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Systems Engineering Provides Successful High Temperature Steam Electrolysis Project

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Abstract. This paper describes two Systems Engineering Studies completed at the Idaho National Laboratory (INL) to support development of the High Temperature Stream Electrolysis (HTSE) process. HTSE produces hydrogen from water using nuclear power and was selected by the Department of Energy (DOE) for integration with the Next Generation Nuclear Plant (NGNP). The first study was a reliability, availability and maintainability (RAM) analysis to identify critical areas for technology development based on available information regarding expected component performance. An HTSE process baseline flowsheet at commercial scale was used as a basis. The NGNP project also established a process and capability to perform future RAM analyses. The analysis identified which components had the greatest impact on HTSE process availability and indicated that the HTSE process could achieve over 90% availability. The second study developed a series of life-cycle cost estimates for the various scale-ups required to demonstrate the HTSE process. Both studies were useful in identifying near- and long-term efforts necessary for successful HTSE process deployment. The size of demonstrations to support scale-up was refined, which is essential to estimate near- and long-term cost and schedule. The life-cycle funding profile, with high-level allocations, was identified as the program transitions from experiment scale R&D to engineering scale demonstration.

Introduction

Background

In July of 2005, Congress passed the *Energy Policy Act of 2005* (EPAct), which states, "The Secretary shall establish a project to be known as the Next Generation Nuclear Plant Project (NGNP)." It continues, "The Project shall consist of the research, development, design, construction, and operation of a prototype plant, including a nuclear reactor that is based on research and development activities supported by the Generation IV Nuclear Energy Systems Initiative… and shall be used, to generate electricity and/or produce hydrogen."

As part of the Department of Energy's (DOE's) Idaho National Laboratory (INL) nuclear energy development mission, the INL contractor—Battelle Energy Alliance, LLC (BEA)—is leading a program to develop and design a High-Temperature Gas-cooled Reactor (HTGR), which was selected as the base design for the NGNP.

An HTGR uses high-temperature helium coolant to produce steam, process heat and/or electricity. In conventional processes, these products are generated by the combustion of fossil fuels such as coal and natural gas, resulting in significant emission of greenhouse gases such as carbon dioxide. Heat or electricity produced by an HTGR could be used to supply process heat or electricity to conventional processes without generating greenhouse gases.

DOE culminated its seven-year Nuclear Hydrogen Initiative in 2009 with an evaluation of the three most mature hydrogen production technologies (Sulfur-Iodine, Hybrid Sulfur, and High-Temperature Steam Electrolysis (HTSE)). This rigorous down-selection, performed by an independent review team, recommended focusing limited R&D funding on the HTSE process and DOE determined to include its future development within the NGNP Project. This work was presented at the 2010 INCOSE International Symposium in Chicago.

The NGNP Project has instituted a scale (from 1 to 10) representing the readiness (or progressive maturity) of technologies. Current HTSE process development is at a technology readiness level (TRL) of 4, having completed all bench scale testing. An integrated laboratory scale test was completed using 15 kWe for 1000 hours but was operated at low pressure and therefore not at a 'relevant environment', as required to achieve TRL-5 (experimental scale). TRL-5 will be achieved when multi-cell stacks are tested at approximately 1 MPa - anticipated in 2012. Current testing is conducted in the Bonneville County Technology Center (BCTC) in Idaho Falls, Idaho. NGNP TRL definitions are shown in Table 1.

Table 1. NGNP Technology Readiness Level (TRL) definitions.

TRL	Technology Readiness Level Definition	Abbreviated Definition
1	**Basic principles observed** and reported in white papers, industry literature, lab reports, etc. Scientific research without well defined application.	Basic principles observed
2	**Technology concept and application formulated.** Issues related to performance identified. Issues related to technology concept have been identified. Paper studies indicate potentially viable system operation.	Application formulated
3	**Proof-of concept:** Analytical and experimental critical function and/or characteristic proven in laboratory. Technology or component tested at laboratory scale to identify/screen potential viability in anticipated service.	Proof of **Concept**
4	**Technology or Component is tested at bench scale to** demonstrate technical feasibility and functionality. For analytical modeling, use generally recognized benchmarked computational methods and traceable material properties.	**Bench** scale testing
5	**Component demonstrated at experimental scale in relevant environment**. Components have been defined, acceptable technologies identified and technology issues quantified for the relevant environment. Demonstration methods include analyses, verification, tests, and inspection.	Component Verified at **Experimental** Scale
6	**Components have been integrated into a subsystem** and demonstrated at a pilot scale in a relevant environment.	Subsystem Verified at **Pilot** scale

