TERRESTRIAL E N E R G Y

Leading the Way to A Bright Energy Future

Presentation to SAMOFAR July 2019 Delft

A.C. Rodenburg M.Sc. Lead Scientist

Private and Confidential

Terrestrial Energy



- Terrestrial Energy is a next-generation global leader in nuclear technology
 - Its technology solves nuclear power's market cost problem
- Terrestrial Energy is on a clear path to market with its IMSR[®] Advanced Reactor
- Terrestrial Energy commenced the nuclear regulatory process in 2015
 - First regulatory review of IMSR[®] power design has been completed successfully, an industry first, and a second regulatory review is in progress
- IMSR[®] development is backed by industry policy and with multiple grant awards from US and Canadian governments
- IMSR[®] deployments supported by leading North American utilities
- Additional funds will achieve a catalytic commercial milestone in two years
 - Regulatory greenlight to prepare licenses for construction of first plant with first customer

IMSR[®] technology will transform global energy markets

Bruce Power represented by Michael Rencheck, President and Chief Executive Officer

Duke Energy represented by Preston Gillespie, Chief Nuclear Officer

Energy Northwest represented by Bradley Sawatzke, Chief Executive Officer

ENGIE represented by Yves Crommelynck, Director, Corporate Nuclear Segment Department

NB Power represented by Gaëtan Thomas, President and Chief Executive Officer

NextEra Energy represented by Mano Nazar, Chief Nuclear Officer

Ontario Power Generation represented by Dominique Minière, President of Nuclear

PSEG Nuclear represented by Pete Sena, PSEG Nuclear, President and Chief Operating Officer

Southern Nuclear Operating Company represented by Stephen Kuczynski, Chairman, President and Chief Executive Officer

Tennessee Valley Authority represented by Joseph (Joe) Grimes, Executive Vice President for all TVA generation





















Advisory board

• Technical and Industrial

- Ernest Moniz, PhD Former US Secretary of Energy. Cecil and Ida Green Professor of Physics and Engineering Systems emeritus, Massachusetts Institute of Technology
 - Senior Counsel to Advisory Board
- Ray O. Johnson, PhD Former CTO of Lockheed Martin Corporation
- John Luxat, PhD Industrial Research Chair in Nuclear Safety Analysis at McMaster University
- Regis Matzie, PhD Former CTO of Westinghouse

Policy and Regulatory

- Michael Binder, PhD Former President and Chief Executive Officer of the CNSC from 2008 to 2018
- Jeffrey Merrifield, JD Former US NRC Commissioner and former SVP of the Shaw Group
 - Legal Counsel to Advisory Board
- Olivia Bloomfield Baroness Bloomfield of Hinton Waldrist, Life Peer in the U.K. House of Lords
- Christine Todd Whitman Former head of the US EPA. Former Governor of New Jersey

Environmental

- James Cameron Former Chairman of Climate Change Capital
- Travis Bradford Professor (energy and natural resource markets, and innovation), SIPA, Columbia University
- Ben Heard, PhD Professor, Clean Energy Systems, University of Adelaide
- Financial
 - Robert Litterman, PhD Former head of risk at Goldman, Sachs & Co. and prominent in global institutional investment management community

In Memoriam: J. R. (Dick) Engel, Chief Engineer of the first operating Molten Salt Reactor at Oak Ridge National Laboratory, TN and a veteran MSR engineer was a member from inception of the Company's technical team and more recently a member of its Advisory Board until his unexpected death in June 2017. Given Dick's career long experience with MSR development and his contribution to IMSR[®] development, the Company wishes to acknowledge Dick's invaluable knowledge, advice and support for IMSR[®] development.

Directors



Hugh MacDiarmid – Chairman, Director

- Former President and CEO of Atomic Energy of Canada Limited
- Over a 35+ year career held numerous executive management positions in technology-intensive businesses and transportation-related industries
- Former partner with McKinsey & Company. MBA Stanford University.



