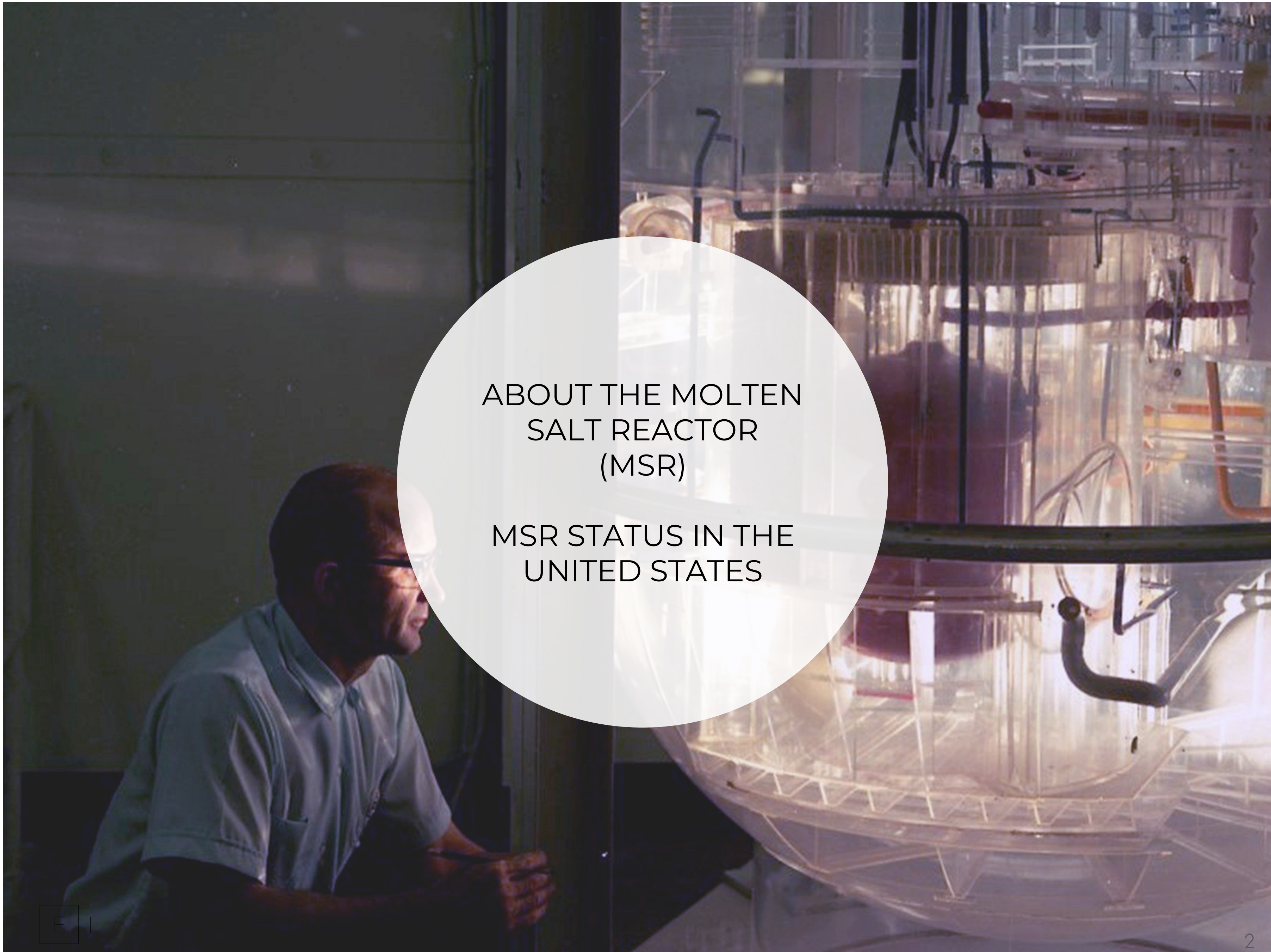
ELYSIUM INDUSTRIES

MSR STATUS IN THE US AND
ELYSIUM INDUSTRIES POTENTIAL MITIGATION OF JAPAN'S SPENT NUCLEAR FUEL & PLUTONIUM CHALLENGES

June 2018

Dr. Youssef Ballout, President
Ed Pheil, Chief Technology Officer


ABOUT THE MOLTEN SALT REACTOR (MSR)
MSR STATUS IN THE UNITED STATES

GENESIS OF MOLTEN SALT REACTOR TECHNOLOGY

- First MSR design in the 1950's was for an AIRCRAFT that can fly indefinitely-cancelled later
- MSR Experiment at Oak Ridge National Lab successfully operated for about 4 years. Cancelled by president Nixon
- MSR technology went dormant until the dawn of the 21st century

DATA AND INTEGRATED RESEARCH PROJECT Solid Fuel MSR - FHR

2007

China toured ORNL, and asked to see and access MSRE data

2011

FHR - Pebble Bed Molten Salt Cooled

- DOE NEUP Integrated Research Project (IRP)
- MIT, University of Wisconsin, UC Berkeley
- 3 years $7.5 million

2014

FHR Extended through September 2017

- 3 years, $5 million

IRP MSR Technologies

- Georgia Tech, Ohio State, Texas A&M College Station, AREVA, ORNL, Italy, Croatia, SINAP China,

2017

FOLLOWING FHR IRP'S

- US companies developing commercial designs started to appear
  - FHR spun off into Kairos Power
- FHR/Kairos were solid fuel NOT liquid fueled MSR's
  - Summer 2015 Elysium discussed how MSR's could improve economics, proliferation safety and concerns
  - DOE started to organize monthly MSR meetings
- Fall 2015 DOE agreed to release additional MSRE documents

DEPARTMENT OF ENERGY (DOE) MSR SUPPORT

2015

2015 DOE Advanced Reactor Concepts

- $40M over 5 years
- Southern Company w/ TerraPower, EPRI, Vanderbuilt Univ, ORNL
- MSR Technologies Workshop 50th Anniversary MSRE (Oct)

2016

- GAIN Workshop (July)
- MOU w/ NRC on GAIN Collaboration (November)
- NRC receives training
- 2 GAIN Vouchers < $500K
- Moving MSRs Forward (Oct)
- MSR Technology Working Group formed (July)

