NGNP-20-RPT-006 Revision 0

January 2007

## NGNP and Hydrogen Production Preconceptual Design Report

## SPECIAL STUDY 20.7: NGNP BY-PRODUCTS AND EFFLUENTS STUDY

**Revision 0** 

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## **BACKGROUND INTELLECTUAL PROPERTY CONTENT**

Section	Title	Description
NONE		NONE

## **REVISION HISTORY**

## **RECORD OF CHANGES**

Revision No.	<b>Revision Made by</b>	Description	Date
0	Charles O. Bolthrunis	Initial Issue	January 2007
	Shaw Energy & Chemicals		-

## **DOCUMENT TRACEABILITY**

Created to Support the Following Document(s)	Document Number	Revision
NGNP and Hydrogen Production	NGNP-01-RPT-001	0
Preconceptual Design Report		

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## ACRONYMS

CCTP	Climate Change Technology Program
GDP	Gross Domestic Product
H <sub>2</sub>	Hydrogen
HPS	Helium Purification System
HTSE	High-Temperature Steam Electrolysis
HyS	Hybrid Sulfur
IDL	Idaho National Laboratory
IHX	Intermediate Heat Exchanger
IRP	Integrated Resource Plan
JAEA	Japan Atomic Energy Agency
MHIL	Mitsubishi Heavy Industries Ltd
MHR	Modular Helium Reactor
NGNP	Next Generation Nuclear Plant
PBMR	Pebble Bed Modular Reactor
PCHXs	Process Coupling Heat Exchangers
PNW	Pacific Northwest
SCFD	Standard Cubic Feet per Day
SCFY	Standard Cubic Feet per Year
SI	Sulfur Iodine
SMR	Steam Methane Reformer
SNL	Sandia National Laboratories
SOEC	Solid Oxide Electrolysis Cells
THTR	Thorium High Temperature Reactor
VLE	Vapor-Liquid Equilibrium
WECC	Western Electricity Coordinating Council
WSP	Water-Splitting Plant
WST	Water-Splitting Technologies

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## 20.7 NGNP BY-PRODUCTS AND EFFLUENTS STUDY

## SUMMARY AND CONCLUSIONS

The objective of this study is to identify and quantify the products, by-products and waste streams produced by the NGNP and Hydrogen Plant and to identify potential markets or other disposition of these streams. Three different water-splitting technologies were considered for hydrogen production in this study: High Temperature Steam Electrolysis (HTSE), Hybrid Sulfur (HyS) and Sulfur-Iodine (S-I) processes.

To identify markets and quantify the products, by-products and waste streams, the size of the NGNP and Hydrogen Plant was first established. The Hydrogen Plant will be a commercial demonstration and must therefore demonstrate the following:

- Commercial materials of construction, component parts, and corrosion conditions
- Transport phenomena at a scale large enough to give experienced engineers assurance of a successful design
- Commercially manufactured catalyst(s)
- Long-term operability, product capacity, and product purity and marketability using commercially available feedstocks
- Interactions with upstream and downstream integrated units replicating the full-scale plant
- Commercial maintenance and reliability goals.
- A basis for estimating equipment capital and plant operating costs.

#### **Hydrogen Plant Size**

In the case of the Hydrogen Plant, there are two size limits that were considered in demonstrating the hydrogen production technology: the smallest practical scale to meet the requirements of a commercial demonstration and a single train of a full-scale plant. Materials development and specific component manufacturing techniques for some of the equipment are not fully developed and will limit fabrication capabilities. Most of the demonstration criteria will be met if the hydrogen plant is large enough to demonstrate that the critical pieces of equipment for each process can be fabricated. The definition of critical equipment here is that piece of equipment that limits the maximum capacity of the train and that is expected to pose a challenge with respect to one or more of the demonstration criteria.

The reference designs show that the critical pieces of equipment in almost all cases were process-coupling heat exchangers. One of these was the Decomposition Reactor in the HyS and S-I processes. Because current data shows this to be heat-transfer limited, it was treated as a heat exchanger. Using heat exchanger scaling considerations, including the concept of the equivalent hydraulic diameter, the following thermal duties were judged to correspond to the smallest

practical Hydrogen Plant required for commercial demonstration and for a single train of a commercial plant. The HyS and S-I production rates should be the same for Process-Coupling Heat Exchangers (PCHXs) of the same duty. Differences shown are due to differences in assumptions in the source material.

Process	Critical Equipment	Smallest Practical Total PCHX Thermal Duty (MW <sub>th</sub> )	Commercial Train Total PCHX Thermal Duty (MW <sub>th</sub> )
High Temperature Electrolysis	Super Heater Heat Exchanger	13	13
Hybrid Sulfur & Sulfur Iodine	Sulfuric Acid Decomposer	5	50

Although the smallest practical Hydrogen Plant required for commercial demonstration will meet most of the technical demonstration criteria, it will not challenge the interaction between the nuclear reactor and the hydrogen plant. A 50 MWth process coupling heat exchanger will be a full scale unit. A nuclear powered water-splitting plant will use at most approximately 200 MW<sub>th</sub> of the 500 MW<sub>th</sub> output from a Pebble Bed Modular Reactor (PBMR). Such a plant will have no fewer than three or four trains of 50 to 66MW<sub>th</sub>. This will be determined either by limits to fabrication capabilities for the process coupling heat exchanger or by availability and reliability considerations. Therefore, changes in demand on the nuclear heat source due to failures in the hydrogen plant will be in approximately 50 to 66 MW<sub>th</sub> increments. A 50 MW<sub>th</sub> demonstration plant can replicate the effect of demand swings on the heat source, while a 5 MWth plant cannot. Moreover, a small plant will not be an important step in demonstrating this technology to the public and in introducing the hydrogen economy. For these reasons, a 50 MW<sub>th</sub> single commercial train demonstration is recommended for the HyS or S-I process. It was also determined that for the HTSE process, the smallest practical demonstration plant was the same size as a commercial train. Using the above sizing criteria, product hydrogen and by-product oxygen production rates are estimated to be as follows for each hydrogen production technology.

	Hydrogen Production (x10 <sup>6</sup> SCFD)		Oxygen Production (x10 <sup>6</sup> SCFD)	
Technology	Smallest Practical	Commercial Train	Smallest Practical	Commercial Train
High Temperature Electrolysis	8.0	8.0	4.0	4.0
Hybrid Sulfur	0.71	7.1	0.36	3.6
Sulfur Iodine	0.97	9.7	0.48	4.8

#### **Potential Markets**

Whatever technology or size is chosen for hydrogen production, electric power will be a major product of the NGNP. Forecasts for both the cost of a number of potential resource alternatives and market clearing prices in the Idaho region suggest a constant price of \$60/MWe for NGNP electricity. This would result in long-term annual revenue of \$71 million. A preliminary market analysis indicates there are limited opportunities for distributing the product hydrogen from the NGNP into the local market within reasonable transportation distances of the INL site. Hydrogen and oxygen production even from the smallest practical hydrogen plants for HyS or SI would be difficult to distribute and would exceed potential industrial demand. It would therefore be appropriate to use the NGNP hydrogen production to fuel a fleet of hydrogen-powered vehicles. This is a market that is non-existent today, but the NGNP hydrogen plant could encourage its emergence. If this could be achieved, an additional long-term revenue stream of \$11 million per year might be realized.

#### **Post-Production Gas Purification**

Post-production purification of the hydrogen required by any of these markets will be substantial. Hydrogen purity requirements are generally 99.9% or greater. The High-Temperature Steam Electrolysis (HTSE) has less demanding requirements in this regard.

For HyS and S-I processes, caustic scrubbing of the gases followed by a disposable adsorbent bed will be required to remove sulfur compounds and iodine species, as appropriate. For all processes, the final step will require an additional drying.

#### Wastes

Daily operations at any facility will generate both liquid and solid waste streams requiring onsite treatment and disposal or offsite disposal, as the case may be. Anticipated waste streams associated with the nuclear reactor and the various hydrogen production technologies will include the following:

#### Nuclear Reactor Wastes & Emissions

■ Tritium removed from the Helium coolant (≈115 Ci/yr)

Radioactive waste material from core components

#### Hydrogen Production

- Gas purification wastes (i.e., caustic liquid wastes, spent carbon)
- Process stream blowdown
- Cooling system blowdown
- Pump seal water
- Solid waste (i.e., spent electrolyzers, absorber packing and catalysts)

#### **Balance of Plant Waste Streams**

- Feed water treatment process wastes (i.e., backwash/reject waste water)
- Spent water treatment media/membranes/resins
- Miscellaneous solid and universal waste
- Potentially contaminated storm water
- Oily wastes
- Sanitary wastes

The appropriate methods for treating or disposing of these wastes will need to be determined as the facilities' design approaches maturity.

#### **Recommendations**

- 1. The size of the NGNP Hydrogen Plant should be a full commercial train.
- 2. A local market for the product hydrogen must be developed. A fleet of buses using hydrogen in internal combustion engines should be investigated. A clear product specification for this market should be developed.
- 3. Feed pre-treatment, product purification, waste treatment and disposal should be included in the Hydrogen Plant conceptual design.
- 4. Focus research and development by selecting a preferred NGNP water-splitting technology by the beginning of the NGNP Conceptual Design Phase and executing a process design for the hydrogen plant including items in Recommendation 3.
- 5. Focus attention on developing practical flowsheets, gathering vital thermodynamic and phase equilibrium data, obtaining converged mass and energy balances, developing materials of construction, equipment design and involving industrial partners in the effort.

## INTRODUCTION

The objective of this study is to identify and quantify the products, by-products and waste streams produced by the NGNP and Hydrogen Plant and to identify potential markets or other disposition of these streams. Quantification as well as characterization of these streams is necessary to identify markets or proper disposal. Therefore, the capacity of the hydrogen plant must be estimated to quantify products and waste streams. This, then, is the first task undertaken by this study. The hydrogen plant is intended to be a commercial demonstration and must therefore meet all the appropriate requirements for such an installation. This study enumerates these requirements, determines the smallest practical size that could be considered for such a plant, and considers an option of making the demonstration a full-scale commercial train. These options are considered for each of the leading water-splitting technologies: High-Temperature Steam Electrolysis (HTSE), the Hybrid Sulfur thermo-electrical cycle (HyS) and the Sulfur-Iodine thermo-chemical cycle (S-I).