TRL	Technology Readiness Level Definition	Abbreviated Definition
7	**Subsystem integrated into a system** for integrated engineering scale demonstration in a relevant environment.	System demonstration at **Engineering** Scale
8	**Integrated prototype of the system is demonstrated** in its operational environment with the appropriate number and duration of tests and at the required levels of test rigor and quality assurance. Analyses, if used support extension of demonstration to all design conditions. Analysis methods verified and validated. Technology issues resolved pending qualification (for nuclear application, if required). Demonstrated readiness for hot startup.	Integrated Prototype Tested and Qualified
9	**The project is in final configuration** tested and demonstrated in operational environment.	Plant Operational **NGNP, First-of-a-kind**
10	**Commercial-scale demonstration** is achieved. Technological risks minimized by multiple units built and running through several years of service cycles.	**Commercial** Scale – Multiple Units **Nth-of-a-kind**

Document Scope

The purpose of this technical paper is to summarize the results of two HTSE process Systems Engineering studies. First, an analysis of the reliability, availability and maintainability (RAM) of the HTSE process, and second, an estimate of the life-cycle costs associated with demonstrating the HTSE process at two scales (pilot and engineeringl). Although a formal pre-conceptual design has not yet been completed for the HTSE process, performing these preliminary studies based on initial assumptions helped define and refine the following:

- Identified and clarified essential process functions
- Defined system boundaries
- Identified components that require significant research and development (R&D)
- Identified performance targets to be achieved as the process matures
- Identified design data needs (DDNs)
- Identified components requiring redundancy
- Clarified funding needs as the program transitions from experimental scale R&D to engineering scale demonstration
- Supported near- and long-term cost and schedule planning

RAM Analysis

RAM refers to reliability, availability, and maintainability. When inspectability is included, the acronym RAMI is used. In practice, a RAM analysis includes an evaluation of all of the 'ilities' that can affect operational availability (inspectability, accessibility, repairability, vulnerability, etc.). At the current level of technical maturity, the study was limited to the RAM analysis because there is inadequate design detail to perform a detailed analysis of the additional parameters.

HTSE Process System Description

For the purpose of this RAM analysis the HTSE process is defined as a set of hydrogen (H_2) producing modules comprised of stacks that are made up of solid oxide electrolysis cells (SOECs). Also included is the infrastructure needed to deliver steam and electricity, and to remove the hydrogen and oxygen products. The analysis does not include the supply water treatment system, product storage systems, the electric power generation unit, or the primary heat transfer system upstream of a secondary (to the reactor) heat exchanger. The system that was analyzed is shown in simplified form in Figure 1.

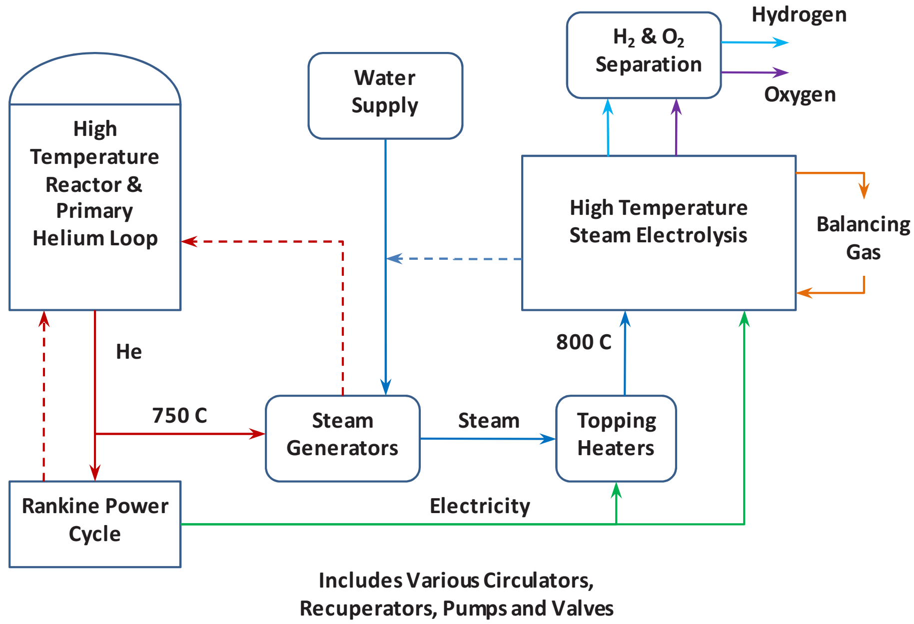


Figure 1. Simple schematic of HTSE process.

Based on the current process flow model, the HTSE process with a steam sweep system to remove oxygen from the anode side of the electrolyzer, integrates the capability of 18 major subsystems and components to produce hydrogen.