2017

- EPRI Advanced Reactor Modeling and Simulation Workshop (January)
- DOE Named first National Technical Director for MSRs (Jan)
    - US became GIF MSR Observing member
- Draft DOE-NE MSR Roadmap
- Molten Salt Chemistry Workshop at ORNL (April)
    - Chemistry issues to help drive development of MSRs and overcome barriers
- 7 GAIN Vouchers < $500K

2018

- 3 GAIN Vouchers < $500K
- 1 Advanced Reactor Development – Elysium $3.2M
- ANL Modeling and Simulation Workshops & Super-Computer access at ANL
- 1 ARPA-E Terrestrial - MSR Pump $3.16M

DOE GATEWAY FOR ACCELERATED INNOVATION IN NUCLEAR (GAIN)

2016

- Terrestrial Energy / Argonne Nat'l Lab (ANL)
- Verification of Molten-Salt Properties at High Temperatures
- TransatomicPower / Oak Ridge National Lab (ORNL)
- Optimization and Assessment of the Neutronics and Fuel Cycle Performance of the TransatomicPower Molten Salt Reactor Design

2017

- **Elysium Industries / Idaho Nat'l Lab (INL) / ANL -** ***Synthesis of Molten Chloride Salt Fast Reactor Fuel Salt from Spent Nuclear Fuel***
- Kairos Power / ANL / INL- *Nuclear Energy Advanced Modeling and Simulation Thermal-Fluids Test Stand for Fluoride-Salt—Cooled, High-Temperature Reactor Development*
- Muons Inc / ORNL - Conversion of Light Water Reactor Spent Nuclear Fuel to Fluoride Salt Fuel
- Terrestrial Energy USA / ANL - *IMSR Fuel Salt Property Confirmation: Thermal Conductivity and Viscosity*
- TransatomicPower / ANL - *Fuel Salt Characterization*

2018

- Terrestrial Energy USA / ORNL - $500K - *Advancement of Instrumentation to Monitor IMSR Core Temperatures and Power Level*
- UrbixResources / ORNL - $320K - *Nuclear Grade Graphite Powder Feedstock Development*
- ThorCon/ ANL - $400K - *Electroanalytical Sensors for Liquid Fueled Fluoride Molten Salt Reactor*

DOE US INDUSTRY OPPORTUNITY FOR ADVANCED NUCLEAR TECHNOLOGY AWARDS (2018)

Advanced Nuclear Technology - Types

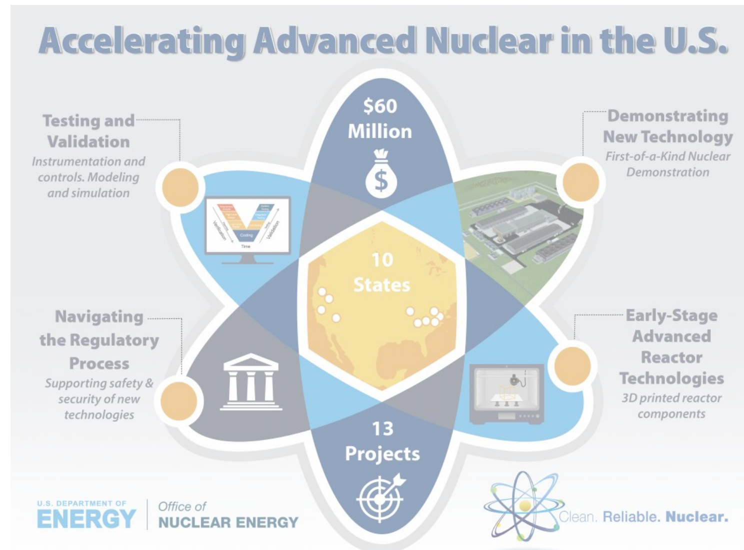
- First of a Kind
- Advanced Reactor Development Projects
- Regulatory Assistance Grants

Advanced Reactor Development Projects

- **Elysium Industries $3.2M - *Modeling and Optimization of Flow and Heat Transfer in Reactor Components for Molten Chloride Salt Fast Reactor Application***

DOE ARPA-E Nuclear MEITNER Awards

- Yellowstone Energy $2.6M
  - Reactor Technology to enhance passive safety and reduce costs for its molten salt reactor
  - Vaporizing Control Rod material to absorb neutrons
- Terrestrial Energy USA $3.15M
  - MSR pump development, including magnetic bearings for sealing
- University of Illinois for Transatomic Power– Urbana Champaign $0.775M
  - Fuel processing system development for MSRs



U.S. COMPANIES FOCUSED ON MSR

Several MSR Companies have emerged with MSR designs across the US and Europe.

A list of US MSR companies shows that:

1. Most are STARTUP companies with funding from private investors
2. Are developing reactors that have FAST or THERMAL spectrum variants
3. Salts are either FLUORIDE or CHLORIDE based
4. Materials under consideration varies from code qualified metals to materials under some level of development, including Silicon Carbide
5. Hot temperature varies for most varies from about 600^{o}C to about 700^{o}C
6. A Fast are suitable to burn SNF, Pu, & Minor Actinides

TABLE 1A: SOLID FUEL MOLTEN SALT COOLED REACTORS (THERMAL)

Reactor Name	Fuel/Salt/Moderator	Country	Developer	Power (MWth)
AHTR Advanced High Temperature Reactor SmAHTR Small Advanced High Temperature Reactor	LEU TRISO in blocks/plates 7LiF-2BeF2 Graphite	**USA**	**ORNL**	**3400** **125**
PB-FHR Pebble Bed – Fluoride Cooled High Temperature Reactor	LEU TRISO in Pebbles 7LiF-2BeF2 Graphite	**USA**	**Kairos Power**	**240**

