Thermochemical Energy Storage for CSP and Nuclear Power Management

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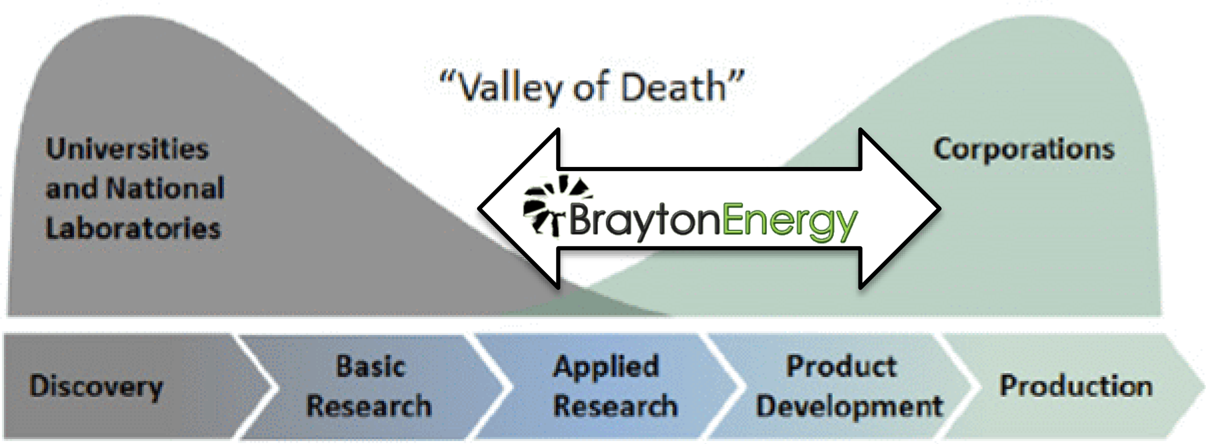
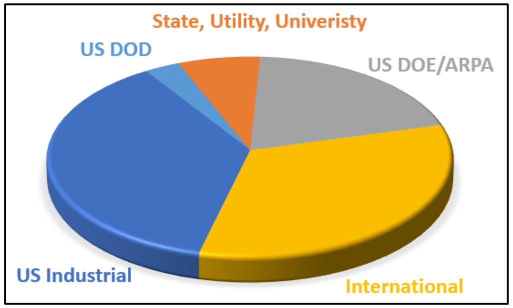
BraytonEnergy

"… to design and build hardware solutions for sustainable, efficient energy systems through applied research, revolutionary innovation, sound engineering, and dedicated partnerships with our clients."

- A private Advanced Energy R&D firm
- Located in Hampton, NH
  - About 50 miles north of Boston

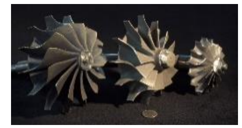


SRI International

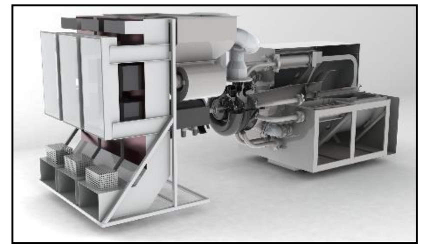


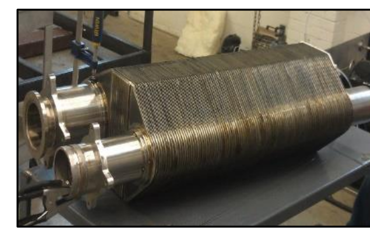
BraytonEnergy

- Turbomachinery solutions
  - Power systems
  - Biomass
  - UAVs
  - Transportation
- CSP components
- High-temperature compact heat exchangers
- Advanced system modeling and analysis
- Energy storage solutions (thermal, CAES)





