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FY09 Projected Hydrogen Cost Estimates for Nuclear Hydrogen Initiative Baseline Processes

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FY09 Projected Hydrogen Cost Estimates for Nuclear Hydrogen Initiative Baseline Processes

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Abstract

DOE NE's Nuclear Hydrogen Initiative (NHI) has been investigating High Temperature Electrolysis and thermo-chemical processes (Sulfur-Iodine and Hybrid Sulfur) for hydrogen production using the Next Generation Nuclear Plant (NGNP). This report summarizes the analysis done to establish a consistent cost framework for the evaluation of the economic potential of these processes as a key input to DOE NE technology prioritization and selection decisions. The NHI analysis is based on the H2A Production Analysis Program developed by the DOE Office of Energy Efficiency and Renewable Energy (EERE). The NHI FY09 cost analysis utilized pre-conceptual design information developed in the NGNP Project's Hydrogen Alternatives Study (led by Shaw Energy & Chemicals) as well as inputs from the NHI technology development groups. The estimates of hydrogen production costs range from 4 \$/kg to more than 7 \$/kg, with high temperature electrolysis generally resulting in the lowest estimated production costs.

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Nomenclature

ASR	Area Specific Resistance
ATR	Autothermal Reforming
BUN	Bunsen Reaction System
CEA	Commissariat a l'Energie Atomique
CECPI	Chemical Engineering Plant Cost Index
DCF	Discounted Cash
DOE	Department of Energy
EE	DOE office of Energy Efficiency and Renewable Energy
FE	DOE office of Fossil Energy
EERE	Energy Efficiency and Renewable Energy
EIA	US DOE Energy Information Agency
ELE	Electrolysis Section
FUS	Feed Purification
GA	General Atomics
HAD	HI Decomposition Systems
HHV	Higher Heating Value
HI	Hydrogen Iodide
HPAS	Hydrogen Plant Alternatives Study
HPS	Hydrogen Production System
HRS	heat Recovery System
HTGR	High Temperature Gas-Cooled Reactor
HTSE	High-Temperature Electrolysis
HyS	Hybrid Sulfur
ILS	Integrated Laboratory Scale
INL	Idaho National laboratory
INERI	International Nuclear Energy Research Initiative
IPE	Icarus Project Estimator
IRR	Rate of Return
IRS	Internal Revenue Service
O&M	Operations & Maintenance page 11 & 19
MACRS	Modified Accelerated Cost Recovery System
NE	DOE office of Nuclear Engineering
NEA	Nuclear Energy Agency page 21
NGNP	Next Generation Nuclear Plant
NHI	Nuclear Hydrogen Initiative
NHSS	Nuclear heat supply system
OTM	Oxygen Transport Membranes
PEM	Polymer electrolyte membrane
PFD	Process Flow Diagram
POX	Partial Oxidation
PPU	Product Purification

ROT **Reactor Outlet Temperatures** SAD Sulfuric Acid Decomposition DOE office of Science SC S-I Sulfur-Iodine Steam-methane reforming SMR Savannah River national Laboratory SRNL Technology Readiness Levels TRL Westinghouse Electric Company WEC ZnO Zinc Oxide

FY09 Projected Hydrogen Cost Estimates for NHI Baseline Processes

Prepared for DOE NE's NHI Program Under Contract to SANDIA NATIONAL LABORATORIES

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Executive Summary

Department of Energy (DOE) Nuclear Engineering's (NE) Nuclear Hydrogen Initiative (NHI) has been investigating several promising methods for hydrogen production with nuclear energy as part of the Department's overall hydrogen program activities. The primary candidates under development are high temperature thermo-chemical based processes (Sulfur-Iodine and Hybrid Sulfur) and high temperature steam electrolysis. The intent of the overall NHI effort was to establish the most promising and cost effective means of hydrogen production using nuclear energy. The nuclear reactor heat source for these processes is the High Temperature Gas-Cooled Reactor (HTGR) system, which is under development by the Department's Next Generation Nuclear Plant (NGNP) Project.

Although these advanced processes are in an early development stage, it is essential that a consistent framework and methodology of evaluating the economic potential of these processes be established to assist in the prioritization of limited development funds and the selection of the most promising processes for demonstration and deployment. Ultimately the objective of the evaluations is to compare the costs of hydrogen production between processes as a critical component in technology selection decisions and to determine which of these processes are potentially the most cost effective and therefore should be considered for development priority.

The development of a framework for data and analysis leverages the experience gained in hydrogen production cost studies coordinated through the H2A Hydrogen Analysis Program of the DOE Office of Energy Efficiency and Renewable Energy (EERE). The H2A tool takes as input the capital and operating cost estimates for a given hydrogen production process. This technical input is combined with set economic parameters. The figure of merit that is the output from the calculation is a necessary selling price for hydrogen in dollars per kilogram that satisfies the cost inputs and economic parameters.

NHI Cost Framework Study Objectives

The objective of the effort is to provide a consistent and transparent framework and methodology for economic assessments of the NHI technologies. Intended applications include:

- Assess the comparative costs of hydrogen production processes to support technology demonstration sequence and/or down-select decisions.
- Support tradeoff studies to optimize the design and the allocation of limited R&D resources.
- Understand relative cost and risk (uncertainty) drivers as guide to R&D resource allocation.
- Assess pertinent market issues and uncertainties as a further guide to R&D.

The nuclear hydrogen production framework can also be used to assess tradeoffs between component cost, performance, Operations & Maintenance (O&M) cost, fuel cycle cost, lifetime and other factors affecting the cost of hydrogen and hence guide related R&D funding priorities. Further, market entry challenges associated with product introduction and higher initial costs and risks will be assessed to gain insights for mitigating strategies for such challenges.

Initial Cost Framework Analyses

The initial adaptation and application of this framework to NHI processes was based on early versions of the thermo-chemical and high temperature electrolytic processes being evaluated by NHI. Those results provided a starting point that was intended to be updated on a continuing basis as results become available from the research program or other sources. First versions of the framework for evaluation took into account the capital cost elements and the operating and maintenance costs of the hydrogen process plant concepts as estimated based generally on inputs from the three technology development groups. The results of these initial analyses based on a mature plant design and optimized efficiency were generally in the range of 3.00 to 3.50 \$/kg of hydrogen for all processes. Due to the early state of development, these inputs had associated with them wide ranges of uncertainty. In addition to the technical uncertainty factors, additional uncertainty was due to the key technical input data coming from three separate sources.

FY09 NHI Cost Framework Study Approach

The NHI cost framework study in FY08 and FY09 utilized information that was developed in the NGNP Project's Hydrogen Alternatives Study which was completed in January of FY09. This study (from a team led by Shaw Energy & Chemicals) developed conceptual designs for the three baseline NHI processes and estimated system performance, capital costs and operating costs to arrive at an estimated selling price of hydrogen produced. The NGNP study focused on the costs and performance of the three baseline processes in the timeframe of the initial operation of the NGNP (early 2020's). The study near term designs led to fairly conservative estimates of system efficiencies and costs. The original intent of this study was to provide a consistent starting point for subsequent iterations to examine the cost drivers and performance improvement. These follow on iterations will not be able to be conducted due to changes in Program directions and funding limitations. However, the NGNP study provided a systematic and consistent estimate of materials and component costs which were subsequently used by the NHI process teams later in FY09 to estimate costs due to changes in materials or energy costs or system performance. These alternative analyses are also summarized in this report and are compared to the original NGNP study results.

NGNP Hydrogen Plant Alternatives Study

The Westinghouse NGNP team Hydrogen Plant Alternatives Study resulted in a set of pre-conceptual/conceptual designs for the three NHI production technologies prepared by the same team and more reliably to the same level of detail with the same underlying assumptions. The study incorporated the most up to date inputs from the three technology development groups, and this input was filtered through critical review by the Shaw team. Their study includes economic data that was intended to feed into the development of the ongoing NHI framework data base that is the subject of the work reported herein. Because it forms the basis for the framework data base and for the economic evaluations in this report, the NGNP Study design work has been summarized in Section 3.

The hydrogen price analysis in the Shaw NGNP study report is a first attempt to compare the three technologies on more uniform basis. The selling prices for hydrogen resulting from that analysis are quite high. The study was an ambitious effort accomplished on a limited budget and a demanding schedule. When the study work was concluded in January there was no opportunity for iteration with the technology development groups. The economic output from the study includes the resulting hydrogen price and selective sensitivity analyses. This included sensitivity to reactor outlet temperature. Although a uniform reactor outlet temperature of 950°C was the given NGNP basis at the time, after the study was concluded other work was initiated giving consideration to lower reactor temperature.

NGNP Study Re-assessment and Additional Cases

The high hydrogen selling cost from the NGNP Study appeared to be a result of some systematic conservatism and several debatable assumptions about the various hydrogen production technologies. A range of alternative designs and cost assumptions were proposed by the NHI process development teams which explored the longer term options and various performance improvement strategies. An alternative set of hydrogen prices for these Re-assessed Cases were calculated.

A final set of further revised economic factors and technical parameters was proposed for calculations to support the NGNP Hydrogen Production System Down-Selection workshop. These Additional Cases are discussed in Section 6.5, and the resulting hydrogen prices for 950°C reactor outlet temperature are also included in Table ES-1.

	Selling Price of Hydrogen (\$/kg H ₂)		
	Re-assessed	Additional (Down-	
	Cases (Case 3)	Selection) Cases	
Sulfur-lodine (S-I)	7.27	5.84	
Hybrid Sulfur (HyS)	4.95	4.69	
High-Temperature Electrolysis (HTSE)	4.23	5.69	

Table ES-1 - Nuclear Hydrogen Prices (950°C ROT)

Comparison between NHI Technologies

The formal approach taken to evaluate nuclear hydrogen technologies provides useful results for comparison of the various technologies.

The range of relative variation in product hydrogen price in the evaluations is the consequence of several factors. One of the most significant is the uncertainty of new technology performance in flow sheets and simulation models that drive the process efficiency. These uncertainties are to be expected at the early development and demonstration phase, and the technology must mature further and simulation models need to be better supported before the uncertainties in product price can converge.

There is a trend, however, that hydrogen selling price is generally lowest for HTSE, intermediate for HyS and usually highest for S-I. As shown in the table above, the S-I process stands out more prominently in analyses using some assumptions and not others.

For the unique and high-technology equipment in the systems – the sulfuric acid decomposer in S-I and HyS and the two different electrolyzers in HyS and HTSE – costs of equipment in the eventual commercial plant are based on development targets and only weakly derived from examination of fabrication technologies and manufacturing details. This is a manifestation of the immaturity of the designs, which need further iteration and refinement within the current development and demonstration phase.

One additional factor is the issue of performance stability and the associated costs for refurbishment, repair or replacement of components with lifetimes shorter than the overall plant. None of the laboratory experiments to date for S-I, HyS or HTSE has run long enough and provided data that can be used to quantify degradation factors or lifetimes. Performance variation with time and limited lifetimes of components can be factored into the analysis, particularly as operating cost and replacement capital inputs.

Comparison to Other Hydrogen Technologies

The nuclear hydrogen technologies can be compared to alternative methods of hydrogen production. Such alternatives are represented by a set of baseline technologies and detailed in Appendix C. One is hydrogen production from ambient temperature electrolysis, and the other is hydrogen production with steam-methane reforming (SMR) using natural gas. The baseline hydrogen production from low temperature electrolysis is further divided into current state-of-the-art low pressure, alkaline electrolysis and a future case with advanced electrolysis.

Figure ES-1 shows the three NHI hydrogen technologies compared to conventional and advanced electrolysis as a function of electricity price. Note that these plots are in terms of today's electricity price escalated going forward at 1% per year, and the hydrogen price is the lifetime levelized value. The cases used for the three nuclear hydrogen technologies are based on those from Section 6.4 as indicated in the figure legend.

As shown in the figure, all of the nuclear technologies produce hydrogen at lower prices for electricity prices above 60 \$/MWh versus advanced electrolysis and above 45 \$/MWh compared to current electrolysis costs.



Figure ES-1 - Hydrogen Prices Compared to Ambient Temperature Electrolysis

The similar comparison to advanced SMR is plotted in Figure 282. Note that these plots are in terms of today's natural gas price escalated at 2% per year, electricity starting at 60 \$/MWe escalated at 1% per year and CO_2 costs as indicated escalated at 1% per year. The nuclear technologies produce hydrogen at lower prices for natural gas prices between 10 and 14 \$/MMBtu for the three nuclear systems. While the price of natural gas has recently gone below 4 \$/MMBtu, the decline is a consequence of the current recession, and futures prices for a year from now are at about 8 \$/MMBtu, Volatility has in the past few years been within the range of 7 to 10 \$/MMBtu with a spike to 12 \$/MMBtu (see Appendix C). Hence, nuclear hydrogen development is a worthy hedge against the uncertainty of such future prices.



Figure ES-2 - Hydrogen Prices Compared to Steam-Methane Reforming

1 Introduction

Department of Energy's (DOE) Nuclear Engineering's (NE) Nuclear Hydrogen Initiative (NHI) is investigating several promising methods for hydrogen production with nuclear energy as part of the Department's overall hydrogen program activities. The primary candidates under development are high temperature thermo-chemical based processes and high temperature electrolytic based processes. There are several other alternative candidates under evaluation with the intent of establishing the most promising and cost effective means of hydrogen production with nuclear energy but these technologies are not as mature and are not considered here. The nuclear reactor heat source utilized in the NHI designs is the High Temperature Gas-Cooled Reactor (HTGR) system, which is being advanced by the Department's Next Generation Nuclear Plant (NGNP) Project.

Although these advanced processes are in an early development stage, it is essential that a consistent framework and methodology of evaluating the economic potential of these processes be established to assist in the prioritization of limited development funds and the selection of the most promising processes for demonstration and deployment.

1.1 *NHI Framework for Economic Evaluation*

Ultimately the objective of the evaluations is to compare the costs of hydrogen production between processes as a critical component in technology selection decisions and to determine which of these processes are potentially the most cost effective and therefore should be considered for development priority.

The development of a framework for data and analysis leverages the experience gained in hydrogen production cost studies coordinated through the H2A Hydrogen Analysis Program of the DOE Office of Energy Efficiency and Renewable Energy (EERE). The H2A tool takes as input the capital and operating cost estimates for a given hydrogen production process. This technical input is combined with set economic parameters. The figure of merit that is the output from the calculation is a necessary selling price for hydrogen in dollars per kilogram that satisfies the cost inputs and economic parameters.

