Advanced Nuclear Technology to Close the Fuel Cycle

ELYSIUM INDUSTRIES USA

Website: elysiumindustries.com
Fire Hose Techy Video: https://m.youtube.com/watch?feature=youtu.be&v=pqVt8cxx-44

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BACKGROUND

ED PHEIL, CHIEF TECHNOLOGY OFFICER AND CO-FOUNDER

- 34 years experience designing all types of reactors
- Reactor operation and reactor operations trainer
- Reactor design/support for 9 different reactors
  - Los Angeles, Trident, CGN, CVN, Seawolf, Virginia, Columbia, NR-1, Astute, Other
- New reactor or core start up testing for 15 reactors
  - Los Angeles, Trident, NR-1, Virginia
- Jupiter Icy Moon Orbiter
- Extensive design work for reactors of all coolants and the cooling methods
- Consulting at IAEA on Safeguards
  - Reactors: Fission (incl. MSR), Fusion, Accelerators, Accelerator Driven Reactors
  - Fuel manufacturing
## ABOUT OUR TECHNOLOGY

### THE MOLTEN CHLORIDE SALT FAST REACTOR (MCSFR)

<table>
<thead>
<tr>
<th><strong>Name</strong></th>
<th>Molten Chloride Salt Fast Reactor (MCSFR)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Neutron Spectrum</strong></td>
<td>Fast Spectrum Neutron Flux</td>
</tr>
<tr>
<td><strong>Fuel Form</strong></td>
<td>Liquid - Fuel Flexibility with DU, LEU, SNF, RG Pu, WGPu, Th, and Unat</td>
</tr>
<tr>
<td><strong>Salt Form</strong></td>
<td>Chloride based Fuel Salt</td>
</tr>
<tr>
<td><strong>Thermal Capacity</strong></td>
<td>125 - 2500 MWth (Flexible)</td>
</tr>
<tr>
<td><strong>Electrical Capacity</strong></td>
<td>50 - 1000 MWe (Flexible)</td>
</tr>
<tr>
<td><strong>Core Outlet Temperature</strong></td>
<td>&gt; 600 Celcius</td>
</tr>
<tr>
<td><strong>Core Inlet Temperature</strong></td>
<td>~ 500 Celcius</td>
</tr>
<tr>
<td><strong>Moderator</strong></td>
<td>None</td>
</tr>
<tr>
<td><strong>Operating Pressure</strong></td>
<td>Low</td>
</tr>
</tbody>
</table>
Design Philosophy/Benefits

› Use of code-qualified materials - Does not require the use of developmental alloys
› Elysium is simplifying all systems such as designing for no core internals and placing components at the top of the vessel for maintenance accessibility.
› Follow an Integrated Design Process, evolved from years of operational and design experience to deliver a reactor plant that incorporates:
   › Inherent Safety
   › Economic Competitiveness
   › Reduction of Environmental Burden
   › Efficient Use of Nuclear Fuel Resources (Closed Fuel Cycle)
   › Enhancement of Nuclear Non-Proliferation
ABOUT OUR TECHNOLOGY

ALTERNATE CONFIGURATIONS

The Elysium Reactor is highly scalable
## Fluoride vs Chloride Salts

<table>
<thead>
<tr>
<th></th>
<th>Fluorides</th>
<th>Chlorides</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost</td>
<td>High cost Li(^7) enrichment</td>
<td>Lower cost without Li(^7) or Be</td>
</tr>
<tr>
<td>Proliferation and</td>
<td>Proliferation/safeguards concern</td>
<td>Mixed uranium/plutonium/fission products to mitigate proliferation/safeguards concern</td>
</tr>
<tr>
<td>Safeguards</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solubility</td>
<td>Very low U/Pu solubility</td>
<td>High solubility of actinides</td>
</tr>
<tr>
<td>Temperature Coefficient</td>
<td>Negative temperature coefficient concerns</td>
<td>Clear negative temperature coefficient without graphite, and thermal poisons</td>
</tr>
<tr>
<td>Corrosion</td>
<td>Fluoride corrosion concerns</td>
<td>Lower corrosion concerns. Low melting point without Li or Be (tritium)</td>
</tr>
<tr>
<td>Regulations</td>
<td>Unqualified structural material, and no regulatory pathway for Th or Li(^7)</td>
<td>Standard materials, simple purification system with higher technical readiness, and common carrier salts.</td>
</tr>
<tr>
<td>Fuel Availability</td>
<td>Need another reactor design to make U(^{233}) from Pu</td>
<td>Fuel is available, and includes LEU, or SNF and Pu waste</td>
</tr>
</tbody>
</table>
ABOUT OUR TECHNOLOGY