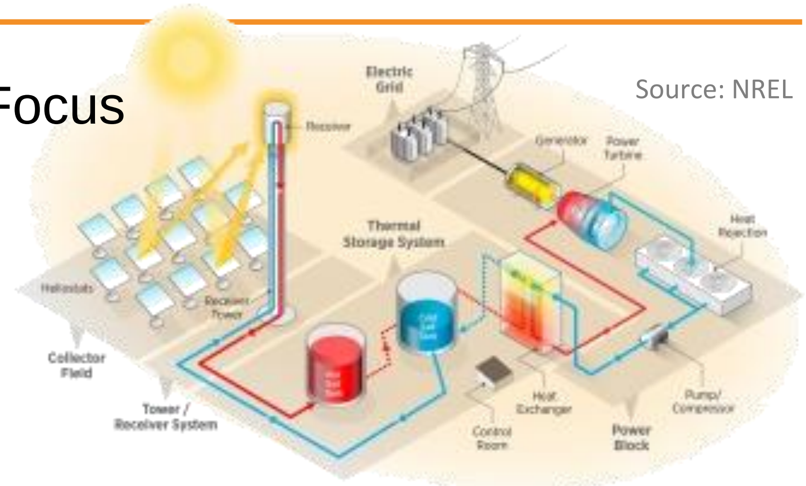







Current Projects

- Concentrated Solar Power (CSP) Focus
  - GEN 3
  - Apollo

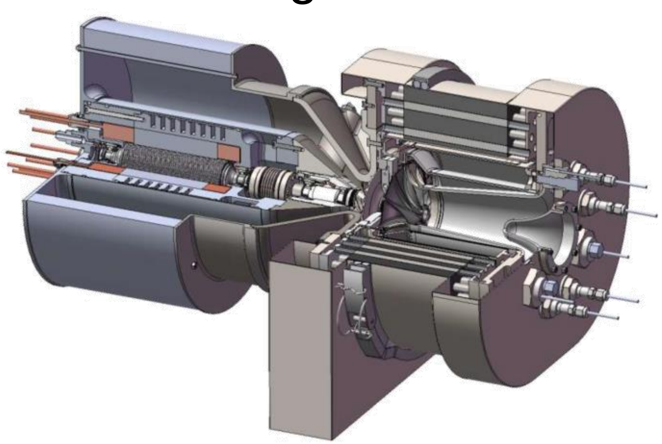


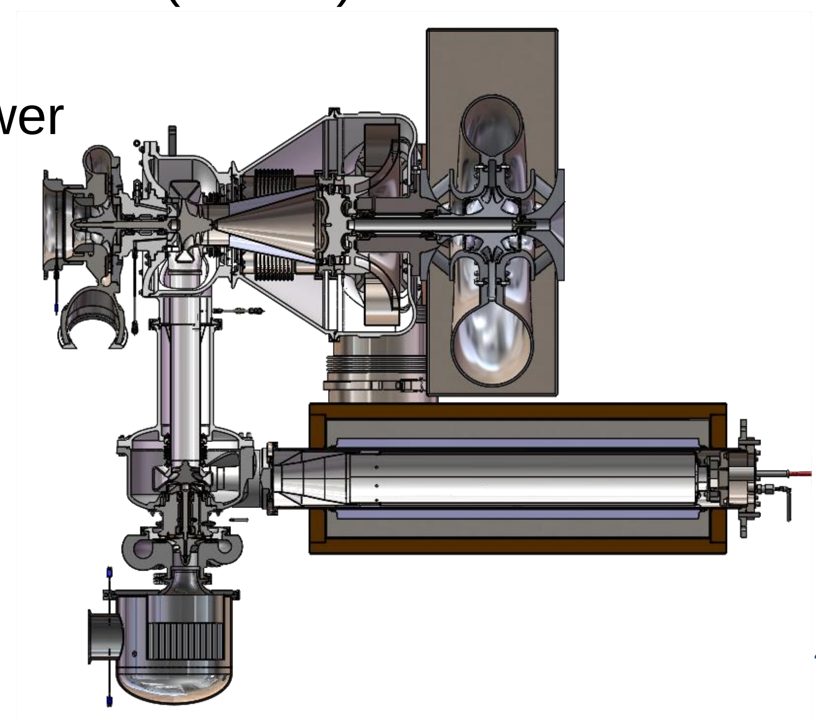
Source: NREL

- Transportable Nuclear Reactor Power Plant (~2MW)

- Advanced Gas Turbine Powered Blower

- Electric Car Range Extender





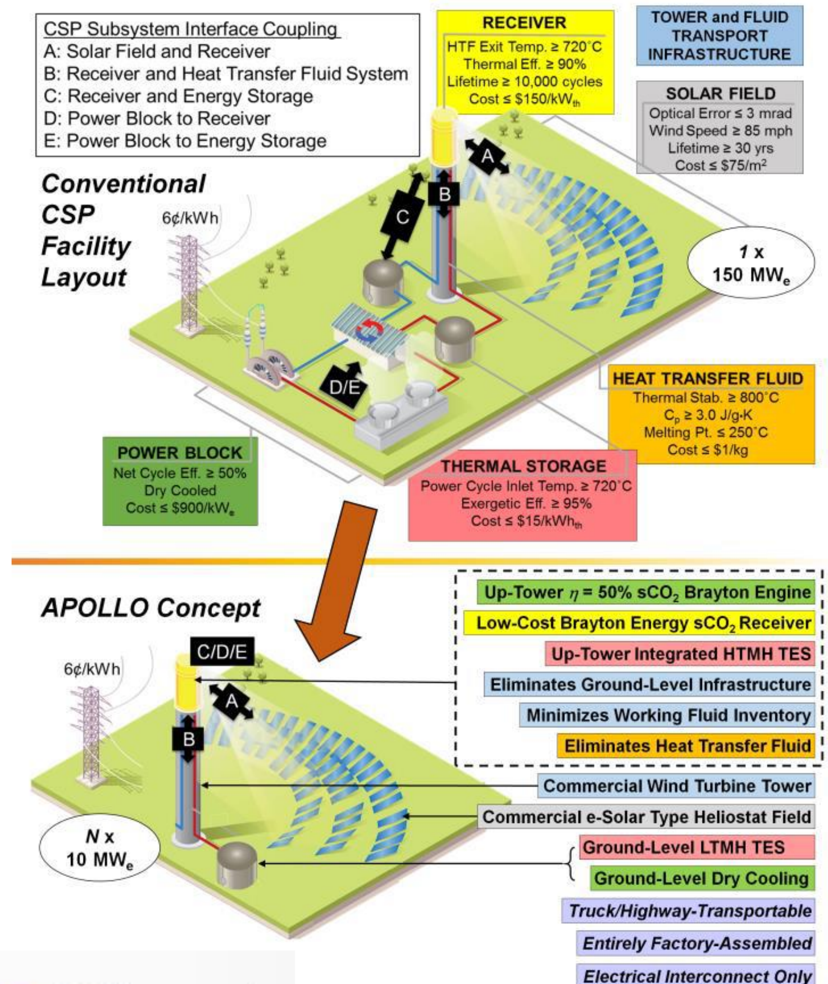
CSP Focus

		Sensible			Phase Change	Thermo-Chemical		Electro-Chemical
PROJECT	**-**	**GEN3 T1 Brayton Energy**		**GEN3 T1 NREL**	**GEN3 T2 BE**	**APOLLO**	**SRI/ Echogen**	**SOA (2018)**
Description	-	Baseline	Alt	Chloride Salt	PCM	Metal Hydrides	Direct Contact	**Batteries**
Media	-	SiO_2 Particles	MgO Brick	KCl/MgCl	$MgCl_2$	$CaSi_2$/TiFe	$MgCO_3$	**Li-ion**
Energy Density	**kJ/kg**	116	96	116	353	343	329	**657**
Bulk Density	***kg/m³***	1,643	3,581	1,540	2,050	2,450	3,580	
Energy Capacity	**kJ/m³**	190,588	343,776	177,870	723,240	840,000	1,176,030	**1,324,042**
Specific Cost	**$/kg**	0.06	0.11	0.32	17.15	5.50	0.40	**73.00**
Capacity Cost	**$\$/kWh_t$**	**2**	**4**	**10**	**175**	**58**	**4**	*160*
	$\$/kWh_e$	*5*	*10*	*25*	*438*	*144*	*11*	**400**
DT of Storage	-	*per 100 °C*	*per 100 °C*	*per 100 °C*	*"isothermal"*	*"isothermal"*	*"isothermal"*	
Difficulty		Particle Trans.		Very Corrosive	cost incl. HEX	H_2 Permeation		