The initial adaptation and application of this framework to NHI processes was based on early versions of the thermo-chemical and high temperature electrolytic processes being evaluated by NHI. Those results provided a starting point that is intended to be updated on a continuing basis as results become available from the research program or other sources. Although it is still early in the development process, these ongoing efforts to provide an integral cost metric are one of several key inputs needed to support R&D decisions in the near-term.

1.2 Scope of This Report

This report provides the updated status as of September 2009 of the NHI framework, and also updates the cost projections based on the latest information provided by the

NHI research program and by the DOE's NGNP program. The report is the final status report for the work under the present contract/purchase order.

The general outline of the report is as follows.

- Review of past work and additional inputs since the last report [Ref. 1]
- Discussion of the conceptual design work done recently under the DOE's NGNP Project and associated hydrogen economic analyses [Ref. 2]
- Recapitulation of the economic analysis approach and method
- Results of analysis from the DOE's NGNP Project hydrogen study
- Revised hydrogen price calculations for Re-assessed Cases after further consideration of the NGNP hydrogen study results
- Additional Cases for the NGNP Down-Selection Review [Ref 3]
- The resulting cost framework data base
- Conclusions

The list of relevant processes under evaluation in the NHI and their acronyms used in this report are shown in Table 1.

	Acronym
Sulfur-Iodine Thermo-chemical - Reactive Hydrogen Iodide (HI) Distillation	S-I
High Temperature Steam Electrolysis	HTSE
Hybrid Sulfur Thermo- Electro-Chemical	HyS

Table 1 - Nuclear Hydrogen Technologies Evaluated

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2 Background

2.1 Objectives

The objective of the effort is to provide a consistent and transparent framework and methodology for economic assessments of the NHI technologies. Intended applications include:

- Assess the comparative costs of hydrogen production processes to support technology demonstration sequence and/or down-select decisions.
- Support tradeoff studies to optimize the design and the allocation of limited R&D resources.
- Understand relative cost and risk (uncertainty) drivers as guide to R&D resource allocation.
- Assess pertinent market issues and uncertainties as a further guide to R&D.

The nuclear hydrogen production framework can also be used to assess tradeoffs between component cost, performance, O&M cost, fuel cycle cost, lifetime and other factors affecting the cost of hydrogen and hence guide related R&D funding priorities. Further, market entry challenges associated with product introduction and higher initial costs and risks will be assessed to gain insights for mitigating strategies for such challenges.

2.2 Earlier Analyses and Data Base Development

Progress on development of the economic analysis framework has been reported annually [Refs. 4, 5 & 1]. Interactions have been continuous with the developers of the three processes under evaluation and with others engaged in the NHI work. The status of the analyses is summarized in terms of the calculated cost of hydrogen for each technology in Table 2.

First versions of the framework for evaluation took into account the capital cost elements and the operating and maintenance costs of the complete nuclear hydrogen plant, the nuclear reactor heat source and the hydrogen process plant. For the version herein, it was decided to model only the hydrogen process plant and to consider the costs of heat and electricity to the process as fixed inputs in terms of dollars per megawatt hour (\$/MWt-h and \$/MWe-h). In the analysis, the heat and electricity to drive the process would be much like fixed operating costs.

Electric energy was priced for reference cases at 60 \$/MWe-h. This value represents the estimated cost of electricity in 2007 dollars from a power plant that would be built today in the current economic and regulatory environment. A range of electric cost from 55 to 75 is used in the sensitivity calculations. These are approximately -10% and +25% and reflect an expectation that electricity costs have a higher up-side uncertainty.

Thermal energy cost is set for reference at 20 \$/MWt-h. This has been calculated from the HTGR plant cost portion of the GA/INL cost tabulation for the S-I plant with reactive HI distillation [Ref. 6]. For sensitivity calculations a low range of 18 \$/MWt-h and a high of 25 \$/MWt-h were used. These are likewise approximately -10% and +25%.

	Earlier Published Estimates	2007 Analysis
Sulfur-lodine HI section: extractive distillation ¹		3.41 \$/kg
Sulfur-lodine HI section: reactive distillation ²	1.95 \$/kg ³	3.05 \$/kg
High-Temperature Electrolysis	1.92 \$/kg ⁴	3.22 \$/kg
Hybrid Sulfur	1.60 \$/kg ⁵ 2.50 \$/kg ⁶	2.94 \$/kg

 Table 2 - Results of Analyses up to the Current Year's Work

¹ International Nuclear Energy Research Initiative (INERI) baseline

² Projected process improvement

³ Ref. 6

- 4 Ref. 7
- ⁵ Ref. 8, electrolyzers 2000 \$/m²
- ⁶ Ref. 9, electrolyzers 2650 \$/m²

In addition to the analyses to produce these results, an initial assembly of an ongoing NHI Component Data Base was done in conjunction with MPR Associates in 2008. The objective of the Data Base is to maintain a continuously updated source of data for additional hydrogen price evaluations with the developing production technologies.

2.3 Recent Work

The work in fiscal year 2009 has concentrated on the integration of the resulting partial conceptual process system designs from the NGNP Hydrogen Plant Alternatives Study [Ref. 2] into a Data Base. Additionally, after that study was completed, the review and evaluation of its resulting cost analysis, as described in this report, were conducted.

A paper was presented at the _____(NEA) Fourth Information Exchange Meeting on the Nuclear Production of Hydrogen in 2009 [Ref. 10] on the initial evaluation of the NGNP Study as fully discussed in this report.

Support was given to the NGNP Hydrogen Production Technology Down-Selection Review Team [Ref. 3], as discussed in Section 6.5.

3 NGNP Hydrogen Plant Alternatives Study

As part of the DOE's NGNP Program, the Westinghouse NGNP team was tasked in 2008 to prepare a Hydrogen Plant Alternatives Study [Ref 2]. The objective of the study was to provide a basis for the further development through assessment of the commercial potential and the technology readiness of the same three hydrogen production technologies in the NHI program, as itemized in Table 1. A team experienced in petrochemical plants from design through construction at Shaw Energy & Chemicals led the task. The Shaw group is a member of the Westinghouse NGNP team. This work is alternatively referred to herein as the "NGNP Study" or the "Shaw Study".

Each hydrogen production technology was to be approached on the same basis. Although the study included additional quantitative and subjective assessments, including for example technology readiness assessments, a significant part of the study consists of analysis of hydrogen selling price and supporting bases for the data used in that analysis.

3.1 *Process Flow Sheets*

The first step in the NGNP Study was to build three simulation models of the hydrogen production system cycles from scratch but based on input gathered from published reports and the work of the technology developers. In general, the assumptions made by the technology developers in their modeling were judged optimistic, particularly in regard to the capability of industrial heat transfer equipment, and consequently process cycle efficiencies were in all three cases lower than those published earlier. The Shaw engineers then developed three process flow sheets, with unit operation and stream flow parameters, from the simulations.

The process flow sheets and further details are found in the report of the Hydrogen Plant Alternatives Study [Ref 2].

3.2 Process Flow Diagrams (PFDs) and Sized Equipment Lists

From the flow sheets, PFDs and sized equipment lists were drawn up for submission to Shaw's cost estimators. The PFDs and sized equipment lists are reproduced in the Data Base that has resulted from the work in this report and which is addressed in Section 7.

3.3 Capital Cost Estimates

The capital costs were divided among regular conventional equipment, familiar equipment with unconventional materials and unique equipment for technology in development.

The capital cost estimates are ordered by major subsystem of the candidate process plants. One part is the equipment costs, which is generally the price of purchased items, as described in the following, and the other part is the cost of installation of the

equipment items, which can sometimes be as much as the purchased equipment. Table 3 shows the make-up of the total capital cost, in which Bulk Material is a significant part. Bulk material comprises a large number of accounts, such as site prep & demolition, site improvements, electrical cable (underground and above ground), pipe, pilings, concrete, specialized coatings, structural steel, buildings, instruments, insulation, painting and paving.

Table 3 - Make-up of Capital Costs

Equipment Cost Installation Cost Construction Labor Expenses & Supplies Construction Equipment Vendor Services Bulk Material EPC Engineering Spares Freight Other Costs - Catalyst, Desiccant, *etc*.

3.3.1 Conventional Equipment Estimates

The process plant capital cost for conventional equipment were estimated based on the data Shaw group maintains from its purchase orders for the many energy and petrochemical plants with which it is involved.

3.3.2 Equipment with Unconventional Materials

Certain portions of the process plant, particularly the Hydrogen Iodide (HI) Section of the S-I plant, required highly corrosion resistant pipe or interior lining (of vessels and valves). The equipment selection calls-out tantalum, which along with tungsten, molybdenum, niobium and rhenium are the "refractory metal" elements. (In their S-I system cost estimate, the Commissariat a l'Energie Atomique (CEA) used 99% niobium -1% zirconium alloy instead of tantalum. (See Section 6.3.1.1). Because they are uncommon and typically difficult to machine or weld, the need for refractory metals adds significant expense. Shaw cost estimators had some familiarity with tantalum tubing and less with tantalum linings. A cost driver for the tantalum lining is the thickness of the lining, for which a design basis is not available from actual development of the S-I process.

3.3.3 Technology Development Item Estimates

For the unique and high-technology equipment in the systems, which are itemized in Table 4, costs of equipment in the eventual commercial plant are based on development targets and only weakly derived from examination of fabrication technologies and manufacturing details. This is a manifestation of the immaturity of the designs, which

can be resolved by further iteration and refinement within the current development and demonstration phase.

Table 4 - Technology Development Items

S-I Hydrogen System Sulfuric Acid Decomposer HI Distillation Column

HyS Hydrogen System Sulfuric Acid Decomposer SO₂ Electrolyzer

HTSE Hydrogen System H₂O Electrolyzer High Temperature Heat Exchangers

3.4 *Reference Designs*

Choice of a basis for plant design, particularly plant sizing and interface with the nuclear heat supply system, can be approached differently with different results. One can choose to size the hydrogen process plant to fit one nuclear reactor unit and then increase plant scale by adding nuclear units. In this evaluation, the choice is to set the size of the hydrogen plant at about the output level of the largest hydrogen plant that users would want or that suppliers would build considering present norms of the petrochemical industry. That plant size is approximately 160,000 Sm³/h (142 million scf/d, 343 t/d, 2,000 moles/s, 4.0 kg/s). For that level, depending on the hydrogen process, the HTGR nuclear units are applied in integer numbers to provide the necessary high temperature heat input according to each process. In the model, additional heat available from the HTGR units is converted into electricity in a Rankine cycle with a condensing steam turbine generator system. This electric power is provided to the hydrogen production system. Excess electric power for the hydrogen process is imported from the electric grid.

For the HTGR, a generic nuclear heat supply system (NHSS) was assumed to generate a nominal 550 MWt of heat and deliver helium at 910°C to the process coupling heat exchanger(s) of the process plant. Helium returns to the NHSS in the range of 275 to 350°C. The three hydrogen production technologies from the NHI were as follows:

The S-I cycle includes the feature of a H_2SO_4 decomposer with silicon carbide tubes, as has been developed at Sandia National Laboratories [Ref. 0]. For this decomposer the NGNP Study model takes the design and costing from a variant of the design by Westinghouse [Ref. 12]. The HI section utilizes the reactive distillation option. The process plant is coupled with three NHSSs and produced 176,000 Sm³/h (4.4 kg/s) of hydrogen. Oxygen is sold as a by-product. The process plant used all of the nuclear heat and so no electricity was generated on-site. 330 MWe of grid power was consumed.

The HyS cycle utilizes the same H_2SO_4 decomposer and acid concentration section as the S-I plant. The SO₂ electrolyzers are polymer electrolyte membrane (PEM) technology. The hydrogen plant is coupled to two NHSSs and produces 160,000 Sm³/h

(4.0 kg/s) of product. Oxygen is sold as a by-product. The Rankine "bottoming" cycle generates 133 MWe for the electrolysis section and an additional 198 MWe is imported.

The HTSE cycle is the variant utilizing air sweep on the anode side of the cells. It takes heat from only one NHSS and puts out 160,000 Sm³/h (4.0 kg/s) of hydrogen. The Rankine "bottoming" cycle generates 176 MWe. 365 MWe is taken from the grid. The oxygen by-product is not sold in the reference design because it is diluted with the sweep air, and the market for such "enriched air" would be limited compared to pure oxygen.

3.5 Input Heat and Power Sources

Without reference to a particular HTGR, the cost of nuclear heat was an input parameter of 30 \$/MWt-h. Electricity cost was set based on a 2008 price of 75 \$/MWe-h. The H2A modelling tool, as published, is based on an assumption that all costs and the selling price have the same rate of inflation. However, for the NGNP Study assessments, energy costs are projected to rise more rapidly than general inflation, and so a modification to the H2A model was been made to add this analysis capability. For the analysis, real escalation, over and above any inflation, is included at 1%/yr over the plant life for the electric power bought or sold. The assumed reactor outlet temperature for evaluating component costs and process efficiencies was 950°C.

3.6 System Study Bases

3.6.1 Sulfur-lodine Thermo-chemical Water Splitting

Research and development on the Sulfur-Iodine cycle has be ongoing at General Atomics since the 1970s and more recently in Japan and France [Refs. 13, 14 & 15]. The process technology is presently the subject of the INERI involving the U.S. and France. As research has been providing process advancements and data for better understanding the chemical phenomena, the cycle flow sheet has changed, and at the present time there are two reference flow sheets.

The two flow sheets differ in the hydroiodic acid HI section of the cycle. The technical issue is a method to further separate the constituents of the product stream of the acid formation step (Bunsen reaction) after sulfuric acid is separated. One utilizes reactive distillation to separate the stream products and the other uses extractive distillation.

Extractive HI distillation was selected as the method for further development in the present INERI program [Ref. 16]. This is the cycle on which the S-I Integrated Laboratory Scale (ILS) experiment is based [Ref. 17].

Reactive HI distillation appears from performance models to be more efficient. However the process modeling is not able to confidently account for non-ideal thermodynamics that characterize the chemical reactions. Although subject to experimental work for several years, the reactive distillation step has not been demonstrated. It is notable that an advantage of reactive distillation had appeared to be the lower electric power consumption of the cycle. However, as the modeling and design have progressed, power consumption has increased, lowering the cycle efficiency and bringing it nearly equal to that of the extractive distillation cycle. In initial analysis of the S-I cycle with reactive distillation, the fraction of electric power was as low as 1%, based on electric power at 40% efficiency [Ref. 18].

Systems and major components/subsystems of the S-I hydrogen system are as follows.

