ISSUED
2007/04/06

911106
Revision 0

Preconceptual Engineering Services For The Next Generation Nuclear Plant (NGNP) With Hydrogen Production

NGNP End-Products Study

Prepared by General Atomics
For the Battelle Energy Alliance, LLC

Sub-Contract No. 00060845
Uniform Filing Code UFC: 8201-4.1.4

GA Project 30283

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GA 1485 (REV. 08/06E)

ISSUE/RELEASE SUMMARY

☐ R & D ☐ DV&S ☒ DESIGN ☐ T&E ☐ NA	APPVL LEVEL	DISC	QA LEVEL	SYS	DOC. TYPE	PROJECT	DOCUMENT NO.	REV
	5	N	I	N/A	RGE	30283	911106	0

TITLE:
NGNP End-Products Study

CM APPROVAL/ DATE	REV	PREPARED BY	APPROVAL(S) ENGINEERING	APPROVAL(S) QA	APPROVAL(S) PROJECT	REVISION DESCRIPTION/ W.O. NO.
7 RELEASED APR 0 6 2007	0	D. Hanson P. Gupta	A. Shenoy	K. Partain	J. Saurwein	Initial Issue A30283.0120

CONTINUE ON GA FORM 1485-1

NEXT INDENTURED DOCUMENT(S)	N/A
COMPUTER PROGRAM PIN(S)	N/A

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ACRONYMS AND ABBREVIATIONS

ALARA	as low as reasonably achievable [radiation exposure][1]
CFR	Code of Federal Regulations
CSNF	commercial [LWR] spent nuclear fuel
D&D	decontamination and decommissioning
DBA	design basis accident
DOE	[United States] Department of Energy
EAB	exclusion area boundary
EFPD	effective full-power days
EIA	Energy Information Administration [Department of Energy]
EPA	Environmental Protection Agency
EPRI	Electric Power Research Institute
EPZ	emergency planning zone
FFF	fuel fabrication facility
FIMA	fissions per initial metal atom
FOAK	first-of-a-kind
GA	General Atomics
GCRA	Gas-Cooled Reactor Associates
GHG	greenhouse gas
GT-MHR	Gas Turbine – Modular Helium Reactor
HLW	high-level waste
HPS	helium purification system
HTA	High Temperature Absorber
HTE	High temperature electrolysis
HTGR	High Temperature Gas-Cooled Reactor
HVAC	heating, ventilating, and air conditioning

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[1] In this report, text in [square brackets] is explanatory; numbers in [square brackets] are tentative values that are likely to change as the design matures.

H2-MHR	Hydrogen [Production]-Modular Helium Reactor
IAEA	International Atomic Energy Agency
IHI	Ingestion Hazard Index
IHX	intermediate heat exchanger
INL	Idaho National Laboratory
LBP	lumped burnable poison
LLW	low-level waste
LOCA	loss of coolant accident
LSC	lanthanum strontium cobaltite
LSM	strontium-doped lanthanum manganate
LTA	Low Temperature Absorber
MHR	Modular Helium Reactor
MTHM	metric ton of heavy metal
MPC	multipurpose canister
MW	mixed waste
NEA	Nuclear Energy Agency [OECD organization]
NERI	Nuclear Energy Research Initiative
NGNP	Next Generation Nuclear Plant
NHI	National Hydrogen Initiative
Ni-YSZ	Nickel-Yttria Stabilized Zirconia Cermet
NOAK	nth-of-a-kind
NP-MHTGR	New Production-Modular Helium Reactor
NRC	[United States] Nuclear Regulatory Commission
O&M	operation and maintenance
PAG	Protective Action Guide
PC-MHR	Plutonium Consumption-Modular Helium Reactor
PCS	power-conversion system
PCDSR	pre-conceptual design studies report
PPMP	[NGNP] Preliminary Project Management Plan
PWR	pressurized water reactor

PyC	pyrolytic carbon
QA	quality assurance
radwaste	radioactive waste
RCRA	Resource Conservation and Recovery Act
RWMB	Radioactive Waste Management Building
SI	sulfur-iodine [process for thermo chemical water splitting]
SDC	samaria-doped ceria
SOEC	solid oxide electrolyzer cell
SOFC	solid oxide fuel cell
SNF	spent nuclear fuel
SMR	steam-methane reforming
SRM	System Requirements Manual
STP	standard temperature and pressure [273 K, 1 atm]
TBD	to be determined
TRISO	TRI-material, ISOtropic with the materials being low-density PyC (buffer), high-density IPyC and OPyC, and SiC.
TRU	transuranic waste
U/U	user/utility [requirements]
VHTR	Very High Temperature Reactor
WGI	Washington Group International
WIPP	Waste Isolation Pilot Plant
YSZ	Yttria-Stabilized Zirconia

1. SUMMARY

The U.S. DOE has chosen the Very High Temperature Reactor (VHTR) for the Next Generation Nuclear Plant (NGNP) Project. The reactor will be a helium-cooled, graphite-moderated thermal reactor designed to produce electricity and hydrogen as required by the Energy Policy Act of 2005. DOE has contracted with three industrial teams, including a team led by General Atomics, for pre-conceptual design engineering services. As part of the contractual work scope, GA has performed a study to identify, quantify and describe the disposition of end products that will be produced by the NGNP and by commercial VHTRs that will be based on the NGNP prototype.[2]

Currently, the bulk of world hydrogen production is by steam reforming of methane with carbon dioxide as a by-product. There are strong environmental and economic incentives for future hydrogen production without generating carbon dioxide as a byproduct. Nuclear hydrogen production is an attractive alternative. Of the advanced reactor concepts, the VHTR is especially well suited for producing hydrogen because of its high-temperature capability and advanced stage of development relative to other high-temperature reactor concepts. In this report, a VHTR coupled to a hydrogen production plant will be referred to as an H2-MHR.

Pre-conceptual designs have been developed for a commercial H2-MHR based upon the sulfur-iodine (SI) thermochemical water-splitting process and for a commercial H2-MHR based upon high temperature electrolysis (HTE) under a NERI contract. These two designs provide the primary basis for an end-products evaluation for the NGNP and for commercial H2-MHRs.

The primary commercial products (commodities) produced by the NGNP and commercial VHTRs will be electricity and hydrogen. The H2-MHR plants will also produce large quantities of high purity oxygen (8 kg of O_2/kg of H_2). Hydrogen is perceived to be primarily a future replacement for fossil fuels although it is also used extensively in petroleum refining, chemical processing, and ammonia production. Consequently, the future market value of hydrogen is assumed to be determined by the future cost of natural gas, the real cost of which is expected to increase significantly in future decades because of supply-and-demand forces and an anticipated carbon penalty. There is also a significant industrial market for high purity oxygen, but the future market value will probably remain stable because it is economically produced by cryogenic distillation of air. The estimated future market prices of these commodities are

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[2] The information in this report will also serve as input to a related task, Economic Assessments for Commercialization. This related task, as the title implies will provide estimates of the future costs for production of electricity and hydrogen by a commercial hydrogen-production VHTR.

summarized in Table 1-1 (the NGNP is assumed to be located at the Idaho National Laboratory, and the commercial H2-MHR is assumed to be located in the Texas-Louisiana Gulf coast area).

The excess electricity produced by the NGNP (beyond that needed for hydrogen production) can be sold to the local grid in the vicinity of the plant site at the Idaho National Laboratory. An attractive end use for the NGNP hydrogen (and, perhaps, for some of the excess electricity as well) would be for production of ammonia to supply the large agricultural fertilizer market in the region. Conceivably, the hydrogen might also be transported for use at refineries in northern Utah. As a last resort, the NGNP hydrogen could be simply vented to the atmosphere (or flared). The oxygen from the NGNP will probably be vented to the atmosphere unless a "green" oxygen consumer can be co-located at the site; any such oxygen consumer (e.g., a cement plant) should not generate significant air emissions, especially not carbon dioxide.

Table 1-1 Estimated Future Price of Commodities

	Market Price (constant 2007 $)		
Commodity	**NGNP Venue (2020 - 2060)**	**H2-MHR (2020 - 2060)**	**Comments**
Electricity (mil/kwh)[3]	55	106	EIA forecast
Hydrogen ($/kg)	2.5	2.5	Set by price of natural gas
Oxygen ($/tonne)[4]	23	23	EPRI forecast
Process Heat ($/MMBtu)[5]	12	12	Set by price of natural gas

Commercial VHTRs based upon the NGNP could be dedicated to electricity production, hydrogen production, or a combination of both. The primary market for hydrogen and electricity from commercial H2-MHRs, at least for the first units, appears to be petroleum refineries to replace natural gas as a heat source and to provide hydrogen for sweetening crude feedstock and for hydrocracking. Such an application may well include the supply of process steam as well. The supply of hydrogen and electricity for ammonia production for fertilizer and other

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[3] Levelized price for 2020 – 2060 timeframe with 1%/yr real escalation (e.g., anticipated carbon tax, etc.) and a 7% discount rate.

[4] Constant 2007 dollars; no real escalation of O_2 prices (cryogenic air distillation provides price stability)

[5] Conversion factor: 0.1345 MMBTU/kg H_2. Levelized price for 2020 – 2060 timeframe with 1%/yr real escalation

industrial applications also appears potentially attractive. Commercial H2-MHRs will produce large quantities of high-purity oxygen. A suitable consumer of this oxygen needs to be identified and co-located at the plant site. This oxygen consumer should not generate significant air emissions, especially not carbon dioxide.

The NGNP and commercial GT-MHR electric plants and H2-MHRs will generate certain waste streams. As with all nuclear power plants, the most significant waste stream will be the spent fuel from the nuclear heat source. The fuel burnup should be maximized to the fullest extent practical to minimize the amount of spent fuel per unit electrical production and unit mass of hydrogen. The spent fuel elements will be stored on site to cool for at least one year. Depending upon the availability of a federal repository, the NGNP spent fuel may be stored on-site for several decades. The spent fuel elements from commercial H2-MHRs will be stored on-site for up to 10 years. The study assumed that unprocessed spent fuel elements will ultimately be disposed of permanently in a federal geological repository (presumably at Yucca Mountain). Unprocessed, spent MHR fuel elements have been shown previously to be a nearly ideal waste form for geological disposal, far superior to zircaloy-clad LWR fuel bundles.

The plants will also generate radioactive and chemical waste streams. Every effort should be made to minimize these waste streams; in general, the most effective means of waste minimization is source reduction, especially during the plant design phase. Past operating experience with HTGRs and past design experience with advanced MHRs indicates radioactive waste streams can be reduced to well below current LWR practice. The key to minimizing radioactive waste is the use of high quality, high performance TRISO-coated fuel to retain the fission products in the core to the fullest extent practical during normal operation and postulated accidents.

Tritium, which will be produced in an H2-MHR by various nuclear reactions, is a special concern. Given its high mobility, especially at high temperatures, some tritium will permeate through the intermediate heat exchanger and the hydrogen plant process vessels, contaminating the product hydrogen. This tritium contamination will contribute to public and occupational radiation exposures; consequently, stringent limits on tritium contamination in the product hydrogen are anticipated to be imposed by regulatory authorities. Design options are available to control tritium in an H2-MHR, but they can be expensive so an optimal combination of mitigating features must be implemented in the design. The most cost-effective means of controlling tritium contamination appears to be the addition of a helium purification system to the secondary heat transport loop which transfers heat from the primary coolant loop containing the reactor to the hydrogen production plant.

The SI-based hydrogen plant can be designed to limit the gaseous and liquid, chemical waste streams to very low levels. The only feedstock is water, and the only products are hydrogen and oxygen; the most hazardous process materials (e.g., sulfuric acid) are fully contained and recycled. In fact, the SI plant appears to have the potential to be a nearly "zero-discharge" facility which would be a worthy design goal. The oxygen product stream will likely contain traces of sulfur dioxide, which may require polishing by caustic scrubbing. A small quantity of corrosion products (mainly metal sulfates) will also be generated.

The HTE-based hydrogen plant will generate very little chemical waste as a result of plant operation. The primary waste stream will be spent solid oxide electrolyzer cells which will need to be replaced periodically since they are expected to have a maximum design life of 5 - 10 years. These spent cells will be produced in quantity and will contain hazardous constituents, which cannot be disposed of in municipal landfills. Consequently, the recovery and potential recycle of these hazardous constituents should be a high-priority R&D task.

The NGNP will be designed to have a 60-year lifetime, and commercial GT-MHRs and H2-MHRs are expected to have comparable design lifetimes. At the end of its operational lifetime, the physical plant will represent the ultimate "by-product" of electricity and hydrogen production, and both the reactor plant and the hydrogen plant will have to be decontaminated and decommissioned. Based upon the past D&D experience with gas-cooled reactors, especially the successful D&D of the Fort St. Vrain HTGR, the D&D costs for both the NGNP and commercial GT-MHRs and H2-MHRs should be comparable to that for a LWR on a per MW(e) basis. An important component of that conclusion is that the core graphite – or at least the vast bulk of it – should qualify as low-level waste. In fact, all of the FSV core graphite qualified as Class A low-level waste (the lowest level classification).

The various end products identified for the NGNP and a commercial H2-MHR are summarized in Table 1-2.[6] Both plants are in the pre-conceptual design phase (e.g., reactor power levels have not been chosen for either plant); consequently, a number of attributes are "to be determined," and other attributes are subject to change as the plant designs mature. Certain assumptions had to be made so that the possible end products for the NGNP could be estimated from those predicted for the commercial H2-MHR designs and from previous MHR designs for electricity production. Without such assumptions, only crude qualitative estimates of the commercial products and waste products could be provided at this stage of design

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[6] The NGNP is assumed to be a full-size 600 MW(t) prototype module, and the commercial plant is assumed to be comprised of four 600 MW(t) modules, consistent with the NERI study.

definition. Not surprisingly, the available information is spotty; the definition of the reactor plant is more complete than the definitions of SI-based and HTE-based hydrogen plants. Nevertheless, the subject evaluation provides insight to the both design effort (e.g., emphasize source reduction to minimize radioactive and chemical waste streams during conceptual and preliminary design) and to the technology programs (e.g., investigate the feasibility of recovery and recycle of hazardous materials in spent HTE electrolyzer cells).

Table 1-2. Summary of End Products

Attribute	**NGNP**[7]	**H2-MHR**[8]	**Comments**
Plant Design			
Location	INL	TX-LA Gulf coast	
Time frame	2020 - 2060	2020 - 2060	
H_2 plant technology	SI and HTE	SI or HTE	
Reactor power	1 x 600 MW(t) MHR	4 x 600 MW(t) MHR	
Core outlet temperature	950 ^oC	950 ^oC	850 ^oC initially
Power conversion cycle	Direct cycle	Direct cycle (HTE)	No PCS with SI plant
Electrical power – to grid	[271 MW_e (SI)]; [292 MW_e (HTE)]	All electrical output to HTE plant	~20 MW_e for NGNP SI & 29 MW_e for HTE; 54% efficiency
Process heat input – SI	[60 MW(t)]	4 x 600 MW(t)	
Process heat input – HTE	[4 MW (t)]	4 x 58 MW(t)	for steam production
H_2 production rate – SI	[526 kg/hr]	3.68 x 10^5 tonne/yr	
H_2 production rate – HTE	[492 kg/hr]	2.68 x 10^5 tonne/yr	
O_2 production rate – SI	[4212 kg/hr]	2.94 x 10^6 tonne/yr	
O_2 production rate – HTE	[3936 kg/hr]	2.14 x 10^6 tonne/yr	
Waste Streams – Reactor Plant			
Spent fuel elements	[384 FE/yr]	1536 FE/yr	Basis: GT-MHR
Spent reflector elements	[15 m^3/yr]	60 m^3/yr	Basis: PC-MHR[9]
Radwaste – gas	[575 m^3(STP)/yr]	2300 m^3(STP)/yr	Specific activity = 10% PC-MHR[10]
Radwaste –liquid	"minimal"	"minimal"	liquid wastes solidified
Radwaste – solid	[7.2 m^3/yr]	29 m^3/yr	Specific activity = 10% PC-MHR

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[7] The values for the NGNP in [square brackets] are tentative values derived from the commercial H2-MHR designs; in fact, the reactor power for the NGNP has not been officially chosen yet, much less the design parameters for the SI and HTE demonstration plants.

[8] The commercial H2-MHR plants described herein do not generate excess electricity for commercial sale; alternative H2-MHR designs could produce both hydrogen and electricity.

[9] PC-MHR is a direct-cycle GT-MHR design fueled with weapons Pu.

[10] See Table 7-5 for noble gas inventories in He purification system; inventories for NGNP and H2-MHR should be an order of magnitude lower.

Attribute	**NGNP**[7]	**H2-MHR**[8]	**Comments**
Waste heat	[~300 MW_t – SI] [~300 MW_t – HTE]	4 x 336 MW_t - SI 4 x 246 MW_t - HTE	dry cooling tower
Waste Streams – Hydrogen Plant (SI Process)			
SO_2	TBD kg/hr	TBD kg/hr	O_2 product stream
[Na_2SO_4]	TBD kg/hr	TBD kg/hr	[caustic scrubber]
Corrosion products	TBD kg/yr	TBD kg/yr	Metal sulfates
Waste heat	TBD MW	TBD MW	Dry cooling tower
Hotel waste	TBD kg/yr	TBD kg/yr	
Waste Streams – Hydrogen Plant (HTE Process)[11]			
Hotel waste	TBD kg/yr	TBD kg/yr	
Spent SOEC[12]	~18,000 kg/5 yr	~2.5 x 10^5 kg/5 yr	
Waste heat	TBD MW	TBD MW	Dry cooling tower

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[11] Toshiba pre-conceptual design of NGNP HTE demonstration plant.

[12] Certain constituents of the spent SOEC are classified as hazardous materials; consequently, there is considerable economic incentive to recover and recycle these constituents.

2. INTRODUCTION AND BACKGROUND

The U.S Department of Energy (DOE) has chosen the Very High Temperature Reactor (VHTR) for the Next Generation Nuclear Plant (NGNP) Project. The reactor design will be a helium-cooled, graphite-moderated thermal reactor that will be designed to produce electricity and hydrogen as required by the Energy Policy Act of 2005. DOE has contracted with three industrial teams, including a team led by General Atomics (GA), for pre-conceptual design engineering services (Work Plan 2006). As part of the contractual work scope, GA has performed a study to identify, quantify and describe the disposition of end products[13] that will be produced by the NGNP and by commercial VHTRs that will be based on the NGNP prototype.

The results of this task (identified as WBS Element 1170 in the Work Plan) will serve as input to another related task, Economic Assessments for Commercialization (WBS Element 1320). This task, as the title implies, will provide estimates of the future costs for production of electricity and hydrogen for the NGNP and for a commercial hydrogen-production VHTR.

2.1 Purpose

The purpose of this study was to identify, quantify and describe the disposition of end-products produced by the NGNP and by commercial VHTRs that will be based on the NGNP prototype.

2.2 H2-MHR Design Status

There is a growing interest throughout the industrialized world in using nuclear energy to produce hydrogen (e.g., NHI, 2005). Currently, the bulk of world hydrogen production is by steam-methane reforming (SMR) with carbon dioxide as a byproduct. There is a growing international demand to curb carbon dioxide emissions because of concerns about global warming. In addition, the price of natural gas has risen dramatically in recent years, and the demand for natural gas may eventually outpace its production. There are strong environmental and economic incentives for future hydrogen production without generating carbon dioxide as a byproduct. Nuclear hydrogen production is an attractive alternative.

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[13] In the various programmatic documents defining the scope of this study (e.g., Work Plan 2006), the terms “end-products” and “by-products” are used interchangeably. “End-product” is judged to be the more appropriate term since it encompasses the full spectrum of products ranging from those with commercial value (“commodities”) to waste products (products without commercial value). Typically, “by-product” connotes a product with little or no commercial value compared to the main product(s). Consequently, “end-product” will be used herein to represent the full spectrum of products.

In principle, nuclear electricity can be used to split water using conventional low-temperature electrolysis. For a conventional light-water reactor (LWR) that produces electricity with approximately 33% thermal efficiency and current generation electrolyzers operating with an efficiency of about 75% to convert electricity to high-pressure hydrogen, the overall efficiency for hydrogen production is approximately 25%. If a Gas Turbine-Modular Helium Reactor (GT-MHR) is used to produce the electricity with 48% thermal efficiency, the overall efficiency for hydrogen production improves to 36%. However, even with high-efficiency electricity production, economic evaluations of coupling nuclear energy to low-temperature electrolysis have generally not been favorable when compared to steam-methane reforming.

Of the advanced reactor concepts, the VHTR is especially well suited for producing hydrogen, because of its high-temperature capability, advanced stage of development relative to other high-temperature reactor concepts, and passive-safety features (e.g., Marshall 2002). In this report, a VHTR coupled to a hydrogen production plant will be referred to as an H2-MHR.[14] A VHTR can also be dedicated to electricity production at high efficiency (~50% with a direct-cycle plant); however, the end-products from a H2-MHR are the focus here. To a good approximation, an electricity producing GT-MHR would have the same reactor-generated end products as an H2-MHR without the chemical commodities and wastes produced by the latter.

2.3 Hydrogen Production Using MHRs

A VHTR can provide the high-temperature process heat to produce hydrogen by either thermo chemical water splitting or by high temperature electrolysis (e.g., Richards 2004). A number of thermochemical cycles for decomposing water into its elemental constituents have been evaluated, and the preferred cycle appears to be the sulfur-iodine (SI) cycle (e.g., Brown 2003); only the SI cycle will be considered herein.

Pre-conceptual designs have been developed for an H2-MHR based upon the SI process and for an H2-MHR based upon high temperature electrolysis (HTE) under a Nuclear Energy Research Initiative (NERI) contract to General Atomics, Idaho National Laboratory (INL), and Texas A&M University. These two NERI reports (GA-A25401, 2006, for the SI-based plant and GA-A25402, 2006, for the HTE-based plant) provide the primary basis for the end-products evaluation for commercial H2-MHRs, which are presented herein; as such, they are heavily excerpted in the sections that follow.

