

Panel Members
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Douglas Chapin (MPR Associates)
Matthew Denman (Sandia National Laboratory)
Thomas Downar (University of Michigan)
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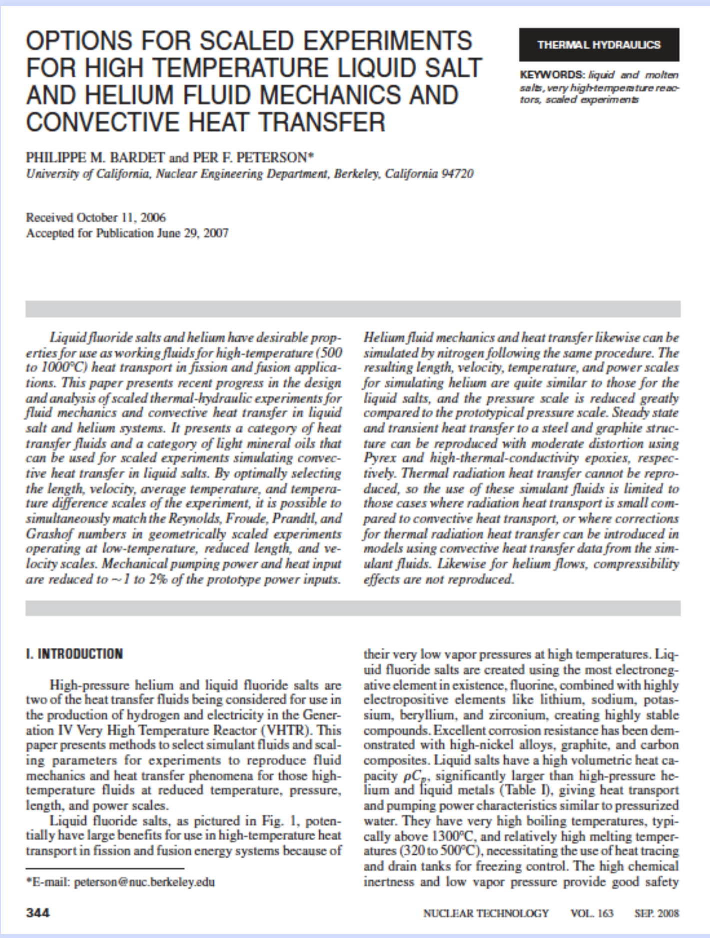
Expert workshops in 2012 developed recommendations for thermal hydraulics methods and validation for FHRs

The similitude of convective heat transfer in oil and molten salts was discovered in 2005

- By appropriate scaling, it is possible to simultaneously match Reynolds, Froude, Prandtl, and Grashof numbers.
- Mechanical pumping power and heat input reduced to 1 to 2% of prototype power inputs.
- Steady state and transient heat transfer to steel and graphite structures can also be reproduced



OPTIONS FOR SCALED EXPERIMENTS FOR HIGH TEMPERATURE LIQUID SALT AND HELIUM FLUID MECHANICS AND CONVECTIVE HEAT TRANSFER

THERMAL HYDRAULICS

KEYWORDS: *liquid and molten salts, very high-temperature reactors, scaled experiments*

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Received October 11, 2006
Accepted for Publication June 29, 2007

