MSR TWG Licensing Perspective

NRC-DOE Workshop on Advanced Reactors

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R+D

Generating the **Greatest Good** ↗

Molten Salt Reactor TWG →

MSR

ONE

TerraPower

Fast
Breeder
Liquid Fuel
Salt Cooled
Uranium
(Could use Th)

TWO

Thorcon

Thermal
Burner
Liquid Fuel
Salt Cooled
Thorium

THREE

Terrestrial Energy

Thermal
Burner
Liquid Fuel
Salt Cooled
Uranium
(Could use Th)

FOUR

Flibe Energy

Thermal
Breeder
Liquid Fuel
Salt Cooled
Thorium

FIVE

Transatomic Power

Hybrid
Burner
Liquid Fuel
Salt Cooled
Uranium

SIX

Elysium Industries

Fast
Breeder
Liquid Fuel
Salt Cooled
Uranium

Southern Company

EPRI

NEI
NUCLEAR ENERGY INSTITUTE

Exelon®

DUKE ENERGY®

Nuclear Reactor Design →

Fast		Thermal
Breeder	vs	Burner
Liquid Fuel		Solid Fuel
Thorium		Uranium

COOLANT CHOICE

Salt, Water, Gas, Metal

R+D

Nuclear Reactor Design →

Fast		Thermal
Breeder	vs	Burner