Once the hydrogen and oxygen capacities are identified, potential markets for these gases as well as the power generated are surveyed and potential revenue streams estimated.

In addition, industrial gas markets depend upon the purity of the products produced. Achieving the required purity generally requires further processing. Additional purification processing of the products is therefore identified for each of the products and water-splitting technologies. Furthermore, this additional processing usually produces additional waste streams that may not be evident from the main process mass balances.

The nuclear reactor, hydrogen production and product purification generate wastes that must be disposed of properly. This study finally examines the nature, quantity and disposal options for these streams.

This study makes recommendations in those cases for which it is possible at this early stage of design development. In several other cases, firm recommendations are not advisable. In those cases, further study is recommended along with directions that the study might take.

## 20.7.1 SIZE OF THE NGNP PROTOTYPE HYDROGEN PLANT

This study assumes that the heat is supplied to the hydrogen plant at its battery limits at 900°C in the form of hot helium and is returned to the heat transport system. It also assumes that the heat transport medium is carried in a secondary loop and therefore does not pass through the core of the PBMR. Only the equipment in the hydrogen plant itself is considered. This choice has been made because it appears clear that the design, fabrication, and operation of commercial scale process coupling heat exchangers (PCHXs), regardless of the technology chosen, will be at least as challenging as that of the primary to secondary loop intermediate heat exchanger (IHX). The PCHXs will have virtually the same design temperature and pressure. Moreover, the PCHXs will have fluids such as sulfuric acid, sulfur dioxide, oxygen, steam and hydrogen to handle in addition to hot helium. In some cases the PCHXs will have to be designed to contain replaceable catalyst. Choices of the heat transfer medium and of reactor outlet temperature are discussed in greater length in Special Study 20.3, <u>High Temperature Process Heat Transfer and Transport</u>, Sections 1.1 and 3.2.

There are two sizing limits that should be considered in demonstrating the hydrogen production technology. One may choose to demonstrate at a scale that is the smallest practical to meet the requirements of a commercial demonstration. Alternatively, the demonstration may be of a single train of a full-scale plant. In either case, the demonstration criteria must be met. Typical criteria for commercial demonstration are:

- Materials of construction and component parts must be those that will be used in the full-scale plant.
- Transport phenomena (heat, mass, and momentum transfer) must be demonstrated at a scale sufficiently large that the operating data will give experienced engineers adequate assurance that a full scale unit can be successfully designed and built.
- Conditions for potential corrosion and deposition of materials should be replicated.
- Reaction kinetics must be demonstrated with commercially manufactured catalyst(s).
- The plant must demonstrate long-term operability, product capacity, and product purity using commercially available feedstocks.
- The plant must demonstrate the manufacturability of the commercial-scale equipment using commercially available materials.
- The demonstration plant must provide assurance of commercial acceptance and marketability of the full-scale plant products.
- Each process unit in the demonstration should be large enough that the interactions with upstream and downstream integrated units will adequately replicate similar interactions in the full-scale plant.
- Operation of the demonstration equipment should give assurance that the full-scale equipment will meet commercial maintenance and reliability goals.

• The demonstration plant should supply a reasonable basis for estimating equipment capital and plant operating costs.

Every processing plant is made up of a series of equipment pieces connected by piping and controlled by several sensors and control valves. Each piece of equipment carries out a certain unit operation and each unit operation consists of a combination of transport phenomena, reaction kinetics, and chemical and phase equilibria. The scalability of each unit operation depends upon several factors among which are the state of knowledge of the basic physical and chemical phenomena, the range of scale of practical experience, and the practical aspects of equipment fabrication. Some operations such as heat transfer are scalable over a very wide range; others like fluidized bed reactors have a much narrower scalable range. The unit operations one would expect to find in a water-splitting plant, with few exceptions, are all widely scalable.

The ability to manufacture equipment sometimes imposes a limit to size and introduces uncertainty in equipment design, especially when new or unfamiliar materials of construction are required. In the case of water-splitting plants that will require operations at very high temperatures and pressures by petrochemical processing standards, the manufacturability of equipment will be a key issue. In the case of the hydrogen plant, most of the demonstration criteria will be met if the plant is large enough to demonstrate the manufacturability of the critical pieces of equipment. The definition of critical equipment here is that piece of equipment that limits the maximum capacity of the train and that is expected to pose a challenge with respect to one or more of the demonstration criteria. The size of that piece of equipment is frequently set by manufacturing limitations. Other equipment in the train may be of equal capacity or the train may have to be split into several sub-trains depending upon size restrictions on downstream equipment.

## 20.7.1.1 Smallest Practical Hydrogen Plant Required for Commercial Demonstration

The smallest practical demonstration size limit for the hydrogen plant is set by that piece of equipment that limits the maximum capacity of the plant. For each of the leading watersplitting technologies, the critical piece of equipment may be different. The following discussion identifies the critical equipment, limiting process parameters and estimated hydrogen production rates for each technology.

#### **High-Temperature Electrolysis**

The following analysis is based on the latest published pre-conceptual design for the high-temperature electrolysis water-splitting technology entitled, "H2-MHR Pre-Conceptual Design Report: HTSE-Based Plant" and dated April 2006.<sup>1</sup> In the case of HSTE, the solid oxide electrolysis cells (SOEC) are expected to be small and many thousands of cells will be required to fulfill the requirements of commercial production.<sup>2</sup> The critical equipment will therefore be one of the heat exchangers that generate steam from the feed water and superheat it to the required process temperature and especially one of those that handle hot hydrogen or oxygen as

well as steam. These heat exchangers are identified as " $H_2$  Recuperator," "Steam Generator," "Super Heater," "Sweep Heater," and " $O_2$  Recuperator", as shown in Figure 20.7-1.<sup>3</sup> Of these heat exchangers, the largest are the recuperators.

The recuperators account for more than half of the thermal duty required to heat the feed and sweep water from ambient temperature to the electrolyzer feed temperature. The blocks shown as single units on the flow diagram, however, must represent more than a single heat exchanger. In the case of the  $O_2$  Recuperator, 30 % of the duty is for sweep water pre-heating, 46% for vaporization, and 24% for superheating. Each of these services will probably be carried out in separate piece of equipment. Similarly, the H<sub>2</sub> Recuperator shows condensation of the water out of the product hydrogen stream on one side of the exchanger with preheat and partial boiling of the feed water on the other side. These services too would also be carried out in separate pieces of equipment. It is not clear whether a temperature versus enthalpy analysis has been carried out on this flowsheet to determine whether the temperature differences are adequate. This suggests that not all of the heat shown as recovered in the recuperators can be recovered in practice. The overall duty of the process-coupling heat exchangers (PCHXs) may therefore be somewhat higher than that shown on the diagram.

According to the energy balance shown on this flowsheet, only about 9.7% of the thermal energy from the nuclear reactor is used to preheat feeds to the electrolyzer. That suggests that efforts at improving efficiency are better spent in the areas of generating and using electrical energy rather than making an extraordinary effort to design and test the recuperators. If the design of the recuperators proves to be problematic, these services can be carried out using thermal energy supplied by the secondary helium loop. For a first demonstration, this would be the preferred course. Recuperators can be added at a later date.

Of the remaining three heat exchangers, the Super Heater appears to be the critical piece of equipment. It has the largest thermal duty and will be heating a mixture of steam and hydrogen. It will also have the most challenging thermal design and will require at least two shell passes. The boiler may have a slightly larger heat transfer area, but its design is relatively straightforward. A rough estimate of the size of the Super Heater shows that an area of about 390 m<sup>2</sup> is required. If the exchanger is constructed of typical <sup>3</sup>/<sub>4</sub> inch tubes 20 feet in length, the duty per tube is about 29kW.

For shell-and-tube heat exchangers the shell side and the tube side have different scale-up issues. As far as the tube side is concerned, a single tube, once characterized, can be multiplied indefinitely so long as the flow in each of the parallel tubes is equal. The scale-up issue on the tube-side is therefore distribution of the flow. A one hundred or more tube heat exchanger will present the tube-side flow distribution challenges that are representative of the commercial-scale design. The ratio of the tube-side head diameter to tube-side nozzle diameter should be at least about four (4). The one hundred or more tube heat exchanger will likely fit that requirement as well.

The shell side presents different issues. Common practice for designing segmental baffled shell and tube heat exchangers bases the effective shell-side heat transfer coefficient on the correlations for the heat transfer coefficient on the outside of a tube bundle in an "ideal" or fully-

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developed flow pattern. This ideal flow pattern occurs at the center of the bundle where the turbulence created by the presence of tubes upstream and downstream is no longer changing. Tubes in other locations will have somewhat different heat transfer coefficients. The effective shell-side coefficient is this ideal coefficient corrected by additional correlations for the tube bundle and baffle geometry.<sup>4</sup>

For shell side Reynolds numbers >100

## $h_{shell} = h_{ideal} * J_c * J_l * J_b$

These "J" values are the correction factors for non-ideal flow patterns that occur due to the flow turning from direct flow across the tube to flow along the tube (as in the window area of the segmental baffle) or flow leakage around or along the baffles. Increasing the diameter of the tube bundle can minimize the need for these corrections. e.g. The cross flow correction Jc is approximately 1.0 when the baffle cut to shell diameter ratio is about 25%. This 25% baffle cut is commonly used in the chemical industry.

Because the tube length is fixed by the desire to use standard manufactured tube lengths and the number of tubes used in the design of heat exchanger must be large enough to produce flow patterns that are very similar to a full scale unit the heat exchanger is likely to necessarily contain 100 or more tubes.



Figure 20.7-1 High Temperature Electrolysis Flowsheet

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In the case where the shell side heat transfer coefficient is limiting, as is expected with helium to steam heat exchangers with helium on the shell side, one would demonstrate at a scale at which the effect of the heat exchanger shell no longer has a significant impact on the flow characteristics of the tube bundle. Both heat transfer coefficients and friction factors both for axial and cross flow have been correlated with the axial hydraulic diameter for tube bundles.<sup>5</sup> Here it is used as a characteristic shell side dimension. The issue of tube side distribution cannot be settled without considerably more detailed study. The axial hydraulic diameter is defined as:

#### <u>4 x Axial Flow Area</u> Wetted Perimeter

When the shell is considered as part of the wetted perimeter, it has a significant impact on bundles with small numbers of tubes. The relationship between the number of tubes and the effect on hydraulic diameter can be seen in Figure 20.7-2. As the ratio of the hydraulic diameters increases past 0.9, the incremental increase in the ratio is decreasingly affected by the number of tubes. Therefore, the minimum size that should be considered for a commercial demonstration by this criterion would be about 100 to 200 tubes.