Liquid fluoride salts and helium have desirable properties for use as working fluids for high-temperature (500 to 1000°C) heat transport in fission and fusion applications. This paper presents recent progress in the design and analysis of scaled thermal-hydraulic experiments for fluid mechanics and convective heat transfer in liquid salt and helium systems. It presents a category of heat transfer fluids and a category of light mineral oils that can be used for scaled experiments simulating convective heat transfer in liquid salts. By optimally selecting the length, velocity, average temperature, and temperature difference scales of the experiment, it is possible to simultaneously match the Reynolds, Froude, Prandtl, and Grashof numbers in geometrically scaled experiments operating at low-temperature, reduced length, and velocity scales. Mechanical pumping power and heat input are reduced to ~1 to 2% of the prototype power inputs. Helium fluid mechanics and heat transfer likewise can be simulated by nitrogen following the same procedure. The resulting length, velocity, temperature, and power scales for simulating helium are quite similar to those for the liquid salts, and the pressure scale is reduced greatly compared to the prototypical pressure scale. Steady state and transient heat transfer to a steel and graphite structure can be reproduced with moderate distortion using Pyrex and high-thermal-conductivity epoxies, respectively. Thermal radiation heat transfer cannot be reproduced, so the use of these simulant fluids is limited to those cases where radiation heat transport is small compared to convective heat transport, or where corrections for thermal radiation heat transfer can be introduced in models using convective heat transfer data from the simulant fluids. Likewise for helium flows, compressibility effects are not reproduced.

I. INTRODUCTION

High-pressure helium and liquid fluoride salts are two of the heat transfer fluids being considered for use in the production of hydrogen and electricity in the Generation IV Very High Temperature Reactor (VHTR). This paper presents methods to select simulant fluids and scaling parameters for experiments to reproduce fluid mechanics and heat transfer phenomena for those high-temperature fluids at reduced temperature, pressure, length, and power scales.

Liquid fluoride salts, as pictured in Fig. 1, potentially have large benefits for use in high-temperature heat transport in fission and fusion energy systems because of their very low vapor pressures at high temperatures. Liquid fluoride salts are created using the most electronegative element in existence, fluorine, combined with highly electropositive elements like lithium, sodium, potassium, beryllium, and zirconium, creating highly stable compounds. Excellent corrosion resistance has been demonstrated with high-nickel alloys, graphite, and carbon composites. Liquid salts have a high volumetric heat capacity ρC_p, significantly larger than high-pressure helium and liquid metals (Table I), giving heat transport and pumping power characteristics similar to pressurized water. They have very high boiling temperatures, typically above 1300°C, and relatively high melting temperatures (320 to 500°C), necessitating the use of heat tracing and drain tanks for freezing control. The high chemical inertness and low vapor pressure provide good safety

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New experiments to verify similitude for key FHR/MSR phenomena will be valuable

It is much easier to study convective heat transfer with oils than with molten salts

- Oils have been used over many years to study convective heat transfer phenomena
  - Many different instrumentation options are available
- Key questions involve understanding scaling distortions
  - Thermal radiation, surface tension, etc.?

Benjamin Gebhart, 1973, Interferogram for natural convection in silicone oil from a heated plate (two sides)

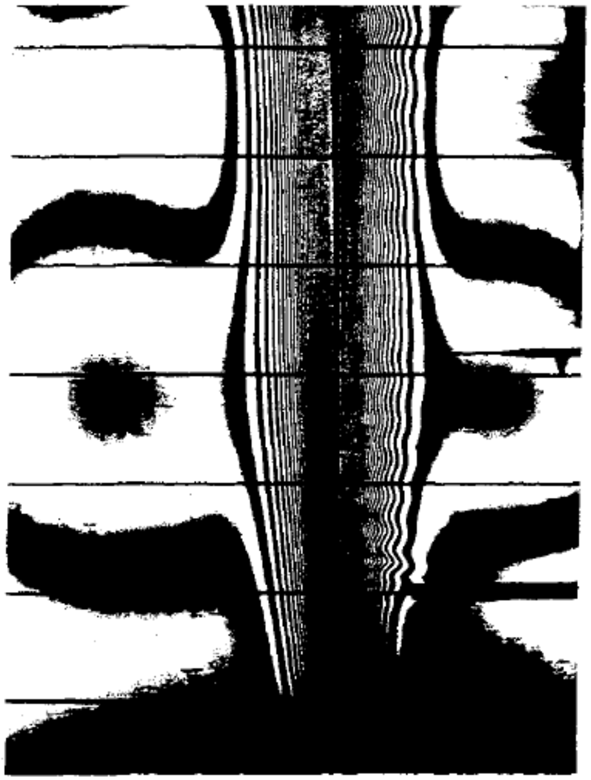
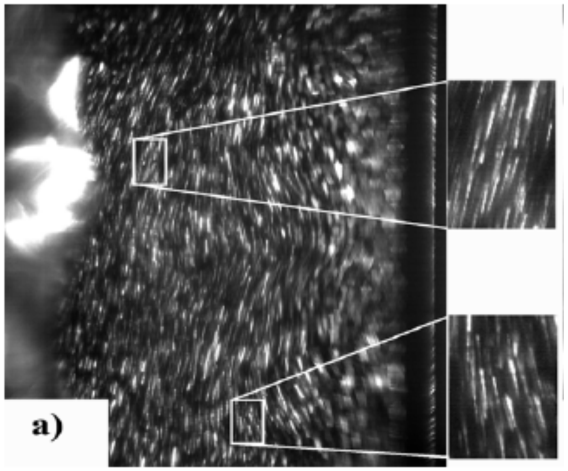