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[14] "H2-MHR" will be used generically to refer to a commercial, prismatic-core VHTR coupled to a hydrogen production plant. It does not refer to a particular plant design (e.g., with a particular hydrogen production technology, with a particular power level, core outlet temperature, etc.).

The NGNP will serve as a prototype for a commercial H2-MHR; as such, it will be designed to produce both electricity and hydrogen as mandated by the Energy Policy Act of 2005. However, the specific design of the NGNP has not yet been determined (PPMP 2006). For the purpose of the current study, it was assumed that the NGNP is a prototype for the H2-MHR designs presented in the two NERI reports cited above. Consequently, the NGNP was assumed to have a prismatic-core MHR heat source coupled to a direct-cycle power conversion system (PCS) for electricity production, and a fraction of the thermal power (~50 MW) was assumed to be supplied to either a SI hydrogen plant and/or an HTE hydrogen plant. One possible configuration is shown in Figure 2-1. These assumptions were made by necessity so that the possible end products for the NGNP could be estimated from those predicted for the commercial H2-MHR designs. Without such assumptions, only crude qualitative estimates of the commercial products and waste products for the NGNP could be provided as this stage of design definition.

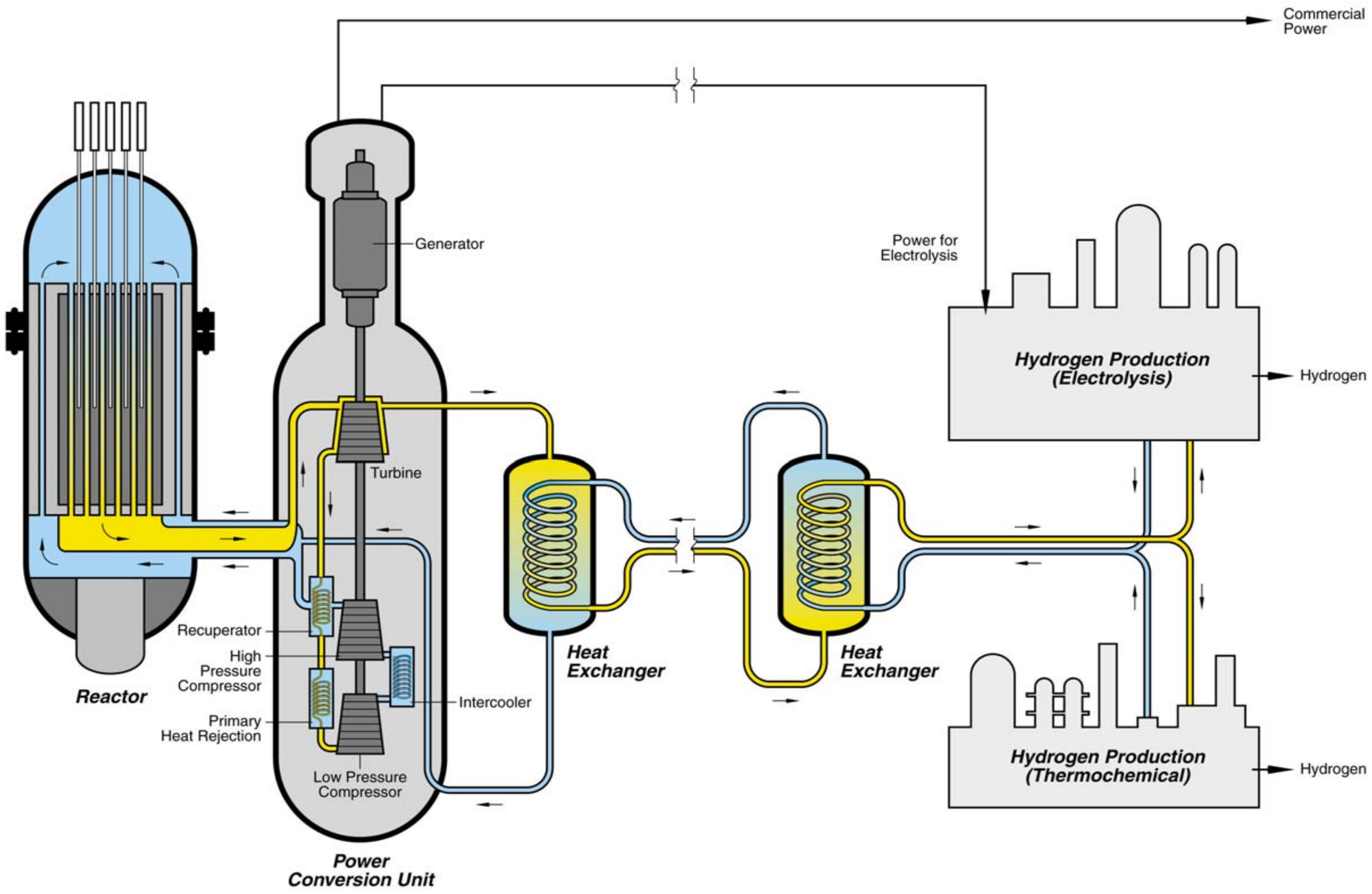

Figure 2-1. Schematic of NGNP for Production of Electricity and Hydrogen

2.3.1 MHR Heat Source

For both the SI-based and HTE-based H2-MHRs, the nuclear heat source has been assumed to be a prismatic-core Modular Helium Reactor (MHR) as shown in Figure 2-2. Passive safety features of the MHR include: (1) ceramic, coated-particle fuel that maintains its integrity at high temperatures during normal operation and loss of coolant accidents (LOCAs); (2) an annular graphite core with high heat capacity that limits the temperature rise during a LOCA; (3) a relatively low power density that helps to maintain acceptable temperatures during normal operation and accidents; (4) inert helium coolant, which reduces circulating and plateout activity; and (5) a negative temperature coefficient of reactivity that ensures control of the reactor for all credible reactivity insertion events. The fuel, the graphite, the primary coolant pressure boundary, and the vented low-pressure containment building provide multiple barriers to the release of fission products.

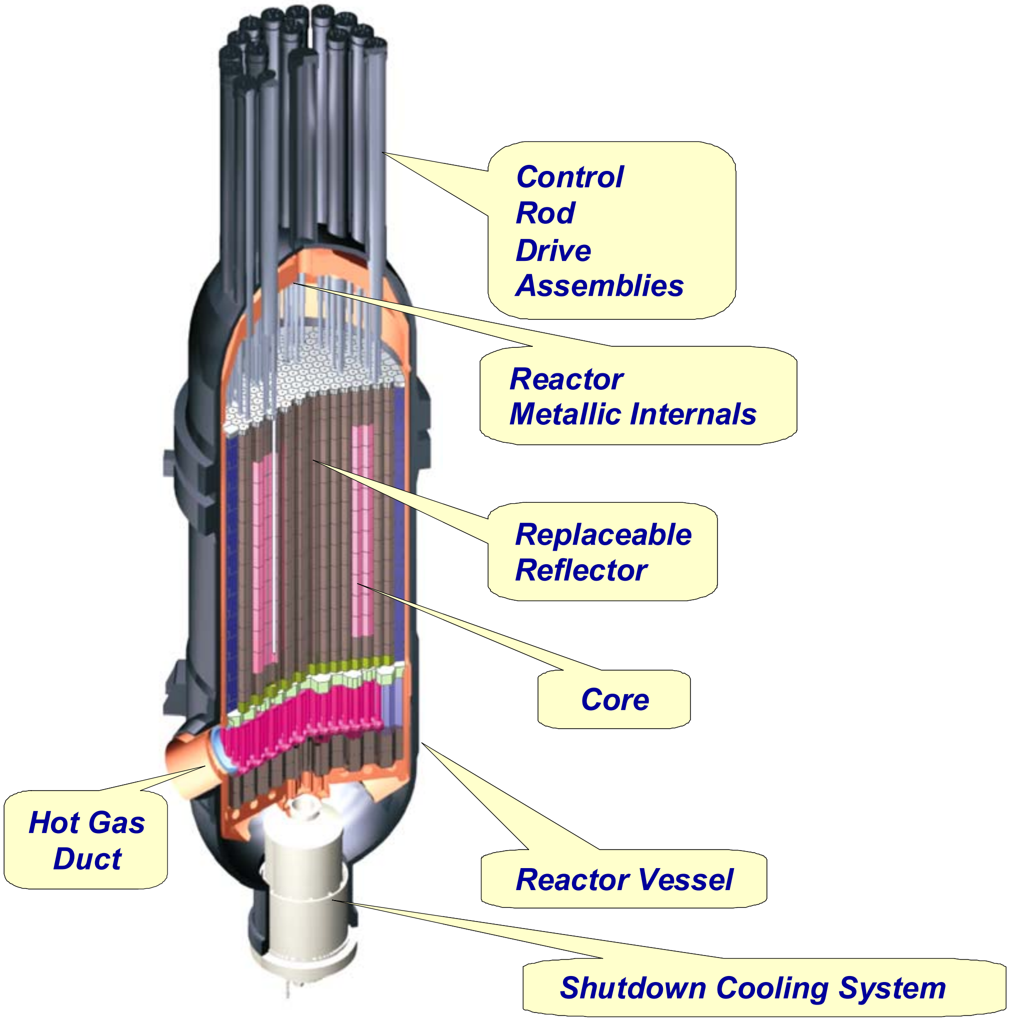

Figure 2-2. MHR Nuclear Heat Source

The MHR fuel element and its components are shown in Figure 2-3. The fuel for the H2-MHR consists of microspheres of uranium oxycarbide that are coated with multiple layers of pyrocarbon and silicon carbide. The H2-MHR core is designed to use a blend of two different particle types; a fissile particle that is enriched to 19.8% U-235 and fertile particle with natural uranium (0.7% U-235). The fissile/fertile-loading ratio is varied with location in the core in order to optimize reactivity control, minimize power peaking, and maximize fuel cycle length. The buffer, inner pyrolytic carbon (IPyC), silicon carbide (SiC), and outer pyrolytic carbon (OPyC) layers are referred to collectively as a TRISO coating. The coating system can be viewed as a miniature pressure vessel that provides containment of radionuclides and gases. This coating system is also an excellent engineered barrier for long-term retention of radionuclides in a spent-fuel repository environment.

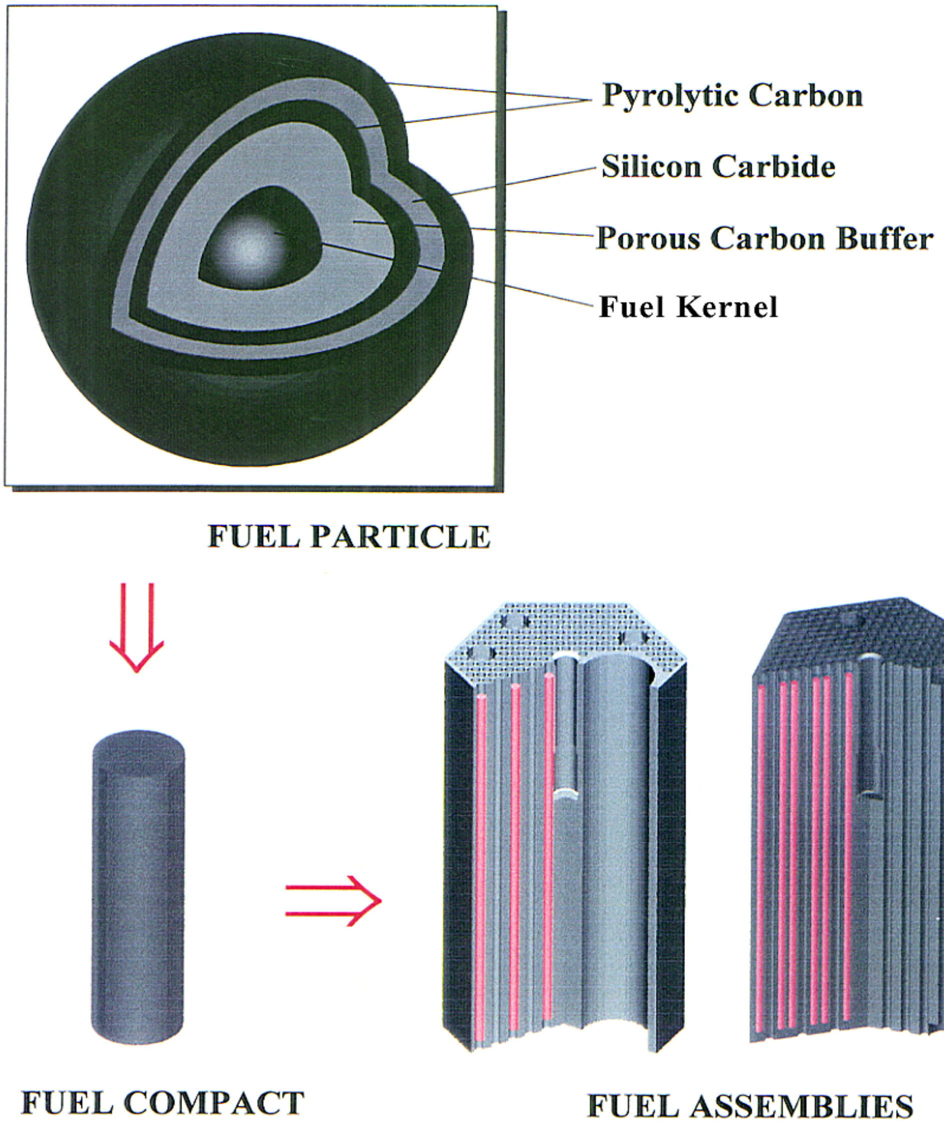

Figure 2-3. MHR Fuel Components

For electricity production, the GT-MHR operates with a thermal power level of 600 MW and an outlet helium temperature of 850 °C to drive a direct, Brayton cycle power-conversion system (PCS) with a thermal-to-electrical conversion efficiency of 48 percent (see Figure 2-4). This design is referred to as the GT-MHR and is described in (Shenoy, 1996). Development of the GT-MHR has advanced under the International GT-MHR Project, which was started in 1995 by GA and Minatom (now Rosatom) of Russia for the disposition of surplus weapons-grade plutonium. The GT-MHR Conceptual Design for plutonium disposition was completed in 1997 and was independently reviewed by a panel of experts representing the U.S., Russia, Japan, Germany and France. The review confirmed the capability of the GT-MHR to deeply burn weapons-grade plutonium in a once-through fuel cycle. The Preliminary Design Phase was completed in 2002 and reviewed by Minatom. Work is currently focused on areas related to technical risks, including coated particle fuel development, demonstration of the PCS with electromagnetic bearings, and verification/validation of computer codes for core design, including core physics, thermal hydraulics, fuel performance, and fission product transport. A journal article (Labar 2003) provides additional information on the GT-MHR design and its technology background.

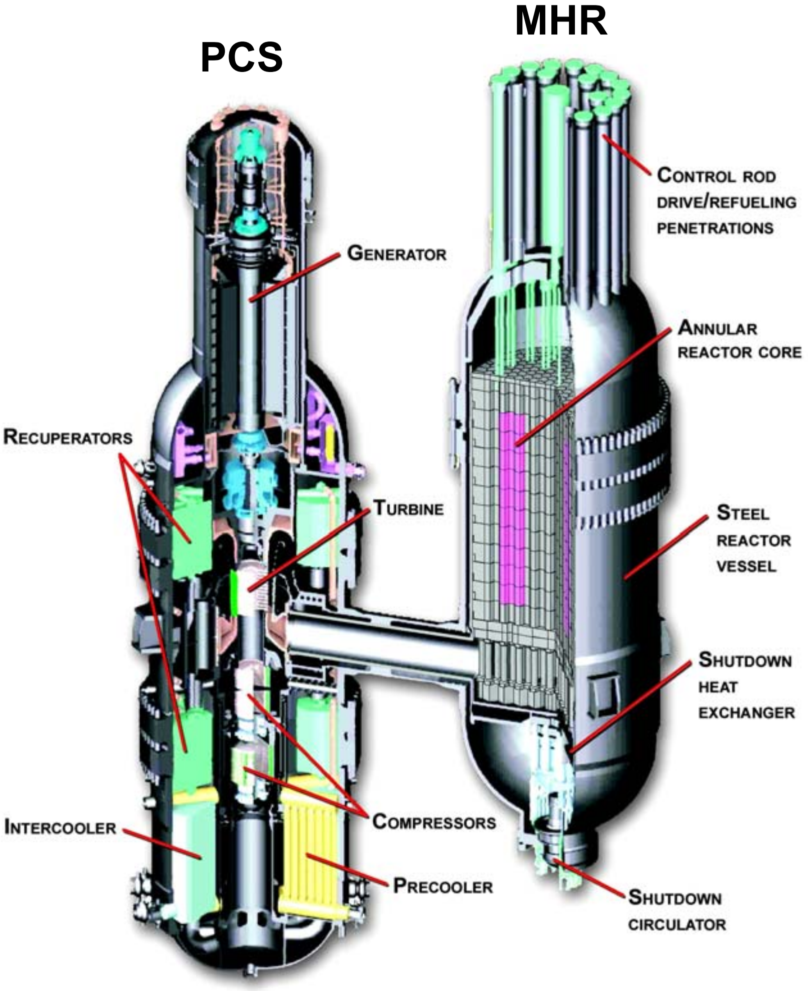

Figure 2-4. GT-MHR for Electricity Production

For hydrogen production, the reactor module design is essentially the same as that for the GT-MHR, but with some modifications to allow operation with a higher coolant-outlet temperature of 950 °C in order to increase hydrogen-production efficiency. If the reactor outlet temperature is increased to 950 °C as projected for the NGNP, the electric generation efficiency can be >50%.

2.3.2 Sulfur-Iodine Thermochemical Process

The commercial plant consists of four 600 MW(t) MHR modules, with each module coupled to an Intermediate Heat Exchanger (IHX) to transfer the heat to a secondary helium loop (Richards 2006a). As shown in Figure 2-5, the MHRs supply the high-temperature process heat required to drive the SI process. The heat is then transferred to the SI-based Hydrogen Production System. With this design, there is no PCS, hence no electricity production.

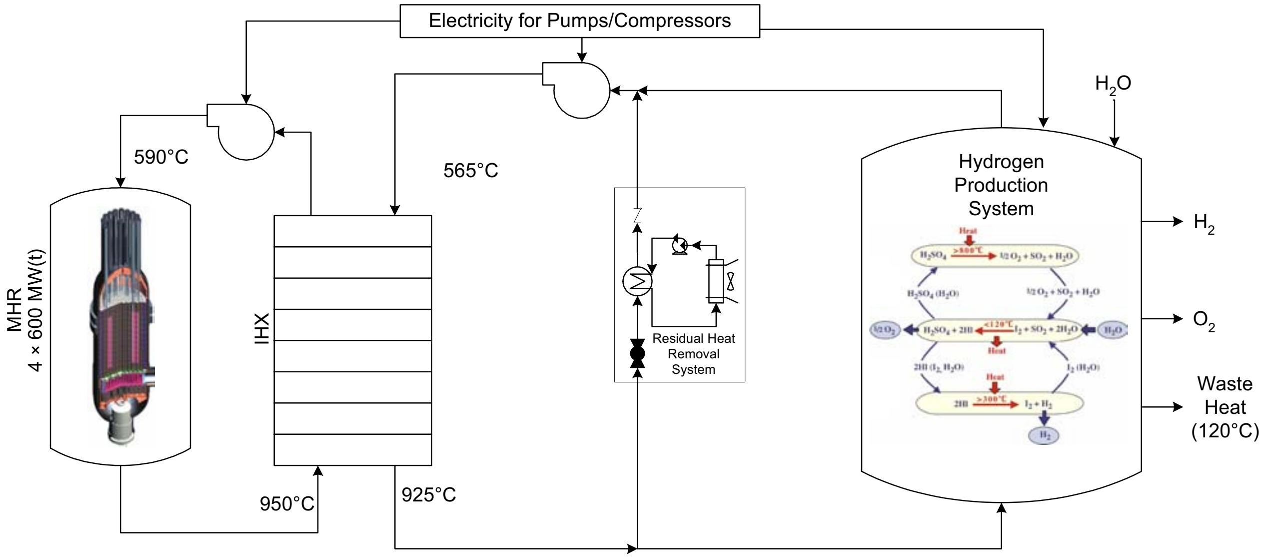

Figure 2-5. SI-Based H2-MHR Process Schematic

Waste heat is rejected using cooling towers in a manner similar to that for electricity-producing plants. In addition to the heat required to drive the SI process, the plant requires approximately 800 MW(e); most of this electricity is needed to power pumps and compressors that are part of the Hydrogen Production System. In the NERI study, it was assumed that the H2-MHR plant is part of an energy park that also includes GT-MHRs that provide the necessary electricity (200 MW(e) per dedicated SI module). Nominal plant design parameters are given in Table 2-1. At a 90% capacity factor, the plant produces 3.68 x 10^5 metric tons of hydrogen per year at an efficiency of 45.0% (based on the higher heating value of hydrogen). An alternative design option is to include a PCS such that the reactor thermal power is split to provide both process heat and the corresponding amount of electricity to supply the house loads for the reactor system and the SI plant.