Most research focused on sCO2 cycle & temps 740 to 780 ℃

Apollo Program – Objective

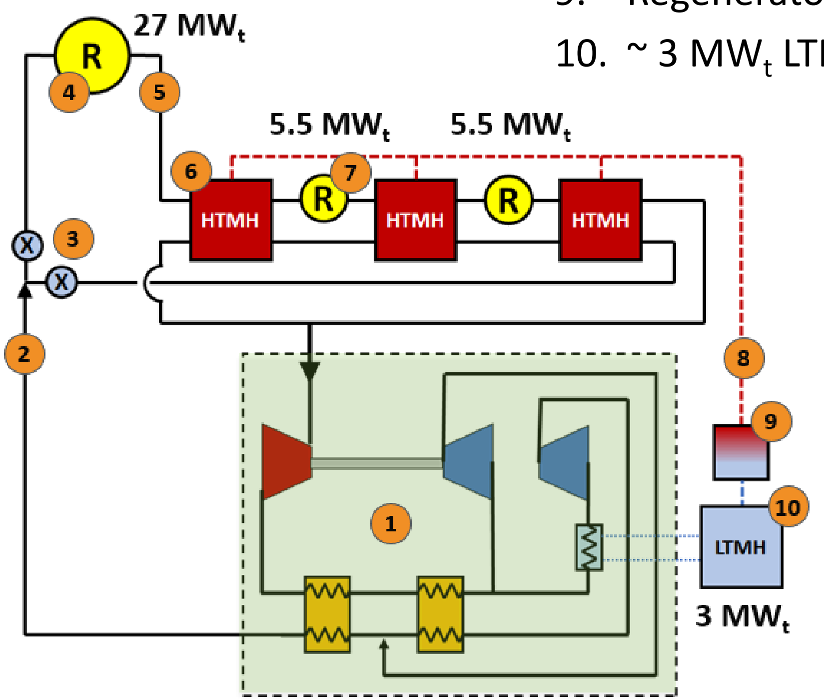
- Meet DOE’s $0.06/kW-hr CSP Energy target by 2020.
- Couple solar absorber, thermal energy storage, commercial wind turbine tower technology, and a high-efficiency sCO2 Brayton cycle into a single system.
- Departure from the state-of-the-art in CSP plant layout.
- Critical to the success of this program is a thermochemical Thermal Energy Storage (TES) system which consists of a coupled high temperature metal hydride (HTMH) and a low temperature metal hydride (LTMH).

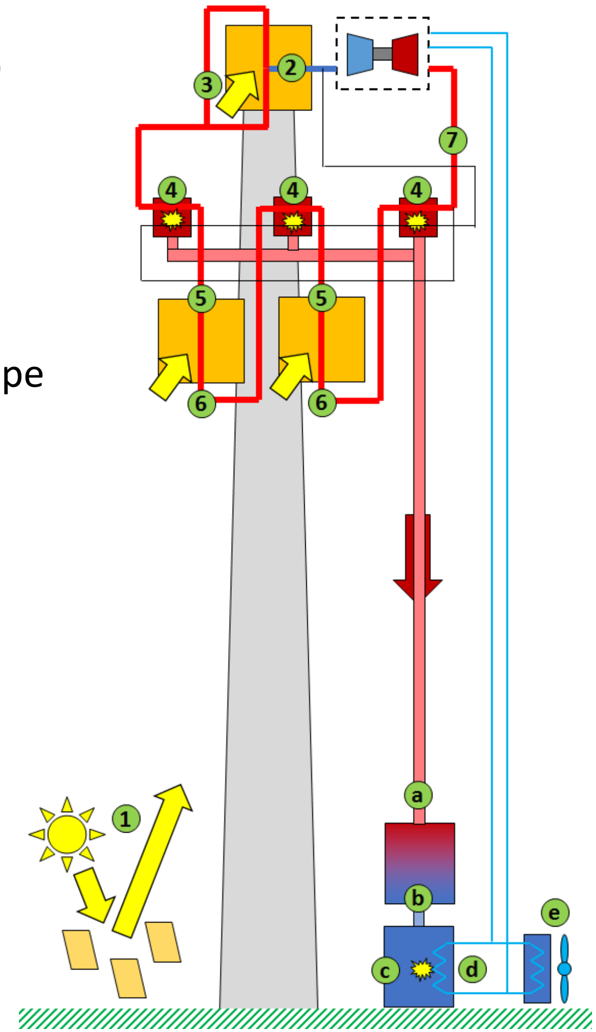


SunShot
U.S. Department of Energy

Apollo – System Schematic

1. RCBC sCO_2 power block
2. Low temp. (~ 570 °C) piping
3. Low temp. (~ 570 °C) valves (x2)
4. 27 MW_t open receiver
5. High Temp (~ 760 °C) piping
6. 5.5 MW_t HTMH TES HEX (x3)
7. 5.5 MWt cavity receiver (x2)
8. Hydrogen (~720 °C) transport pipe
9. Regenerator
10. ~ 3 MW_t LTMH TES HEX



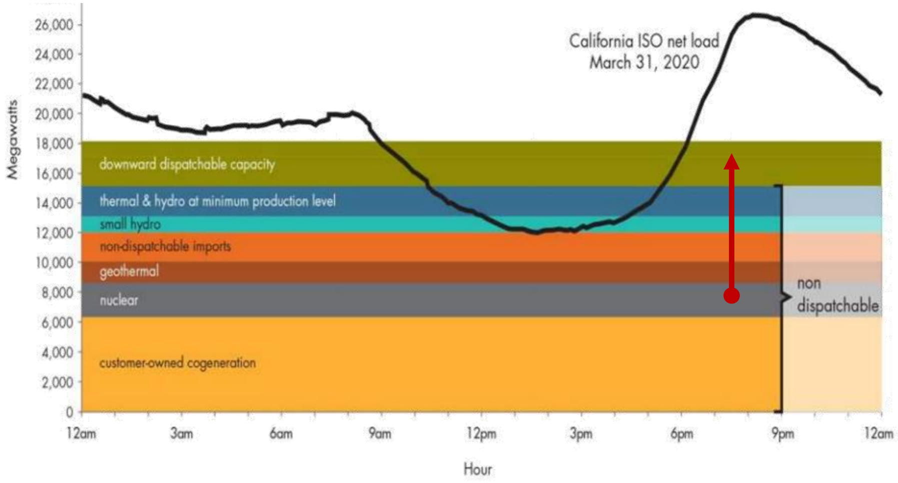


Apollo Program – Metal Hydrides

Why metal hydrides?