Figure 5 Disturbances in silicone oil (*Pr* = 6.7), first damped, then amplified after reaching the location of neutral stability.

B. Gebhart, Instability, Transition, And Turbulence In Buoyancyinduced Flows, Annu. Rev. Fluid Mech., Vol. 5, pp. 213-246, 1973.

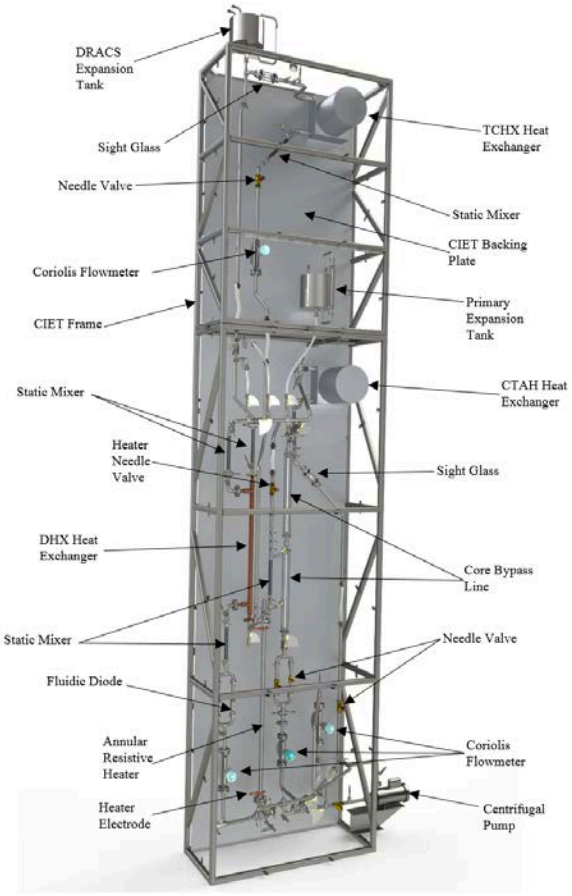
Bardet *et al.*, 2005, particle image velocimetry in Drakesol swirling flow