#### Effect of Number of Tubes on Hydraulic Diameter

Figure 20.7-2 Influence of the Number of Tubes on the Hydraulic Diameter Shell Effect

For a 100 tube Super Heater, the duty would be about 2.9  $MW_{th}$ . The corresponding duty for all three of the process-coupling heat exchangers in the secondary helium loop would be 5.7

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 $MW_{th}$ . The corresponding recuperator duty is 7.5  $MW_{th}$ . The total PCHX duty without recuperation would be 13.2  $MW_{th}$ .

Production ra	tes for this size unit:	
Hydrogen:	0.224 kg/s or 8.0 mill	ion Standard Cubic Feet per Day (SCFD)
Oxygen:	1.78 kg/s or 4.0 millio	on SCFD
Required electrolysis	power input:	28 MWe
Required cell area:		$11,400 \text{ m}^2$

The cells are arranged in stacks of 500 cells of  $100 \text{ cm}^2$  per cell. Stacks are grouped in modules of 40 stacks and the modules are organized in units of eight modules. The total plot space required for the units would be about  $250\text{m}^2$ .

#### Hybrid Sulfur (HyS)

The analysis in this section is based upon material provided by Westinghouse and prepared especially for this study. The material is attached to this report as Appendix A. The configuration of the HyS process is in some ways similar to that of HTSE (see Figure 20.7-3 and Figure 20.7-4). Each process has a step that requires high temperature heat and each also has a significant electrical input for electrolysis. In addition to electrolyzers, the HyS process requires an additional reactor, or decomposer, for sulfuric acid decomposition, towers for sulfuric acid scrubbing as well as scrubbing of the product gas streams to remove residual sulfur dioxide. In both the HyS and HTSE processes, the surface required for electrolysis is orders of magnitude larger than that required for heat transfer. A full-scale HyS plant (200MW<sub>th</sub> thermal input to the decomposer) requires approximately 30 large electrolyzer units. Each of these units will contain about 250 cells. Scale-up would be accomplished by multiplying the number of cells in a unit.

Demonstration of a unit with the full 250 cells will probably not be needed. Therefore, a unit sized for even a rather small demonstration of the decomposer will easily be able to demonstrate commercial feasibility of the electrolyzers. The critical piece of equipment is therefore not in the electrolysis section of the HyS plant. Rather, the Decomposition Reactor (R-H002) will clearly limit the production capacity of the system and be the critical piece of equipment.

None of the other heat exchangers will pose scale-up issues; their design is straightforward. Likewise, the  $H_2SO_4$  Column (A-H001) will be easily scaled. The sizing issues of this piece of equipment will involve choosing a diameter for the vapor flow, determining the number of equilibrium stages and determining the height of an equilibrium stage. The number of stages is calculated from vapor liquid equilibrium data which must be available before the plant can be designed. Both the diameter and height of an equilibrium stage depend upon the choice of contact device: the type of trays or packing. The methods for scaling up to large units from relatively small tests for these are well-known, especially for aqueous systems.

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Figure 20.7-3 Hybrid Sulfur Process -- Decomposition Section

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Figure 20.7-4 Hybrid Sulfur Process -- Electrolysis Section

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The Decomposition Reactor is the only piece of equipment that might be a challenge with respect to the scaling demonstration criteria. The reactor's heat transfer surface will probably be constructed of a ceramic material, such as silicon carbide, due to its chemical resistance and strength at high temperature. Bonding and sealing between this material and the metal shell, tubesheet, or piping will be a major item for demonstration. The heat transfer coefficient will be significantly lower and the duty higher than the other exchangers in this plant.

Four different concepts have been proposed for the commercial Decomposition Reactor. One of these concepts is a microchannel ceramic design currently being developed by Ceramatec®, an advanced materials and electrochemical technology company located in Salt Lake City, UT. Ceramatec's decomposer concept is shown in Figure 20.7-5.



Figure 20.7-5 Ceramatec® Decomposer Concept

Figure 20.7-6 shows the Ceramatec® plan for development and demonstration of this design. Their engineers expect that a successful commercial-scale unit with a duty of  $50 MW_{th}$  can be constructed once a unit of 5 to 10 MW<sub>th</sub> has been demonstrated.<sup>6</sup>

The second concept utilizes a decomposer with bundles of tubes containing catalyst. Each tube contains a smaller diameter inner to convey the reaction products (e.g.,  $SO_2$ ,  $O_2$ ,  $H_2SO_4$  and water). Bench-scale work with this decomposer design is currently being carried out at the Sandia National Laboratories on sulfuric acid decomposition<sup>7</sup>. The latest information available from them is that the reaction is heat transfer limited. Their work includes development of a commercial decomposer concept. Figure 20.7-7 shows the design of the Sandia bench-scale unit.



## Figure 20.7-6 Ceramatec® Development Path



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The third concept is a commercial-scale design being developed by Westinghouse Electric Company.<sup>8</sup> This design is in some ways similar to the Sandia design except that the flow direction is reversed: the cold sulfuric acid enters through the central tube and, after vaporization, flows through the catalyst in the annular space. Figure 20.7-8 depicts the Westinghouse concept. This concept is the reference design for this study.



Maximum Operating Pressure : Maximum Operating Temperature :

900°C

#### Figure 20.7-8 Westinghouse Decomposition Reactor Concept

The reasoning used for selecting the size of the smallest practical Decomposition Reactor required for commercial demonstration is similar to that used in the case of the HTSE heat exchangers, above. The design of this decomposition reactor is expected to be similar to a baffled shell-and-tube heat exchanger. In the case of this decomposer, the manufacture of tubes and construction of the tube bundles will be of critical concern. For this study, practical tube dimensions were selected based on conversations with a silicon carbide manufacturer.<sup>9</sup> The dimensions chosen were 63.5 mm OD for the outer, capped tube and 15.1 mm OD for the inner tube. The most important dimension is tube length. Tubes are now being manufacture dof about 4 ¼ m in length. The manufacturer thought it would not be difficult to manufacture tubes about 6 m in length. Extrapolating for development driven by need over the next ten years, 10 meter tubes were chosen. From the strength and corrosion data provided, wall thicknesses were

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calculated: 4.3mm for the outer tube and 2mm for the inner. Residence time was checked using the latest information from Sandia National Laboratory.<sup>10</sup> An estimate was made of the heat transfer coefficient and duty for each tube. From these calculations, a duty of 42.6 kW was calculated for each tube. A Decomposition Reactor with a duty of 5 MW<sub>th</sub> requires 118 tubes of this size. As recalled from Figure 20.7-2, this is a reasonable size to test pressure drop and heat transfer phenomena.

Production rates for a unit with a 5 MW<sub>th</sub> decomposition reactor (based on Appendix A: the HyS mass and energy balance):

Hydrogen:	0.0198 kg/s	or	710,000 SCFD
Oxygen:	0.157 kg/s	or	355,000 SCFD
Required electrolysi	s power input:		1.36 MWe
Required cell area:			408.5 m <sup>2</sup>

For a commercial HyS unit, the electrolysis cells are expected to be arranged in stacks of about 250 cells of 2.5 m<sup>2</sup> per cell. Each stack is contained in a rubber-lined pressure vessel with removable heads for cleaning and maintenance. Figure 20.7-9 shows a commercial Norsk Hydro electrolysis unit. Commercial HyS electrolyzers are expected to be similarly configured.<sup>11</sup>



Figure 20.7-9 Standard Norsk Hydro 5000 SCFH H<sub>2</sub> Electrolysis Unit

### Sulfur-Iodine (S-I)

The analysis in this section is based on the most recent published information on the S-I process consisting of two reports: "H2-MHR Conceptual Design Report: S-I Based Plant"<sup>12</sup> and "Centralized Hydrogen Production from Nuclear Power: Infrastructure Analysis and Test-Case Design Study."<sup>13</sup>

Examination of the flowsheets and equipment lists in these reports shows that most of the equipment consists of pumps, turbines, drums and heat exchangers. The practicality of developing turbines or expanders that will operate successfully under these service conditions is doubtful. The other types of equipment mentioned are all widely scalable. In the Bunsen reaction section, five columns are shown that act as both absorbers and reactors. The only scaling issue of concern with these columns is liquid distribution. Once the relative liquid and vapor rates are known, there are well-known methods and techniques to ensure adequate liquid distribution and interphase contact.

For the reactive distillation section, the reactive distillation column itself may be a critical piece of equipment. However, there is currently insufficient available information to make this judgment. Reaction kinetics, chemical equilibrium and vapor-liquid equilibrium data for these species at several temperatures and the operating pressure would be required to make a theoretical determination of the equipment sizing. Moreover, continuous testing in an integrated plant, especially when trace impurities are present, may well invalidate the theoretical calculations. Therefore, the reactive distillation column should be considered a critical item until shown to be otherwise. Consequently, the size of the smallest practical hydrogen plant to demonstrate production as a commercial prototype based on the reactive distillation column can not be estimated.

Since scale up of distillation can be accomplished over very broad ranges, it is probable that the sulfuric acid decomposition reactor rather than the reactive distillation column will set the size of the smallest practical demonstration plant. Analysis of the flowsheets and decomposition reactor designs shows that the functions performed by the HyS decomposition reactor are matched exactly by the blocks H208A, H208B, H209, H210A, and H210B, as shown in Figure 20.7-10, below. Differences in performance of this section between the reports representing these technologies are due to one of three causes:

- differences in heat integration schemes
- differences in maximum process temperature
- differences in the thermochemical and equilibrium data used.

Intermediate temperatures in the heat exchangers shown on the S-I flowsheet for the blocks in question are not provided. The feasibility of the heat integration scheme, therefore, cannot be judged. Equally aggressive heat integration should give equal, or nearly equal, results in both processes. The temperature of the hot helium into the decomposer is 27K higher in the S-I flowsheet than in the HyS counterpart. This is an important factor in reactor performance, but it depends upon assumptions about the nature of the nuclear reactor from which the heat is supplied and the losses in the heat transport system. Given the same assumptions about these subsystems, the maximum process temperature will be the same in both cases.