CHLORIDE SALT CHEMISTRY

Fuel Salt Functions
- Solvent for nuclear fuel
- Working fluid for transporting nuclear heat to the intermediate loop
- Prevent release of fission products

Chloride-based fuel and intermediate salts
- Chloride salts melt 300°C lower than similar Fluoride salts in the absence of Li and Be
- Avoids the use of Li-7 and the associated problems with tritium production, supply chain issues, and proliferation concerns with Li-6
- Lower corrosion for Chloride salts than Fluorides (better options for control)
- High Solubility of Actinides
- Does not require the use of developmental alloys

Purification Systems with High Technical Readiness
- Chloride salt allow easy removal of only some fission products, keeping actinides in the reactor
- Only use very simplified version with simple removal of some of the fission products. Alternatively, operate 50-100 years, then use centralized soluble fission product removal
ABOUT OUR TECHNOLOGY

ENHANCEMENT OF NUCLEAR NON-PROLIFERATION AND SAFEGUARDS

Design to Prevent Diversion or Illegal Utilization

- Chloride salt allows fission product removal without separating Actinides
- Uranium & Plutonium always mixed AND always with some fission products
- Continuous monitoring of fuel addition and fuel product waste stream inventories
- No spent fuel removed from reactor - no opportunity for diversion of fissile materials
- Consume old SNF & Pu

Physical Protection consistent with IAEA Guidelines

- Purification (cleanup) systems contained within reactor
- Containment structures designed to mitigate external threats
  - Below grade construction
  - Restricted plant access
## Fuel Cycle Options

### Fuel Flexibility

<table>
<thead>
<tr>
<th>Option 1</th>
<th></th>
<th>Option 2</th>
<th></th>
<th>Option 3</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Start-up:</strong></td>
<td>Spent nuclear fuel (SNF) from commercial reactors and plutonium</td>
<td><strong>Start-up:</strong></td>
<td>High Assay Low Enriched U (HLEU)</td>
<td><strong>Start-up:</strong></td>
<td>HLEU</td>
</tr>
<tr>
<td><strong>Steady State:</strong></td>
<td>SNF, Natural U, or Depleted U</td>
<td><strong>Steady State:</strong></td>
<td>Natural U and Depleted U</td>
<td><strong>Steady State:</strong></td>
<td>Mixed: Thorium, AND NU or DU</td>
</tr>
<tr>
<td><strong>Advantages:</strong></td>
<td>Lower costs, consumes waste (Can consume any weapons material)</td>
<td><strong>Advantages:</strong></td>
<td>Familiar fuel</td>
<td><strong>Advantages:</strong></td>
<td>More Fuel Options</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Pure Th/U233 ?</td>
</tr>
</tbody>
</table>
FUEL CYCLE OPTION 1

SPENT NUCLEAR FUEL (SNF)

Pu & SNF - US

- WGPu 8 tons/reactor startup
  Availability
  - 34 mt PMDA – Reactors Max
  - 19 mt additional “Excess” – 3 more Reactors
    Hope for 2 Reactors
- RGPu >10 mt/reactor startup
  - Very little available in US
  - UK, Franc, Japan, Russia, Republic of Korea (S. Korea)
- SNF ~68 mt/reactor startup, less if using RGPu
- 100 Reactors = 6,800 mt SNF to start up
  Add in Fuel 3 kg/day or 1 mt/year of SNF
  Availability
  2000 years worth

Blanket:

- Generate New Reactor Startup Fuel Faster
  - Shorter doubling time
FUEL CYCLE OPTION 2

NORMAL OPTION

- Fissile x10 = Fertile
- High Assay LEU 10-20% enriched
  - High fuel load due to fast reactor, open core, 50% fuel outside core
- Feed-In starts as mostly 20% enriched
  - Decreases slowly over 5-10 years to natural
- Pu builds over time
- U235 concentration decreases
- Continuously changing ratios of U235, Pu, U238
- Reach Steady State Concentration (10% Pu, 90% U238)

HLEU for a Fast MSR start up is expensive

MCSFR does not have long term need for HLEU, can NOT support a long term HLEU production facility
Why FAST MSR?
CHEMISTRY