Within the HTSE process, high-temperature heat (as steam) is introduced along with electricity to split water into hydrogen and oxygen within the SOECs. Over 80% of the energy required for electrolysis is delivered as electricity. Initial NGNP deployment is planned for a reactor outlet temperature (ROT) of 750°C to 800°C, but some heat loss will occur in heat exchangers and piping. HTSE SOECs currently operate best at about 800°C, so a small amount of topping heat is planned. Although theoretical efficiency improves as the temperature increases, practical considerations have limited current demonstrations to about 800 °C. Process efficiency is increased by recuperating excess heat back into the process. The hydrogen produced from the HTSE process has a purity of 99.9% with only water and oxygen as by-products.

Methodology

To initiate the RAM analysis, candidate commercial software was evaluated. The primary selection criteria compared capabilities to perform the analysis for both simple and complex systems as a function of procurement cost and ease of use. As a result Blocksim 7.0.11, by Reliasoft, was procured and NGNP Engineering staff was trained. This software is used by a number of DOE Laboratories and Department of Defense organizations. Reliability Block

Diagrams (RBD) were constructed for use in the software and coupled with suitable failure and repair data. Monte Carlo simulations were run under a variety of iterations and durations. Although the final physical configuration of the HTSE process will change as the design matures, useful preliminary results were achieved. These preliminary results will form a basis for HTSE process reliability improvements.

General RAM Analysis Assumptions

A selection of RAM analysis assumptions for the HTSE process include:

- SOEC modules will be replaced by activating an in-line spare with no down-time. The modular nature of the HTSE process will allow this instantaneous replacement at TRL-6 and beyond. This assumption means that the performance of SOECs does not affect process availability. High SOEC degradation and failure rates, however, would significantly increase the number of readily available spares required which would significantly increase the cost of hydrogen production.
- When failed parts are replaced or repaired, the entire system will be as reliable as new
- Target availability for NGNP is greater than or equal to 90%.
- Failure distribution for the components does not include premature failures during the early service life nor does it include failures unique to startup or shutdown. This is a customary assumption in the absence of specific component failure data.
- SOEC modules are not expected to fail abruptly, but are deemed failed when hydrogen production gradually decreases to 70% of original output
- Useful SOEC service life at TRL-10 (NOAK commercial demonstration) is 6 years
- Replacement heat-up and cool-down times for major process components are not included (could be as much as 4 days combined).
- Component failure rate data was extracted from the Savannah River Site Generic Data Base Development (WSRC-TR-93-262, REV. 1) dated May 19982. These data represent large gas systems, both at nuclear power plants and from Savannah River Site systems, and provide a starting point for analyzing component reliability. Key failure rate data for major HTSE process components is shown in Table 2.

Table 2. HTSE process component failure rates.

HTSE Components	Comparable Components	Number of Components	Failures per Hour per Component	Failure Criticality Index (%)
Topping heaters and recuperators	Heat exchangers	4	1.45 E-05	34
Motor operated valves	Motor operated valves	24	1.14 E-05	28
Sweep, water, recycle pumps	Centrifugal pumps	4	3.50 E-05	15
Pressure relief valves	Pressure relief valves	10	1.06 E-05	10
Hydrogen recirculator	Compressor	1	6.00 E-05	6
O_2/H_2 separation tanks	Condensers	2	1.45 E-05	4
Steam generators	Heat exchanger	2	1.45 E-05	3

These assumptions provide optimistic RAM results because the data are generally from lower temperature environments (e.g., light water reactors) relative to the HTSE process. As R&D and demonstration advance, actual failure rates will be used and the analysis improved. The failure criticality index shows the relative contribution of component types to the unavailability of the HTSE process. Based on these assumptions, the topping heaters and recuperators represent about a third of the impact on HTSE process availability, and the motor operated valves contribute about a fourth of the unavailability.

Assuming that the SOECs will be replaced instantaneously is reasonable due to the modular nature of the process. And as a result SOEC performance does not affect HTSE plant availability. The driver to improve SOEC performance comes from the cost of having too frequent replacement. As shown in the life-cycle cost estimate, the SOECs are the most significant cost contributor.

RAM Analysis Results

The RAM analysis identified that the HTSE process could achieve over 90% availability at TRL-10, which is the NOAK commercial demonstration. This result assumes that the current failure rates of major process components will be advanced so that these rates will be similar to the performance of NGNP components that will be operated at higher temperatures and pressures. High-temperature topping heaters and motor-operated valves were identified as the components that could most significantly affect the availability of the HTSE plant.

