IES Integrated Energy Systems Program

Office of Nuclear Energy | Department of Energy | https://ies.inl.gov

IES Integrated Energy Systems

NUCLEAR THERMAL ENERGY DELIVERY RESEARCH, TESTING NEED, AND PLANNING

Nuclear Heat for Industrial Applications

UPRISE

(Utility Power Reactor Incremental Scaling Effort)

Baton Rouge, LA

May 27-29, 2026

Rami M. Saeed, Ph.D.
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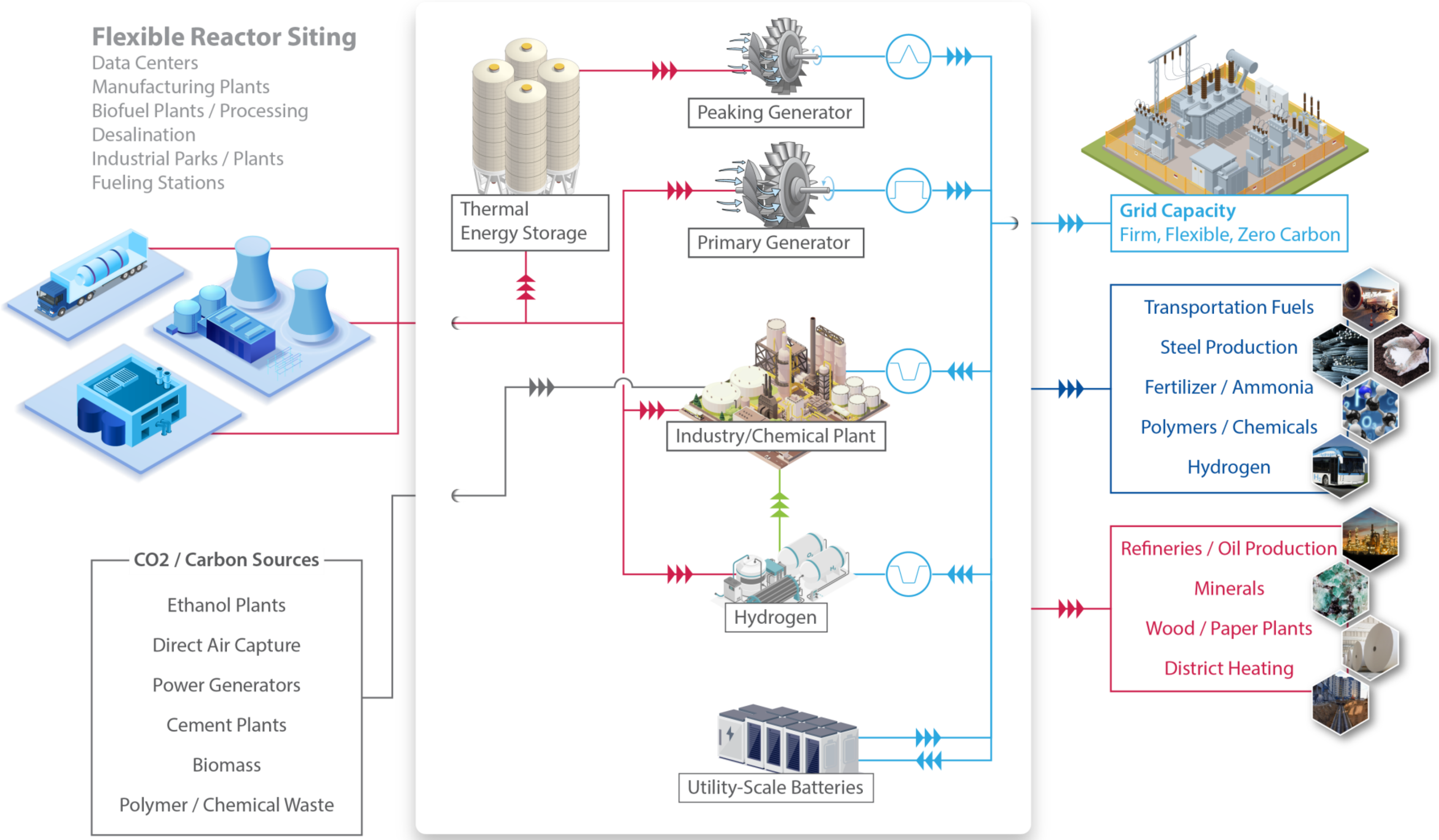
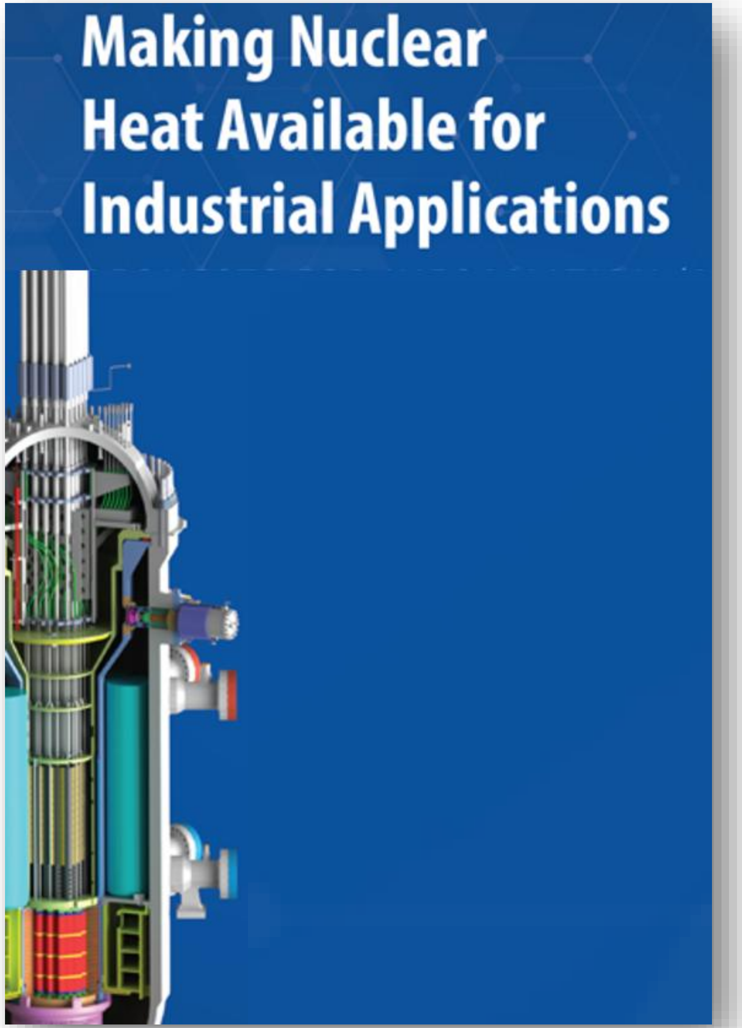
DOE-NE IES Program
Idaho National Laboratory

Integrated Energy Systems Program:



Meeting Objectives



Why we are here today…

- Determine the minimum/necessary testing requirements to design and license heat exchangers for heat delivery
- Identify additional testing that might be necessary to design and license the balance of the heat delivery system.
- Identify the trusted methods, calculations, material data sets and trusted codes/software for licensable engineering designs.
- Prioritize near term “80% universal solution” to long term testing needs, also identify the nice to have category (vs. necessity) Day-3

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Context & Guidelines

Fluid Systems

- Steam – Steam
- He – Steam
- He – Salt
- Salt – Steam
- …

Failure Mode

- Thermal Stress
- Corrosion / Erosion
- Scaling
- Vibration fatigue
- Radiation affects

Heat Exchangers

- Type (*Helical-coil, Shell & Tube, diffusion bonded*)
- Materials*
- Joints and seals
- Fabrication

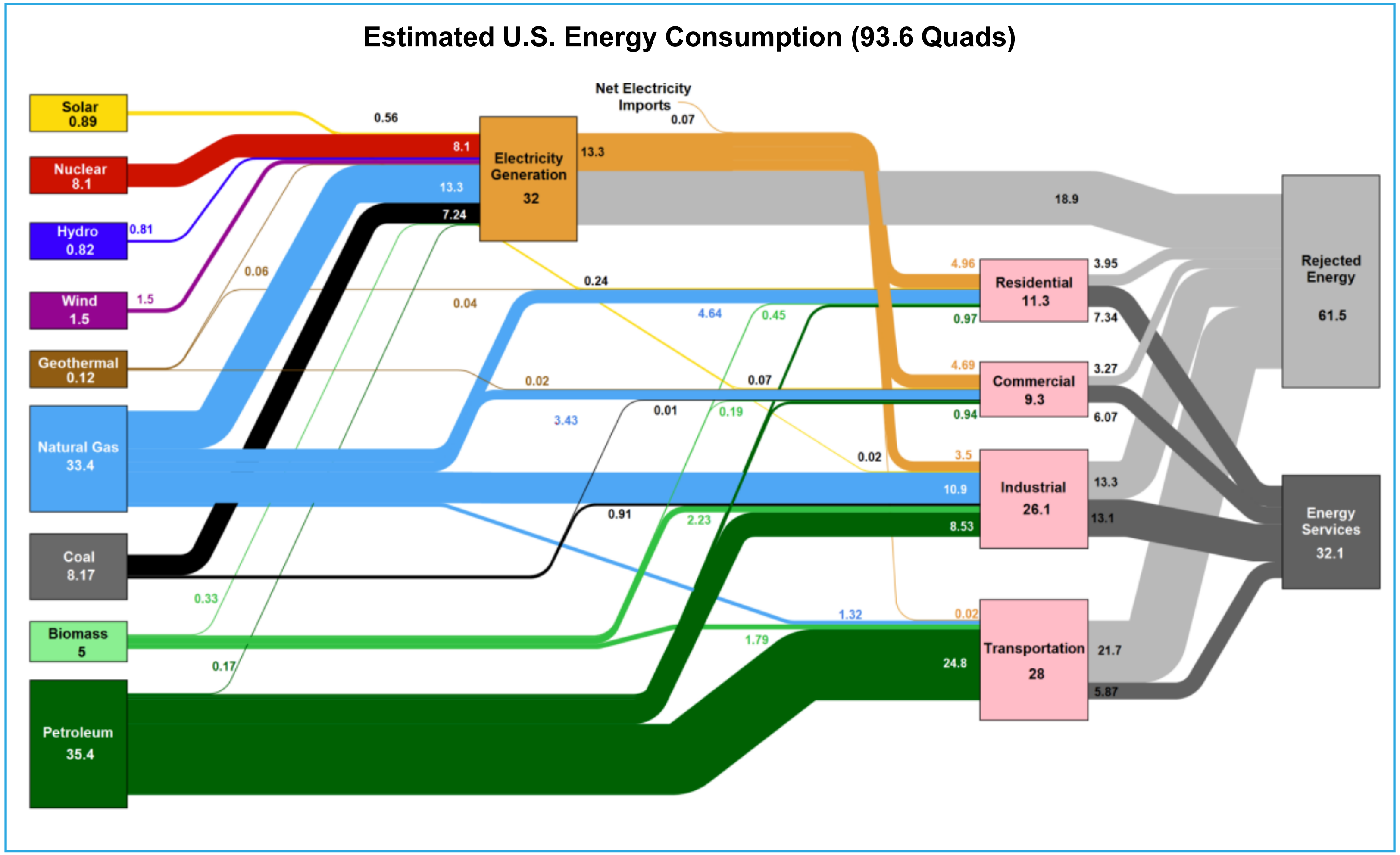
**High temp: Inconel alloys*
**Lower temp: stainless-steel*

Engineering Models

- Existing VS Gaps
- Code and standards / compliance
- Properties and trusted models

What can we trust?
Where do we need testing?

Nuclear heat Untapped Opportunity…



U.S. energy flow chart

Produced by Lawrence Livermore National Laboratory in Oct. 2024. Data is based on DOE/EIA SEDS (2024)

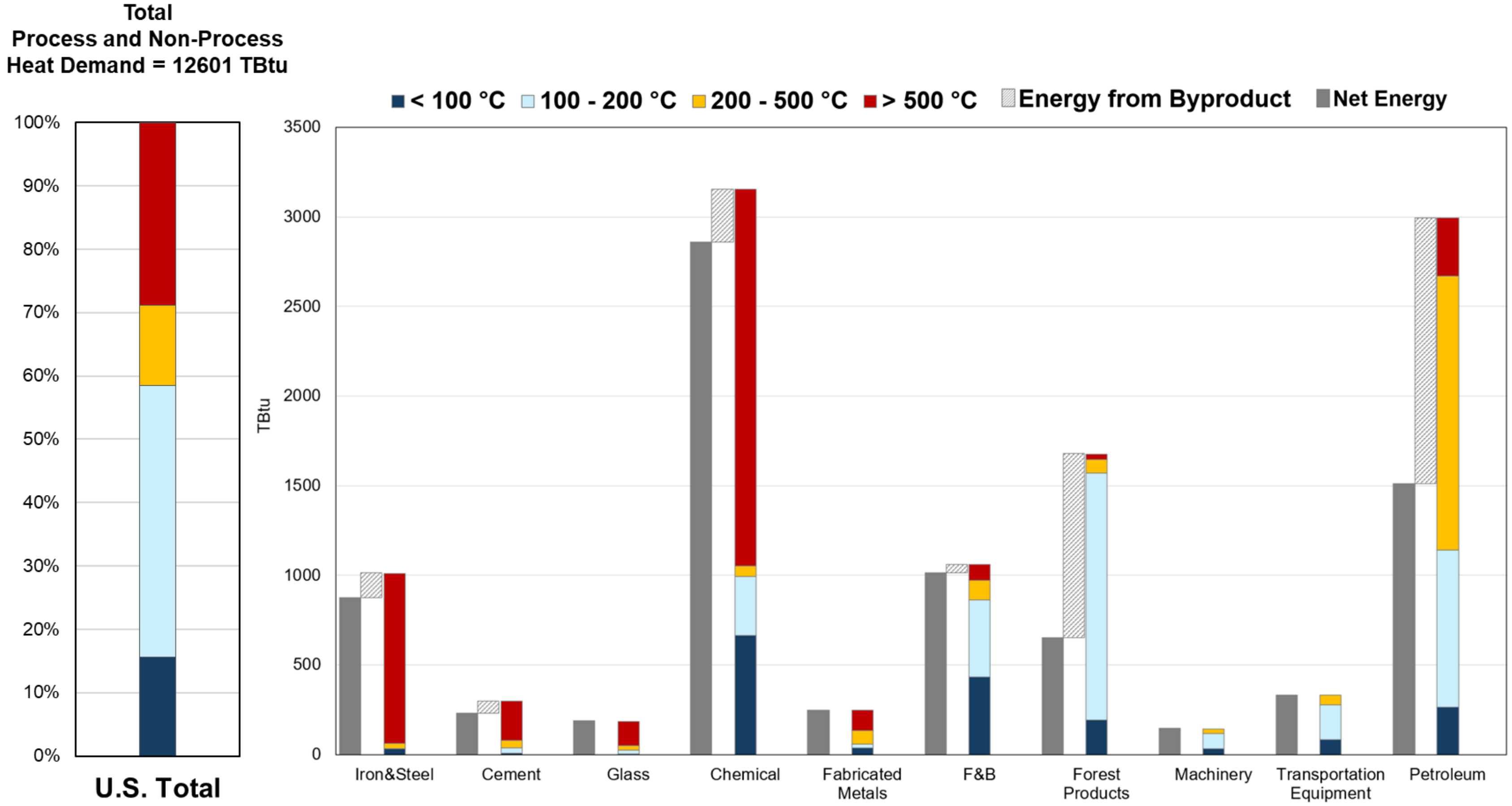
Where the Opportunity Lies

- → 0 BTU of direct nuclear heat to industry today
- → 78% of industrial demand is heat-driven
- → Industrial heat alone = 3× nuclear output today

Expanding nuclear into direct thermal applications represents the most significant untapped growth vector for nuclear energy, beside powering future datacenters

70% of global primary energy is consumed as heat rather than electricity

About 70% of heat demand in the United States is for applications below 500°C.