Table 2-1. Nominal Plant Design Parameters for SI-Based H2-MHR

MHR System	
Number of modules	4
Module power rating	600 MW(t)
Core inlet/outlet temperatures	590°C / 950°C
Peak fuel temperature – normal operation	1250°C - 1350°C
Peak fuel temperature – accident conditions	< 1600°C
Heat Transport System	
Primary coolant fluid	helium
Primary coolant pressure	7.0 MPa
Primary coolant flow rate	320 kg/s
Total pressure drop – primary circuit	100 KPa
Secondary heat transport fluid	helium
Secondary heat transport fluid pressure	7.1 MPa
Secondary heat transport fluid flow rate	320 kg/s
Secondary loop cold leg/hot leg temperatures	565°C / 925°C
Total pressure drop – secondary circuit	146 KPa
Hydrogen Production System	
Peak process temperature	900°C
Peak process pressure	7.0 MPa
Product hydrogen pressure	4.0 MPa
Annual hydrogen production	3.68×10^5 metric tons
Plant hydrogen production efficiency	45.0%

Water thermally dissociates at significant rates into elemental hydrogen and oxygen only at temperatures approaching 4000 °C. As indicated in Figure 2-6, the SI process consists of three primary chemical reactions that accomplish the same result at much lower temperatures.

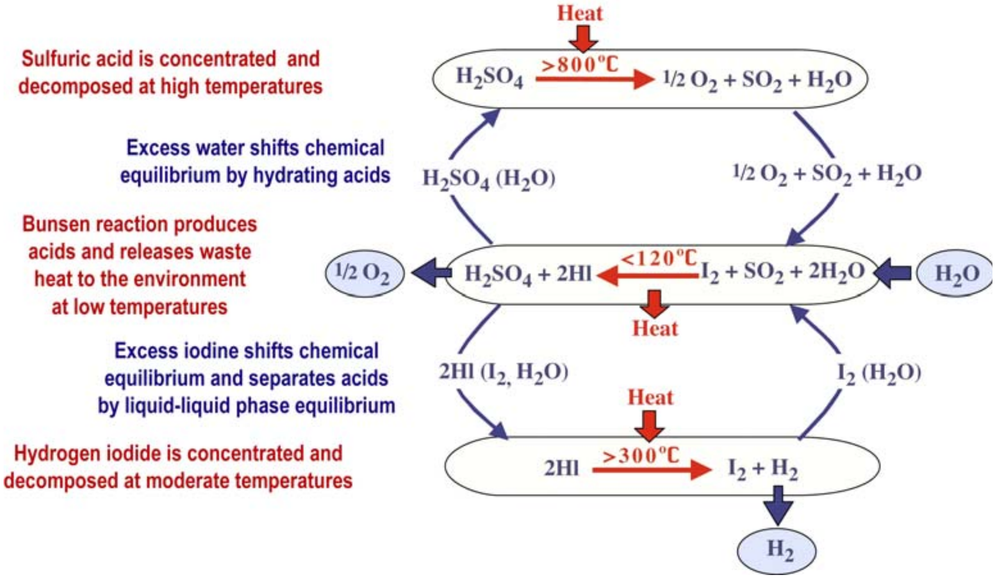

Figure 2-6. The SI Thermo chemical Water Splitting Process

The process involves decomposition of sulfuric acid and hydrogen iodide, and regeneration of these reagents using the Bunsen reaction. Process heat is supplied at temperatures greater than 800 °C to concentrate and decompose sulfuric acid. The exothermic Bunsen reaction is performed at temperatures below 120 °C and releases waste heat to the environment. Hydrogen is generated during the decomposition of hydrogen iodide, using process heat at temperatures greater than 300 °C. The product hydrogen gas is produced at a pressure of 4.0 MPa. Two different processes are being investigated for HI decomposition. One process, referred to as reactive distillation, involves reacting the HI-water-iodine mixture in a reactive bed to effect the separation process and produce hydrogen. The other process, referred to as extractive distillation, uses phosphoric acid to strip HI from the HI-water-iodine mixture and to break the HI-water azeotrope.

The NERI study of an SI-based plant (Richards 2006a) assumed that the commercial H2-MHR would utilize reactive distillation. However, recent data indicate that the kinetics for reactive distillation are unfavorable, and extractive distillation is now the leading candidate for both the NGNP and a commercial H2-MHR using the SI process. Unfortunately, at this writing, the process design and evaluation are not as advanced for extractive distillation as that presented in the NERI report for reactive distillation. Given that the NGNP is in the pre-conceptual design phase, the practical impact on this study is judged to be insignificant. Obvious differences, such as the use of phosphoric acid and its potential to contribute to waste streams, have been identified and will be discussed in a subsequent section.

As shown in Figure 2-7, the overall process naturally divides itself into three process sections in which there is significant recycle and interconnection and which are connected to the other sections by a minimum number of streams. These natural sections roughly correspond to the three major chemical reactions. Sections 1, 2 and 3 are used to designate the portions of the process flow sheet associated with the Bunsen reaction (where the acids are formed,) with the sulfuric acid decomposition reaction, and with the HI decomposition reaction, respectively.

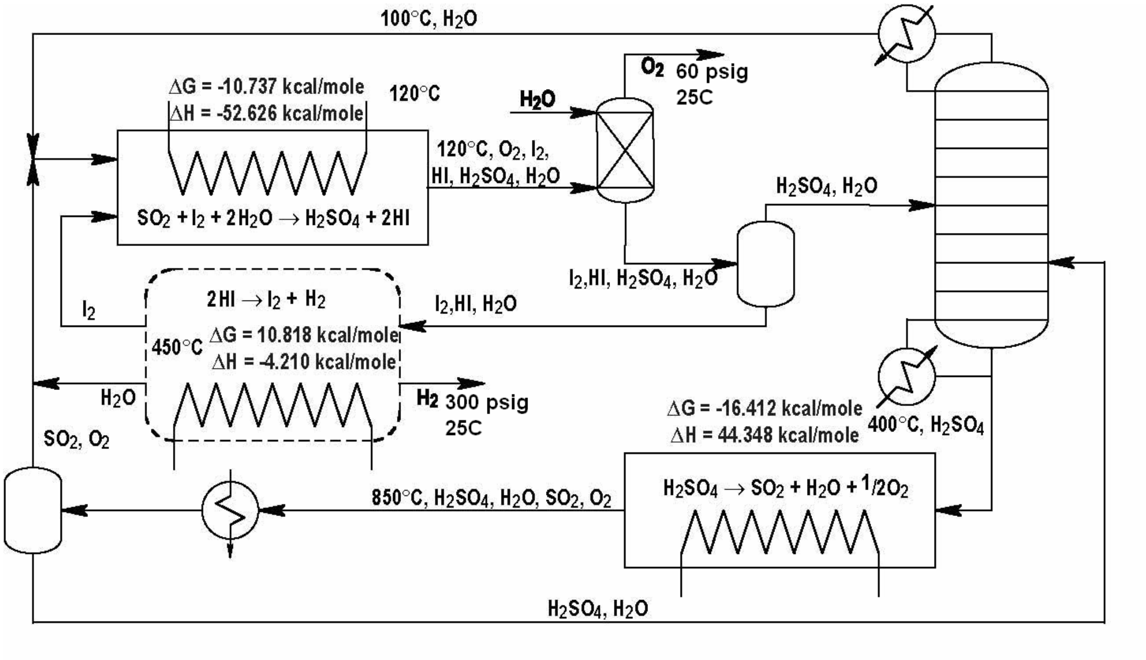

Figure 2-7. Simplified SI Process Flow Schematic

In Section 1, sulfur dioxide and iodine are contacted with water to form two immiscible acid phases. The lighter sulfuric acid phase can be separated from the heavier hydriodic acid phase in the presence of excess iodine. The sulfuric acid phase is then concentrated before undergoing decomposition to sulfur dioxide and oxygen in Section 2. The hydrogen iodide in the lower phase is separated from water and iodine before undergoing decomposition to iodine and the product hydrogen in Section 3. In the extractive distillation process, phosphoric acid is used to facilitate separation of hydrogen iodide from water and iodine. The phosphoric acid is re-circulated entirely within Section 3.

Sulfur, iodine, and phosphoric acid are completely recycled in the SI process. The only raw material to feed is water, and the only products are hydrogen and oxygen. There is one-half mole of oxygen (O_2) generated for each mole of hydrogen (H_2) produced. The oxygen is produced in Section 2, during sulfuric acid decomposition, and is separated from sulfur dioxide in Section 1. As shown in the diagrams, there is significant material exchange between Section 1 and Section 2, and also between Section 1 and Section 3.

The recommended capacity of the NGNP demonstration SI-based hydrogen plant is for a 60 MW(t) heat input from the reactor to produce 7.5 million standard cubic feet per day (73 mole/sec) of hydrogen (Labar 2007). Table 2-2 summarizes the mass balance for such a 60 MW(t) hydrogen plant.

Table 2-2. Simplified Mass Balance for 60 MW(t) NGNP SI Plant.

All Values in kg/sec	H_2O**	HI	(I_2 + I)	H_2SO_4	SO_2	O_2	H_2
Section 1 In	21.08	-	167.05	-	4.68	1.17	-
Section 1 Out	18.44	18.71	148.49	7.17	-	1.17	-
Section 2 In	5.27	-	-	7.17	-	-	-
Section 2 Out	6.59	-	-	-	4.68	1.17	-
Section 3* In	14.05	18.71	148.49	-	-	-	-
Section 3* Out	14.05	-	167.05	-	-	-	
Net In	1.32	-	-	-	-	-	-
Net Out	-	-	-	-	-	1.17	0.15

* 159.22 kg/sec phosphoric acid circulating within Section 3

** 2/3 of the net water input to the process enters in Section 3, remainder in Section 1

2.3.3 High Temperature Electrolysis

For high-temperature electrolysis, Modular Helium Reactors, as shown in Figure 2-8, supply the heat to generate both steam and the electricity to decompose the steam into hydrogen and oxygen (Richards 2006b). Electricity is generated using a direct, Brayton-cycle PCS. Approximately 90% of the heat generated by the MHR modules is used to produce electricity. The hydrogen plant is sized such that all of the electricity is used for hydrogen production; there is no excess electricity for sale. The remainder of the heat is transferred though an IHX to produce high quality steam. Steam is supplied to both the anode and cathodes sides of the solid oxide electrolyzers. The steam supplied to the cathode side is electrolytically split into hydrogen and oxygen. The oxygen is transferred through the electrolyte to the anode side. The steam supplied to the anode side is used to sweep the oxygen from electrolyzer modules. The steam supplied to the cathode side is first mixed with a small portion of the hydrogen stream to ensure reducing conditions and prevent oxidation of the electrodes. Heat is recuperated from both the hydrogen/steam and oxygen/steam streams exiting the electrolyzer. A small quantity of electricity is generated from the oxygen/steam stream to provide power for plant house loads.

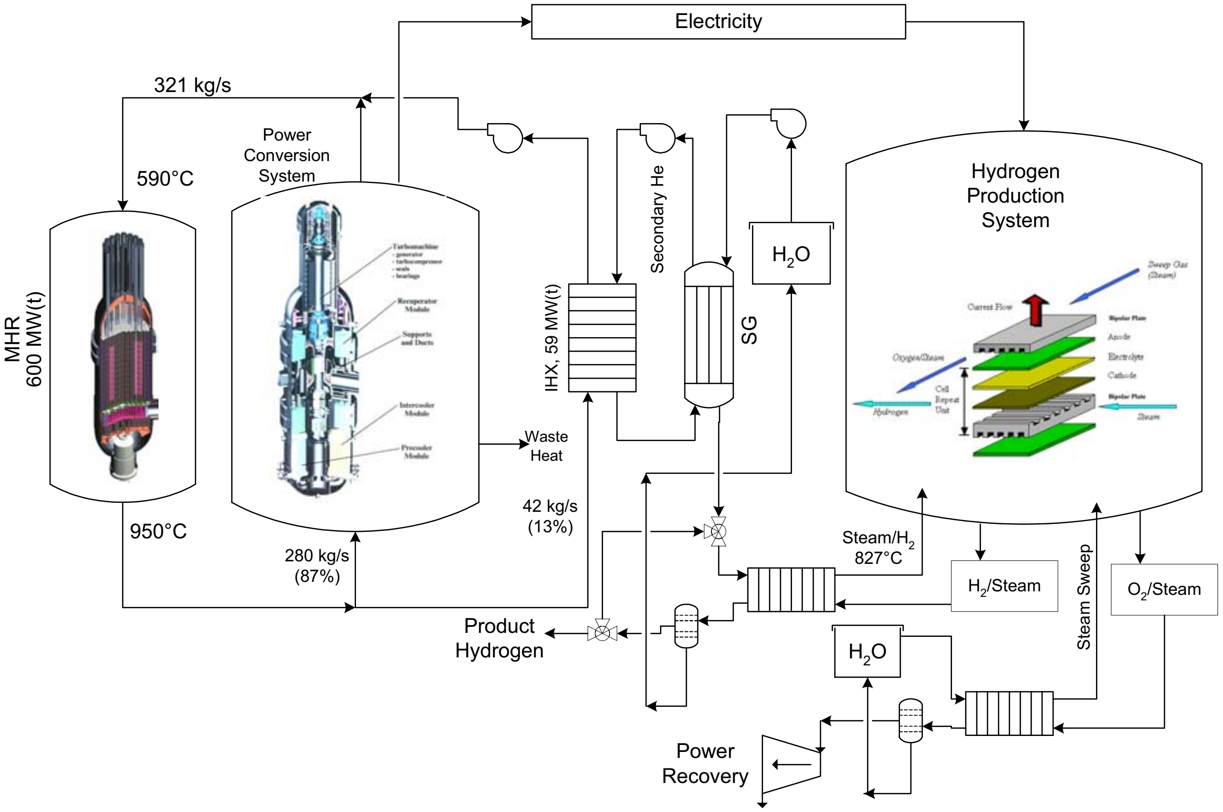

Figure 2-8. HTE-Based H2-MHR Process Schematic

The full-scale commercial plant includes four 600-MW(t) MHR modules. The reactor design and PCS are essentially the same as that for the GT-MHR, but with some minor modifications to allow operation with a higher coolant-outlet temperature of 950°C in order to increase hydrogen-production efficiency. Nominal plant design parameters are given in Table 2-3. At a 90% capacity factor, the plant produces 2.68 x 10^5 metric tons of hydrogen per year at an efficiency of 55.8% (based on the higher heating value of hydrogen) with a product gas pressure of 4.95 MPa.

Table 2-3. Nominal Plant Design Parameters for HTE-Based H2-MHR

MHR System	
Number of modules	4
Module power rating	600 MW(t)
Core inlet/outlet temperatures	590°C / 950°C
Peak fuel temperature – normal operation	1250°C - 1350°C
Peak fuel temperature – accident conditions	< 1600°C
Helium mass flow rate	321 kg/s
Total MHR System pressure drop	80 KPa
Power Conversion System	
Mass flow rate	280 kg/s
Heat supplied from MHR System	542 MW(t)
Turbine inlet/outlet temperatures	950°C / 600°C
Turbine inlet/outlet pressures	7.0 MPa / 2.8 MPa
Generator efficiency	98 %
Electricity generated	292 MW(e)
Electricity generation efficiency	53.9%
Heat Transport and Recovery System	
Primary helium flow rate	42 kg/s
Secondary helium flow rate	18.1 kg/s
IHX heat duty	59 MW(t)
IHX primary side inlet/outlet temperatures	950°C / 679°C
IHX secondary side inlet/outlet temperatures	292°C / 917°C
Steam production rate	23.6 kg/s
Mass flow rate of hydrogen added to steam	0.3 kg/s
Temperature of steam/hydrogen supplied to SOE	827°C
Hydrogen Production System	

MHR System	
Peak SOE temperature	862°C
Peak SOE pressure	5.0 MPa
Product hydrogen pressure	4.95 MPa
Annual hydrogen production	2.68 × 10^5 metric tons
Plant hydrogen production efficiency	55.8%

Electrolysis is performed at high temperatures using solid oxide electrolyzer (SOE) modules. The module design is based on the planar cell technology (see Figure 2-9) being developed as part of a collaborative project between INL and Ceramatec of Salt Lake City, UT. Stacked assemblies of 100-mm x 100-mm cells have been tested successfully at INL and design parameters have been developed for a 12.5 kW(e), 500-cell stack. An SOE module would contain 40 500-cell stacks and consume 500 kW(e). Eight modules could be installed within a structure that is similar in size to the trailer portion of a typical tractor-trailer. Approximately 292 of these 8-module units would be required for a full-scale plant with four 600 MW(t) MHR modules. Figure 2-10 illustrates this SOE module concept.

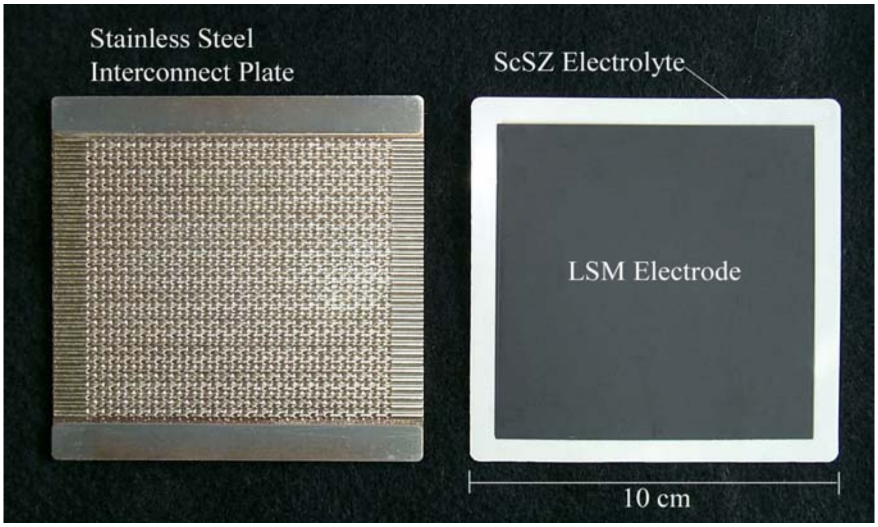

Figure 2-9. Interconnect Plate and Single SOE Cell

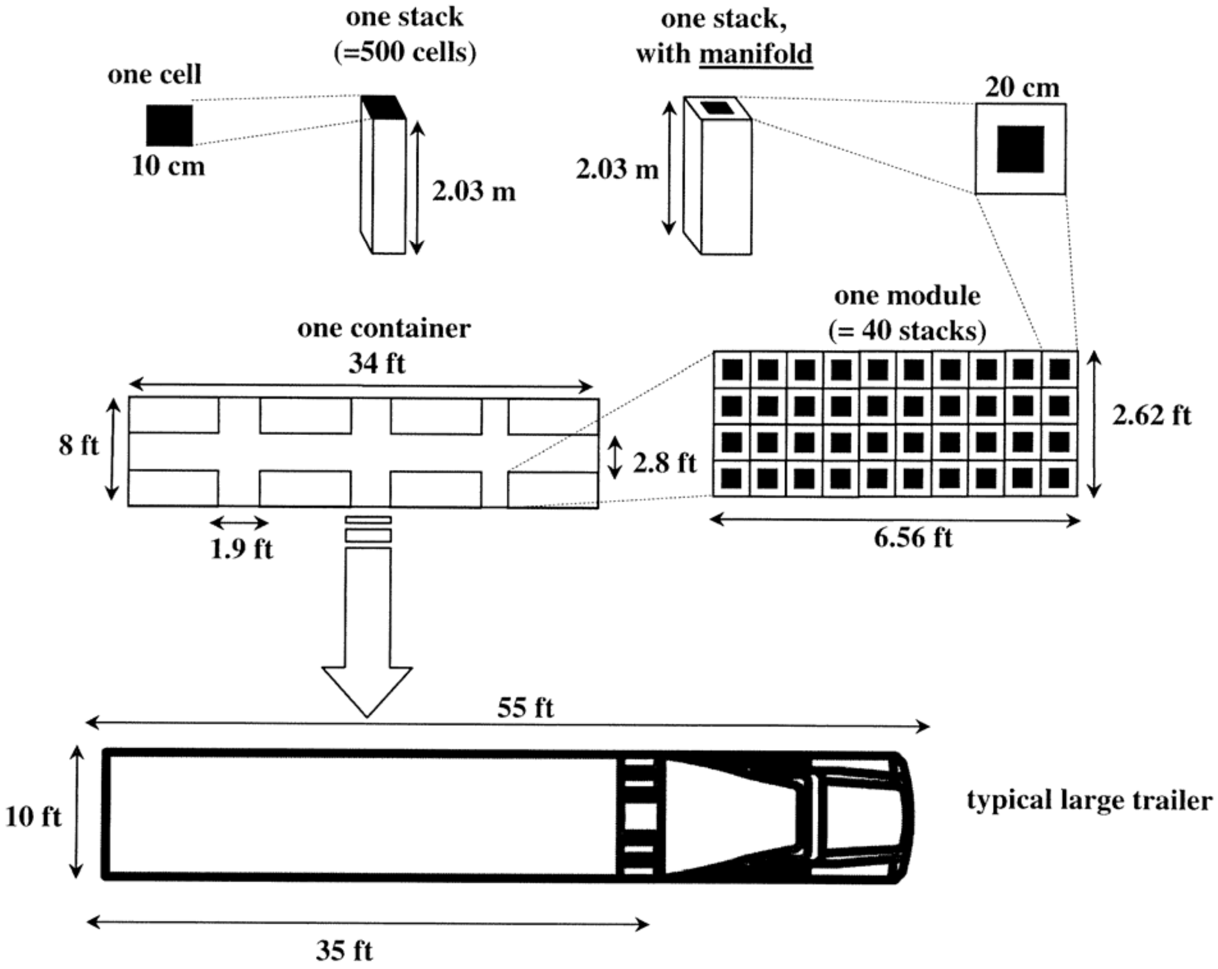

Figure 2-10. SOE Module Concept

Figure 2-11 shows a schematic diagram of a unit solid oxide electrolyzer cell (SOEC). Conceptually, a solid oxide electrolyzer cell is a solid oxide fuel cell (SOFC) operating in reverse.[15] The electrolysis stack for the HTE-based H2-MHR will be operated at or near the thermal-neutral voltage (1.288 V at 850 °C). At this voltage, the endothermic heat of reaction is balanced by ohmic heating in the stack, such that no additional heat is required for the stack to maintain high temperature.