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Figure 20.7-10 S-I Process Section 2 Flowsheet

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The thermodynamic and phase equilibrium data for this system has been studied extensively by the team developing the HyS process and was used in the preparation of the mass balance used in this study.<sup>14</sup> This work was published after the publication of the S-I reports upon which this discussion is based. If an equally rigorous data development effort was made in preparation of the mass and energy balances for the S-I process, it is not mentioned in the reports. There are no substantial differences between the two processes with regard to the sulfuric acid decomposition step. With the same heat supply, decomposition will produce the same results in both processes. This section of the plant is interchangeable between the two processes as well.

Production rates for a unit with a 5 MW<sub>th</sub> decomposition reactor (based on information in Richards, *et.al.*, *SI-Based Plant*, April 2006)<sup>15</sup> :

Hydrogen:	0.0270 kg/s	or	966,000 SCFD
Oxygen:	0.214 kg/s	or	483,000 SCFD

Note that required inputs to other sections of the above processes as well as power requirements other than electrolysis have not been considered.

Mitsubishi Heavy Industries Ltd. and Japan Atomic Energy Agency have put forward a fourth alternative concept based on a tubular design for the sulfuric acid decomposer and a separate plate design for the sulfur trioxide decomposer. The scale-up principles are the same for the designs discussed here and therefore appropriate demonstration sizes for these designs are expected to be the same as those suggested above.<sup>16</sup>

## 20.7.1.2 Commercial Train

In sizing a commercial train, the question is how large, rather than how small one can make the critical piece of equipment and still have it operate successfully. For a HTSE system powered by a PBMR, about ten percent of the thermal energy from the reactor is used to heat feed steam and sweep gas provided that the heat recovery shown in the HTSE-Plant Report can be achieved.<sup>17</sup> In that case, the largest process-coupling heat exchanger would be the Boiler. The Super Heater would be nearly as large. Both heat exchangers would be reasonably sized with about 910 tubes, each tube being 19 mm in diameter and 6 meters in length. The Recuperators would be even larger, but these services would not be carried out in a single shell. A single train rated at about 50 MW<sub>th</sub> for process-coupling duty would be required for each nuclear reactor. The hydrogen production would be about 2.0 kg/s or about 70 million SCFD. This is the size of a medium-to-large sized steam reformer with an output that would provide hydrogen for a refinery. Distribution of high pressure and temperature steam to the cells and reliance on a single heat exchanger train would probably not favor a single train in a commercial unit until adequate operating experience were gained. Early commercial designs would probably favor a plant with three to four heat exchange trains delivering steam to the electrolysis cells. A

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demonstration unit would probably consist of a single train with a process coupling duty of about 13.2  $MW_{th}$ . If the demonstration did not include recuperation, this would be the same size as the smallest practical hydrogen plant required for commercial demonstration.

Presuming that the Decomposition Reactor is the critical piece of equipment for either the HyS or S-I process, we can make an estimate of the size of the largest unit. A 50 MW<sub>th</sub> decomposition reactor will have approximately 2500 ceramic fingers with each finger about 65 mm in diameter and 10 meters long. The vessel will be about  $4\frac{1}{2}$  meters in diameter and have a metal wall thickness of about 12 to 13 centimeters. From a process perspective, there are several reasons to limit the diameter of the vessel. As the number of tubes and the diameter increases, flow distribution in the tubes becomes more difficult. In addition, the baffle spacing may become small and the variation in velocity across the tube bundle will be large. Alternative shell baffling patterns have to be considered with a resulting loss in heat transfer effectiveness. From a mechanical viewpoint, there are design and fabrication limits that would be encountered, especially with regard to the tubesheet thickness. For a first commercial plant, a 50 MW<sub>th</sub> decomposer would be a reasonable choice for a train size. The production rate from one train would be 0.198 to 0.270 kg/s of hydrogen (depending upon the material balance one uses) and 0.793 to 1.08 kg/s for a four-train plant. This is equivalent to 28 to 39 million SCFD in common industrial units.

The question remains as to whether the first commercial operation of this technology should be of a commercial train or of the smallest practical plant to demonstrate production as a commercial prototype. In the petrochemical and chemical industry, the tendency is to build the smallest practical plant that will meet the demonstration goals. This provides an adequate commercial demonstration of the technology and a smaller cost and risk. In many cases, this is executed by retrofitting an existing, outmoded unit. In the case of the NGNP, there are additional considerations that are not usually encountered by process industry demonstration plants. One issue is the destination of the hydrogen and oxygen products. This will be discussed in more detail below, but it should be noted that the production of both hydrogen and oxygen from even the small demonstration units will be large with respect to the available markets. A small demonstration unit will facilitate the demonstration of several hydrogen-producing technologies at a lower cost and with less disruption. Nevertheless, there are advantages in making the first demonstration plant a commercial train.

The most important factor that must be considered is the influence of upsets in the operation of the hydrogen plant on the nuclear reactor. A small hydrogen plant will not fully demonstrate interactions with the nuclear reactor. This is not a consideration from the point of view of the hydrogen plant, but it may be important in demonstrating nuclear safety cases and in licensing issues. A 50 MWth process coupling heat exchanger will be a full scale unit. A nuclear powered water-splitting plant based on either HyS or S-I will use approximately 200 MW<sub>th</sub> of the 500 MW<sub>th</sub> output from a Pebble Bed Modular Reactor (PBMR). Such a plant will have no fewer than three or four trains of 50 to 66 MW<sub>th</sub>. This will be determined either by limits to fabrication capabilities for the PCHX or by availability and reliability considerations for the plant. Therefore, major changes in demand on the nuclear heat source due to failures in a commercial hydrogen plant will be in approximately 50 to 66 MW<sub>th</sub> increments. A 50 MW<sub>th</sub>

demonstration plant will replicate one train of a full commercial plant and therefore will imitate the effect of demand swings on the heat source. A 5 MWth plant cannot do this.

For the same or similar reasons, a commercial scale train will better replicate the configuration that will have to be licensed for any subsequent commercial plant.

In the chemical industry funding and siting are less encumbered by the need for broad understanding and acceptance than in the nuclear industry. Therefore demonstration projects are built for technical and product marketing purposes, not to gain wide support. In developing a hydrogen economy, however, broad acceptance is important and a demonstration that is convincing to the technically unsophisticated is valuable. A commercial train demonstration will be broadly convincing. It will also provide better data on plant operating costs including operating personnel as well as on security and safety. It is not possible to make a firm recommendation in this matter without a better understanding of the relative importance of these benefits and drawbacks. Unless cost and the disposition of hydrogen product are overriding concerns, a full-size train demonstration is preferred and hence recommended as the reference.

## 20.7.2 POTENTIAL MARKETS FOR NGNP PRODUCTS

## 20.7.2.1 Electricity

Whatever technology or size is chosen for hydrogen production, electric power will be a major product of the NGNP. For a 50 MW<sub>th</sub> sized commercial train for the hydrogen plant demonstration, about 160 MWe of export power would be available. When the hydrogen plant is down for a planned or unplanned outage, the maximum power for export is about 200 MWe. Power from the NGNP can be traded on the wholesale, short-term market at the Mid-Columbia trading hub or contracted to the Idaho Power Company – the regional service utility. Predicting the market or contract price of electricity when production comes on-line in 2018 timeframe relies on others' forecast and judgment. Based on discussions with personnel from the Idaho Power Company<sup>18</sup> and their Integrated Resource Plan (IRP) for 2006<sup>19</sup>, two approaches serve to bracket such a forecast. The first is based on the forecast for the levelized costs of a number of potential resource alternatives considered in Idaho Power's 2006 IRP. Using comparably sized alternatives that range from regional pulverized coal plants to geothermal plants, the 30-year levelized prices are in the range of 55 to 65\$/MWh (2006\$). The second approach applies the forecasted market clearing prices for the regional Idaho bubbles within the Western Electricity Coordinating Council (WECC), which are included in the same IRP reference. Using the Pacific Northwest (PNW) Idaho South Region for 2018, off-peak prices vary from 57 to 76\$/MWh (current year \$) over the year whereas on-peak prices vary from 76 to 108\$/MWh. Assuming a few percent underlying inflation, the off-peak prices in 2006\$ are in the same range as for the alternative generation options above. For an initial power revenue estimate, a constant price of 60\$/MWh is suggested. Using a conservative capacity factor of 85% and a 160 MWe export power level, the annual revenue would be about \$71 million /yr for a long-term projection. However, during the early years of operation, the plant is expected to have higher unplanned outages typical of first-of-a-kind plants. Moreover, the operating priorities will favor system and process testing and will therefore result in a lower capacity factor. In addition, uncertainty about availability will mean the price of the power will likely be based on a non-firm basis. Hence, for the first six years, an average capacity factor of 75% and a power price of 45\$/MWh are judged to be appropriate for initial estimates. This results in an annual revenue during that six year period of \$47 million / yr. More detailed information and sources may be found in Appendix B.

## 20.7.2.2 Hydrogen

A preconceptual market analysis indicates there are limited opportunities for distributing the product hydrogen from the NGNP into the local market within reasonable transportation distances of the INL site. Table 20.7-1 NGNP Gas Production Rates presents a review of the expected range of quantities of gases to be produced for three water-splitting technologies and for the smallest practical demonstration unit as well as for a commercial train as discussed in the sections above.

The production rates of hydrogen shown for the HTSE process can be misleading. In the case of the HTSE cycle, considerably more of the energy from the PBMR is used to make hydrogen than for the other technologies. This is because the critical piece of equipment in each

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case is in the heat transfer train and the fraction of thermal energy used to split water in each case is quite different. In the case of HyS, the ratio of thermal energy to electrical energy is over 3.6. For HTSE, the ratio is 0.2 for full recuperation and 0.46 for no recuperation. The size of the demonstration unit is dependent upon the critical equipment, not on the hydrogen production.

Size	Technology	Hydrogen (10 <sup>6</sup> SCFD)	Oxygen (10 <sup>6</sup> SCFD)
Smallast	HTSE	8.0	4.0
Practical	HyS	0.71*	0.36*
	S-I	0.97*	0.48*
Commonaio1	HTSE	8.0	4.0
Train	HyS	7.1*	3.6*
	S-I	9.7*	4.8*

 Table 20.7-1
 NGNP Gas Production Rates

\*These are values derived from diverse sources which have not been reconciled. The production quantities for each gas are expected to be equal for both technologies of the same size. See the discussion under "Sulfur Iodine," above.