TABLE 2A: USA THERMAL NEUTRON SPECTRUM LIQUID FUEL MOLTEN SALT REACTOR

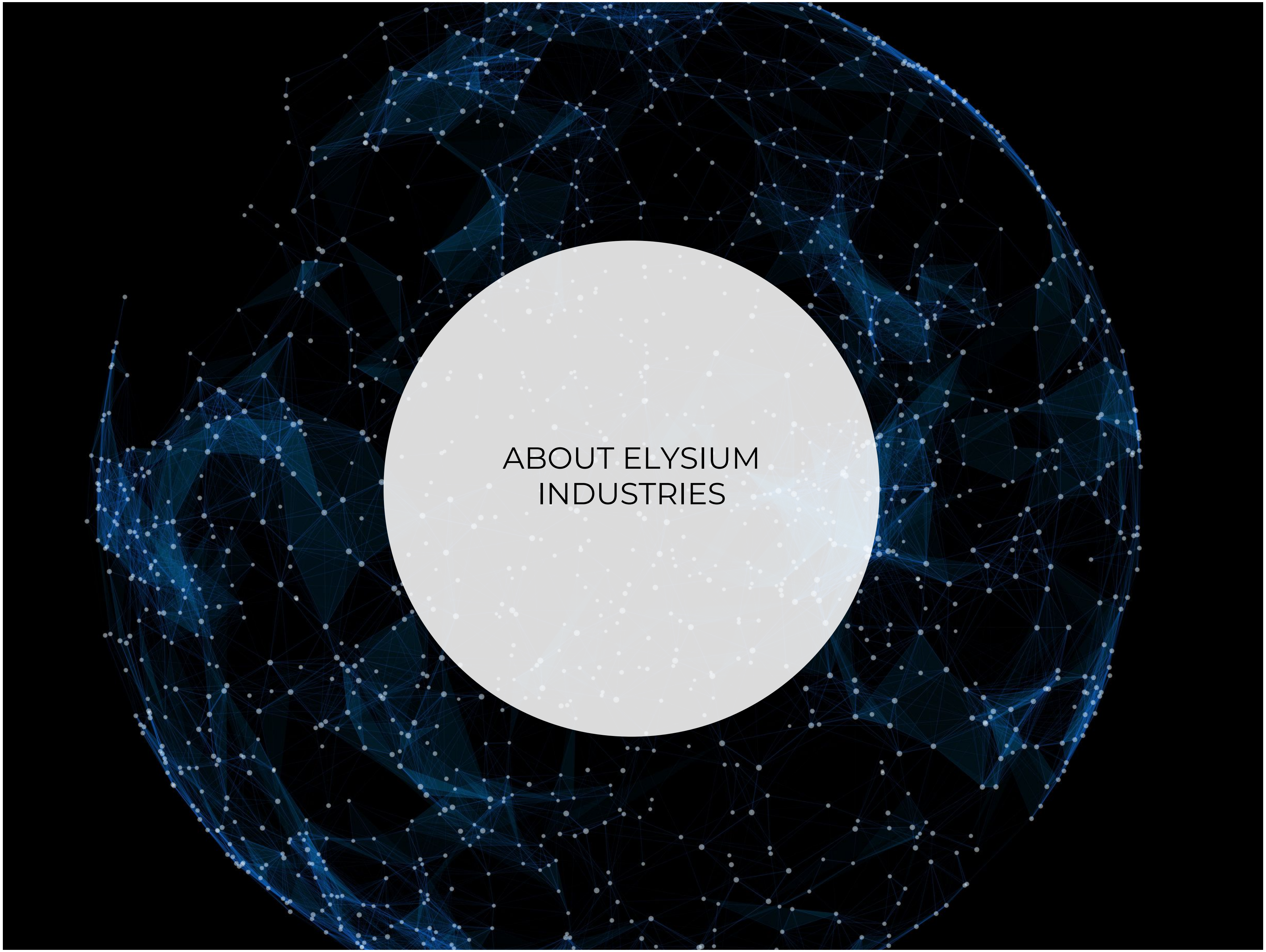
Reactor Name	Fuel/Salt/Moderator	Country	Developer	Power (MWth)
Transatomic MSR (ZrH 1.6 moderator)	LiF-UF4, LEU ZrH1.6	**USA**	**Transatomic Power**	**1250**
iMSR - Integral Molten Salt Reactor	LEU Fluorides Graphite	**Canada USA**	**Terrestrial Energy**	**400**
Thorcon Reactor	LEU, Th NaF-BeF2 Graphite	**USA team**	**Thorcon International**	**557**
LFTR - Liquid Fluoride Thorium Reactor	Th-233U 7LiF-2BeF2 Graphite	**USA**	**Flibe Energy**	**600**
GEM*STAR	U-Pu-SNF-MA 7LiF-2BeF2 Graphite	**USA**	**Muons, Inc**	**500**
Process Heat Reactor	UF4 NaF-BeF2 Be	**USA**	**Thorenco**	**40**

TABLE 3A: USA FAST/EPITHERMAL NEUTRON SPECTRUM LIQUID FUEL MOLTEN SALT REACTOR

Reactor Name	Fuel/Salt/Moderator	Country	Developer	Power (MWth)
MCSFR - Molten Chloride Salt Fast Reactor	SNF & Pu (Preferred) Or HLEU NaCl-UClx-OtherClx	**USA Canada**	**Elysium Industries**	**10 - 4000**
MSFR - Molten Salt Fast Reactor	HLEU w/ DU makeup Chloride Salt	**USA**	**TerraPower**	**2500**
SCIFR - Sodium Chloride Integral Fast Reactor	TRU NaCl-ThCl4-TRU-Cl3	**USA**	**Flibe Energy**	**600**
SAFR - Simple Advanced Fast Reactor	Static fuel in NaF-BeF2 Hg Coolant	**USA**	**Schattke Advanced Nuclear Engineering**	**50**

U.S. GOVERNMENT POSITION ON MSR

- MSRE Documents release in 2007
- Several US private companies were formed to work on MSR
- 2015 DOE started supporting Liquid fueled MSRs
- DOE is now funding MSR work at US National Labs