Liquid Fuel		Solid Fuel
Thorium		Uranium

COOLANT CHOICE

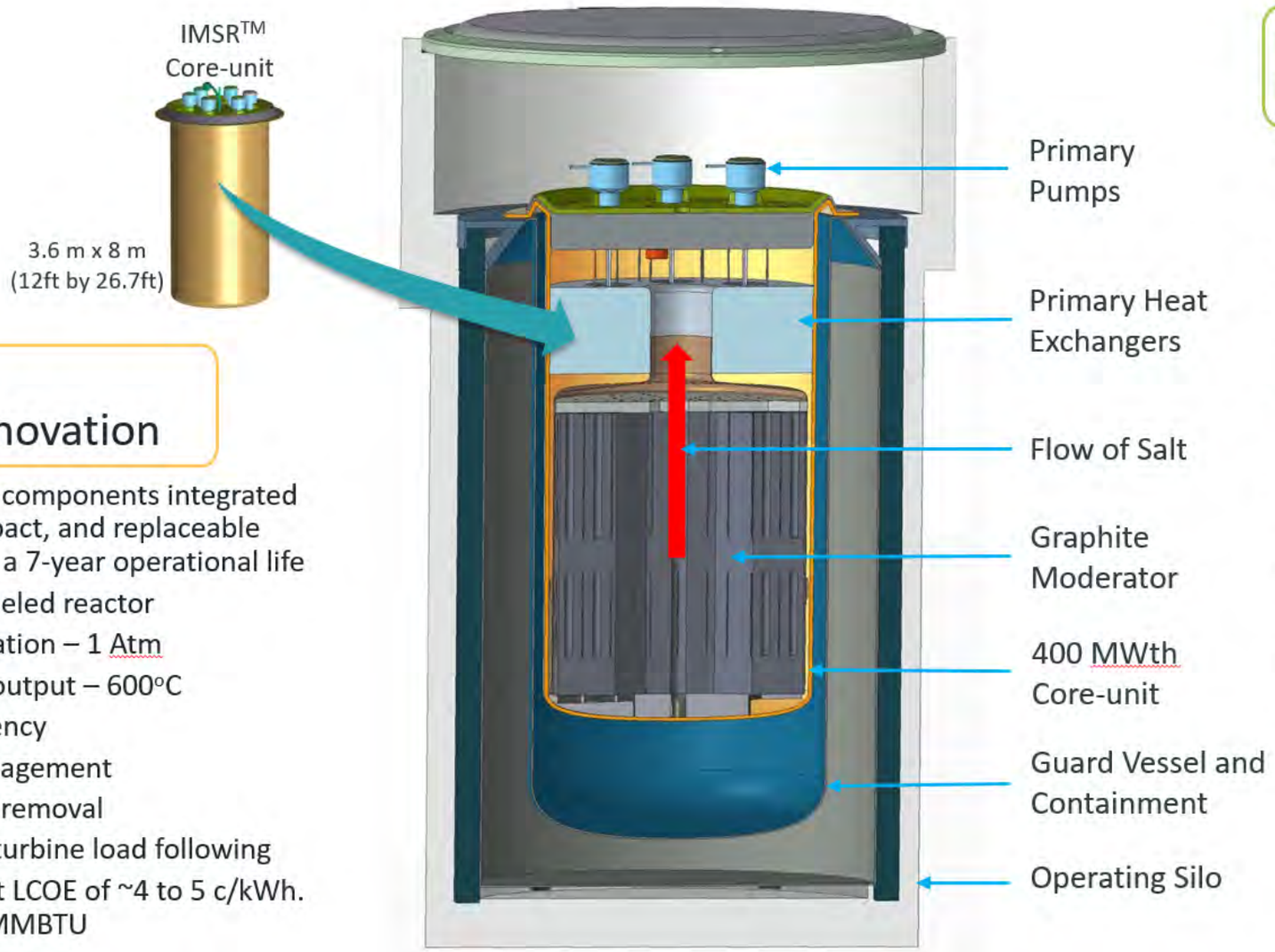
Salt, Water, Gas, Metal

R+D

Advanced Reactor Features →

	High temperature	Low pressure	Online refueling	Sustainable fuel cycle	High power density	Wide range of fuel cycle options	Complete walkaway safety	30+ years of R&D conducted
LWR	✗	✗	✗	✗	✓	✗	✗	✓
HTGR	✓	✗	✓	✗	✗	✗	✓	✓
SFR	✗	✓	✗	✓	✓	✗	✓	✓
MSR	✓	✓	✓	✓	✓	✓	✓	✗

TERRESTRIAL ENERGY'S INTEGRAL MOLTEN SALT REACTOR – IMSR™



Cost-Focused Technology Innovation

- All primary reactor components integrated into a sealed, compact, and replaceable reactor vessel with a 7-year operational life
- Advanced, liquid fueled reactor
- Low pressure operation – 1 Atm
- High temperature output – 600°C
- 48% thermal efficiency
- Passive power management
- Passive decay heat removal
- Dynamic core and turbine load following
- IMSR™ power plant LCOE of ~4 to 5 c/kWh. LCO-BTU 5 to 6 $/MMBTU