Based on current the RAM analysis, HTSE availability stabilizes at 93% after the first year, see Figure 2. An implication of this graph is that the HTSE process (as analyzed) varies no more than plus or minus 1% after the first year. This is primarily due to the assumption that repairs and replacements will restore the systems as good original and therefore show no gradual decline. HTSE process target availability (90%) may also be achieved through additional redundancy if component reliability cannot be sufficiently improved, but this redundancy will increase cost.

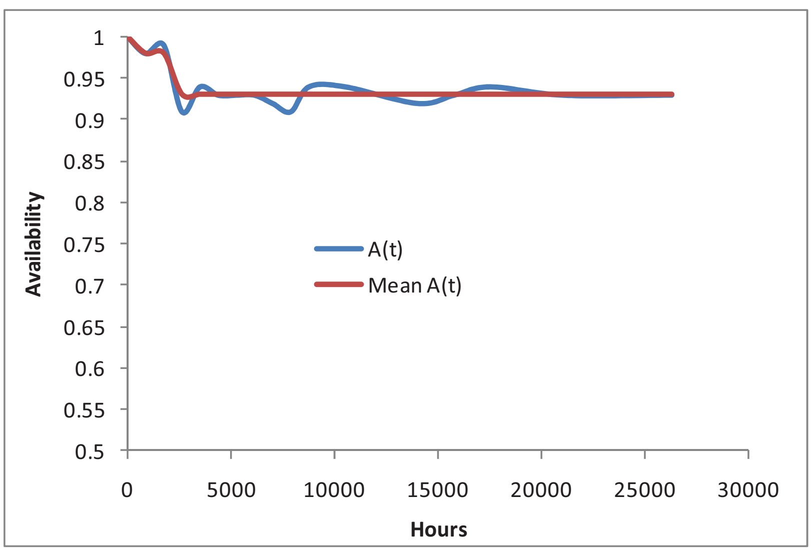


Figure 2. First-year steady-state availability, A (t).

Conclusion/Recommendations (RAM analysis)

Based on these RAM analyses, the HTSE process is expected to achieve 90% availability at TRL-10. The development of SOFC technology is several years ahead of SOEC technology and continued SOFC advances should be leveraged to improve SOEC technology. It is also believed that current industrial components can be improved to operate at the higher temperatures and pressures needed for the HTSE process.

Improving the current SOEC performance (useful service life) for each future TRL level is aggressive and will require focused R&D to meet a near-term pilot scale demonstration and an eventual 2021 FOAK demonstration milestone.

The results from this preliminary RAM analysis are informative, but do not reflect the final system design. As the HTSE process design becomes mature, its component descriptions and specifications will become detailed. At that time, failure data for specific components will be more available and accurate, and a more detailed and useful RAM analysis will be performed.

Good progress has been made on determining the factors affecting cell degradation, and a number of cell manufactures are working with the INL to advance SOEC maturity.

Life-Cycle Cost Estimate

General Assumptions and Basis

Development and demonstration of the HTSE technology will involve successive scale-up from the current power level of tens of kWe up to tens of MWe. This section describes the estimated cost and schedule (as available) for pilot scale demonstration (TRL-6) and engineering scale demonstration (TRL-7). Subsequent sections of this report will address these phases. As development advances from experimental scale R&D to pilot scale demonstration, the need for larger, more complex facilities and hardware will require additional funding. Figure 3 shows a simplified arrangement of the next scale-ups to be accomplished and the relationship between R&D and Engineering.

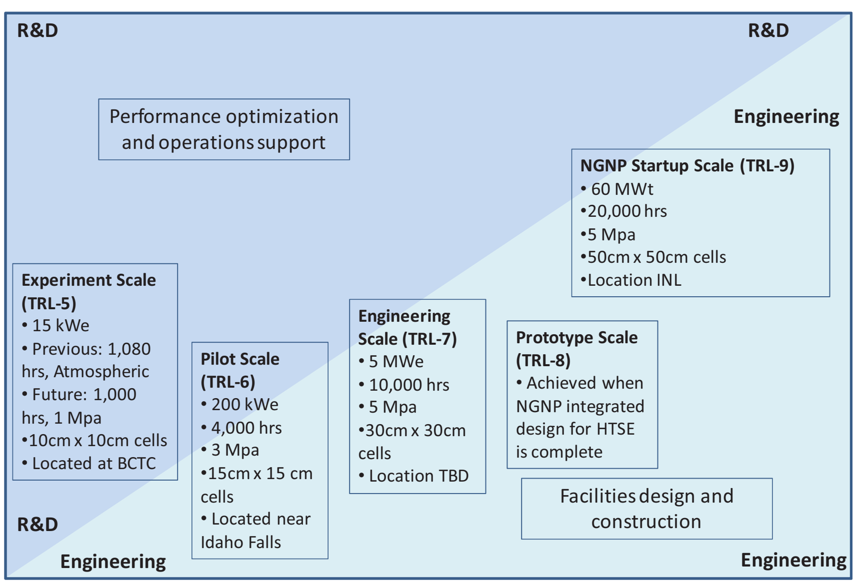


Figure 3. R&D and Engineering integration.