ELYSIUM FUEL CONVERSION

Requires fewer and easier processing steps than existing reprocessing technologies AND requires no separation of proliferation sensitive material

No separation of proliferation sensitive material:

- U/Pu/MA/FP’s always kept together
- Main safeguards and proliferation concerns are eliminated

No aqueous processing:

- Decay heat is less of a factor
- Earlier processing possible
- Fewer criticality concerns
- Higher throughput
- Single chemical step vs 100’s
  - 100x lower Cost

### DEPARTMENT OF ENERGY - GAIN PROJECT

#### SYNTHESIS OF MCSFR FUEL SALT FROM SPENT NUCLEAR FUEL

**Project Title**

Synthesis of Molten Chloride Salt Fast Reactor (MCSFR) Fuel Salt from Spent Nuclear Fuel (SNF)

**Project Work Scope**

1. Assess three different methods for conversion of SNF and metallic fuel to MCSFR fuel salt, recommending best process(es), and
2. Demonstrate the feasibility of the preferred SNF conversion method. Experience will be gained in converting SNF to MCSFR fuel salt, and assess scale-up feasibility.

**Testing Location**

Idaho National Laboratories

**Topic Area**

Advanced nuclear fuel development, fabrication and testing (includes fuel materials and cladding)

**Project Value**

Around US$300,000

**Project Timeline**

1 year
Corrosion is easier to manage in the chloride system than in the fluoride system—and MSRE experience in potential control provides strong justification that the Cl-based system will be very good.
Future Fuel StartUp 3rd Option

• Goal: Process that does a BAD job concentrating Pu

• Don’t segregate Pu, U, MA, or FP completely on either side
  • Like LEU Uranium enrichment, but chemical

• Process under development

• 3 Chemistry Steps or Less
  • Low Cost
  • Proliferation Resistant – Not Separations/Not Reprocessing
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

Two chemistry Steps – On-Line

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 the Integral Fast Reactor program and conferences on chloride salt pyro-processing methods.
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
Operation Options

- Breeding Ratio < 1.0 – Burner/Converter - Open
- Breeding Ratio ~ 1.0 – Iso-Breeder – Closed Cycle
  - No excess fuel
  - On-line Solubles Purification
- Breeding Ratio ~1.01-1.02
  - Long Burn 50+ years
  - Batch Central Purification – Split
- Breeding Ratio >> 1.0
  - New Fuel
  - On-Line Solubles Purification?
  - Cl-37 enrichment?
  - Reflector?
  - Blanket?
Math

- 53 mt Pu = 7 Reactor Startups Max
- Expectations – Prototype & 1st Commercial
- 4% LWR Burnup = 96% left Ratio 24x
  - 42% MCSFR vs 33% LWR Ratio 1.25x
  - 24x X 1.25x = 30x the power left
- 50 years of burn x 30x = 1500 years of fuel at 20% Nuclear
- Depleted Uranium 10x = 15,000 years
Waste

- Recycle Zirconium to LWR’s
- Recycle Chlorine/Cl-37

- Fission Products Only
  - 0.1-1% Actinides
  - Fission Product Mining
Fuel Sources

• SNF / WGPu – Denatured with high burn or MOX SNF
• SNF Pu “enrichment”
• HEU Denatured
  • Navy HEU SNF – Denature
• Defense Waste
• Megatonnes-to-Megawatts
Questions?
FUEL PRODUCTION DATA

Fuel Conversion
- Conversion of SNF & actinide metals to chloride fuel
- Refine processes to get correct compositions from SNF & metal fuel
- Further optimize to minimize cost/proliferation concerns and maximize safety

Co-benefit
- Zr recycling
- Megatons to MegaWatts-Pu
- SNF waste storage reduction
- Navy SNF elimination

Chlorine-37 Enrichment Processes/Cost
- Centrifuge ZrCl4, HCL (KLYDON)
- Electro-chemical
- Evaporation/Condensation
- Diffusion

Co-benefit
- Zr recycling
- Reduced Zr absorption xsection

Nuclear waste anti-nuclear opposition reduction
Value to country/military/world - need government to consider and provide feedback
OUR TEAM

TECHNICAL LEADERSHIP

DR. YOUSSEF BALLOUT
President
Experience: 30 years
Naval Nuclear Laboratory
Virginia Military Institute
Institute for Aviation Research

EDWARD PHEIL
Co-founder and Chief Technology Officer
Experience: 32 years
Naval Nuclear Laboratory

