SIMULATING A SMALL MODULAR MOLTEN SALT REACTOR

L3 MAPPS Inc. | Power Systems and Simulation

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Outline

• Introduction
• Simulation Technology Updates and Configuring Molten Salt Reactor (MSR) Plant Model
• Current Status
• Wrap-up
SMRs → Focus on Molten Salt Reactor Design, Simulation Assisted Engineering
Introduction

• Small Modular Reactors (SMRs)
  – Nuclear reactors with power between 10 MWe and 300 MWe
  – Less than 10 MWe often called Micro Modular Reactors (MMRs)
  – Often integral and modular, designed for factory fabrication
  – Numerous designs emerging
    – Water Cooled (Land Based and Marine Based)
    – High Temperature Gas Cooled
    – Fast Neutron Spectrum
    – Molten Salt
    – MMRs
  – Global market size: $150B between 2025 and 2040 [Pillsbury]

• Canada: a frontrunner
  – Canadian Nuclear Safety Commission conducting Pre-Licensing Vendor Design Reviews (VDR)
    – 10 different designs ranging from 3 MWe to 300 MWe
    – 2 more VDR agreements under development
  – Ontario Power Generation working with GEH to introduce grid-scale SMR
  – Global First Power developing MMR demonstration plant

• Simulation for training but – more importantly today's context – for initial design & verification support/testing – Simulation Assisted Engineering

TERRESTRIAL ENERGY

IMSR®: Integral Molten Salt Reactor

• Announced L3Harris-Terrestrial Energy agreement on 30 September 2020
  • “This partnership will help Canada to advance domestic small modular reactor technology, while creating good jobs as the country moves towards generating energy with fewer carbon emissions.” – The Honourable Navdeep Bains, Minister of Innovation, Science and Industry, Government of Canada
IMSR Synopsis

• 195 MW core-unit scaled into a 2-unit 390 MW power plant
• Generation IV design
• Uranium fluoride salt fuel is Standard Low Enriched Uranium (LEU <5% enrichment)
• High temperature secondary side
• Reactor vessel core-unit has a 7-year life
• Designed for 56-year operational life; high level waste is stored in-plant throughout plant life and beyond if necessary
• Potential load-follower to support variable renewables
• Thermally very stable – permits IMSR to operate at both high temperature and lower pressure
  – 700°C high temperature operation achieves greater than 44 percent thermal efficiency for electric power generation
  – Low-pressure operation avoids considerable engineering complexity and costs
• Transformative potential commercial results from combination of high-temperature and low-pressure operation, inherent and passive safety, smaller size, and modularity of IMSR power plant design → Upfront investment < US$1B
  – Electric power markets: LCOE < US$50 per MWh
  – Industrial heat markets: In-furnace cost of heat < US$6 per MMBtu
• Terrestrial Energy headquartered in Oakville, Ontario, Canada
Process Simulation Context

• Operating Plant → Examples: CANDU, PWR, BWR, AGR

Well Established Plant Data → Straightforward → Operator Training Simulator

• Plant Being Designed → Today’s Example: IMSR

Evolving New Plant Design → Challenging → Simulation Assisted Engineering (SAE)
Simulation Assisted Engineering

• Terrestrial Energy and L3Harris going beyond operator training to use simulators to aid in NPP design, procedure development, design verification and Human Factors Engineering (HFE)

• Capitalize on integrated, cross-discipline simulation to provide common simulation environment for collaboration

• End goal of shortening the time for:
  1. NPP design and development
  2. Verification and Validation
  3. Operator Training

• Continued use of L3Harris’ Orchid® technology and IMSR simulation to test/benchmark design changes and incorporate plant control systems

• Simulator integrated as part of comprehensive HFE Program

• Plans to recruit operators in 2023, start training in 2024 – operators needed for plant commissioning

source: Terrestrial Energy presentation at L3Harris Owners Circle™ Conference (5-6 October 2021)

### Elements of IMSR400 HFE Program

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<th>Planning and Analysis</th>
<th>Design</th>
<th>Verification and Validation</th>
<th>Implementation and Operation</th>
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<td>Human-System Interface Design</td>
<td>HF Verification and Validation</td>
<td>Design Implementation</td>
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<td>Operating Experience Review</td>
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<td>Task Analysis</td>
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<td>Staffing &amp; Qualification</td>
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<td>Treatment of Important Human Actions/Human Reliability</td>
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Plant Modeling with Orchid® Simulation Environment

- Whole, integrated power plant modeled with only two software tools – results in fully integrated, high-fidelity, real-time power plant model for SAE and OTS
- **Orchid® Core Builder** Visual Core Model Development → ***Comet Plus™**: full 3-dimensional, 2 energy group, neutronics model using Nodal Expansion Method; design and offline calculations
- **Orchid® Modeling Environment** Graphical Drag-Drop-Connect → ***Non-homogenous, 2-phase models a.k.a. ANTHEM™ (SGs, Cooling Systems), Room models (Containment, Reactor Buildings), ***Homogeneous, 2-phase models (Primary Auxiliaries, BOP), Electrical and I&C models, runtime Comet Plus™ in Orchid® Modeling Environment and interfaces to external systems
- Intuitive, graphical development, test and runtime capabilities with built-in configuration management – L3Harris and end-users interface with simulated plant through graphical user interface – great for rapid prototyping as well