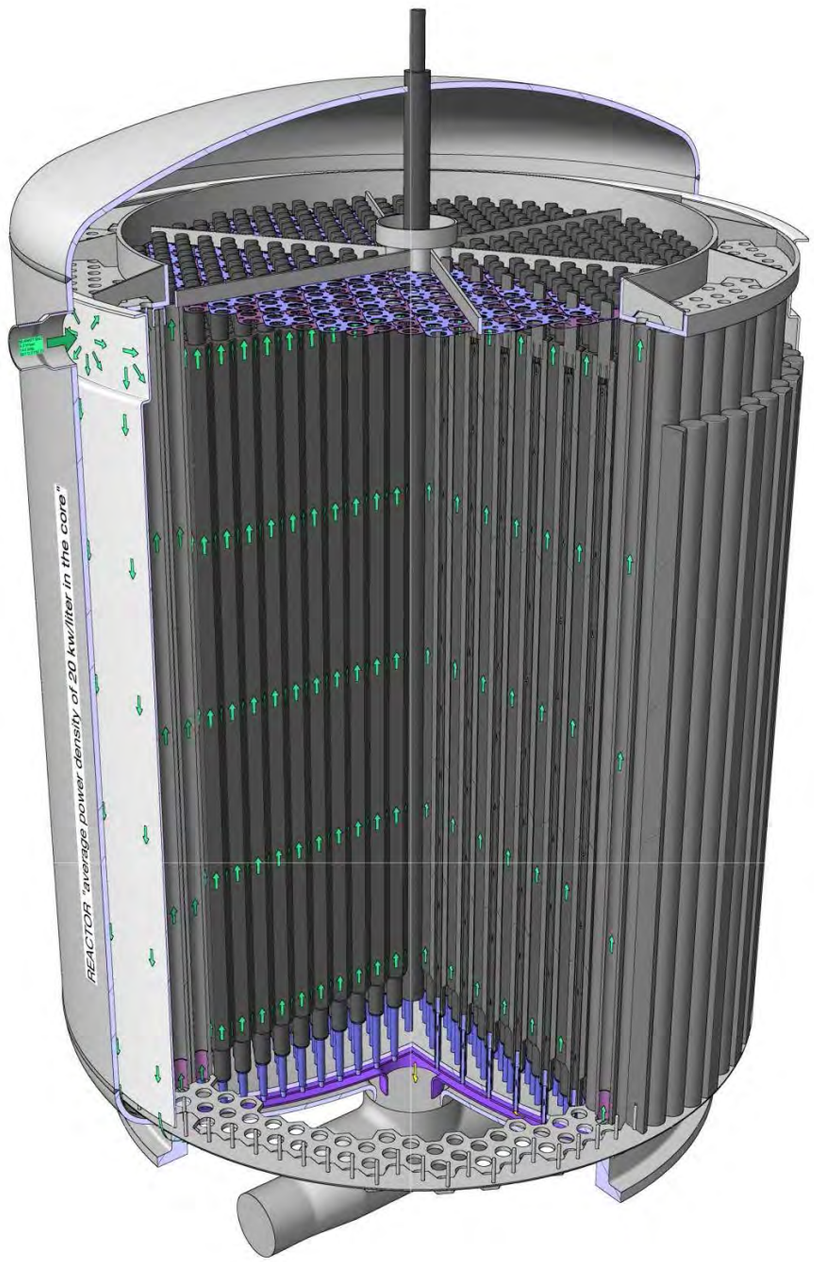
Clean, Convenient, Cost Competitive, Scalable Energy

- Power and heat that is cost competitive with fossil fuel combustion
- IMSR™ heat easy to couple to industrial processes
- IMSR™ heat delivered by common industrial salt
- Dispatchable, on-demand heat and power for industrial processes and for electric power markets
- Factory production in support of rapid global deployment
- A Small Modular Reactor for lower project financing risks
- No NOX, SOX or CO_2

TERRESTRIAL
ENERGY USA

Key commercial claim is that IMSR™ is a better way to generate heat than fossil fuel combustion and is being brought to market in the 2020s

Flibe Energy LFTR



- Design objectives:
  - 600 MWt/250 MWe modular core
  - conversion ratio >= 1.0
  - Replaceable core internals
  - fuel salt in graphite tubes
  - Reactor vessel shielded by thorium blanket and graphite reflector
- Materials and fluids:
  - ^{7}LiF-BeF_2-UF_4 fuel salt
  - ^{7}LiF-BeF_2-ThF_4 blanket salt
  - ^{7}LiF-BeF_2 coolant salt
  - Graphite moderator and reflector
  - Hastelloy-N reactor vessel and piping

TerraPower's Molten Chloride Fast Reactor (MCFR) advances nuclear in key areas

Enhance engineered **safety**

- No fuel fabrication
- Online refueling
- High temperature

Minimize **energy costs**

- Non-reactive coolant
- Strong negative temperature & void coefficients
- Near-zero excess reactivity

Offer **new options** for nuclear waste

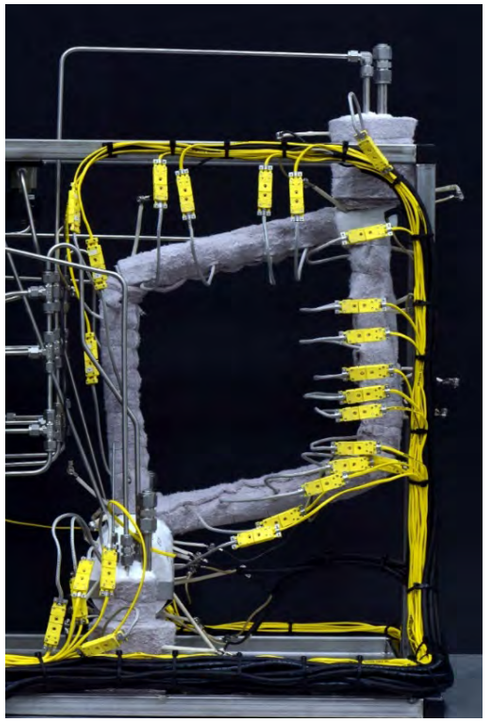
- Only startup enrichment
- Consume DU, NatU, and/or UNF
- Start with partial UNF load