HTSE process development and demonstration is assumed to coincide with NGNP design, construction, startup and deployment by 2021. Planned pilot scale HTSE process demonstrations (TRL-6) will begin in the 2014 time-frame in a facility near Idaho Falls, Idaho.

The engineering scale demonstration (TRL-7) is planned to be approximately an order of magnitude larger than pilot scale (in terms of power usage) and is planned to begin in the 2017 time-frame at a location to be determined. Although current cost and schedule estimates show this as a new facility, it may be possible (due to the modular nature of the HTSE process) to retrofit the pilot scale facility for this larger scale.

Current plans for achieving TRL-8 (prototype scale) include integrated component demonstration during the TRL-7 demonstration. TRL-8 will also include a complete design for TRL-9 demonstration. Due to the modular nature of the HTSE process, it is not planned to require a separate facility or scale-up between TRL-7 and TRL-9. The FOAK demonstration (TRL-9) will begin using nuclear heat in 2021. TRL-10 is the NOAK commercial demonstration and will occur when about 10 HTSE's have been deployed.

The absence of a validated HTSE process conceptual design creates uncertainty related to cost. Since the HTSE technology is currently at TRL-4, it is assumed that the technology will reach TRL-5 in FY 2011 or FY 2012 and within a reasonable cost and schedule to meet NGNP milestones. Therefore this TEV does not include costs for achieving TRL-5. Current HTSE R&D includes: cell and small stack testing, high-temperature materials development, molecular modeling, detailed computational fluid dynamics (CFD) analysis, and system modeling. All NGNP supporting R&D (including the HTSE process) is managed by the NGNP Technology Development Office (TDO).

A summary of scale-up parameters are shown in Table 3. These performance targets will be revised as appropriate as each scale-up is accomplished.

Table 3. HTSE process scale-up parameters.

	Pilot Scale	**Engineering Scale**	**Prototype Scale ***	**NGNP Operational FOAK**	**Commercial Demonstration NOAK**
Startup	2014	2017	2019	2021	After 10 HTSEs built
TRL	6	7	8	9	10
Year TRL achieved	2015	2019	2020	2023	-
Heat source	Non-nuclear	Non-nuclear	-	NGNP	HTGRs
Heat load	200 kWe	5 MWe	-	60 MWt	600 MWt
Cell size (cm)	15 x 15	30 x 30	-	50 x 50	50 x 50
Pressure (MPa)	3	5	-	5	5
Cell performance service life (hrs)	4,000	10,000	-	20,000	50,000 (6 years)
Hydrogen output (Nm^3/hr)	50	250	-	7,000	76,000

* The modular nature of the HTSE process allows TRL-8 to be achieved if component integration is demonstrated at TRL-7 and when the design for TRL-9 is completed.

Because the cost of the HTSE process is dominated by SOEC performance, extending its useful service life will decrease the cost of hydrogen production to a greater degree than by improving any other component. The historically demonstrated HTSE SOEC performance, as measured in degradation rate is 8.2% per 1,000 hours based on SOEC test results in 2009. This equals about 5 months before the hydrogen production decreases to 70% of initial capacity. Currently demonstrated SOEC cell performance by other researchers is about 2% per 1,000 hours, or over 20 months of useful service life.

Pilot Plant Scale Demonstration (TRL-6)

Pilot Scale System Description INL is providing a state of the art Testing and Demonstration Facility (T&DF) in Idaho Falls, Idaho near University Boulevard to be completed in 2012. It is anticipated that HTSE process pilot scale testing will be conducted in this facility. The key parameter is to utilize up to 200 kWe power. One of four high-bays will be made available with 40 foot clear space ceilings and approximately 3200 ft^2 (40' x 80') of floor space. Other back-up facilities have been identified but they may have limitations regarding electrical capacity and ceiling height.

Pilot Scale Cost Pilot scale planning level estimates are shown in Table 4. And the corresponding cost profile is shown in Figure 4.

Table 4. Pilot scale estimated costs.

