

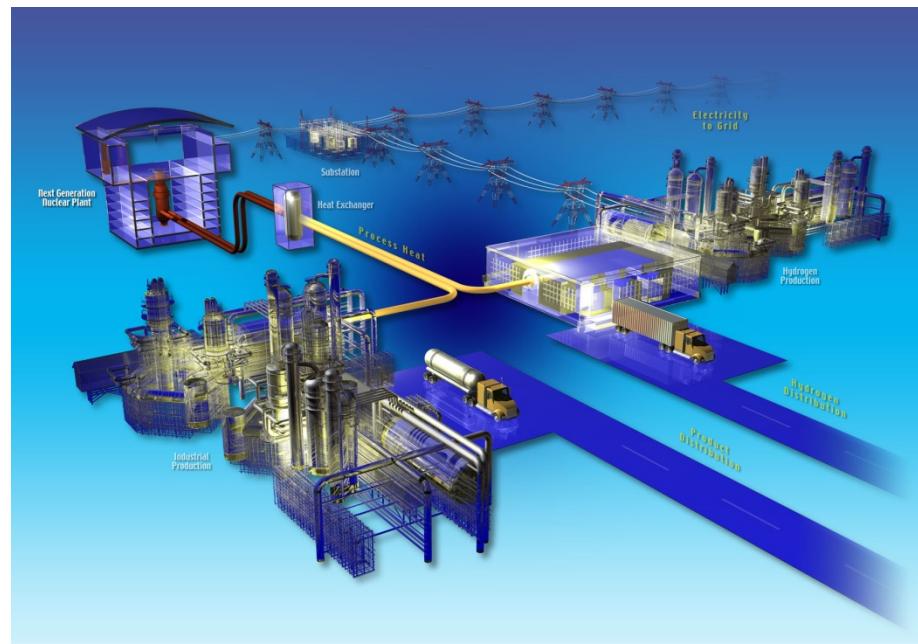
Systems Engineering Provides Successful High-Temperature Steam Electrolysis Project

June 20, 2011

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Systems Engineer

Idaho National Laboratory



Idaho National Laboratory (INL) Accomplishments

- Established in 1949
- **Develop Navy nuclear propulsion** systems and operator training
- Reprocess Navy Nuclear Fuel
- **Design, construct and operate 52 nuclear reactors**
- Produce key medical and industrial isotopes
- One of DOE's 10 multi-program labs
- DOE's designated **lead lab for nuclear energy**
- 8,000+ workers
- 890 Square Miles
- Develop nuclear reactor safety code
- Tank armor production
- **NASA program support**
- Completed significant Decommissioning
- Converted over 8 million gallons of liquid high level radioactive waste to 4,400 m³



Beyond Electricity – Applications of High Temperature Gas Reactors (HTGRs)