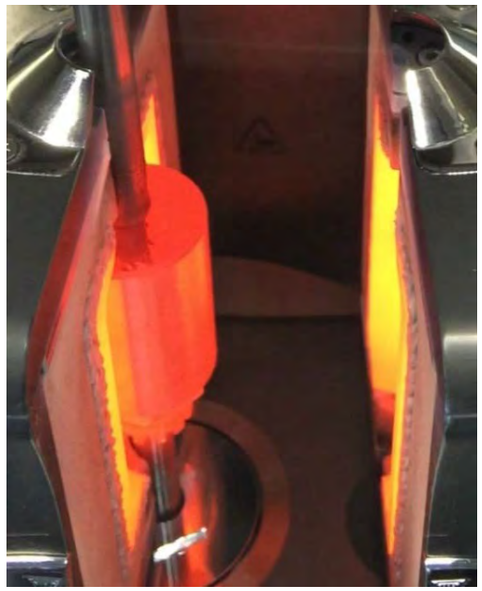
Provide **reliable supply** of energy to all nations

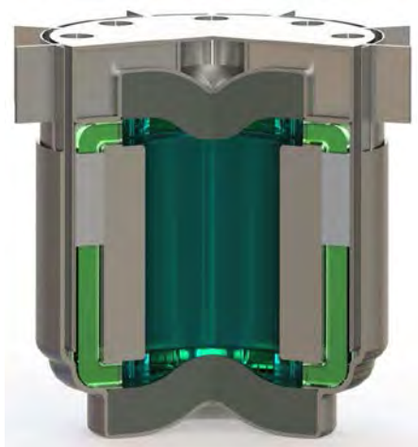
- No ongoing enrichment
- Strong non-proliferation traits
- Reduced water use
- Opens up non-electric markets

Maximize proliferation resistance

- Actinides stay in core, daughter core, or closely-coupled clean-up system
- Actinides always mixed with lanthanides