- Sulfuric Acid Decomposition Section (SAD)
 - Sulfuric Acid Decomposer scaled with heat transfer area from SiC bayonet tube design by Westinghouse
 - o 2 Trains per 3 Reactor Units, 6 Total SAD Trains
- Bunsen Reaction System (BUN)
 - o Bunsen Reactor
 - o Three-Phase Separator
 - o 1 Train per 3 Reactor Units, 3 Total BUN Trains
- HI Decomposition Systems (HAD)
 - o Reactive Still
 - o Recuperators
 - Process Coupling Heat Exchanger
 - o 1 Train per 3 Reactor Units, 3 Total HAD Trains
- Balance of S-I Plant
 - Feed Purification (FUS)
 - Reactor Products Handling &
 - Product Purification (PPU)
 - Instrumentation and Controls

Figure 1 is a schematic diagram of the overall system model used for the results in Sections 6.2 & 6.4.1.





3.6.2 Hybrid Sulfur Thermo- Electrochemical Water Splitting

The HyS cycle is a two-reaction water splitting process that uses thermal input for oxygen generation at high temperature and a separate low temperature electrolysis step for hydrogen generation. The thermo-chemical step is sulfuric acid decomposition, a step that HyS has in common with the S-I process. The electrochemical step is electrolysis of water and sulfur dioxide in a PEM cell, similar to the PEM fuel cell. R&D to date at Savannah River National Laboratory (SRNL) applies to the demonstration of the electrolysis cell.

System modelling was done in the 1980s by Westinghouse Electric Company (WEC), in whose laboratories in the U.S. the cycle was first experimentally investigated. (HyS is sometimes referred to as the "Westinghouse hybrid cycle".) Work on this process was suspended after initial success and was re-initiated in 2003. An integrated detailed flow sheet is being developed by WEC and SRNL with the benefit of improved thermodynamic data. However, while some results from this work concerning the flow sheet and thermodynamic performance have been published [Ref. 9], published cost data is limited.

Systems and major components/subsystems of the HyS hydrogen generation system are as follows.

- SAD
 - Sulfuric Acid Decomposer scaled with heat transfer area from Si-C bayonet tube design by Westinghouse
 - o 2 Trains per 2 Reactor Units, 4 Total SAD Trains
- Electrolysis Section (ELE)
 - SO₂ Electrolyzers
 - 192 electrolysis modules plus 48 spares
 - A module contains 200 cells
 - Each cell is 1 m2 in area for a total of 200 m² of cell area per module
- Other Process System Sections
 - o FUS
 - o PPU

Figure 2 is a schematic diagram of the overall system model used for the results in Sections 6.2 & 6.4.2.



Figure 2 - HyS Base Case

3.6.3 High Temperature Steam Electrolysis

Several different flow sheets and heat balances have been proposed for the HTSE cycle and its coupling to an HTGR heat source. These differ only slightly in contrast to the significant process differences between the two S-I variants. HTSE work at Idaho National Laboratory (INL) has concentrated on progressive development and testing of the cells, stacks of cells and modules of stacks. System design has generally addressed an ILS experiment.

A number of flow sheets for the cycle with the nuclear heat source have been proposed [Refs. 19 through 25]. HTSE flow sheets can differ as to the sweep gas on the O_2 output (anode) side of the cell, the optimum temperature of the HTSE cell for a given nuclear heat source maximum temperature and the general arrangement of the heat transport between the heat source and the process plant.

Systems and major components/subsystems of the HTSE hydrogen generation system are as follows.

- ELE
 - o Sweep Gas Coupling Heat Exchanger
 - Process Coupling Heat Exchanger (Steam Generator)
 - Solid Oxide Electrolyzers
 - 68 electrolysis modules plus 8 spares
 - A module contains 4 stacks of 2,500 cells
 - Each cell is 50 cm x 50 cm in area for a total of 2,500 m² of cell area per module
- Other Process System Sections
 - o FUS
 - Heat Recovery System (HRS)
 - o PPU

Key features of the HTSE Hydrogen Production System (HPS) are as these:

- Air sweep on anode side of cells
- Oxygen byproduct not valued because of dilution
- Uncertainty in water and air purity requirements; Feed and process purification systems included
- Electrolyzer operating temperature: 800°C, Feed supply temperature: 870°C, (ROT = 950°C)
 - o Electrolysis is between adiabatic and "thermo-neutral"
 - Sensible heat in both feed streams used to partially provide entropic heat:
 - from feed heating 23%
 - from steam/H₂ 14%
 - from sweep air 8%
 - from Joule heating in cells 77%

Figure 3 is a schematic diagram of the overall system model used for the results in Sections 6.2 & 6.4.3.





3.7 Operating& Maintenance Cost Estimates

The operating and maintenance cost factors used in the NGNP Study cost analyses are summarized as follows for the three production technologies.

3.7.1 For Sulfur-lodine HPS

The operating and maintenance cost factors for the S-I hydrogen production system are these:

- Staff requirements (4 shifts/day):
 - Maintenance staff requirements:
 - 4 maintenance personnel per shift (mechanical, electrical, controls) plus
 - 4 day shift only

- Operating staff requirements:
 - Water treatment: 1 operator per shift
 - Decomposition: 4 operators per shift
 - Bunsen and HI : 3 operators per shift
 - Management: 1 Plant manager, 1 Assistant, 1 Engineer and 1 Administrator
- Maintenance
 - Annual Fixed O&M
 - 0.5% of Direct Capital (excepting SAD)
 - o Annual Variable O&M
 - Feed Water
 - Process Steam
 - Make-up Catalyst
 - Cooling Water
 - Iodine
 - o Replacements
 - Decomposer Tubes 20% (2250 tubes) every 2 years
- Waste disposal
 - Water treatment wastes
 - o lodine contamination

3.7.2 For Hybrid Sulfur HPS

The operating and maintenance cost factors for the HyS hydrogen production system are these:

- Staff requirements (4 shifts/day):
 - Maintenance staff requirements:
 - 4 maintenance personnel per shift (mechanical, electrical, controls) plus
 - 8 day shift only
 - Operating staff requirements:
 - Water treatment: 2 operator per shift
 - Decomposition: 2 operators per shift
 - Electrolysis: 2 operator per shift
 - Management: 1 Plant manager, 1 Assistant, 1 Engineer and 1 Administrator
- Maintenance
 - o Annual Fixed O&M
 - 0.5% of Direct Capital (excepting ELE & SAD)
 - Annual Variable O&M
 - Make-up Catalyst
 - Zinc Oxide (ZnO) (for waste neutralization)
 - Make-up Acid and Caustic
 - o Replacements
 - Decomposer Tubes 20% (2250 tubes) every 2 years
 - SO2 Electrolyzers
 - Replace 20% of cells completely every year

- Refurbish (i.e.- replace damaged cells in cell assemblies in seven more modules every year.
- Replace all modules at 20 years
- o Waste disposal
 - Water treatment wastes
 - Sulfur dioxide and blowdown neutralization

3.7.3 For HTSE HPS

The operating and maintenance cost factors for the HTSE hydrogen production system are these:

- Staff requirements (4 shifts/day):
 - Maintenance staff requirements:
 - 5 maintenance personnel per shift (mechanical, electrical, controls) plus
 - 4 day shift only
 - Operating staff requirements:
 - Water treatment: 1 operator per shift
 - Heat Recovery: 2 operators per shift
 - Electrolysis: 2 operator per shift
 - Management: 1 Plant manager, 1 Assistant, 1 Engineer and 1 Administrator
- Maintenance
 - Annual Fixed O&M
 - 0.5% of Direct Capital (excepting ELE)
 - o Annual Variable O&M
 - o Replacements
 - High Temperature Heat Exchangers 15 years
 - High Temperature Pipe 15 years
 - Electrolyzers
 - Assemblies: 7 (10%) refurbished every year
 - Cells: 4 additional stacks (6%) replaced every year
 - Enclosures: 2 (3%) replaced every year
 - o Waste disposal
 - Water treatment wastes

3.8 Other Factors

An additional factor not directly resolved in the current analyses is the issue of performance stability and the associated costs for refurbishment, repair or replacement of components with lifetimes shorter than the overall plant. None of the laboratory experiments to date for S-I, HyS or HTSE has run long enough and provided data that can be used to quantify degradation factors or lifetimes. Performance variation with time and limited lifetimes of components can be factored into the analysis, particularly as operating cost and replacement capital inputs, but this has not yet been done for lack of that data.

4 Analysis Input Data and Methods

4.1 H2A Modeling Tool

In 2005, DOE organized the H2A Production Analysis Program, which is further described in Appendix A. The primary objectives of that effort were as follows:

- Improve the consistency and transparency of the ground rules and assumptions for the economic analyses of hydrogen systems within the DOE hydrogen programs, as well as within related industry programs. (The specific economic ground rules are addressed in Appendix B.)
- Develop a tool for consistent analyses and reporting of the economics of hydrogen production and delivery systems, as well as for R&D direction and portfolio analyses.
- Validate the consistent ground rules, assumptions and analyses methodology through deliberations with a select group of key industrial collaborators, including nuclear utility and vendor representatives.

The H2A model is a spreadsheet-based (Microsoft Excel[®]) calculation tool which gives the required selling price of hydrogen for the input capital and operating cost factors for a hydrogen production plant and for the specified economic parameters, including the rate of return on investment. Specifically, the model may be applied for the integrated energy supply and process plant for hydrogen production, or the input energy to the plant may be generalized in terms of costs for heat in \$/MWt-hr and costs for electric power in \$/MWe-hr.

4.2 H2A Revision

In 2007, DOE reconvened the H2A participants to review and refine the modeling tools and update the cases to be modeled. Refinements to the modeling tools were to be based on improvements for convenience and small errors found in the interim by users and by the original developers. For example, input from nuclear developers identified refinements needed for the handling of interest during construction and the timing of accounting for debt. The refined H2A tool has since been published on the Internet by NREL [Ref. 26]. This version was used in the analyses reported herein.

4.3 Economic Parameters

The calculations generally use the H2A ground rules (economic drivers and other parameters) that are itemized in Appendix B. The more significant assumptions for the analyses are given in Table 5.

Table 5 - Major Assumptions for Analysis of Economics

Reference Dollar Year	3nd Quarter 2008
Assumed Start-up Year	2030
Plant Location	US Gulf Coast

Plant Maturity Assumption Financing

After-Tax Real IRR

Project Overall Capital

Nth of a kind plant 100% Equity 10% (equivalent to D/E = 75/25 with 20% IRR and 10% debt rate)

10%

Contingency Plant Life 30 years Lifetime Capacity Factor 8,200 hr/yr (93.5%) Construction Period 3 years 25% / 40% / 35% Costs in Construction Years Start-up Period 1 year Income Tax Rate (composite) 38.9% Depreciation 20 yr, MACRS Property Tax Rate 1% of Overnight Capital Cost 1% of Overnight Capital Cost Insurance Rate As scheduled + 0.5% per year Capital Replacement 15% of Change in Annual Operating Working Capital Costs

5 Results: Life-Cycle Cost of Hydrogen

The reader is referred to the Westinghouse NGNP Hydrogen Plant Alternatives Study [Ref. 2] for a complete presentation of the study.

5.1 NGNP Study Base Case Results

A levelized selling price for hydrogen over the plant lifetime is calculated using the H2A analysis for each technology – Sulfur-Iodine, Hybrid Sulfur and High Temperature Steam Electrolysis. The reference case costs are for the hydrogen product with 1%/yr electricity cost escalation, credit for the parallel production of oxygen and 100% equity financing at 10% IRR. The levelized hydrogen selling prices for the reference case for each plant are summarized in Table 6, along with the prices for the alternate parameters.

	Levelized Selling Price of Hydrogen (\$/kg H ₂)		
	Sulfur-Iodine	Hybrid Sulfur	High Temperature Steam Electrolysis
Reference Cases	10.71	6.83	6.04
Excluding Electricity Cost Escalation	10.12	6.43	5.31
Excluding O ₂ Credit	11.09	7.21	Reference Case has no O_2 Credit

5.2 Sensitivity Analyses

In the NGNP Hydrogen Plant Alternatives Study [Ref 2], sensitivity analyses were included. These are reproduced here. The price values are in all cases centered on the price shown as the Reference Cases in Table 6. Although in later sections of this report various other hydrogen prices are presented, those would in general show the same relative sensitivities as are presented in these plots.

Variations were made to the key input parameters for estimated 10% and 90% probability indicative limits. The parameters considered key are the following.

Capital Costs:

• Overall, of Major Sections, of Major Equipment

Finance / Performance Variation

- After-Tax Real IRR 8%, 10%, 12% (100% Equity)
- Capacity Factor 85%, 94%
- Process Output base and x2
- With and without CO₂ avoidance credit

Power Input

- Thermal Power Cost 25 \$/MWt-h, 30 \$/MWt-h, 35 \$/MWt-h
- Electric Power Cost 65 \$/MWe-h, 75 \$/MWe-h, 85 \$/MWe-h

<u>Other</u>

- Process Plant Materials and Services +20%, -50%
- Other factors (staff, etc.) at 10% and 90% probability

There are two tornado plots for each technology – one for the variation in capital cost input and one for variation in inputs other than capital cost.

5.2.1 S-I with Reactive HI Distillation

The tornado plot for the capital cost uncertainties is Figure 4. Shown at the top of the figure is the effect on price of an overall +30% -15% in total capital cost. Following that in the tornado plot are the influences of the individual component inputs.

Figure 5 shows the tornado plot and the sensitivity ranking for selected inputs other than capital cost. Included in these is the most significant economic driver, the Internal Rate of Return (IRR). Other factors one would anticipate having a large effect are the process plant efficiency, in terms of output of helium all other inputs being the same, and the process plant efficiency. The thermal and electrical power cost and the capacity factor are selected and also two significant operating and maintenance cost elements, the staffing level and the annual cost of materials and services for maintenance and repair.


Figure 4 - Tornado for Capital Costs for S-I with Reactive HI Distillation



Figure 5 - Tornado for Other than Capital Costs for S-I with Reactive HI Distillation

5.2.2 Hybrid Sulfur Thermo- Electrochemical Water Splitting

Figure 6 shows the effect on hydrogen selling price of the capital cost elements in the analysis. As with the HTSE case, the electrolyzer cost uncertainty is the most significant factor.

The effects of the economic and performance factors are in the tornado plot in Figure 7. Thermal power cost, process efficiency and electric power cost are the major drivers.



Figure 6 - Tornado for Capital Costs for HyS



Figure 7 - Tornado for other than Capital Costs for HyS

5.2.3 High Temperature Steam Electrolysis

Figure 8 shows the effect on hydrogen selling price of the capital cost elements in for HTSE. The electrolyzer cost is the most significant cost driver, as would be expected.

