TERRESTRIAL ENERGY

Vision: to change the way the world thinks about nuclear energy

Mission: To commercialize a strategic and carbon-free energy technology for global industry

March 2015

RETHINKING ENERGY

The Integral Molten Salt Reactor

Molten Salt Reactor Workshop

April 17th, 2015

Delft University

RETHINKING ENERGY

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TECHNOLOGY

LIQUID FUEL IS THE KEY

Liquid fuel form is foundation of most MSR advantages

Solid fuel is a complex challenge

- Slightest change to solid fuel means years of testing
- Irradiation damage limits burn up
- Decay heat removal means coolant must continue in every foreseeable circumstance

Liquid Fluoride Fuel Salts

- Fuel unaffected by radiation, simplifies fuel qualification
- Fuel is the coolant, simplifies Decay Heat removal
- Low pressure and very high boiling point

Many Liquid Fuels examined in 1950s and 60s. Only Fluoride Salts proved practical

ADVANTAGES OF MOLTEN SALT REACTORS

Safety

- Inherent safety, passive decay heat removal
- Low pressure and no chemical driving force
- Caesium and Iodine stable within the fuel salt

Reduced Capital Cost

- Inherent safety can simplify entire facility
- Low pressure, high thermal efficiency, superior coolants (smaller pumps, heat exchangers). No complex refuelling mechanisms

Long Lived Waste Issues

- Ideal system for consuming existing transuranic wastes
- Even MSR-Burner designs can see almost no transuranics going to waste

Resource Sustainability and Low Fuel Cycle Cost

- Thorium breeders obvious but MSR-Burners also extremely efficient on uranium use (~1/6th the needs of LWRs)

U.S. HISTORIC TIMELINE

First envisaged in 1940s

1950s becomes leading candidate in the well funded Aircraft Reactor Program

- Huge knowledge base developed
- Successful ARE test reactor operates in 1954 at up to 860 ^{o}C

1960s to 1970s MSBR "Thorium Breeder"

- World thinking is "breeders" needed due to shortage of uranium
- Sodium Fast Breeder and Molten Salt Breeder dominate U.S. efforts
- Very successful 8MWth MSRE 1965-69, minor issues uncovered

1970s Falling of the Political Axe

- Program cancelled mid 1970s
- Fascinating work on MSR-Burner reactor the DMSR, 1979-80

MOLTEN SALT RECTOR EXPERIMENT (1965-1969)

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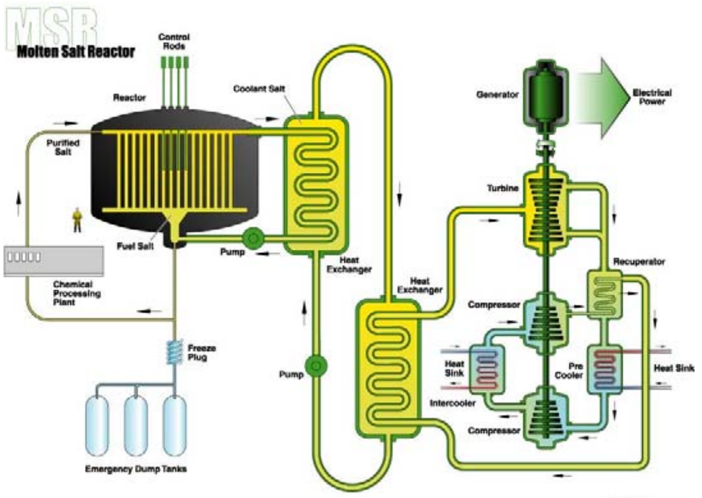
THE 1970s SINGLE FLUID, GRAPHITE MODERATED MOLTEN SALT BREEDER REACTOR (MSBR) – 1000 MWe



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SUMMARY OF CURRENT WORLD MSR EFFORTS

- **Chosen as one of six Gen IV designs in 2002**
- **Widespread grassroots support**
- **Funded U.S. efforts now on MSR-Cooled designs (FHR)**
    - Advantages over helium coolant
    - Lacks MSRs resource usage and waste profile advantages
- **European efforts on Fast Spectrum MSFR. Many challenges, long horizon**
- **China has major 500M$ program, first a MSR-Cooled test reactor by 2020 and followed closely by a true Salt “fuelled” reactor**
- **India keeping options open, little known 1970s effort**
- **Several MSR Start Up firms worldwide**

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Why the Renewed Interest?