***Today’s Focus***
SIMULATION TECHNOLOGY UPDATES
AND CONFIGURING MOLTEN SALT
REACTOR PLANT MODEL

Project Scope, Configuring Plant Model and
Simulation Technology Impacts
IMSR Flow Diagram (Simplified) / Model Implementation

Non-homogenous, 2-phase model (ANTHEM™)

Homogeneous, 2-phase model

Image source: Terrestrial Energy
IMSR SAE Project Scope

• Configuration 1
  – ANTHEM™ Thermal-Hydraulic (TH) Model: Reactor vessel (Core-unit), Guard Vessel - including ANTHEM™ update for Steam Generators and Liquid Salts (Fuel Salt, Secondary Coolant Salt & Solar Salt)
  – Point Kinetics (PK) reactor model to interface with ANTHEM™ TH model

• Configuration 2
  – Configuration 1 + BOP model to provide dynamic boundary conditions to IMSR SGs
  – Emergency Heat Removal System (EHRS)

• Configuration 3
  – Configuration 2 + Comet Plus™ multi-nodal neutronics model (replaces PK model) to interface with ANTHEM™ TH model

• Orchid® Technology and Training
## Inputs Required to Update Technology and Configure Plant Model

### L3Harris Foundational Technology Updates
- Additional Delayed Neutron groups (Comet Plus™)
- Update of Neutron Scattering (Comet Plus™)
- Liquid (Moving) Fuel (Comet Plus™ and ANTHEM™)
- Liquid Phase to include salts (not only water) (ANTHEM™)
- Incorporate Salt Properties (ANTHEM™)
- Additional heat transfer and friction correlations (ANTHEM™)

### Geometric Data
- Detailed construction drawings (includes dimensions, lengths, widths, thickness and diameters, etc.)
- Elevations (relative and absolute) of the components relative to each other
- P&ID and/or Isometrics
- Heat Exchangers dimensions (Number of tubes, diameters, areas of exchange, etc.)
- Any special components that could affect the geometry such as orifices, nozzles, baffles etc.

### Operational Conditions
- Pressures, Temperatures, Flows
- Heat and Mass Balance
- Pumps Dynamic Heads, Flow Rates and Speed
- Heat Exchanger Heat Load
- Reactor Thermal Power
Reactor Design and Orchid® Core Builder Updates

- **IMSR involves**
  - Fuel within fluoride coolant salt moving inside vessel
  - Integral reactor core with graphite moderator
  - Neutrons mainly in thermal spectrum

- **Raised questions**
  - What is impact of having non-static Uranium in core model?
  - How do we deal with Decay Heat products and Delayed Neutrons if they are moving in core?
  - Are 6 groups of Delayed Neutrons sufficient for this type of core?
  - Are two Neutron Energy groups sufficient to model this type of core?
  - What core nodalization is required?

- **Serpent-2** (Monte Carlo reactor burnup physics calculation code) and DRAGON5 (lattice code) used to produce required data processed by Orchid® Core Builder
  - Reference Data
  - Perturbation Data
  - Validation Data

- **Orchid® Core Builder Updates**
  - Orchid® Core Builder updated to read and process data from Serpent-2 and DRAGON5
  - Data set already homogenized into two energy groups
  - Preliminary results revealed L3Harris Comet Plus™ needed to include Upscattering (thermal neutrons going back to fast energy spectrum)
  - Addition of 2 more Delayed Neutron groups needed
  - Nodalization information not available from design codes → Orchid® Core Builder updated to easily read user-defined nodalization
Liquid (Moving) Fuel Model Implementation

- Modeling Liquid (moving) fuel for IMSR instead of Solid Fuels modeled for Conventional NPPs required re-evaluation of reactor and TH model implementation and interfaces
- Certain calculations (code) handled by Comet Plus™ transferred to ANTHEM™ to accommodate fuel movement

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<thead>
<tr>
<th>Modeling Implementation/Interfaces for PWRs (Typ.)</th>
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<tr>
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<td>ANTHEM™ Calculations</td>
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<td>Flux</td>
<td>Moderator Density</td>
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<td>Fission Heat</td>
<td>Fuel Temperature</td>
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<td>Decay Heat</td>
<td>Boron Concentration</td>
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Incorporating Liquid Salts in ANTHEM™

**ANTHEM™ components for Conventional Reactors**

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<thead>
<tr>
<th>Vapor Phase (VP)</th>
<th>Liquid Phase (LQ)</th>
<th>Water properties calculated from steam tables</th>
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<td>Water Vapor</td>
<td>Liquid Water</td>
<td>Non-Condensables properties come from well-defined correlations</td>
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<td>Non-Condensables (N2, O2, H2, CO2)</td>
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**Liquid Salts incorporated in ANTHEM™ for IMSR**