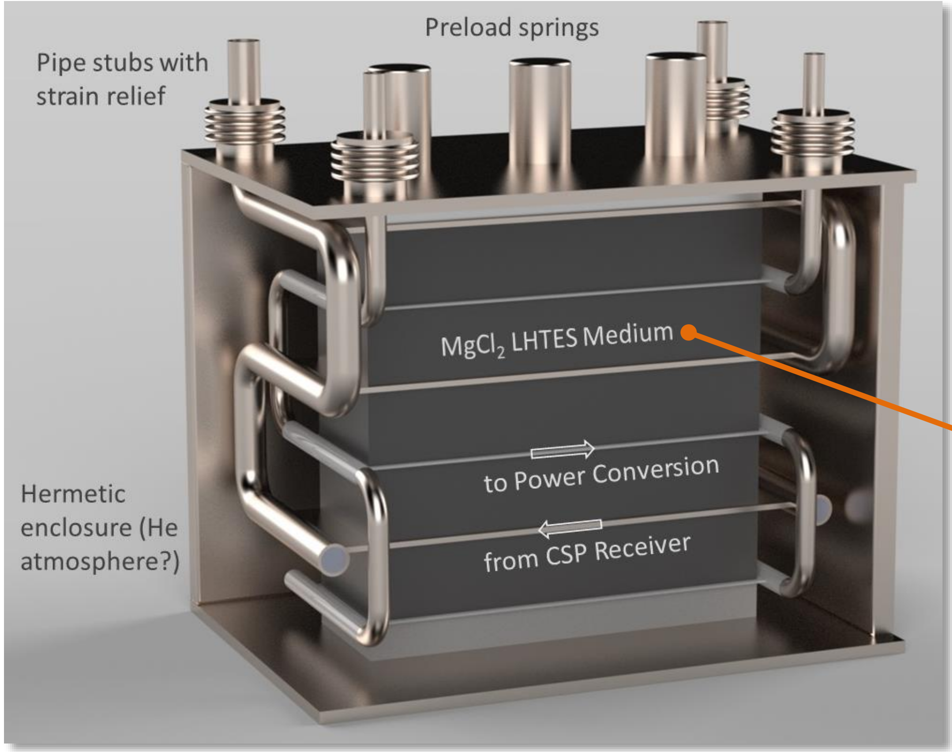
- Metal hydrides (MH): Brayton seeking a thermal storage system light enough to be placed on top of tower, thereby reducing piping and field installation costs.

- SRNL's unique MH formulation +
  Brayton integral heat exchanger ➔
  high exergetic efficiency, low cost, light weight

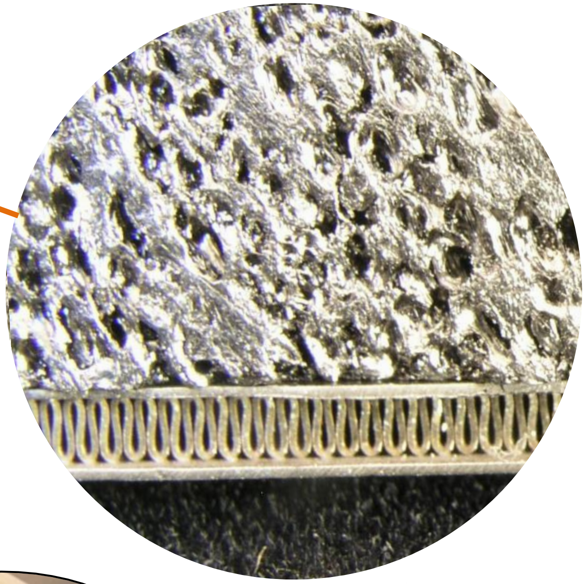


Source: Energy Storage and the California "Duck Curve", Stanford

Alternative TES Media



$MgCl_2$ Infused Graphite Foam

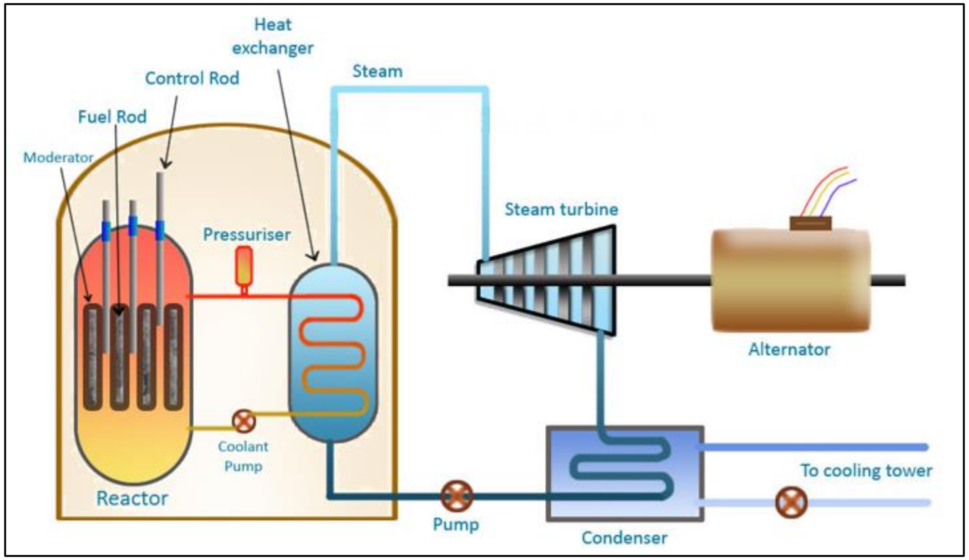


Argonne NATIONAL LABORATORY

Unit-Cell Plate Fin Heat Exchanger Cell

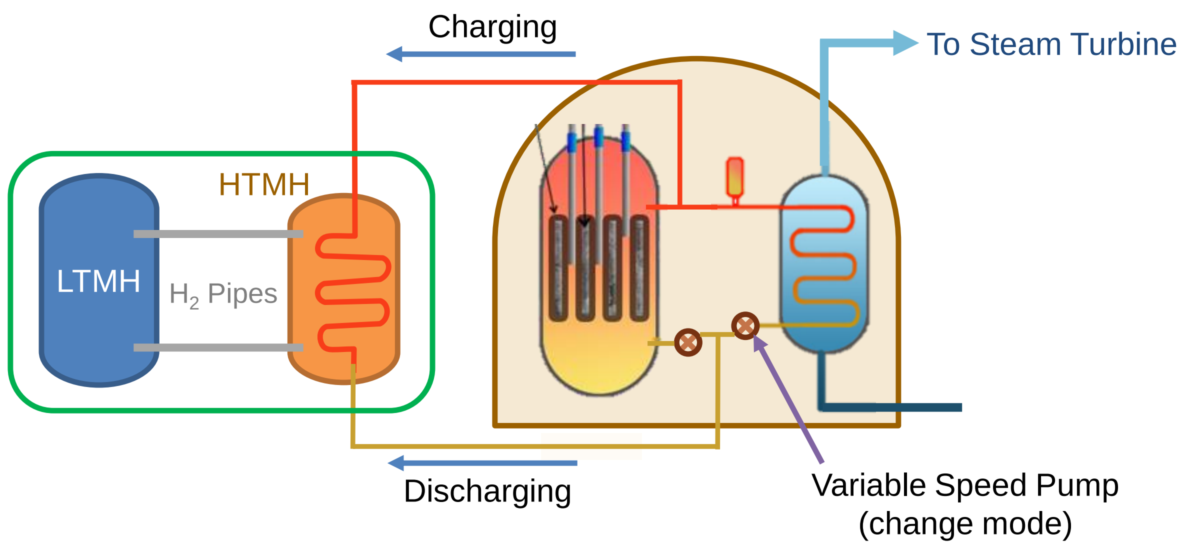
NUCLEAR ENERGY APPLICATION

Base Load
Nuclear
Power Plant



Source: Kiran Daware. “Basic Layout And Working of a Nuclear Power Plant”.