HTSE and Thermo-Chemical Hydrogen Production
Coal Gasification

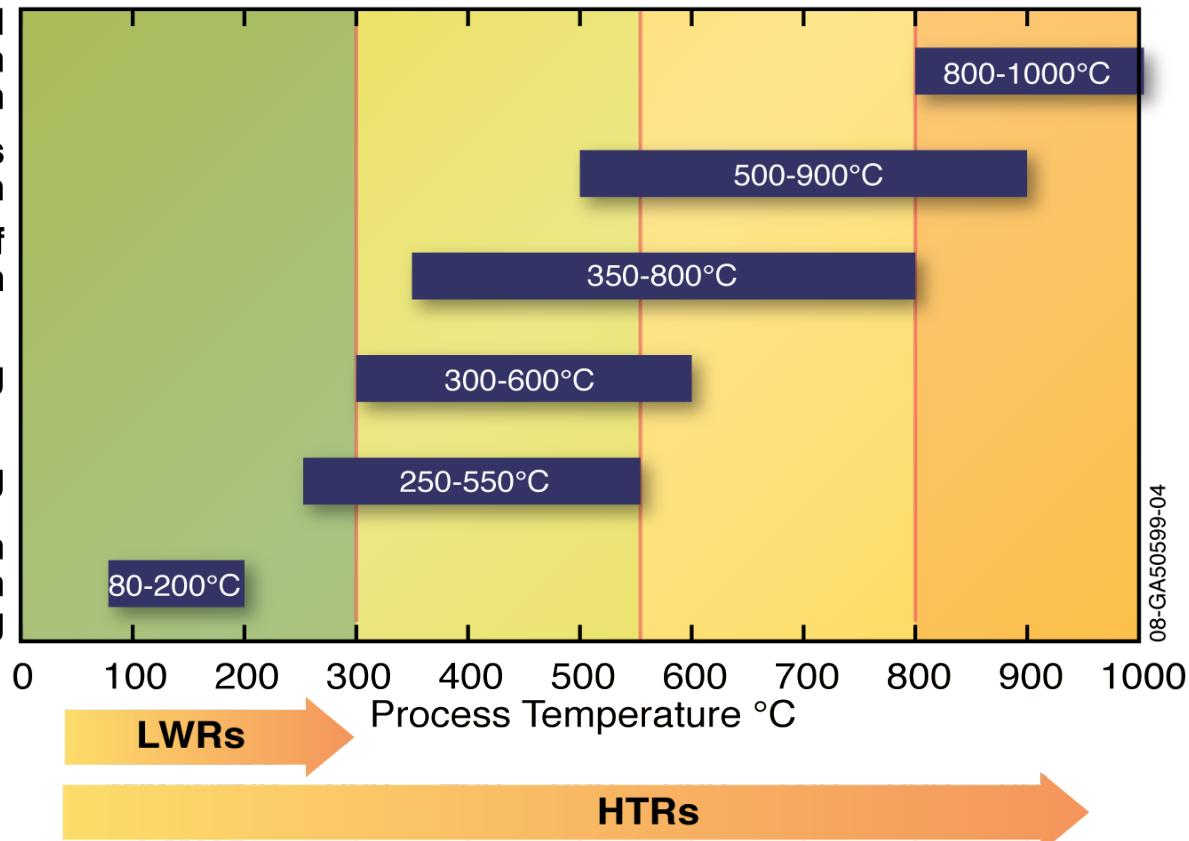
Steam Reforming of Natural Gas
Biomass Hydrothermal Gasification