The effects of the economic and performance factors are in the tornado plot in Figure 9. Because the HTSE concept utilizes mostly electric power for the hydrogen production, the cost of electric power is the principal cost factor.



Figure 8 - Tornado for Capital Costs for HTSE



Figure 9 - Tornado for other than Capital Costs for HTSE

5.3 Reactor Outlet Temperature Sensitivity

As part of the NGNP Hydrogen Plant Alternatives Study [Ref 2], sensitivity analyses were conducted of the hydrogen selling prices for various Reactor Outlet Temperatures (ROT) for each of the technologies. Intuitively, the lowering of the ROT would have an effect of increasing the contribution of the HPS cost to the hydrogen selling price and reducing the contribution of the NHSS cost to the price.

The results are reproduced here with an error in the HyS calculation corrected from cases presented in Ref. 2 for lower ROT. The correction reduces slightly the HyS hydrogen price sensitivity at lower ROTs. The error was corrected before the calculation of the Additional Cases (Section 6.5).

These sensitivity results for ROT are recognized as a first order extrapolation of design parameters, which are probably extrapolated beyond what is reasonable for quantitative results. The modeling and assumptions for HTSE are particularly debatable, since that the cell operating curve, or polarization curve, is set by the operating conditions and the inherent cell properties, such as area specific resistance (ASR). If one chooses to operate at a different voltage, the cell current (and hydrogen output) will be impacted. One can not assume, as the NGNP Study did, a fixed cell size and constant current density operating point and vary the voltage. In Section 6.5 Additional Cases are presented for which the influence of lower ROT is instead provided by calculation done by the three NHI technology development entities.

Basis for the analyses summarized following is a constant plant hydrogen output. Starting points in each case are the configurations of the Reference Cases in Table 6. Refer to the NGNP Study report for further details on the model.

The calculated process efficiencies under the given modeling and assumptions as a function of ROT are shown in Figure 10. The corresponding overall plant system efficiencies – which include for the case of variation of ROT the reduced capital cost of the NHSS – is shown in Figure 11. Noted in the figure are the points at which additional NHSS units have to be added to supply the required high-quality heat to the processes.

The selling price of hydrogen as a function of the ROT is shown in Figure 12.



Figure 10 - Process Efficiency as a Function of ROT



Figure 11 - Plant Efficiency as a Function of ROT



Figure 12 - H₂ Price for Three Technologies as a Function of ROT

It can be seen in Figure 12 that HTSE has not only the lowest calculated hydrogen selling price, but also the least sensitivity to NHSS reactor outlet temperature. The magnitude of sensitivity can be explained by the HTSE process cycle using the least amount of high-temperature heat among the three processes. At a 950°C reactor outlet temperature, the reference HTSE HPS uses a small fraction of the heat from one reactor unit. As reactor outlet temperature declines, the fraction from the HTGR is less, and to provide the required heat for the electrolysis process greater amounts of ohmic heating are utilized. Thus, as the temperature of the heat from the NHSS decreases, the amount of heat per unit output of the HTSE process is even less. However, since the fraction of high-temperature heat in the reference 950°C case is so small, the influence on hydrogen selling price is slight. At or below a NHSS outlet temperature of about 850°C, the energy budget is such that no process heat is required.

Both Hybrid Sulfur and Sulfur-Iodine cycles have rapid capital cost increase and increasing power consumption as the conversion in the Sulfuric Acid Decomposer per pass declines with lower maximum process temperature. Sulfuric Acid Decomposition section flows need to be greater, pumping power is higher, and energy for acid concentration is greater.

Hybrid Sulfur has the most sensitivity to NHSS reactor outlet temperature at the 750°C end of the range calculated. This is a phenomenon of the limit on usable heat set by the pinch point in the Sulfuric Acid Decomposer. All heat below approximately 500°C can only be used for electric generation.

The same sensitivity is not shown by the Sulfur-Iodine cycle because the NHSS heat goes to both the sulfuric acid decomposition section and to the HI section. Therefore less heat is committed to the Acid Decomposer and consequently limited by the pinch.

A notable result is that, based on the computational model and assumptions of this evaluation, the hydrogen price with all factors considered is relatively flat as a function of reactor outlet temperature down to about 800-850°C for S-I and HTSE. However, this trend is misleading. Rather, the relatively modest increase in selling price is due to the fact that HTSE is increasingly importing inexpensive electricity for process use and is relying less and less on nuclear heat from the HTGR for process heat. In other words, HTSE technology is more appealing at lower temperatures because its process heat demands are being provided through other more economical energy sources than a HTGR.

6 Further Assessment of Hydrogen Price

Resulting hydrogen selling prices from the NGNP Study analysis were high compared to earlier estimates, particularly the 2007 NHI framework cases [Ref. 1]. The high price is the result of conservative assumptions in the development of the three process flow sheets, in the cost estimating process and in the energy cost parameters input to the cost calculations.

As a starting point for further evaluations of the NHI technologies, a series of changes to the cost inputs were made. The NHI process development teams were asked to review the NGNP Study and to suggest areas where there might be alternative assumptions or configurations. Without altering the systematic approach to the parallel evaluation of the technologies, these adjustments were made and calculations made for Re-assessed Cases to enable exploration of sensitivities.

6.1 Issues with NGNP Study Bases

The main issues with the analyses that resulted from the NGNP Study (Shaw Study) are the following.

- H₂ price results very sensitive to economic assumptions: cost of heat and electricity plus electricity escalation
- Equipment costing was done at peak of commodity prices (summer 2008)
- Problem remains using "Target" costs for new technology items, *e.g.* solid oxide electrolyzers
- Lack of usable performance lifetimes and output change rates
- Process flow sheet uncertainties (particularly S-I) give varying electric power consumption

6.1.1 Revised Economic Assumptions and Cost of Heat and Electricity

A first adjustment to the NGNP Study results is made to the energy cost inputs. The nuclear heat cost and electric power costs are reduced to the same values used in the 2007 analyses, and so nuclear heat cost is reduced from 30 to 20 \$/MWt-h and electricity cost from 75 to 60 \$/MWe-h. Also, the escalation in the cost of imported electric power is taken out to provide a consistent comparison with earlier studies and to be more in line with current economic realities.

6.1.2 Revised Equipment Costing

To adjust for the cost estimating having been done at around the time of the peak in the commodity "bubble", three cost factors were considered. In mid-2008 the price of

carbon steel plate as an index was up a factor of 1.7 from its average in 2005 to 2007. The price of nickel, which is reflected in the cost of stainless steel and might more accurately track the cost of the process plant capital equipment was up by 1.4 over 2005-2006 (nickel peaked in late 2007). The Chemical Engineering Plant Cost Index (CECPI), which is a composite of equipment, site material, labor and engineering costs in the industry, peaked at 1.3 times the 2005-2007 value. In consideration of these indices, a factor of 1.5 is taken to be the approximate excess capital cost due to the cost estimating at the cost peak.

6.2 Resolving Energy and Capital Cost Factors

The analyses that are the reference cases in the NGNP Study (Shaw Study) were modified in two steps according to the adjustments to energy costs and overall capital costs described in Sections 6.1.1 and 6.1.2. The changes are as outlined below for the Re-assessed Base Cases.

- <u>Base Case 1</u> 2008 NGNP Study
 - HTSE 35% efficiency
 - SI 25% efficiency
 - HyS 33 % efficiency

Note: Efficiency refers to the Hydrogen Production System, therefore excluding the Power Generation System.

• Base Case 2 – NGNP Study with revised operating costs

For all three H_2 production technologies:

- Process efficiencies same as Base Case 1
- Capital costs same as Base Case 1
- Operating Costs revised from Base Case 1 as follows, for all three technologies
- nuclear heat cost reduced from 30 to 20 \$/MWt-h
- o heat calculated as transferred to process instead of reactor generation
- electricity cost reduced from 75 to 60 \$/MWe-h
- electricity escalation reduced from 1 %/yr to 0
- NHSS electric load removed
- process water and cooling water per H2A instead of Shaw NGNP Study algorithms
- <u>Base Case 3</u> NGNP Study with revised operating costs and capital costs

For all three H₂ production technologies:

- Process efficiencies same as Base Case 1
- Capital costs reduce conventional equipment capital costs of Base Case 1 by 33%.

HTSE:

 \circ $\,$ reduce by 1/3 the cost of initial conventional equipment, spares, and site materials

- o reduce by ¼ the replacement cost for life-limited heat exchangers
- o electrolyzer cost is same as in Base Case 1

S-I:

- reduce by ¹/₃ the cost of initial conventional equipment, spares, and site materials
- \circ sulfuric acid decomposer cost is same as in Base Case 1

HyS:

- reduce by ¹/₃ the cost of initial conventional equipment, spares, and site materials
- o sulfuric acid decomposer cost is same as in Base Case 1
- SO2 electrolyzer cost is same as in Base Case 1
- Operating Costs
 - o revised from Base Case 1 as follows, for all three technologies
 - nuclear heat cost reduced from 30 to 20 \$/MWt-h
 - heat calculated as transferred to process instead of reactor generation when calculating cost \$/MW in this analysis cost is per heat transferred to the process; in the NGNP Study analysis it was \$/MW generated in core
 - electricity cost reduced from 75 to 60 \$/MWe-h
 - electricity escalation reduced from 1 %/yr to 0
 - NHSS electric load removed
 - process water and cooling water per H2A values instead of algorithms used by Shaw in the NGNP Study

Hydrogen selling prices declined significantly. The results are as shown in Table 7 and Figure 13.

Casa	Projected H ₂ Price, \$/kg				
Case	S-I	HyS			
Base Case 1: 2008 NGNP Study	10.71	6.04	6.83		
Base Case 2: 2008 NGNP Study w/ revised operating costs	8.34	4.34	5.19		
Base Case 3: 2008 NGNP Study w/ revised operating costs and w/ revised capital costs	7.27	4.23	4.95		

Table 7 - Re-assessed E	Base Case	Comparisons
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Base Cases for HTSE do NOT include a credit for the sale of O_2 , whereas an O_2 credit IS included in all three Base Cases for S-I and HyS. For HTSE, inclusion of an O_2 credit is considered in the additional HTSE cost cases that follow.

Details of the inputs and results for these analyses are found in the Data Base, and the data can be seen in the figures in Section 7.



Figure 13 - Re-assessed Base Case Comparisons

Shown in Figure 14 through Figure 16 are the breakdowns of the contributions to the hydrogen price for Base Case 3 for each of the Re-assessed Cases.



Figure 14 - S-I Re-assessed Base Case 3 Results

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Figure 15 - HyS Re-assessed Base Case 3 Results



Figure 16 - HTSE Re-assessed Base Case 3 Results

6.3 Other Issues with NGNP Study Bases

Even after lowering the NGNP Study (Shaw Study) capital costs generally, as done in Base Case 3, there remain concerns about the high capital cost of the S-I system, and also for the HyS system. For the HyS and HTSE systems the use of "target" costs for the electrolyzers was questioned. In addition, the maintenance and replacement schedules used for the two types of electrolyzers did not seem to align with the expected performance lifetimes that are inferred from the small amount of testing done to date on each type of electrolyzer.

6.3.1 Comparisons with Other Capital Cost Estimates

Higher equipment capital cost appears to be the predominant factor causing the higher hydrogen prices in the present analyses compared to those calculated in earlier work (for example see Table 2). Selected comparisons indicate, however, indicate that the revised capital costs may not be excessive,

6.3.1.1 CEA 2008 Sulfur-lodine Plant Cost Estimate

A comparison of the equipment capital costs for the S-I hydrogen production system can be made to the same general technology applied by the CEA in their conceptual S-I studies [Ref. 27]. This comparison, samples of which are shown in Table 8, indicates that the capital costs are not necessarily too high.

	NGNP (Shaw)	CEA (n th of a kind)	CEA scaled & converted
S-I Plant Hydrogen Output, moles/s	2180	1000	2180
Bunsen Reaction Section (BUN)	\$ 274 M	€ 73 M	\$ 214 M
Sulfuric Acid Decomp. Sec. (SAD)	\$ 289 M	€ 385 M	\$ 1,132 M
HI Decomposition Section (HAD)	\$ 1,942 M	€ 1,259 M	\$ 3,704 M
Feed Purification Section (FUS)	\$ 45 M		
Product Purification Section (PPU)	\$ 136 M		
Total Plant Cost	\$ 2,683 M	€ 1,716 M	\$ 5,050 M
Hydrogen Price	10.70 \$/kg	10.00 €/kg	14.00 \$/kg

Table 8 - Comparing S-I System to CEA's

6.3.1.2 AstroCosmos Refractory Metal Component Cost Estimate

Additional attention was given to the tantalum material for the corrosive service components of the S-I plant concept, because they stand out as expensive capital items in the Shaw cost estimates. The most significant of these components are heat exchangers in the HI section. General Atomics made a specific request to a maker of tantalum and tantalum-clad process equipment for cost quotes to compare to the Shaw estimates. AstroCosmos Metallurgical is the a producer of corrosive-resistant, reactive metals equipment for the pharmaceutical, steel, waste management and other chemical processing industries, and is a subsidiary of Groupe Carbone Lorraine. AstroCosmos was a supplier of tantalum-clad components for the S-I ILS demonstration, although the ILS does not have the same HI section (extractive separation rather than reactive distillation).

AstroCosmos declined to offer on any tantalum or tantalum-clad items for which the operating temperature exceeded 200°C (400°F), whereas the temperatures in the HI distillation section range from 250 to 300°C in the Shaw process flow diagrams. They gave "budget quotations" only for four heat exchangers in the sulfuric acid decomposition section. Their reply says, "Tantalum begins to suffer from hydrogen embrittlement at temps above 400° F, and we do not suggest using tantalum in this type of environment."

For the components that AstroCosmos did quote, Table 9 shows the comparison to the Shaw estimates (unmodified). The quotes are two to three times higher in price than the Shaw estimates. They were queried and confirmed that their quotes did not include specific development or first-of-a-kind costs.

Item	Shaw estimate, per unit	AstroCosmos estimate, per unit	Ratio of AstroCosmos cost over Shaw cost
HX-102 lodine feed cooler ~ 6,000 ft ² each	\$ 1,087,000	\$ 3,320,000	306%
HX-103 Reverse Bunsen reactor vapor cooler ~ 1,020 ft ² each	\$ 411,000	\$ 678,000	167%
HX-111 Bunsen reactor trim cooler HX-112 Bunsen reactor cooler (apparently identical) ~ 8,800 ft ² each	\$ 1,690,000	\$ 4,320,000	255%

Table 9 - Comparison of NGNP Study and AstroCosmos Costs for Selected
S-I Equipment

Note: All are tantalum welded tubes, with tantalum lined carbon steel tubesheet and carbon steel shell.