Load Following
Nuclear
Power Plant



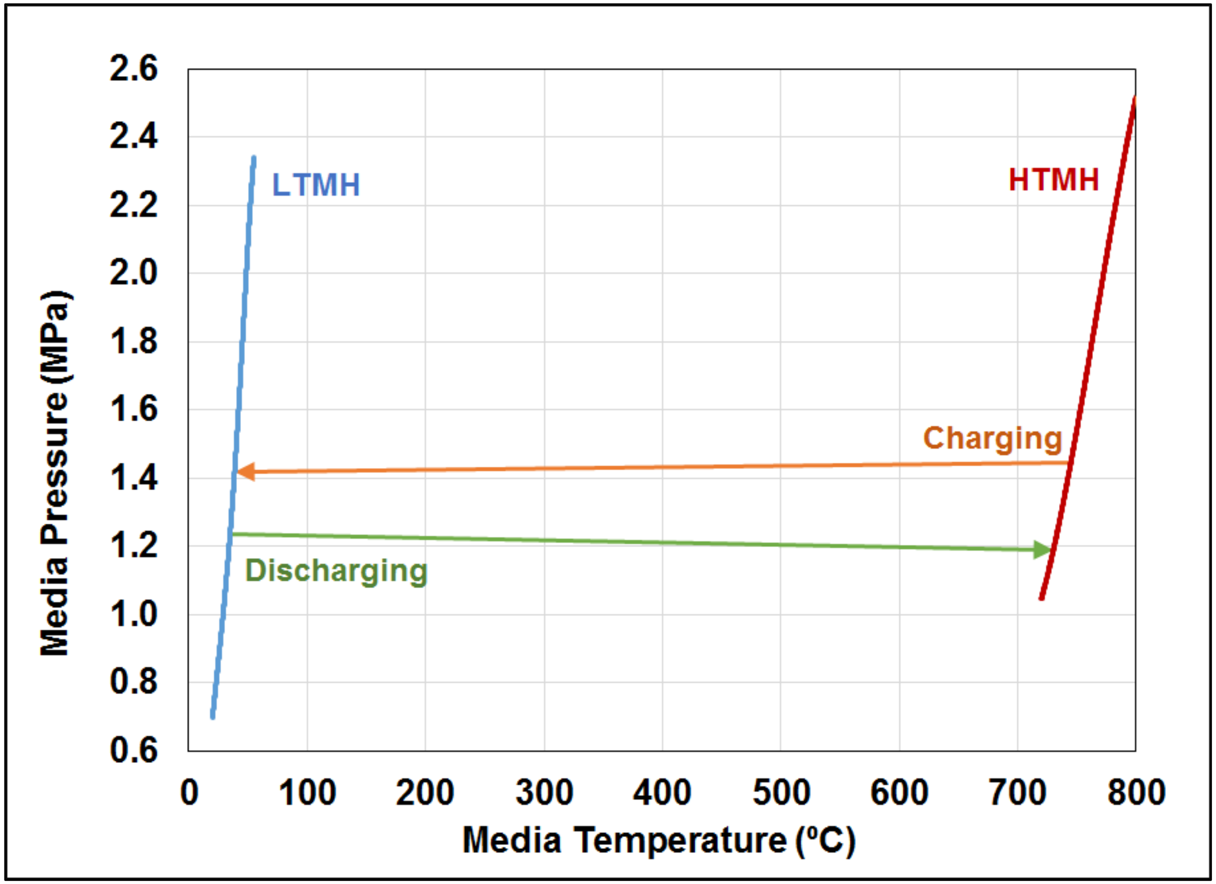
NUCLEAR ENERGY APPLICATION

- Isothermal storage enables the reactor to operate within narrow temp range
  - Pick and choose MHs for desired reaction temperature
  - Common Rxn Temperatures: 600-800^{o}C
  - Viable heat source for steam turbines, sCO2, or small recuperated gas turbines

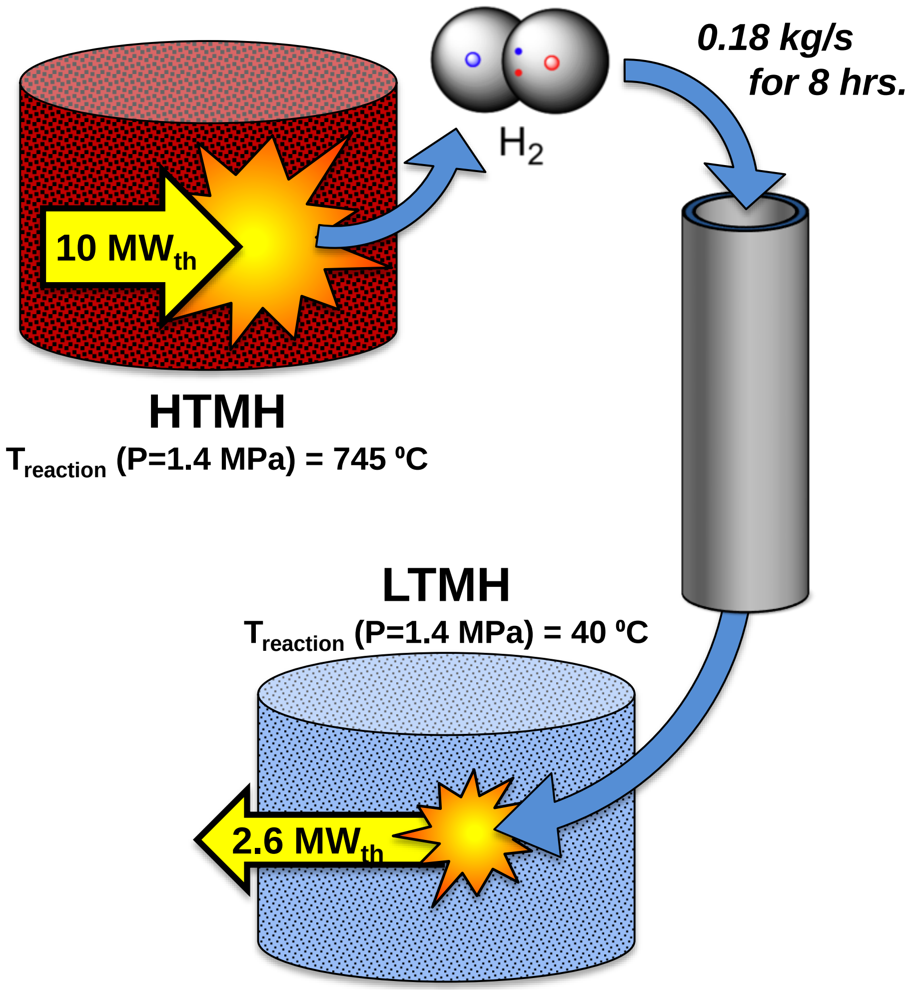
- Load Following Storage
  - Viable option for heat source during peak energy demand
  - Low Temperature Storage → Minimal Heat/Energy Loss
  - Increase Energy Storage → More Metal Hydride and H_2