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[15] Hence, the development and qualification of SOECs for use in HTE-based hydrogen production plants benefit greatly from the extensive research and development done for SOFCs during the past several decades.

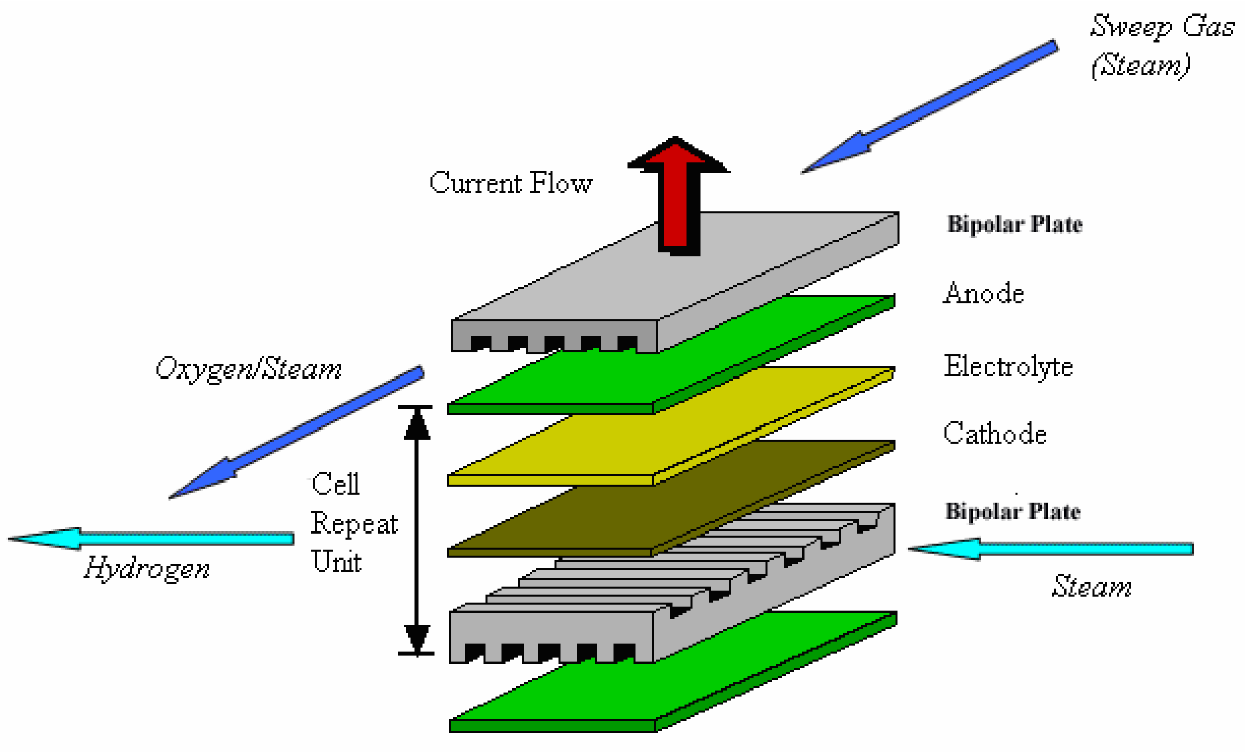


Figure 2-11. SOE Cell Schematic

The stack consists of individual cells, each with a 100-mm x 100-mm active area. The cell electrolyte is fabricated from either yttria- or scandia-stabilized zirconia. A 1.5-mm cathode plate made of nickel cermet material is bonded to one side of the electrolyte. A 0.05-mm anode plate is bonded to the other side of the electrolyte. The anode is composed of a mixed (i.e., both electronic and ionic) conducting perovskite, lanthanum manganate ($LaMnO_3$) material. Bipolar plates with a doped lanthanum chromite (e.g., $La_{0.8}Ca_{0.2}CrO_3$) are attached to the outside of the anode and cathode, and join the anode and cathode of adjacent units to form the stack. The bipolar plates also provide flow passages between each of the units in the stack for the steam-hydrogen mixture and separate passages for the steam/oxygen sweep gas. The relatively small active area of the individual cells is determined by the thermal expansion compatibility between the electrolyte and the electrodes.

A pre-conceptual design for an HTE-based demonstration plant for the NGNP has been proposed by Toshiba (Hoashi 2006). As with the SI plant, the heat source is assumed to be a 600 MW(t) MHR module coupled by an IHX to the hydrogen plant. Electrolysis is performed at high temperatures using tubular design SOE cells being developed by Toshiba Corporation, Japan The composition of the Toshiba electrodes are different from that assumed in the NERI study (see Section 7.1.3 for specifics). The NGNP prototype will have 10 electrolyzer modules.

Figures 2-12 and 2-13 show the process flow sheet and the cell configuration, respectively, for the prototype tubular single cell design for lab-scale tests. The dimension of the single cell is about 1.2 - 1.3 cm in diameter with an active electrode area of about 15 cm^2.

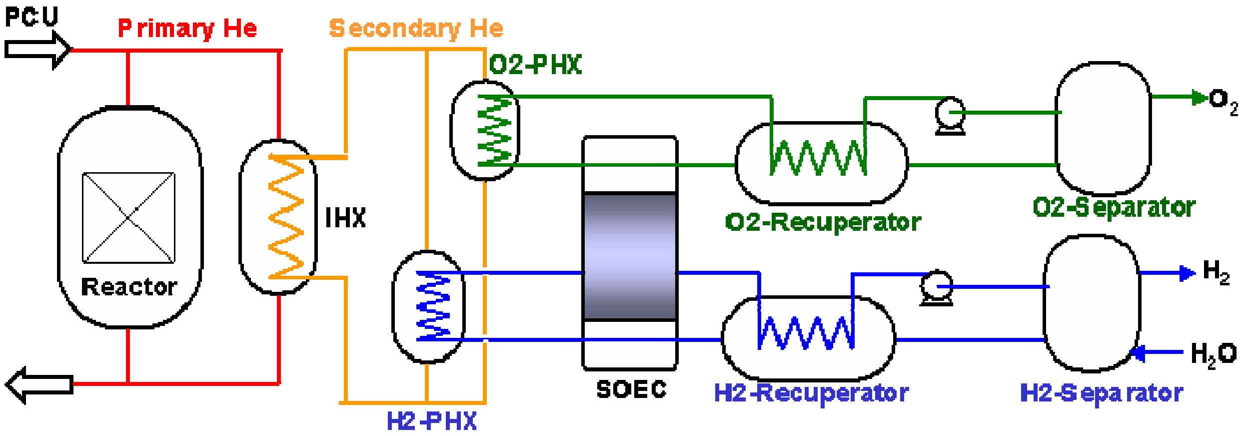


Figure 2-12. HTE Process Flow Sheet for NGNP Demonstration Plant

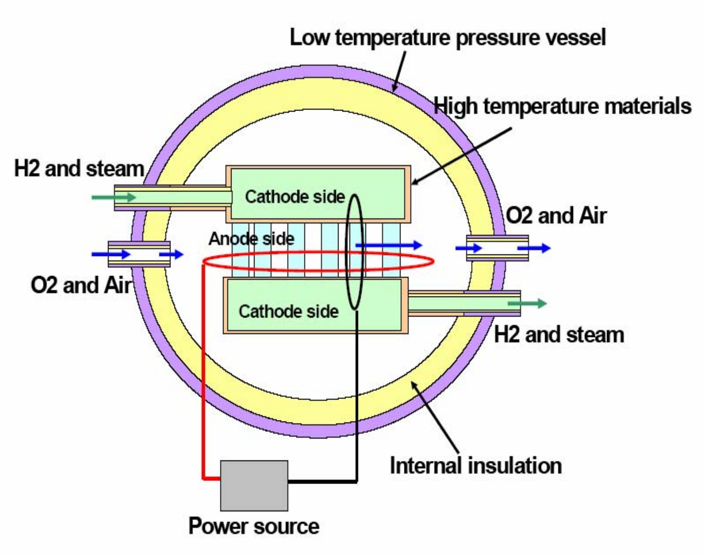
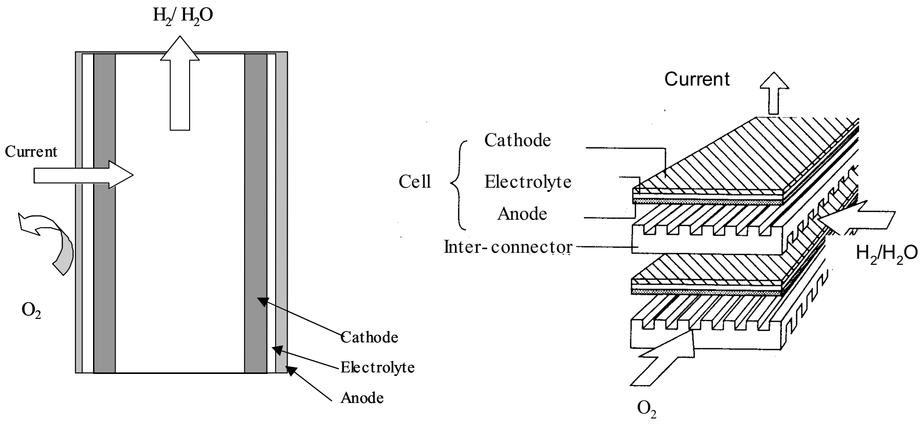


Figure 2-13 Configuration of High Pressure SOEC for NGNP HTE Demonstration Plant

Each electrolyzer module produces 600 standard m^3/hr of hydrogen, and 10 such modules will be installed for a total production rate of 6000 standard m^3 of hydrogen per hour (0.167 kg/sec). About 4 MW of reactor power will be transferred via the IHX to make steam; another ~38 MW of reactor power will be used to provide the electricity for the HTE plant. The selection of 10 modules for the NGNP is based primarily on the need to demonstrate operation and control of several solid-oxide electrolyzers. The design consists of SOEC units within a flanged pressure vessel that allows top-head removal and replacement of the SOECs. Table 2-4 provides the design conditions for the SOECs. It should be noted that a change of operating current density of the electrolysis cells varies their size because the number of HTE cells is in proportion to operating current density. For comparison, a tubular type and a planar type HTE electrolytic unit cell shape is shown in Figure 2-14.

Table 2-4. Design Conditions for Toshiba HTE Demonstration Plant

Design Temperatures	
Inner temperature	900° C
Vessel temperature	200° C
Design Pressure	
Vessel	5 MPa
Differential Pressure between Anode and Cathode of HTE cell	0 MPa
Fluid	
Anode	N_2 and O_2
Cathode	H_2O and H_2
Electrolysis Cell	
Shape	Cylindrical
Current density	0.6 A/cm^2



Tubular type

Planar type

Figure 2-14. Comparison of Tubular-Type and Planar-Type HTE SOECs

2.4 Scope of Work

As defined in (Work Plan 2006), the scope of this study includes:

- By-product identification: What by-products are produced, what quantities will be generated, and what are their physical and chemical characteristics? These by-products include electricity, hydrogen, oxygen, waste heat, chemical wastes, and radioactive wastes (including tritium).[16]

- Down select: Establish criteria and evaluate potential disposition options to identify preferred management strategy for each by-product.

- Potential disposition options & requirements: Identify potential disposition paths, including interim, long term storage, and recycle for each by-product. Describe any necessary treatment/stabilization if required, and assess risks and benefits of potential disposition pathways for each by-product.

- Options for by-product management: Can wastes be eliminated or reduced, or production of commodities increased? Identify risks and benefits. Describe potential design implications for critical plant equipment, and NGNP sizing

- Commercial Value: Develop understanding of current or potential market for byproducts with commercial value. Identify key factors affecting these markets. Provide input to WBS 1320, Economic Assessments for Commercialization.[17]

The emphasis in the Work Plan is on commercial VHTRs based upon the NGNP prototype. However, the contractual Scope of Work requires the end products to be evaluated for both the NGNP and follow-on commercial VHTRs, and both are considered herein.

2.5 Assumptions

Since the two relevant H2-MHR designs are both at the pre-conceptual design stage, a number of assumptions had to be made before the study could be performed; these assumptions are summarized here and repeated throughout the body of the report as they apply.

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[16] Statement is reproduced verbatim from (Work Plan 2006); as discussed previously, "end-product" is considered a more appropriate term.

[17] Note that the scope of work for this task does not include estimating waste disposal costs which will be addressed as part of the "Economic Assessments for Commercialization" task.

The assumptions are conveniently classified as programmatic and economic assumptions:

Programmatic Assumptions

1. The NGNP prototype will have a thermal power of 600 MW (i.e., full scale).
2. Commercial H2-MHRs will employ a prismatic core.
3. The NGNP primary circuit will include both a direct-cycle PCS and an IHX to transfer heat to the hydrogen production plant.
4. Both SI and HTE H_2 plants must be evaluated.
5. Unprocessed, spent MHR fuel elements will be the final waste form.
6. Previous GT-MHR studies are applicable to H2-MHR.
7. H-3 contamination of the product hydrogen can be controlled to acceptable levels.

Economic Assumptions

1. Results are presented in constant January 2007 dollars.
2. Projected values/costs for the commercial H2-MHRs assessed for 2020 - 2060 timeframe.[18]
3. Future natural gas price will determine future H_2 value.
4. Future electricity value will be set by the cost of new electricity generating capacity.

2.6 Report Organization

As indicated in Section 2.1, the purpose of this study is to identify, quantify and describe the disposition of end-products produced by the NGNP and by commercial VHTRs that be based on the NGNP prototype.

This report is intended to be a stand-alone document although the reader is encouraged to acquire key references that are called out in the various sections (especially the two NERI reports describing the SI- and HTE-based H2-MHR designs).

The report is organized as follows. After the introductory and background information presented here in Section 2, the various products that will be generated in the NGNP and a commercial H2-MHR, ranging from commodities (e.g., electricity, hydrogen, etc.) to waste products (e.g., radioactive waste, etc.), are described in Section 3. The requirements, both regulatory and user-generated, are summarized in Section 4; they are taken primarily from the GA-prepared NGNP System Requirements Manual (SRM 2007). The various options for disposition of these products, again ranging from commodities to waste, are described in Section 5. The estimated future values of the commodities are presented in Section 6, and the planned management of waste streams, both radionuclide and hazardous waste, is discussed in Section 7. The potential

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[18] Consistent with previous EPRI studies (e.g., Dilling 2003).

for tritium contamination of the product hydrogen is described in Section 8 along with various design options for minimizing it to acceptable levels. Since the ultimate by-product at the end of the plant design lifetime is the physical plant itself, decontamination and decommissioning (D&D) of the facility is discussed briefly in Section 9. Finally, a series of conclusions and recommendations are presented in Section 10.

3. PRODUCTS IDENTIFICATION

The proposed commercial H2-MHR consists of an MHR nuclear heat source combined with either an SI-based hydrogen production plant or an HTE-based hydrogen plant. After distributing the process heat and/or electricity to the hydrogen plant, the balance of power will be distributed as electricity to the grid. The end products that will be produced by the facility, ranging from commodities to waste products, are described below.

At this stage of pre-conceptual design, essentially the same spectrum of products is expected from operation of the NGNP and commercial H2-MHRs, and the quantities generated per MW(t) should be comparable. The degree of correspondence for the hydrogen plant will depend upon the extent to which the NGNP hydrogen plant is truly prototypical of the H2-MHR hydrogen plant for the technology (SI or HTE) chosen for the latter. Qualitatively, the spectrum of products should be essentially the same; however, design optimization of the commercial plant based upon NGNP “lessons learned” should reduce the quantities of waste products per mass of hydrogen produced.[19] Estimated production rates are given in this section for the NGNP; production rates for commercial H2-MHRs are given elsewhere in the report (e.g., Section 7) and in the two NERI reports (Richards 2006a and Richards 2006b).

3.1 Reactor Plant

The NGNP prototype reactor plant is assumed to be a 600 MW(t) MHR reactor module, which has the essential features of a GT-MHR with a 950 ^{o}C core outlet temperature. When operating as a GT-MHR with a 850 ^{o}C core outlet temperature, the plant has a thermal efficiency of 47% for dedicated electricity production and a design capacity factor of 90% (Shenoy 1996).

3.1.1 Commercial Products

The two major commercial products obtained from operating a MHR are:

1. Electricity
2. Process heat.

With the use of a Power Conversion System (PCS), the process heat is converted into electricity. However, the efficiency of converting process heat into electricity is limited by the Carnot cycle and the remaining amount of process heat is usually discharged into the environment (if the waste heat can instead be recovered and used for other processes, it can add more revenue to the reactor plant). Alternatively, because of the high core outlet temperatures characteristics of the VHTR, the thermal output of the reactor can also be used for

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[19] Implicit here is the perspective that the design of the MHR is more mature than the design of the hydrogen plant and that the latter will benefit more from optimization than the former.

various process heat applications. The two hydrogen production processes (SI and HTE) discussed in this report are examples of utilizing all or part of the process heat of the reactor plant for applications other than electricity generation.

It should be noted that the SI-based H2-MHR described in the first NERI report (Richards 2006a) had no PCS. All of the process heat was supplied to an SI hydrogen plant. The plant was assumed to be sited in a energy park with other GT-MHRs dedicated to electricity production. The HTE-based H2-MHR described in the other NERI report (Richards 2006b) sized the hydrogen plant such that it consumed all of the electricity generated by the plant's PCS. Consequently, neither of these H2-MHR designs produced excess electricity for commercial sale. Alternative designs with either an SI-based or HTE-based hydrogen plant are possible which would produce excess electricity for commercial sale if the economics were favorable. Other design variants are also possible which would permit generation of process steam (e.g., by replacing the precooler, intercoolers and recuperator with a steam generator).

For the proposed NGNP prototype demonstration facility (Labar 2007), the process heat required for hydrogen production for the SI process is 60 MW(t) and for the HTE process is 42 MW(t), ~4 MW(t) to make steam and 38 W(t) to make the electricity needed for the HTE plant. The NERI reports describe the detailed designs of a 4 x 600 MW(t) MHR plant for hydrogen production by the SI and the HTE processes.

3.1.1.1 Electricity

The cost of electricity varies with demand, which is further influenced by local weather. The NGNP prototype is targeted for the state of Idaho where the current cost of electricity is about 49 mil/KWh whereas the NGNP commercial H2-MHR is envisioned to be located in the Texas Louisiana Gulf coast area where the cost of electricity is about 94 mil/kwh (EIA 2007).[20] Obviously, it is desired to produce electricity from an MHR at a cost lower than the selling price of electricity to generate profit over the life cycle of the plant operation. However, the NGNP prototype is not expected to be a profitable business but rather to be a demonstration of successful operation of the MHR and its capability to produce H_2 at high efficiency and reliability. Detailed cost estimates for the NGNP prototype and commercial GT-MHR plant will be provided in the pre-conceptual design studies report (PCDSR). The hydrogen production plant (SI as well as HTE) will utilize part of the electricity from the reactor plant and the rest of it will be available for sale to the grid.

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[20] 2006 electricity prices for all sectors through November 2006; average of TX and LA prices (http://www.eia.doe.gov/cneaf/electricity/epm/table5_6_b.html)

3.1.1.2 Process Heat

The value and utility of process heat are determined by the application for which it is being used. For the NGNP project, the hydrogen production plant (SI as well as HTE) will use only a fraction of the process heat from the reactor module; the rest of the high temperature process heat can be converted to electrical power in the PCS. Alternatively, depending upon the application, some or all of the process heat could be converted to process steam.

3.1.2 Waste Products

As with all nuclear power plants, the major waste from the MHR is the spent nuclear fuel. It should be noted that the GT-MHR is designed to achieve significantly higher fuel burn-up than LWRs, which will reduce the quantity of fuel required and hence the quantity of waste fuel to be disposed per MW-yr(e) produced (Labar 2004, Richards 2002). The reactor plant will also produce gaseous, liquid and solid radioactive waste; these topics are discussed in Section 7.

If a wet cooling tower were used to reject waste heat from the reactor to the environment, then it would result in wastewater generated at the outlet of the cooling tower that would need to be properly treated before discharge back into a water body. At present, dry cooling towers are favored for both the NGNP and commercial H2 MHRs so this potential waste stream is likely eliminated.

3.2 H_2 Production Plant – SI Process

The SI plant would consume both electricity and high temperature process heat from the reactor module. Table 2-2 provides the mass balance of materials for a 60 MW demonstration SI hydrogen plant.

3.2.1 Commercial Products

Hydrogen: A 60 MW(t) SI plant would produce 526 kg/hr when running at full capacity. The hydrogen product of the plant will be such that it can be used as a commercial item for sale. A small fraction of the tritium produced in the reactor module may contaminate the product hydrogen and will need to be controlled to acceptable levels; this topic is discussed in Section 8.

Oxygen: A 60 MW(t) SI plant will produce 4212 kg/hr of oxygen at low pressure. For the NGNP, most of the oxygen will probably be vented to the atmosphere. For a commercial H2-MHR, a “green” consumer of high-purity oxygen will be co-located with the hydrogen plant to utilize the oxygen.

3.2.2 Waste Products

Waste Heat. The SI hydrogen plant will produce a significant quantity of low-grade waste heat.

Chemical Wastes. During routine operation there are no designed liquid wastes from the hydrogen plant proper and only minimal losses as vapors. Phosphoric acid has a very low vapor pressure, even at elevated temperatures, and the acid concentration step is not expected to produce a waste stream requiring treatment. A small amount of sulfur dioxide may be lost to the environment. Small amounts of liquid wastes may be produced during maintenance activities. The only routine chemical wastes expected are those produced during process water purification (and cooling water blow down if wet cooling is used). These wastes have not yet been quantified. It is expected that some corrosion products, mainly sulfates of the metals present in the materials of construction of the process equipment (e.g., Cr, Ni, Fe), will be produced over the lifetime of the plant. There are no carbon or NO_x wastes (i.e., no greenhouse gases) generated from operation of the SI hydrogen plant.