AstroCosmos was asked to review the Shaw quotes, and their evaluation was that the Shaw quotes were low. In a specific response they said, "As an example although only as a budget estimate, Shaw's total price for item HX -111 is \$ 1.69 million and the cost to AstroCosmos for Tantalum Tubes alone for item HX -111 is \$ 2.6 million. The estimated prices by Shaw would not even cover the material cost on most of the Units."

6.3.1.3 SRNL Plant Cost Estimates

In an earlier phase of the development of each technology, SRNL prepared equipment cost estimates for both S-I and HyS plants [Refs. 28 & 8]. These were done with the Aspen Icarus Process Evaluator[®] software and data base [Ref. 29]. It is useful to use these data for cases to compare to the NGNP Study and revised NGNP Study analyses.

6.3.2 Using "Target" Costs for New Technology Items

Problems remain using "Target" costs for new technology items, particularly the HTSE solid oxide electrolyzers and the HyS sulfur dioxide electrolyzers. The operational and cost values used for the two electrolyzers are shown in Table 10 along with the accepted target values for the respective fuel cell that shares the technology.

To illustrate the sensitivity to electrolyzer costs, Figure 17 show the results of calculations in each case with doubled electrolyzer initial and replacement equipment cost. The resulting higher hydrogen selling price in each case is significant.

		\$/m²	V	A/cm ²	\$/kWe
H	TSE				
	SOEC Cell stack	750	1.00	0.05	266
	Modular Assembly	825	1.20	0.25	295
	SECA SOFC "target" (400 \$/kWe for fuel cell system)	CA SOFC "target" (1,125)		400	
H	HyS				
	SO ₂ Electrolysis Cell	1,080	0.60	0.50	350
	Modular Assembly	1,500	0.60	0.50	490
	PEM Fuel Cell projection (75 \$/kWe for automotive system)	750			(245)

Table 10 - Electrolyzer	Costs for NGNP	Study Compared to	Targets.
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Figure 17 - Sensitivity to Electrolyzer Cost - HyS and HTSE

6.3.3 Lack of Lifetime and Output Change Rate Data

Although for each electrolyzer there is a corresponding fuel cell technology that appears to demonstrate good lifetime, the assumed replacement schedule for the HyS and HTSE electrolyzers in the analyses are somewhat arbitrary. This is because there is a lack of usable performance lifetimes and output change rates from present development work.

MPR Associates reviewed the assumptions from the Shaw NGNP Study and proposed alternate electrolyzer replacement programs and lifetime. Figure 18 shows the results of using that replacement logic, and the impact on hydrogen price is slight.



Figure 18 - Sensitivity to Electrolyzer Replacement Frequency - HyS and HTSE

6.3.4 Alternate Flow Sheets

For the S-I cycle, an alternate case would use an earlier General Atomics (GA) flow sheet, particularly one that incorporated more advantageous HI section thermodynamic factors [Ref. 30]. That results in a very significant efficiency improvement over the NGNP Study case from 25% to 42%.

An alternative flow sheet for HyS is one for which the electrolyzer cell voltage is lowered from 600mV to 525, applying a projected improvement. A second improvement is reduced thermal demand in the acid concentration step. These changes would increase cycle efficiency from 33% to 38%

For HTSE, the alternative is to eliminate the air sweep subsystem, which makes an efficiency improvement from 35% to 36%

6.3.5 Other Issues with NGNP Study Bases

In the analysis of the HTSE hydrogen plant, the anode air sweep option was used as the reference, and when diluted with air, by-product oxygen is not likely to be saleable, whereas in the S-I and HyS flow sheets there is a pure oxygen by-product. A further revision to the HTSE analysis is the case of no air sweep equipment and adds sale of by-product oxygen.

Two additional adjustments are made to attempt to bring the S-I, HyS and HTSE evaluations to a common level of capital cost uncertainty. In the HI section ("Section 3") of the S-I process, the highly corrosive fluids require vessels, piping and equipment

specially lined with either tantalum or niobium alloy, which for the process industry are exotic materials. The technologists familiar with the S-I Integrated Laboratory Experiment were of the opinion that the extent of this corrosion resistant material was excessive in the Shaw design, and so a case is considered with the amount of exotic material lining reduced (by approximately 30% in the HI feed and distillation equipment and by 50% in the iodine recovery portion) and replaced with glass or Teflon[®] lining.

The second adjustment is to a non-conservative cost input to the Shaw evaluation. The equipment capital costs for the SO_2 electrolyzer in HyS and the steam electrolyzer in the HTSE are based on projected cost targets. For both electrolyzer technologies the cost targets were adopted from the development programs for the associated fuel cells, and those targets appear to be far from being achieved. To show the effect of a more realistic outcome to compare with the S-I case a calculation is done for the price if the uninstalled costs of these components were doubled.

6.4 Resolving Other Re-assessed Case Assessment Factors

A series of additional hydrogen selling price calculations were done for selected combinations changes responding to the other issues that are discussed in Section 6.3. These Re-assessed Cases are detailed in the following three subsections for the three NHI technologies and summarized in Section 6.4.4.

6.4.1 S-I Evaluation for the Other Re-assessed Cases

The S-I analyses for the Re-assessed Base Cases were further modified according to the adjustment factors in Section 6.3. The changes are as outlined below.

- SRNL/GA Flow sheet Process Efficiency (42%)
 - Same product output as NGNP Study; reduce thermal input as per the SRNL "Phase B" report, which uses GA process flow sheet
 - Electric input per unit output per SRNL "Phase B" report [Ref. 28]
 - Remove process steam import from Shaw case (assume better heat integration)
- CEA Flow sheet Process Efficiency (37%)
 - Same product output as NGNP Study; reduce thermal input as in CEA flow sheet [Ref. 31]
 - Electric input per unit output per CEA flow sheet
 - Remove process steam import from Shaw case (assume better heat integration)
- SRNL/GA S-I Study Capital Costs
 - Replace Hydrogen Production System installed capital cost per unit output in Shaw model with values from SRNL "Phase B" report calculated with Aspen Icarus Project Estimator (IPE)

- CEA Capital Costs
 - Replace total direct capital cost in Shaw model with value from CEA per unit output [Ref. 27]
- Tantalum Reduced in HI Section
 - Reduce capital cost of selected components designated in Shaw design to be tantalum or tantalum-lined in the HI section (distillation feed subsection, distillation subsection and iodine recovery subsection) where temperatures appear to be low enough to allow non-metallic linings.

Hydrogen selling prices were calculated for these other Re-assessed Cases. The results are as shown in Table 11 and Figure 19.

Cas	e	H ₂ Price, \$/kg
2	Base Case 2	8.34
4	Base Case 2 Tantalum removed from HI section 	6.87
5	Base Case 2 – SRNL/GA Efficiency (42%)	7.03
6	Base Case 2 – CEA Efficiency (37%)	7.33
7	Base Case 2 – CEA Capital Costs – CEA Efficiency (37%)	12.53
8	Base Case 2 – SRNL/GA Capital Costs – SRNL/GA Efficiency (42%)	4.04
3	Base Case 3	7.27
9	Base Case 3 Tantalum removed from HI section 	6.24
10	Base Case 3 – Tantalum removed from HI section – GA Efficiency (42%)	4.94

Table 11 - Specific S-I Re-assessed Case Comparisons



Figure 19 - Specific S-I Re-assessed Case Comparisons

6.4.2 HyS Evaluation for the Other Re-assessed Cases

The HyS analyses for the Re-assessed Base Cases were further modified according to the adjustment factors in Section 6.3. The changes are as outlined below.

HyS Cost Factors:

- SO₂ Electrolyzer Cost Increased 2x
 - Electrolyzer costs increased by factor of two from 1500 \$/m² uninstalled to 3000 \$/m²
- SRNL Icarus Capital Costs
 - Replace Hydrogen Production System installed capital cost in Shaw model with value from SRNL HyS report calculated with Aspen Icarus Project Estimator (IPE)
- Improved Process Efficiency (38%)
 - Same thermal input to process as NGNP Study; increase product output per unit thermal input due to lower cell voltage (525 mV versus 600 mV)

Hydrogen selling prices were calculated for these other Re-assessed Cases. The results are as shown in Table 12 and Figure 20.

Cas	6e	H₂ Price, \$/kg
2	Base Case 2	5.19
4	Base Case 2 – SRNL Icarus Capital Costs	4.35
5	Base Case 2 – SRNL Icarus Capital Costs – Improved Process Efficiency (38%)	3.87
3	Base Case 3	4.95
6	Base Case 3 – 2x Electrolyzer Cost	5.39
7	Base Case 3 – Improved Process Efficiency (38%)	4.45







6.4.3 HTSE Evaluation for the Other Re-assessed Cases

The HTSE analyses for the Re-assessed Base Cases were further modified according to the adjustment factors in Section 6.3. The changes are as outlined below.

- O₂ Credit Added
 - \circ O₂ credit of 20 \$/t (half the reference 40 \$/t) for O₂ diluted with air
 - 40 \$/t for cases with air sweep eliminated
- No Import Electricity
 - Flow sheet from NGNP Study for Hydrogen Production System scaled down in size linearly to point of no imported electric power
 - \circ Capital Costs scaled to lower hydrogen production with exponent 0.7
- Electrolyzer Cost Increased 2x
 - Electrolyzer costs increased by factor of two from 295 \$/kWe (825 \$/m²) uninstalled to 600 \$/kWe (1,650 \$/m²)
- Eliminate Sweep Air Hardware and Sweep Gas Turbine
 - Eliminate air sweep supply system (air purification subsystem, compressor and cooler)
 - Eliminate sweep gas energy recovery turbine
 - Process Efficiency changes to 36% due to removal of hardware
- Improved PCS Efficiency (50%)
 - Power conversion (steam turbine-generator) efficiency changed from 39% to 50%

Hydrogen selling prices were calculated for these other Re-assessed Cases. The results are as shown in Table 13 and Figure 21.

Cas	e	H2 Price, \$/kg
2	Base Case 2	4.34
4	Base Case 2, with -20 \$/t O ₂ credit	4.17
5	Base Case 2, with -No import Electricity	6.58
6	Base Case 2, with -Eliminate Sweep Air Hardware and Sweep Gas Turbine -Process Efficiency changes to 36%, due to removal of hardware -40 \$/t O ₂ credit	3.81
7	Base Case 2, with -Eliminate Sweep Air Hardware and Sweep Gas Turbine -Process Efficiency changes to 36%, due to removal of hardware -40 \$/t O ₂ credit -PCS Efficiency is 50%	4.24
3	Base Case 3	4.23
8	Base Case 3, with –20 \$/t O ₂ credit	4.06
9	Base Case 3, with –Eliminate Sweep Air Hardware and Sweep Gas Turbine –Process Efficiency changes to 36%, due to removal of hardware –40 \$/t O ₂ credit	3.72
10	Base Case 3, with -Eliminate Sweep Air Hardware and Sweep Gas Turbine -Process Efficiency changes to 36%, due to removal of hardware -40 \$/t O ₂ credit -2x Electrolyzer Cost	3.59

Table 13 - Specific HTSE Re-assessed Case Comparisons



Figure 21 - Specific HTSE Re-assessed Case Comparisons

6.4.4 Summary of Results

Figure 22 shows the range of hydrogen prices for the Re-assessed Cases presented in Sections 6.1 through 6.4.



Figure 22 - Summary of Results

6.5 Additional Cases

The NGNP Hydrogen Production System Down-Selection team held a workshop in June at which time the results up to the point in the previous section were presented [Ref. 3]. After that presentation and the presentations of the three technology advocates, the team requested some Additional Cases, including cases for reactor outlet temperature lowered from 950°C to 750°C. The analysis includes comparison to price for hydrogen produced from Steam-Methane Reforming. These Additional Cases were provided to the team in a brief report [Ref. 31]. The following reproduces that work.

6.5.1 Inputs and Assumptions

The bases for the hydrogen price calculation for the Additional Cases are as follows.

For all cases

- The starting point capital and operating costs are from the Hydrogen Plant Alternatives Study (HPAS) by Westinghouse NGNP Team led by team member Shaw Energy & Chemicals Group (the NGNP Study) as per Section 3.
- The calculation method uses the H2A tool with the ground rules (economic drivers and other parameters) as per Appendix B.
- The inputs include the energy costs changed from the NGNP Study in the subsequent NHI evaluation, as per Section 6.1.1.
 - Nuclear heat from 30 \$/MWt-h in the NGNP Study to 20 \$/MWt-h*
 - Electric power
 - from 75 \$/MWe-h in the NGNP Study to 60 \$/MWe-h
 - escalation from 1%/yr to zero
 - H2A default water costs
 - Assume heat integration with steam cycle
 - No thermal energy (process steam) input
- In addition the inputs include reduced capital cost for conventional equipment included in the subsequent NHI evaluation as per Section 6.1.2.
- The plant size is changed from 550 MWt in the NGNP Study to 600 MWt.
- None of the price calculations include a credit for byproduct oxygen.
- The plant power conversion system efficiency used is 40%
- There are two sets of cases:

^{*} See details on following pages of assumptions for nuclear heat cost used in Shaw calculations of 750°C cases.

- for ROT 950°C, which is the NGNP Study reference ROT, with the NGNP Study process efficiencies.
- for ROT 750°C using the same costs and the assumptions in the NGNP Study report for calculating lower ROT, but with the process plant heat and electric power consumption per unit output (*i.e.*- process efficiencies) from the Down-Selection workshop, including updated data on Sulfurlodine [Ref. 33].

For Sulfur-Iodine Water Splitting

• HI section equipment and bulk materials costs lower for reduced tantalum content. The amount of reduced cost is 2/3 the amount reduced in the cases in the 22 June presentation (50% reduction on selected equipment items *vs.* 75% reduction).

For High Temperature Steam Electrolysis the following additional changes

- SOEC cost changed to 2,000 \$/m². (Approximately doubled from the NGNP Study and 33% more per unit area than the HyS electrolyzer cells.)
- Complete electrolysis module replacement every 3 years.

For the Comparative SMR Case

- The H2A advanced SMR case from Ref. 42.
- Natural gas at 8 \$/MMBtu
- CO₂ cost/penalty at 25 \$/t

6.5.2 750°C ROT Case Details

The assumptions in the NGNP Study specific to the lower ROT cases are the following. Note that unlike for the cost calculations at the reference 950°C ROT, nuclear heat cost changes must be accounted in each case.