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Transatomic Power

TRANSATOMIC POWER CORPORATION

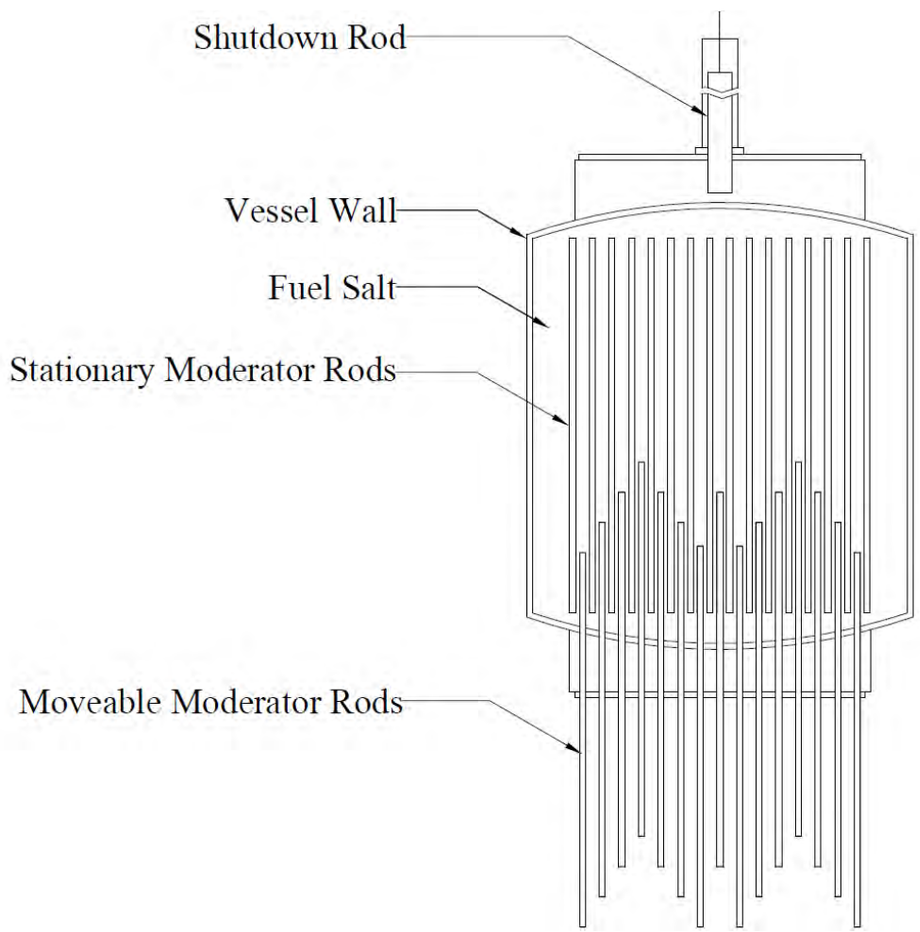


Figure 1. A conceptual depiction of a reactor vessel design that uses moveable or additional moderator rods for reactivity control.

Design Features:

- Moderator: Zirconium Hydride
- Fuel Salt: $LiF\text{-}UF_4$
  - Actinide Content: 5% LEU
- Power Output: 520 MWe
- Spectrum: Epithermal/Thermal

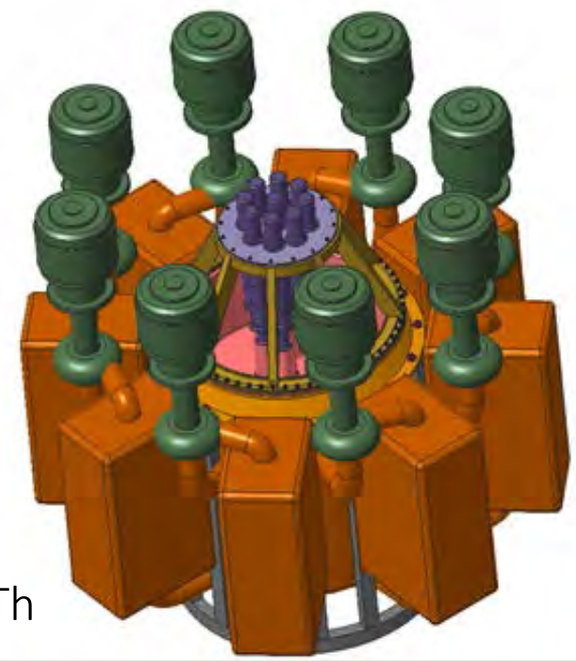
Elysium Industries

Molten Chloride Salt Fast Reactor (MCSFR)

Design Objectives	*Safety*	*Economic Competitiveness*	*Low Environmental Impact*
	Efficient Nuclear Fuel Use	*Enhance Non-Proliferation and Safeguards*	

Plant Concept

- 1 GWe/2.5GWth
- Chloride fuel salts
- Fast spectrum neutron flux
- Breeding ratio ~1
- Core outlet: ~ 600 ºC
- Core inlet: ~ 500 ºC
- High TRL purification systems
- Design for maintainability
- Fuel Flexible: DU/LEU/SNF/RGPu/WGPu/Th