Jim Reinsch – Director

- Directed Bechtel's global nuclear operations, presided over Bechtel Canada, United States and Southwest Asia
- Former President of the American Nuclear Society and member of the board of directors of the Nuclear Energy Institute
- Member of board of directors of Ontario Power Generation
- Member of Committee on Nuclear Power, Emirates Nuclear Energy Corporation



David Hill, PhD – Director

- Extensive nuclear project, research and laboratory management experience
- Held executive management positions in the foremost national nuclear laboratories in the US from 1984 to 2012, including Argonne, Oak Ridge and Idaho National Laboratories
- PhD in Mathematical Physics, Imperial College, and MBA University of Chicago



Fred Buckman, PhD – Director

- Former President and CEO of Shaw Group (now Chicago Bridge & Iron). Former President and CEO of Pacificorp
- Serves on a number of corporate boards including General Fusion and Standard Insurance
- Adjunct Professor of Nuclear Engineering at University of Michigan; PhD in Nuclear Engineering from MIT



Simon Irish – CEO, Director

- 20 years investment banking and investment management experience in London and New York.
- Former head of Man Global Strategies in North America, a division of Man Group Plc.
- MA Cambridge University. MSc London Business School



David LeBlanc, PhD – CTO, Director, President

- Globally recognized expert scientist in field of MSR technologies
- Over a decade of post-doctoral research focused on design improvements to facilitate the commercial development of MSR technologies in the modern economy
- PhD in Physics from University of Ottawa

Management



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William Smith, P.Eng. – SVP of Operations and Engineering

- 35+ years experience in nuclear power industry in Canada, with Ontario Hydro and Ontario Power Generation
- Former Senior Vice President of Siemens Canada, a \$3.2 Billion annual turnover organization with 4,800 personnel
- BEng from Carleton University and MBA from Schulich School of Business at York University



Canon Bryan – CFO

- Held multiple management positions, served as officer and director for private and public companies in Canada and the US
- Business experience principally in the energy and natural resource industries



Robin Rickman – VP Business Development

- 42 years' nuclear experience including US Department of Defense, Department of Energy, and the civil nuclear power industry
- Former director of the Westinghouse Small Modular Reactor Program
- Bachelor of Science in Business Management from the University of Phoenix



Louis Plowden-Wardlaw – General Counsel, Company Secretary

- Former Head of Legal at the Royal Bank of Canada, London
- Experienced lawyer and executive with more than 20 years' experience in private practice, and in-house in public and private companies
- LLB University of Birmingham. MSc London Business School

Why do nuclear technology choices matter?

A fundamental relationship



Technology choices drive CAPEX

IMSR® approach to safety drives cost reduction

Central challenge of reactor design is dissipating heat in all circumstances

IMSR[®] cooling method is a great safety advantage

CONTROL

- Strong negative reactivity coefficient of temperature
- Passive shutdown Safety Case

COOL

- Assures heat dissipation in all circumstances
- Fuel is a molten salt and also the coolant *Enables convective cooling of fuel*
- A small reactor (400 MWth) that operates at 700°C Thermal radiative cooling 9x greater than a reactor core operating at 300°C

CONTAIN

- Chemical containment Salts chemically bind volatile fission products
- No chemical driving forces
- Zirconium metal-water reactions absent
- No physical driving forces Operates at one atmosphere
- Integral architecture

IMSR[®] Safety Case achieved with simple, natural and passive mechanisms that are secure and robust

IMSR[®] has a Safety Case that drives cost reduction

Integral Molten Salt Reactor – IMSR®

Does not use water to cool nor solid fuel Uses a molten salt coolant and a liquid fuel

• Excellence in passive safety

- IMSR[®] operates at atmospheric pressure
- Heat is dissipated passively so IMSR[®] is "walk-away safe"

Leads to many commercial advantages

- IMSR[®] less complex so less expensive
- Provides 600 °C heat so has many market missions
 - For electric power and industrial processes, and for deep decarbonization
- Smaller (195 MWe)
- Clean path to market in 2020s
 - Final regulatory step in progress with Canadian Nuclear Safety Commission
- Proven and deployment ready technology
 - IMSR[®] builds on 50 years of the U.S. Department of Energy molten salt reactor work at Oak Ridge National Laboratory (ORNL)
 - IMSR[®] is a proprietary design of Molten Salt Reactor system and improves on the ORNL designs
 - Clean and sustainable energy