For all cases

- Hydrogen output remains the same (142 Mscf/d).
- Nuclear heat cost is decreased for lower capital cost due to less costly materials of construction at lower ROT.
- Nuclear heat cost is increased for higher helium pumping requirement at lower ROT and the same thermal power, reactor inlet temperature remaining the same.

For Sulfur-Iodine and Hybrid Sulfur Water Splitting

- Nuclear reactor modules are added to maintain the same thermal power from usable high-temperatures into the HPS. (As in 950°C cases, thermal power not used by the HPS generates electricity in the power conversion system.)
 - Costs for electric power consumption are added for incrementing reactor modules
 - Nuclear heat cost is decreased for nuclear heat source sharing factors with more reactor modules.
- Recirculation rates in the sulfuric acid decomposition section increase due to lower conversion per pass. This increases capital cost of process equipment handling increased flows.

For High Temperature Steam Electrolysis

- Electrolyzer cell current density remains the same as the 950°C case, and the capital cost of electrolyzer modules is unchanged.
- Lower temperature results in higher resistance in the electrolysis cells.
 - This requires higher voltage for the same hydrogen output and hence greater electric power is consumed in the electrolysis.
 - This also increases the joule heating in the cells and correspondingly reduces the nuclear heating requirement.
- Since less nuclear heat is required, the process coupling heat exchangers decrease in size and capital cost.
- Electric power consumption is greater and so distribution equipment costs increase.

Table 14 shows the overall parameters in these cases compared to the NGNP Study ...

		<u>HT:</u>	<u>SE</u>	HyS		<u>HyS</u> <u>SI</u>	
		NGNP study	These Results	NGNP study	These Results	NGNP study	These Results
Reactor Thermal Rating (MWt)		550	600	550	600	550	600
No. of Units at Site (N)		1	1	2	2	3	3
Site Thermal Rating (MWt)		550	600	1,100	1,200	1,650	1,800
ROT (°C)		950	750	950	750	950	750
Efficiency of Elec. Prod. By HTGR (η)		39%	40%	35%	40%	N/A	40%
Assumed Capacity Factor (HTGR)		94%	94%	94%	94%	94%	94%
HTGR Energy: Process Heat, Electric	ity or Both	Both	Both	Both	Both	Process Heat	Both
Ultimate Heat Sink Temperature (°C)		20	20	20	20	20	20
Hydrogen Production	Hydrogen (kg/hr)	14,400	14,400	14,400	14,400	15,840	14,400
	Hydrogen (kg/day)	343,500	343,500	343,500	343,500		343,500
	Oxygen (kg/hr)	115,200	115,200	115,200	115,200	126,720	115,200
From NGNP/HTGR	Heat (hot gas) (Mwt)	88	83	712	1,239	1,650	1,077
(TOTAL FOR N-Pack)	Elec. Plant (Mwt)	440	517	388	561	0	123
	[Elec Plant Mwe]	176	207	133	224	0	49
	Elec. Import (Mwe)	365	328	198	12	330	157
	Percent Process Heat	6%	6%	46%	68%	67%	68%
Gas Temperatures/Excess Energy	Tsupply (°C)	910	710	910	710	910	710
	Treturn (°C)	829	629	522	522	344	269
	Excess T (Energy) Use	Electricity	Electricity	Electricity	Electricity	Electricity	Electricity
	Excess T (Energy) (MWe)	176	207	133	224	N/A	49
Efficiency, LHV		32.8%	33.7%	30.1%	26.1%	21.4%	30.0%

6.5.3 Results

The results for the Additional Cases are shown in Table 15 and in Figure 23.

	LevelizedSelling Price of Hydrogen (\$/k								
	950°C ROT	750°C ROT, NGNP Study Assumptions, Efficiencies from Workshop							
Sulfur-lodine (S-I)	5.84	6.89							
Hybrid Sulfur (HyS)	4.69	6.64							
High-Temperature Electrolysis (HTSE)	5.69	5.75							

Table 15 - Hydrogen Prices for Additional Cases



🛛 S-I 🔳 HyS 🗆 HTSE

Figure 23 - Hydrogen Prices for Additional Cases

7 NHI Cost Framework Data Base

An initial assembly of a Data Base was done previously for the NHI framework in conjunction with MPR Associates. This work was planned to make use of a formal, structured relational data management system, such as Microsoft Office Access[®]. Budgetary limitation made it necessary to shelve that work and to begin with a data base composed of linked files in Microsoft Excel[®].

The Data Base links summary pages to the sources of capital and operating costs from the NGNP Study estimating worksheets, CEA presentations and SRNL reports.

It was intended to maintain more than economic data in the Data Base. For example, technology readiness levels (TRLs) are shown in the Data Base. These are the TRL rankings assigned for subsystems and components in the NGNP Study (Ref. 2).

Because the Data Base files are so large, they are not included in this report. The Data Base is documented and embedded in a separate report [Ref. 34]. The top sheets from the files are reproduced in Figure 24 through Figure 26.

	\$/kg				Breako	ut of Hyd	lrogen Se	illing Price											
					Cap	oital Char	ges	Fixed Operating & Maintenance Costs				Variable Operating Costs							
	And	-	October Control	On Golies	Policy Contraction of	(abo, b) (a) (a) (a) (a) (a) (a) (a) (a) (a) (a	Marine State	Province and Services by	And a service of the	Contraction of the state	We and Chenness	S. Association	Outro oot	Provin.	Coline Do	(Destination of the second	No. Of Street of	100000000	
Sulfur-lodine	Shaw NGNP HPAS	10.71	3.64	0.47	0.21	0.11	0.10	0.48	0.02	0.11	0.28	0.17	0.01	0.15	2.26	3.04	-0.34		
	Shaw case with revised	8.34	3.41	0.44	0.20	0.11	0.09	0.47	0.02	0.11	0.28	0.22	0.02	0.15	0.92	2.23	-0.33		
	Shaw case with revised energy cost parameters and lower equipment and material capital costs	7.27	2.61	0.34	0.17	0.11	0.07	0.36	0.02	0.11	0.28	0.22	0.02	0.15	0.92	2.23	-0.33		
	Shaw case with revised energy cost parameters and SRNL/GA efficiency	7.03	3.38	0.44	0.20	0.11	0.09	0.47	0.02	0.11	0.28	0.22	0.02	0.00	0.92	1.10	-0.33		
	Shaw case with revised energy cost parameters and CEA efficiency	7.33	3.39	0.44	0.20	0.11	0.09	0.47	0.02	0.11	0.28	0.22	0.02	0.00	0.70	1.61	-0.33		
	SRNL study S-I capital with SRNL/GA flowsheet efficiency	4.04	1.20	0.16	0.07	0.11	0.02	0.16	0.02	0.11	0.28	0.22	0.02	0.00	0.92	1.10	-0.33		
	CEA capital cost with CEA ref. flowsheet efficiecncy	12.53	7.23	0.94	0.44	0.11	0.18	1.01	0.02	0.11	0.28	0.22	0.02	0.00	0.70	1.61	-0.33		
	Revised Shaw base case with Ta material reduced in HI section	6.87	2.32	0.30	0.16	0.11	0.06	0.32	0.02	0.11	0.28	0.22	0.02	0.15	0.92	2.23	-0.33		
	Revised Shaw base case with Ta material reduced in HI section and lower equipment and material capital costs	6.24	1.85	0.24	0.13	0.11	0.05	0.25	0.02	0.11	0.28	0.22	0.02	0.15	0.92	2.23	-0.33		
	Revised Shaw case with Ta reduced, lower equipment and material capital costs and SRNL/GA flowsheet efficiency	4.94	1.82	0.24	0.13	0.11	0.05	0.25	0.02	0.11	0.28	0.22	0.02	0.00	0.92	1.10	-0.33		
Hybrid Sulfur	Shaw NGNP HPAS	6.83	1.76	0.23	0.23	0.16	0.01	0.23	0.03	0.15	0.28	0.06	0.01	0.24	1.49	2.29	-0.33		
	Shaw case with revised	5.19	1.66	0.22	0.24	0.16	0.01	0.23	0.03	0.15	0.29	0.06	0.01	0.25	0.58	1.64	-0.33		
	Shaw case with revised energy cost parameters and lower equipment and	4.95	1.48	0.19	0.23	0.16	0.01	0.20	0.03	0.15	0.29	0.06	0.01	0.25	0.58	1.64	-0.33		
	material capital costs Shaw case with revised energy cost parameters, lower equipment and material capital costs and frictible alerticitycase cost	5.39	1.71	0.22	0.37	0.16	0.01	0.23	0.03	0.15	0.29	0.06	0.01	0.25	0.58	1.64	-0.33		
	Shaw case with revised energy cost parameters, lower equipment and material capital costs and improved efficiency	4.45	1.38	0.18	0.22	0.16	0.01	0.19	0.03	0.15	0.29	0.06	0.01	0.25	0.51	1.35	-0.33		
	SRNL Icarus capital costs	4.35	1.04	0.14	0.19	0.16	0.00	0.14	0.03	0.15	0.29	0.06	0.01	0.25	0.58	1.64	-0.33		
	SRNL Icarus capital costs and improved efficiency	3.87	0.94	0.12	0.21	0.16	0.00	0.13	0.03	0.15	0.29	0.06	0.01	0.25	0.51	1.35	-0.33		
																		1	
Electolysis	Shaw NGNP HPAS	6.04	1.21	0.16	0.15	0.14	0.01	0.15	0.03	0.01	0.26	0.01	0.01	0.00	2.72	1.18	0.00		
	Shaw case with revised energy cost parameters	4.34	1.14	0.15	0.15	0.14	0.01	0.15	0.03	0.01	0.27	0.01	0.01	0.00	1.46	0.82	0.00		
	Shaw case with revised energy cost parameters and O2 credit	4.17	1.14	0.15	0.15	0.14	0.01	0.15	0.03	0.01	0.27	0.01	0.01	0.00	1.46	0.82	-0.17		
	Shaw case with revised energy cost parameters and lower equipment and material capital costs	4.23	1.05	0.14	0.15	0.14	0.01	0.14	0.03	0.01	0.27	0.01	0.01	0.00	1.46	0.82	0.00		
	Shaw case with revised energy cost parameters and lower equipment and material capital costs and O2 credit	4.06	1.05	0.14	0.15	0.14	0.01	0.14	0.03	0.01	0.27	0.01	0.01	0.00	1.46	0.82	-0.17		
	Shaw case with revised energy cost parameters, 02 credit, remove sweep gas system and change PCS efficiency to 50%	4.24	1.25	0.16	0.25	0.14	0.01	0.17	0.03	0.01	0.27	0.01	0.01	0.00	1.46	0.82	-0.17		
	snaw case with revised energy cost parameters, O2 credit and remove sweep gas system	3.81	1.07	0.14	0.15	0.14	0.01	0.14	0.03	0.01	0.27	0.01	0.01	0.00	1.36	0.82	-0.33		
	Shaw case with revised energy cost parameters, 02 credit, remove sweep gas system and lower equipment and material costs Shaw case with sectional ensemption.	3.73	1.01	0.13	0.14	0.14	0.01	0.14	0.03	0.01	0.27	0.01	0.01	0.00	1.36	0.82	-0.33		
	parameters and lower equipment and material capital costs, O2 credit and double electrolyzer cost	3.59	1.07	0.14	0.15	0.14	0.01	0.14	0.03	0.01	0.27	0.01	0.01	0.00	1.14	0.82	-0.33		
	Shaw case with revised energy cost parameters and resized for no import electricity	6.58	2.17	0.28	0.20	0.41	0.01	0.30	0.08	0.02	0.72	0.01	0.02	0.00	0.00	2.36	0.00		

Figure 24 - Hydrogen Cost Sheet from Data Base

Framework for Economic Evaluation of Nuclear Hydrogen Production

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Sulfur-lodine	Shaw NGNP HPAS	25%	10.71	Ş	2,683,017,000	\$	139,544,980	Ş	202,842,832	\$	41,243,156			2								
	Shaw case with revised energy cost parameters	25%	8.34	\$	2,683,017,000	\$	139,544,980	Ş	113,532,904	\$	41,243,156											
	Shaw case with revised energy cost parameters and lower equipment and material capital costs	25%	7.27	Ş	2,018,938,188	\$	122,034,648	Ş	113,532,904	\$	41,243,156											
	Shaw case with revised energy cost parameters and SRNL/GA efficiency	42%	7.03	\$	2,683,017,000	\$	139,544,980	Ş	113,582,138	\$	41,243,156											
	Shaw case with revised energy cost parameters and CEA efficiency	36%	7.33	\$	2,683,017,000	\$	139,544,980	Ş	87,094,408	\$	41,243,156											
	SRNL study S-I capital with SRNL/GA flowsheet efficiency	42%	4.04	Ş	860,478,834	\$	90,336,449	Ş	113,582,138	\$	41,243,156											
	CEA capital cost with CEA ref. flowsheet efficiecncy	36%	12.53	\$	5,954,665,586	\$	221,103,193	Ş	87,094,408	\$	41,243,156											
	Revised Shaw base case with Ta material reduced in HI section	42%	6.87	\$	1,774,668,750	\$	115,019,577	Ş	113,532,904	\$	41,243,156											
	Revised Snaw base case with La material reduced in HI section and lower equipment and material capital costs	25%	6.24	\$	1,380,035,232	\$	104,786,720	Ş	113,532,904	\$	41,243,156											
	Revised Snaw case with 1a reduced, lower equipment and material capital costs and SRNL/GA flowsheet efficiency	42%	4.94	\$	1,380,035,232	\$	105,807,055	\$	113,582,138	\$	41,243,156											
Hybrid Sulfur	Shaw NGNP HPAS	32%	6.83	s	917,965,000	\$	94,482,096	s	122.072.076	ŝ	37,302,727			2								
	Shaw case with revised	32%	5.19	s	917.965.000	S	94,482,096	s	65.163.420	۰ s	37.302.727											
	energy cost parameters Shaw case with revised energy cost parameters and lower equipment and	32%	4.95	s	784.328.643	s	91.756.753	s	65.163.420	s	37.302.727											
	material capital costs Shaw case with revised energy cost parameters, lower equipment and material	32%	5.39	s	953,500,643	\$	95,478,539	s	65,163,420	\$	37,302,727											
	capital costs and double electrolyzser cost Shaw case with revised energy cost parameters, lower equipment and material	33%	4.45	\$	917,965,000	\$	90,133,874	s	56,744,458	\$	37,302,727											
	capital costs and improved efficiency SRNL Icarus capital costs	32%	4.35	\$	456,660,000	\$	83,701,091	ş	65,163,420	\$	37,302,727											
	SRNL Icarus capital costs	33%	3.87	\$	456,660,000	\$	82,078,165	ş	56,744,458	\$	37,302,727											
	and improved enciency																					
High Temperature Electolysis	Shaw NGNP HPAS	35%	6.04	\$	508,851,000	\$	69,804,719	\$	224,887,754	\$	-			3								
	Shaw case with revised energy cost parameters	35%	4.34	\$	508,851,000	\$	69,804,719	\$	163,663,083	\$	-											
	Shaw case with revised energy cost parameters and O2 credit	35%	4.17	\$	508,851,000	\$	69,804,719	Ş	163,651,000	\$	18,651,364											
	Shaw case with revised energy cost parameters and lower equipment and material capital costs	35%	4.23	\$	442,587,023	\$	68,310,071	Ş	163,663,083	\$	-											
	Shaw case with revised energy cost parameters and lower equipment and material capital costs and O2 credit	35%	4.06	\$	508,851,000	\$	68,310,071	\$	163,663,083	\$	18,651,364											
	Shaw case with revised energy cost parameters, 02 credit, remove sweep gas system and change PCS efficiency to 50%	35%	4.24	\$	620,252,023	\$	71,357,060	Ş	163,663,083	\$	37,302,727											
	Shaw case with revised energy cost parameters, O2 credit and remove sweep gas system	36%	3.81	\$	460,234,000	\$	68,528,029	\$	152,189,395	\$	37,302,727											
	Snaw case with revised energy cost parameters, 02 credit, remove sweep gas system and lower equipment and material costs	36%	3.73	\$	410,176,014	\$	67,469,713	Ş	152,189,395	\$	37,302,727											
	Snaw case with revised energy cost parameters and lower equipment and material capital costs, O2 credit and double electrolyzer cost	36%	3.59	\$	410,176,014	\$	69,117,349	\$	127,698,485	\$	37,302,727											
	Shaw case with revised energy cost parameters and resized for no import electricity	35%	6.58	\$	508,851,000	\$	63,150,164	Ş	-	\$	-											