3.3 H_2 Production Plant – HTE Process

The HTE process would consume both electricity and high temperature process heat from the power plant. In the HTE process, hydrogen is produced at the cathode (Ni-YSZ cermet) and oxygen is released at the anode (LSM).

3.3.1 Commercial Products

Hydrogen: A 29 MW(e) HTE plant[21] will produce 492 kg/hr of hydrogen when running at full capacity. Hydrogen gas will be recovered on the cathode side of the electrolytic cell. The hydrogen product of the plant will be such that it can be used as a commercial item for sale. As with the SI plant, a small fraction of the tritium produced in the reactor module may contaminate the product hydrogen and will need to be controlled to acceptable levels (Section 8).

Oxygen: A 29 MW(e) HTE plant will produce 3936 kg/hr of oxygen at low pressure. Oxygen gas will be recovered on the anode side of the electrolytic cell. As with the SI process, most of the oxygen produced by the NGNP will probably be vented to the atmosphere. For a commercial H2-MHR, a “green” consumer of high-purity oxygen will be co-located with the hydrogen plant to utilize the oxygen.

3.3.2 Waste Products

Waste Heat: The HTE hydrogen plant will produce significant amounts of low-grade heat.

Chemical Waste: The HTE plant will produce little chemical waste beyond hotel waste during normal operation and maintenance. However, the SOE cells will have to be replaced periodically at the end of their lifetime (nominally five years). The spent SOE cells will contain certain hazardous materials, such as LSM, that cannot be disposed of in a municipal landfill.[22]

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[21] 4 MW(t) to raise steam and ~55 MW(t) to make the requisite electricity.

[22] Since the HTE process is still under active development with a goal of extending its service lifetime, a lifetime of 5 to 10 years should be assumed parametrically when evaluating disposal costs.

4. REQUIREMENTS IMPACTING END-PRODUCTS DISPOSITION

The System Requirements Manual (SRM) is intended to be the top-level design document for the NGNP. The SRM serves as the roadmap document that identifies the source of the NGNP top-level requirements (i.e., mission needs and objectives) and how these top-level requirements flow down through subordinate requirements at the plant, system, subsystem, and ultimately the component level. Design requirements for the NGNP include both institutionally imposed and functionally derived requirements. Each pre-conceptual engineering services contractor is preparing an SRM as part of its workscope.

The System Requirements Manual prepared by GA (SRM 2007) has adopted a particular protocol for identifying requirements which is reproduced here:

"If the plant-level requirement is an institutional requirement, the source of the requirement is given in brackets following the requirement. If a source is not shown following the statement of the requirement, the requirement is a functionally derived requirement. A number is assigned to each requirement for identification purposes. The identification number has the format 3.x.y where 3.x is the SRM section number and y is the requirement number. If a requirement is subordinate to a higher-level requirement (i.e., it stems from the higher-level requirement), the subordinate requirement has the format 3.x.y.z, where 3.x.y is the identification number for the higher-level requirement and z is the unique number for the subordinate requirement. Brackets { } are used herein to identify a value that is preliminary in nature because of design uncertainty or insufficient documentation, or that requires verification."

4.1 Plant-Level Requirements

The plant-level requirements given in Section 3 of the GA-prepared SRM have been reviewed, and those judged to *directly* impact end-products disposition are reproduced in this section. Consistent with the SRM, requirements that are specific to achievement of the six NGNP high-level functions (F1 - F6 below) are grouped by function. The various references cited in the requirements are identified in Table 4-1. In some cases, the decision to include or exclude a certain requirement was rather arbitrary; in any case, the plant design will have to meet all of the requirements whether they are included here or not.

Table 4-1. SRM References Cited in Requirements

Ref. 2	"Next Generation Nuclear Plant – High Level Functions And Requirements," INEEL/EXT-03-01163, Idaho National Laboratory, September 2003
Ref. 9	"Utility/User Incentives, Policies, and Requirements for the Gas Turbine-Modular Helium Reactor," DOE-GT-MHR-100248, Rev. 0, Technology Insights, September 1995

F0. Overall Plant-Level Requirements

PLT 3.0.9 - The NGNP shall be designed for an operating life of 60 calendar years from the date of authorization to operate. Provisions shall be made for economic replacement of components that cannot be designed for 60-year operation. [Ref. 2, Section 3.1.11; U/U Requirement, Ref. 9, Section 3.1.2 and SRM Section 2.3.5, Fig. 1].

F1. Develop and Demonstrate a Commercial-Scale Prototype VHTR

PLT 3.1.1.1 – The NGNP reactor shall consist of a graphite moderated, prismatic block core. [Ref. 2, Sections 3.1.3 and 3.1.5].

PLT 3.1.1.3 – The NGNP shall use qualified TRISO-coated uranium oxycarbide (UCO) or uranium dioxide fuel. The fuel particles shall be agglomerated into cylindrical compacts. Qualified uranium dioxide fuel may be acceptable for initial fuel loading, but shall be replaced by UCO, when it is has been qualified. [Ref. 2, Sections 3.1.7 and 3.1.10]

PLT 3.1.1.6 - The NGNP shall include a helium purification system to maintain the helium coolant purity.

PLT 3.1.2.1 - The reactor shall have a nominal power level of 550 MW(t) with a stretch capability to about 600 MW(t).

PLT 3.1.8 – The NGNP shall be designed to achieve fuel burn up consistent with maximum fuel utilization while minimizing waste streams, optimizing fuel economics, and ensuring low proliferation risk. [Ref. 2, Section. 3.1.9].

PLT 3.1.9 - The NGNP shall be designed to satisfy the following top-level radionuclide control regulatory requirements:

- During normal operation, offsite radiation doses to the public shall be < limits specified in Appendix I of 10 CFR 50 and 40 CFR 190
- Occupational radiation exposures shall be ≤10% of the limits specified in 10 CFR 20
- During DBAs, offsite doses at the site EAB shall be less than those specified in the Manual of Protective Action Guides and Protective Actions for Nuclear Incidents (EPA-520/1-75-001) for sheltering and evacuation

[Ref. 9, Section 3.1.13 and U/U Requirement, SRM Section 2.3.5, Fig. 1].

PLT 3.1.10 - The design of the NGNP systems and processes shall be such that the volume of low-level radioactive dry and wet waste, as shipped off-site, shall be less than 3.6 m^3, annually (excluding replaceable reflector elements). [U/U Requirement, SRM Section 2.3.5, Fig. 1].

PLT 3.1.11.6 - The NGNP shall be designed to demonstrate a probability of $< 5 \times 10^{-7}$ per plant year that offsite doses at or beyond the site EAB of 425 meters will [not] exceed the limits specified in the Manual of Protective Action Guides and Protective Actions for Nuclear Incidents (EPA-520/1-75-001) for sheltering and evacuation. [U/U Requirement, SRM Section 2.3.5, Fig. 1].

PLT 3.1.11.7 - The NGNP shall be designed to demonstrate that plant personnel exposure of <70 person-rem/GW_e-year. [U/U Requirement, SRM Section 2.3.5, Fig. 1].

PLT 3.1.11.14 - The NGNP design shall include provisions for satisfying the plant decommissioning requirements as specified in Section 3.12 of Ref. 9. [U/U Requirement, Ref. 9, Section 3.11].

F2. Develop and Demonstrate High-Efficiency Power Conversion

None identified that impact end-products disposition.

F3. Obtain Licenses and Permits to Construct/Operate the NGNP

None identified that impact end-products disposition.

F4. Develop and Demonstrate Hydrogen Production

PLT 3.4.1 - Hydrogen production shall be demonstrated using a thermo chemical process and a high-temperature steam electrolysis (HTE) process. [Ref. 2, Section 3.4.2]

PLT 3.4.1.1 - The thermo chemical process to be demonstrated by the NGNP shall be the sulfur-iodine (SI) process.

PLT 3.4.2 - The NGNP shall be designed for continuous operation in either the 100% electric power production mode or in the cogeneration mode with the equivalent of up to 50 MW(t) of the reactor's thermal energy used for hydrogen production. [Ref. 2, Section 3.4.1].

PLT 3.4.2.5 - Leakage of the working fluid used to transport the heat shall be less than {10%} per year. Radionuclide release associated with working fluid leakage shall be within occupational and public dose limits specified in 10 CFR 20.

PLT 3.4.5 - The interface system between the NGNP and the hydrogen production plants shall be designed to ensure that tritium migration into the hydrogen production systems will be limited, such that the maximum amount of tritium released from the integrated NGNP facilities or found in drinking water does not exceed EPA standards. [Ref. 2, Section 3.4.5].

PLT 3.4.6 - The total concentration of radioactive contaminants in the hydrogen product gas and associated hydrogen production systems shall be minimized to ensure that worker and public dose limits for the integrated NGNP and hydrogen production facilities do not exceed NRC regulatory limits. [Ref. 2, Section 3.4.6].

PLT 3.4.8.1 - The hydrogen production and storage facilities shall comply with 29CFR1910.103. If the hydrogen facility produces and stores significant quantities of oxygen, compliance with 29CFR1910.104 shall also be required. [Ref. 2, Section 4.2.5]

PLT 3.4.8.2 - Emissions from the hydrogen plant shall comply with all applicable requirements of the Clean Water Act/Water Programs (CWA), 40CFR100-149, as well as compliance with all state and local requirements. [Ref. 2, Section 4.1.2]

PLT 3.4.8.3 - Emissions from the demonstration hydrogen plant shall comply with the requirements of 40CFR61, National Emissions Standards for Hazardous Air Pollutants (NESHAP), and all applicable state and local air permit requirements. [Ref. 2, Section 4.1.2]

PLT 3.4.8.4 - Exposures to any given hazardous chemical shall not exceed the maximum acceptable levels as stated in OSHA 29CFR1910.1000, Subpart Z, plus other OSHA substance-specific standards.

F5. Include Testing Provisions

PLT 3.5.8 – For demonstration of commercial plant radiological source terms, the NGNP shall be designed to experimentally determine the fission product activity that could potentially be released should there be a rupture in the primary coolant boundary. [PLT 3.1.9; PLT 3.1.11.6].

F6. Enable Demonstration of Energy Products and Processes

PLT 3.6.1 - The NGNP Project shall establish a test bed for evaluating various uses of hydrogen produced by the NGNP hydrogen production plant(s). [Ref. 2, Section 3.6.1].

PLT 3.6.2.4 - The hydrogen storage facilities shall comply with 29CFR1910.103. [Ref. 2, Section 4.2.5].

PLT 3.6.4.1 - Provisions shall be included in the design of the NGNP to add capability to produce ≥540°C (1000°F) steam to develop/demonstrate the production of process steam to displace coal, oil and natural gas use in process industries such as petrochemical plants, refineries, aluminum mills, and steel mills.

PLT 3.6.4.2 - The provisions made in the NGNP design to add steam production capability shall be equally adaptable to adding additional capability for high temperature process heat to develop/demonstrate production of reducing gas for steel making, substitute pipeline gas, ammonia and methanol.

PLT 3.6.4.3 - The NGNP shall include provisions to add process systems (e.g., a steam-methane reformation process for H_2 production and/or a methanol production process) to develop/demonstrate the utilization of process steam and/or process heat produced by the NGNP.

4.2 System-Level Requirements

The SRM allocates the plant-level requirements to the individual plant systems, buildings and structures. Inclusion here of system-level requirements that are obvious reproductions of plant-level requirements is not, in general, considered necessary for the purpose of this report. However, certain system-level requirements do provide a degree of specificity that is not obvious from the parent plant-level requirements, and they are reproduced below by system. In any case, the various systems will have to meet all of the requirements assigned to them in the SRM.

Reactor System (11)[23]

The reference fuel cycle shall be based on the use of a once-through uranium fuel cycle with U-235 enrichment no greater than 19.9%.[24]

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[23] The number in parenthesis after the system name is the system number as defined in the SRM.

[24] The system-level requirements in the SRM are not numbered at this writing.

The Reactor System shall achieve fuel burn up consistent with maximum fuel utilization while minimizing waste streams, optimizing fuel economics, and ensuring low proliferation risk

The Reactor System shall be capable of utilizing alternate fuel cycles (Pu fuel, deep-burn of LWR spent fuel, etc.).

Fuel Handling and Storage System (21)

The capacity of the irradiated fuel storage facility shall be consistent with the design fuel cycle and shall be adequate to store all of the irradiated fuel elements discharged from the reactor over a 10 year period of plant operation, plus an additional reactor core including all replaceable reflectors.

The design of the irradiated fuel storage facility shall permit expansion, without impact on plant power operations, to accommodate storage of all of the spent fuel and replaceable reflectors generated over the life of the plant.

Primary Helium Purification Subsystem (24)

The helium purification trains shall be designed to remove the following major chemical impurities: CO, CO_2, H_2 (including tritium), N_2, 0_2, H_2S, CH_4, and other hydrocarbons. Lesser amounts of impurities such as Br, I, H_2O, Kr, and Xe shall also be removed along with filterable particulates and certain metallic elements.

Each helium purification train shall process the primary coolant helium at a constant volumetric flow rate regardless of the primary coolant system pressure. At 100% of rated reactor power and vessel system pressure, the helium purification subsystem shall process primary coolant at a rate of (TBD) kg/s.

Each helium purification train shall be sized such that the fraction of radionuclide activity removed from the circulating primary coolant is 2.9×10^{-5} per second.

Radwaste and Decontamination System (25)

The radwaste and decontamination system shall collect radioactive and potentially radioactive floor and equipment liquid runoff. These waste streams shall be routed to the liquid radioactive waste subsystem.

Radioactive liquid wastes generated throughout the plant shall be collected in receiver tanks located in the Radioactive Waste Management Building.

Provisions shall be included to reduce activity levels contained in collected liquid effluent.

Highly titrated [*sic*. tritiated] liquid effluent from the helium purification train(s) or other source(s) of highly concentrated radioactive liquid waste shall be collected in a tank separate from the low-activity liquids.

The gaseous waste-processing portion of the system shall incorporate two separate flow paths:

1) Effluents that do not require a decay period or whose activity levels are known to be minimal shall be monitored and released.
2) Effluents not meeting the prescribed federal release standards shall be accumulated in storage tanks for subsequent processing and disposal.

The gaseous effluent release path for monitored releases shall be through the Reactor Building HVAC system exhaust flow. Release rates for this waste stream shall be based on both content and activity levels of the gaseous waste stream being released.

The gas waste portion of the radwaste system shall have sufficient storage capacity to allow for radioactive decay prior to release.

The radwaste system design shall provide for compressing solid waste, solidifying high-activity liquid wastes, cutting up large items, or otherwise packaging radwaste materials for disposal.

Solid waste storage shall be provided in the form of sealed drums.

Decontamination equipment shall be skid-mounted. Each decontamination skid shall provide steam, wash water (including detergent and/or other additives), rinse water, drying air, and vacuuming service.

Decontamination system wastes shall be collected locally and routed to the appropriate radwaste subsystems.

All radioactive wastes generated within the facility shall be collected, monitored, treated, and processed onsite, prior to shipment offsite.

Radioactive effluents that cannot be processed or diluted to meet discharge standards shall be solidified to allow for disposal as solid waste.

Radioactive, and potentially radioactive gases shall be collected and monitored prior to and during release.

The design of the radioactive gas waste system shall provide for automatic termination of a release upon detection of activity levels in excess of established limits. Termination of the release shall occur before the detected high activity effluent reaches the HVAC system exhaust duct.

Radioactive gases known to be of high concentration (e.g., regeneration gases from the helium purification regeneration subsystem) shall be processed directly to the radioactive gas waste storage tanks for hold-up and monitoring prior to release.

The radwaste system shall have the capability to handle low-level radioactive dry and wet wastes, up to a processed volume of 3.6 m^3 per year, for shipping offsite, excluding core replaceable reflectors.

Plant Monitoring System (35)

Analytical instrumentation shall be capable of detecting and quantifying certain specific chemical and radioactive impurities circulating in the primary coolant helium.

Condensable radionuclide analyses shall be accomplished by means of plate-out probes located in the hot circulating primary coolant flow stream.

Radiation sensing equipment shall provide for the following types of monitoring: Area ambient gamma radiation, airborne radioactivity, process effluent radioactivity, and radiation (and possible contamination) levels at the plant site boundary.

The Balance of Plant (water) Sampling equipment shall be designed to monitor, indicate, record, and alarm selected water quality parameters for the various Balance of Plant water systems.

Secondary Heat Transport System (42)

A helium purification system similar to that designed for the primary coolant helium shall be provided to maintain the purity of the secondary loop helium. This purification system shall be installed in the Reactor Service Building adjacent to the primary coolant purification system to minimize duplication of services required by the systems.

Leakage of the working fluid used to transport the heat shall be less than {10%} per year. Radionuclide release associated with working fluid leakage shall be within the occupational and public dose limits specified in 10CFR20.

SI-Based Hydrogen Production System (43)

Chemicals used in the production of hydrogen shall be re-cycled to the maximum extent practical to minimize the quantity of chemical waste.

Corrosion allowances for all engineering materials used in chemical processing shall be {2.95} mil/year for tubing and valves, and {19.7} mil/year for vessels and columns.

The design shall include means to reject {TBD} MW(t) of waste heat.

Emissions from the hydrogen plant shall not exceed established EPA limits on the amount of sulfur dioxide and other hazardous pollutants that can be discharged to the local atmosphere. Requirements stated in the Clean Air Act/Air Programs (CAA), and in 40CFR5099 shall also apply to the design and operation of the plant. All applicable state and local environmental protective requirements shall also be recognized and incorporated during the design of the plant.

The hydrogen plant shall comply with OSHA requirements contained in 29CFR1910.119 to prevent or minimize the consequences that could occur during catastrophic releases of toxic, reactive, flammable, or explosive chemicals (e.g. hydrogen gas, sulfur dioxide, sulfur trioxide, and sulfuric acid) in excess of threshold quantities.

HTE- based Hydrogen Production System (44)

None identified that impact end-products disposition.

Reactor Complex (51)

Following a reactor vessel depressurization event, and the attendant building pressure equalization, the Reactor Building shall confine and/or filter for release the gaseous contents. The release rate shall be equal to or less than one building volume/day.

A designated storage, packaging, and shipping facility area for low-level contaminated radiological wastes shall be provided within the Radioactive Waste Management Building. This area shall be capable of handling various amounts of dry and wet waste, that when processed for shipping offsite would constitute a total volume of no more than 3.6 m^3 (125 ft^3) per year.

The Radioactive Waste Management Building shall house equipment capable of processing, preparing, and monitoring non-fuel radioactive waste for disposal offsite.

The Reactor Services Building shall include a hot service facility having the capability to provide decontamination services for core service tools, reactor equipment service facility tools, primary circulators, shutdown circulators and heat exchangers, and neutron control assemblies, as well as other plant equipment that might require radiological decontamination.

All radioactive wastes generated within the facility shall be monitored, treated, and processed onsite, prior to shipment offsite.

Circulating Water System (72)

Waste heat generated within the overall facility shall be collected and transported via the Circulating Water System for dissipation to the atmosphere via mechanical draft cooling tower(s).

Mechanical draft cooling tower(s) shall provide adequate cooling capacity for the all of the Nuclear Island and Balance of Plant equipment items that generate waste heat, with sufficient reserve for additional equipment not yet defined.

Nuclear Island Heating, Ventilating, and Air Conditioning (HVAC) System (81)

The nuclear Island HVAC system shall ensure habitability within areas of the facility that house equipment and controls essential to maintaining the safety response of the plant. The system shall control the temperature and humidity of the air in these spaces by removing noxious materials, particularly airborne dust, as well as radioactive smoke and gases.

Balance of Plant HVAC System (82)

The Balance of Plant HVAC System shall maintain environmental conditions (air quality, pressure, temperature, and humidity) in buildings and structures located within the Balance of Plant areas of the facility. The system shall maintain acceptable ranges for these conditions as required for component operability and personnel habitability during both normal and off-normal modes of plant operation. Special consideration shall be given to the necessity for removing and controlling chemical fumes, dust, smoke, particulates, and noxious gases.

Waste Water System (84)

The plant shall not rely on offsite municipal wastewater treatment. Non-radioactive plant wastes shall be processed, treated, and monitored onsite prior to disposal offsite.

5. PRODUCTS DISPOSITION OPTIONS

As introduced in Section 3, the products from the NGNP prototype and the H2-MHR with a commercial value are electricity, hydrogen, oxygen and process heat. The projected future market prices of these commodities are addressed in Section 6.

The disposition options for the NGNP and the commercial H2-MHR are addressed separately because the markets are different and the quantities of products, especially hydrogen, are quite different. However, the waste streams, especially the spent fuel elements, will in general require federally approved facilities for their final disposal so less distinction between the NGNP and the commercial H2-MHR with regard to waste disposition is foreseen.

5.1 Commercial Products

5.1.1 NGNP

The NGNP is assumed to be a 600 MW(t) MHR coupled to a direct-cycle PCS for electricity production and to an IHX for supplying process heat to SI-based and HTE-based plants that will produce hydrogen and oxygen.

Electricity:

The SI water splitting process is a consumer of both high temperature process heat and electricity. For the NGNP prototype, the hydrogen plant will only require a fraction of the heat available from the reactor, and the rest can be used for electricity production. The hydrogen plant will only require a small fraction (~10%) of the electrical power from the reactor; a 60 MW SI demonstration plant will require up to 20 MW of electrical power. This demonstration SI plant will produce 526 kg/hr of hydrogen. Minimizing the electrical consumption is a key component of current design work. The excess 271 MW(e) can be sold to the local electrical grid at the wholesale cost of electricity.