Annual heat demand by temperature range and industry

Data collected, analyzed and visualized by INL. Input values compiled from "Manufacturing Thermal Energy Use in 2014." for U.S. 2014, from "Quantification of the European industrial heat demand by branch and temperature level" for the European Union (EU), and from "Decarbonizing Low-Temperature Industrial Heat in the U.S." and "Manufacturing Energy and Carbon Footprints (2018 MECS)" for U.S. 2018.

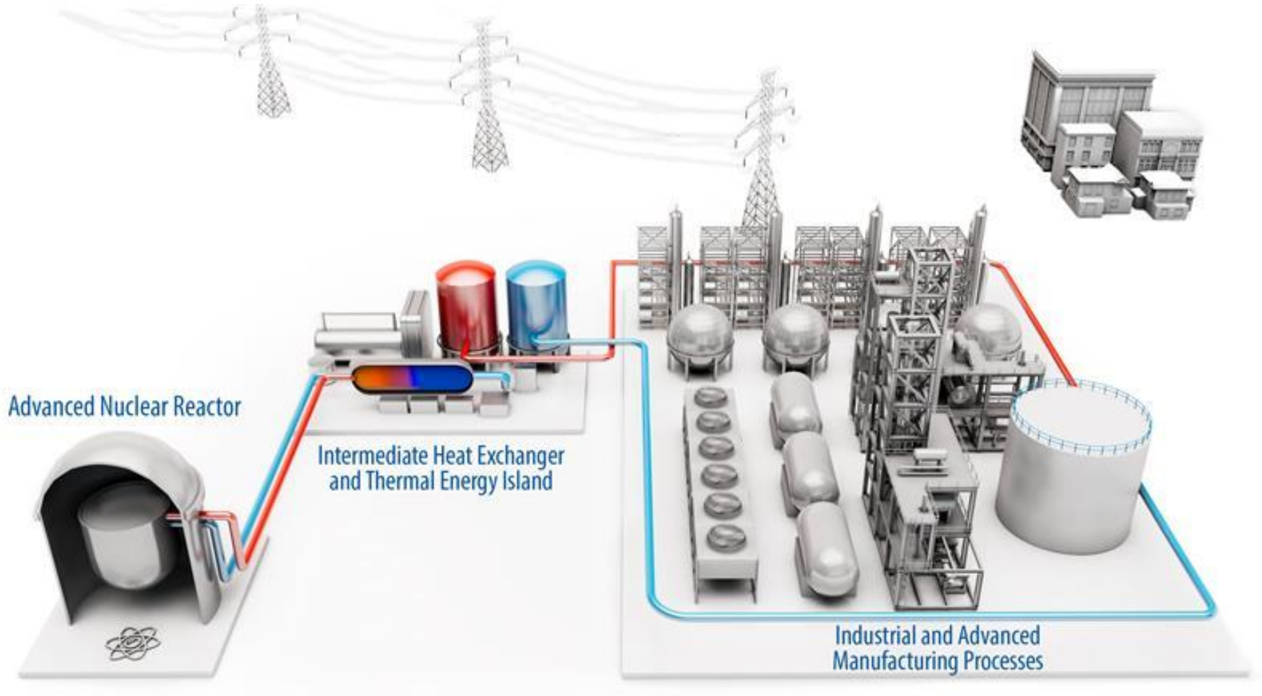
Past Experience in Using Nuclear Heat

- Despite 20,000+ reactor-years of global nuclear experience, direct industrial heat remains almost entirely unexplored….
  - <1% of the total nuclear thermal output of over 440 reactors (non-electric heat)
  - Average efficiency of nuclear systems is ~32-45% for power applications
    - *Using heat for cogeneration, the thermal efficiency can be improved up to 80-90%.*

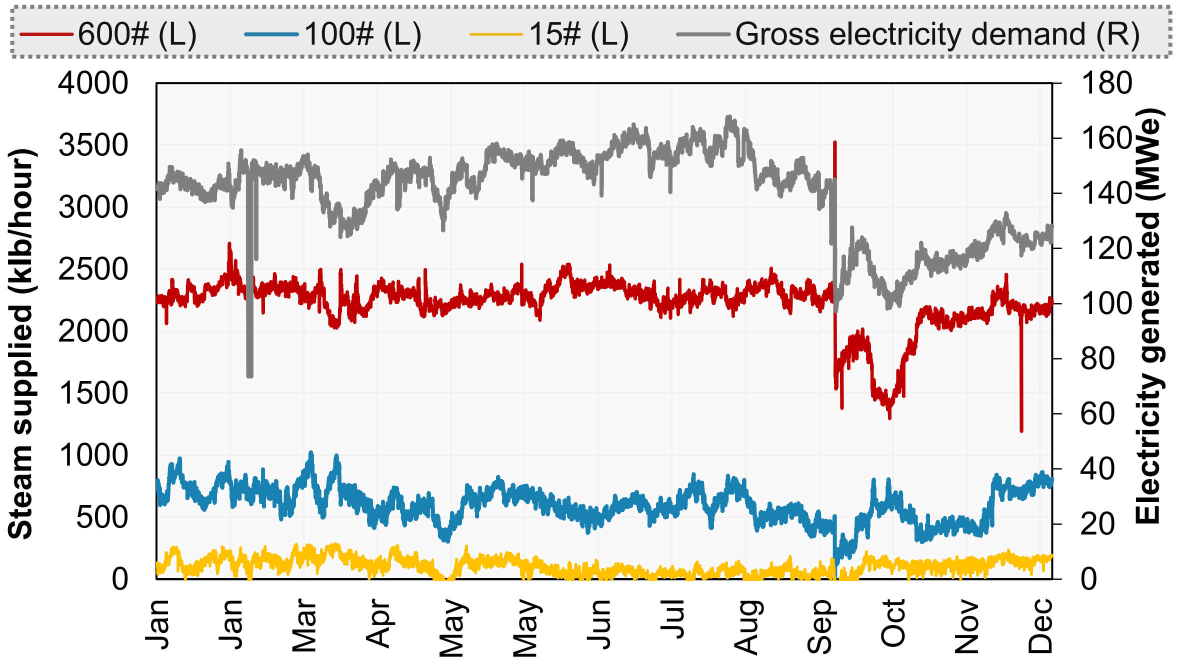
District Heating	Water Desalination	Industrial Process Heat
56	**17**	**7**
reactors	reactors	reactors
~500 reactor-years	**~200–250 reactor-years**	**Ever… globally**
Average 5% thermal output Typically, < 150°C Well-established but limited scope	Multi-effect distillation Multi-stage flash Temperatures < 130°C	Steam-based, < 250°C No high-temp, no chemicals Any new demo is FOAK

– *IAEA - "Current and future generation: Nuclear Power in the World Today" 3 October 2025*
– *NEA – "Beyond Electricity: The Economics of Nuclear Cogeneration", 2022*
– *See Summary Report from the GIF NEANH Virtual Workshop and Information Exchange on Development of Cogeneration Applications of Gen IV Nuclear Technologies, July 2022.*
– *IAEA - "The Use of Nuclear Power Beyond Generating Electricity: Non-Electric Applications " 2021*

Managing Dynamic Heat Loads……

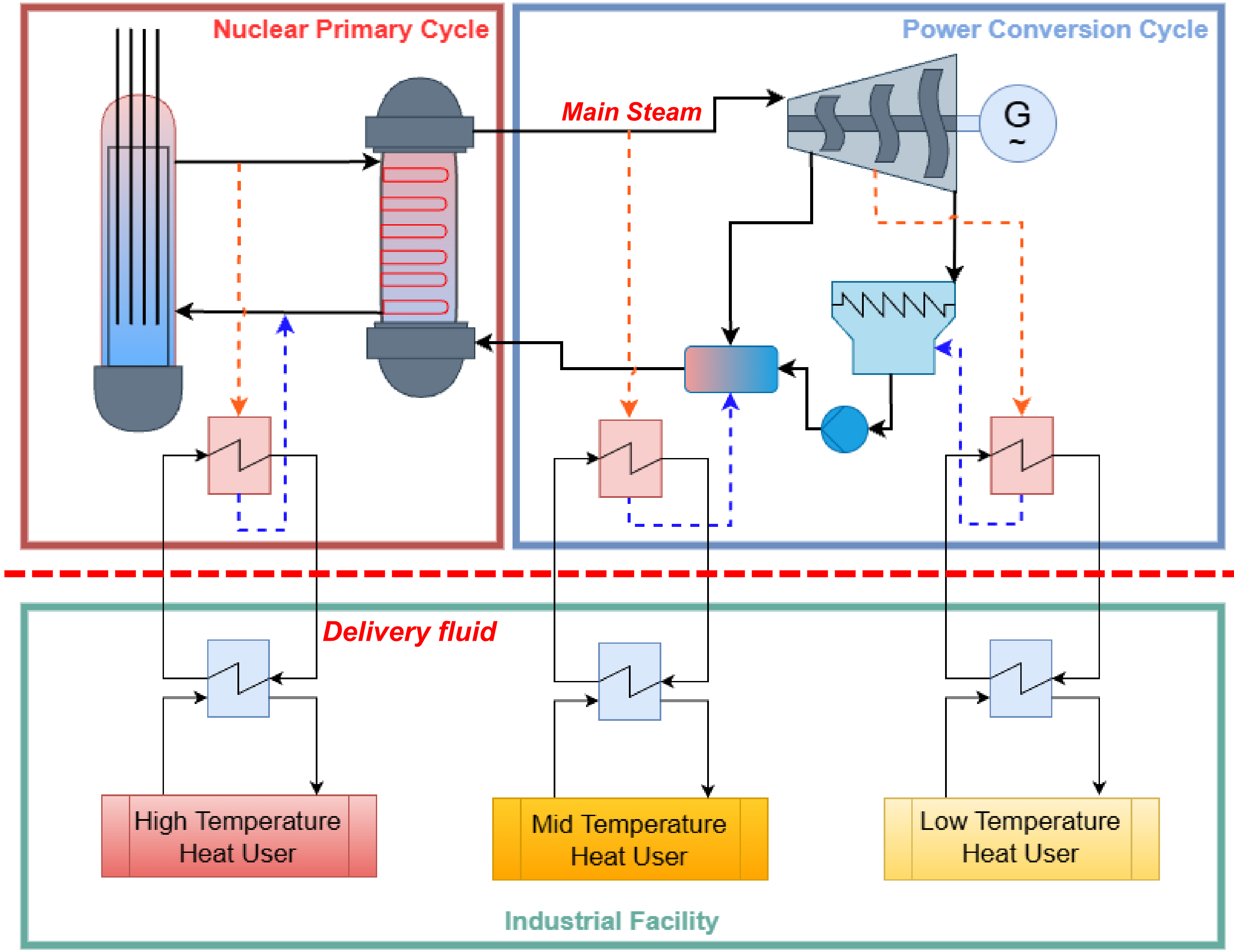


Eastman Chemical: multiple steam pressures, strong seasonal swings, concurrent electricity needs).



- Nuclear wants to run steady…. Industrial demand is dynamic, multi-stream, with multiple simultaneous heat streams at different pressures/temperatures
- Fluid interface capabilities (including heat exchangers) are the enabling technologies + TES buffer

System Level Configurations (near-term)



Reference configurations:

- *LWR, SFR, HTGR reactors.*
- *Rankine (steam) power cycles.*
- *Fluids across plant boundaries: steam and salt*
- *Steam is converted to water for return*
- *Industrial heat requirements: steam*
- *Nuclear plant is protected from high & low return temperature fluctuations (by-pass / heat sinks)*
- *Are there any missing configurations?*

Plant boundary for exporting heat

Intermediate HX

Industry-facing HX

HX Permutations: Reactor to Industrial Heat Transfer Matrix

Priority 1 | Priority 2 | Potential/Later priorities

PRIMARY LOOP			SECONDARY / PROCESS LOOP		
Reactor	**Primary Fluid**	**HX1**	**Secondary Fluid**	**HX2**	**Process Fluid**
HTGR	**Helium**	→	**Steam**	→	**Steam (HP/MP/LP)**
LWR	**Steam**	→	**Steam**	→	**Steam (HP/MP/LP)**
LMFR	**Sodium**	→	**Molten Salt**	→	**Steam (HP/MP/LP)**
HTGR	**Helium**	→	**Molten Salt**	→	**Steam (HP/MP/LP)**
HTGR	Helium	→	Steam	→	N_2 / Air / CO_2
LMFR	Sodium	→	Molten Salt	→	N_2 / Air / CO_2
LWR	Steam	→	Steam	→	N_2 / Air / CO_2
HTGR	Helium	→	Molten Salt	→	N_2 / Air / CO_2
HTGR	Helium	→	N_2/Air/CO_2	→	Steam (HP/MP/LP)
LMFR	Sodium	→	N_2/Air/CO_2	→	Steam (HP/MP/LP)
LWR	Steam	→	N_2/Air/CO_2	→	Steam (HP/MP/LP)
HTGR	Helium	→	N_2/Air/CO_2	→	N_2 / Air / CO_2
LMFR	Sodium	→	N_2/Air/CO_2	→	N_2 / Air / CO_2
LWR	Steam	→	N_2/Air/CO_2	→	N_2 / Air / CO_2