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<th>Vapor Phase (VP)</th>
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<th>Liquid can be water and/or molten salts</th>
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<tr>
<td>Water Vapor</td>
<td>Liquid Water</td>
<td>Salt properties come from different experimental correlations</td>
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<td>Fuel Salt</td>
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<td>Secondary Coolant Salt</td>
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<td>Solar Salt</td>
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<td>Emergency Coolant Salt</td>
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**Molten Salt properties made available from experimental results**

- Salt data/correlations considered for ANTHEM™ update: Salt Composition, Thermal Conductivity, Viscosity, Specific Heat, Density
Heat Exchangers and ANTHEM™ Updates

- Heat exchangers (PHX, SHX, EHX, SG, RH) differ from Conventional NPP Steam Generators modeled
  - Additional heat transfer and friction correlations added to ANTHEM™
    (e.g. cross flow outside tubes)
  - Improved non-condensable modeling for heat transfer applications
    (e.g. below 0 °C conditions)

Image source: TEMA
CURRENT STATUS

Work Performed to Date, Results
IMSR Simulation Work Performed to Date

- Started work on IMSR development with goal to
  - Update Orchid® Core Builder and core model
  - Adapt and update ANTHEM™ objects and code to use molten salt
  - Develop and integrate IMSR simulation models
- With data and assistance from Terrestrial Energy, Orchid®-based IMSR simulation created

- **Orchid® Core Builder**
  - Orchid® Core Builder reads Serpent-2/DRAGON5 data to generate inputs for Comet Plus™

- **Orchid® Modeling Environment (ANTHEM™)**
  - Reactor Vessel with risers, PHX and downcomers
  - Fuel Salt Loops including Guard Vessel
  - Coolant Salt Loops with PHX and SHX
  - Solar Salt Loops with SHX, Super-Heater, Evaporator, Preheater and Reheater
  - Steam Generators with separate vessels (Preheater / Evaporator / Superheater) and Reheaters
  - EHRS including Emergency Heat Removal Loops with EHX

- **Orchid® Modeling Environment (Homogeneous, 2-phase)**
  - Balance of Plant model including Steam, Turbine, Generator and Feedwater
IMSR Simulation Work Performed to Date

- IMSR Simulation
  - Establishes heat transfer between loops and performs flow and pressure calculations
  - Replicates heat balance (from THERMOFLEX heat balance software)
  - Includes new heat transfer and friction correlations
  - Uses controller emulators to replicate Terrestrial Energy’s control philosophy
  - Integrates real-time Comet Plus™ and ANTHEM™ models
  - Compared L3Harris simulation results with Terrestrial Energy’s original (non-real-time) Flownex simulation environment results
Configuration 3 Model Results

- Orchid® Core Builder used to run static (offline) flux solution based on neutronic source data from Serpent-2/DRAGON5 and determined core nodalization
- Adjustments needed/implemented e.g. improved nodalization, upscattering → greatly improved result
- Finalized implementation of real-time, multi-nodal Comet Plus™ neutronics model and integration with ANTHEM™

- For comparison with Flownex simulation, L3Harris’ Orchid®-based simulation was run with
  – ANTHEM™ Salt Circuits and Steam Generators
  – Homogenous, 2-phase Hydraulic BOP systems
  – Comet Plus™ neutronics model
  – Control emulators
- Differences between the Flownex and Orchid® simulations
  – Control logic in simulations at different maturity levels and not same (control design work ongoing)
  – Solar Salt / Steam Generators configuration is different (L3Harris model to be updated with final SG design)
WRAP-UP

SMRs, IMSR, SAE, Plans
Closing Observations

- IMSR reactor core, salt circuits, steam generators and BOP modeled and integrated
- Multiple configurations delivered to Terrestrial Energy for SAE
- Orchid® simulation delivering strong results
- Going forward: Continued use of Orchid® technology and IMSR simulation to test/verify design changes and incorporate/validate plant control systems

- High expectations for penetration of SMRs in market to effectively combat Climate Change
- Pleased to collaborate with Terrestrial Energy on transformative IMSR design
- Simulation to support evaluation of new plant design (Simulation Assisted Engineering) will form basis for Operator Training Simulators
- Simulation technology (Orchid®) updates were needed to accommodate MSR properties

Image source: Terrestrial Energy
Closing Observations

TRADE RELEASE

L3HARRIS RECOGNIZED FOR INNOVATIVE MOLTEN SALT REACTOR SIMULATOR

Highlights:

• Receives 2021 Organization of Canadian Nuclear Industries’ Innovation Award
• Delivered first-of-a-kind small modular reactor (SMR) simulator to Terrestrial Energy
• Provides Canadian technology that simulates innovative liquid nuclear fuel and molten salts

• 25 November 2021: L3Harris work on IMSR simulation results in OCNI Innovation Award