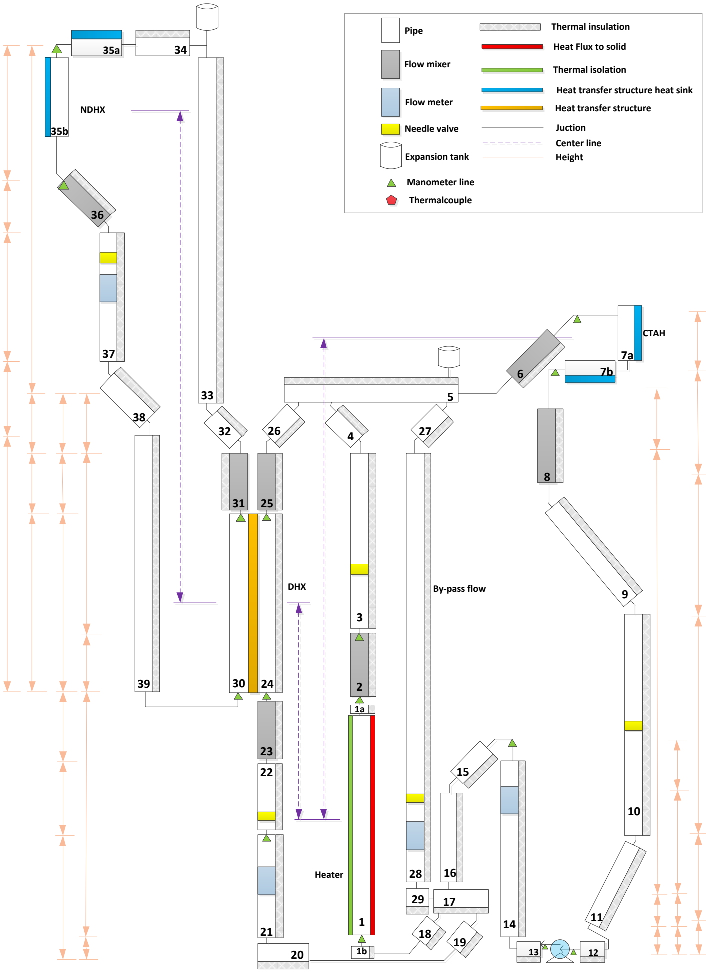
Philippe M. Bardet, Boris Supiot, Per F. Peterson, and Omer Savas, "Liquid Vortex Shielding for Fusion Energy Applications," Fusion Science and Technology, Vol. 47, pp. 1192-1196, 2005.

Scaled Dowtherm Integral Effects Test facilities have low cost

UCB Compact Integral Effects Test (CIET) In Operation



CIET Front View



Nodalization for CIET/FHR simulation

Materials and component testing should accelerate further

- Capabilities to manufacture and purify fluoride salts has been reestablished in U.S., China and Czech Republic
- Static corrosion tests have found favorable performance for structural materials (316, Alloy N, graphite) with clean flibe
- A variety of loop tests have been constructed and are planned in China and the U.S.
- In-reactor irradiation in the MITR is providing valuable information on materials performance and tritium generation/transport/recovery
- Multiple options exist for salt chemistry control
- Modern electrochemical diagnostics are being applied to measure salt chemistry