HX = Heat Exchanger HP/MP/LP = High/Medium/Low Pressure Steam

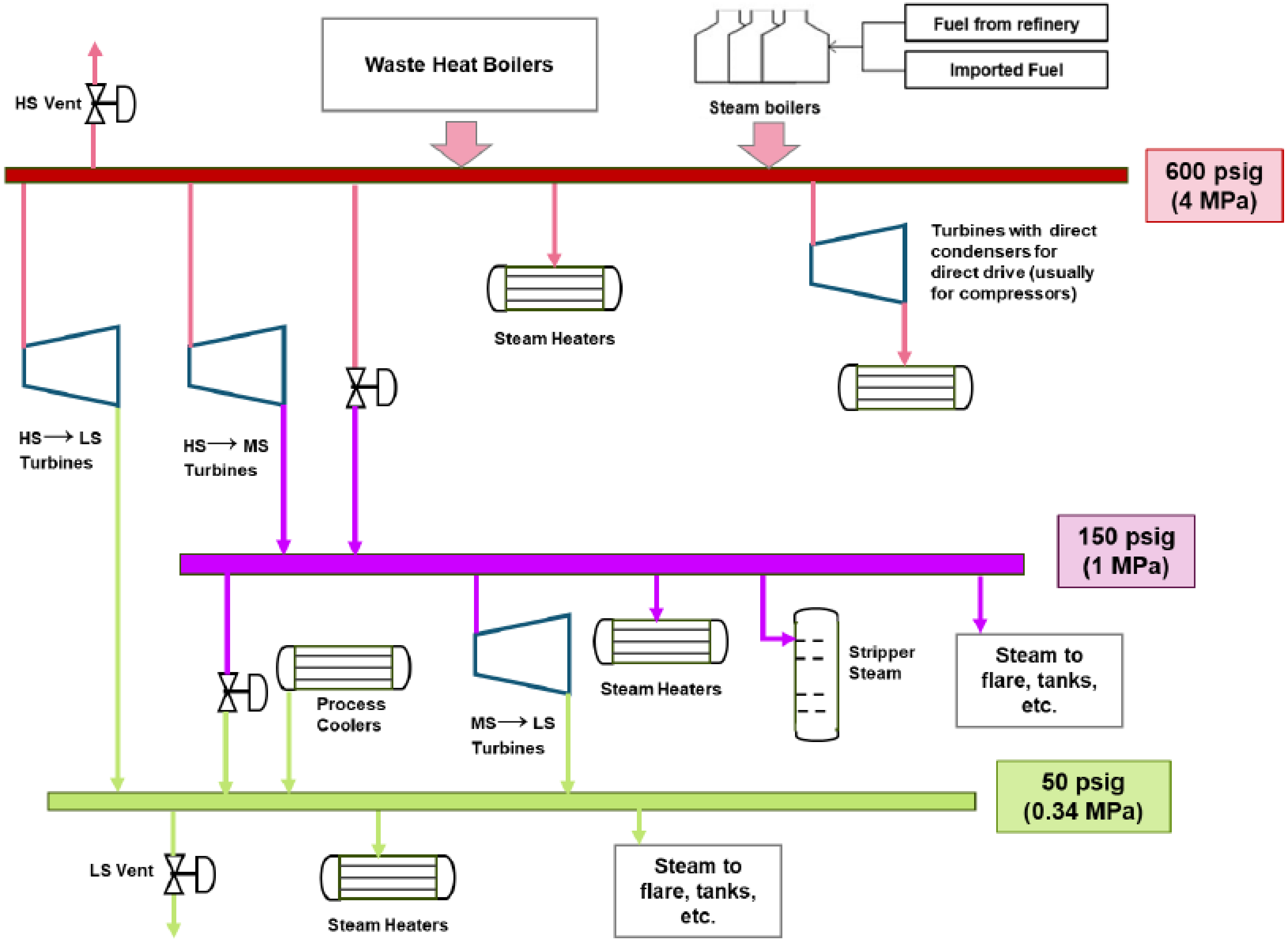


Figure 4. Generic refinery steam system.

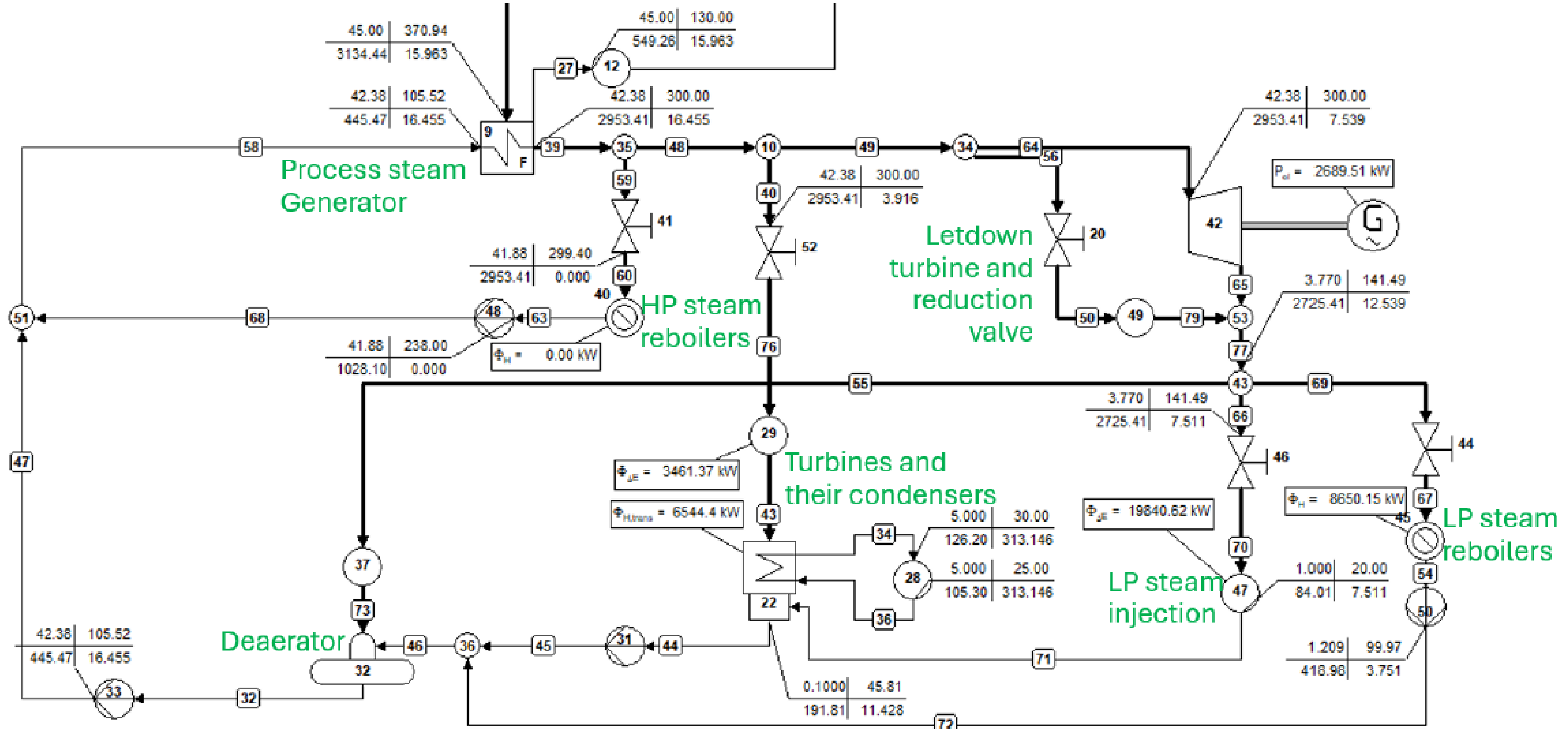


Figure 9. Simplified process steam system for the reference refinery.

List Relevant Failure Models

- Fatigue
- Thermal stresses
- Corrosion & erosion
- Vibration
- Scaling
- Joints and seals “especially for modular / small advanced manufacturing HXs
- Accounting for the impact of dynamic loads vs startup & shutdown

Next session will highlight the available data and failure modes studied in the past:

- *Current data does not address or cover all the possible failure modes*
- *Deeper dive into the failure modes that need to be addressed and tests that need to be done*

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Survey of Available Data

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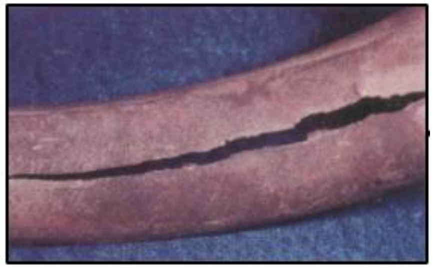
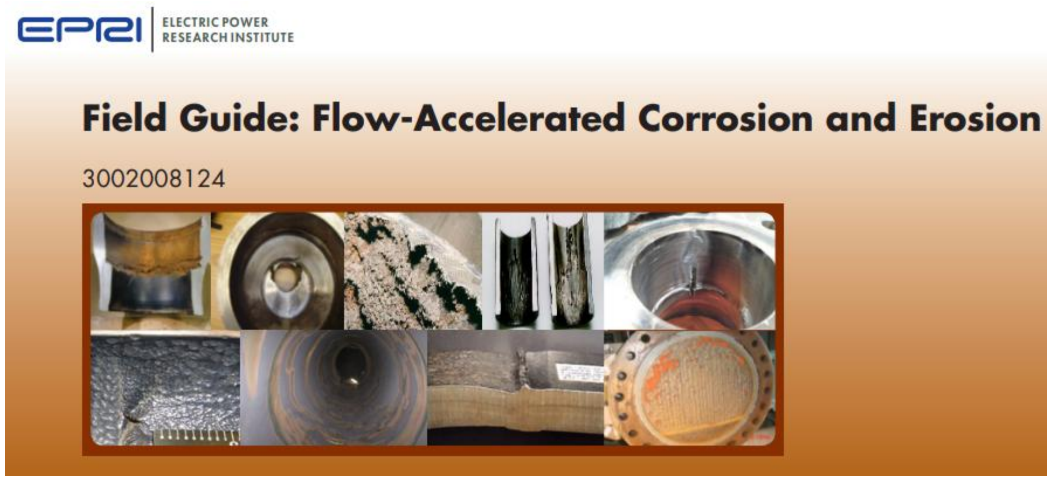
Outline

- **Dominant Heat Exchanger (HX) Failure Modes/Mechanisms**
  - Thermal stresses, fatigue
  - Corrosion, erosion
  - Fretting, joint failure
- **Lessons from Demonstrations/Facilities/Operations**
  - LWR operating data (EPRI reports & databases on HX replacement, corrosion/erosion, component replacements. <~570°F (300°C)
  - Early gas-cooled reactors with helical coil HXs. 1,000-1,750°F (550-950°C)
  - Japan (JAEA) < 1,750°F (950°C)
  - Best Practices from Concentrating Solar Power (NRL) <~ 1,050°F (565°C)

Corrosion





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Dominant HX Failure Modes/Mechanisms

- Thermal stresses, fatigue, operating outside vendor-specified temperature ramp rates or number of thermal cycles
- Corrosion, erosion / poor water chemistry, insufficient material testing, high temperature
- Fretting, joint failure / thermal expansion, inadequate quality control during manufacturing

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Lessons from Demonstrations/Facilities/ Operations

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EPRI | ELECTRIC POWER RESEARCH INSTITUTE

Compilation of Results and Feedback Regarding Feedwater Heater Replacements at Fossil and Nuclear Power Plants

297 HXs total

Table 3-4
Age of the Feedwater Heater at Time of Replacement

Age of Feedwater Heater	Number of Cases	Percentage
< 10 years	2	5%
11 – 20 years	7	18%
21 – 30 years	22	55%
31 – 40 years	4	10%
> 40 years	5	12%

Table 3-10
Actions Taken to Extend Heater Life or Postpone Replacement

Actions Taken	Number of Cases
Plugged Tubes	15
Eddy Current Testing	5
Insurance Plugging of Tubes	5
None	5
Hole Cut / Drilled in Partition Plate	4
Structural Repairs	4
Sleeves or Inserts used on tubes	4
Bypassed the Heater, Removed Heater from Service	3
Stabilized plugged or damaged tubes	3
Tubesheet Repairs	3
Changed the Operating Liquid Level	2
Changed Water Chemistry	2
Conducted an Internal Inspection	2

Table 3-10
Actions Taken to Extend Heater Life or Postpone Replacement

Actions Taken	Number of Cases
Plugged Tubes	15
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None	5
Hole Cut / Drilled in Partition Plate	4
Structural Repairs	4
Sleeves or Inserts used on tubes	4

Take-Home: HXs need to be compatible with diverse actions for maintenance / repair. Industry has extensive experience operating / maintaining shell & tube HXs.

Corrosion-Erosion Considerations – EPRI

EPRI

Topics:
Corrosion
Erosion
Steam lines
Power plant availability
Inspection
Nondestructive testing

EPRI NP-3944
Project 2231-2
Final Report
April 1985

1985, 89 pages

Erosion/Corrosion in Nuclear Plant Steam Piping: Causes and Inspection Program Guidelines

EPRI | ELECTRIC POWER RESEARCH INSTITUTE

Field Guide: Flow-Accelerated Corrosion and Erosion

3002008124

182 pages <250°C

EPRI has considerable data for water and steam <250°C

Failure Analysis Database

The Failure Analysis Database consists of samples obtained by EPRI on behalf of the energy industry to assess material or component condition, determine the primary failure mechanism, or define root causes. The examples provided in this database cover an extensive set of materials including carbon, ferritic and austenitic stainless steels, Co-base hardfacing, weld overlays, nickel-base alloys, and directionally solidified or single crystal blade materials. The types of failure or degradation observed in this database are intended to address common mechanisms described in the boiler tube failures series (3002010388), high energy piping theory and practice (1015505 and 1016212), state of knowledge for low temperature corrosion (3002009209), and/ or emerging issues in the energy industry that may not be well-documented in the listed EPRI references. As part of an on-going initiative to populate and extend

Early gas-cooled reactors with helical coil HXs

Helical Coil HXs

- Early gas-cooled reactors proved performance of helical coil HXs
  - Peach Bottom Unit 1 HTGR (115 MWt, 1966–1974)
  - Fort St. Vrain HTGR (842 MWt, commercial operation: 1979–1989)
  - AVR HTGR (Germany, 46 MWt, 1967–1988 @ temperatures >900 °C)
  - U.K Dragon reactor and Japan HTTR
- These prototypes established helical coil HXs for coupling to HTGRs due to compactness, efficiency, manufacturability, reliability and maintainability.

Take-Aways

- Previous reactors have up to 20 years experience in steady state operation, although we do not have full data for international plants.

Peach Bottom Experience

- Operated ~7 years of full power equivalent days.
- Steam generator exposed to 760°C on gas-side and 538°C/16 MPa on steam side
- Post-operation inspection showed the steam generator to be in "very satisfactory condition."

Fort St. Vrain Experience

- Chronic ingress of moisture into the reactor from water-lubricating bearings and steam generator leakage associated with unique concrete pressure vessel.