Metal Hydride 101: Pairing

- A well-chosen pairing of metal hydrides will enable the free flow of hydrogen between the two media at the desired temperatures
- Connecting pipes must be sized for the appropriate pressure drop to maintain intended operating temperatures



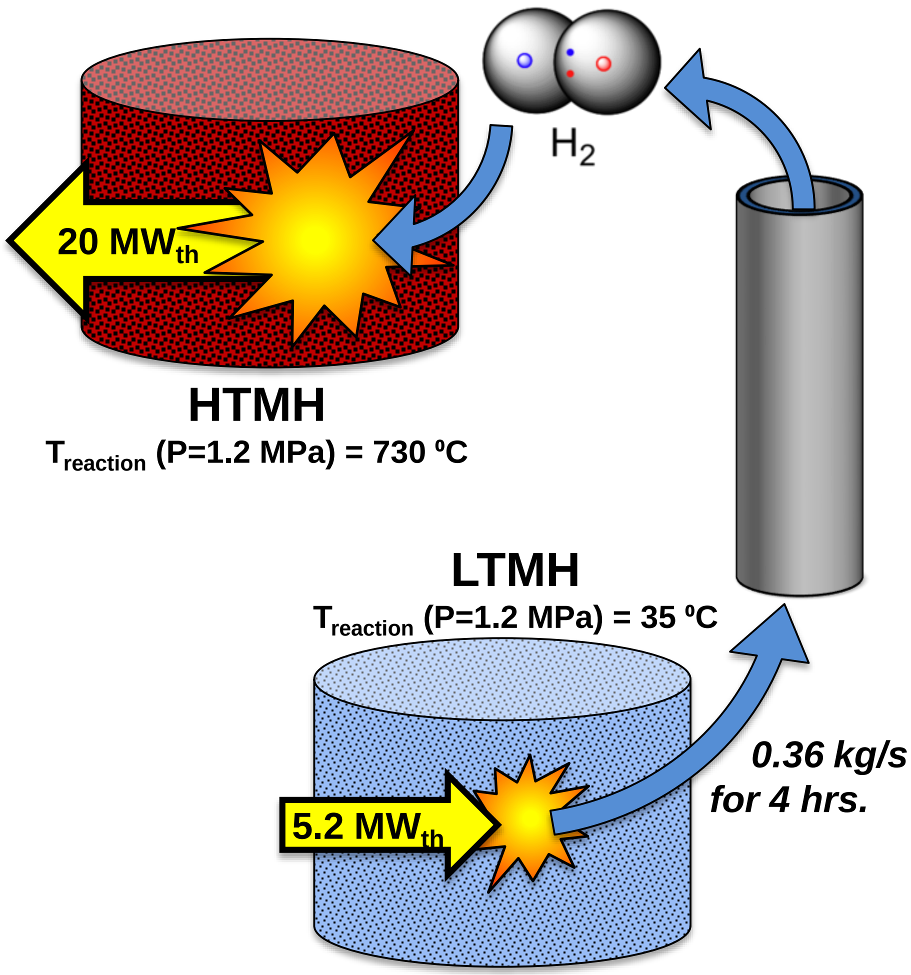
Metal Hydride 101: TES Charging



- Thermal (concentrated solar) energy is added to the HTMH, which *endothermically* releases hydrogen at its high reaction temperature
- The hydrogen flows into the LTMH, where it is *exothermically* absorbed at a lower reaction temperature
  - The released energy is absorbed by a flowing glycol loop, which then rejects it to ambient via an air cooled heat exchanger
- The energy is stored at low temperature in chemical bonds within the LTMH

Metal Hydride 101: TES Discharging

- Waste heat from the sCO_2 power cycle is absorbed into the same flowing glycol loop and transferred into the LTMH
  - This thermal energy is absorbed by the LTMH, which *endothermically* releases the stored hydrogen at its low reaction temperature
- The hydrogen flows back into the HTMH, where it is *exothermically* absorbed at a high reaction temperature
  - The released energy is transferred into the sCO_2 power cycle working fluid, heating it to the cycle turbine inlet temperature

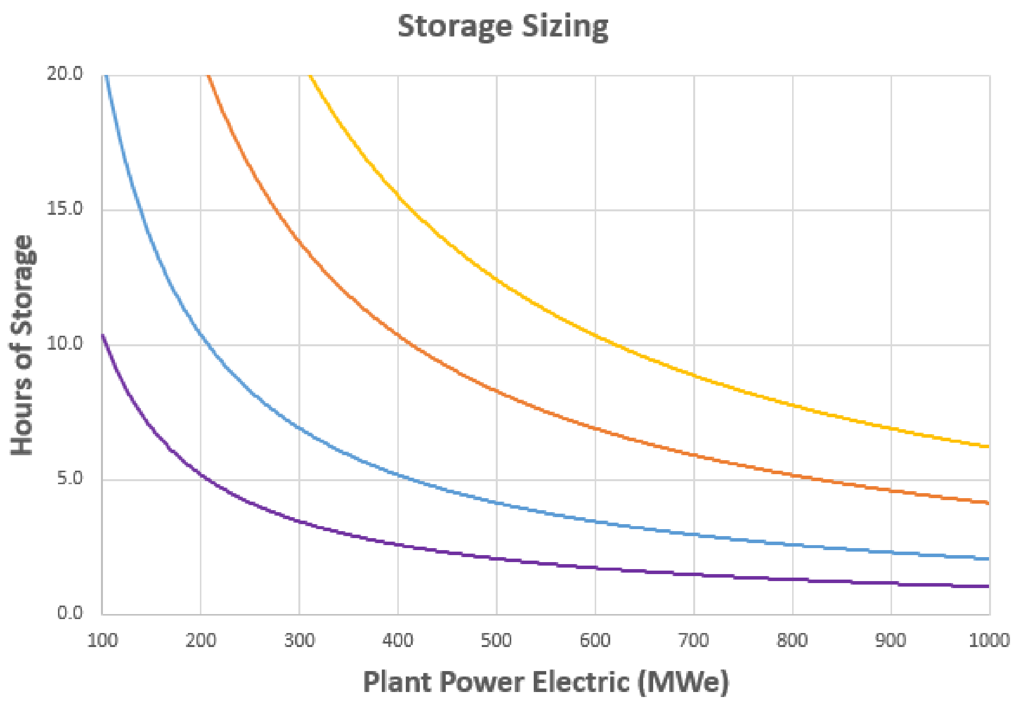


Apollo Metal Hydrides

	HTMH	LTMH
Compound	Ca_2Si	TiFe
ΔH (kJ/molH_2)	110	28
ΔS (kJ/molH_2-K)	130	114
Bulk Density (kg/m^3)	1400	3129
Thermal Conductivity* (W/m-K)	3.5	7
Weight Capacity (kg_{H2}/kg_{MH})	0.023	0.0153
Specific Heat (J/kg-K)	950	500
Raw Material Cost ($/kg)	-	5.2