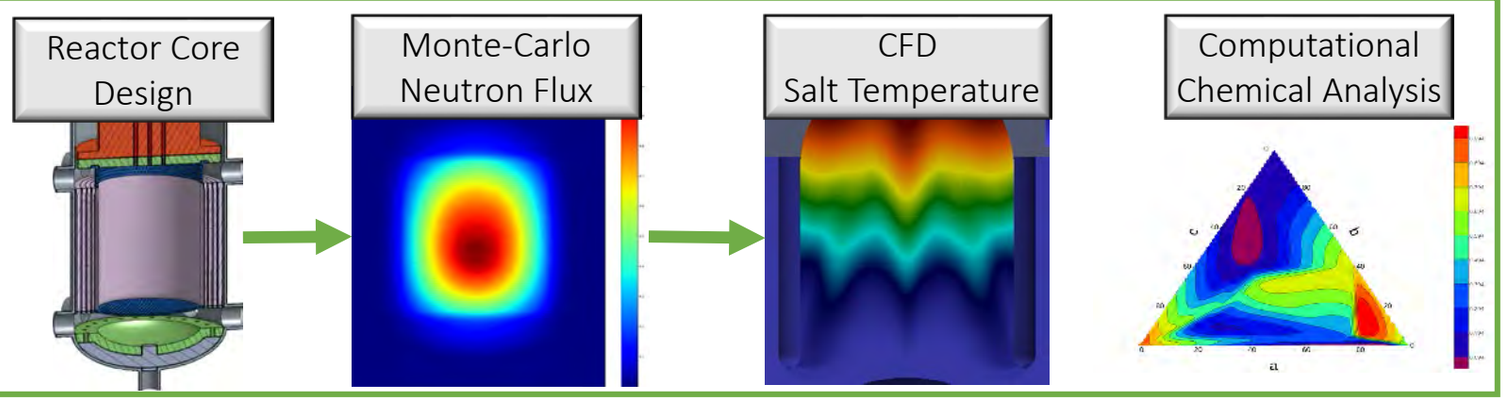


Safety & Proliferation Resistance

- Low operating pressure – Fuel < Secondary
- Secondary T_{cold} > Fuel $T_{m.p.}$
- Negative reactivity/void coefficients,
  - self regulating/shutdown
- **Fuel drain system**
- No actinide removal/separation
- Simple Chlorine based soluble fission product removal
- FP Vitrification with Cl recycling
- Passive corrosion control
- Passive safety, incl. decay heat removal
- No exothermic reactions
- Low excess reactivity

Design Approach

- Integrated Physics-Fluid design methodology
- Computational chemical analysis
- Test & validate



ThorConIsle - 500MWe Factory Built

Use shipyard to build the entire power plant in a factory to minimize cost and schedule risk. Use the ocean/big rivers as our highway. Existing shipyard capacity is enough to build more than 100 GWe of new capacity per year.

Use proven technology from MSRE to minimize risk and schedule.

Full passive safety to shutdown, cool, and contain. No electricity or operators required to handle accidents.

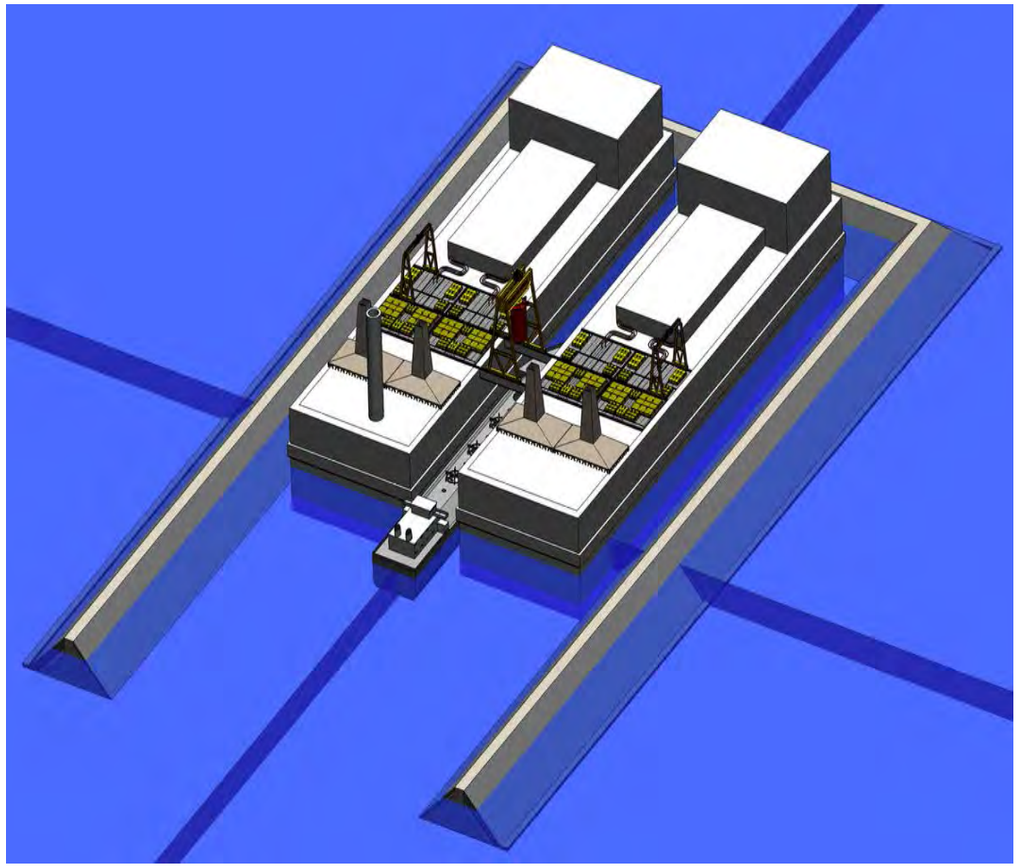
Several months grace period.