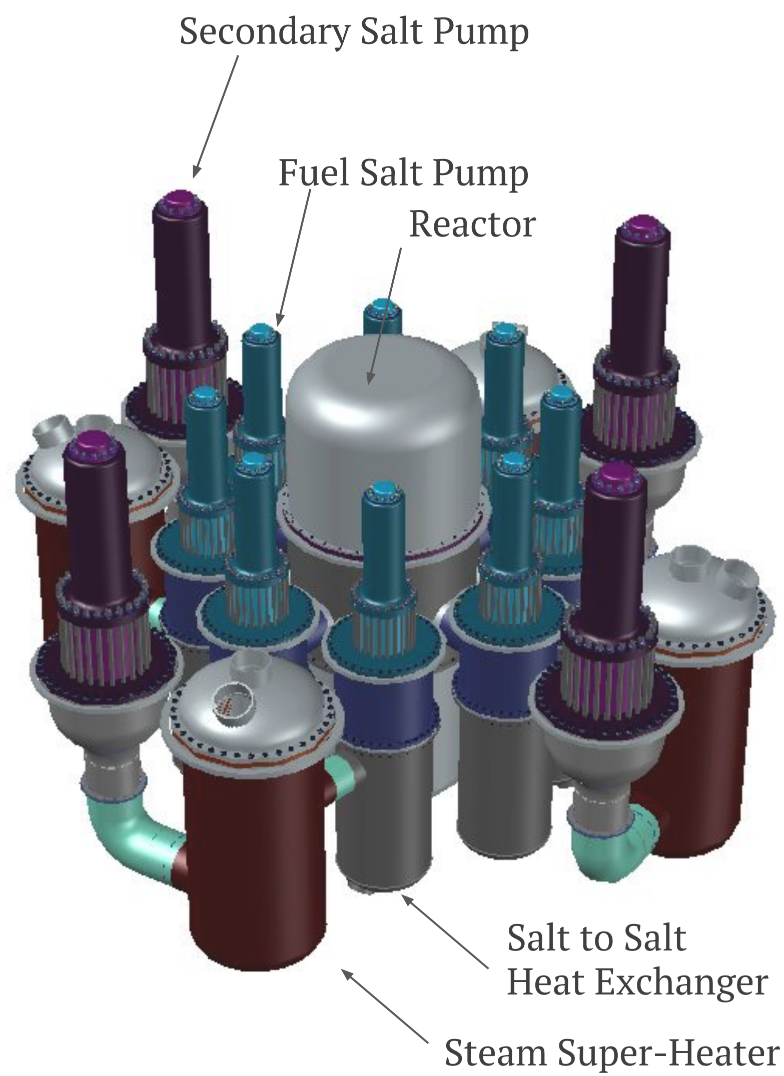
ABOUT ELYSIUM INDUSTRIES

THE ELYSIUM REACTOR

Modular Reactor

8 Salt to Salt Heat Exchangers

4 Steam Super-Heaters

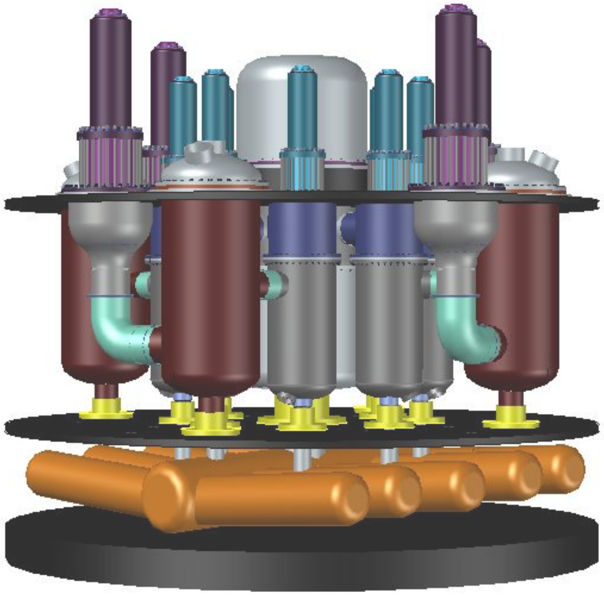


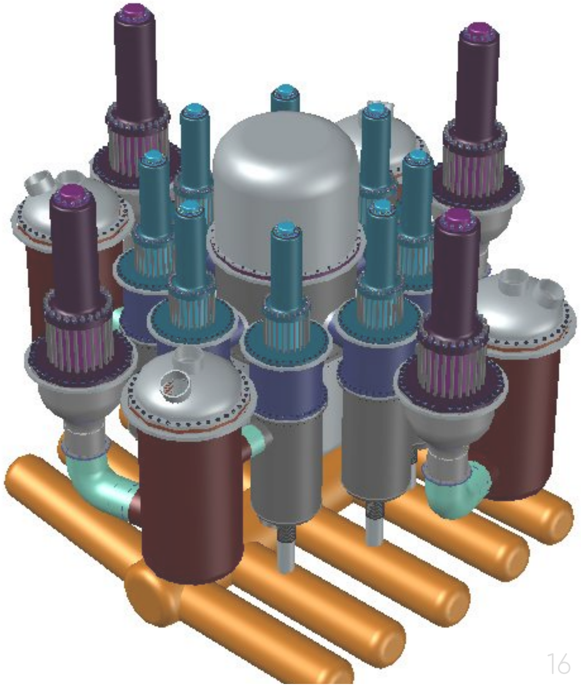
ABOUT THE TECHNOLOGY

The Molten Chloride Salt Fast Reactor (MCSFR)

Name	Molten Chloride Salt Fast Reactor (MCSFR)
Neutron Spectrum	Fast Spectrum Neutron Flux
Fuel	Liquid - **SNF, RGPu,WGPu**, DU, LEU, Unat, DU, Th
Salt Form	Chloride based Fuel Salt
Thermal Capacity	10* - 4000 MWth (Flexible)
Electrical Capacity	25 - 2000 MWe (Flexible)
Core Outlet Temperature	610 - 750 - 1000 C
Core Inlet Temperature	510 - 550 - 600 C
Delta Temperature	100 - 200 - 400 C
Moderator	None
Operating Pressure	Low

* 10MWth Prototype in US for fast Regulatory license, then uprated to higher power





ABOUT THE TECHNOLOGY

Safety

Low Operating Pressure

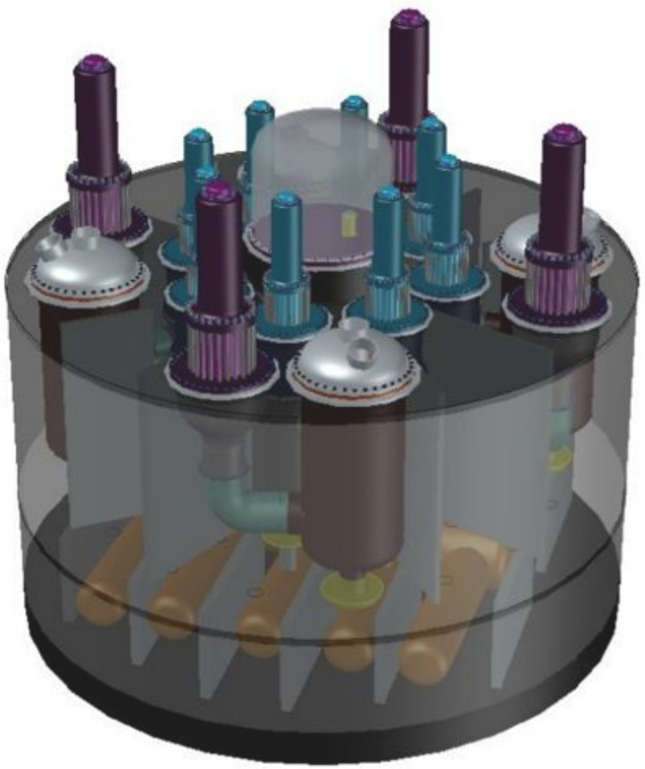
- Reduced complexity, size and cost of highly pressurized components
- Mitigates external threats due to its design to withstand aircraft impact, below grade construction, and restricted plant access