The HTE process will use electricity as well as process heat from the reactor plant. Up to 29 MW(e) of reactor electrical power will be utilized by the HTE plant with a hydrogen capacity of 492 kg/hr. Some electrical power will be generated at the anode side of the SOE cells and for the NGNP prototype, the value of the electrical power generated will be so small that it will not be practical to install a recovery system. Approximately 4 MW(t) of process heat will be required to produce steam for the electrolytic process. The reactor output in excess of what is used by the HTE plant, which is approximately 292 MW(e), can be sold to the local grid.

Hydrogen:

Small amounts of hydrogen could be bottled and used on the INL site and within the immediate local area. Storage of the hydrogen for use in fuel cell applications is a possibility. Another scenario is that the hydrogen could be transported to oil refineries in northern Utah either via tube trailers or as a liquid and sold to users at their cost of hydrogen production, assuming that the NGNP was able to supply a reliable, steady quantity of hydrogen. If these sale prices were insufficient to cover the cost of transportation, any unwanted hydrogen could be vented at no added cost. This is more likely, especially early in the startup phase of plant operation.

The hydrogen and a fraction of the electricity from the NGNP could also be utilized to produce ammonia to be used as fertilizer for local agriculture which is extensive.[25] The ammonia plant could be integrated into the NGNP complex, or it could be a stand-alone remotely sited facility, possibly utilizing other feedstock as well. If integrated with the NGNP, it could serve as a demonstration of the following:

- Process heat requirements for the production of hydrogen needed to support a small ammonia production line
- Electrical requirements to support the production of nitrogen by cryogenic air distillation, also as needed to support a small ammonia production line
- Integrated control system to operate the reactor, hydrogen, nitrogen and ammonia production demonstration units as a single facility
- The ability to recover and utilize any waste heat resulting from the exothermic reaction of hydrogen and nitrogen to form ammonia

At first consideration, this ammonia-production option seems more practical than transporting hydrogen to remote refineries and deserves serious investigation.

Oxygen:

Ideally, a “green” user of high-purity oxygen should be co-located at the NGNP plant site. It would be programmatically (and politically) important that the oxygen consumer not be a significant emitter of greenhouse gases (GHG), and especially not carbon dioxide.

Alternatively, small amounts of oxygen could be bottled and used on the INL site or within the immediate local area. However, such uses are unlikely to use a significant fraction of the oxygen produced. In fact, most of the oxygen will probably be vented to the atmosphere at no additional cost. Any sulfur dioxide emissions will likely be well within legal limits; if not, the oxygen stream will be polished by caustic scrubbing so that air emission is insignificant.

5.1.2 Commercial H2-MHR

In this study, the commercial H2-MHR is assumed to be 4 x 600 MW(t) MHR coupled to either a SI-based or HTE-based hydrogen plant as described in the NERI reports (Richards 2006a,

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[25] For example, Idaho leads the nation in potato production producing 11.2 billion pounds in 2005 according to the USDA.

Richards 2006b). In the NERI reports, the SI-based H2-MHR is assumed to be in an energy park with other dedicated electricity-producing reactors. The plant site is assumed to be the Texas-Louisiana Gulf coast area.

Electricity:

Tables 2-1 and 2-3 provide the reactor plant and hydrogen plant parameters for a 4 x 600 MW(t) MHR plant coupled to an SI-based plant and an HTE-based plant, respectively.

The SI-based plant consists of four 600 MW(t) MHR modules, with each module coupled to an IHX, which transfers the heat to a secondary helium loop, which further transfers the heat to the SI System. The commercial SI hydrogen plant will produce 46,692 kg/hr of hydrogen (3.68 x 10^5 tonne/year for a plant capacity of 90%). The total process heat generated by a four module MHR is 2400 MW(t) which is used in the hydrogen production system. The electrical power requirement of the hydrogen plant is approximately 812 MW(e). There will be no electricity produced by the reactor (and hence, no PCS is required). Waste heat is rejected using cooling towers in a manner similar to that for electricity producing plants.

For the commercial HTE-based H2-MHR, the hydrogen plant will utilize ~10% of the heat available from the reactor to produce high temperature steam, and the other 90% will be used for electricity production. A hydrogen production plant of capacity 33,993 kg/hr (2.68 X 10^5 tonne/year for a plant capacity of 90%) requires 1168 MW(e) of electrical power. However, minimizing the amount of electrical power required for the production of hydrogen is a key component of the on-going design work. The net electrical output of the reactor plant after supplying 10% of its process heat is 1170 MW(e) (at 54% thermal efficiency) which is utilized to meet the electrical power requirement of the hydrogen plant. There will be no excess electricity produced by the reactor. Waste heat is rejected using cooling towers in a manner similar to that for electricity producing plants.

Since both the SI-based and HTE-based hydrogen plants are highly modularized, it is unlikely that a large fraction (say, >25%) of hydrogen-production capacity would be off-line for extended periods of time.

Hydrogen:

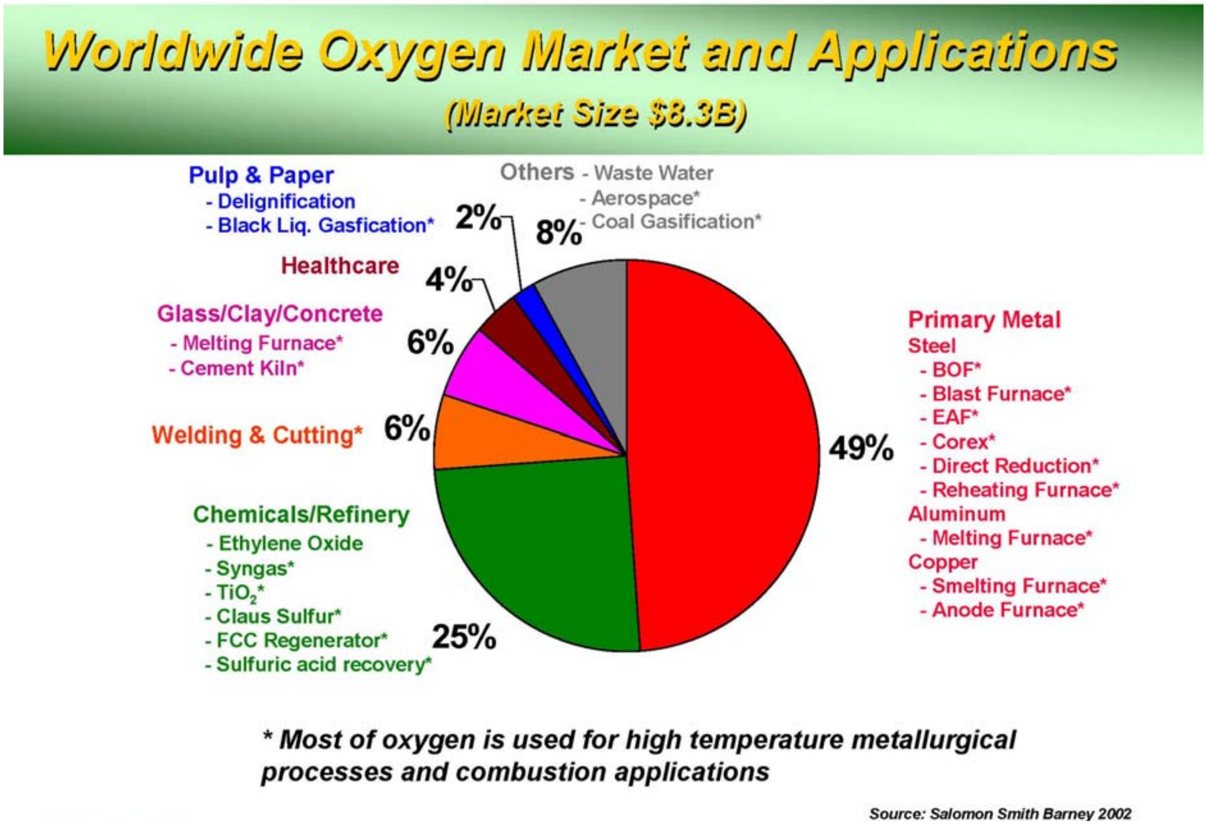
The primary market for hydrogen and electricity from commercial H2-MHRs, at least for the first units, appears to be petroleum refineries to provide hydrogen for sweetening crude feedstock (hydro treating), hydro cracking, and other unit operations. It can also be used as feedstock for fertilizer and methanol production and for other chemical processes. The biggest users of hydrogen are ammonia production plants and petroleum refineries (in fact, ~90 of the hydrogen consumed today is for gasoline and ammonia production). Some of the small-scale hydrogen markets include metallurgical and aerospace users.

Hydrogen is an environmentally attractive transportation fuel that has the potential to displace fossil fuels. Its widespread use as a transportation fuel has a number of obstacles to overcome, including the cost of fuel cell powered vehicles, on-board hydrogen storage, and hydrogen distribution infrastructure; all seem manageable over time (NHI 2005).

Oxygen:

The commercial H2-MHR will produce a significant amount of high purity oxygen. There is a large international market for high purity oxygen (see Figure 5-1). There is always an option of storing the oxygen in tanks and supplying to small scale users like hospitals, etc., but these markets are served by established companies that produce oxygen by cryogenic distillation of air, and small volume oxygen generators are becoming increasingly prevalent.

Ideally, a “green” user of oxygen should be co-located in the vicinity of the commercial H2-MHR to efficiently consume the large volumes of oxygen produced. The end user of oxygen should not produce significant quantities of greenhouse gases. In fact, many of the major consumers of high purity oxygen shown in Figure 5-1 produce large quantities of carbon dioxide.



*** Most of oxygen is used for high temperature metallurgical processes and combustion applications***

Source: Salomon Smith Barney 2002

Figure 5-1. Global Oxygen Market

5.2 Waste Streams

The major waste streams for both the NGNP and a commercial H2-MHR are spent fuel elements and radioactive wastes from the reactor plant and chemical waste, primarily from the hydrogen plant(s). These wastes will be disposed of in federally licensed facilities, and the disposition options for the NGNP and commercial H2-MHR waste streams appear to be quite similar. These disposition options are summarized below. Given the importance of this topic, a detailed waste assessment is provided in Section 7.

Spent Fuel:

The spent fuel elements will be stored on site to cool for at least one year. Depending upon the availability of a federal repository, the NGNP spent fuel may be stored on-site for several decades. The spent fuel elements from commercial H2 MHRs will be stored on-site for up to 10 years. It is assumed that, ultimately, the unprocessed spent fuel elements will be disposed of permanently in a federal geological repository (presumably at Yucca Mountain).

Radioactive Waste:

The reactor plant will generate gaseous, liquid and solid radioactive wastes. Every effort will be made to minimize these waste streams; in general, the most effective means of waste minimization is source reduction, especially during the design phase. The gaseous waste, primarily noble gases, will be treated to remove particulates and condensables and held to allow the shorter-lived radionuclides time to decay. The remaining noble gases (essentially 10.7-yr Kr-85) can be bottled for long-term storage or vented to the atmosphere with proper monitoring. The liquid radioactive waste will be concentrated and solidified. This solidified waste along with the solid waste (spent resins, hotel waste, etc.) will be shipped to a federally licensed, low-level waste (LLW) repository. NGNP LLW may be stored on the INL reservation for an indefinite period of time.

Tritium, which will be produced in an MHR by various nuclear reactions, is a special concern for a nuclear hydrogen plant. Given its high mobility, especially at high temperatures, some tritium will permeate through the intermediate heat exchanger and the hydrogen plant process vessels, contaminating the product hydrogen. Tritium migration in an MHR and the design options for controlling it to acceptable levels are described in Section 8.

Chemical Waste:

The hydrogen plant is designed to minimize releases of chemicals to the environment. For an SI-based hydrogen plant, a small amount of sulfur dioxide may be emitted, but it will likely be well within EPA guidelines. If sulfur dioxide emissions from the SI-based hydrogen production process are not within limits, it can be removed from process streams by caustic scrubbing. This polishing step would generate a small aqueous sodium sulfate waste stream, which would be concentrated, solidified and land-filled.

Every effort will be made to return even the small amounts of liquid wastes that may be produced during maintenance activities to the process. HI and Iodine from hydrogen polishing will be scrubbed using water, and the streams will be sent directly back to the Bunsen section such that no waste stream is generated.

For an HTE-based hydrogen plant, very little chemical waste is expected to be produced as a result of plant operation (beyond some hotel wastes). However, the SOE cells will need to be replaced after reaching their effective lifetime (5-10 years). The cell material contains YSZ as electrolyte, Ni-YSZ as cathode and LSM as anode. Certain of the SOEC materials, including the LSM anodes, are classified as hazardous materials;[26] therefore, rather large quantities of spent SOEC would need to be disposed of in hazardous waste landfills licensed by the federal government. The future availability of hazardous waste landfill is uncertain, and the disposal costs are significant and increasing. Although beyond the scope of this study, the practicality of recovery and recycle of these materials will need to be investigated if the use of SOEC (and SOFC) technology becomes widespread.

Waste Heat:

The nuclear reactor as well as the hydrogen production plant will generate significant amounts of low-grade waste heat. If located in an urban or agricultural setting this waste heat might conceivably find use for district heating or aquaculture. At the INL Reactor Technology Complex there is not likely to be any significant use for this waste heat, in which case the waste heat will be discharged to the environment via dry cooling towers.

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[26] Per their Material Safety Data Sheets (http://raider.muc.edu/~habeckjc/msdsmain.htm)

6. COMMERCIAL PRODUCTS

The future market prices of commercial products (commodities) produced by the NGNP and a commercial H2-MHR in the 2020 – 2060 timeframe are estimated in this section. The NGNP will be sited at the INL in southern Idaho, and the commercial H2-MHR is assumed to be sited on the Texas-Louisiana Gulf coast in a region with petroleum refineries and petrochemical plants. The estimates are presented in constant January 2007 dollars.

Technology Insights prepared a comprehensive report for the Electric Power Research Institute (EPRI) in 2003 (Dilling 2003), entitled "High Temperature Gas-Cooled Reactors for the Production of Hydrogen: An Assessment in Support of the Hydrogen Economy," which addressed this same topic. The present study takes no significant exceptions to those published results; in a practical sense, the projections presented in this section can be considered an update of the relevant EPRI work that was done five years ago. As with the EPRI study, the present study relied heavily upon price projections provided by the DOE's Energy Information Administration (EIA).[27]

This section also briefly addresses the uncertainties associated with future trends in the energy production and distribution infrastructure and the impact on commodity price forecasts. Increasing concern about energy security and environmental issues are leading to substantial interest in the use for hydrogen as a substitute for fossil fuels, particularly in the transportation sector. However, hydrogen production requires significant amount of energy input and therefore the adoption of a hydrogen economy will likely be a gradual process in partnership with electric utilities and oil companies; hence, the timing of a transition to a hydrogen economy is also quite uncertain.

6.1 NGNP

The NGNP prototype is scheduled to come online by 2016 to 2018. In this study, the NGNP is assumed to be a 600 MW(t) MHR coupled to direct-cycle PCS and to an IHX to supply process heat to SI-based and HTE-based plants that will produce hydrogen and oxygen (Section 2). The primary commodities produced for potential sale in the local and regional areas are assumed to be electricity and hydrogen; oxygen and process heat are perceived to be of lesser value in the anticipated market.

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[27] The EIA web site (http://www.eia.doe.gov/) provides official US government energy statistics, including historical data and short- and long-term forecasts to the year 2030.

6.1.1 Electricity

The state of Idaho relies mainly upon electricity produced by hydroelectric power plants. Hydropower is a relatively cheap source of electricity and the current price of electricity in this location is about 49 mil/KWh (EIA 2007). The Energy Information Agency projects that the average nationwide cost of electricity – in constant 2005 dollars - will remain fairly stable through 2030 at ~80 mil/kwh because of new capacity anticipated to come online (Figure 6-1). The projected market price of electricity is summarized in Table 6-1. Accepting the EIA assumption of stable prices to 2030 and assuming a real escalation rate of 1% per year for the years 2030 to 2060 (e.g., because of a increasing carbon tax), then the future levelized[28] cost of electricity for the 2020 - 2060 timeframe is evaluated to be 55 mil/kwh if the current cost of electricity is 49 mil/KWh.

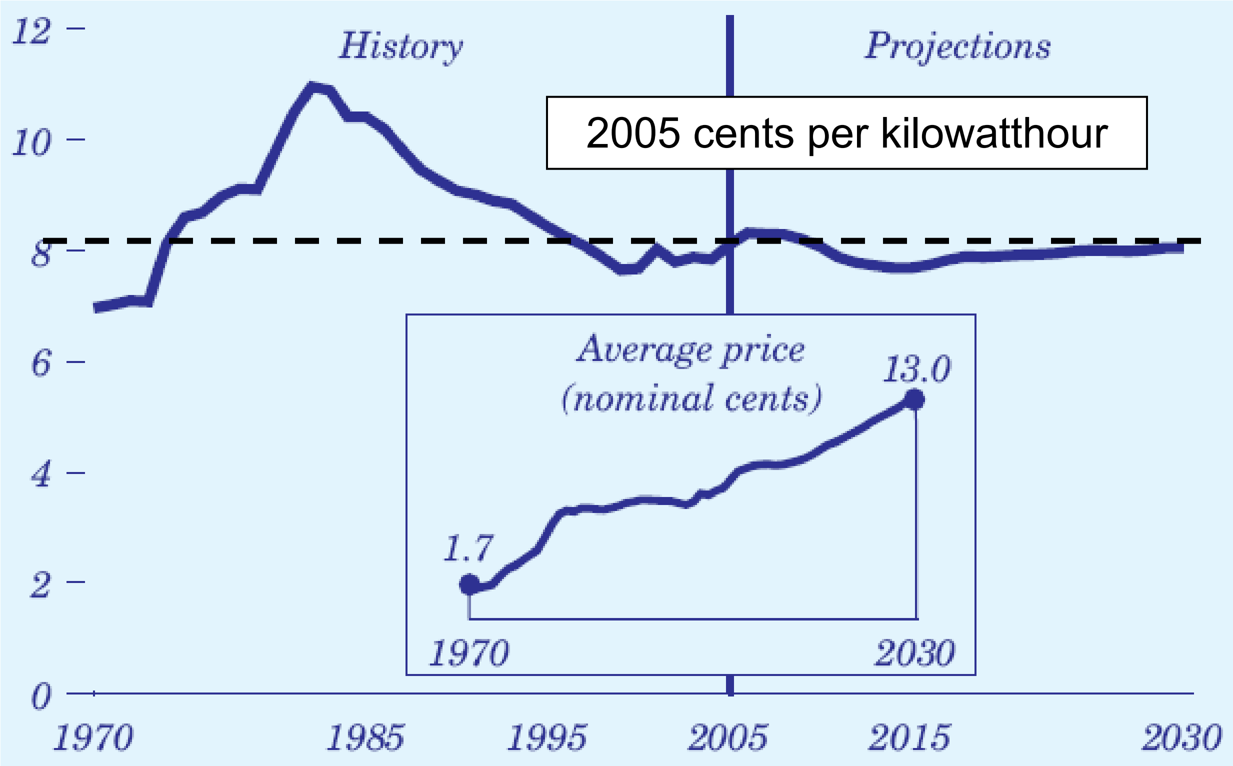

Figure 6-1. Future Cost of Electricity (EIA 2007 Projection)

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[28] The “levelized” cost for the 2020 – 2060 timeframe is a constant value with the same present value as the constant value from 2007 to 2030 combined with a 1% real escalation per year from 2030 to 2060.

Table 6-1. Projected Future Electricity Prices

	Electricity Price (mil/kwh)	
	Current 2007 dollars	Levelized value 2020 - 2060
Selling Price in Southern Idaho (EIA 2007)	49	55
Selling Price in Texas Gulf Coast area (EIA 2007)	94	106

The EIA projection of stable electricity prices to 2030 is somewhat surprising, given that the growing international demand for reduced greenhouse gas emissions may well result in a carbon penalty or tax of some sort on fossil fuel-derived electricity, which will particularly impact the coal-fired plants that produce about half of the nation's electricity (EIA 2007). Buying carbon credits will be the simplest solution, but the cost will not likely be trivial and will certainly be passed on to the consumer. If required, CO_2 sequestration is likely to be technically challenging and expensive, again with the costs passed on to the consumer.

The NGNP prototype, coupled with a non-hydrocarbon-based, hydrogen production technology, can provide hydrogen as a replacement for hydrocarbons used as feedstock for hydrogen production. (The use of nuclear heat to replace natural gas-fired heat for steam reforming of methane would also reduce the total carbon dioxide produced per mass of hydrogen product, but the reforming process itself would still produce significant quantities of carbon dioxide.)

The electricity in excess of that used for hydrogen production can either be sold to the local grid for sale at the wholesale market value to cover some of the expenses of the prototype operation or, conceivably, could be used to produce nitrogen by cryogenic air distillation which is needed as a feedstock for ammonia production (which could have extensive application as a chemical fertilizer in Idaho's extensive agriculture industry).

6.1.2 Hydrogen

The NGNP technology demonstration phase will provide insight to the cost of nuclear hydrogen production independent of natural gas and, thus, help to project reliable production costs for a commercial plant.

It is assumed that the future market value of hydrogen is determined by the projected future price of natural gas (both on a per Btu basis). The EIA estimate for future natural gas prices is shown in Figure 6-2 (EIA 2007). In the EIA reference case, lower 48-state wellhead prices for natural gas are projected to decline from current levels to an average of $5.01/1000ft^3 (2005 dollars) in 2013, then rise to $5.98/1000ft^3 in 2030; Henry Hub spot market prices are projected to decline to \$5.49/MMBtu (\$5.33/1000 ft^3) in 2013 and then rise to \$6.52/MMBtu (\$6.33/1000ft^3) in 2030.