Potential uses for hydrogen are generally wide-ranging (See Table 20.7-1). Modest quantities of hydrogen are used in glass and chemical production. Somewhat larger quantities are used in metal processing and fabrication. These applications are often served by compressed gas packaging (i.e. cylinders and "tube trailers"). "Tube trailers" are tractor trailers with large high pressure cylinders permanently attached. Food production via hydrogen at the consumption site. Hydrogen used as transportation fuel in fuel cell vehicles is typically high pressure (e.g. 5000 PSI) and high purity.

Production of the transportation fuels by petroleum refineries typically use 10's of millions to 100 million SCFD of hydrogen. These applications are almost exclusively served by on-site hydrogen generation or by pipelines that are served by steam reformers. Refining operations using hydrogen create a large amount of waste fuel gas containing carbon monoxide, methane, light hydrocarbon gases, some hydrogen, and inerts. This fuel gas is commonly burned in furnaces. The steam methane reformer is one of the chief sinks for this gas. Even when refineries buy hydrogen over-the-fence from gas producers, they can sell the heating value of the fuel gas to the reformer operator. Therefore, refining would not usually be a good market for NGNP hydrogen.

#### Table 20.7-2 Uses of Hydrogen

- Chemical and Pharmaceutical Industry
  - Production of substitute natural gas
  - Production of high-density polyethylene and polypropylene
- Electrical Industry
  - Fuel gas in production and sealing of glass tubes
  - > Hard soldering in manufacture of electronic equipment
- Semiconductor Industry
  - Transport gas for diffusion processes
  - > Reactant gas with oxygen to generate water vapor for wet oxidation
- Power Stations
  - For cooling generators, motors and frequency converters
- Hydrogenation of oils and greases
  - Delays oxidation
- Metal Processing- Ferrous Metals
  - Increased ductility
  - Higher yield point
- Metal Processing Non-ferrous metals
  - Annealing of copper and copper alloys
  - Production of magnesium by electrolysis
- Welding and Cutting
  - Plasma cutting and welding
  - > Soldering and welding in a protective atmosphere
- Glass/ Quartz
  - Fuel gas with oxygen for cutting and melting of quartz
- Petroleum Industry
  - > Desulfurize and hydrocrack crude oil fractions
- Transportation
  - ➤ Fuel cells
  - Internal combustion engines

A key factor in hydrogen marketing is the distribution options. Table 20.7-3 lists the common hydrogen shipping methods. As can be seen from a comparison of the distribution options and the potential NGNP hydrogen production capacities (Table 20.7-1 NGNP Gas Production Rates), tube trailers or liquid hydrogen would be required for the smallest practical hydrogen plants for either the S-I or HyS processes. The HTSE smallest practical plant or the S-I or HyS commercial train would have to fill 2 to 3 liquid hydrogen tankers simultaneously for 24 hours every day. If shipping took place for only 12 hours, then the number of tankers would double and the storage capacity for liquid hydrogen would have to be at least 126 m<sup>3</sup> (or 33,000 gallons). Production from the smallest practical hydrogen plants for HyS or S-I would stretch the capability of tube trailer shipping.

#### Table 20.7-3 Distribution Options for Hydrogen

- Pipeline (necessary for full plant : 4 trains)
  - > 0.5 to over 100 million SCFD
  - > Depends upon pipeline availability
- Liquid (choice for commercial train)
  - About 1 million SCFD
  - Requires extra purification and liquefaction
- Tube trailer (choice for smallest required hydrogen plant)
  - Up to about 400,000 SCFD
- Cylinders
- Up to about 100,000 SCFD

A 250 mile radius is the accepted economic transportation range of compressed hydrogen gas. Figure 20.7-11 shows the geographic area encompassed by a 250 mile radius drawn from the proposed INL site. Six companies were identified within this area that use bulk compressed hydrogen. All of these companies carry out metals processing operations. Their combined annual consumption is less than 200,000 Standard Cubic Feet per *Year*. The smallest practical hydrogen plant for the NGNP will produce over 700,000 Standard Cubic Feet per *Day*. There are three refineries, no float glass producers and no chemical producers that use hydrogen within this area.

The economic shipping radius is 1000 miles for liquid hydrogen. Consequently the potential market would expand. Even with this expansion, the demand for liquid hydrogen is low in comparison to the potential NGNP hydrogen plant production. The total North American capacity for liquid hydrogen is 89 million SCFD and about 1/3 of that capacity is idle. Liquid hydrogen use is expected to grow at the same rate as the GDP, about 2 <sup>1</sup>/<sub>2</sub> to 3% per year. A commercial train installed at the NGNP using the HyS process would displace about 12% of the current liquid hydrogen market. Hydrogen to be liquefied must be purified to a very high degree to avoid fouling of the liquefaction equipment. Hydrogen produced for fuel cell use must be similarly purified. The additional cost of purification and liquefaction is about \$1.50 per kilogram.<sup>20</sup> The entry of NGNP-produced hydrogen into the Western U.S and Canada would disrupt this market in the future, without an expansion in demand. The interest in hydrogen for the NGNP project is primarily to stimulate growth in the hydrogen economy. It would therefore be appropriate to use the NGNP hydrogen production to fuel a fleet of hydrogen-powered vehicles. This is a market that is non-existent today, but the NGNP hydrogen plant could encourage its emergence. A kilogram of hydrogen has a heat of combustion equivalent to a gallon of gasoline and about 10% less than a gallon of diesel fuel. The U.S. Climate Change Technology Program target for urban buses is 10 miles per gallon gasoline equivalent.<sup>21</sup> If buses powered by hydrogen were to average 15 miles per hour in urban traffic and run 16 hours per day, the output from the smallest practical NGNP hydrogen plant with the HyS process could support a fleet of approximately 70 buses. A commercial train sized plant could support 700 buses. Similar alternative transportation opportunities should be studied and developed.





An alternative consideration is to include a coal-to-liquid and/or coal-to-methane demonstration element to the NGNP mission as a second phase of further development. The Big Horn coal deposits in the vicinity of Hot Springs, Wyoming could become a feedstock source. There are active coal mines in this area. Coal conversion through the gasification to syngas and either Fischer-Tropsch technology for liquids or methanation for Substitute Natural Gas (SNG) would be a substantial market for both oxygen and hydrogen. Direct coal liquefaction would not use by-product oxygen. A gasification and syngas-based coal-to-liquids plant using all the hydrogen from a 50 MWth water-splitting plant would produce about 5000 barrels per day of liquid fuels. About half of the by-product oxygen would be used. A similarly based SNG plant would produce about 2.4 million SCFD of SNG. Without a local market for hydrogen, the NGNP by-products would have to be liquefied to be exported. Construction of a pipeline for these quantities of gas would not be practical.

For now, the market and price for hydrogen from an NGNP demonstration Hydrogen Plant is uncertain. As a conservative basis for the by-product revenue projection, the hydrogen price from comparably sized conventional SMR plant is suggested. For a levelized natural gas price of \$7.5/MMBtu for the time period of interest and assuming no CO<sub>2</sub> penalties, the prices range from \$1.65/ kg for a large capacity plant to about \$1.80/kg for a plant comparably sized to

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the NGNP commercial train-based plant. For the latter, and using the same capacity factor logic as presented for the power revenues, namely 85% for the long-term and 75% for the first six years, the resultant revenues would be \$11 million per year long-term and \$9.5 million per year average for the first six years.

## 20.7.2.3 Oxygen

Oxygen is the major by-product of the water-splitting technologies. Oxygen applications most common in the area surrounding the INL site are: Oxy-fuel cutting, combustion enrichment for glass and ore smelting, and breathing oxygen. The usage rates for most of these are small in comparison to the potential NGNP hydrogen plant production. Some local larger oxygen users are Melaleuca, Inc. (chemical processing), Montana Resources, Advanced Silicon Materials LLC, and Thompson Creek Mining Company (all metals and minerals).

Oxy-fuel cutting is the most common application of high-pressure cylinder packaging quantities of oxygen. INL itself may be the largest market in the area for these oxygen gas cylinders. Because producing oxygen from air is a relatively low cost operation, most moderate size, low purity applications are served by on-site vacuum-swing adsorption units. The larger quantities associated with ore-smelting and mining combustion enrichment needs are usually served by on-site adsorption or cryogenic air separation systems. The high purity requirements for breathing oxygen are almost exclusively supplied by liquid oxygen tanks filled from centrally-located large scale cryogenic air separation plants.

The economical shipping radius for compressed or liquefied oxygen gas is about 150 miles. Most of the applications outside the INL site are associated with mining. There is also potential welding gas and breathing oxygen markets around Salt Lake City, Utah. These are just outside the economic shipping distance. The opportunities for marketing the oxygen by-product from the NGNP hydrogen plant are therefore limited and would depend upon expansion of local mining operations or displacement of existing air separation capacity. Air separation produces a nitrogen by-product which is also used by many of these operations. Bulk oxygen currently costs approximately \$0.04 per kg and the price varies with the local cost of electricity. Provided that INL does not use the produced oxygen for its own needs, and if a market could be found, revenue of approximately \$0.8 million per year might be generated.

## 20.7.3 PRODUCT REQUIREMENTS AND PURIFICATION NEEDS

## 20.7.3.1 Hydrogen

Post-production purification of the hydrogen required by any of these markets will be an important requirement. For the high temperature steam electrolysis process, steps for removal of sulfur and halogen compounds are not necessary. Water must be removed and some adsorption will be required.

In the HyS process, the hydrogen is generated out of a sulfuric acid electrolysis bath. The vapor pressures of both sulfuric acid and sulfur trioxide at the operating conditions of these baths are very low. Some sulfur dioxide will be stripped out of the electrolyzer bath, however. Sulfur dioxide in the gas phase must be removed to very low levels. Both scrubbing with caustic and adsorption will be required. Scrubbing will also guard against carry over of droplets during process upsets.