Cogeneration of Electricity and Steam

Oil Shale and Oil Sand Processing

Petroleum Refining

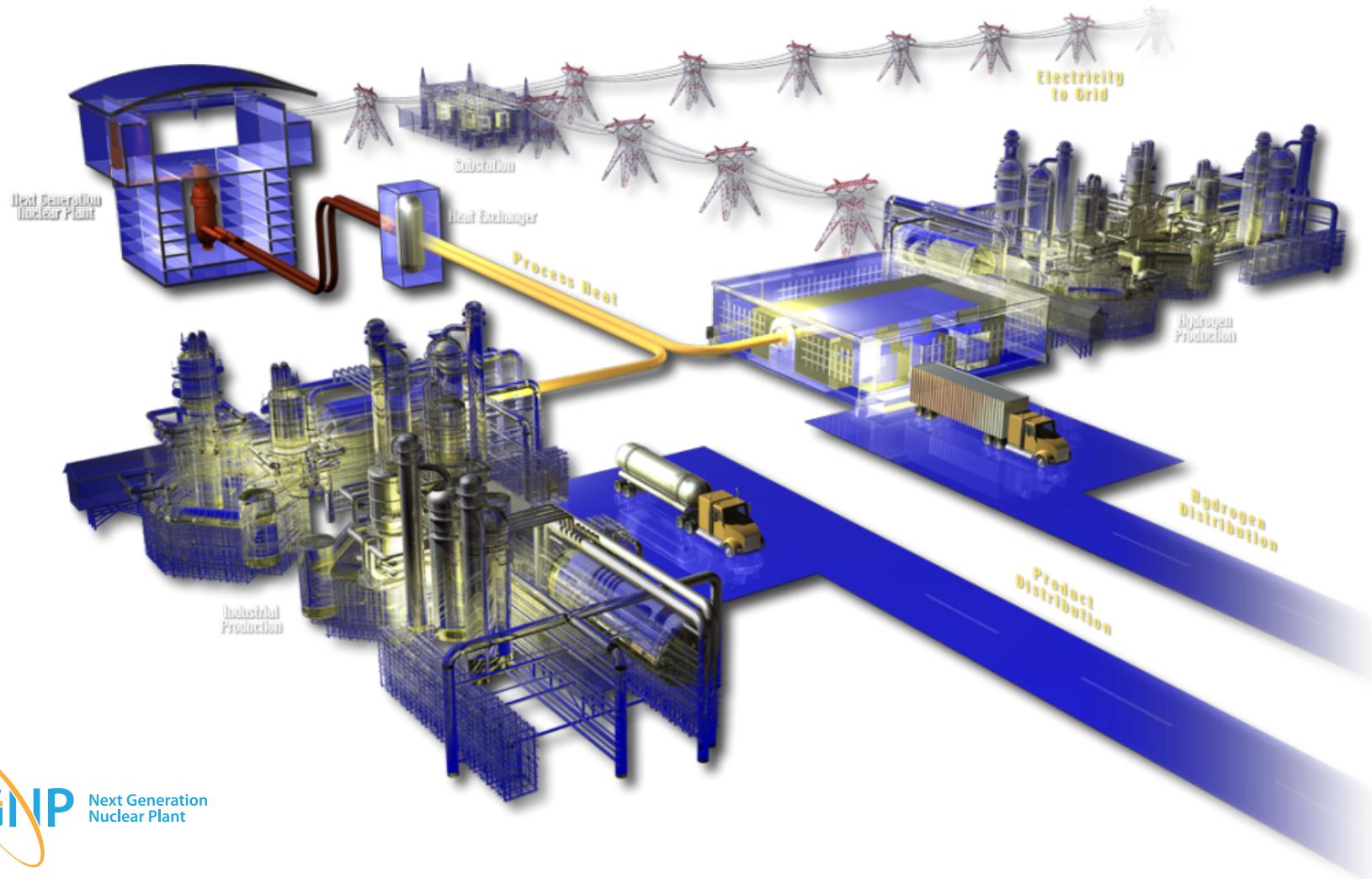
Ethanol Concentration
Seawater Desalination
District Heating