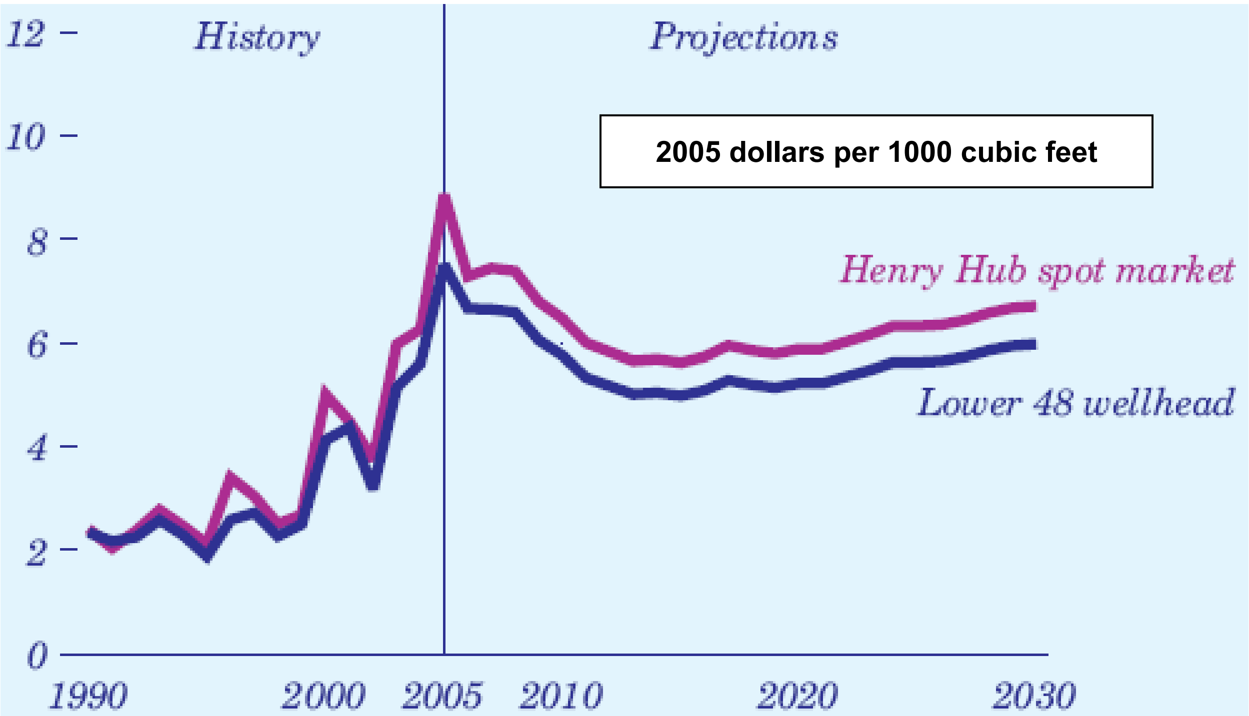

Figure 6-2. Future Cost of Natural Gas (EIA 2007 Projection)

An attempt has been made here to estimate with a realistic real escalation rate the future price of natural gas. The natural gas prices are projected for the commercial venture time frame of 2020 to 2060 at real escalation rates of 1%, 2% and 3% to predict the future levelized price of natural gas (Figure 6-3). Given those escalation rates, the net present value was calculated with a 7% discount rate, and the resulting levelized future prices in the 2020 to 2060 timeframe are also shown on Figure 6-3.

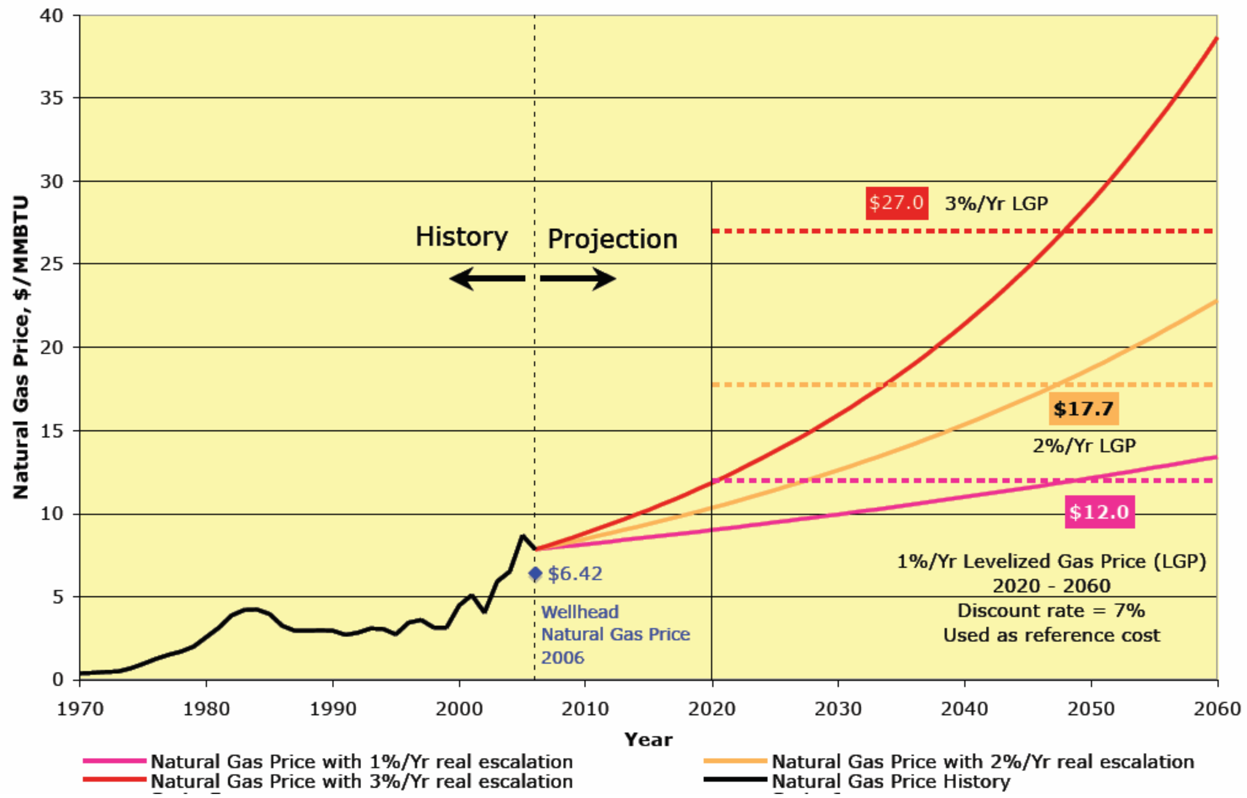

Figure 6-3 Projected Natural Gas Prices to 2060

Additional factors could lead to even higher escalation rates. These factors include booming national and global economies and rapid industrialization of countries like China and India as well as the political tensions among the Gulf countries and the western nations (Europe and North America) influencing the future price of fossil fuels. The authors believe that these factors will produce at least a 1% real escalation rate (and likely higher). In addition to supply-and-demand factors, the growing international concern over the production of greenhouse gases could well impose a carbon penalty on fossil fired industries which would have a direct impact on the price of burning natural gas. Consequently, for the current study, 1% real escalation per year is set as the baseline for future price projections.

6.1.3 Oxygen

Based upon the EPRI study (Dilling 2003), the market price of oxygen was estimated to be \$20/tonne in 2002 dollars. When escalated from 2002 to 2007 dollars, the market price of O_2 is estimated to be \$23/tonne. At this price, oxygen isolated from the SI or HTE process will contribute a credit of \$0.16 per kg H_2 produced. In the NGNP time frame, the oxygen credit is assumed to remain the same because no real escalation is expected due to the oxygen price stability provided by cryogenic air distillation.

6.1.4 Process Heat

As discussed in Section 6.1.2 for the market price of hydrogen, the future projected cost of natural gas (Figure 6-2) also provides a reasonable lower bound on the future value of nuclear process heat (assuming that fuel costs are the dominant component of the cost of natural gas-fired process heat; obviously, equipment costs, etc., contribute to a degree as well).

6.2 Commercial H2-MHR

The commercial H2-MHR plant is assumed to be a 4 x 600 MW(t) MHR coupled to either a SI-based or HTE-based hydrogen plant as described in the NERI reports (Richards 2006a, Richards 2006b). As previously mentioned, it is assumed to be sited on the Texas-Louisiana Gulf coast. As with the NGNP, the primary commodities produced for potential sale in the local and regional areas are electricity and hydrogen; oxygen and process heat are again perceived to be of lesser value in the anticipated market.

6.2.1 Electricity

As discussed in section 6.1.1, the EIA projection indicates that the average cost of electricity will remain constant to 2030. If a real escalation rate of 1% per year (for the reasons discussed above) is assumed for the years 2030 to 2060, then the future levelized cost of electricity for the 2020 - 2060 timeframe is evaluated to be 106 mil/KWh if the current cost of electricity is 94 mil/KWh, the average of the cost of electricity in Texas and Louisiana (EIA 2007, Table 6-1).

For perspective, the current estimate of levelized bus bar electricity generation cost for NOAK GT-MHRs is 31 mil/KWh (2003 dollars) from (Labar 2004). Escalating that cost estimate to 2006, then assuming it to remain constant until 2030 and applying 1%/year real escalation from 2030 – 2060 leads to a levelized value of bus bar electricity generation cost in the NGNP timeframe of 2020 to 2060 of about 37 mil/kwh. Updated cost estimates will be provided for the NGNP and commercial H2-MHRs in the PCDSR.

6.2.2 Hydrogen

Hydrogen is projected to be a replacement for fossil energy, especially in the transportation sector. In this report, it is assumed that the future market value of hydrogen is determined by the projected future price of natural gas.

The historical prices of natural gas and their predictions to the year 2020 are available from the EIA (Figure 6-2). In Figure 6-3, the EIA data have been extended from the year 2006 to the year 2060 at real escalation rates of 1%, 2% and 3% per year. A single levelized value is then derived from the present value of natural gas price discounted at 7%.

The figure-of-merit chosen here to estimate the future market value of nuclear hydrogen is the future projected price of natural gas. This choice was made because, in the hydrogen economy, hydrogen is primarily a CO_2-free replacement for fossil energy, especially in the transportation sector (NHI, 2005). Another viable figure-of-merit for assessing the future value of nuclear hydrogen is the future cost of hydrogen produced by steam reforming of methane, the process used for >90% of today's hydrogen production. In fact, future SMR hydrogen cost was the primary figure-of-merit in the oft cited EPRI report (Dilling 2003) and the two NERI reports (Richards 2006a, Richards 2006b). Actually, there is a close coupling between these two figures-of-merit because the future cost of SMR hydrogen will be strongly dependent upon the future cost of natural gas which is used in the SMR process as both the feedstock and the process heat source.

Using the hydrogen production costs in the NERI reports, one can estimate when nuclear hydrogen would become cost competitive with SMR hydrogen as a function of the cost of natural gas. Based on the estimated, levelized natural gas price with 1%/yr real escalation in Figure 6-3 ($12/MMBTU) the estimated production cost of hydrogen (Figures 6-4 and 6-5) for the U.S market in the years 2020 – 2060 is $2.5 per kg of hydrogen (Table 6-2).[29]

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[29] The price of hydrogen has been converted from $/MMBTU to $/kg using the higher heating value of 0.139 MMBtu/kg (the higher heating value includes the energy that could be obtained by condensing the water vapor).

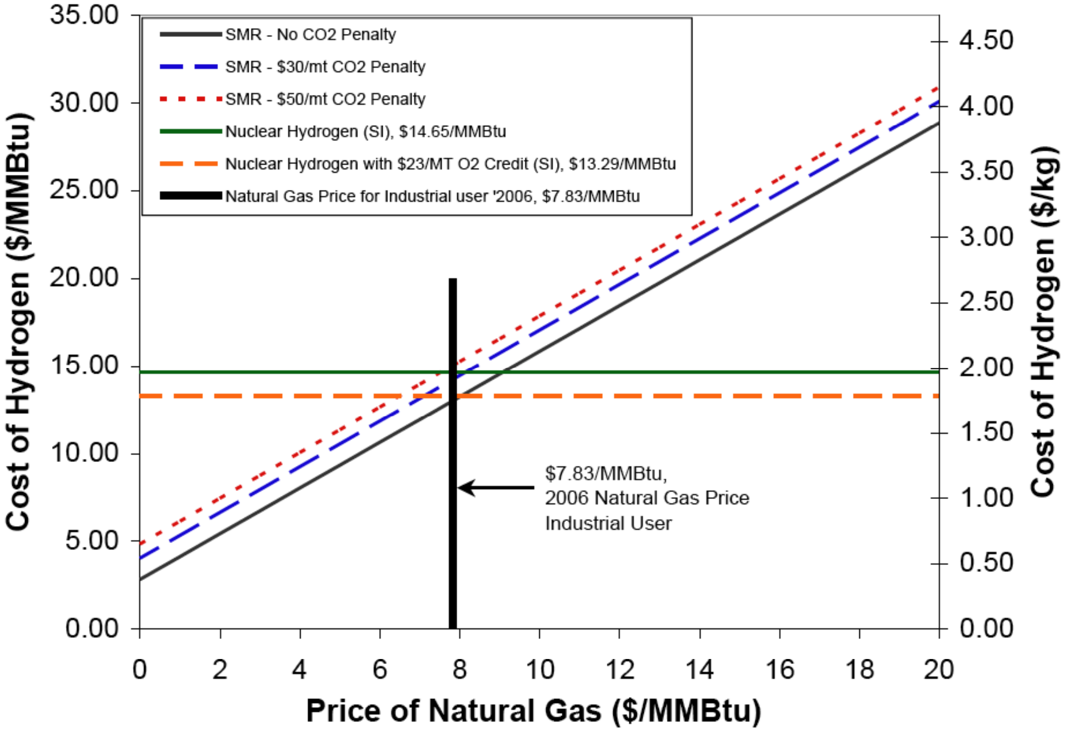

Figure 6-4. Comparison of Cost of Nuclear H_2 (SI Process) with Cost of SMR H_2

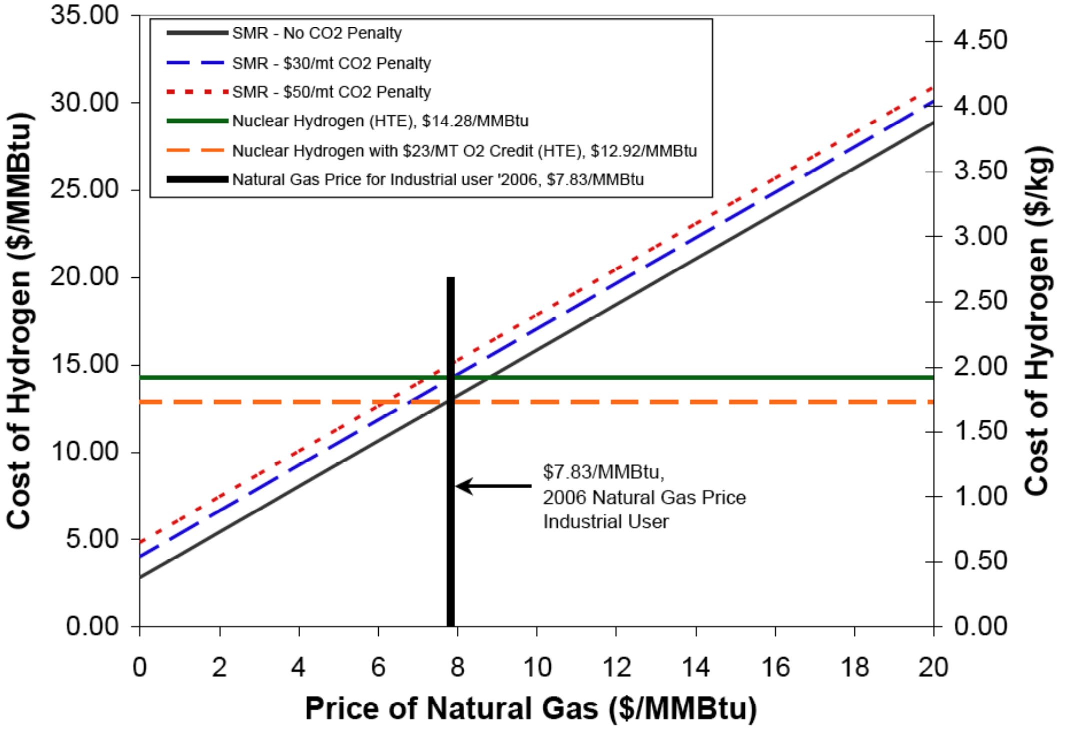

Figure 6-5. Comparison of Cost of Nuclear H_2 (HTE Process) with Cost of SMR H_2

Table 6-2. Nuclear Hydrogen Production Costs

	Hydrogen Production (\$/kg H_2 Produced)	
	2007 dollar	**Levelized value in 2020-2060 timeframe**
SI Process	1.97	1.97
HTE Process	1.92	1.92
O_2 Credit	0.16	0.16
SI with O_2 Credit	1.81	1.81
HTE with O_2 Credit	1.76	1.76
SMR	1.78	2.50
CO_2 Penalty @ \$30/Tonne	0.16	0.23
CO_2 Penalty @ \$50/Tonne	0.28	0.39
SMR@ \$30/Tonne CO_2	1.94	2.73
SMR@ \$50/Tonne CO_2	2.06	2.89

If required, CO_2 sequestration and disposal costs would correspond to an addition of \$0.16 and \$0.28 respectively, to the cost per kg H_2 produced by SMR. From Table 6-2, it is seen that if CO_2 penalty is imposed for greenhouse gas emissions, then the hydrogen production from natural gas in the NGNP timeframe will cost about \$2.7 to \$2.9 per kg H_2 produced. Similarly, the hydrogen production from natural gas in the NGNP timeframe (2020 to 2060) will cost about \$2.7 to \$2.9 per kg H_2 produced with CO_2 penalty.

When the levelized price of natural gas exceeds about \$8/MMBTU,[30] then nuclear hydrogen from a NOAK H2-MHR using either SI or HTE is predicted to be competitive with SMR hydrogen. Nuclear hydrogen becomes competitive with natural gas as a carbon-free general energy source when the levelized price of natural gas in the 2020 – 2060 timeframe rises to about \$14/MMBTU (i.e., a real escalation rate slightly greater than 1%). Note that the current natural gas price is about \$8/MMBTU (for industrial users).

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[30] Industrial user values of natural gas prices.

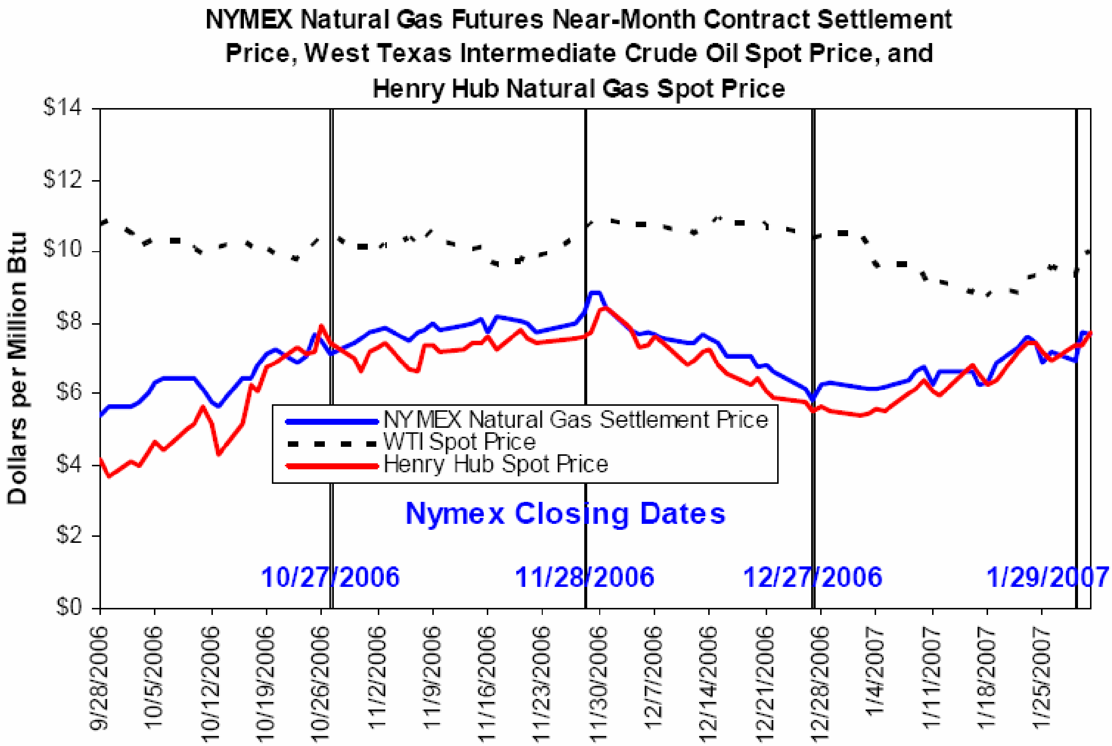
6.2.3 Oxygen

Based upon the EPRI study (Dilling 2003); the price of oxygen is $20/tonne in 2002 dollars; when escalated to 2007 dollars, the price is $23/tonne. This credit for oxygen corresponds to approximately $0.16 per kg of H_2 produced on a commercial scale in today's dollars. The oxygen credit is conservatively assumed to remain the same (in 2007 dollars) in the 2020 to 2060 timeframe because no real escalation is expected due to the oxygen price stability provided by cryogenic air distillation. There is no compelling reason at this writing for pricing oxygen differently on the Gulf coast than in southern Idaho although there is likely a larger market at the former location.

6.2.4 Process Heat

As discussed in Section 6.1.4, the future projected cost of natural gas (Figure 6-3) provides a lower bound on the future value of nuclear process heat (again assuming that fuel costs are the dominant component of natural gas-fired process heat

A final cautionary note is in order: in 2002, EPRI estimated that the cost of natural gas today would be ~5 $/MMBTU; in fact, the actual cost as of January 2007, was ~8 $/MMBTU (see Figure 6-6).