Figure 25 - Summary Sheet for S-I from Data Base

Framework for Economic Evaluation of Nuclear Hydrogen Production

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Sulfur-lodine	Shaw NGNP HPAS		25%	10.71	\$ 1,500,518,00	0 \$ 1,182,499,000	\$ 90,967,141	\$ 387,332,742	\$ 29,872,243	\$ 202,842,832	\$ 18,705,596	\$ 41,243,156		2			
	Shaw case with revised energy cost parameters		25%	8.34	\$ 1,500,518,00	0 \$ 1,182,499,000	\$ 90,967,141	\$ 289,080,000	\$ 29,872,243	\$ 113,532,904	\$ 18,705,596	\$ 41,243,156					
	Shaw case with revised energy cost parameters and lower equipment and material capital costs		25%	7.27	\$ 1,012,293,32	1 \$ 1,006,644,868	\$ 73,456,809	\$ 289,080,000	\$ 29,872,243	\$ 113,532,904	\$ 18,705,596	\$ 41,243,156					
	Shaw case with revised energy cost parameters and SRNL/GA efficiency		42%	7.03	\$ 1,500,518,00	0 \$ 1,182,499,000	\$ 90,967,141	\$ 142,455,120	\$ 48,577,839	\$ 113,582,138	ş -	\$ 41,243,156					
	Shaw case with revised energy cost parameters and CEA efficiency		36%	7.33	\$ 1,500,518,00	0 \$ 1,182,499,000	\$ 90,967,141	\$ 208,838,400	\$ 48,577,839	\$ 87,094,408	ş -	\$ 41,243,156					
	SRNL study S-I capital with SRNL/GA flowsheet efficiency		42%	4.04	\$ 424,438,71	8 \$ 436,040,117	\$ 41,758,610	\$ 142,455,120	\$ 48,577,839	\$ 113,582,138	ş -	\$ 41,243,156					
	CEA capital cost with CEA ref. flowsheet efficiecncy		36%	12.53	\$ 2,755,253,65	2 \$ 3,199,411,935	\$ 172,525,354	\$ 208,838,400	\$ 48,577,839	\$ 87,094,408	ş -	\$ 41,243,156					
	Revised Shaw base case with Ta material reduced in HI section		25%	6.87	\$ 812,150,75	0 \$ 962,518,000	\$ 66,441,738	\$ 289,080,000	\$ 29,872,243	\$ 113,532,904	\$ 18,705,596	\$ 41,243,156					
	Revised Shaw base case with Ta material reduced in HI section and lower equipment and material capital costs		25%	6.24	\$ 553,341,32	2 \$ 826,693,909	\$ 56,208,881	\$ 289,080,000	\$ 29,872,243	\$ 113,532,904	\$ 18,705,596	\$ 41,243,156					
	Revised Snaw case with Ta reduced, lower equipment and material capital costs and SRNL/GA flowsheet efficiency		42%	4.94	\$ 553,341,32	2 \$ 826,693,909	\$ 57,229,216	6 \$ 142,455,120	\$ 48,577,839	\$ 113,582,138	\$ -	\$ 41,243,156					
Hybrid Sulfur	Shaw NGNP HPAS		32%	6.83	\$ 395,549,00	0 \$ 522,416,000	\$ 50,105,323	\$ \$ 316,003,516	\$ 18,001,707	\$ 122,072,076	\$ 26,375,066	\$ 37,302,727		2			
	Shaw case with revised energy cost parameters		32%	5.19	\$ 395,549,00	0 \$ 522,416,000	\$ 50,105,323	\$ \$ 242,825,323	\$ 18,001,707	\$ 65,163,420	\$ 26,375,066	\$ 37,302,727					
	Shaw case with revised energy cost parameters and lower equipment and material capital costs		32%	4.95	\$ 338,222,18	7 \$ 446,106,457	\$ 47,379,980	\$ 240,099,980	\$ 18,001,707	\$ 65,163,420	\$ 26,375,066	\$ 37,302,727					
	Shaw case with revised energy cost parameters, lower equipment and material capital costs and double electrolyzser cost		32%	5.39	\$ 507,394,18	7 \$ 446,106,457	\$ 51,101,766	\$ 243,821,766	\$ 18,001,707	\$ 65,163,420	\$ 26,375,066	\$ 37,302,727					
	Shaw case with revised energy cost parameters, lower equipment and material capital costs and improved efficiency		33%	4.45	\$ 395,549,00	0 \$ 522,416,000	\$ 45,757,101	\$ 203,787,501	\$ 18,001,707	\$ 56,744,458	\$ 26,375,066	\$ 37,302,727					
	SRNL Icarus capital costs		32%	4.35	not b	oken-out	\$ 39,324,318	\$ 232,044,318	\$ 18,001,707	\$ 65,163,420	\$ 26,375,066	\$ 37,302,727					
	SRNL Icarus capital costs and improved efficiency		33%	3.87	1000		\$ 37,701,392	\$ 195,731,792	\$ 18,001,707	\$ 56,744,458	\$ 26,375,066	\$ 37,302,727					
High Temperature																	
Electolysis	Shaw NGNP HPAS		35%	6.04	\$ 274,161,00	0 \$ 234,690,000	\$ 39,196,014	\$ 138,729,492	\$ 30,608,704	\$ 224,887,754	ş -	\$ -		3			
	energy cost parameters		35%	4.34	\$ 274,161,00	0 \$ 234,690,000	\$ 39,196,014	\$ 96,360,000	\$ 30,608,704	\$ 163,663,083	\$-	\$-					
	cost parameters and O2 credit Shaw case with revised energy cost		35%	4.17	\$ 274,161,00	0 \$ 234,690,000	\$ 39,196,014	\$ 96,360,000	\$ 30,608,704	\$ 163,651,000	\$-	\$ 18,651,364					
	parameters and lower equipment and material capital costs Shaw case with revised energy cost		35%	4.23	\$ 241,995,02	3 \$ 200,592,000	\$ 37,701,366	\$ 96,360,000	\$ 30,608,704	\$ 163,663,083	\$ -	\$-					
	parameters and lower equipment and material capital costs and O2 credit		35%	4.06	\$ 274,161,00	0 \$ 234,690,000	\$ 37,701,366	6 \$ 96,360,000	\$ 30,608,704	\$ 163,663,083	\$ -	\$ 18,651,364					
	parameters, 02 credit, remove sweep gas system and change PCS efficiency to 50% Shaw case with revised energy cost		35%	4.24	\$ 419,660,02	3 \$ 200,592,000	\$ 40,748,356	\$ 96,360,000	\$ 30,608,704	\$ 163,663,083	\$-	\$ 37,302,727					
	parameters, O2 credit and remove sweep gas system Shaw case with revised energy cost		36%	3.81	\$ 225,544,00	0 \$ 234,690,000	\$ 37,919,324	\$ 96,360,000	\$ 30,608,704	\$ 152,189,395	\$-	\$ 37,302,727					
	parameters, O2 credit, remove sweep gas system and lower equipment and material costs Shaw case with revised energy cost		36%	3.73	\$ 209,584,01	4 \$ 200,592,000	\$ 36,861,009	\$ 96,360,000	\$ 30,608,704	\$ 152,189,395	\$-	\$ 37,302,727					
	parameters and lower equipment and material capital costs, O2 credit and double electrolyzer cost		36%	3.59	\$ 209,584,01	4 \$ 200,592,000	\$ 38,508,644	\$ 96,360,000	\$ 30,608,704	\$ 127,698,485	\$-	\$ 37,302,727					
	parameters and resized for no import electricity		35%	6.58	\$ 274,161,00	0 \$ 234,690,000	\$ 32,541,460	\$ 96,360,000	\$ 30,608,704	\$ -	ş -	\$-					

Figure 26 - Detail Sheet from Data Base

8 Conclusions

First versions of the framework for evaluation took into account the capital cost elements and the operating and maintenance costs of the hydrogen process plant concepts as estimated based generally on inputs from the three technology development groups. Due to the early state of development, these inputs had associated with them wide ranges of uncertainty. In addition to the technical uncertainty factors, additional uncertainty was due to the key technical input data coming from three separate sources.

The Westinghouse NGNP team Hydrogen Plant Alternatives Study (NGNP Study) resulted in a set of pre-conceptual/conceptual designs for the three NHI production technologies prepared by the same team and more reliably to the same level of detail with the same underlying assumptions. The study incorporated the most up to date inputs from the three technology development groups, and this input was filtered through critical review by the Shaw team. Their study includes economic data that was intended to feed into the development of the ongoing NHI framework data base that is the subject of the work reported herein. Because it forms the basis for the framework data base and for the economic evaluations in this report, the NGNP Study design work has been summarized in Section 3.

The hydrogen price analysis in the Shaw report is a first attempt to compare the three technologies on a uniformly fair basis. The selling prices for hydrogen resulting from that analysis are quite high. The study was an ambitious effort accomplished on a limited budget and a demanding schedule. When the study work was concluded in January there was no opportunity for iteration with the technology development groups. The economic analysis results are summarized in Section 5. The economic output from the study includes the resulting hydrogen price and selective sensitivity analyses. This included sensitivity to reactor outlet temperature. That is a particularly interesting result, because although a uniform reactor outlet temperature of 950°C was the given NGNP basis at the time, after the study was concluded other work was initiated giving consideration to lower reactor temperature.

The high hydrogen selling cost from the NGNP Study appeared to be a result of some systematic conservatism and several debatable assumptions about the various hydrogen production technologies. These are discussed in Section 6.1. A collection of analytical results for various alternative evaluations based on the NGNP Study is discussed in Section 6.4, and a new set of hydrogen prices for these Re-assessed Cases were calculated. These Re-assessed Cases are reproduced in Table 16.

A final set of further revised economic factors and technical parameters was proposed for calculations to support the NGNP Hydrogen Production System Down-Selection workshop. These Additional Cases are discussed in Section 6.5, and the resulting hydrogen prices for 950°C reactor outlet temperature are also included in Table 16.

	Selling Price of Hydrogen (\$/kg H ₂)								
	Re-assessed	Additional (Down-							
	Cases (Case 3)	Selection) Cases							
Sulfur-Iodine (S-I)	7.27	5.84							
Hybrid Sulfur (HyS)	4.95	4.69							
High-Temperature Electrolysis (HTSE)	4.23	5.69							

Table 16 - Nuclear Hydrogen Prices (950°C ROT)

8.2 Comparison between NHI Technologies

The formal approach taken to evaluate nuclear hydrogen technologies provides useful results for comparison of the various technologies.

The range of relative variation in product hydrogen price in the evaluations is the result of several factors. One of the most significant is the uncertainty of new technology performance in flow sheets and simulation models that drive the process efficiency. These uncertainties are expected at the early development and demonstration phase, but the technology must mature further and simulation models need to be better supported before the uncertainties in product price can converge.

There is a trend, however, that hydrogen selling price is generally lowest for HTSE, middling for HyS and usually highest for S-I. As shown in Table 16, the S-I process stands out more prominently in analyses using some assumptions and not others.

For the unique and high-technology equipment in the systems – the sulphuric acid decomposer in S-I and HyS and the two different electrolyzers in HyS and HTSE – costs of equipment in the eventual commercial plant are based on development targets and only weakly derived from examination of fabrication technologies and manufacturing details. This is a manifestation of the immaturity of the designs, which need further iteration and refinement within the current development and demonstration phase.

One additional factor is the issue of performance stability and the associated costs for refurbishment, repair or replacement of components with lifetimes shorter than the overall plant. None of the laboratory experiments to date for S-I, HyS or HTSE has run long enough and provided data that can be used to quantify degradation factors or lifetimes. Performance variation with time and limited lifetimes of components can be factored into the analysis, particularly as operating cost and replacement capital inputs.

8.3 Comparison to Other Hydrogen Technologies

The nuclear hydrogen technologies can be compared to alternative, hydrogen production technologies. Such alternatives are represented by a set of baseline technologies and detailed in Appendix C. The first is hydrogen production from SMR using natural gas, and the other is hydrogen production with ambient temperature electrolysis. The baseline hydrogen production from low temperature electrolysis is
further divided into current state-of-the-art low pressure, alkaline electrolysis and a future case with advanced electrolysis.

Figure 27 shows the three NHI hydrogen technologies compared to conventional and advanced electrolysis as a function of electricity price. Note that these plots are in terms of today's electricity price escalated going forward at 1% per year, and the hydrogen price is the lifetime levelized value. The cases used for the three nuclear hydrogen technologies are based on those from Section 6.4 as indicated in the figure legend.