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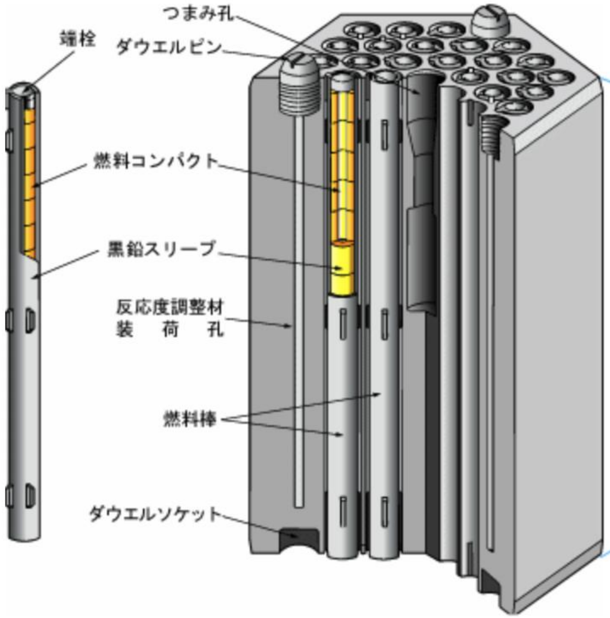
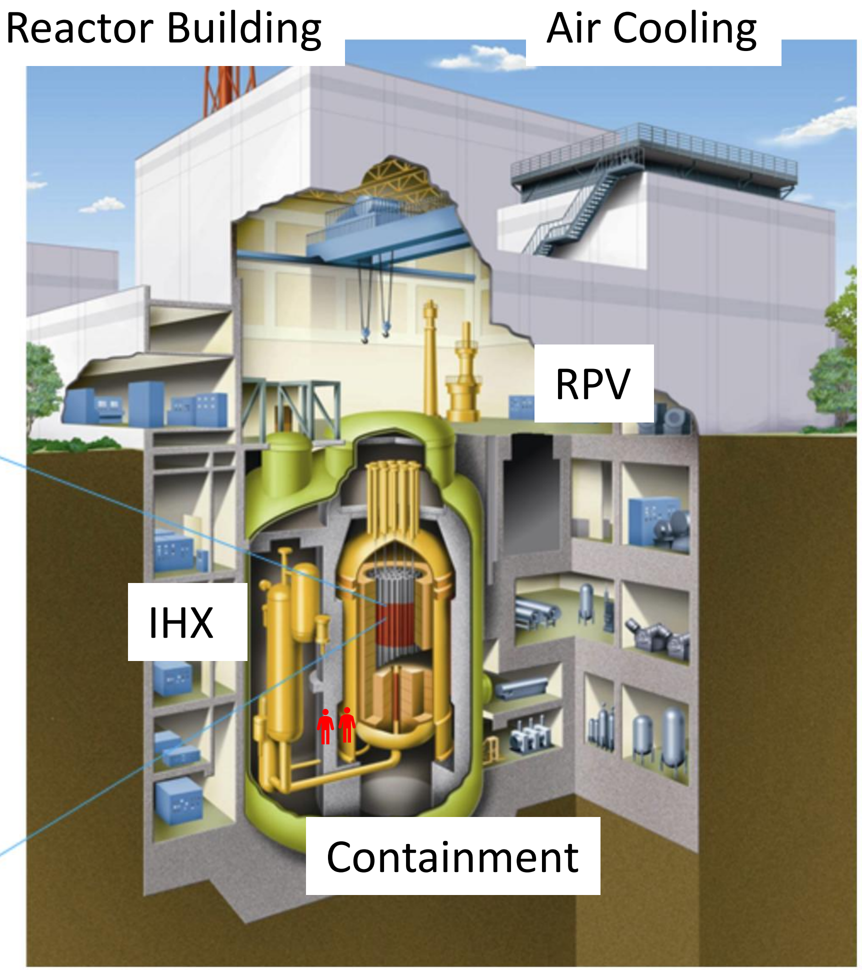
Japanese Atomic Energy Agency (JAEA)

High Temperature Test Reactor (HTTR) facility

- Thermal power: 30 MWth
- Coolant: He
- Inlet/outlet T: 395ºC/950ºC
- Primary coolant pressure: 4 MPa
- Containment contamination: 0.1μSv
- First criticality in 1998
- Restarted in 2021
- H_2 demonstration targeted in 2030.

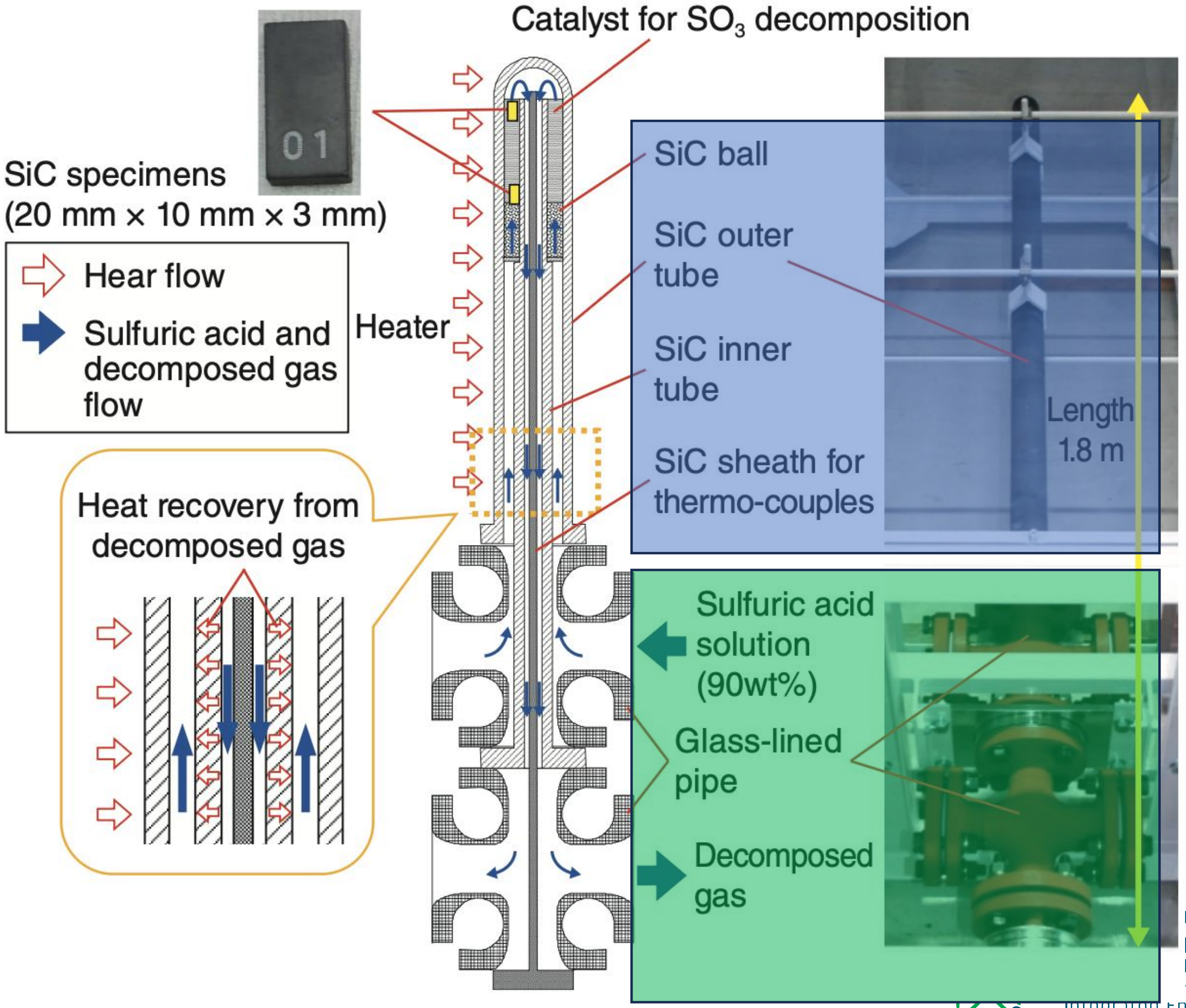




JAEA HTTR Temperatures & Materials

Pipe materials for high temperature delivery:

- SiC ceramics (sulfuric acid corrosion resistance 0.0595 mm/yr)
- SS with inner glass lining (900ºC<)
- Inconel/Hastelloy (hydriodic decomposer, <500ºC)
- SS with fluro-plastic lining (Bunsen reactor, <100ºC)



NREL: CSP Best Practices Study (2020)

NREL: CSP Best Practices Study Continued (2020, NREL/TP-5500-75763)

- Shell-and-tube designs with flat tubesheets are the most common but also **most failure-prone**
- Header-coil designs with welded tubes showed **no commercial failures**
- Top causes of failure identified across dozens of plants:
  1. Operating outside vendor-specified temperature ramp rates
  2. Exceeding allowable numbers of thermal cycles
  3. Poor water chemistry
  4. Inadequate quality control during tube-to-tubesheet welding and rolling in the factory

  Issues are largely preventable with proper specifications and oversight
- **HXs fail most often not due to poor materials, but because the design didn't account for real-world operating conditions — particularly transients, start-ups, shut-downs**
- One of the most consistent findings is that **control systems** are not adequately designed to protect heat exchangers.
- The CSP experience **strongly favors 2 × 50% heat exchanger trains** over a single 100% unit for critical applications.

NREL SolarDynamics

SolarPACES Solar Power & Chemical Energy Systems | WORLD BANK GROUP Energy & Extractives | EPRI ELECTRIC POWER RESEARCH INSTITUTE

Concentrating Solar Power Best Practices Study

Mark Mehos,[1] Hank Price,[2] Robert Cable,[2] David Kearney,[2] Bruce Kelly,[2] Gregory Kolb,[2] and Frederick Morse[2]

- Lessons from 94 plants
- Identified 1,008 issues

Header-coil HX

Idaho National Laboratory

Battelle Energy Alliance manages INL for the U.S. Department of Energy's Office of Nuclear Energy. INL is the nation's center for nuclear energy research and development, and also performs research in each of DOE's strategic goal areas: energy, national security, science and the environment.

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Group Lead – Thermal Systems Analysis (B843)

Thermal Integration Opportunities at INL

Testbed for Resilient Industrial and Manufacturing users of Power & Heat

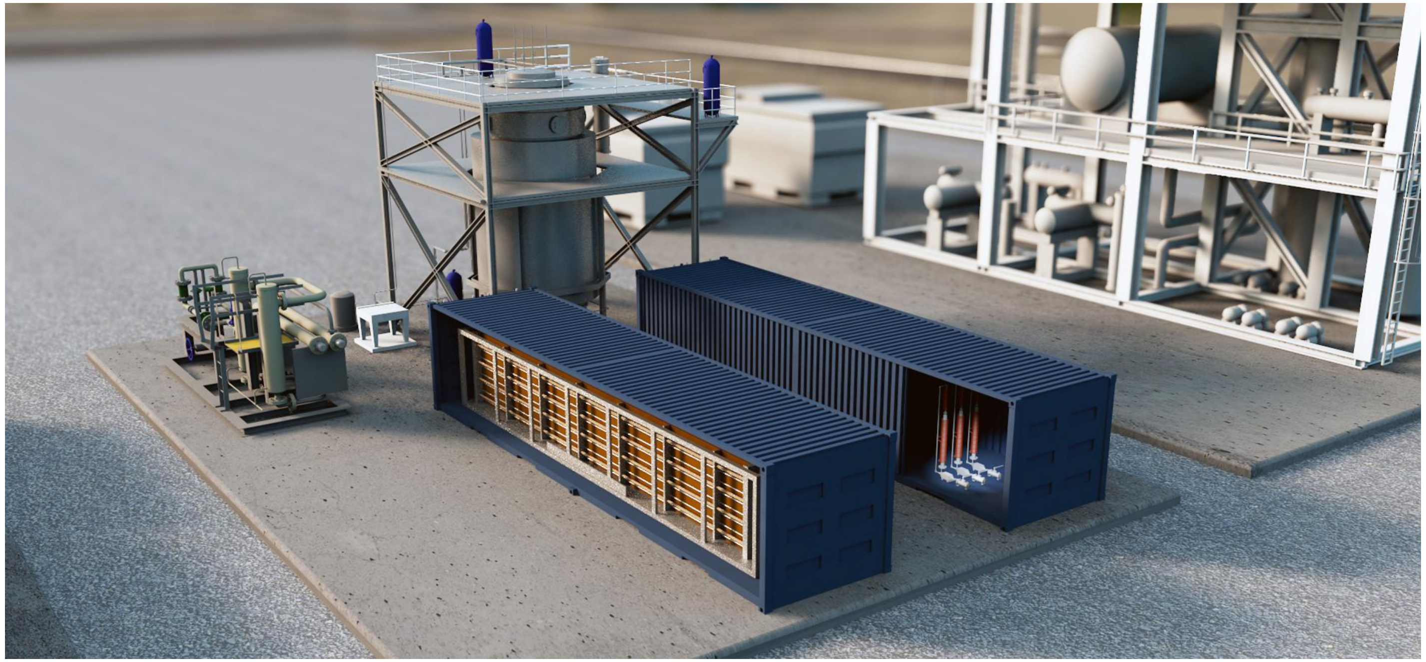
&

MARVEL Microreactor

What is “TRIUMPH”?

- **TRIUMPH =** Testbed for Resilient Industrial and Manufacturing users of Power & Heat
- **Status: Just Awarded (Industrial Technologies Office); $15MM + $5MM Industry Cost Share**
- **Mission:**
  - **Demonstrate*** integrated energy systems for **manufacturing and industrial** technologies using nuclear and non-nuclear **heat and power.**
  - **Test systems for future campaigns to test:**
    - Chemical Reactors and Advanced Manufacturing Processes
    - Heat Exchangers
    - Compatibility with: Salt, Helium, Steam, and Sodium Heat Delivery Systems
- **Location:** INL’s Energy Technology Proving Ground - HTTF facility

TRIUMPH: Testbed for Resilient IndUstrial and Manufacturing Users of Power and Heat



The core concept of TRIUMPH is to combine Thermal Energy Storage and induction heating to deliver flexible, resilient thermal energy for manufacturing and industrial processes. TES absorbs (or emulates) variable daily energy inputs and releases reliable heat meeting industrial thermal demands. Induction heating adds agile, precision-controlled thermal delivery for high transients. Together, they enable real-time, dynamically tunable heat output that adapts to changing process demands

TRIUMPH: Testbed for Resilient IndUstrial and Manufacturing Users of Power and Heat

Technology Summary – TRIUMPH is a first-of-its-kind industrial research ecosystem designed to help American manufacturing unlock the full potential of hybrid electrothermal energy systems. TRIUMPH will integrate 3 distinct technologies for:

Thermal Energy Storage	Induction Heating	Chemical Manufacturing
 	 	 

3-YEAR GOAL

Establish testbed capabilities for hybrid thermal and electrothermal energy integration into chemical manufacturing processes.