IMSR[®] is transformative clean energy technology



The Replaceable IMSR® Core-unit

Why IMSR[®] is a "game-changer"

Cost-competitive, easier to build and provides high quality heat





IMSR[®] – a low cost clean energy solution

IMSR® power plants are cost competitive with combined cycle natural gas



TOTAL SYSTEM COST

Electric power life-cycle emissions by energy source



IMSR[®] carbon footprint can drive decarbonization

TERRESTRIAL E N E R G Y

IMSR® – Key innovation

Key innovation is integration of primary reactor components

- Reactor core
- Primary heat exchanger
- o Pumps
- A sealed reactor vessel within a compact replaceable unit
 - 7-year operation
- Integral design captures full commercial value
 - o Inherent safety
 - Operational simplicity
 - High capital recovery
- Patents pending and granted

The reactor core is replaced every 7 years





Sealed and replaceable IMSR[®] Core-unit



IMSR[®] is simpler and safer by design



How an IMSR[®] power plant works





IMSR[®] is ideal for providing industrial heat and electric power



IMSR[®] 600°C heat can be coupled to many industrial activities in an industrial park – it is not just for electric-grid power provision

IMSR[®] has many uses and is deployable in many industries

- IMSR[®] provides dispatchable heat and power to many industries
 - Electric power generation
 - Baseload and "Black start" capable for grid resilience
 - Dispatchable for Variable Renewable Energy back-up and grid-balancing
 - Industrial heat and power
 - Chemical industry: Ammonia, hydrogen...
 - Petrochemical industry: Oil refining, gas-to-liquids, synthetic fuels...
 - Desalination
- IMSR[®] can compete with fossil fuels on cost and convenience
- IMSR[®] can scale to meet our global energy challenge
 - 85% of supply is currently from fossil fuel combustion
 - Energy services are valued at \$5 Tn of \$76 Tn Gross World Product p.a.



IMSR[®] can reshape a \$5 trillion per year global energy market

IMSR® Power Market Opportunity

Scenario / GWe	NPPs in operation	NPPs under construction	Retirement of NPPs	Additional NPPs	Total new NPP demand
Conservative	392	63	80	345	720
Base-case	392	63	150	610	915
Upside	392	63	200	4, 245	4,500

Western fleet of nuclear power plants is aging

- Between 80 GWe and 200 GWe will retire by 2040

- Coal replacement, growth in electricity and zero-emission environment policies create a further 345 GWe to 4,245 GWe of new nuclear demand
- Terrestrial Energy base-case is 340 IMSR power plant sales by 2040
 - Worth \$312.8 Bn in value
- In Canada alone an additional 18.1 GWe of power generation is needed by 2040
 - Due to retirements of existing NPPs and from the replacement of 10 GWe of coal fired power provision
 - Demand exists today

IMSR[®] is a scalable clean energy technology with a large market opportunity



Project timeline and milestones



Where we are now

Company milestones and recent developments

2016	1Q	 ✓ Commenced regulatory engagement with CNSC for IMSR[®] VDR ✓ Awarded C\$5.7 Mn Cleantech grant by SDTC Canadian Federal Government
2016	2Q	✓ Formed Industrial Advisory Board with senior executives from ENW, OPG, PSEG, Southern
2016	3Q	 Duke Energy and NB Power join Industrial Advisory Board
2016	4Q	 Innovation Award from the Organization of Canadian Nuclear Industries (OCNI)
2017	1Q	 TEUSA invited by USDOE to continue with \$1 Bn loan guarantee application TVA joins Industrial Advisory Board
2017	3Q	 NextEra Energy and Bruce Power joins Industrial Advisory Board
2017	4Q	 KEY MILESTONE - Successful completion of VDR Phase 1 for IMSR[®] power plant design with first regulatory opinion, a nuclear industry first James Reinsch and Frederick Buckman join Board of Director
2018	February	 Former United States Secretary of Energy, Dr. Ernest Moniz joins Advisory Board
2018	March	 Innovation Award from the US Nuclear Industry Council TEUSA Signs MOU with Energy Northwest for Idaho National Laboratory Project
2018	May	 Dr. John Luxat joins Advisory Board TEUSA selected for \$3.15 Mn grant award from US DOE ARPA-E program
2018	June	✓ UK Nuclear Sector Deal and Baroness Bloomfield (U.K. House of Lords) joins Advisory Board
2018	July	✓ IMSR [®] simulator supply agreement with L3 MAPPS, first major supply chain commitment
2018	September	 Nuclear Energy Innovation Capabilities Act and DOE Research and Innovation Acts signed into law in the United States
2018	October	 KEY MILESTONE – VDR Phase 2 for IMSR[®] power plant design starts, a nuclear industry first ENGIE joins Industrial Advisory Board
2018	November	 TEUSA awarded US DOE grant to advance IMSR[®] licensing activities with US NRC Canada publishes its "SMR Roadmap"
2019	April	✓ Dr. Michael Binder, President and CEO of CNSC from 2008 to 2018 joins Advisory Board
2019	May	✓ Terrestrial Energy admitted to the Generation IV International Forum, first private company to do so