BRIAN MORRIS
Director of Technology
Experience: 30 years
Naval Nuclear Laboratory

DR. JERRY CUTTLER
Regulatory Affairs
Experience: 43 years
Canadian Power Utility Services
Atomic Energy of Canada

DR. MICHAEL HANSON
Manager of Chemical & Materials
Experience: 30 years
Naval Nuclear Laboratory
General Electric
PPG Industries
OUR TEAM
MANAGEMENT

CARL PEREZ
Co-founder and Chief Executive Officer
Airbus
Citibank

SEIRA MORI
Co-founder and Chief Operations Officer
National Environmental Commission of Bhutan
University of Tokyo

VICE-ADMIRAL WILLIAM HILARIDES (RET.)
SENIOR ADVISOR
FORMER COMMANDER OF NAVSEA
OVERSAW $88B BUDGET IN 3 YEARS
MANAGED 150,000+ CONTRACTS
AND 60,000 PEOPLE

DR. YASUHIRO YAMAKAWA
Director
Entrepreneurship professor at Babson College
10 years in utility/telecom industry
Focus on corporate innovation and entrepreneurial failure

RANDALL ROE
DIRECTOR
FORMER VICE-CHAIRMAN & CHIEF LOBBYIST AT BURNS & ROE
LOBBIED OVER $1B IN GOVERNMENT CONTRACTS TO:
- REDUCE DOE NUCLEAR WASTE STOCKPILE
- DEVELOP DOD MISSILE DEFENSE SYSTEMS

ELYSIUM INDUSTRIES LIMITED: CONFIDENTIAL PRESENTATION
## Solid vs Liquid Fuels

<table>
<thead>
<tr>
<th>Solid Fuel</th>
<th>Liquid Fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Has large industrial infrastructure and database</td>
<td>Easier to make and no tight manufacturing tolerances</td>
</tr>
<tr>
<td>Traps fission products</td>
<td>Fission products can be removed on-line</td>
</tr>
<tr>
<td>Needs cladding barrier replacement</td>
<td>No cladding damage to limit lifetime</td>
</tr>
<tr>
<td>Sustains damage</td>
<td>Fuel is not damaged</td>
</tr>
<tr>
<td></td>
<td>Already molten</td>
</tr>
<tr>
<td></td>
<td>Easier to process to close the fuel cycle</td>
</tr>
</tbody>
</table>
## TECHNICAL TOPICS

### TECHNICAL RISK MITIGATION

<table>
<thead>
<tr>
<th>Risk</th>
<th>H,M,L</th>
<th>Mitigation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Source Availability</td>
<td>H</td>
<td>Consider multiple fuel options: SNF, excess Pu, and ~15% Enriched Uranium</td>
</tr>
<tr>
<td>Use of Compact HXs</td>
<td>H</td>
<td>Discussions with vendors, possibly increase number of loops to reduced HX size, or insert multiple modules in each shell</td>
</tr>
<tr>
<td>Reliability of Salt Purification Systems</td>
<td>H</td>
<td>Testing of systems with surrogate salts, continued use of consultants with extensive experience in chloride chemistry</td>
</tr>
<tr>
<td>Erosion limits Flow Velocities, Poor Economics</td>
<td>M</td>
<td>Small scale loop testing at high flow rates, use carburizing or nitriding to increase surface hardness</td>
</tr>
<tr>
<td>Fuel Salt Production</td>
<td>M</td>
<td>Investigate multiple processing routes, use proven Cl₂ - H₂ method, engage existing fuel vendors early - Accepted for DOE Grant for Fuel Salt Production</td>
</tr>
<tr>
<td>Supply Chain for 15-20% Enriched Uranium</td>
<td>M</td>
<td>Down blend HEU for demonstration reactor, discussions with BWXT, Urenco, collaborate with other end users</td>
</tr>
<tr>
<td>Maintenance</td>
<td>M</td>
<td>Loop design to allow access to components, bolted flanges for loop removal, flush salt to reduce activity, design for remote and robotic maintenance</td>
</tr>
<tr>
<td>Accounting for Actinides</td>
<td>M</td>
<td>Development of spectroscopy that will be capable of estimated amounts of actinides</td>
</tr>
<tr>
<td>Enriched Cl(^{37}) is unavailable or too costly</td>
<td>L</td>
<td>Develop supply chain, in discussions with Urenco and Centrus Energy, do not enrich chlorine and use larger core, accept lower conversion/breeding</td>
</tr>
</tbody>
</table>