As shown in the figure, all of the nuclear technologies produce hydrogen at lower prices for electricity prices above 60 \$/MWh versus advanced electrolysis and above 45 \$/MWh compared to current electrolysis costs.



Figure 27 - Hydrogen Prices Compared to Ambient Temperature Electrolysis

The similar comparison to advanced SMR is plotted in Figure 28. Note that these plots are in terms of today's natural gas price escalated going forward at 2% per year, electricity starting at 60 \$/MWe escalated at 1% per year and CO₂ costs as indicated escalated at 1% per year. The nuclear technologies produce hydrogen at lower prices for natural gas prices between 10 and 14 \$/MMBtu for the three nuclear systems. While the price of natural gas has recently gone below 4 \$/MMBtu, the decline is a consequence of the current recession, and futures prices for a year from now are at about 8 \$/MMBtu, Volatility has in the past few years been within the range of 7 to 10 \$/MMBtu with a spike to 12 \$/MMBtu (see Appendix C). Hence, nuclear hydrogen development is a worthy hedge against the uncertainty of such future prices.



Figure 28 - Hydrogen Prices Compared to Steam-Methane Reforming

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APPENDIX A - H2A MODELING TOOL

Background

In 2003/2005 the DOE offices of Energy Efficiency and Renewable Energy (EE), Fossil Energy (FE), Nuclear Energy (NE) and Science (SC) conducted the H2A Production Analysis study, which developed the H2A modeling tools.

The H2A Production Analysis modeling consists of "tools" in two formats: one to assess the cost of producing hydrogen in central plants and one for forecourt (filling station) hydrogen production. Each of these tools was used to evaluate a number of hydrogen generation processes. The work looked at a range of non-nuclear and nuclear hydrogen generation processes, and it considered various technologies for near-term utilization and for projected technology readiness out to 2030.

The DOE H2A Production Analysis

As of the date of this report, a significant part of the H2A work product is available at the Internet website:

http://www.hydrogen.energy.gov/h2a_production.html

On the website are details of the assumptions and ground rules for the development of the tools and copies of the tools, which are in the form of Microsoft Excel spreadsheets. Hydrogen production models are divided into two categories – centralized production systems and "forecourt" production systems (those for generation of hydrogen at sites for fueling hydrogen-powered vehicles). There are thirteen specific cases for centrally generated hydrogen technologies. These are the current and future production technology case studies: biomass, coal with and without CO_2 capture and sequestration, natural gas with and without CO_2 capture and sequestration, and conventional electrolysis with grid or locally generated electricity. In addition the site has a case of future central hydrogen production from nuclear energy with high-temperature electrolysis, which is derived from the work last reported on this contract/purchase order [Ref. 1].

The inputs for the H2A tool for all cases require the user to define several characteristics of the process being studied, including process design, capacity, capacity factor, efficiency, feedstock requirements, capital costs, and operating cost. The tool includes agreed-upon H2A reference values for several financial parameters, but the user is also given the opportunity to vary parameters such as internal rate of return, plant life, feedstock costs, and tax rate, to examine the technology using their own basis. The calculation part of the tool uses a standard discounted cash flow rate of return analysis methodology to determine the hydrogen selling cost for the desired internal rate of return, which is the main result of the exercise.

As an example of the computational model, Figure A1 shows the cash flow for a typical all-equity case in which the first three years constitute the plant construction and the plant operating life is thirty years. The cumulative cash flow grows more negative until

plant startup in the third analysis year. The flow is negative until about the twelfth year. The small plateau at the twenty-third year is the result of lengthy a twentieth operating year outage for refurbishment.



Figure A1 – Cash Flow Example: HyS Base Case 3

APPENDIX B - Economic Ground Rules

For nuclear hydrogen production, the financial parameters are drawn from the past H2A effort as applicable for this current effort, with the following modifications:

- Reference year dollars are 2007, versus 2005.
- Cost estimates from prior years are updated proportionally to the US Consumer Price Index (U.S. Department of Labor, Bureau of Labor Statistics) past year average to July 2007 value.
- Facility lives of 30 years of operation are applied as the analyses period for the most recent evaluatios of hydrogen production systems reported herein. A 40-year lifetime was used in earlier work. Any shorter life limiting components are replaced at designated intervals.
- Annual 8,200 operating hours (93.5% capacity factor) has been applied to all production options as a common reference. A 90% capacity factor was used in earlier work.

The following remaining financial parameters are directly assumed from the past H2A effort:

- An after income tax internal rate of return (IRR) of 10% has been applied as a reference value. The sensitivity of the levelized hydrogen price to the IRR is determined for the range of IRR from zero to 25%.
- An effective income tax rate of 38.9 % is applied based on a federal tax rate of 35% and a state tax rate of 6%.
- Accelerated depreciation facility lives of 20 years and the Modified Accelerated Cost Recovery System (MACRS) schedule per the IRS code are applied for the energy source plants, as well as the hydrogen production plants.
- The analyses have zero inflation rate. In the Discounted Cash flow (DCF) model, the results are deflated back to reference year dollars so inflation is nominally irrelevant, but it refines the depreciation costs and the related after income tax cash flows.
- 100% equity financing is selected for the reference cases, with sensitivities for various debt financing considerations.
- All nuclear production concepts are assumed to be commercially mature and have been evaluated for a consistent 2030 to 2070 service timeframe.
- Capital cost contingency adjustment is made to the total initial capital cost such that the resulting cost represents a mean or expected value. This cost is the baseline value from which hydrogen price sensitivity can be calculated. Periodic replacement capital includes the same contingency.
- A nominal three year construction period is applied with 25%, 40% and 35% of the costs incurred respectively
- Periodic capital replacements, e.g. the intermediate heat exchangers, are added to the capital cash flow and depreciated over the useful lives. In addition, an allowance for an annual capital replacement of 0.5%/year is included. The H2A DCF analyses

apply both periodic and annual capital replacements rigorously with their respective depreciation schedules.

- A constant site size of 400 acres has been applied for all options at an assumed unit cost of 5000 \$/acre.
- Salvage values are 10% of total initial capital costs after the 40 year plant life.
- Working capital is accounted as 15% of the yearly increase in operating costs.
- An average burdened labor rate of 50 \$/hour, plus a 20% G&A adder, have been applied consistently for the plant staffs, which are estimated separately for the different options along with the respective maintenance cost estimates.
- Property taxes and business insurance are consistently estimated based on 2%/year of the total initial capital costs.
- Sales taxes are not included on basis that facilities and related purchases are wholesale and through a general contractor entity.
- Plant startup is considered to occur over one year. In that period, revenues are assumed to be 50% of subsequent full-year revenues and variable costs are assumed to be 50% likewise. Fixed annual costs are taken at 100% in the startup year.
- The delivery pressure at all production plant gates is consistently 21 bar (300 psig). If a significantly higher pressure is inherent to the process, a pumping power credit is applied for pressure greater than 300 psig.
- No central storage is included at the production plants other than buffer storage, as required for efficient operations.
- Hydrogen purity specifications are based on current PEM fuel cells projected for mass vehicular applications, which include 98% minimum hydrogen content, CO < 10ppm, sulfur < 10ppm, etc.
- CO₂ capture and sequestration is properly applied as a cost to emitting technologies, but it can also enter in to the evaluation of the nuclear hydrogen cases as a credit. In accordance with the H2A modeling ground rules sensitivity included at 27.3\$/tonne CO₂ (100\$/tonne C).
- Oxygen byproduct credit is included in the reference cases. The reference credit to be applied at 40 \$/MT, which is about today's industrial oxygen price on the basis of expected market saturation.

APPENDIX C - Non-Nuclear Baselines

Although the primary objective of the work reported has been the development of the nuclear hydrogen production cost framework, the framework is being presented with input parameters that are the current results of a best effort to model the leading candidate technologies. These cases and the source data are discussed in the next sections, and the results in terms of hydrogen selling price show no clear advantage to any one of the nuclear hydrogen technologies - relative to each other. In addition, the nuclear hydrogen technologies need to be compared relative to the alternative, hydrogen production technologies.

Such alternatives are represented by a set of baseline technologies. The first is hydrogen production with low temperature electrolysis and the other is hydrogen production from natural gas. The baseline hydrogen production from low temperature electrolysis is further divided into current state-of-the-art low pressure, alkaline electrolysis and a future case with advanced electrolysis. The baseline hydrogen production from natural gas is further divided into current steam methane reforming and a future reforming technology case including CO_2 sequestration.

In summary, there are four baselines, as itemized in Table C 1 and described further following.

Conventional Alkaline Electrolysis		
Advanced Electrolysis		
Conventional Steam Methane Reforming		
Advanced Reforming Case with CO ₂ Sequestration		

Table C 1 - Baseline Cases Evaluated

Conventional Alkaline Electrolysis

Commercial-scale electrolysis is a relic of the early and mid-20th century, in the period before natural gas became relatively inexpensive and available. It is dependent on inexpensive electricity, and generally found use where hydroelectric power would be abundant. The significant supplier of these electrolysis units is a division of Norsk Hydro, the large aluminum and energy company in Norway. The cost for conventional alkaline electrolysis in Figure C1 is based on data from Norsk [Refs. 35, 36 & 37]. Key factor in this calculation is a base electrolyzer cost of 660 \$/MWe.

Advanced Electrolysis

Water electrolysis for production of hydrogen and oxygen in small batches and particularly at high levels of purity can entail another technology. It is essentially the reverse of the leading hydrogen fuel cell technology, known alternatively as Proton Exchange Membrane or Polymer Electrolyte Membrane cells (either way using the acronym, PEM). This is the generally the reverse of the leading technology for vehicle PEM fuel cells.

Since the start of the national and international research and development efforts for the Hydrogen Economy, the scale-up of these technologies has been an important objective. One goal is the use of either alkaline or PEM electrolyzers that operate at high pressure to match the pressure of prospective vehicle fueling systems.

The DOE has published goals for water electrolysis for a total system cost (electrolyzers plus supporting systems) as low as 125 \$/kWe [Ref. 38]. The proponents of automotive PEM fuel cells cite a cost goal for the cell stacks of 30 \$/kWe [Ref. 39]. Several manufacturers of smaller PEM electrolysis units are proposing scale-up and efficiency improvement. Norsk Hydro has added a product line of PEM electrolyzers. General Electric has a recent initiative in low cost alkaline electrolyzers. However, no definite progress on lower cost or higher efficiency in large units has been apparent. For the calculation in Figure C 1, the DOE nearer term (2025 time frame) of 300 \$/kWe [Ref. 40] was used – but with a baseline context of an ambitious goal.



Figure C 1 - Baseline Hydrogen Price for Electrolysis

Steam Methane Reforming

The incumbent baseline for bulk hydrogen is based on the conventional SMR process with natural gas as feedstock and fuel for the reaction. The process involves a catalytic conversion of the hydrocarbon and steam to hydrogen and carbon oxides. This is the process used for 80 to 90% of the 45 million metric tons produced annually worldwide. In present applications, resulting CO_2 is released to the atmosphere.

The price calculation uses the DOE H2A Production Analysis case posted on the DOE Internet website for current hydrogen production from natural gas without CO_2 sequestration [Ref. 41]. (Refer to Appendix A for discussion of the DOE H2A Production Analysis.) The result is shown in Figure C 2.

Advanced Reforming Case with Sequestration

Advanced technologies for reforming natural gas into hydrogen include Partial Oxidation (POX) with oxygen and Autothermal Reforming (ATR). Both have the advantage of being exothermic, and therefore, they do not have the CO₂ emissions that come from the combustion of natural gas to power the process. Both have the disadvantage of requiring oxygen from an air separation plant, which is energy intensive, although there is the prospect of using Oxygen Transport Membranes (OTMs) to supply O₂ from air with elimination of the air separation.

However, the opinion of experts participating in the H2A Program is that even out to 2030, steam reforming of hydrocarbons will continue to be the most efficient, economical, and widely used process for production of hydrogen and hydrogen/carbon monoxide mixtures. Other technologies have not been shown to improve efficiency over the commercial SMR process.

Future SMR is projected to have some improved efficiency, but today's process efficiency is already 70% of theoretical (base on Hight Heating Value [HHV]). Future efficiency of conversion in the analysis is projected to improve to 80%.

Future SMR, however, is modeled with added CO_2 capture and sequestration. Only the CO_2 in the process product stream can be captured easily, and so the approximately 5% of CO_2 that comes from combustion for process heat escapes up the burner stack. Capture from SMR product stream is not a costly added feature, because the process in any case requires separation of the CO_2 from the hydrogen product stream. An amine wash "acid gas" recovery system is utilized, where the CO_2 is separated by chemical absorption on circulating scrubbing liquid such as a mix of dimethyl ethers of polyethylene glycol at high pressure (the commercial Selexol process). But the larger part of the cost associated with CO_2 capture is the compression of the gas, transport and actual sequestration. This cost is less of a capital cost element and more of an operating cost for parasitic energy to accomplish the removal.

The model used for the generation of the Advance SMR calculation in Figure C 2 is an unpublished H2A analysis done contemporaneously with the case from the DOE Internet website for current hydrogen production from natural gas without CO_2 sequestration [Ref. 42].



Figure C 2 - Baseline Hydrogen Price for SMR

The independent variables in the baseline hydrogen price calculation are the costs of electricity and of natural gas. Electricity generation to industrial users vary over a wide range dependent on regional supply costs. While electric energy cost is rising, various reliable sources can be found to predict future costs.

Natural gas prices are and have been in recent years highly volatile. The natural gas price varies seasonally and also to market forces. Figure C 3 shows the price of natural gas on a steep rise over the past five years. This year prices have varied from under 6 \$/MMBtu to over 8 \$/MMBtu. As of this writing (September) the price is at a yearly low of 5.80 \$/MMBtu, due to the low demand of gas for heating in summer. However, natural gas futures for the forthcoming winter months are at about 8 \$/MMBtu.

Superimposed on the price trends of recent years in Figure C 3 are the US DOE Energy Information Agency (EIA) price projections. While these predictions are relatively flat, the successive releases of their Energy Outlook shows continuation of a definite upward trend. Finally, superimposed in the figure are plot lines of real escalation of the price of gas at 0%, 1% and 2% from a value today of 6 \$/MMBtu.



Figure C 3 - Natural Gas Prices

APPENDIX D - Presentation to Down-Selection Workshop

A presentation summarizing the contents of this report, excepting the Additional Cases in Section 6.5, was made to the NGNP Hydrogen Production Technology Down-Selection Review Team [Ref. 3] in Denver on 22 June 2009. The PowerPoint graphics for that presentation are embedded following.



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Framework for Economic Evaluation of Nuclear Hydrogen Production