IMSR® TECHNOLOGY

IMSR® relative market position in SMR sector



Unfavorable

Favorable



Many technology choices for a power plant

Today's market factors driving reactor development:

- Smaller simpler plants that are faster to build
- Less expensive, lower project risk and easier to finance
- *Higher temperature operation for more efficient power generation and to supply high-grade heat to industry*



Liquid fuel, salt-cooled reactors offer unique and highly compelling technology and commercial advantages

Generation IV MSR's have transformative commercial potential



IMSR® design for high technology readiness

IMSR[®] builds on 50 years of ORNL reactor design work and on many demonstrated technologies.

IMSR[®] is a molten salt reactor system that uses:

- Fluoride chemistry
- Under 5% LEU once-through fuel cycle
- Thermal spectrum
- Graphite moderator
- Integral core architecture

IMSR[®] has no fundamental technology challenges remaining







IMSR® produces less waste – a very good start

• IMSR[®] power plants generate less waste

- 30% less fission product waste per kWh(e) by mass
- 50% less plutonium per kWh(e) by mass
- IMSR[®] Spent Fuel Salt is a high economic value waste stream
 - Massive quantities of fissionable thermal energy remain in spent nuclear fuel
 - IMSR[®] Spent Fuel Salt is easier to recycle and reprocess compared to solid spent fuel from Conventional Reactors
 - IMSR[®] fuel is easier to "qualify" with a regulator

<u>If policy supports:</u> IMSR[®] technology is capable of virtually eliminating the need for long-term disposal of spent nuclear fuel

IMSR[®] has many advantages over conventional nuclear

ADVANTAGE	IMSR®	PWR
Smaller reactor	195 MWe	1,000 MWe
Lower total CAPEX	\$700 Mn to \$800 Mn	\$8,000+ Mn
Lower pressure operation	1 Atm with many cost, engineering and safety benefits	172 Atms leading to increased complexity and economic penalty
Highly modular design	Standardization of components for factory production	Non standard and bespoke components
High temperature output	600 °C	290 °C
High thermal efficiency	47% thermal efficiency and 40%+ greater revenues for electric power provision	33% thermal efficiency resulting in low capital efficiency
Load following	Dynamic core and turbine for fast load response	Un-dynamic core and turbine limits use to grid baseload only
Inherent reactor control	Passive power management with many cost, engineering and safety benefits	Active engineered reactor control leading to increased complexity and economic penalty
Passive decay heat management	Passive decay heat management with many cost, engineering and safety benefits	Active decay heat management leading to increased complexity and economic penalty
Broader industrial utility	Heat for many industrial processes and for power generation	Grid baseload power generation only
Higher value product	High-grade heat delivered in the form of a common industrial salt circulating in a low pressure system	Low grade heat circulating in a high pressure system

- General Molten Salt Reactor considerations
- Brief Technical Summary of the IMSR400 design



INDUSTRIAL EXPERIENCE WITH MOLTEN SALTS

- Aluminium production
- ~1000°C molten fluoride baths →
- NaF-AlF3 mixture (cryolite)
- >40,000,000 tonnes/year





- Solar Thermal Power Plants
- Andasol Parabolic CSP
 - 28,500 tonnes molten nitrate thermal storage tanks