- **LWR fleet has served world well but only incremental improvements possible**
- **Passive safety of MSRs opens possibility of true cost innovation**
- **MSR's open up possibilities for reduced waste profile and ability to consume existing waste**
- **Can be configured as factory fabricated, Small Modular Reactors**
- **For a "new" MSR, logical to first look to the past…**

CHALLENGES OF 1970'S MSR-BREEDER DESIGN

- **Online Fission Product Removal**
- **Tritium Control**
- **Reactivity Temperature Coefficients (only weakly negative)**
- **Use of Highly Enriched Uranium (HEU)**
- **Off Gas handling**
- **Nobel Metal Plate out in Heat Exchangers**
- **Long Term Corrosion or Radiation Damage**
- **Graphite Replacement Operations**

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WHY GRAPHITE?

Graphite use does present challenges

Disposal Issues

- Varies greatly by region, depending upon ^{36}Cl regulations
- Largely a "perception" issue but still of importance

Adds chemical potential

- In fact however, almost no added safety concerns
- No Weigner energy as used at high temperatures
- Graphite near impossible to burn, Windscale fire was fuel and aluminum cladding burning, Chernobyl was 2000 C+ Corium driving reactions

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WHY GRAPHITE?

- **Graphite offers many large advantages**
- **Only unclad moderator possible**
- **Graphite use enables protection of all structural materials from high neutron fluence by "*undermoderated*" outer zones**
- **More thermal spectrum aids reactor control and slows reactions in general (long neutron lifetimes)**
- **Makes power output truly scalable from large to very small**
- **Massive reduction in needed fissile concentration and starting fissile loads**
- **If Low Enriched Uranium is fuel source, as low as 1% enrichment possible and 2 to 4% practical**
- **Advantages of Fast Spectrum more likely as 2nd generation MSR**

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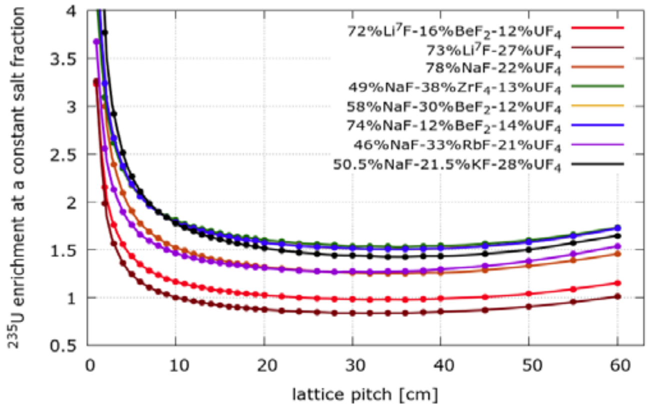
Sponsored work by Ondrej Chvala, U Tennessee Knoxville
Figure of Merit (FOM) Conversion Ration over Enrichment

- The dependence of ^{235}U enrichment on the lattice pitch for the salt fraction value which maximizes FoM.



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WHY A THORIUM BREEDER?

- **The Thorium MSR-Breeder is an admirable goal**
- **Would represent literally millions of years of fuel with great waste profile**
- **However, the Breeder approach represents many large challenges, especially on line fuel reprocessing that will lengthen development time**
- **Long development time means finding private investment extremely hard**
- **Most governments seem unwilling to lead any major nuclear development (but they will follow private capital's lead)**
- **We now know that Uranium is abundant, is there a pressing need for a Breeder?**
- **A MSR-Burner can be many times more efficient on Uranium than current LWRs. Evolution to MSR-Breeders can be a longer term goal**
- **MSR-Burner approach of running off Low Enriched Uranium solves many challenges and offers great overall simplification to shortens development period**
- **The last major work of ORNL in the late 1970s was a MSR-Burner, the Denatured Molten Salt Reactor (DMSR)**

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Original MSR-BURNER The Denatured Molten Salt Reactor

Oak Ridge`s 1000 MWe *30 Year Once Through Design* (1980)

Originally mandate to increase MSR anti-proliferation

Startup with LEU (20% ^{235}U) + Th

No salt processing, just add small amounts of LEU

Low power density core gives 30 year lifetime for graphite (8m x 8m)

Similar fissile startup load to LWR (3.5 t/GWe)