Cost to compete with coal ($1.2B/GWe, 3 cents/kwhr). Two years order to grid (assuming site already approved and permitted).

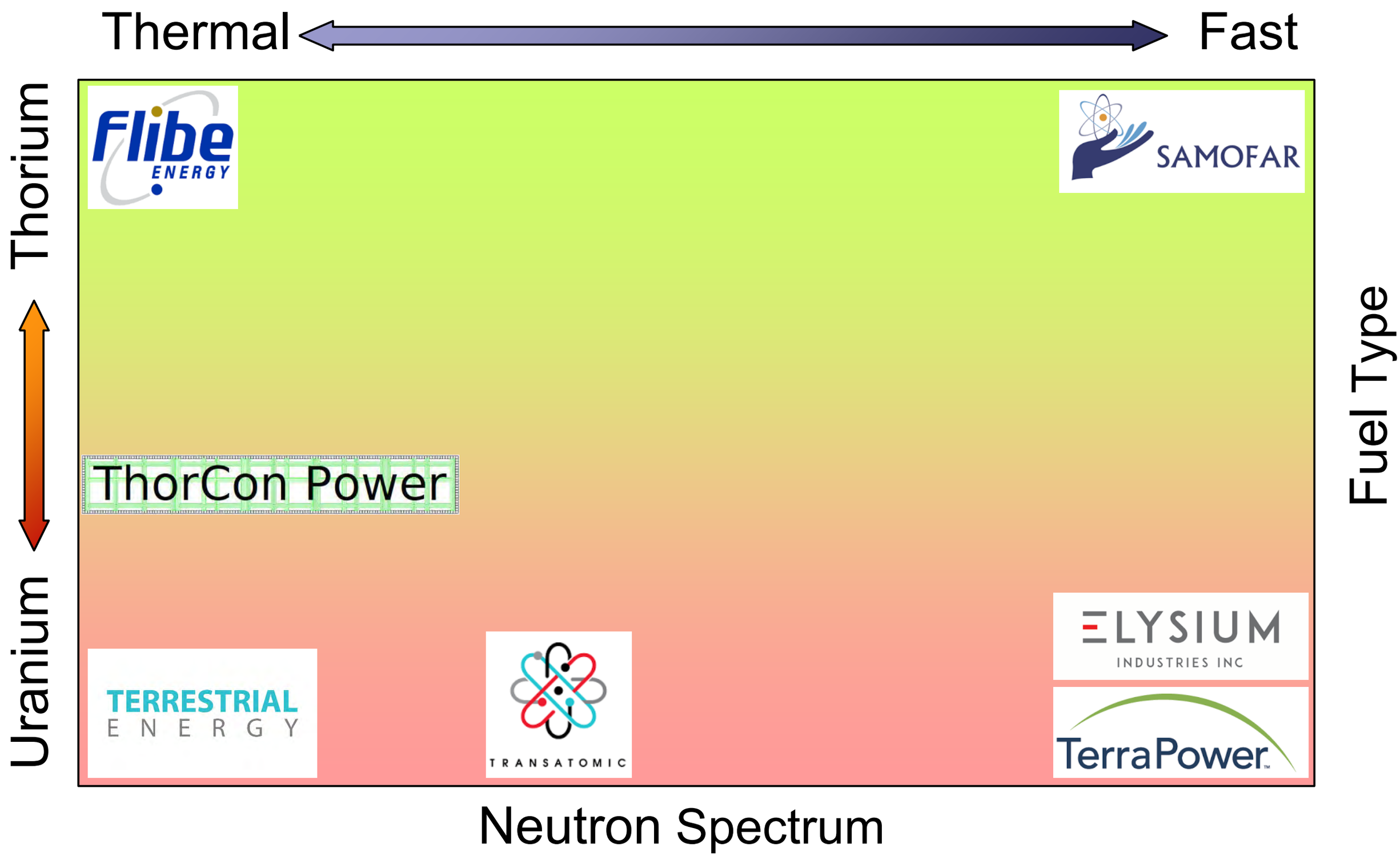
Actually test accident conditions.