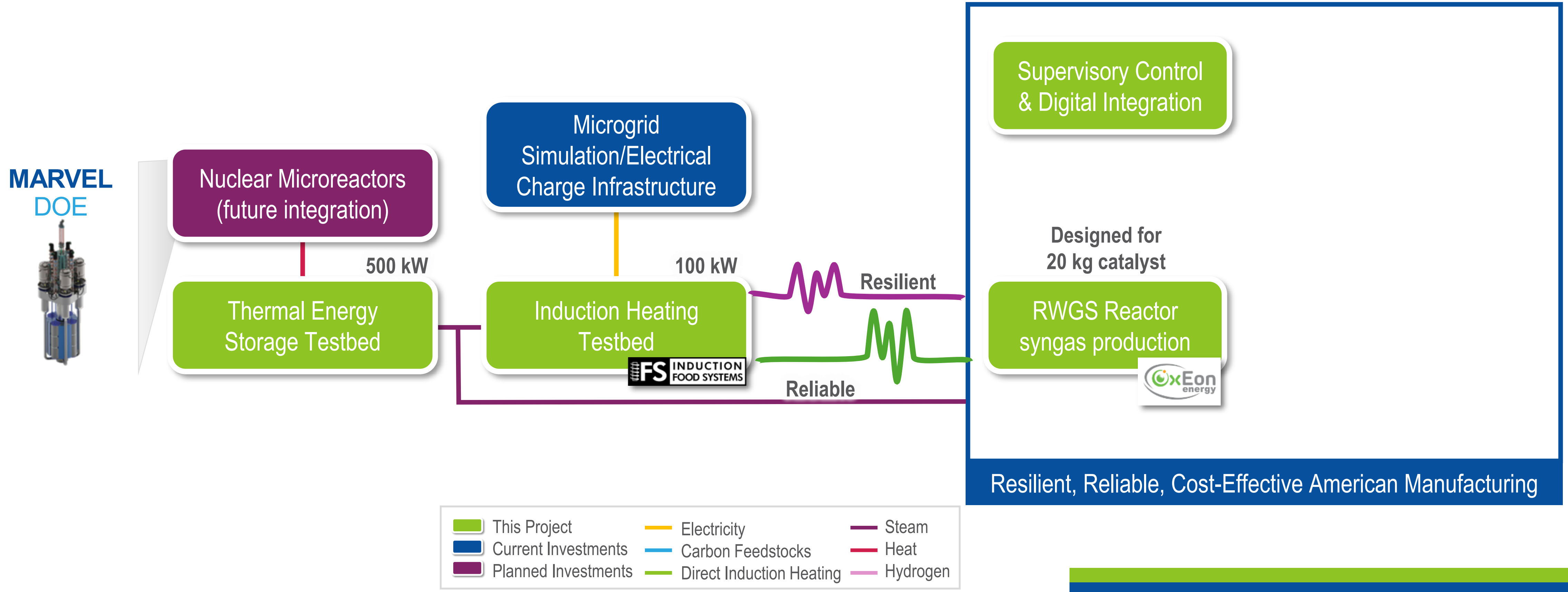
LONG TERM GOAL

Establish a cross-sector, pilot-scale energy-manufacturing ecosystems for end-to-end studies of integrated technologies.

Current Scope, 3-Year Project

Thermal integration in a chemical manufacturing system

Thermal storage provides baseload lift for high-temperature processes, induction heating provides precision topping heat with fast dynamic response.



Reconfigurable testbed components offering flexibility in process integration and design

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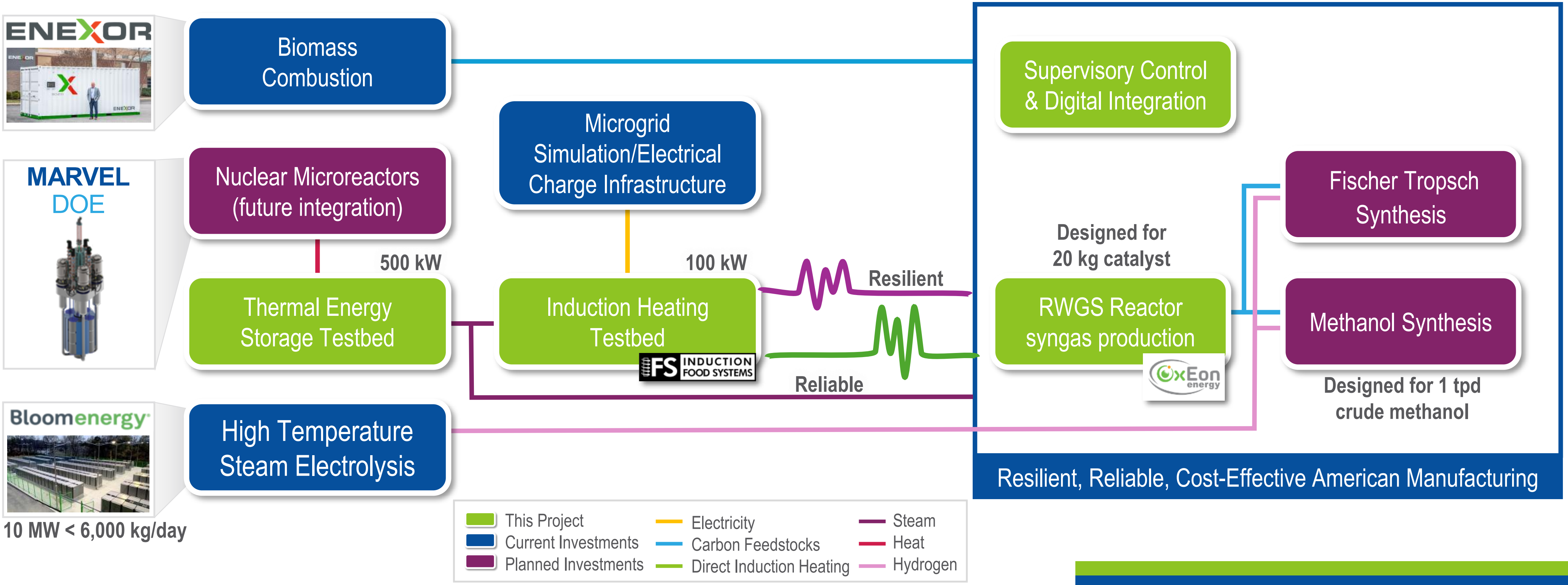
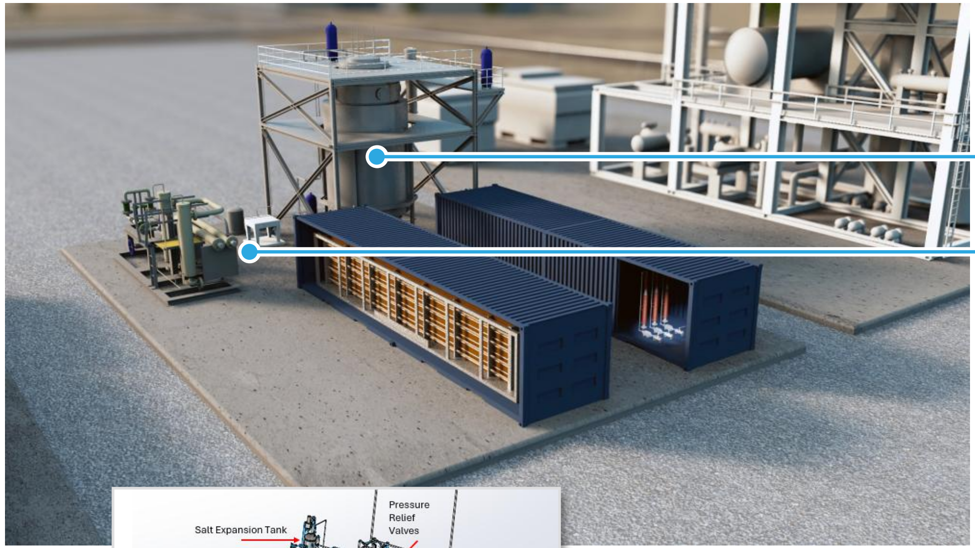
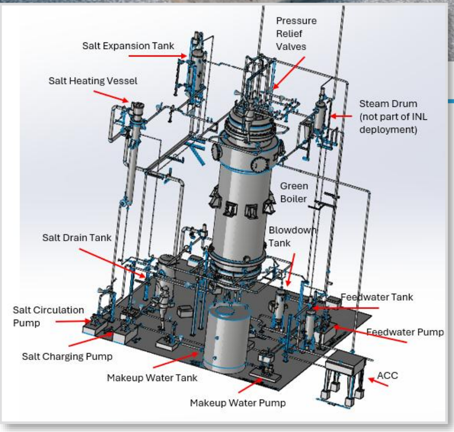


Reconfigurable testbed components offering flexibility in process integration and design

Test Capabilities, Fluids, and Thermal Components

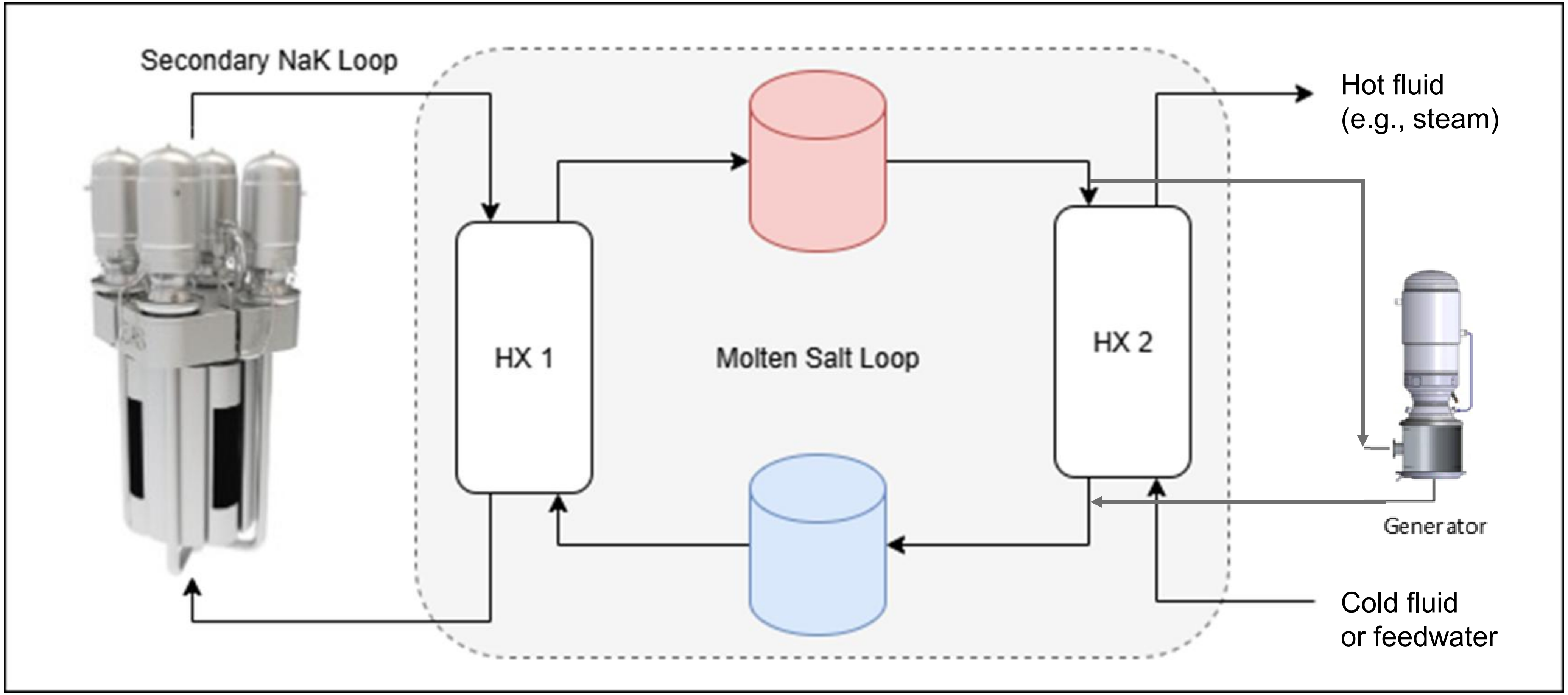




Testing for Steam, Salt, Helium and Sodium

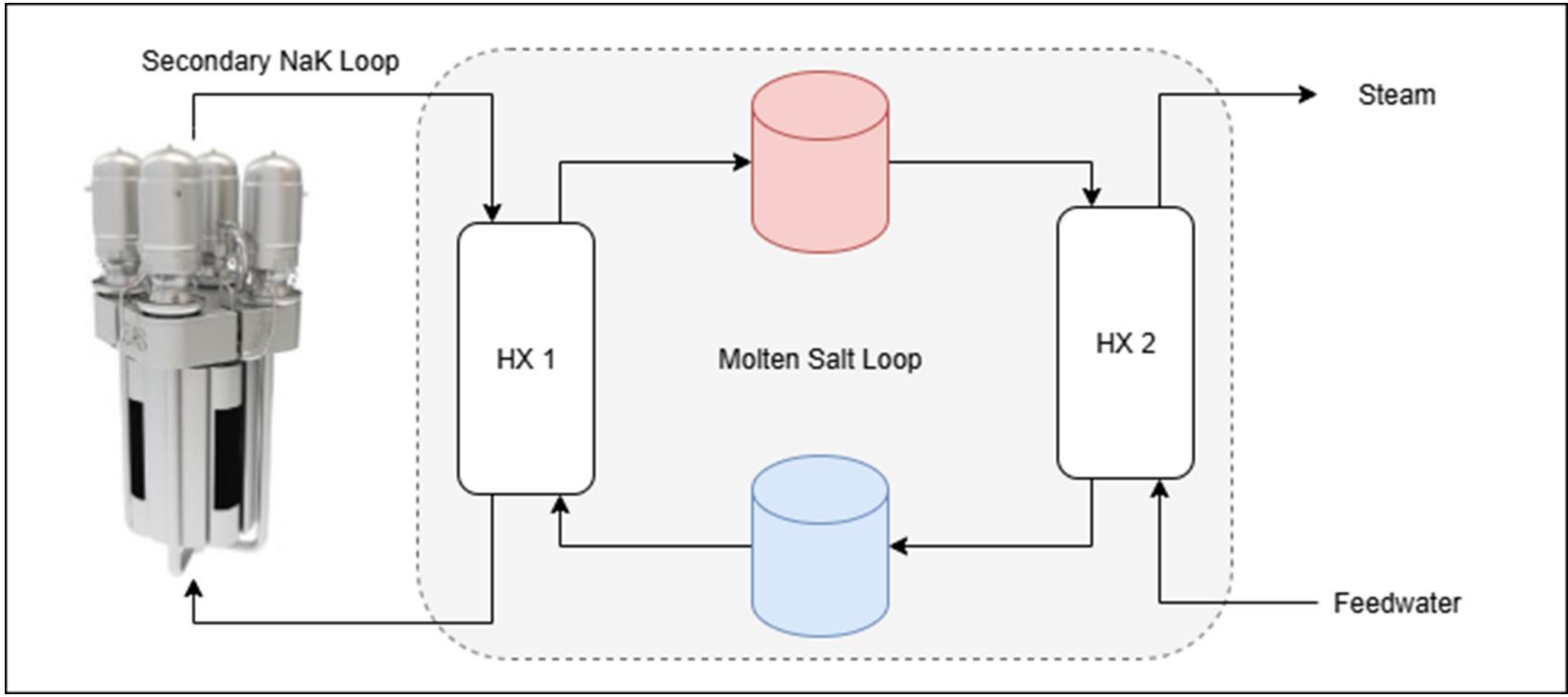
- **Existing:**
  - Existing **Steam** loop up to 560°C, 16MPa
  - Existing **salt and gas loop**
  - Flanged interfaces for future:
    - Steam to Steam HX
    - Steam to salt HX
    - Helium to Salt HX
    - Sodium to Salt HX
  - Induction heating and Resistive heaters (Swapable pipes for salt/gas/Na) to emulate transient loads
  - Salt reservoir for TES + Solid Media TES
  - Air Cooled radiators (industrial heat sink or load/demand emulators)
  - Solid Media and salt thermal storage