1/6th to ¼ the uranium needs of LWR, 0.1 cents/kwh fuel cost

1/9th the Transuranic waste (Pu etc) of LWR

Much better reactivity coefficients than MSBR

- MSBR -0.9 pcm/K
- Grenoble Recalculation of MSBR ~+1 pcm/K
- DMSR -6.8 pcm/K

DEBUNKING SOME *MSR-BURNER MYTHS*

- ***Unless it's a Breeder, its "unsustainable"***
- **Could replace every LWR, Coal and Gas plant with MSR-Burners and not need to increase current uranium mining. Not millions of years worth like thorium, but easily thousands as even a ten fold uranium price increase is trivial**
- ***The MSR-Burner means the same Pu waste problem as LWRs, solves nothing***
- **MSR-Burners produce far less Pu than LWRs and there is the ability to recycle all Pu and other Transuranics off site and at any time. Same ability as the MSR-Breeder to "Close the Fuel Cycle" and only have fission products (and some harmless U238) as waste (but a nation's choice, salt caverns for waste is a ready solution)**
- ***MSR-Burners require uranium enrichment to continue***
- **OK, I'll concede a point there. Although again we could replace LWRS and fossil with MSR-Burners and need no more enrichment than today. As well, there is an fascinating CANDU-MSR-Burner possible synergy of One CANDU feeding Pu fissile to sustain 3 or more MSR-BURNERS without any enrichment facilities**

ISSUES SOLVED BY THE MSR-BURNER APPROACH

Fission product removal

- No need for any on site processing

Tritium Control

- Able to use non "FLiBe" carrier salts to curtail tritium production

Reactivity Coefficients

- MSR-Burners have far superior reactivity coefficients

Off Gas Management

- No need to rapidly pull out off gasses, many options now available

HEU Usage

- Uranium always denatured, Pu content has high 240 and 242 content and never separated

REMAINING CHALLENGES ARE MATERIALS RELATED

Nobel Metal Plate out in Heat Exchangers

- HX repair in-situ never a real option
- Implies provision for complete Swap Out

Long Term Corrosion or Radiation Damage

- High Nickel alloys or even some stainless steels perform superbly but proving a 30 to 60 year lifetime will be a challenge

Graphite Replacement

- Graphite use gives very strong advantages
- Its lifetime however is limited by power density

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DESIGN CHOICES - ***SEAL OR SWAP?***

Graphite has limited lifetime if power density is high

Does one Seal the reactor for the plant lifetime or go to high power density and plan for graphite replacement?

Early ORNL work chose 4 year Swap

Graphite swapping far more difficult than many assume

Later ORNL work chose a low power density to keep the reactor sealed

- Leads to higher capital and fuel costs (larger core = more startup fuel salt)

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WHAT IS TERRESTRIAL ENERGY'S IMSR?

Integral Molten Salt Reactor

- **Simple MSR-Burner design like the 1980 DMSR**
- **Integrates all primary systems into a sealed reactor vessel**
- **Planned in 80 MWth, 300 MWth and 600 MWth sizes**
- **Off the shelf Steam Turbines**
- **Small Modular, factory fabrication**
- **Alternate salts and new off gas systems**
- **New passive decay heat removal *in situ* without dump tanks**
- **Not determined if thorium used (numerous pros and cons either way)**
  - Thorium could replaces most of the fertile U238
  - Use very low enrichment if no thorium, modestly higher with

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IMSR'S ***SEAL AND SWAP*** APPROACH

- **Many technical challenges are addressed in IMSR's patent pending technology**
- **Stated simply, the IMSR primary vessel is a permanently sealed system with an economically high power density but much less than a 30 year lifetime**
- **After a 7 year design life, an identical IMSR Core-unit replaces the old unit for an indefinitely long plant lifetime**
- **Redundancy of heat exchangers so any failure does not require replacement operations**
- **IMSR = "Sealed for Life" + "Replaceable"**

IMSR CORE-UNIT

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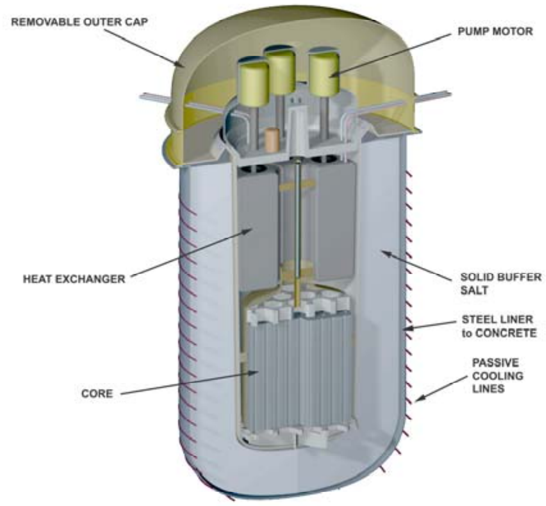
IMSR CORE-UNIT WITHIN BUFFER SALT LINER