Experienced team. Built four largest crude carriers in the world, gmail, streetview, google books.

Each hull is 500 MWe. Ballasted to sea bed. 50% the size of UltraLarge Crude Carriers (In 2001 we build four ULCCs at $89M each) Graphic shows two 500 MWe hulls plus a jetty surrounding them



Molten-Salt Reactor Design Space



If we want our regulators to do better,
we have to embrace a simple idea:
regulation isn't an obstacle to thriving free markets;
it's a vital part of them.

~James Surowiecki

MSR Licensing Perspective:

- Non power test reactors licensed as part 104(c)
  - Expected that NUREG 1537, appropriately modified, will provide guidance
  - Gap analysis of Chapters 4, 5, 6, and 9 underway
  - Could be used as input to NRC for ISG on MSRs
- Commercial reactors likely to use NUREG 800
  - Gap analysis needed on Chapters 4, 5, 6, 9, and 11
- Need for Fuel Qualification definition in MSRs
- Special considerations of MSR materials and chemistry challenges
  - Radiation, Temperature, and Corrosion
- Safeguards approaches for MSRs

Assumptions in current LWR based documents need to be evaluated for MSRs.

- Heterogeneous fuel
- Swelling of fuel
- No delayed neutron migration to outside of core
- Fuel rods or fuel elements (not liquid fuel)
- Assumptions about cladding
- Water moderation
- Assumptions that fuel and coolant are distinguishable
- Xenon and Samarium override, Spectrum matters
- No concept of fuel salt makeup systems
- New accident/hazard scenarios for MSRs, many LWR scenarios don’t apply

On Failure…

- Failure makes our goals seem tougher
- Failure makes our abilities seem weaker
- Failure damages our motivation
- Failure makes us risk averse
- Failure limits our ability to think creatively
- Failure makes us feel helpless
- Failure leads us to make incorrect and damaging generalizations

We must maintain mental toughness.

- The United States is the world's largest supplier of commercial nuclear power.
- We have the best nuclear engineering schools in the world.

- The NRC has successfully granted 20 year license extensions to 86 nuclear power plants

- Apart from Chernobyl, no nuclear workers or members of the public have ever died because of exposure to radiation from a commercial nuclear reactor.
- The US nuclear fleet continues to set reliability records, operating with a 92.2% capacity factor in 2016.

- America's national lab system is the best on the planet. Their discoveries have spawned entire industries, saved lives, generated new products, and helped to reveal the secrets of the universe.

Peaceful nuclear power improves the well-being and prosperity for millions of people throughout the world.

- We must take Calculated Risks.
- We must re-engage creativity.
- We must focus on factors we can control.
    - Hard work, Discipline, Planning, Extended Effort, Commitment

Nuclear energy is where the most extreme engineering and regulatory challenges arise. There is no place for passing on responsibility, or accepting failure. This industry demands immediacy, continuous improvement, and the ruthless pursuit of excellence.

Q&A