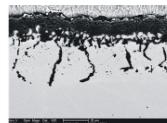
High Temperature Gas Reactors can provide energy production that supports many industrial applications including petrochemical and petroleum industries

Next Generation Nuclear Plant (NGNP): Enables Nuclear Energy to Enter Other Markets Beyond Electricity

Including: Process Heat, Hydrogen, and Electricity



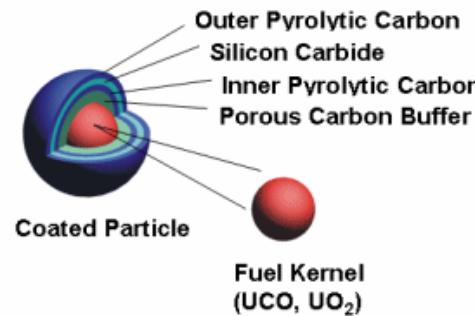
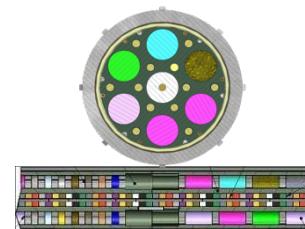
NGNP Technology Development



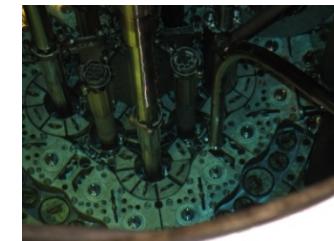
High Temperature Materials



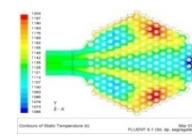
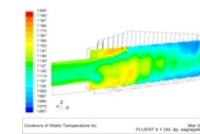
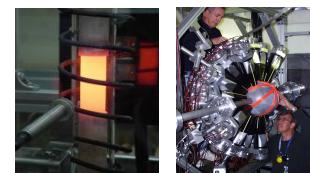
Graphite Development



Fuel Fabrication, Irradiation, and Safety Testing



Design and Safety Methods Development



Triso Fuel Particle

~3mm

<10⁻⁵

Failures at 1,600 °C

Captures Fission Products

Solid Oxide Fuel vs Electrolysis Cells

(High efficiency, long-term stability, fuel flexibility, low emissions, low cost, but higher temperature and material compatibility issues)



Developing Technology

(Rolls Royce, Ceres Power)

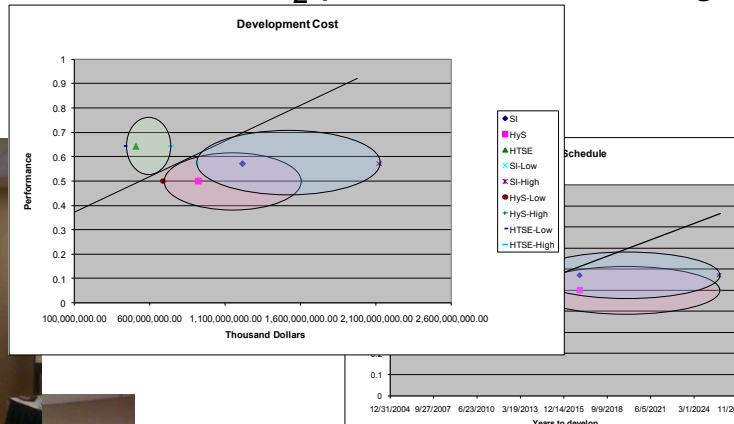
Emerging Technology

(INL HTSE)