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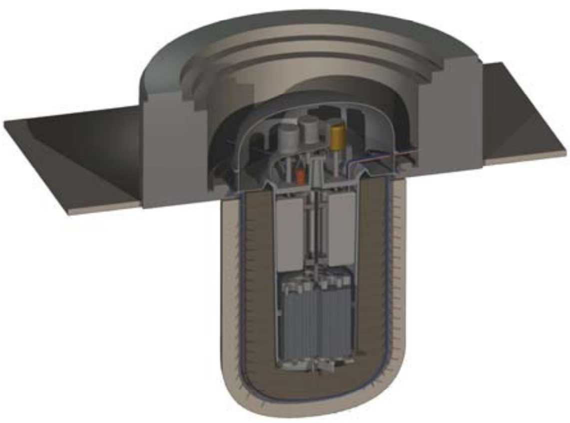
OUTER CONTAINMENT SHELL
(Steel Top Plates Not Shown)



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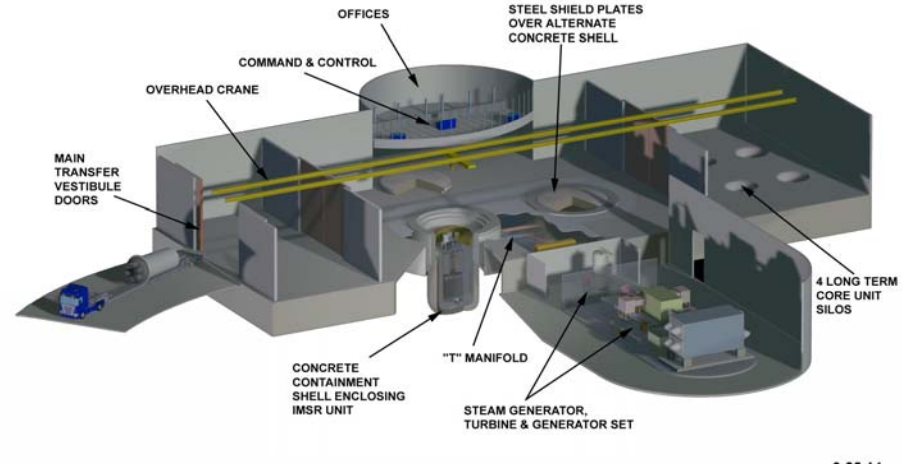
IMSR 80 MWth FACILITY



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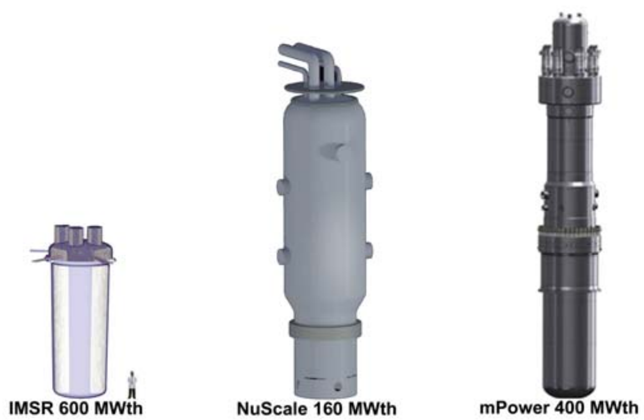
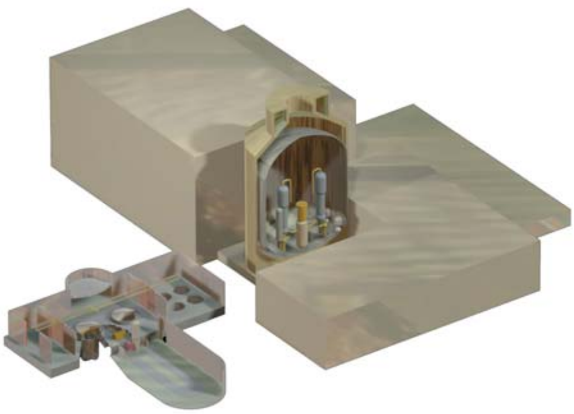
IMSR PEER COMPARISON



IMSR 80MWth vs 300MWth vs 600MWth

IMSR600 (291 MWe) VERSUS AP600 (600 MWe)