Conclusions on Next Steps

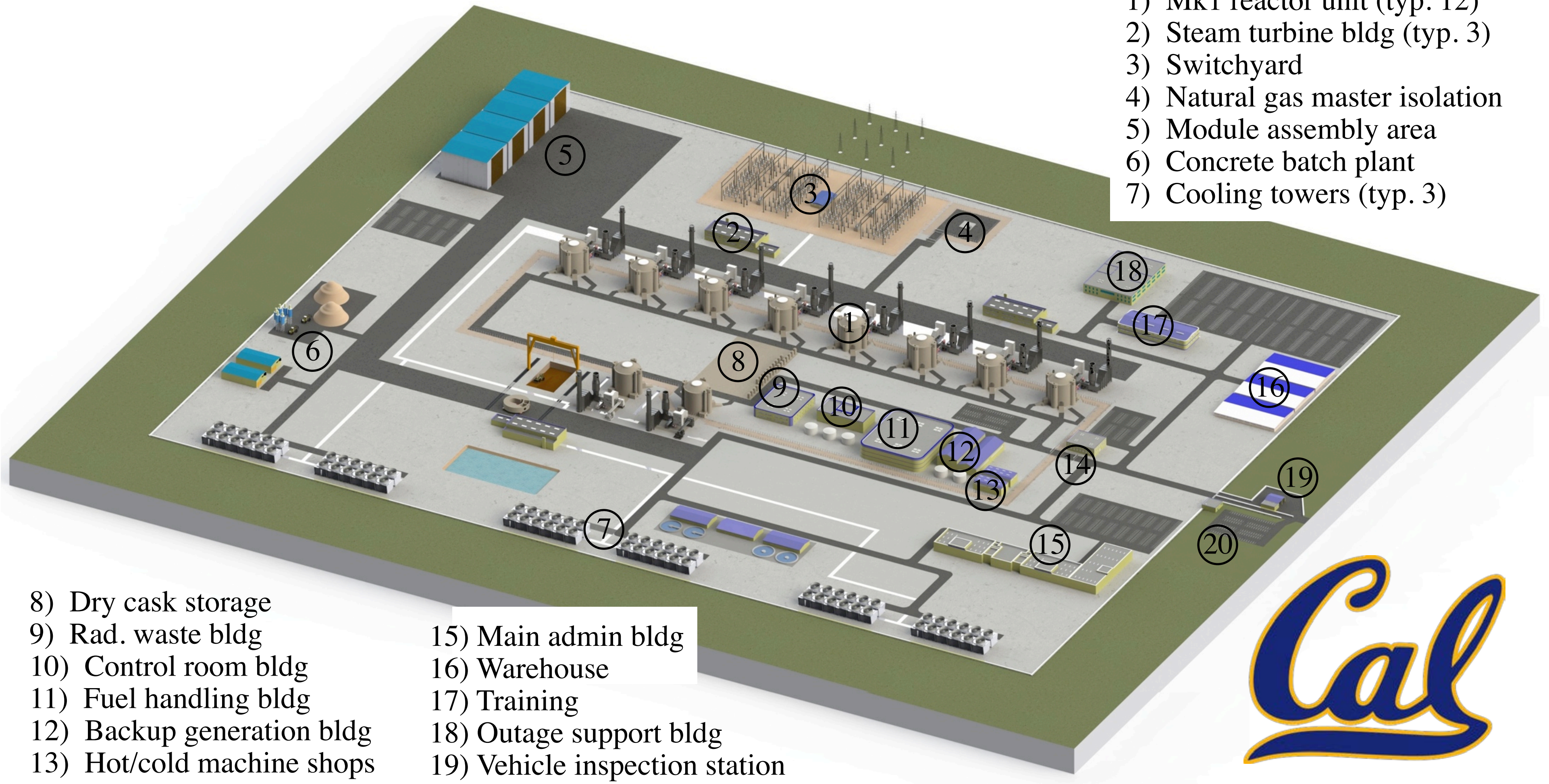
Conclusions on Next Steps

- Initial focus of commercial development for FHRs and MSRs will be on smaller reactors (50-600 MWe/module)
  - Expect designs that allow replacement of high-temperature components (including reactor vessels)
- FHRs and MSRs will remain a major focus of start-up efforts
  - Analogies with NASA Commercial Orbital Transfer Services program
  - Lower entry barriers due to:
    - High thermal margin to core structural damage compared to SFRs and LFRs
    - Ability to use passive LWR safety codes and inexpensive separate and integral effect test data
    - MSRs - low fuel development costs balanced by complex accident source terms and licensing
    - FHRs - higher fuel development cost balanced by simplified design and licensing
  - Chinese TMSR program, along with U.S. university and lab R&D, will significantly influence development rates and strategies

Questions?

Notional 12-unit Mk1 PB-FHR nuclear station

1200 MWe base load; 2900 MWe peak



1) Mk1 reactor unit (typ. 12)
2) Steam turbine bldg (typ. 3)
3) Switchyard
4) Natural gas master isolation
5) Module assembly area
6) Concrete batch plant
7) Cooling towers (typ. 3)
8) Dry cask storage
9) Rad. waste bldg
10) Control room bldg
11) Fuel handling bldg
12) Backup generation bldg
13) Hot/cold machine shops
14) Protected area entrance
15) Main admin bldg
16) Warehouse
17) Training
18) Outage support bldg
19) Vehicle inspection station
20) Visitor parking

For more info: http:// fhr.nuc.berkeley.edu