(In $1000)			FY-2011	FY-2012	FY-2013	FY-2014	FY-2015	FY-2016	FY-2017	FY-2018
Unescalated Costs (2010 $)	% of Total	Total								
R&D										
R&D	69%	15500	500	5000	6000	4000				
Operations	31%	7000				2000	2000	2000	1000	
Total	100%	22500	500	5000	6000	6000	2000	2000	1000	
Engineering										
PM & Safety Authorization	9%	3700	100	200	2000	1400				
Design	16%	6500	1000	1000	1000	1000	1000	1000	500	
Construction & Installation	17%	7000			6000	1000				
Procure Stacks	50%	20000			10000	10000				
Start-up	7%	3000			1000	2000				
Total	100%	40200	1100	1200	20000	15400	1000	1000	500	
Summary			**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**
R&D		$22,500	500	5000	6000	6000	2000	2000	1000	0
Engineering		$40,200	1100	1200	20000	15400	1000	1000	500	0
Total		**$62,700**	**$1,600**	**$6,200**	**$26,000**	**$21,400**	**$3,000**	**$3,000**	**$1,500**	**$0**

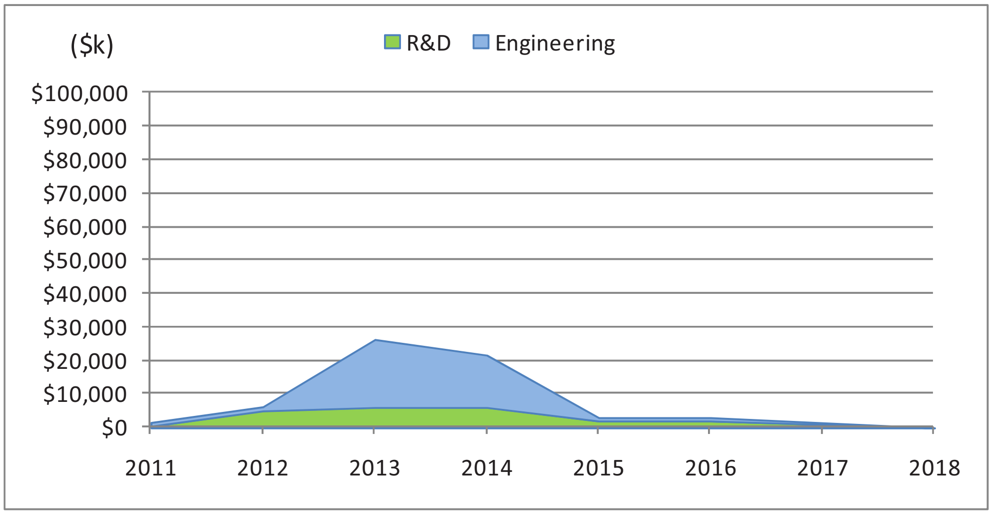


Figure 4. Pilot scale cost profile.

Engineering Scale (TRL-7)

Engineering System Description Although it may be possible to reconfigure the pilot scale test in T&DF to accommodate larger cells, stacks and modules, it is assumed that a new facility will be required for this demonstration. The key sizing parameter is that the SOECs will utilize up to 5 MWe power.

Engineering Scale Cost Engineering scale planning level estimates are shown in Table 5, and the corresponding cost profile is shown in Figure 5. There is greater confidence in the pilot scale cost estimate and the DEI NOAK estimate than there is for the engineering scale estimate because the pilot scale work is nearer term and can be based on costs associated with the already-constructed and operated integrated laboratory scale experiment at BCTC. The DEI NOAK cost estimate is based on recent inquiries of vendors based on a potential HTSE process configuration.

Table 5. Engineering scale estimated costs.

(In $1000)			**FY-2014**	**FY-2015**	**FY-2016**	**FY-2017**	**FY-2018**	**FY-2019**	**FY-2020**
Unescalated Costs (2010 $)	% of			PP		Engr			
	Total	Total							
R&D									
R&D	48%	12000	2000	3000	4000	3000			
Operations	52%	13000				4000	4000	3000	2000
Total	100%	25000	2000	3000	4000	7000	4000	3000	2000
Engineering									
PM & Safety Authorization	9%	10600	100	1500	5000	4000			
Design	12%	13500	1000	5000	4000	1000	1000	1000	500
Construction & Installation	27%	31000		8000	15000	8000			
Procurement Stacks	47%	54000			27000	27000			
Start-up	5%	6000			2000	4000			
Total	100%	115100	1100	14500	53000	44000	1000	1000	500
Summary			**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
R&D		$25,000	2000	3000	4000	7000	4000	3000	2000
Engineering		$115,100	1100	14500	53000	44000	1000	1000	500
Total		**$140,100**	**$3,100**	**$17,500**	**$57,000**	**$51,000**	**$5,000**	**$4,000**	**$2,500**