IMSR SLIDE SHOW OVERVIEW

CHALLENGES SOLVED WITH IMSR

- **"Sealed for life" offers enormous regulatory advantages to accelerate development**
- **Spent vessel is now intermediate storage of graphite**
- **Airborne release risk during swap eliminated**
- **Long cool down time before moving unit**
- **Material lifetime and corrosion issues greatly eased**
- **Allows evolution in design with ease**
- **Offers obvious "razor blade" analogy of continuous sales to attract industrial partners**

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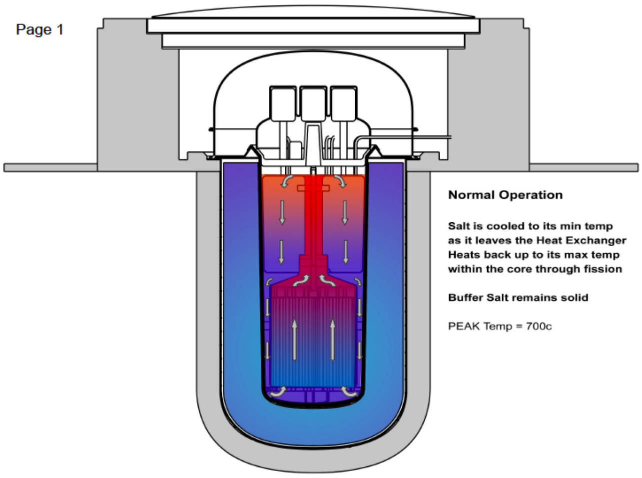
IMSR SAFETY - DECAY HEAT REMOVAL INNOVATION



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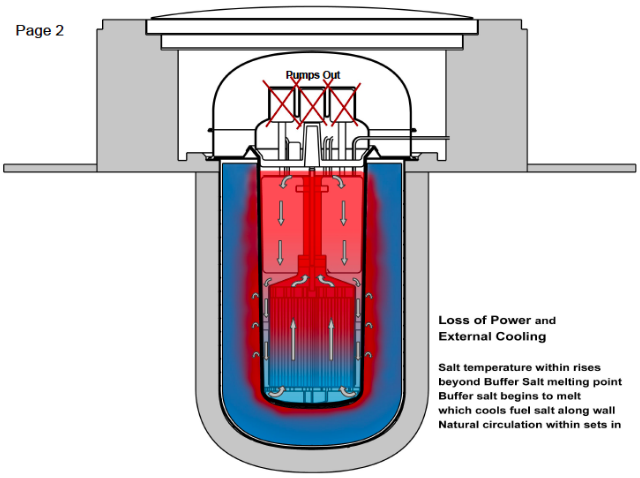

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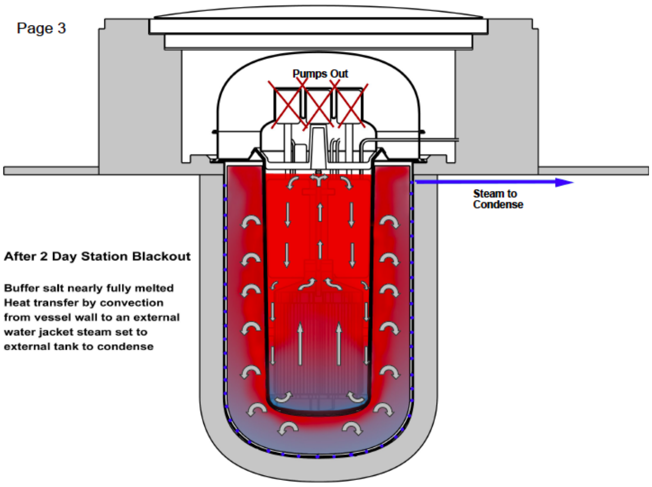

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THE BOTTOM LINE

IMSR main deliverable is +600 °C hot clean salt

- Direct use for process heat applications
- Add steam generator for process steam
- Add Turbine/Gen for power

Simple approach, easiest to achieve regulatory licence and public acceptance

Cost innovation the end result

- Annual fuel cost under 0.2 cents/kwh
- 2013/14 Cost estimate of 2$ a watt (e), 0.6$ a watt (th) for larger IMSR600
- For IMSR80, 32.5MWe at ~5$ a watt
- Phase I Detailed Cost Engineering has added confidence in these estimates, Phase II work to confirm

Design simplicity key but of course much work ahead

- Pump Development, Salt Selection, HX design, Valve/Disconnect systems, Steam Generation