MARVEL can provide power for heat and electric applications



Options for Thermal and Heat Exchangers Tests

- Heat Source: MARVEL Microreactor
- Heat Exchanger 1:
  - Sodium to Salt
- Heat Exchanger 2:
  - Salt to Steam
  - Salt to Helium
  - Salt to X
- **INL selected five teams for MARVEL industrial users :**
  - **GE Vernova**
  - **Amazon (AWS)**
  - **DCX USA**
  - **Conocophillips (process heat)**
  - **Radiation Detection Technologies**



John Moorehead
Industry Engagement Executive
INL

Thermal Integration Opportunities
at INL and
Energy Technology Proving Ground

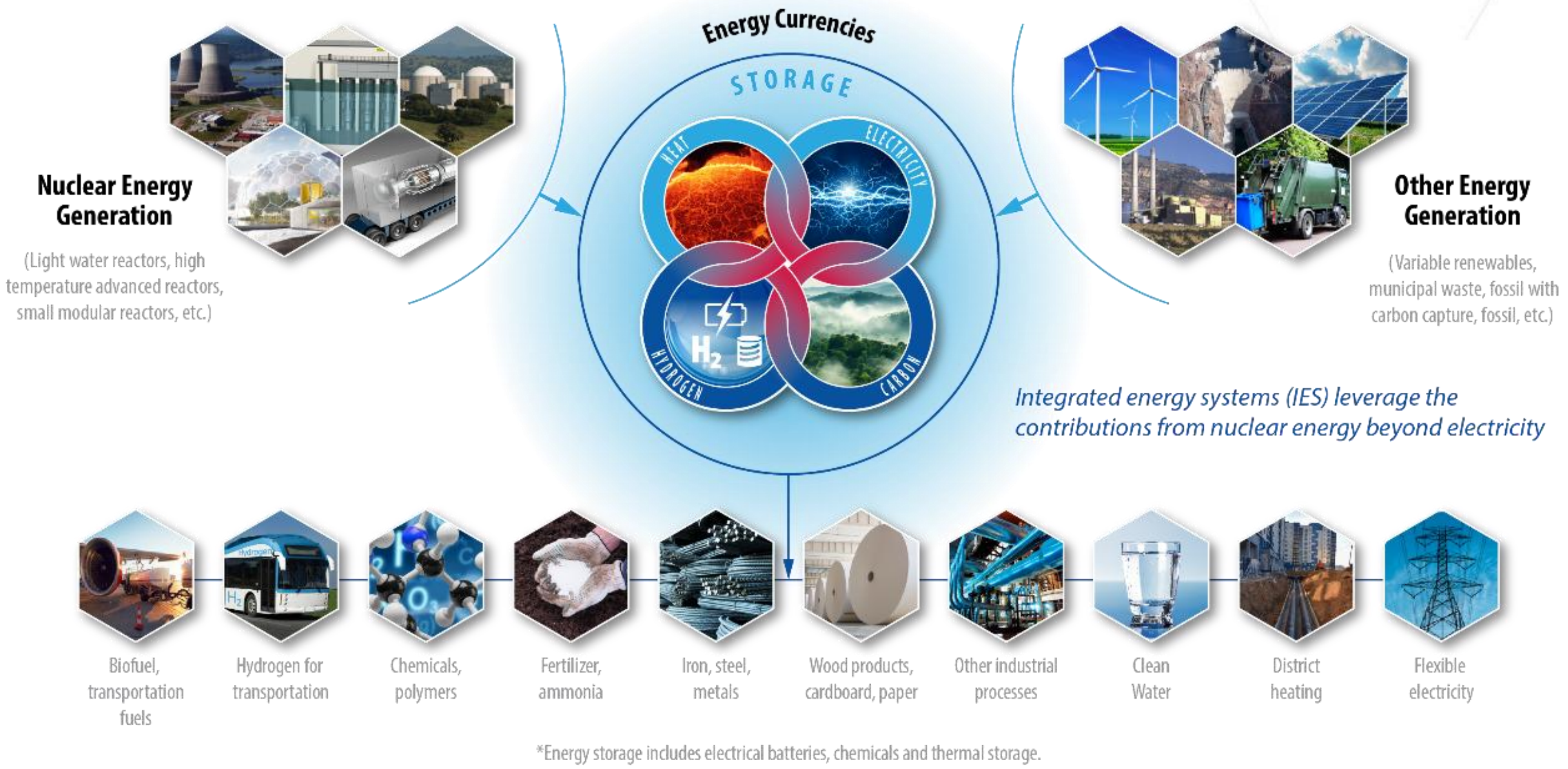
Advanced Energy Technology Scale-up and Demonstration

INL/MIS-26-91341

INL/MIS-25-85026

Integrated Energy Systems (IES)

Integrating Energy Systems will help transform the fragmented and often inefficient U.S. energy ecosystem into a cohesive, resilient, and sustainable system of systems.



IES initiative will:

Integrate major energy sectors

- *nuclear, fossil, renewable, energy storage, products and transportation*

Integrate key energy currencies

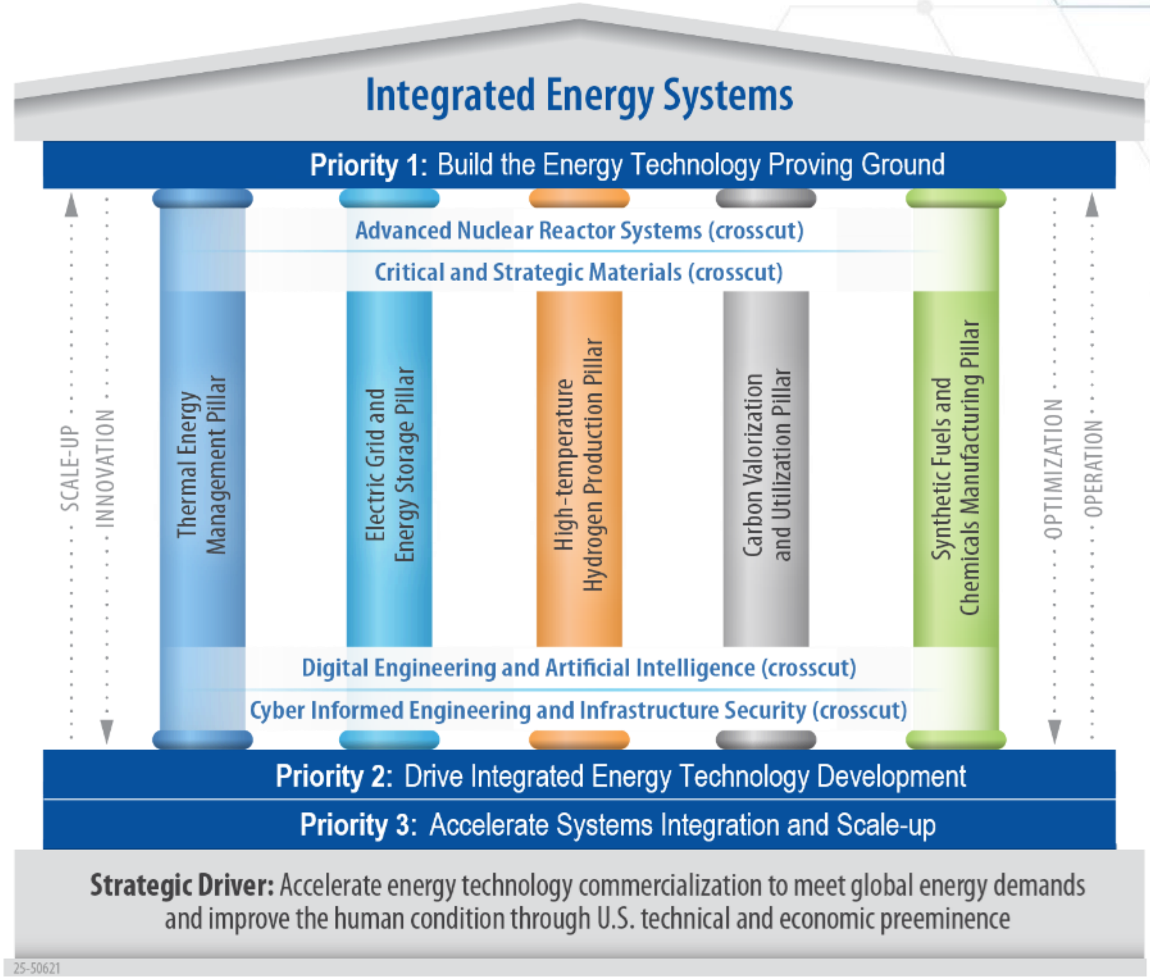
- *heat & electricity, hydrogen & carbon*

Promote research collaboration

- *overcome technical barriers*
- *drive energy independence*

Strategic Approach

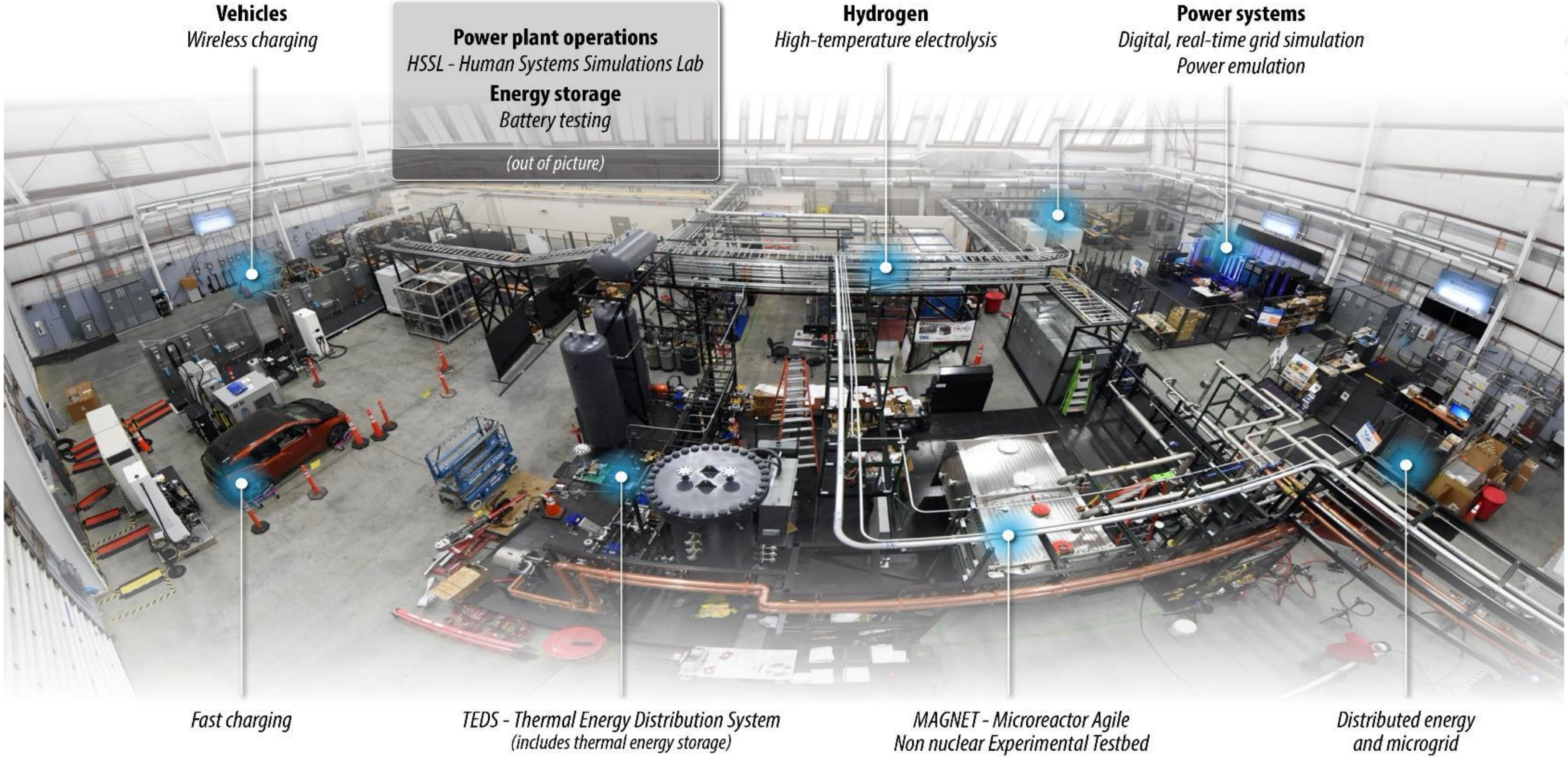
- Build new research infrastructure
- Integrate advanced energy technologies by executing five core research pillars
- Bridge the scale-up and research-to-commercialization and gap.
- Utilize crosscutting initiatives to support IES priorities.