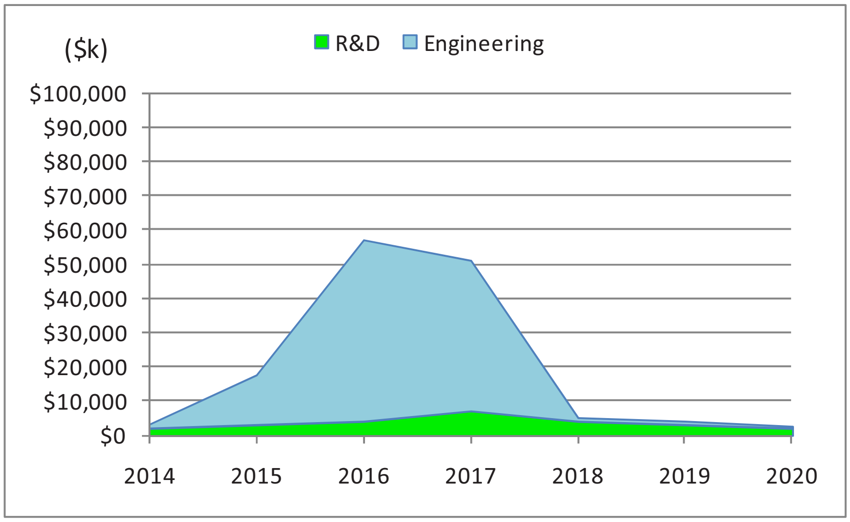


Figure 5, Engineering scale cost profile.

Capacity adjustments were based on the six-tenths factor rule:

$$C2 = C1\,[q2 / q1\,]^{\,n}$$

Where:

$C_1 =$ the cost of the equipment item at capacity q_1

$C_2 =$ the cost of the equipment at capacity q_2

n = the exponential factor, which typically has a value of 0.6 (see *Plant Design and Economics for Chemical Engineers (5th Edition)*, New York: McGraw Hill, 2002).[3]

Using this rule of thumb, scaling up the cost of the pilot scale to the engineering scale based on hydrogen production increases (from 50 to 250 Nm^3/hr) indicates an engineering cost of $106M. This is consistent with the $115M estimated capital cost for the engineering scale demonstration.

It should be noted that the cost of the actual SOCEs (not including the pressure vessels, manifolds, etc.) is more likely to be linear, as a function of scale, than follow the 0.6 rule.

Prototype Scale Demonstration (TRL-8)

Because scaling (based on power usage) between TRL-7 and TRL-9 is an order of magnitude, and similar to previous scale-ups, a separate demonstration for TRL-8 is not planned. The design concept is that the pressure vessels that house the SOEC stacks will be sized to allow transport by conventional trucks. Increasing the scale (including power usage) can be accomplished by increasing the number of modules. It is planned that the component integration requirement for TRL-8 will be accomplished at TRL-7 and that TRL-8 will be achieved when the TRL-9 design is complete. No separate costs are estimated for accomplishing TRL-8 because these costs are included in the previous and subsequent TRL costs.

NGNP Operational Scale FOAK Demonstration (TRL-9)

TRL-9 is achieved when the HTSE process is integrated with the NGNP and begins full hot startup. Because of the modular nature of the HTSE process, it may be possible to demonstrate commercial viability as soon as TRL-7. The TDRM and TRL process define subsequent demonstrations at component, sub-system and system scales, and the HTSE process modules could be industry-ready earlier than 2021.

A FOAK demonstration is generally more costly than subsequent deployments because:

- Some FOAK technologies are not successful
- Some FOAK technologies will be over-designed such that subsequent costs can be reduced without impacting safety or performance
- Subsequent procurements will benefit from economy of scale as suppliers improve manufacturing and fabrication techniques
- Subsequent procurements will benefit from increased competition from more suppliers as the risk of supplying is reduced

No estimate of costs is provided for this scale due to the uncertainty of technical detail and the distant time for demonstration (10 years from now).