	Surface vehicle fuel cell	Application Glass, Chemicals	Refining
Purity Requirement (Mol %)	>99.99	>99.995	>99.90
Contaminant ( max ppmv)			
Total non-H <sub>2</sub> or particulates	100	50	1000
Total hydrocarbons	2	1	N/A
Oxygen	5	1	1
Inerts (He, N <sub>2</sub> , Ar)	60	2	<1000
Carbon oxides	1	1	10
Total Sulfur	0.004	5	5
Formaldehyde	0.01	N/A	N/A
Formic Acid	0.2	N/A	N/A
Ammonia	0.1	N/A	1
Total halogenates	0.05	N/A	1
Water	5	1.5	10
Particulates	<10 <sup>-3</sup> mm @10 <sup>-6</sup> g/l	N/A	N/A

## Table 20.7-4 Hydrogen Purity Requirements

In the S-I process, the hydrogen is generated by the decomposition of hydrogen iodide. The vapor pressure of both iodine and hydrogen iodide are considerably higher than that of the sulfur species in the HyS process. The vapor pressure of hydrogen iodide is quite high, even at 25°C and it is moderately soluble in water. Therefore, there will probably be traces of hydrogen iodide in the product hydrogen even after the water scrubber shown on the flowsheet.<sup>22</sup> The purification section should include a caustic scrub to continue to remove iodine species and guard against any carryover of liquid droplets during upsets. This should be followed by a

consumable adsorbent bed such as alumina or activated carbon. The total iodine in the product hydrogen would then be reduced to less than 1 parts per million by volume (ppmv).

For all processes, the final step may require an additional thermal swing drying step to lower the water content to less than 5 ppmv. The purity requirements of some markets are listed in Table 20.7-4.

Considerable purification would be needed to market oxygen from the thermo-chemical processes. Oxygen purity specifications do not explicitly address levels of sulfur dioxide because this compound is not involved in current commercial processes for producing oxygen. However, sulfur dioxide contamination will be an issue. Sulfur dioxide contaminating the oxygen would probably have to be removed to less than 1 ppmv. The low sulfur dioxide requirement for the welding gas cylinders is not related to the actual oxy-fuel cutting process. It comes from the potential use of the gas indoors where the end user may be exposed to the products of the combustion process. Breathing oxygen specifications should allow virtually no sulfur dioxide in the product because of its toxicity. Additionally, the "No Odor" requirement and the "others by infrared" require sulfur dioxide concentrations to be less than 0.1 ppmv. Furthermore, production of liquid oxygen will not tolerate either sulfur dioxide or water because it will condense and freeze during the liquefaction process, clogging the equipment.

Removing the sulfur dioxide from the product oxygen would require a caustic scrub followed by a consumable adsorbent bed.

Table 20.7-5 lists the purity requirements for the various market segments for compressed and liquefied oxygen.

	Oxy-fuel cutting	Application Combustion Enhancement	Breathing
Required Purity (Mol %)	>99.5	>99	>99
Contaminant			
Total hydrocarbons	N/A	<0.5 ppmv	<50 ppmv
Inerts (N <sub>2</sub> , Ar)	<0.4%	<1%	<1%
Carbon Dioxide			<300 ppmv
Carbon Monoxide			<10 ppmv
Total Sulfur			No Odor
Total Halogenates (Br, Cl, F, I)			
Solvents			<0.1
Others by Infrared			<0.1
Water	<50 ppmv	<50 ppmv	<6.6 ppmv (liquid)

## Table 20.7-5 Oxygen Purity Requirements

# 20.7.4 NGNP BY-PRODUCTS, WASTE STREAMS AND EMISSIONS AND THEIR DISPOSAL

Daily operations at any facility will generate both liquid and solid waste streams requiring onsite treatment and disposal or offsite disposal, as the case may be. This section attempts to identify all anticipated waste streams associated with the nuclear reactor and the various hydrogen production technologies, as well as waste streams common to all the technologies. Specifically, waste streams are identified and discussed for the feed water treatment systems, water splitting technology options and non-process wastes such as solid wastes, sanitary wastes, oily wastes and contaminated storm water.

## 20.7.4.1 NGNP Reactor Wastes and Emissions

#### <u>Tritium</u>

There are three sources of tritium in the helium coolant. The chief source is the activation product from the small fraction of helium atoms in the coolant that are  $He^3$ . The second source is activation products from impurities and control material such as  $Li^6$  and  $B^{10}$ . Ternary fission may is a third source, but the product remains almost entirely in the fuel particles.

Tritium is removed from the coolant by the Helium Purification System (HPS) in the form of tritiated water. This waste can be stored or discharged to the environment at concentrations below the allowable limits. Leakage to the atmosphere and permeation to the secondary coolant and process fluids can be limited by appropriate design of the penetrations, seals and the Helium Purification System.

Estimation of tritium production for the NGNP is based upon extrapolation from THTR operating data. In that plant the annual discharge was 91Ci, whereas the limit was 1000 Ci per year. The tritium level in the coolant remained constant which indicates that the production rate was equal to the discharge rate. Tritium production from activation of He<sup>3</sup> is proportional to the reactor power due to higher thermal flux in the core and the primary coolant density due to the higher probability of He<sup>3</sup> activation. Based on a 500 MWth PBMR with a 9 MPa coolant pressure, the tritium production from He<sup>3</sup> is estimated to be approximately 115 Ci per year.

<u>Component</u>	Primary Radioactivity Sources		<u>No.</u> <u>Units in</u> Reactor	Frequency of Removal	<u>Number</u> <u>Units</u> Removed	Volume per Unit, m <sup>3</sup>	<u>Volume</u> <u>per Year,</u> Avg m <sup>3</sup>	Volume over 40 years, EOL, m <sup>3</sup>
Fuel Elements, whole	All fission and act produ	products ivated ucts	~45100 0	daily	[610]	1.13E-4	[25]	[910]
Replaceable Outer Side Reflectors	Nuclide           C-14           Sr-90           Ag-110m           Cs-137	Half- life, Yr           5700           29           0.7           30	[1080]	18 years	[1080]	TBD		[56.3]
Replaceable Inner Reflectors	Same a reflec	s side tors	[400]	18 Years	[400]	TBD		[22]
Replaceable Top Reflectors	Same a reflec	s side tors	TBD	18 years	TBD	TBD	TBD	TBD
Operating Control Rods	Activated Incoloy and B <sub>4</sub> C		24	[6 years]	[6]	[0.05]	[0.05]	[1.8]

Table 20.7-6	Volume of Core	<b>Components to</b>	Waste for a	<b>PBMR NGNP</b>
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Table 20.7-6 above, provides a summary of the estimated radioactive waste material that may be produced by a PBMR-based NGNP. The assumptions used in the preparation of this estimate are as follows:

- 1. Reactor life is 40 years with 90% availability
- 2. The replaceable outer side reflector is 0.4m thick and the total height is 10.92 m
- 3. The replaceable inner reflector is also 0.4m thick with the same height as the outer reflector.
- 4. The top replaceable reflector is 1.2 m thick (this probably will not need replacement)
- 5. The control rods are 0.1m in diameter and 6.5m long.
- 6. The replacement schedule for the control rods will be approximately every 6 years
- 7. Fuel sphere replacement rate is 610 per day
- 8. The estimate does not include the end-of-life disposal of fuel or internals.

## 20.7.4.2 Feedwater Treatment

At this time, feedwater source quality is not known. Municipally supplied potable water may not be available, whether due to proximity issues to the municipal distribution system due to the location of the project site or due to supply inadequacies. Water may therefore be groundwater or river water. Water purity for any of the three processes under consideration has not been identified and there has been insufficient research and development done in this area to determine the affect of dissolved solids on any of the processes or their components. Undoubtedly, very pure water with low suspended and dissolved solids will be required.



Several different technologies, or combinations of technologies, are available to meet the anticipated process water purity requirements. The final scheme for the feed water system can be chosen once feedwater quality and purity requirements have been better defined. However, the feedwater system will most likely consist of one of the treatment process schemes shown in Figure 20.7-12 Hydrogen Plant Water Treatment Schemes, above.

The size of the feedwater treatment system from preliminary mass balances is approximately 150 gpm for the process. However, such factors as pump sealing requirements, boiler feed water, and other plant uses (i.e., site potable water and miscellaneous plant water use) may increase the required size of some of the components and systems.

Waste streams will vary depending on the technology used. All the technologies identified above, except for ultraviolet disinfection and ion exchange demineralizers, will produce a periodic backwash or continuous reject stream requiring treatment. An ion exchange system will require facilities for bulk chemical storage, for preparation of regenerant, and for neutralization of the regeneration waste streams.

Liquid waste, solid wastes and applicable disposal methods for each technology are identified in Table 20.7-7 below.

Process Technology	Liquid Waste	Solid Waste	<b>Disposal Method</b>
PreFiltration		Screened Solids	Onsite or licensed waste hauler
Multi-Media Filtration	Backwash water & solids	Periodic media replacement over design life of system	<i>Liquid</i> – onsite wastewater treatment system
			Solid – licensed waste hauler
UltraFiltration	Backwash water & solids	Periodic media replacement over design life of system	<i>Liquid</i> – onsite wastewater treatment system
			<i>Solid</i> – licensed waste hauler
UltraViolet Disinfection		Periodic media replacement over design life of system	<i>Universal Waste –</i> licensed waste hauler
Reverse Osmosis	Reject Water, Membrane Cleaning Wastes	Prefilters and membranes	<i>Liquid</i> – onsite neutralization & wastewater treatment system
			<i>Solid</i> – licensed waste hauler
Ion Exchange Demineralizers	Regeneration Wastes	Periodic resin replacement over	<i>Liquid</i> – onsite neutralization system
		design life of system	Solid – resin supplier or licensed waste hauler

Resin suppliers may offer contract services to test, replace and dispose of spent ion exchange resins. The appropriate strategy for resin disposal will need to be investigated during subsequent design phases.

## 20.7.4.3 Water Splitting Process Waste Streams

#### Liquid Waste Streams

Each of the technologies requires feedwater makeup to replace water that is converted into hydrogen and oxygen by the process. Although there is a net loss of water, water is lost as a gas and any dissolved solids or other corrosion products in the water will remain in the process and continue to increase in concentration until purged from the system. Periodic blowdowns will be required to reduce the concentration of these dissolved solids. Onsite treatment, such as chemical precipitation, will be required to remove the metal contaminants prior to discharge of

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the liquid waste streams. Further research and development will be required to determine the allowable cycles of concentration within each process before a process blowdown is required.

Furthermore, all three technologies may utilize closed loop cooling systems to cool the process liquid and power generation waste heat. These closed loop cooling systems will utilize cooling towers and will require periodic blowdown to reduce dissolved solids and corrosion products concentration in the cooling water.