Drain Tanks

- A critical and simple safety feature for molten salt reactors that does not require operator intervention
- If the chloride fuel salt overheats or the plant loses power, the freeze plug melts and the fuel drains to a passively cooled criticality safe storage tanks

Vision

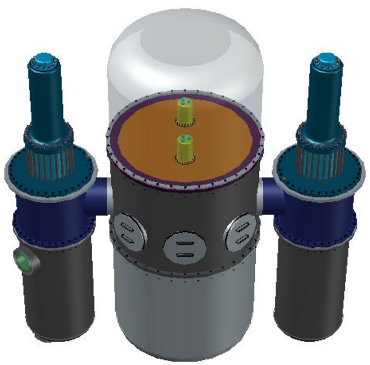
- Large surface area tanks to air
- Much higher heat transfer
  - ➢@ 600+C (to 1000C) vs <300C for water, up
- Heat pipes to air Heat exchanger
- Alternatives to freeze valve
  - ➢Pumped draining via flow valves



FLEXIBLE POWER

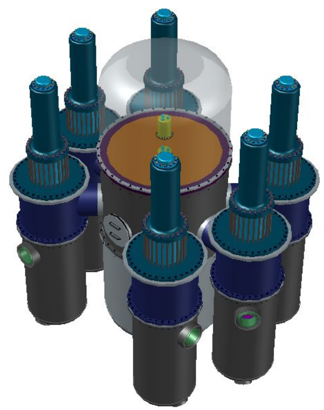
250 MW electric*

350 MW electric**



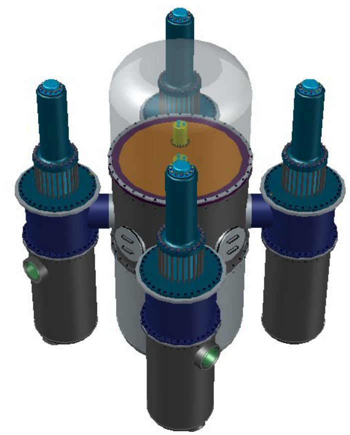
500 MW electric*

700 MW electric**



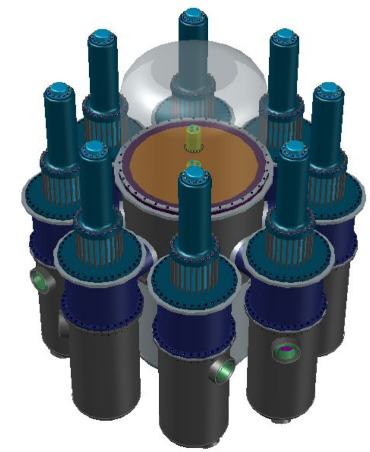
750 MW electric*

1050 MW electric **



1000 MW electric*

1400 MW electric**



Power Rating

* Assumes 600 C T-hot **Assumes 950 c T-hot

FLEXIBLE ENERGY USES

Electricity @ 30x LWR fuel utilization

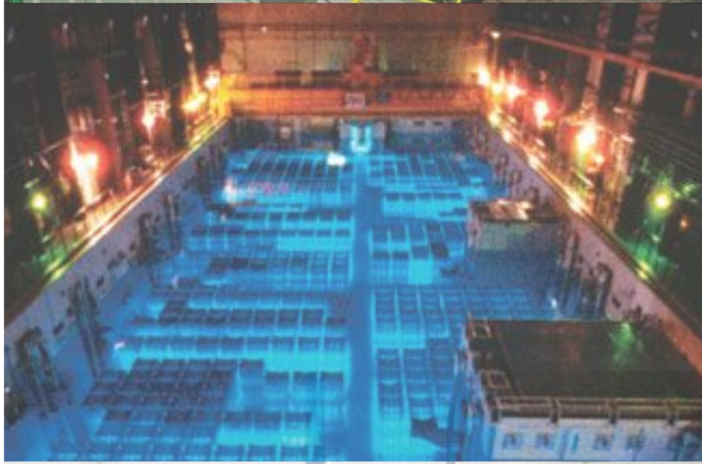
- Electric Vehicle Power

Burn up Pu & SNF Waste

- Reduce storage costs and proliferation concerns

Process Heat

- Desalination
- District heating and absorption cooling
- Concrete & steel preheating
  - Thermal booster or electricity for higher temperatures
- Hydrogen production (650 to 950 c)
- Synthetic fuel
- Fertilizer manufacturing



FLEXIBLE FUEL

Preferred Fuel Cycle - Pu & SNF

Also, HLEU/LEU, NU, DU, Th

Pu & SNF

- WGPu 8 tonnes/reactor startup
- RGPu>10 tonnes/reactor startup
    - 46.9 tonnes within and outside of Japan (as of end of 2016)
    - 9.8 tonnes held domestically
- SNF ~68 tons, less if using RGPu
    - Japan Atomic Power Company: 6,659 casks
    - Japan Nuclear Fuel Company: 3,393 tonnes (PWR & BWR)
    - TEPCO: 49,940 casks
- Add in Fuel from SNF -

    3 kg/day

    0.4 tonne/year/GWth

    1 tonne/year/GWe

Blanket:

- Generate New Reactor Startup Fuel Faster
    - Shorter doubling time
- > 1 year periodic RG Pu removal

FISSION PRODUCT REMOVAL, NOT FUEL

Simple On-line Soluble Fission Product Removal

Fuel Chemistry Cleanup/Conditioning

Gasses - Fuel salt is degassed every 30 minutes

- Kr, Xe, Rn

Particulates - Noble metals filtered out every 4 hours

- Zr,Nb, Mo, Tc, Ru, Rh, Pd, Ag, Cd, In, Sn, Sb, Hf, Hg, Tl, Pb, Bi, Te, Se, Po, I, At

Soluble Fission Products

Lanthanides extracted at a processing rate of ~40 litres/day

- La, Ce, Pr, Nd, Pm, Sm,Gd, Dy, Ho, Er, Tm, Yb, Y (lanthanides?)