Life-Cycle Cost Estimate Conclusions & Recommendations

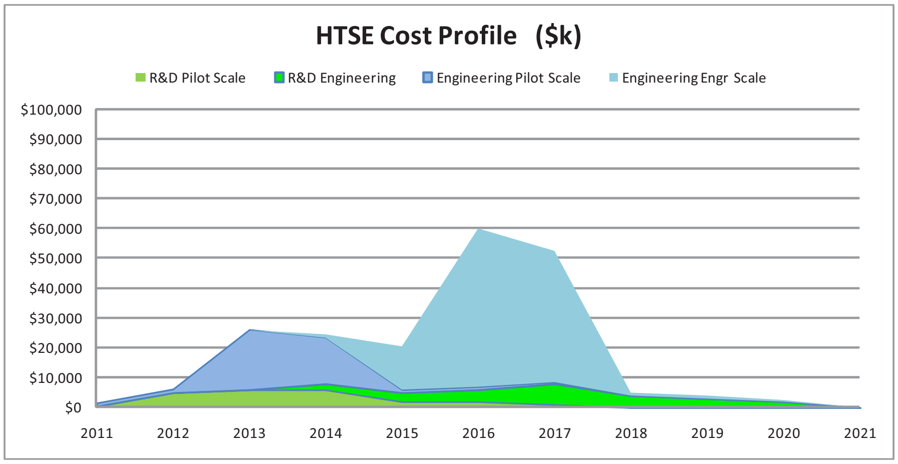
The estimates represented in this report are considered Class 5 estimates in accordance with recommended practices and procedures provided by the Association for Advancement of Cost Engineering International (AAECI). What this means is that the estimates are very uncertain and should only be used for concept screening or feasibility evaluations. This type of estimate is based on a level of project definition (expressed as a percentage) that is less than 2%. Therefore, these cost estimates provide possible categories, amounts, and timing of funding needed to demonstrate the HTSE process through NGNP demonstration. They present a preliminary basis for life-cycle planning, and will be updated as the HTSE process advances through progressive TRLs.

Table 6 represents a high-level breakdown of the total program costs associated with HTSE process R&D and NGNP Engineering deployment. These costs are assumed to spread over 15 years, from FY 2012 through FY 2024.

A composite of these costs is shown graphically in Figure 6, Composite HTSE Cost Profile.

Table 6. Summary of total HTSE program costs.

Scale (TRL)	R&D & Operations ($M)	Engineering/Capital ($M)	Total ($M)
Pilot (TRL-6)	23	40	63
Engineering (TRL-7)	25	115	140
Total	48	155	203



R&D	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	Total
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
Total												202800

Figure 6. Composite HTSE Cost Profile

Summary

The RAM analysis identified which components had the greatest impact on HTSE process availability and indicated that the HTSE process could achieve over 90% availability at TRL-10, which is the NGNP target availability at the NOAK commercial demonstration. This result assumes that the current failure rates of major process components will be advanced so that these rates will be typical of the performance of NGNP components to be operated at higher temperatures and pressures. Although the milestone for this report specifies a RAMI Analysis, inspection (the "I" in RAMI) was not included due to the lack of specific design details. Subsequent studies will determine the tradeoff between additional technology development versus the degree of redundancy required to ensure the deployed system is commercially viable.

The second study developed a series of life-cycle cost estimates for the various scale-ups required to demonstrate HTSE process viability. They are considered Class 5 estimates in accordance with the Association for Advancement of Cost Engineering International (AAECI). What this means is that the estimates are very uncertain and should only be used for concept screening or feasibility evaluations. This type of estimate is based on a level of project definition (expressed as a percentage) that is less than 2%. Therefore, these cost estimates provide only possible categories, amounts, and timing of funding needed to demonstrate the HTSE process. They present a preliminary basis for life-cycle planning, and will be updated as the HTSE process advances through progressive TRLs. The total potential programmatic cost estimate is about $200M for R&D and Engineering (capital) costs for TRLs 6 and 7. Based on the lack of technical design detail, this cost estimate could easily vary by minus 50% to plus 100%.

Both studies were useful in identifying near- and long-term efforts necessary for successful HTSE process deployment. The size of demonstrations to support scale-up was refined, which is essential to estimate near- and long-term cost and schedule.

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Biography

Charles Park is a Registered Professional Engineer (PE) who has worked at the Idaho National Laboratory (INL) since 1982, with an emphasis in Systems Engineering and Project Management. He currently supports the Next Generation Nuclear Plant (NGNP) and the production of hydrogen using nuclear power. He is also a Certified Systems Engineering Professional (CSEP) with the International Council on Systems Engineering (INCOSE) and a certified Project Management Professional (PMP)with the Project Management Institute (PMI). Charles helped oversee construction of the Columbia Generating Station (a General Electric 1100 MW Boiling Water Reactor) near Richland, Washington, and was a project engineer with a regional consulting engineering firm before that. He has a Bachelor of Science degree in Civil Engineering from the University of Idaho, and his essential skill is coaxing order out of chaos.

Emmanuel O. Opare received a B.S in Mechanical Engineering from Brigham Young University-Idaho and has working experience in Venture Capital, Entrepreneurship, Manufacturing and Systems Engineering. Currently a Systems Engineer at the Idaho National Lab, he supports the Next Generation Nuclear Plant (NGNP) project with Systems Engineering activities like Risk Management and Analysis, Requirements Management and RAM Analysis.

Emmanuel is a member of American Society of Quality Engineers (ASQ) and INCOSE and has research interests in strategic management, operational research, system reliability, and adaptation of biological designs to physical systems (Biomimicry). Emmanuel is also a sculptor by talent.