End State Targets

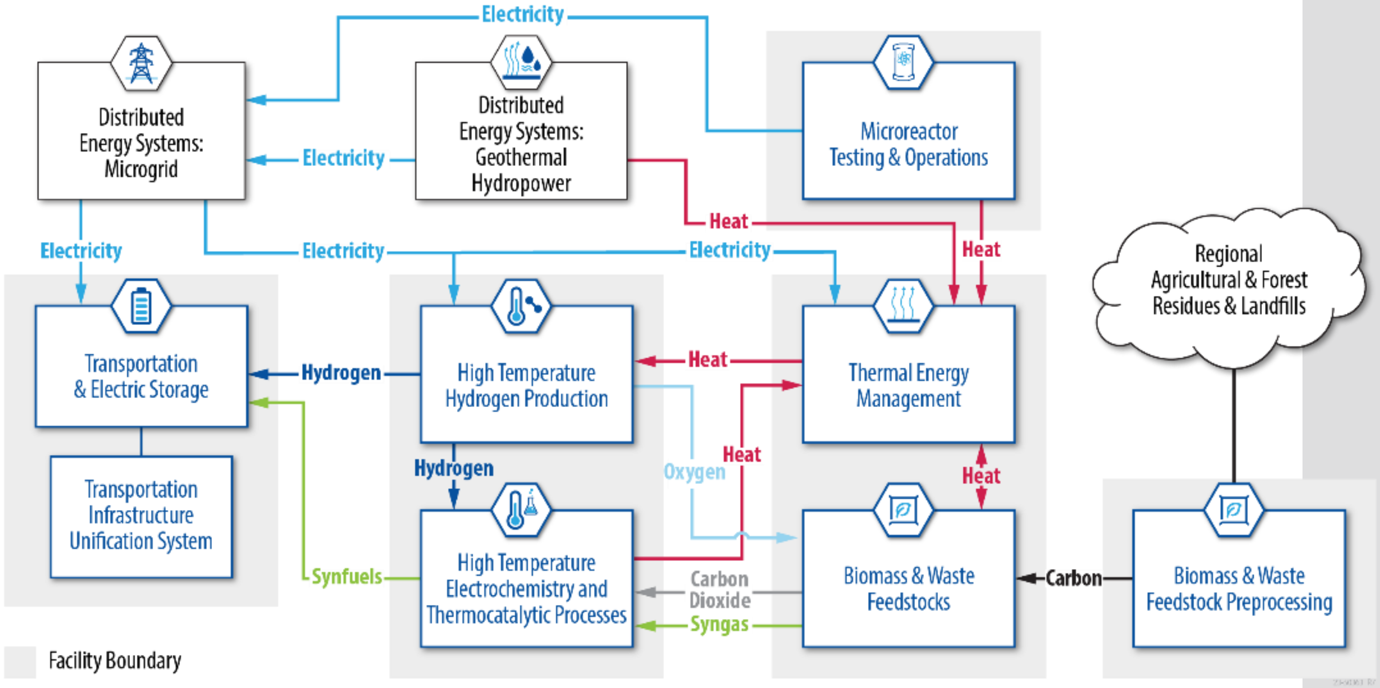
- **Successful Industry Partnerships:** Pilot-scale demonstrations at the Energy Technology Proving Ground to verify integrated energy systems.
- **Technology Readiness:** Advance early-stage innovations to market-ready stages.
- **Technology Influence:** Influence deployment and marketing of integrated energy systems.
- **Accelerated Development:** Mitigate risks to encourage adoption of integrated energy technologies.
- **Lasting U.S. Energy Impacts:** Create long-term benefits for the U.S. energy economy for energy independence.

Dynamic Energy Transport and Integration Laboratory (DETAIL)



Proving Ground Integrated Research Areas

Driving Multi-Scale Research Programs



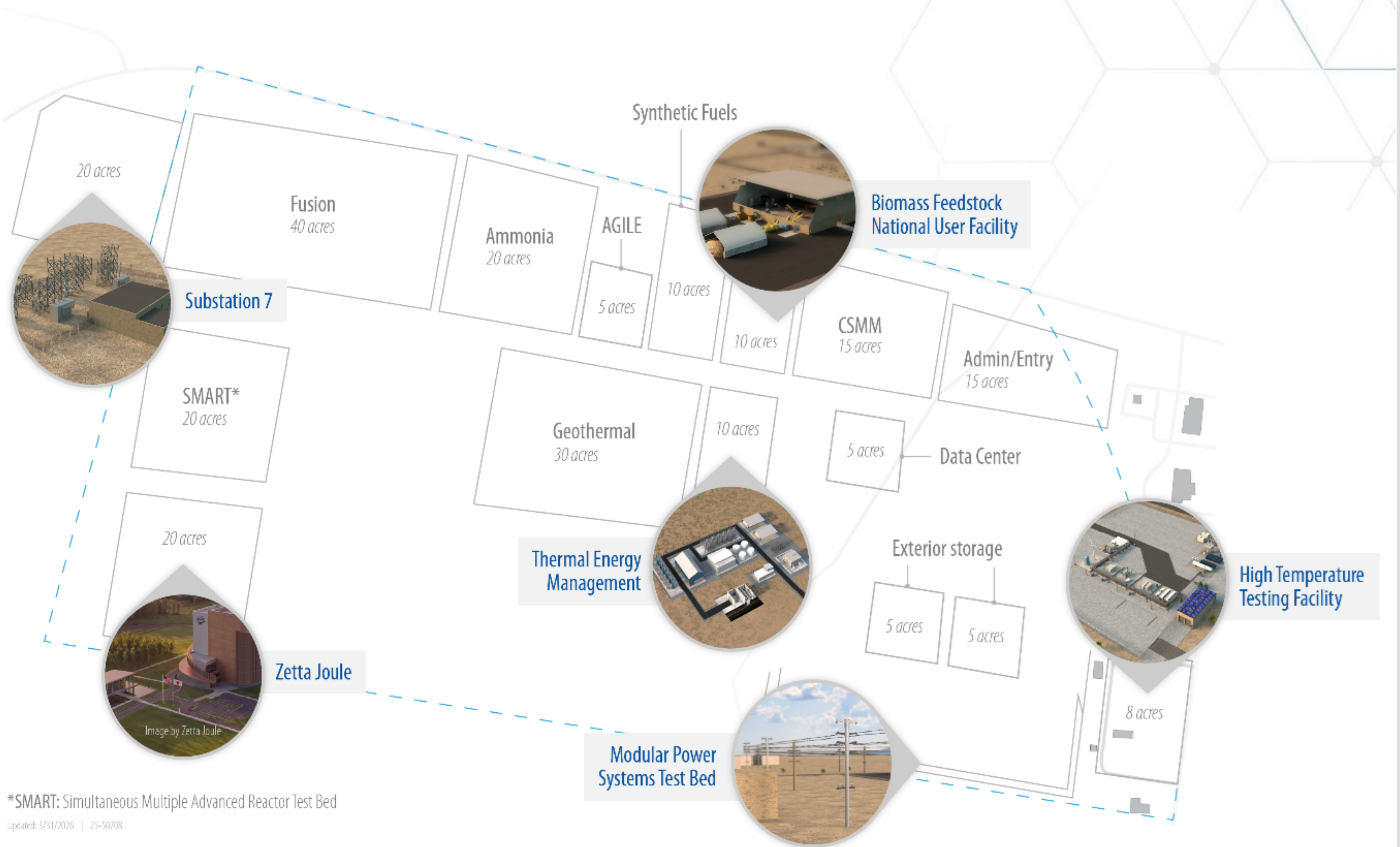
Research Nodes

- High Temp. Hydrogen Production
- **Thermal Energy Management**
- Biomass & Waste Feedstocks
- Electro & Thermocatalytic Processes
- Transportation & Electric Storage
- Distributed Energy Systems
- Critical & Strategic Minerals & Materials
- Microreactor Testing & Operations

Interconnects

- Digital Engineering & Cyber Security
- Real-Time Power & Energy Analysis

Proposed Proving Ground Layout

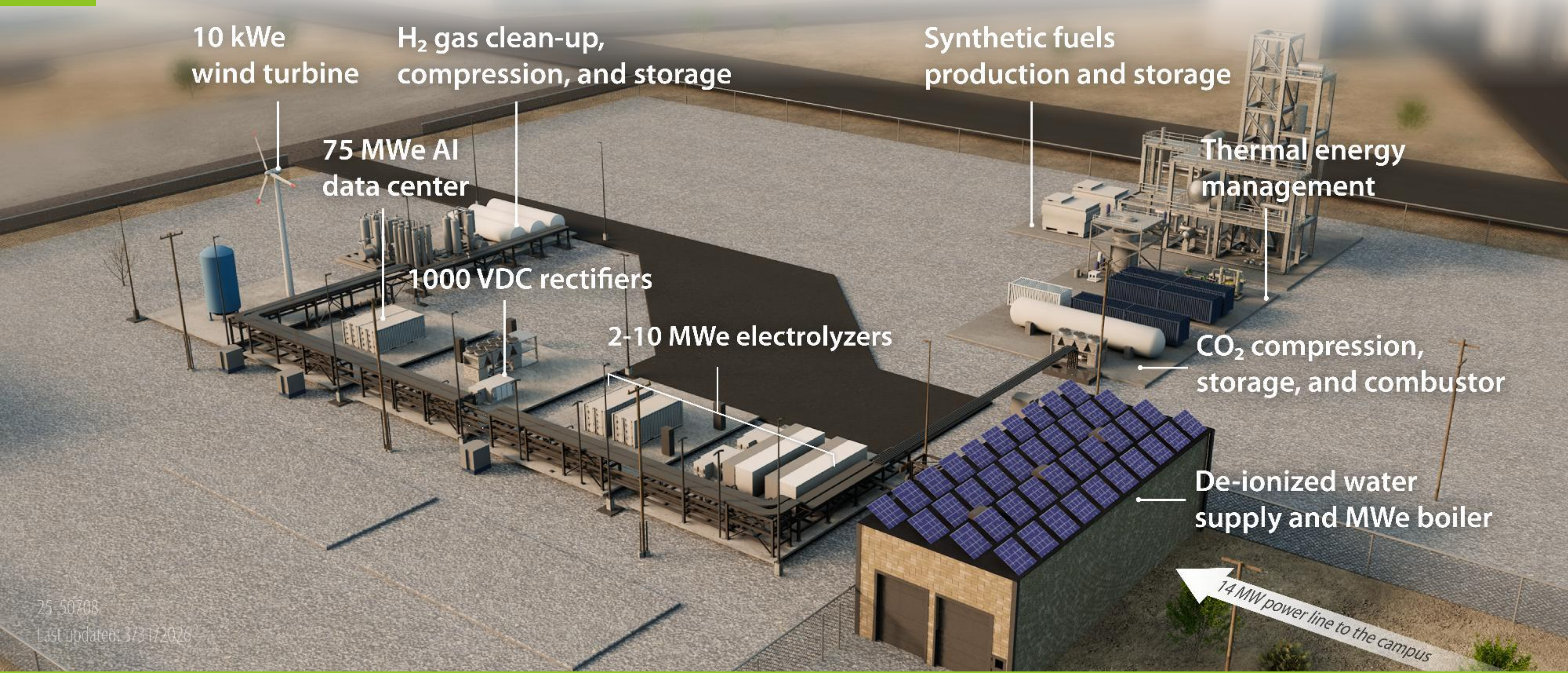


*SMART: Simultaneous Multiple Advanced Reactor Test Bed

Key Proving Ground Areas

- Impact entrance with admin and conference space
- Central Thermal Energy Management
- Fuels, Chemicals, and Materials R&D Centers
- Industrial Engagement Centers
- Advanced Grid and Energy Storage Centers
- Advanced Fission and Fusion Test Areas

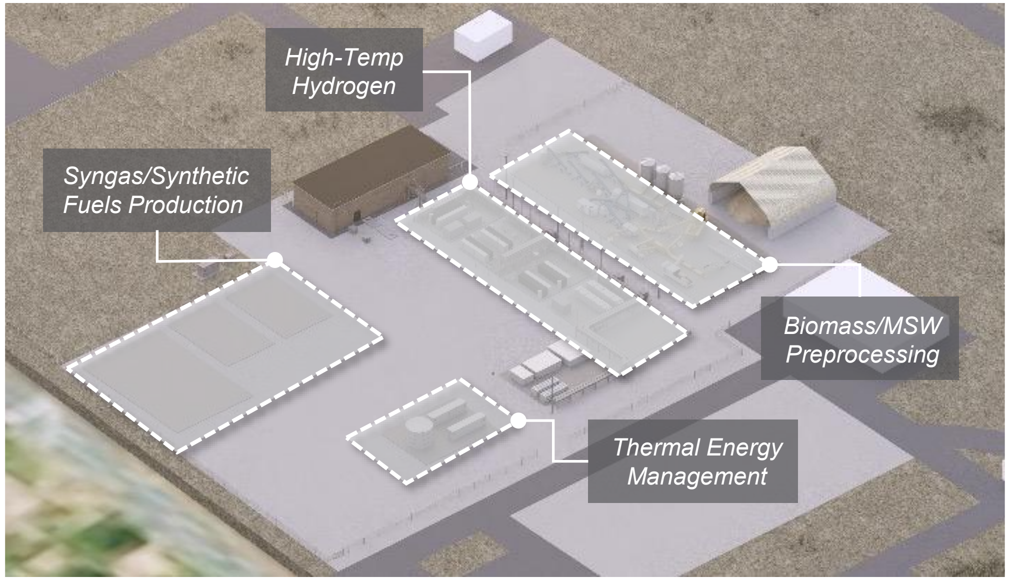
Synthetic Fuels and Chemicals Facility



Proving Ground Development

High Temp Test Facility

Biomass/MSW Preprocessing System



$12.4M

INL Indirect Investment

FY23 – FY26 Site Readiness

$66.3M

Direct Investment

FY23 – FY26 in-hand

- Alternative Fuels and Feedstocks Office (AFFO)
  - Hydrogen = $22.2M
  - Biomass = $3.0M
- Nuclear Energy (NE) Office = $6.1M
- Industrial Technologies Office (ITO) = $15M
- Bloom Energy = $20M (SOEC system)

$26.9M

Additional Investment

FY27 – FY28 projected

- Alternative Fuels and Feedstocks Office (AFFO) = $12.0M
- Nuclear Energy (NE) Office = $9.9M
- Industrial Technologies Office (ITO) = $5.0M
- Industry = Following slide

$55.6M

Industrial Business Pipeline

FY26 – FY30

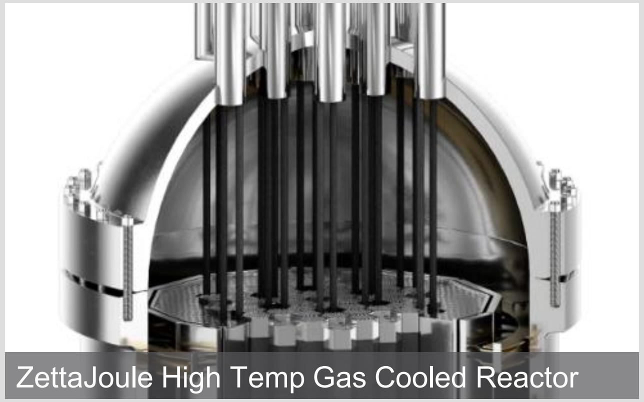
**Other areas of identified potential research is not included.*

What is “TRIUMPH”?