*Enhanced with 10wt% of Expanded Natural Graphite

Scalability of MH



MH Volume: HT / LT ($1000m^3$)
10 / 6.73
20 / 13.5
40 / 26.9
60 / 40.4

*40% electrical conversion efficiency assumed

48.8m

109.8m

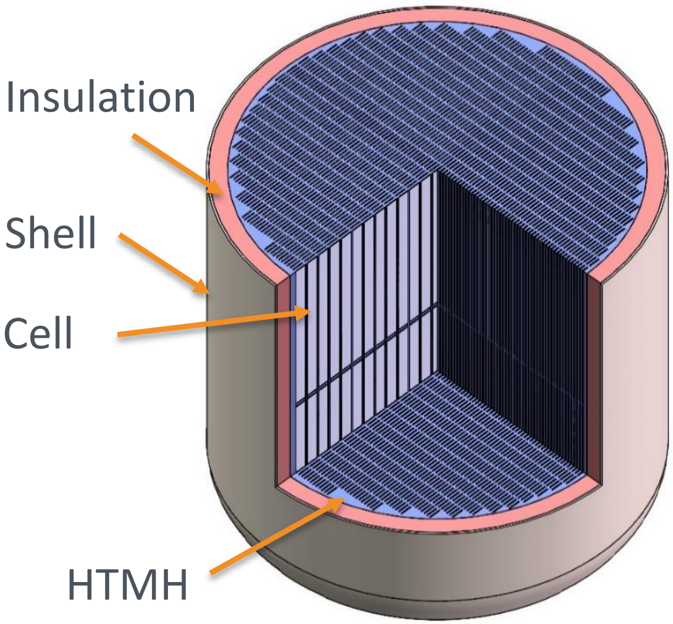
→ 5,351m^2

High Temperature MH Storage

- At high temperature stainless steel losses much of its strength resulting in a high cost
- Nickel alloys like 740H and 625 have a much higher strength but are expensive
- Hydrogen gas reformers use internal insulation on their hydrogen lines to reduce metal temperatures
  - A similar internal insulation is proposed for the HTMH storage tanks
- For simplicity of modeling it was assumed the liner was a single 200mm layer of GREENTHERM 23 LI which has a conductivity of 0.26 W/m-K

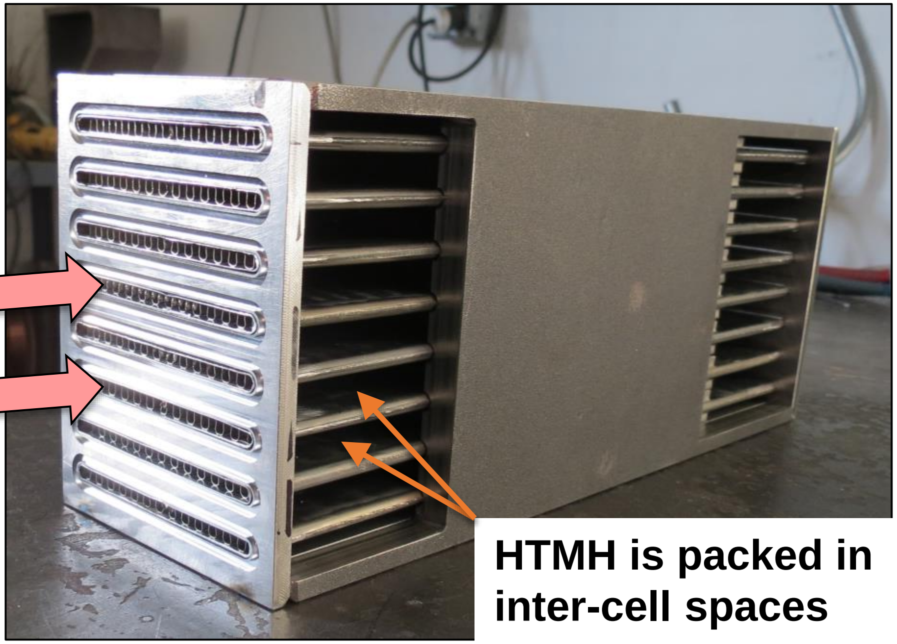
Source: JT Thorpe. “Reformers”.

High Temperature MH Storage



- Cost per module is shown
  - 3 modules required
  - Each module consists of 2 Pressure Vessels
- Majority of cost is in cells
  - Large surface area is required to transfer large amount of heat
- Size PV according ASME BPVC Division VIII Section 1
  - Material used for shell is P91 which has excellent strength and is readily available

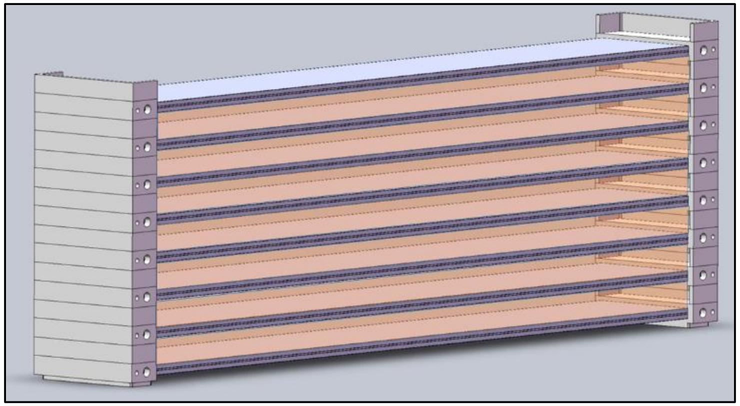
HTF flows within internally-supported and heat-transfer enhanced cells