SE Applications for Successful HTSE

- Rigorous, transparent down-selection of H₂ production technologies



Criteria	S												Comments
	NGNP/T/HSE	Widespread Adoption											
Process Robustness (R0/0)	1	1	1	1	1	1	1	1	1	1	1	1	Availability during Operations (Sec 4.4)
Process Control	1	1	1	1	1	1	1	1	1	1	1	1	Purity of Hydrogen (Sec 4.3)
Contamination Control	1	1	1	1	1	1	1	1	1	1	1	1	Purity of Hydrogen (Sec 4.3)
Hydrogen outlet temperatures	1	1	1	1	1	1	1	1	1	1	1	1	Purity of Hydrogen (Sec 4.3)
H2 purity level	1	1	1	1	1	1	1	1	1	1	1	1	Purity of Hydrogen (Sec 4.3)
Storage	1	1	1	1	1	1	1	1	1	1	1	1	Availability during Operations (Sec 4.4)
Delivery and safety	1	1	1	1	1	1	1	1	1	1	1	1	Key Assumptions and Constraints (Sec 4.3)
H2 Storage and Distribution	1	1	1	1	1	1	1	1	1	1	1	1	Cost of Hydrogen (Sec 4.10)
Material Availability	1	1	1	1	1	1	1	1	1	1	1	1	Cost of Hydrogen (Sec 4.10)
Site Specific	1	1	1	1	1	1	1	1	1	1	1	1	Quantity of Hydrogen Produced (Sec 4.2)
Site Specific	1	1	1	1	1	1	1	1	1	1	1	1	Availability during Operations (Sec 4.4)
Site Specific	1	1	1	1	1	1	1	1	1	1	1	1	Key Assumptions and Constraints (Sec 4.3)
Site Specific	1	1	1	1	1	1	1	1	1	1	1	1	Cost of Hydrogen (Sec 4.10)
Site Specific	1	1	1	1	1	1	1	1	1	1	1	1	Development Impact (Sec 4.9)
Site Specific	1	1	1	1	1	1	1	1	1	1	1	1	Healthcare Impacts (Sec 4.10)
Site Specific	1	1	1	1	1	1	1	1	1	1	1	1	Waste during Operations (Sec 4.9)
Site Specific	1	1	1	1	1	1	1	1	1	1	1	1	Cost of Hydrogen (Sec 4.10)
Site Specific	1	1	1	1	1	1	1	1	1	1	1	1	Technology Maturity (Sec 4.7)
Site Specific	1	1	1	1	1	1	1	1	1	1	1	1	Technology Maturity (Sec 4.7)

	HyS-Low	HyS-High	HTSE-Low	HTSC-High
HyS-Low	1	0	0	0
HyS-High	0	1	0	0
HTSE-Low	0	0	1	0
HTSC-High	0	0	0	1