- **TRIUMPH =** Testbed for Resilient Industrial and Manufacturing users of Power & Heat
- **Status: Just Awarded (Industrial Technologies Office); $15MM + $5MM Industry Cost Share**
- **Mission:**
  - **Demonstrate*** integrated energy systems for **manufacturing and industrial** technologies using nuclear and non-nuclear **heat and power.**
  - **Test systems for future campaigns to test:**
    - Chemical Reactors and Advanced Manufacturing Processes
    - Heat Exchangers
    - Compatibility with: Salt, Helium, Steam, and Sodium Heat Delivery Systems
- **Location:** INL’s Energy Technology Proving Ground - HTTF facility

Proving Ground Industry Partnerships

Stage	Company	Notes
On Site	Bloom Energy	SOEC Equipment value
Contract	Holtec	Thermal Cost share/revenue
	Rock Energy Storage	Thermal Test revenue
	Ceres	SOEC Test revenue
	ZettaJoule (on site SMR)	Nuclear CRADA & SPP revenue
Contract development	Denso	SOEC Test revenue
	Topsoe	Oxy-fired combustion & Co-electrolysis
	Topsoe	SOFC test revenue/equipment value
	ENEXOR	Combustion Cost share
	DCX/ASU	Data Center Test revenue
	Casale	Methanol and Urea Test revenue
	Biomass equipment	Carbon Utilization Cost share
Letter of Interest	CERES	SOFC Test revenue
	FCE	SOEC Test revenue
	FCE	SOFC Test revenue
	Denso	SOFC Test revenue
Expression of Interest	OxEon	SOEC Test revenue
	Casale	SAF/Diesel Revenue
	Topsoe	
	Conoco	
	Shell	
	Bachman Electric	Control Systems Revenue
	Siemens	
	Atlas Copco	Compressor Cost share


ZettaJoule High Temp Gas Cooled Reactor


Topsoe High Temp Hydrogen


Casale Hydrogen & Synthetic Fuels/Chemicals

Last updated: January 22, 2026
INL/MIS-26-90134

Proving Ground Timeline

DESIGN & COMMISSION

2026
- Advance Construction Microreactor Facility*
- Thermal Energy Test Bed
- CO_2 Production & Storage Test Bed
- Modular Data Center Test Bed
- Biomass & Waste Feedstocks Preprocessing Test Bed

2027
- Simultaneous Multiple Advanced Reactor Test Bed (SMART) Facility Design
- Modular Data Center (>1MW)
- Critical Materials Demonstration Facility
- Modular Power Systems Test Bed
- Synthetic Fuels & Chemicals Test Bed

2028
- SMART Facility Construction
- Thermal Energy & Carbon Management Facility
- Open Architecture Catalyst Test Bed

2029
- Agile Electro & Thermocatalytic Facility
- Advanced Reactor Demonstration Design
- SMART Facility Commissioning**
- Transportation Infrastructure Unification System

2030
- Proving Ground Training Center
- Proving Ground Operations Center

OPERATIONS & RESEARCH

2026
- High Temperature Test Facility

2027
- CO_2 Production & Storage Test Bed
- Modular Data Center Test Bed
- Biomass & Waste Feedstocks Preprocessing Test Bed

2028
- Modular Data Center (>1MW)
- Modular Power Systems Test Bed
- Synthetic Fuels & Chemicals Test Bed
- Thermal Energy Test Bed

2029
- Critical Materials Demonstration Facility
- Open Architecture Catalyst Test Bed

2030
- Thermal Energy & Carbon Management Facility

2031
- Advanced Reactor Demonstrations
- Transportation Infrastructure Unification System
- Agile Electro & Thermocatalytic Facility

2032
- Proving Ground Training Center
- Proving Ground Operations Center
- *ALL FACILITIES COMMISSIONED AND OPERATIONAL*

Infrastructure construction ongoing
e.g. Power Utility Building (PUB), Substation 7, Outer West Loop

*Precursor to SMART
**Microreactor V&V Testing

MARVEL Can Enable a New Class of Nuclear Reactors

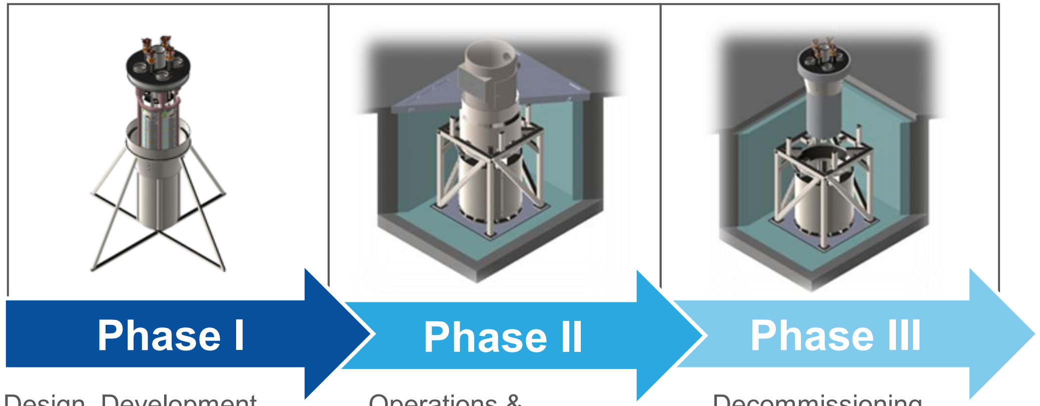
(Microreactor Applications Research, Validation & EvaLuation)

Project Goals:

Development of a small operational fission reactor that enables the nuclear community to gain useful data and lessons from the design, review, fabrication, installation, and operation (including novel applications) of a microreactor.

Primary Objectives:

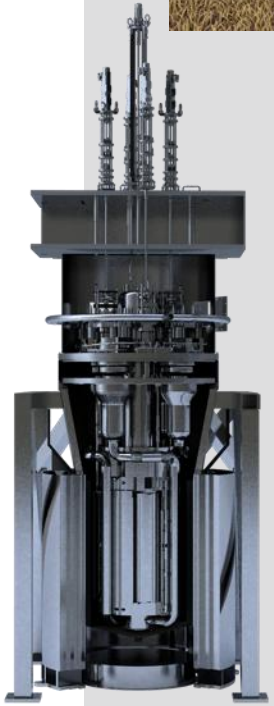
- Enable follow-on commercial demonstration by trailblazing path forward
- Share data & lessons learned to help mature commercial designs
- Train future advanced reactor operators
- Demonstrate passive safety and self-regulating aspects of microreactors
- Provide a testbed to demonstrate advanced controls, novel nuclear-electricity application, and novel nuclear-heat applications.



Design, Development, Construction, & Criticality

Operations & Applications Testing

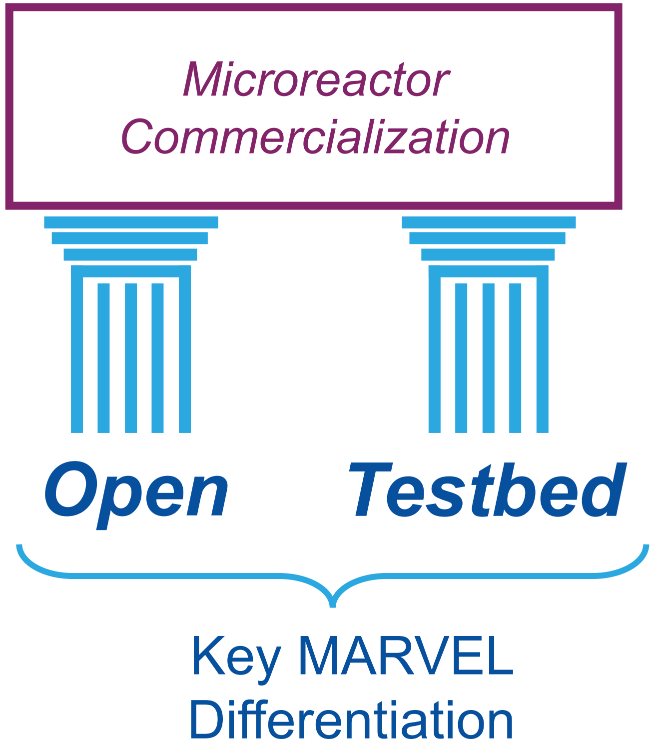
Decommissioning



- 85 kW-thermal
- <20 kW-electric
- ~15 feet tall, <10 tons
- NaK primary coolant (natural circulation)
- Secondary NaK (forced) and tertiary salt coolant
- TRIGA fuel
- Radial control drums
- Graphite, Be and BeO reflector
- 2 operators
- Self-regulating

MARVEL Value Proposition

- First-of-a-kind demonstration that will proliferate ‘know-how’ and provide opportunity to test novel features of microreactors
- Key attributes:
  - **Open**: Design & operational data access
  - **Testbed**: Platform for testing new technologies & nuclear applications
- Opportunities for collaboration:
  - **Vendors**: Design, technology testing, validation data
  - **Industry users**: New ways to leverage nuclear
  - **DOE programs**: Demonstrating new technology/applications
  - **Universities**: Furthering nuclear R&D
  - **Regulator**: Building confidence in adv. reactor ops

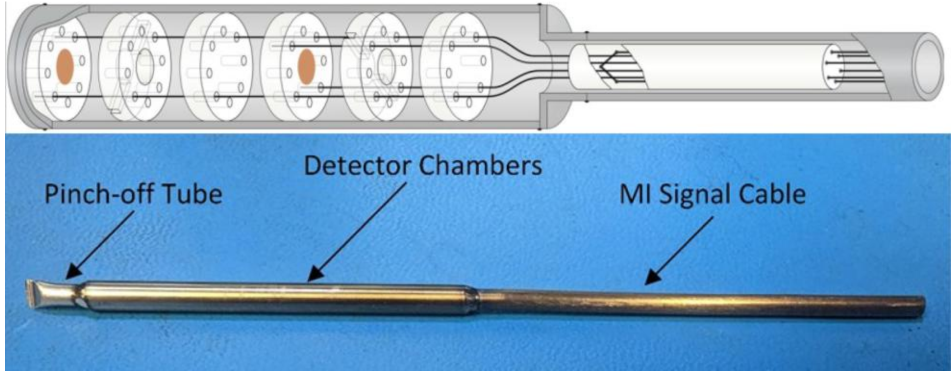


MARVEL Value: *Open Platform for Testing, Data Generation, and Technology/ Application Demonstration*

MARVEL as a Testbed: First End Users Selected

- The MARVEL team announced the first set of end users to leverage MARVEL as a testbed:
  - **Amazon Web Services (AWS) Inc.** proposes coupling the MARVEL reactor with a modular data center, a new service that makes it simple and cost-effective for defense and government agencies to build data centers anywhere in the world independently of traditional power infrastructure.
  - **DCX USA and Arizona State University** propose to use MARVEL to demonstrate the feasibility of a microreactor to power a data center for AI to yield valuable data on how to provide a stable, continuous power supply capable of handling the demands of AI.
  - **General Electric Vernova** proposes to use MARVEL to demonstrate remote and autonomous reactor operations and establish standards for broader application of the technology with commercial reactors.
  - **Radiation Detection Technologies (RDT) Inc.** proposes to use MARVEL to test advanced high-performance sensor technologies that could help monitor the performance of advanced reactors.
  - **Natura Resources, NOV and ConocoPhillips** propose to leverage MARVEL for a pilot-scale desalination project using nuclear-generated process heat to demonstrate how nuclear energy can help address water challenges in oil and gas operations.
- The next step is to develop a detailed implementation plan for their proposal before then proceeding to hardware execution.

AWS Data Center Module

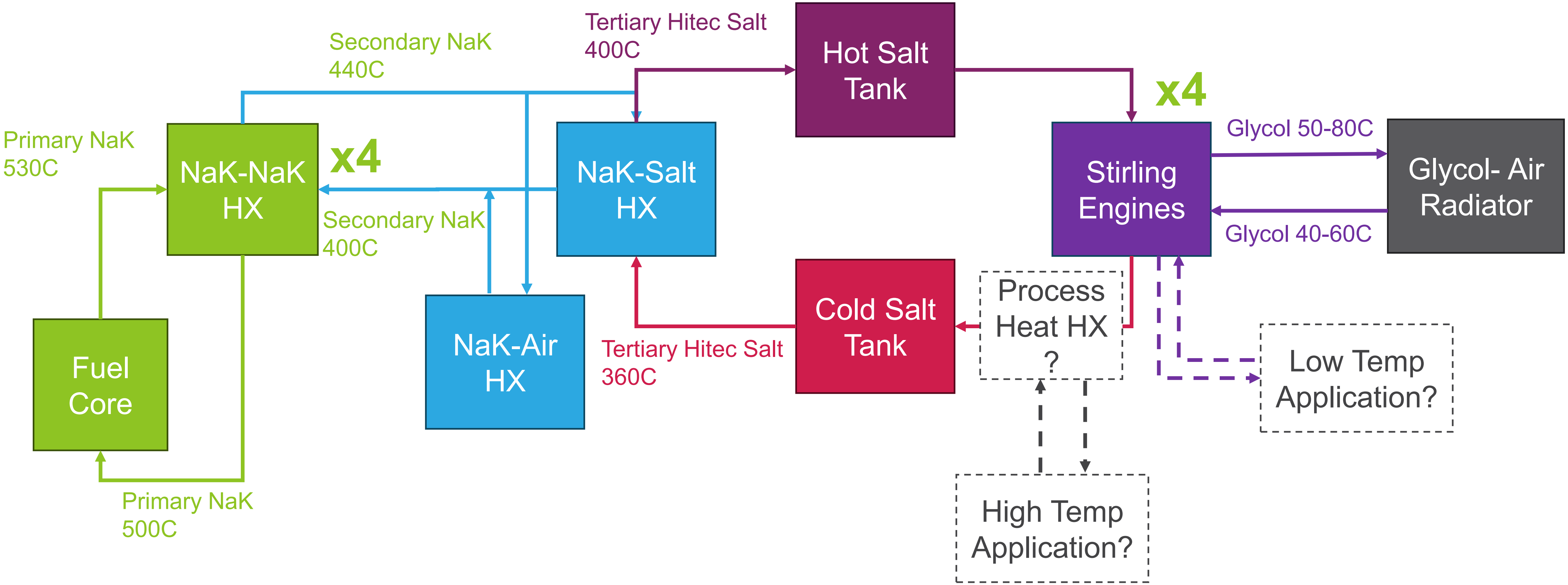


RDT Micropocket Fission Chamber

Idaho National Laboratory

Battelle Energy Alliance manages INL for the U.S. Department of Energy's Office of Nuclear Energy. INL is the nation's center for nuclear energy research and development, and also performs research in each of DOE's strategic goal areas: energy, national security, science and the environment.

MARVEL Balance Of Plant – Block Diagram



Disclaimer: Temperatures listed are not finalized