Due to heat and corrosion considerations, mechanical seals for the various pump applications will most likely require pressurized seal water systems to cool and flush the seals thereby increasing the life of the seals. Water purity requirements for this seal water are not known at this time. Further research and development will need to be done to determine the most appropriate pump sealing system. Regardless, seal cooling and flushing water will need to be treated appropriately.

The oxygen and hydrogen product will require further processing to meet purity requirements. This processing will require caustic scrubbing to remove residual sulfur compounds and sulfuric acid mist. Neutralization of the spent caustic stream will be required. Oxygen production from the smallest practical hydrogen plant would be about 13,600 kg per day. Removing the bulk of the 5% sulfur dioxide would produce about 1400 kg/day of NaHSO4, or about 470 tonnes/year of NaHSO4 in a dilute water solution from the scrubbing step and consume about 470 lb/day of NaOH. Additionally, about 45,000 kg/year of adsorbent would be consumed to remove the final 100 ppmv of sulfur dioxide from the oxygen product.

Routine maintenance operations will occasionally require vessels or pumps to be taken offline and drained. Drained liquids may be acidic or basic and require neutralization treatment.

The S-I process has additional associated waste handling and disposal concerns. Bulk iodine will be required to replenish iodine lost in the process and may require additional chemical processing systems to meet purity requirements. At this time, iodine purity is not identified and will need to be addressed in subsequent research and development. Regardless, appropriate waste treatment technologies will need to be used to treat potential liquid waste streams associated with the chosen processing systems.

In addition, extractive distillation with phosphoric acid may be used in the sulfur-iodine process. Typical treatment of phosphoric acid waste streams includes neutralization, followed by the addition of chemical coagulants (e.g., polyaluminum chloride). Careful consideration should be given to the handling and treatment of phosphoric acid wastes.

#### Solid Waste Streams

It is inevitable that equipment and components will wear out and degrade over the design life of the facility. These components will need to be replaced as part of an ongoing maintenance plan. The following components are identified as requiring periodic replacement, whether due to reduction in performance from scaling or material corrosion and degradation:

- SO<sub>2</sub> absorber packing
- Spent electrolyzer cells and membranes (HTSE and HYS Processes)
- Spent catalysts
- Heat exchanger tubes

Process Technology	Liquid Waste	Solid Waste	Disposal Method
All Technologies	Feed Water Treatment Waste Process Blowdown Cooling System Blowdown Pump Seal Water Purge & Drain from Maintenance Operations	Spent ion exchange resins or reverse osmosis membranes Used equipment	<i>Liquid</i> – onsite wastewater treatment system <i>Solid</i> – scrap dealers, municipal solid waste, ion exchange resin and membrane manufacturers (recycle)
High Temperature Electrolysis		Spent electrolyzer anodes and cathodes	Solid – Licensed Waste Hauler (with hazardous waste disposal permit)
Hybrid Sulfur	Spent Caustic from Gas Purification 	Spent electrolyzer anodes and cathodes SO <sub>2</sub> absorber packing	Licensed Waste Hauler or Media supplier Recovery specialist for platinum on electrodes
Sulfur Iodine	Liquid wastes from iodine processing Spent Caustic from gas purification Phosphoric Acid Waste from Distillation	Spent activated carbon from iodine processing and ventilation scrubbers SO <sub>2</sub> absorber packing	<i>Liquid</i> – onsite waste processing system <i>Solid</i> – Licensed Waste Hauler or Media supplier

Table 20.7-8	Summary	of Water	-Splitting	Process	Wastes
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Solid waste generated by all processes will include activated carbon used for the purification of the product gas streams, as required. Activated carbon may be disposed by a licensed waste hauler, or returned to the carbon supplier for regeneration or disposal.

Considering the chemical characteristics and toxicity of iodine, additional activated carbon disposal will be required for spent carbon from scrubbers for any iodine processing area ventilation systems.

Liquid waste, solid wastes and disposal methods for all including individual water splitting technologies are summarized in below

## 20.7.4.4 Other Plant Non-Process Waste Streams

#### Solid Waste

The State of Idaho requires industrial, commercial and utility waste generators to track the volume of wastes generated, determine whether or not each is classified as a hazardous, universal or mixed waste and ensure that all wastes are properly disposed of according to federal, state and local requirements. Any new facility will be required to develop plans for the proper identification and storage of hazardous and universal waste. These wastes will need disposal by the appropriate licensed waste haulers.

#### Storm Water

Storm water runoff will be generated at the facility and appropriate mitigation measures and treatment will need to be identified and implemented. A Storm Water Pollution Prevention Plan will be required to be developed and implemented. Runoff volumes and peak discharge rates can not be developed until a final site layout is determined for the facility.

#### **Oily Wastes**

Storm water and building drains in maintenance, shipping/receiving and parking areas may be contaminated with oil. Appropriately designed oil/water separation systems will be required to treat these waste streams. The facility will need to contract with a licensed waste hauler to remove the oily waste.

#### Sanitary Wastes

Sanitary wastes may either be treated onsite with a packaged treatment system or discharged to a publicly owned treatment system, if available. Discharge to a publicly owned system may necessitate installation of a pump station and force main to transfer the sanitary waste to the collection system. In addition, the sanitary discharge will need to meet the local sewer discharge requirements and may have additional effluent restrictions if any process wastewater is discharged to the sewer. Local authorities can implement local discharge limitations for industrial or commercial users. These limits typically include limits on metals, such as iron, copper and mercury, as well as other toxic pollutants. Additional pre-treatment at the facility may be required.

## 20.7.5 RECOMMENDATIONS

### **Recommendation 1: Size of the NGNP Hydrogen Plant**

The recommended size of the reference NGNP Hydrogen Plant commercial demonstration is based on a Decomposition Reactor with a thermal duty of  $50MW_{th}$ . Only a plant of at least this size will fully demonstrate this technology commercially. A retreat from this size should be made only if disposing of the hydrogen product becomes an overriding factor.

Demonstration of the HTSE process with a 50  $MW_{th}$  process-coupling heat exchanger will produce as much as half of the hydrogen as is sold as a liquid in the United States today. It should be demonstrated with a 13  $MW_{th}$  PCHX.

#### Recommendation 2: Develop a Market for the Product Hydrogen

Currently, there is no easily accessible market for hydrogen produced by the NGNP Hydrogen Plant. As part of the demonstration, development of a local transportation system using buses and other vehicles using hydrogen as an internal combustion engine fuel should be investigated actively. In addition, consideration is warranted for a later coal-to-liquids demonstration element of the NGNP Project. Disposal of the product hydrogen from this plant will be an important consideration whatever the size of the plant. Once a market is identified and the requirements are clear, a purity specification for the hydrogen product can be developed.

### **Recommendation 3: Conceptual Design of Purification and Waste Disposal**

Feed pre-treatment, product purification, waste treatment and disposal are frequently ignored until late in the development of a demonstration project. The effect of these factors on the cost and on the design of the main production unit itself can be important. These elements should be included explicitly in the conceptual design of the NGNP Hydrogen Plant. To do this successfully the purity specification for the hydrogen product is required.

## Recommendation 4: Progressing the Design of the NGNP Hydrogen Plant

Begin to develop clear Design Data Needs by choosing a preferred technology for the NGNP Hydrogen Plant by the beginning of the NGNP Conceptual Design Phase. Advance the decision point for choosing the water-splitting technology and progress that technology by developing a process design including the aspects described in Recommendation 3 as part of the NGNP Conceptual Design Phase. This effort will further focus the research and development effort.

## **Recommendation 5: Technology Development**

See the section on Technology Development, below.

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## DEFINITIONS

Adsorbent	Solid substance used to condense gases, liquids or dissolved substances on its surface.
Bunsen Reaction	A reaction of water, sulfur dioxide and iodine to form iodic acid and sulfuric acid
Catalyst	A substance that accelerates the rate of a chemical reaction but remains unchanged afterwards
Ceramic	Any of various hard, brittle, heat-resistant and corrosion- resistant materials
Chemical Equilibria/Equilibrium	When the net change of reactants and products in a chemical reaction is zero.
Chemical Precipitation	In water or wastewater treatment, the addition of chemicals (e.g., lime, caustic soda or ferric chloride) to remove dissolved metals or soluble organic contaminants.
Critical Equipment	The piece of equipment that limits the maximum capacity of the train and that is expected to pose a challenge with respect to one or more of the demonstration criteria.
Decomposition	A reaction in which a single compound reacts to give two or more substances
Demineralizer	In water treatment, a substance or system used to remove minerals or mineral salts from a liquid
Electrochemical	Pertaining to the interaction or interconversion of electric and chemical phenomena
Electrolysis	The passage of a direct electric current through an ion- containing solution. Electrolysis produces chemical changes at the electrodes.
Enthalpy	A thermodynamic quantity that is equal to the sum of the internal energy of a system plus the product of the pressure-volume work done on the system.
Equivalent Hydraulic Diameter	Equal to (4 x axial flow area ÷ wetted perimeter)
Extractive Distillation	The extraction of the volatile components of a mixture by the condensation and collection of the vapors that are produced as the mixture is heated
Fluidized Bed Reactor	A reactor in which a bed of small solid particles is suspended and kept in motion by an upward flow of a fluid or gas.
Friction Factor	A dimensionless number used in studying fluid friction in pipes, equal to the pipe diameter times the drop in