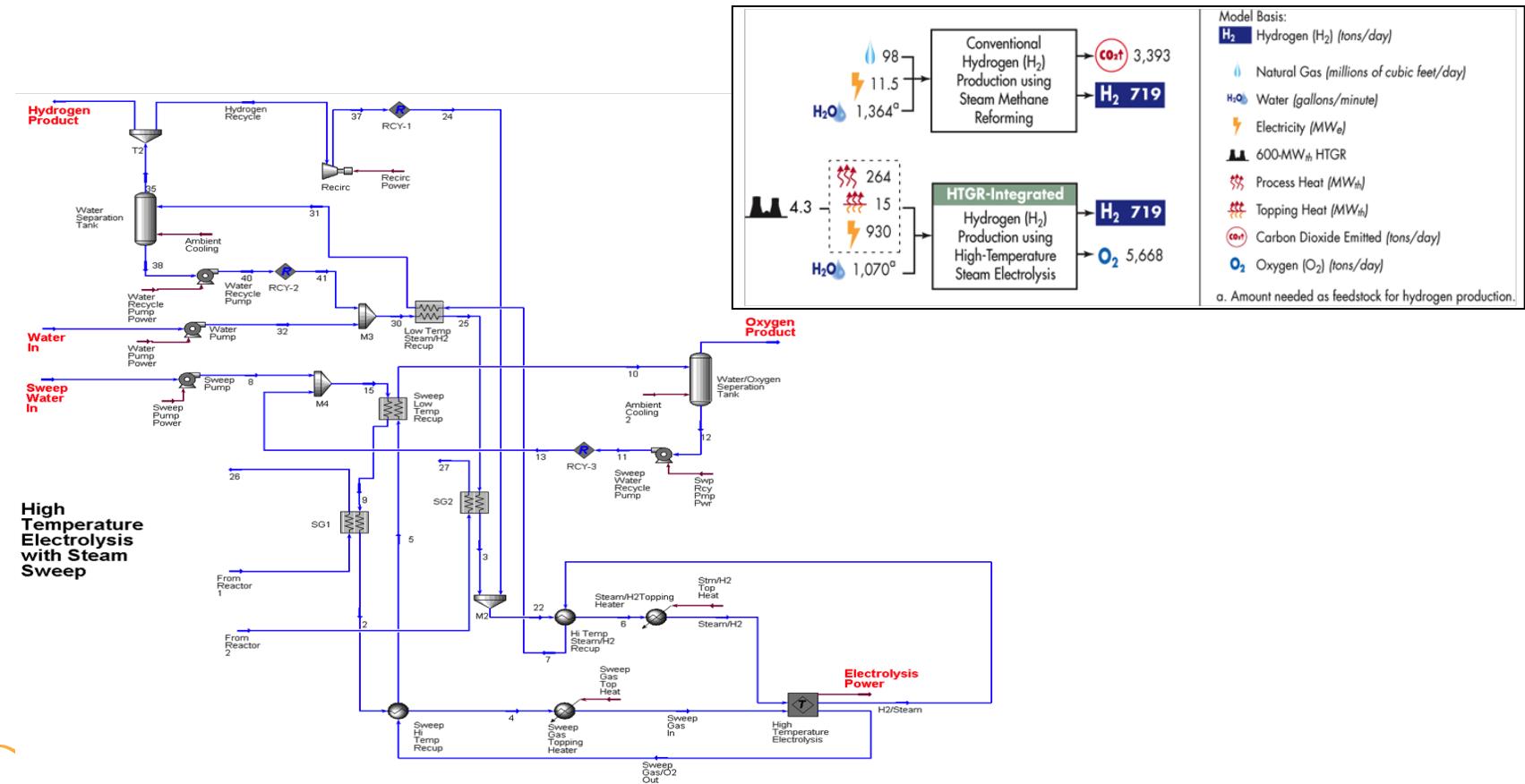
Goals	Criteria	Wt%	Worse <----- Scoring -----> Better					Comment	Ratings			Score		
			1	2	3	4	5		HTSE	HyS	SI	HTSE	HyS	SI
Performance (35%)	Quantity of H ₂ Produced	10%	<10	10–12	12–15	15–20	>20	1,000's kg/day Independent of Need Demand circa 2009	3	2	2	0.3	0.2	0.2
	Purity of Hydrogen	5%	None	Almost none	Some	Most	All		5	3	4	0.25	0.15	0.2
	Serve Various Applications	15%	Useless	Almost none	Some	Most	All		4	4	3	0.6	0.6	0.45
	Waste Management	5%	Extreme	Significant	Typical	Modest	None		4	3	2	0.2	0.15	0.1
Cost (30%)	Cost of Production	10%	>9	7–9	5–7	3–5	<3	\$/kg Confidence in scoring \$M	3	3	2	0.3	0.3	0.2
	Cost Uncertainty	10%	Unrealistic	Optimistic	Consistent	Conservative	Very Conservative		3	3	2	0.3	0.3	0.2
	Development Cost (Relative)	10%	>1,200 (very high)	1,000–1,200 (high)	800–1,000 (medium)	600–800 (med-low)	<600 (low)		4	3	2	0.4	0.3	0.2
Risk (35%)	Technical Maturity (TRLs)	15%	<2.5	2.5–3.4	3.5–4	4.1–4.5	>4.5	Composite	3	2	1	0.45	0.3	0.15
	Development Risk	20%	Insurmountable	High	Medium to High	Low to Medium	Low	Composite	3.5	3	2	0.7	0.6	0.4
								Total	32.5	26	20	3.5	2.9	2.1