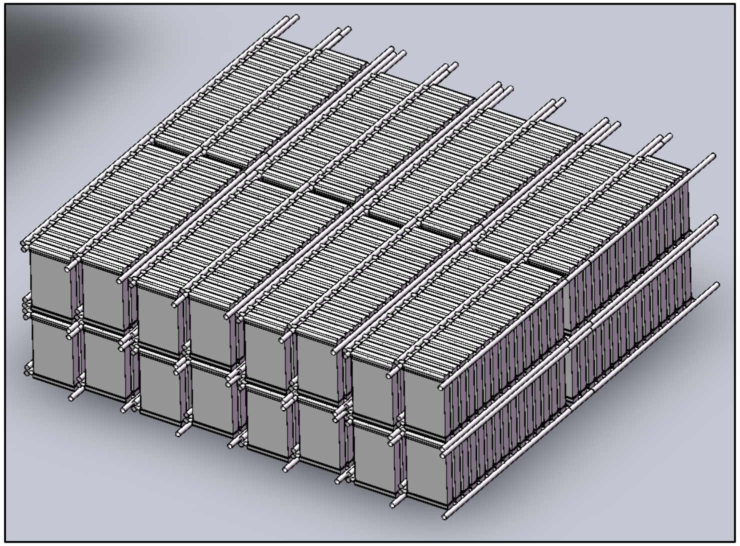
HTMH is packed in inter-cell spaces

Low Temperature MH Storage

- A series of Shell-Tube heat exchangers represents a low-cost solution
  - Glycol in Tubes, LTMH in shell
  - Shell-side H_2 connections required
  - Challenging to make full use of LTMH
    - May require excess LTMH
    - Optimization required



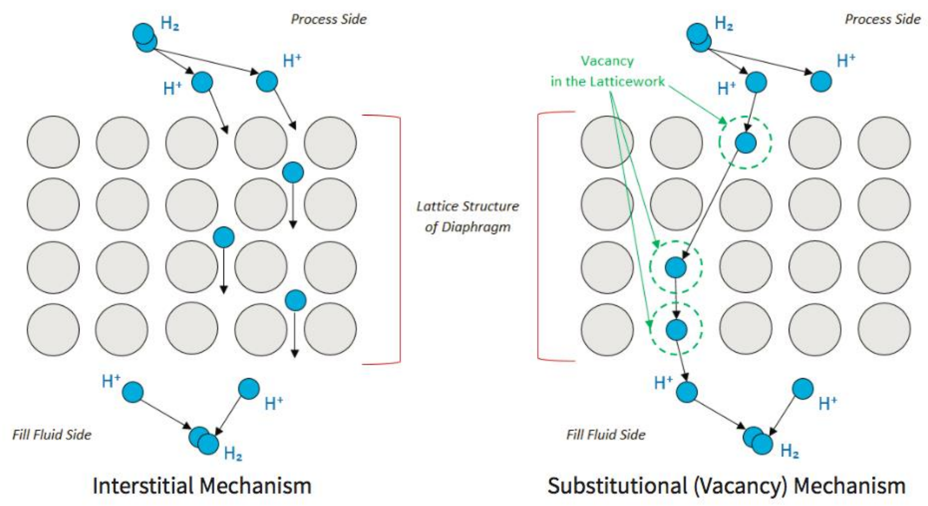
- Alternative design utilizes unit cell plate-fin configuration (as described in HTMH section)
  - High utilization of LTMH media
    - Little to no excess media required
  - Excessive glycol flow area
  - Self-supporting enclosure eliminates the need for thick vessel walls to react the 1.5 MPa shell-side LTMH pressure



Difficulties – Hydrogen Permeation

- The diffusion of hydrogen ions through thin metal walls
- H^+ is the smallest element
- Diffusion rate dependent on:

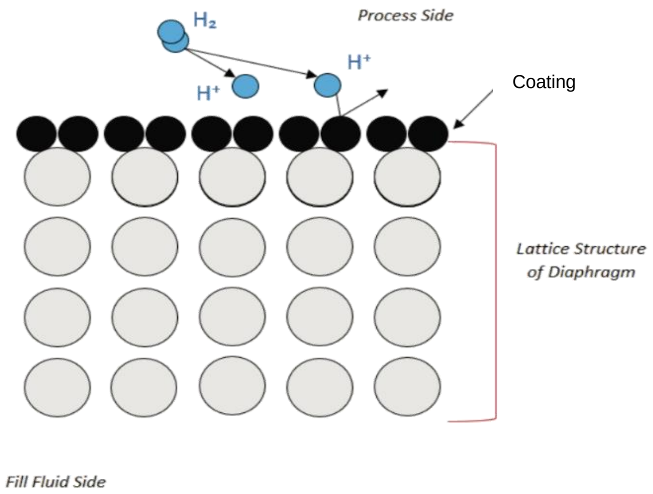
  Temperature, H_2 concentration, Diaphragm Material
- Damage turbomachinery if diffuse into working fluid
- Loose H_2 inventory over time → Energy Loss



Source: “Hydrogen Permeation”. Yokogawa.

Difficulties – Hydrogen Permeation

- How to Slow Hydrogen Permeation
  - Material Selection: resistance to oxidizing (Hastelloy)
  - Insulation: Internally Insulate to reduce outer shell wall temperature
  - Plating: Coat process side with tighter lattice work, more oxidization resistant material (CrO, Gold)

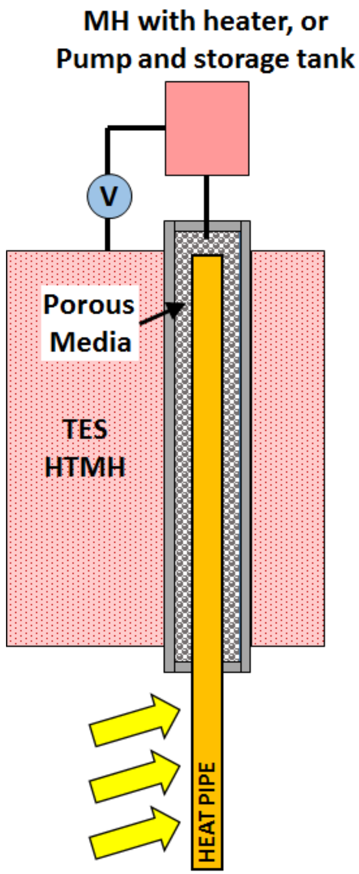


Source: “Hydrogen Permeation”. Yokogawa.

Active H_2 Capture and Recovery

- Hydrogen permeation from the HTMH into hot metals <u>*will*</u> occur in HTMH storage vessel

- Permeated hydrogen may be captured from the circulating HTF loop and returned to the system. In this system:
  - A passive MH formulation that can absorb freed H_2 from the HTF loop
    - The MH is periodically isolated from the loop and connected to dehydrogenated HTMH or LTMH (via valving), and then heated to release the captured hydrogen and return it back into the TES



Metal Hydrides Energy Storage

- Competitive, Low cost, High energy capacity material
- Low temperature storage yielding minimal energy/heat loss
- Scalable storage allowing for range of utilities
- Selection of MHs to tailor reaction temperature to system characteristics
- Employ methods to minimize and/or capture hydrogen permeation

Thank You!

Questions?