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BUSINESS

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INTRODUCTION TO TERRESTRIAL ENERGY

Terrestrial Energy Inc. ("TEI")

- Founded in Jan 2013 and is headquartered in Mississauga, Ontario, Canada

A nuclear technology company with proprietary Molten Salt Reactor ("MSR") technology

- TEI intends to have built and licensed its first commercial Integral Molten Salt Reactor ("IMSR") by early next decade
- TEI's team consist of over 28 directors, employees, consultants and advisors

Completed Phase I of its business plan

- Completed seed financing
- Completed IMSR Pre-Conceptual Design Report (PCDR)
- Formed board, management team and advisory board to support Phase II

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MILESTONES

January	2013	Incorporated Terrestrial Energy Inc. in the Province of Ontario, Canada
January	2013	Completed Founders Financing Round. Molten Salt Reactor intellectual property committed to Terrestrial Energy
March	2014	Appointed Hugh MacDiarmid as Chairman of the Board
June	2014	Appointed Dr. David Hill to Board; Held executive management positions at Oak Ridge National Laboratory, Argonne National Laboratory and Idaho National Laboratory
July	2014	Completed Seed Financing Round
July	2014	Completed Phase I R&D
August	2014	Filed MSR patent applications in 59 countries
September	2014	Completed Pe-Conceptual Design Report
September	2014	Public launch. Hugh MacDiarmid delivered keynote speech to members of Ontario power industry at Economic Club of Canada, Toronto
December	2014	Entered letter of intent with Canadian Nuclear Laboratories
January	2015	Entered initial collaboration with Oak Ridge National Laboratory Entered strategic Collaboration with University of Tennessee
February	2015	Jeffrey Merrifield, Michael Edwards and Paul Blanchard join International Advisory Board
March	2015	James Reinsch joins International Advisory Board

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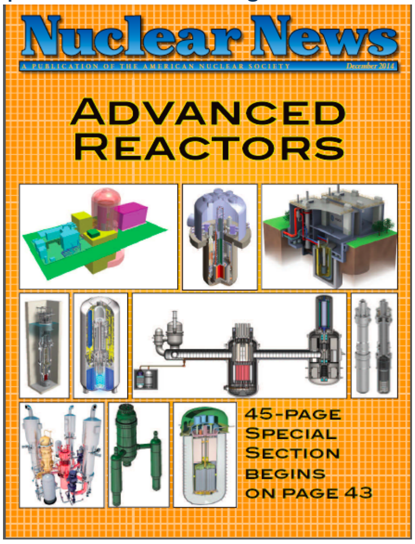
Our Biggest Surprise?
Our Reception in the Existing Nuclear Community



DEVELOPMENT PLAN

Phase I: Pre-Conceptual Design – COMPLETE

- Completed Pre-Conceptual Design Report
- Filed patent applications in 59 countries
- Build corporate governance structures to support Phase II

Phase II: Conceptual Design – COMMENCED (To be completed early 2017)

- Complete Conceptual Design Report
- Complete Phase I of Vendor Design Review with CNSC
- Pre-feasibility Study

Phase III: License and build FOAK IMSR – 5-7 years

- Definitive Feasibility Study
- Full engineering design details of FOAK IMSR power plant
- Site selection and permitting of FOAK IMSR power plant site
- Licensing of IMSR
- Construction of demonstration commercial plant

Phase IV: Commercialization – Commencing early next decade

PHASE II DEVELOPMENT in 2015 and 2016

- **TEI is expanding team, enlisting strategic technical partners, funding University and National Lab work in North America and Europe**
- **Goal to complete 3 files to help secure Phase III funding**
  - **Design** - specified to Conceptual Design Standard ready for engineering blue print
  - **Licensing** - specified to a CNSC Phase I Vendor Design Review standard
  - **Economics** - specified to a Pre-Feasibility Study standard

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IMSR – A NEW PARADIGM FOR NUCLEAR ENERGY

A new economic proposition

- **Cost-competitive**
  - IMSR600 LCOE projected as competitive with Coal and current Natural Gas
- **Scalable**
  - A global energy source to rival fossil fuels
- **Accessible heat and electrical energy**
  - Secure, reliable, portable, grid independent energy

A new social proposition

- **Passive Safety**
  - A completely different narrative in nuclear safety
- **Far smaller and more manageable waste footprint**
  - The possibility of virtually no long-term nuclear waste
- **Exemplary proliferation resistance**
  - Geopolitically acceptable nuclear power

The IMSR has the potential to "change the game" in energy production

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