Total 32.5 26 20 3.5 2.9 2.1

Out of 5

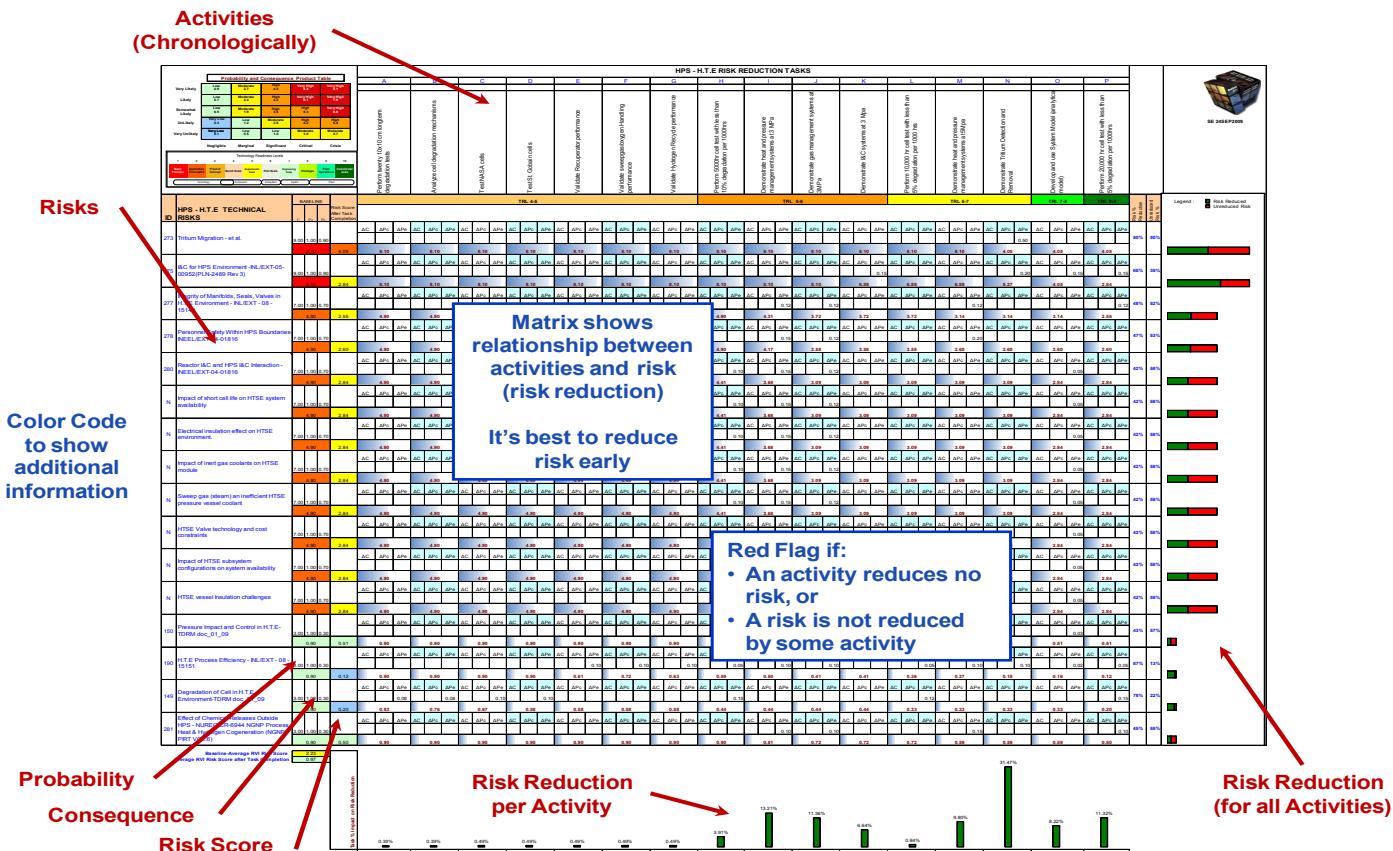
SE Applications for Successful HTSE

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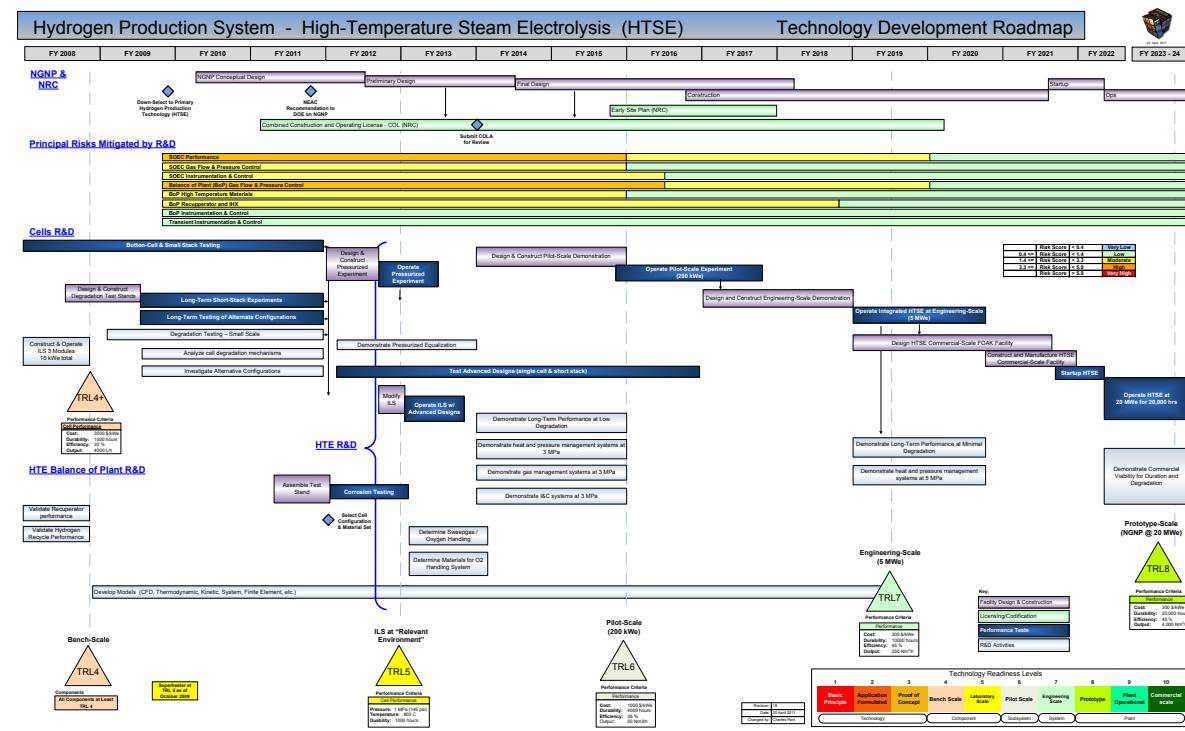


SE Applications for Successful HTSE

- Rigorous, transparent down-selection of H₂ production technologies
- *HTSE Flowsheets integrated* with industrial process applications
- Relational Risk Management process to focus development
- Developed detailed Test Plans for methodical testing
 - 8 components advancing through 4 maturity levels