Other Soluble FPs and actinides remain in the fuel salt

- Rb,**Cs**, Fr, **Sr**, Ba, Ra, Tb, Eu, Br plus all the transuranic elements

Leveraging years of development from Integral Fast Reactor program and conferences on chloride salt pyro-processing methods

Japan has Skills in Chloride Salt Pyro-Processing

FISSION PRODUCT REMOVAL, NOT FUEL

Long Term Burn, Partial Clean Up

Gasses - Same

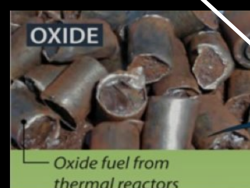
Particulates - Same

Eliminate On-Line Solubles Purification

- Operate for 50-100 years
- Slightly positive Breeding Ratio exactly offsets Fission Product Poison buildup
- Ship to Central Facility from all MCSFRs
  - Remove 95% of Fission Products
  - Leave 5% FP for proliferation protection
- Split fuel to supply two reactors
  - Back fill with converted SNF & carrier salt
- Why?
  - Lower plant capital, operating cost, faster build
  - Lower per plant risk
  - Specialized experience at central facility lowers risk
  - Much lower overall cost
  - Central Facility near plutonium and SNF storage facilities for access and combined new fuel and reused fuel

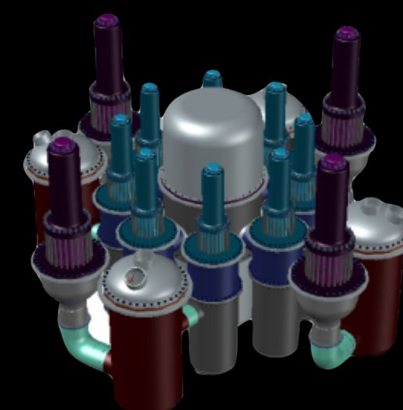
ELYSIUM FUEL PRODUCTION PROCESS

Plutonium Metal or Oxide



Waste Products
Fission Gas, Cladding, Insoluble Fission Products

Spent LWR/HWR Fuel → Chopping → Liquid Chlorination (Japanese*) → Particulate Filter →



No Separation of Proliferation Sensitive Materials:

- U/Pu/MA/FP's always kept together
- Main safeguards and proliferation concerns are eliminated
- Short lived Fission Product Waste (100-300 yr)
- Zirconium recycling
- Medical, etc. Isotope recovery

No Aqueous Processing:

- Decay heat is less of a factor
- Earlier processing possible
- Fewer criticality concerns
- Higher throughput
- Single chemical process vs 100's (100x)
- Lower cost

* Y. Sakamura, T. Inoue, Et. al (CRIEPI), J.N. Mat. 340 (2005) pg. 39-51

How Elysium can assist Japan with its SNF, Pu & radioactive waste challenges

The Elysium MCSFR can deliver many benefits to Japan including:

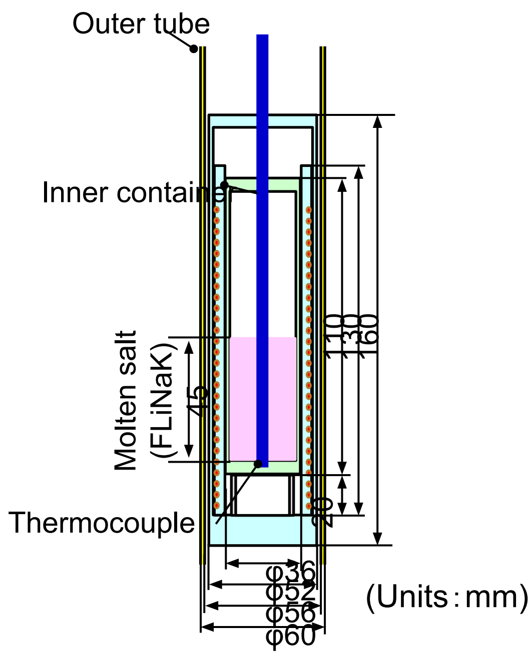
- Begin eliminating long-lived actinides in radioactive waste before the completion of Japan's Geological Disposal Program in the mid 2030s
- Mitigate the difficult discussions and negotiations with local governments and the public over siting a permanent long term storage disposal facility in Japan.
- Efficient, simpler and less capital intensive than traditional nuclear reactors and eliminates the need for SNF reprocessing and long term storage disposal facilities.
- A simple method to consume/reduce excess Pu (47 tonnes) 10 t/Reactor for startup only
- Each year Consumes 1 t SNF/GWe reactor, 30x as much energy as using MOX
- Very low proliferation risk and will be aligned with Japan's commitment to non-proliferation and peaceful use of nuclear energy.

How Japan can support MSR Development in the United States

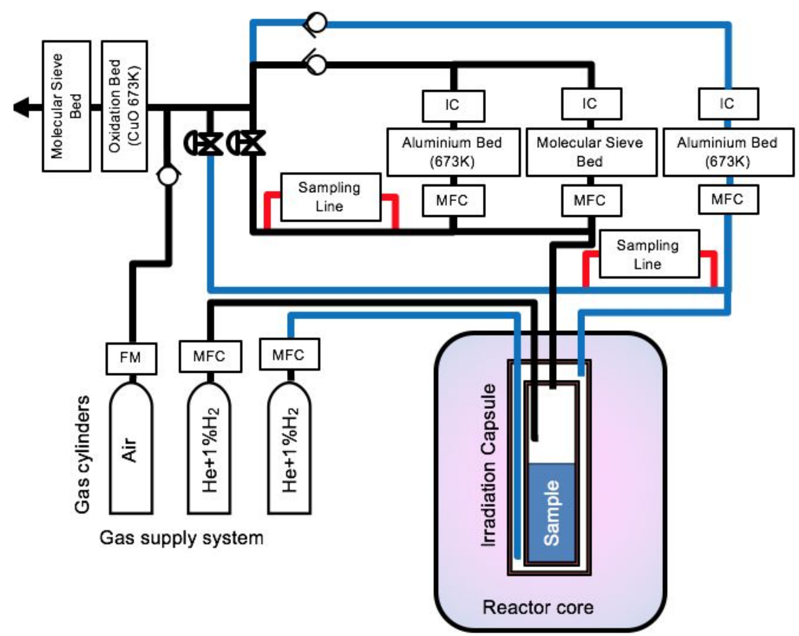
- Molten salt pumps, valves, piping, instrumentations and controls, heat exchangers, structural materials.
- Molten salt fabrication
- Materials testing (chemistry loop, high temperature, corrosion, erosion, etc.)
- Additive manufacturing
- Manufacturing controls
- Remote robotic maintenance processes and equipment development
- Irradiation test programs at JOYO (or other facilities) for structural alloys and fuel salt in fast neutron test reactor
- Construction of components and pressure vessels
- Modular construction facilities
- Power plant design and analysis
- Materials and project management
- Supply chain management
- Radioactive waste reserves