NUCLEAR EXPERIENCE WITH FLUORIDE SALTS





ADVANTAGES OF MOLTEN SALT REACTORS

• Safety

- Enhanced ability for passive decay heat removal
- Inherent Stability from strong negative reactivity coefficients
- 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-Burners can *close fuel cycle* and see almost no transuranics going to waste
- Resource Sustainability and Low Fuel Cycle Cost
 - Thorium breeders obvious but MSR-Burners also very efficient on uranium use



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





CHALLENGES OF 1970'S MSR-BREEDER DESIGN

- Online Fission Product Removal
- Tritium Control
- Reactivity Temperature Coefficients (only weakly negative)
- Use of Highly Enriched Uranium
- Long Term Corrosion or Radiation Damage
- Graphite Replacement Operations

ISSUES SOLVED BY THE MSR-BURNER APPROACH

- Fission product removal
 - No need for any salt processing (Recycle options when desired)
 - Salts used as batches with periodic fuel additions
- Tritium Control
 - Able to use non "FLiBe" carrier salts to curtail tritium production
 - NaF, RbK and ZrF₄ among potential ingredients

Reactivity Coefficients

• MSR-Burners have superior reactivity coefficients

• Proliferation

• Uranium always LEU (denatured), Pu content has high 240 and 242 content and never separated even if fuel eventually recycled

REMAINING CHALLENGES ARE MATERIAL RELATED

• Long Term Corrosion or Radiation Damage

• High Nickel alloys or even stainless steels perform superbly but proving a 30+ year lifetime a challenge for both reactor vessel and primary heat exchanger

Graphite Replacement

- Unclad graphite use gives very strong advantages
- Very low enrichment fuel (~2% enriched LEU)
- Makes Out of Core Criticality virtually impossible
- Protects vessel wall from high neutron flux
- Its lifetime however is directly related to power density



Integral Molten Salt Reactor

- LEU fueled MSR-Burner design like the 1980 DMSR
- Integrates all primary systems into a sealed reactor Core unit
- 7 year Core unit "Seal and Swap" approach to graphite lifetime
- Shorter lifetime for vessel and HX simplify qualification
- Planned as 400 MWth (~ 192 MWe)
- Alternate salt and new off gas system
- New passive decay heat removal *in situ* without dump tanks
- Safety at forefront which leads to cost innovation



SCHEMATIC VIEW OF IMSR POWER TRAIN





IMSR SINGLE UNIT, TWIN SILOS FOR SWITCHLOADING









IMSR[™] NPP CONSISTS OF NUCLEAR ISLAND AND BALANCE-OF-PLANT



IMSR[™] Nuclear Island produces 600°C industrial heat. Balance-of-Plant can be a broad range of industrial applications – not just power provision

IN-SITU DECAY HEAT REMOVAL – NEW INNOVATION

- Freeze Valve and Dump Tank the "traditional" approach
- Results in unwanted lower penetrations and regulator likely to assume failure to drain is possible
- IMSR approach has long been in-situ decay heat removal
- Convection and natural circulation brings decay heat to vessel wall
- Radiant transfer to Guard Vessel (Guard=Containment)
 - 700 C surface 9x radiant heat compared to 300 C
- From there, water jacket options or PRISM type RVACS
- Reactor Vessel Auxiliary Cooling System



PRISM RVACS Well Studied and Accepted

Passive Systems versus Active Systems



DRAWBACKS OF RVACS DESIGN FOR MSR USE

- Drawbacks of RVACS include the potential activation of passing air to Argon41 (110 min half life)
- Significant neutron shielding required to bring Ar41 rates to acceptable (and what level is publically acceptable?)
- As well, any remote possibility of breach of containment (Guard Vessel) means a relatively direct pathway for radionuclides

IRVACS







CHALLENGES SOLVED WITH IMSR

- "Sealed for life" offers enormous regulatory advantages to accelerate development
- Airborne release risk during graphite swap eliminated
- Long cool down time before moving unit
- Material lifetime and corrosion issues greatly eased
- Good fuel economy on Once Through
- Future recycling to "close" fuel cycle and improve fuel economy commercially attractive
- Offers obvious "razor blade" analogy of continuous sales to attract industrial partners

TERRESTRIAL E N E R G Y

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