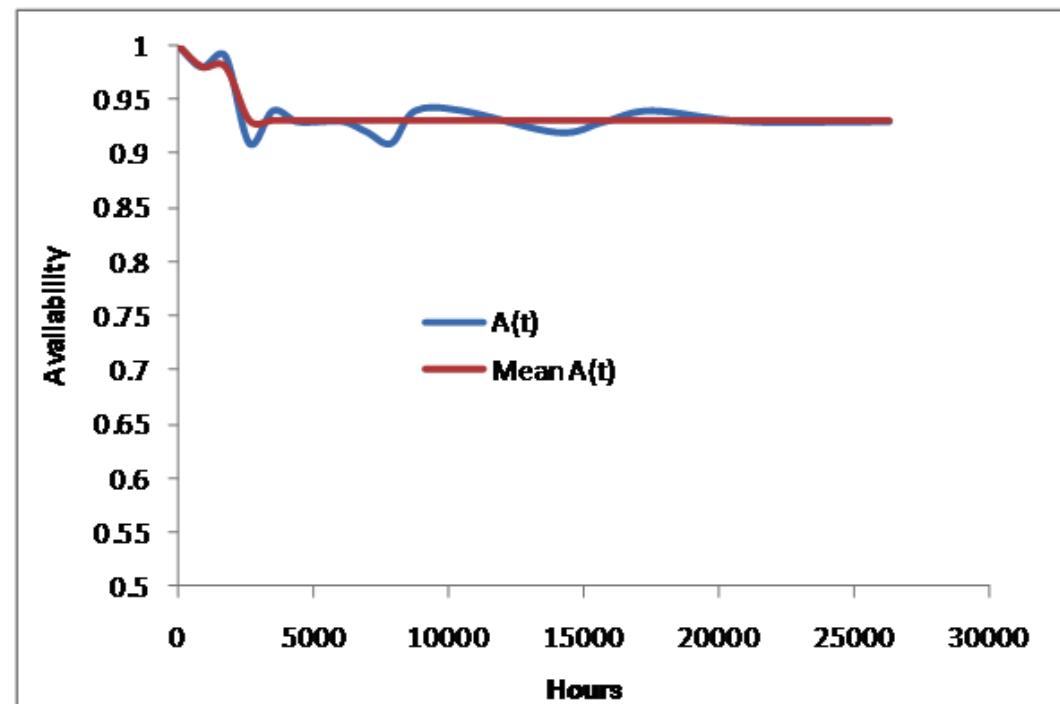
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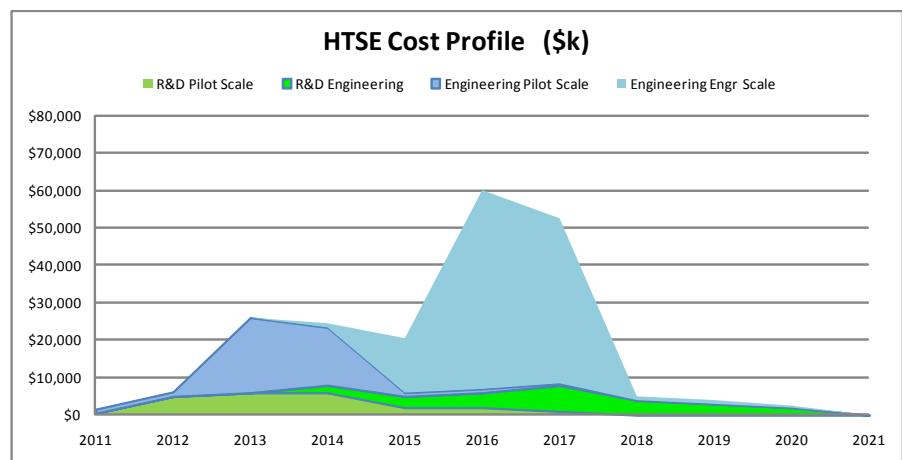
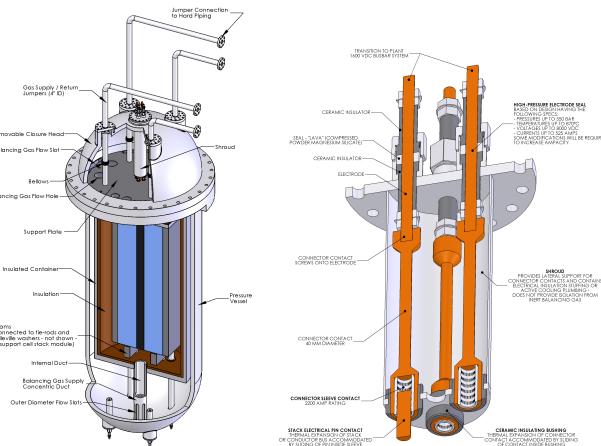
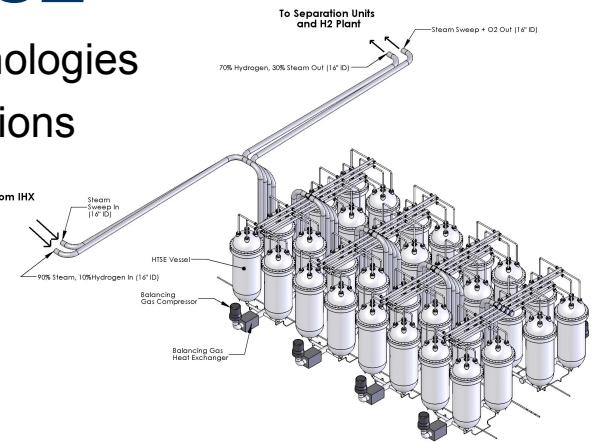
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	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	Total
R&D												
R&D Pilot Scale	500	5000	6000	6000	2000	2000	1000					22500
R&D Engineering				2000	3000	4000	7000	4000	3000	2000		25000
Total	500	5000	6000	8000	5000	6000	8000	4000	3000	2000		47500
Engineering												
Engineering Pilot Scale	1100	1200	20000	15400	1000	1000	500	0				40200
Engineering Engr Scale				1100	14500	53000	44000	1000	1000	500		115100
Total	1100	1200	20000	16500	15500	54000	44500	1000	1000	500		155300
												202800

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- Preliminary RAMI Analysis to guide design
- Life-cycle cost estimates completed
- Requirements Management

Summary:

- NGNP / HTSE Project involved significant SE
- SE was implemented in the early stages of the project
- Used innovative SE tools and methods as needed

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