MOLTEN SALT IRRADIATION IN REACTOR

Elysium and Thorium Tech Solution (TTS) are investigating cooperation to simulate Fast Neutron High flux conditions. TTS designed an irradiation device with OECD Halden Reactor Project/IFE in Norway. A new design is underway for Kazakhstan.



Irradiation Capsule was designed by TTS for Kazakhstan reactor



Irradiation system in reactor

STEPWISE TESTS FROM THERMAL TO FAST

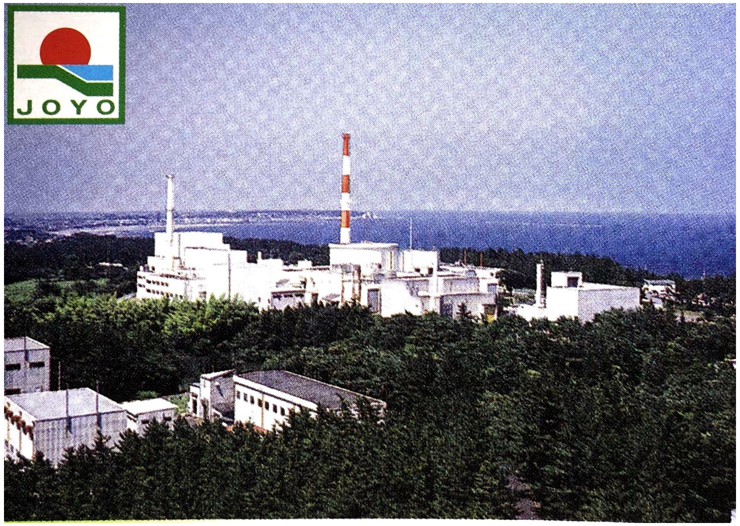
We foresee stepwise testing with the best available nuclear facilities from thermal reactors to fast reactors based on international friendship.

TTS and INP of Kazakhstan signed MOU to use WWR-K reactor to burn Pu and MA using liquid fuel. Testing of liquid fuel may initiate in Kazakhstan then come to Japan

Kazakhstan

WWR-K rector
INP

JAPAN



JOYO fast-neutron reactor
JAEA

WHY IS JAPAN AN IMPORTANT STAKEHOLDER?

- Extensive experience in construction and operation of nuclear power plants for more than half a century
- Long history of world class advanced reactor technology development efforts
- Robust supply chain
- Proven strong project management and performance
- High interest in safe and sustainable operation of nuclear reactors
- Highly competent workforce and nuclear technology development infrastructure, (especially SNF Reprocessing, Pyro-processing, MSR, & Fast reactor)
- Commitment to the use of nuclear technology for peaceful purposes

CONCLUSION

The US government is very serious about supporting MSR technology

The Elysium MCSFR **closes the fuel cycle**

Low cost, no separations, improved proliferation safety

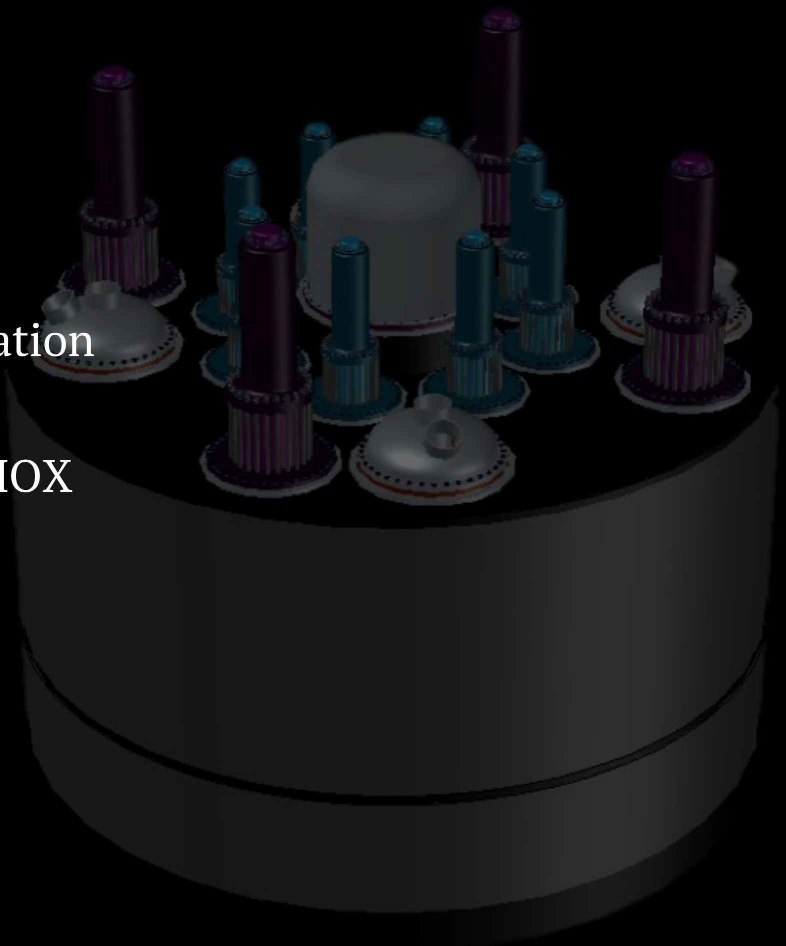
Extend existing Uranium energy by 30x vs MOX