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	pressure in the fluid due to friction as it passes through the pipe, divided by the product of the pipe length and the kinetic energy of the fluid per unit volume
Halogen	Any of a group of five chemically related nonmetallic
	elements including fluorine, chlorine, bromine, iodine
	and astating
Hazardous Waste	Per Idano Statute 39-4403, a waste or combination of
	wastes of a solid, liquid, semisolid, or contained gaseous
	form which, because of its quantity, concentration or
	characteristics (physical, chemical or biological) may:
	(a) Cause or significantly contribute to an increase in
	deaths or an increase in serious, irreversible or
	incapacitating reversible illnesses; or
	(b) Pose a substantial threat to human health or to the
	environment if improperly treated, stored, disposed of, or
	managed. Such wastes include, but are not limited to.
	materials which are toxic, corrosive, ignitible, or
	reactive or materials which may have mutagenic
	teratogenic, or carcinogenic properties but do not include
	solid or dissolved material in domestic sewage or solid
	or dissolved materials in irrigation return flows or
	industrial discharges which are point sources subject to
	ndustrial discharges which are point sources subject to
	national pollution discharge enfinitation system permits
	under the federal water pollution control act, as amended,
	33 U.S.C., section 1251 et seq., or source, special
	nuclear, or byproduct material as defined by the atomic
	energy act of 1954, as amended, 42 U.S.C., section 2011
	et seq
Heat Exchanger	A device in which energy is transferred from one fluid to
	another across a solid metallic or ceramic surface.
Heat Transfer Coefficient	A constant that represents how easily heat can move.
Inert	Not readily reactive with other elements; forming few or
	no chemical compounds.
Light Hydrocarbon	Hydrocarbons up to a molecular weight of about 72
Mixed Waste	Solid waste that contains both hazardous and radioactive
	waste.
Multimedia Filtration	In water treatment, a process that uses multiple types of
	filtering media to remove solids greater than 10 microns
	in size.
Osmotic Pressure	The hydrostatic pressure produced by a solution in a
	space divided by a differentially permeable membrane
	due to a differential in the concentrations of solute
Purity	Relating to the absence of other chemical compounds or
	chemical species
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Reaction Kinetics	The rate of a chemical reaction.
Reactive Distillation	<ul> <li>A unit operation combining both a chemical reaction and distillation. Typically, reactants are fed continuously to a distillation column in which the reaction takes place.</li> <li>Reactants are simultaneously separated from the products thereby allowing the reaction to proceed.</li> </ul>
Recuperator	A heat exchanger that helps boost the efficiency of a process. The recuperator passes some of the heat of the product gas back to the process as it comes through the exchanger.
Reverse Osmosis	The process of forcing a solvent from a region of high solute concentration through a membrane to a region of low solute concentration by applying a pressure in excess of the osmotic pressure.
Scalability	The ability to increase process production rates without significant changes to reaction kinetics or transport phenomena.
Scrubber	An air pollution control device that uses a high energy liquid spray to remove aerosol and gaseous pollutants from a gas stream. The gases are removed either by absorption or chemical reaction
Steam Reformer	A piece of equipment that carries out the endothermic steam reforming reaction, that is, reacting
Thermochemical	Relating to the chemistry of heat and heat-associated chemical phenomena.
Train	Refers to a collection of equipment or components that form a functional process group.
Transport Phenomena	Any of various mechanisms by which particles or quantities move from one place to another. There are three main types of transport phenomena: heat transfer, mass transfer, and fluid dynamics (or momentum transfer).
Tritium	Common name for hydrogen-3 ( <sup>3</sup> H), which is a radioactive isotope of hydrogen.
Tritiated Water	Liquid formed with tritium combines with oxygen.
Tube Trailer	Tractor trailer with permanently attached large high pressure cylinders.
Ultrafiltration	A variety of membrane filtration in which hydrostatic pressure forces a liquid against a semi-permeable membrane. Suspended solids and solutes of high molecular weight are retained, while water and low molecular weight solutes pass through the membrane.
Ultra Violet Disinfection	In water and wastewater treatment, the destruction of bacteria, viruses and pathogens by using light in the

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	ultraviolet spectrum (i.e., 254 nm)	
Universal Waste	Per Idaho Universal Waste Rule, Universal Wastes are	
	defined certain commonly generated hazardous wastes.	
	Specifically, a hazardous waste exhibiting any of the	
	following characteristics can be classified as a universal	
	waste:	
	(a) The waste is frequently generated in a wide variety of	
	settings (other than industrial settings usually associated	
	with hazardous wastes).	
	(b) The waste is generated in a vast community and in	
	sufficient quantities to cause difficulties in managing the	
	waste properly for both the regulated community and the	
	regulators.	
	(c) The waste is present in significant volumes in the	
	municipal solid waste stream (non-hazardous waste	
	management systems).	
	Wastes identified in Idaho as universal wastes include	
	batteries, agricultural pesticides, thermostats, spent lamps	
	containing mercury or lead and mercury containing	
	items.	
Upset	Relating to a disruption in a process that affects	
	efficiency or operation.	
Water Splitting	Carrying out the net reaction that decomposes water into	
	its constituent elements.	

## REQUIREMENTS

There are no requirements generated by this special study.

## LIST OF ASSUMPTIONS

#### Hydrogen Plant

Heat is supplied to the hydrogen plant at its battery limits at 900°C in the form of hot helium and is returned to the heat transport system.

The heat transport medium is carried in a secondary loop and therefore does not pass through the core of the PBMR.

The heat and material balances produced in earlier reports for the three  $H_2$  production technologies examined are reasonable estimates of the demonstration plant performance.

VLE, thermo-chemical, and transport property estimates for the various species at these high temperatures and pressures are accurate.

Performance property estimates for the solid oxide separation materials in the electrolyzers and decomposers, namely permeation rate, energy consumption, and potential leakage rate of the prototype devices are reasonable.

#### Hybrid Sulfur

The decomposer design proposed by Westinghouse assumes that the residence time is not controlling and heat transfer into the reaction zone is controlling.

The Westinghouse decomposer design assumes that the tube supplier will develop 10 m long tubes in time to build the demonstration plant.

Bulk caustic scrubbing will reduce the 5%  $SO_2$  in the  $O_2$  product to 100 ppmv. The capacity of the adsorbent used to remove the remaining  $SO_2$  is about 4.5 %  $SO_2$  by mass.

Commercial H<sub>2</sub> production train size is set by the largest practical size of the Decomposition Reactor. (same assumption is made for the S-I process)

#### **Commercial**

Projected growth of hydrogen and oxygen demand from traditional users in the region that can be served from the demonstration plant is equivalent to the growth in the North American GDP.

## TECHNOLOGY DEVELOPMENT

#### **High Temperature Steam Electrolysis**

Technology development for the high-temperature electrolysis process should focus on the design and fabrication of the electrolyzer cell. The selection of the basic material for the electrolytic cells has been completed. The main focus of the development of these cells will be in scaling up both the size of the cells and the manufacturing process so that the thousands of cells can be reliably fabricated at a reasonable cost.

The impact of common impurities found in high temperature steam should be investigated. In testing the ILS unit steam should be generated and transported in vessels and piping fabricated from those materials expected to be used in the commercial plant. Furthermore commercial water treatment and boiler feedwater treatment should be used.

Design and testing of the seals on the cells that contain the feed steam and the  $O_2$  and  $H_2$  product will be critical. Prior to building the demonstration plant these seals should be demonstrated at the bench and pilot scale to show acceptable leakage rates at process conditions over long periods of time. Seal testing should also prove that they can withstand multiple start-up and shutdown cycles that include both pressure and thermal cycling from ambient up to operating conditions. Some of the development activity could leverage from other development programs supporting equipment using metal oxide membrane technology.

Another area of technology development for the HTSE process is the large heat exchangers in various services. The first effort should be to perform a temperature-enthalpy analysis of the entire system including the recuperators. A thermal design of these exchangers should be carried out by an experienced industrial heat transfer professional.

The high temperature and pressure of the process combined with the high  $H_2$  or  $O_2$  content in some of the streams make material selection and testing necessary. Thermal stresses, creep,  $H_2$  embrittlement, and stress corrosion are all possible problems with these exchangers. It is unlikely that carbon steel or stainless steel can meet the needs of these heat exchanger designs. A program to test and evaluate the construction materials at small scale will likely be required. Following on basic material selection, design and fabrication method development will also be necessary.

A significant part of these technical programs will be evaluations of the cost to produce the critical components to ensure that the projected capital cost of any commercial facility is reasonable.

#### **Sulfuric Acid Decomposition**

A parallel development effort extending to the pilot scale is needed for the competing conceptual designs of the Decomposition Reactor. The conditions in this reactor are such that it is likely that only a ceramic material can be used for the heat transfer surfaces. Granting this, there are several issues faced by any design:

- Bonding and sealing ceramic to metal
- Catalyst life, replacement of catalyst or incorporating catalyst into the reactor
- Thermal design of the piece of equipment
- Developing a design that can be fabricated.

A search for all work being carried out world-wide should be made on the subject of ceramic to metal bonding and this work should be followed and actively supported.

Work on the decomposition reactor at Sandia, UNLV and Ceramatec should be supported and other work in Korea and Japan followed.

Thermal designs of each of the concepts as well as conceptual mechanical designs should be attempted by heat exchanger fabricators or other heat exchanger professionals.

#### **Hybrid Sulfur**

Verification of the thermodynamic, VLE, and transport properties of the mixtures expected within the HyS process is needed. The current estimates of these properties are based on extrapolation of experimental data.

There is a need to determine the effect of impurities in the feedwater and make-up acid on the performance of the decomposition catalyst and the electrolyzers.

Work at Savannah River National Laboratory on the electrolyzer should be supported. This work includes finding a separation membrane for the cells, optimizing catalyst loading on the electrodes and otherwise optimizing the cell. Work is still required in scaling up these cells to a commercial size.

#### **Sulfur-Iodine**

The current process design is not based on a converged mass and energy balance. Adequate thermodynamic data must be gathered and a converged mass and energy balance developed. Efforts at solving other issues in this technology without a converged flowsheet simulation may be futile. An effort should be made to simplify the flowsheet significantly.

The flow scheme makes extensive use of expanders for both vapor and liquid streams to recovery energy within the process. An analysis of the process conditions against practical design limits for such rotating equipment is necessary to understand if the current process is viable or what changes are required.

Basic work is required in assessing the ability to separate the various species involved in the reactions. This depends not only on phase equilibrium data, but also on equipment design.

There is a need to determine the effect of impurities on the performance of the reactions and separations in this process.

The Decomposer Reactor design requires the same design evaluation, testing and development as described above for the HyS process. The Recuperator poses very similar design issues as the HTSE heat exchangers and will require a similar development program.

## **APPENDICES**

## APPENDIX A: HYBRID SULFUR MATERIAL BALANCE AND FLOWSHEET

## APPENDIX B: ELECTRICITY PRICE DATA

B-1: Electricity Price Data : Western Electric Coordinating Council, The Fifth Northwest Electric Power and Conservation Plan, 2005, Vol. 3, Appendix C: "Wholesale Electricity Price Forecast"

B-2: Excerpt from the Idaho Power Company 2006 Integrated Resource Plan

B-3: E-mail from Karl Bokenkamp of Idaho Power Company

## APPENDIX C: REVISED SLIDES FROM MEETING OF DECEMBER 6, 2006