Passive safety and operation

Flexible Fuel – SNF, Pu, LEU, DU, NU, Th

Flexible Power - 25 to 2000 Mwe

Flexible Uses – Electricity, SNF/Pu consumption, Many process heat uses



THANK YOU FOR YOUR KIND ATTENTION

ELYSIUM INDUSTRIES

www.elysiumIndustries.com

APPENDIX

TABLE 1B: INTERNATIONAL SOLID FUEL MOLTEN SALT COOLED REACTORS

Reactor Name	Fuel/Salt/Moderator	Country	Developer	Power (MWth)
TMSR-SF2 Thorium Molten Salt Reactor - Solid Fuel	LEU TRISO in Pebbles 7LiF-2BeF2 Graphite	**China**	**SINAP, CAS**	**400**
IHTR - Indian High Temperature Reactor	Th, U Pebbles Graphite	**India**	**Bhaba Atomic Research Center**	**600**

TABLE 2B: INTERNATIONAL THERMAL NEUTRON SPECTRUM LIQUID FUEL MOLTEN SALT REACTOR

Reactor Name	Fuel/Salt/Moderator	Country	Developer	Power (MWth)
TMSR-LF2 ThoriumMolten Salt Reactor – Liquid Fuel	Th-LEU 7LiF-2BeF2 Graphite	China	SINAP, CAS	400
FUJI-U3	Th-233U 7LiF-2BeF2 Graphite	Japan		450
AMBIDEXTER Advanced Molten-salt Break-even Inherently-Safe-Dual-mission Experimental and Test Reactor	233UF4-ThF4 7LiF-2BeF2	Korea	Ajou University	250
Copenhagen Atomics Waste Burner	Th, SNF 7LiF-ThF4 D2O	Denmark	Copenhagen Atomics	50
CUBE-100	Any fuel Fluorides	Denmark	Seaborg Technologies	250
SSR-U Stable Salt Thermal Reactor (Fuel tubes)	Static LEU fluoride in tubes ZrF3 or ThF4 coolant/breeder	UK	Moltex Energy	300-2500

TABLE 3B: INTERNATIONAL FAST/EPITHERMAL NEUTRON SPECTRUM LIQUID FUEL MOLTEN SALT REACTOR

Reactor Name	Fuel/Salt/Moderator	Country	Developer	Power (MWth)
MSFR Molten Salt Fast Reactor	Th-233U 7LiF	EU	EVOL SAMOFAR	3000
U-Pu FMSR U-Pu Fast Molten Salt Reactor	U-Pu 7LiF-NaF-KF	Russia		3200
FMSR-burner	PuF3-AmF3 LiF-NaF-KF	Russia		1650
MOSART	SNF+0.1MA/TRU LiF-NaF-BeF2	Russia		2400
SSR-W Stable Salt Thermal Reactor	Low purity PuCl3 Static in tubes Fluoride coolant	UK	Moltex Energy	750-2500
IMSBR Indian Molten Salt Breeder Reactor	LiF-ThF4-UF4+	India	BARC	1900

TECHNICAL TOPICS

SOLID VS LIQUID FUELS

Solid Fuels	**Liquid Fuels**
Has large industrial infrastructure and database	**Easier to make and no tight manufacturing tolerances**
Traps fission products	**Fission products can be removed on-line**
Needs cladding barrier replacement	**No cladding damage to limit lifetime**
Sustains damage	**Fuel is not damaged, self repairing**
	Already molten
	Easier/Cheaper to process to close the fuel cycle

TECHNICAL TOPICS

Technical Risk Mitigation

Risk	H,M,L	Mitigation
Use of Compact HXs	H	Discussions with vendors, possibly increase number of loops to reduced HX size, or insert multiple modules in each shell
Reliability of Salt Purification Systems	H	Testing of systems with surrogate salts, continued use of consultants with extensive experience in chloride chemistry
Erosion limits Flow Velocities, Poor Economics	M	Small scale loop testing at high flow rates, use carburizing or nitriding to increase surface hardness
Fuel Salt Production	M	Investigate multiple processing routes, use proven Cl2 - H2 method, engage existing fuel vendors early - Accepted for DOE Grant for Fuel Salt Production
Supply Chain for 15-20% Enriched Uranium	M	Down blend HEU for demonstration reactor, discussions with BWXT, Urenco, collaborate with other end users
Maintenance	M	Loop design to allow access to components, bolted flanges for loop removal, flush salt to reduce activity, design for remote and robotic maintenance

SUMMARY CALCULATIONS

Costs per KW and MWh

	Costs per kW and MWh		
	PWR	**Generic MSR**	**Elysium**
Capitalized Costs			
Capitalized pre-construction costs	$131 /kW	$131 /kW	$131 /kW
Capitalized direct costs	$2,218 /kW	$1,888 /kW	$1,862 /kW
Capitalized indirect costs	$2,470 /kW	$2,103 /kW	$419 /kW
Capitalized owner's costs	$703 /kW	$599 /kW	$599 /kW
Capitalized supplementary costs	$78 /kW	$75 /kW	$60 /kW
Capitalized financial costs	$1,155 /kW	$997 /kW	$669 /kW
Capitalized Costs Total	**$6,755 /kW**	**$5,794 /kW**	**$3,740 /kW**
Per MWh	**$70 /MWh**	**$60 /MWh**	**$39 /MWh**
Annualized Costs			
Annualized O&M costs	$20 /MWh	$16 /MWh	$16 /MWh
Annualized fuel costs	$7 /MWh	$3 /MWh	$3 /MWh
Annualized financial costs	$0.3 /MWh	$0.3 /MWh	$0.3 /MWh
Annualized Costs Total	**$28 /MWh**	**$19 /MWh**	**$19 /MWh**
Levelized Cost of Electricity	**$97 /MWh**	**$79 /MWh**	**$58 /MWh**

SUMMARY CALCULATIONS

COST COMPARISONS WITH PWR AND GENERIC ADVANCED REACTOR

	PWR	Generic MSR	Elysium
Capitalized Costs Total	**$6,755 /kW**	**$5,794 /kW**	**$3,740 /kW**
Relative to PWR		-$961 /kW	-$3,015 /kW
Relative to Generic MSR			-$2,054 /kW
Annualized Costs Total	**$28 /MWh**	**$19 /MWh**	**$19 /MWh**
Relative to PWR		-$9 /MWh	-$9 /MWh
Relative to Generic MSR			$0 /MWh
Levelized Cost of Electricity	$97 /MWh	**$79 /MWh**	**$58 /MWh**
Relative to PWR		-$18 /MWh	-$40 /MWh
Relative to Generic MSR			-$21 /MWh