Note:The West Texas Intermediate (WTI) crude oil price, in dollars per barrel, is converted to $/MMBtu using a conversion factor of 5.80 MMBtu per barrel. The dates marked by vertical lines are the NYMEX near-month contract settlement dates.

Source: Natural gas prices, *NGI's Daily Gas Price Index* (http://Intelligencepress.com); WTI price, Reuters News Service (http://www.reuters.com).

Figure 6-6. Current Price of Natural Gas

7. WASTE ASSESSMENT

In addition to producing commercial products, an H2-MHR employing either the SI or the HTE hydrogen production process will generate waste products as well. The plant designs will incorporate best engineering practices (e.g., source reduction, recycle, etc.) to minimize these waste streams, but practically they cannot be eliminated completely. The most obvious - and the most challenging - waste stream will be spent nuclear fuel.

Some of these waste streams can be characterized and quantified during pre-conceptual design with reasonable confidence once certain fundamental plant parameters (e.g., core type, power level, fuel cycle, etc.) are specified; the number of spent fuel elements is a good example. Other waste streams can be qualitatively characterized but cannot be accurately quantified during pre-conceptual design because the quantities are strongly dependent upon the design and performance of individual systems and components; the volume of liquid radioactive waste produced by regenerating the helium purification system (HPS) and the mass of sulfur dioxide emitted from the SI plant are but two examples.

At the current stage of design definition for the NGNP and for commercial H2-MHRs, the best indication of the waste streams that these facilities will generate are the waste assessments that have been performed for previous MHR designs that were more advanced. In this regard, the waste streams for the reactor plant have been better characterized than those for the SI- and HTE-based hydrogen plants. For the latter, there is very limited quantitative information at this writing.

Waste assessments have been performed previously for several MHR designs, including the steam-cycle, New Production-Modular Helium Reactor (NP-MHTGR, Lanik 1991) and the direct-cycle, Plutonium Consumption-Modular Helium Reactor (PC-MHR, Olsen 1995). Of the two, the assessment for the PC-MHR is ostensibly more directly relevant to the NGNP and a commercial H2-MHR since both are assumed herein to include a direct-cycle PCS. In any case, the waste assessment for the PC-MHR was in large measure based upon that performed earlier for the NP-MHTGR with adjustments made for replacement of the steam generator with a gas turbine (Olsen 1995). The essential results of the PC-MHR waste assessment are summarized below as an indication of the waste streams that are anticipated for NGNP and the commercial H2-MHR. As the designs for these two plants mature, more quantitative waste assessments will be performed and the designs optimized to minimize the waste streams to the extent practical.

Waste disposal costs are not explicitly included in the workscope for this special study (Work Plan 2006). They will be addressed in the economic assessment of the commercial H2-MHR to be included in the PCDSR. As part of their assessment of the operation and maintenance

(O&M) costs for the commercial GT-MHR (GCRA 1994), Gas-Cooled Reactor Associates (GCRA) provided cost estimates for waste disposal which should be directly relevant to the commercial H2-MHR assessment.

The information on waste streams presented in this section could be organized in several different ways. For example, there could be separate subsections devoted to the NGNP and the commercial H2-MHR as was done in previous sections. However, given the limited design definition of these two plants (e.g., the power level has not been chosen for either), the information generally applies equally to both plants. Any differences that can be identified at this writing (e.g., the NGNP hydrogen plant will almost certainly not be commercial scale) will be described below.

7.1 Waste Characterization

The waste streams expected to be generated by the MHR heat source and the SI- and HTE-based hydrogen plants are described below.

7.1.1 Reactor Plant

The MHR nuclear heat source will generate spent nuclear fuel elements, radioactive waste, waste heat and, to a lesser extent, hazardous waste and mixed waste (both radioactive and hazardous). As described above, the best currently available indication of the waste streams that will be generated is the waste management assessment that was performed previously for the direct-cycle PC-MHR (Olsen 1995).

The PC-MHR program was conducted at GA during 1993-1995 under USDOE funding; the mission was to destroy surplus US weapons plutonium (PC-MHR 1994, PC-MHR 1995). A 600 MW(t) direct-cycle PC-MHR was shown to be capable of destroying almost 90% of the Pu-239 (and >60% of the total Pu) in a single pass while producing electricity with a 48% thermal efficiency. A standard PC-MHR complex would include four reactor modules, the supporting fuel fabrication facilities, and the spent fuel storage facilities. The configuration and key design parameters of the reactor module, summarized in Table 7-1, are quite similar to those for the commercial GT-MHR and for a commercial H2-MHR. Each module is located within a steel-lined, reinforced concrete, high-pressure, low-leakage reactor containment structure, which is, located underground.

Table 7-1. Key Design Parameters for the PC-MHR

Parameter	**Design Value**
Plant design	Direct-cycle MHR with annular prismatic core
Power conversion system	gas turbine with recuperation & intercooling (Brayton cycle)
Thermal power	600 MW/module; 4 module/standard plant
Net electrical power	286 MW/module;
Outlet temperature	850°C
Thermal efficiency	48%
Feedstock	Surplus weapons Pu (94% Pu-239)
Fuel form	TRISO $PuO_{1.68}$ particles in prismatic fuel element
Fuel cycle	Once-through
Fuel burn up	<85% FIMA
Fast Fluence	$<5 \times 10^{25}$ n/m^2
Safety & licensing	EPA PAGs (e.g., 5 rem thyroid, 1 rem WB)
Final waste form	Whole-element disposal without processing

The fuel particles for the PC-MHR have the same TRISO coating system as the fissile particle for the GT-MHR[31] except that the buffer layer thickness is adjusted to reflect the use of highly enriched, weapons Pu feedstock instead of the LEU feedstock in the commercial designs. The particle designs are compared in Table 7-2.

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[31] The nominal particle design which is being irradiated in the AGR-1 test under the DOE Advanced Gas Fuel Development Program (AGR Plan/1).

Table 7-2. Comparison of PC-MHR and GT-MHR Particle Designs

Parameter	**Commercial GT-MHR**		**PC-MHR**
	Fissile Particle	**Fertile Particle**	
Composition	$UC_{0.5}O_{1.5}$	$UC_{0.5}O_{1.5}$	$PuO_{1.60}$
Enrichment, %	19.8 (U-235)	0.7 (natural U)	94 (Pu-239)
Design burn up (% FIMA)	26	7	85
Dimensions (μm)			
Kernel Diameter	350	500	195
Buffer thickness	100	65	110
IPyC thickness	35	35	35
SiC thickness	35	35	35
OPyC thickness	40	40	40
Particle diameter	770	850	635

A preliminary waste assessment was performed for the PC-MHR in order to identify, quantify, and characterize radioactive, non-radioactive hazardous, and mixed waste streams for the Reactor Complex and Fuel Fabrication Facility (Olsen 1995). A further objective was to provide an outline for the waste minimization program plan which was being developed in accordance with DOE Order 5400.1, General Environmental Protection Program, the Resource Conservation and Recovery Act, and prudent environmental engineering. The essential results are summarized below and are indicative of waste streams anticipated for the NGNP and a commercial H2-MHR.

7.1.1.1 Spent Fuel Elements

The largest and most significant waste stream from an MHR is the spent fuel. The spent fuel elements from both the PC-MHR and the commercial GT-MHR have been well characterized (e.g., Richards 1994 and Richards 2002, respectively). The characteristics of commercial GT-MHR spent fuel are summarized below because the spent fuel from both the NGNP and a commercial H2-MHR is expected to be quite similar.[32]

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[32] Consistency with the rest of this section would argue for presenting the information for the PC-MHR spent fuel; however, relevance is considered more important than consistency.

7.1.1.1.1 Physical Description

The GT-MHR fuel element and its components were shown in Figure 2-3. The manufacturing processes and quality-control methods are described in detail in (Bresnik 1991). Detailed fuel product specifications and acceptance criteria, including allowable defect fractions, are given in (Munoz 1994). The following subsections provide descriptions of the coated fuel particles, fuel compacts, and fuel-element graphite blocks.

7.1.1.1.1.1 Coated Fuel Particles

The fuel for the GT-MHR consists of microspheres of uranium oxycarbide that are TRISO-coated with multiple layers of pyrocarbon and silicon carbide. The GT-MHR core is designed to use a blend of two different particle types: a fissile particle that is enriched to 19.8% U-235 and a fertile particle with natural uranium (0.7% U-235). The fissile/fertile-loading ratio is varied with location in the core, in order to optimize reactivity control, minimize power peaking, and maximize fuel burnup. The TRISO coating system is a miniature pressure vessel that provides containment of radionuclides and gases during normal operation and postulated accidents. This coating system is also an excellent engineered barrier for long-term retention of radionuclides in a repository environment. Coated particle design parameters are given in Table 7-2; fuel quality and performance specifications are given in Table 7-3.

Table 7-3. GT-MHR Fuel Quality and Performance Requirements

Parameter	Maximum Expected (P ≥50% Confidence)	Design Limit (P ≥95% Confidence)
As-Manufactured Fuel Quality Defect Fractions		
Heavy metal contamination	$\leq 1.0 \times 10^{-5}$	$\leq 2.0 \times 10^{-5}$
Missing buffer	$\leq 1.0 \times 10^{-5}$	$\leq 2.0 \times 10^{-5}$
Missing or permeable IPyC	$\leq 4.0 \times 10^{-5}$	$\leq 1.0 \times 10^{-4}$
Defective SiC	$\leq 5.0 \times 10^{-5}$	$\leq 1.0 \times 10^{-4}$
Missing or defective OPyC	$\leq 1.0 \times 10^{-4}$	$\leq 1.0 \times 10^{-3}$
Allowable Core-Average Failure Fractions		
Normal operation	$\leq 5.0 \times 10^{-5}$	$\leq 2.0 \times 10^{-4}$
Accidents	$\leq 1.5 \times 10^{-4}$	$\leq 6.0 \times 10^{-4}$

7.1.1.1.1.2 Fuel Compacts

Each fuel compact is a mixture of fissile, fertile, and graphite shim particles bonded together with a carbonaceous matrix into a cylindrical-shaped compact with dimensions 12.45 mm

(0.49 in.) in diameter and 49.3 mm (1.94 in.) in length. The fuel compacts are stacked in the blind fuel holes of the graphite fuel element. Graphite plugs are cemented into the tops of the fuel holes to enclose the stacked compacts. Because of sorption mechanisms, the fuel compacts can provide an additional barrier to the release of metallic fission products. Fuel compact design parameters are given in Table 7-4.[33]

Table 7-4. GT-MHR Fuel Compact Design Parameters

Parameter	**Design Limit**
Diameter, mm	12.45
Length, mm	49.3
Volume, cm^3	6.0
Shim particle composition	H-451 or TS-1240 graphite
Shim particle size	99 wt % < 1.19 mm; 95 wt % < 0.59 mm
Shim particle density (g/cm^3)	1.74
Binder type	Petroleum pitch[34]
Filler	Petroleum derived graphite flour
Matrix density (g/cm^3)	0.8 to 1.2
Volume fraction occupied by matrix	0.39
Volume fraction occupied by shim particles in an average compact	0.41
Volume fraction occupied by fissile particles in an average compact	0.17
Volume fraction occupied by fertile particles in an average compact	0.03
Number of fissile particles in an average compact	4310
Number of fertile particles in an average compact	520
Mass of carbon in an average compact, g[35]	6.62

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[33] The fuel-compact matrix for future MHRs would be derived from phenolic resin rather than petroleum pitch which was the reference feedstock for Fort St. Vrain fuel and for the GT-MHR conceptual design (Shenoy 1996).

[34] The fuel compacts being developed by the AGR fuel program for use in the NGNP employ a resin-based matrix rather than petroleum pitch-based matrix.

[35] This value excludes carbon in the layers of the coated particles. For an average compact, there is an additional 1.32 g of carbon associated with fissile particles and an additional 0.20 g of carbon associated with fertile particles.

7.1.1.1.1.3 Graphite Blocks

The standard fuel-element graphite block and the arrangement of fuel holes, coolant holes, and lumped burnable poison[36] (LBP) holes are shown in Figure 7-1. The graphite blocks are manufactured from high-purity, nuclear-grade graphite. Each block is a right hexagonal prism; fuel and coolant holes run parallel through the length of the block in a regular triangular pattern of two fuel holes per coolant hole. The minimum web thickness between a coolant hole and fuel hole is 4.5 mm (0.18 in.). Design parameters for the standard fuel element are given in Table 7-5. In addition to standard fuel elements, the GT-MHR active core contains fuel elements with a single, larger diameter channel (3.75 to 4.0 in.) to allow insertion of additional poison for reserve shutdown capability.

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[36] B_4C is used as lumped (or fixed) burnable poison to control reactivity. Compacts containing B_4C and graphite shim granules are inserted into holes designated for lumped burnable poison, which are located near the corners of the block.

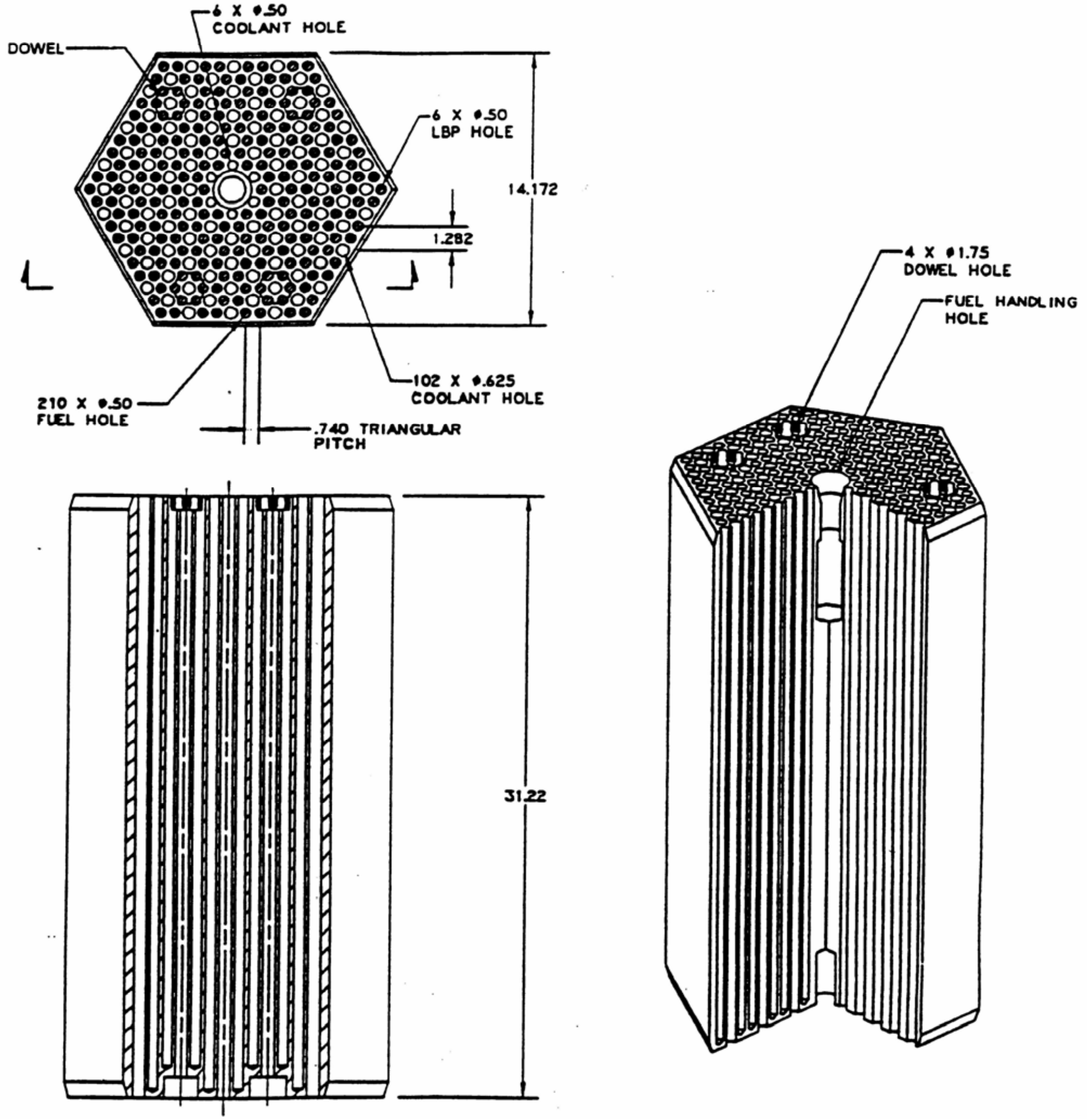

Figure 7-1. Standard MHR Fuel Element

Table 7-5. Standard GT MHR Fuel Element Design Parameters

Parameter	Design Value
Shape	Hexagonal Prism
Type of graphite	Nuclear Grade H-451[37]
Mass of graphite per element	90 kg
Dimensions	794 mm (31.2 in.) in length
	360 mm (14.2 in.) across flats of hexagon
Volume	0.0889 m^3
Total number of fuel holes	210
Number of fuel holes under dowels	24
Fuel hole diameter	12.7 mm (0.5 in.)
Fuel hole length	752.6 mm (29.63 in.) under dowels
	781.5 mm (30.77 in.) not under dowels
Number of fuel compacts per fuel hole	14 for holes under dowels
	15 for holes not under dowels
Number of fuel compacts per element	3126
LBP holes per element	6
LBP hole diameter	12.7 mm (0.5 in.)
LBP hole length	781.5 mm (30.77 in.)
Total number of coolant holes	108
Coolant hole diameter	15.88 mm (0.625 in.) for larger holes; 12.7 mm (0.5 in.) for the 6 smaller holes near the center of the block
Pitch of coolant/fuel-hole array	18.8 mm (0.74 in.)
Total mass of an average fuel element[38]	122 kg
Mass of carbon in an average fuel element[39]	110.7 kg
Mass of low-enriched uranium fuel in an average fresh fuel element	3.43 kg
Mass of natural uranium fuel in an average fresh fuel element	0.995 kg

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[37] H-451 graphite is no longer available; an equivalent graphite will be developed and qualified for the NGNP and commercial MHRs.

[38] This value includes graphite and fuel compacts, but excludes lumped burnable poison.

[39] This value excludes carbon in the layers of the coated particles. For an average fuel element, there is an additional 4.13 kg of carbon associated with fissile particles and an additional 0.62 kg of carbon associated with fertile particles.

Parameter	Design Value
Number of fissile particles in an average fuel element	1.35×10^7
Number of fertile particles in an average fuel element	1.63×10^6
Electrical energy generated by an average fuel element at discharge	0.637 Mw_e-yr

7.1.1.1.2 Fuel Cycle

For the equilibrium fuel cycle, one-half of the core (510 fuel elements) is reloaded every 417 full-power days, corresponding to an equilibrium residence time of 834 effective full-power days (EFPD) for each fuel element.[40] Each reload segment contains 1746 kg of low-enriched uranium and 507 kg of natural uranium. With a capacity factor of 85%, the GT-MHR would discharge 510 fuel elements every 16 months, or an average of about 380 elements per calendar year. Over its 60-yr plant life, a single GT-MHR module would discharge a total of about 23,000 spent-fuel elements. At discharge, an average fuel element has generated approximately 0.637 Mwe-yr of energy.

7.1.1.1.3 Radionuclide Inventories

The GT-MHR spent fuel radionuclide inventory can be categorized as activation products, fission products, and actinides. The activation products are generated primarily as the result of nuclear reactions with impurities in graphite and fuel compacts. The actinide inventories were obtained from the three-dimensional burn up calculations (Sherman 1995). The fission product inventories were calculated using the GARGOYLE code (Shirley 1993). The ORIGEN code (Croff 1980) was used to calculate the activation product inventories since GARGOYLE lacks the necessary activation cross-sections for all impurity elements.

The activation product inventories for the GT-MHR were assumed to be the same as those calculated for the PC-MHR (Richards 1995), since the impurity concentrations, neutron fluxes, and fuel-residence times are nearly the same for both reactor cores. The impurity levels assumed for activation analysis are given in Table 7-6. With the exception of nitrogen, these impurity levels are the same as those used by the British to calculate activation product inventories in graphite from decommissioned Magnox and Advanced Gas Reactors (White 1984). The nitrogen content was assumed to be at the design limit of 100 ppm, in order to obtain a conservative estimate of C-14 inventory.

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[40] For the PC-MHR, the equilibrium fuel residence time was slightly shorter at 779 EFPD.

Table 7-6. Assumed Impurity Levels in GT-MHR Fuel Elements

Element	Concentration, ppm	Grams Per Fuel Element
Lithium	0.04	4.4×10^{-3}
Beryllium	0.02	2.2×10^{-3}
Nitrogen	100	11.1
Chlorine	3	0.33
Calcium	30	3.3
Manganese	0.15	1.7×10^{-2}
Iron	9	1.0
Cobalt	0.36	4.0×10^{-2}
Nickel	3.5	0.39
Zinc	0.6	6.6×10^{-2}
Molybdenum	1.3	0.14
Silver	0.001	1.1×10^{-4}
Cadmium	0.06	6.6×10^{-3}
Tin	0.5	5.5×10^{-2}
Barium	1.0	0.11
Europium	0.005	5.5×10^{-4}

Inventories in GT-MHR spent fuel elements at discharge for the dominant radionuclides are given in Table 7-7 (Richards 2002). For comparison, inventories for spent fuel discharged from a typical pressurized water reactor (PWR) are also given. The PWR inventories were obtained from (Benedict 1981); they are for fuel irradiated to a burnup of 33,000 MW_t-d per metric ton of heavy metal (MTHM) and residence time of 876 EFPD.

Table 7-7. GT-MHR Discharge Inventories for Key Radionuclides

Nuclide	Half-Life (y)	Specific Activity (Ci/g)	GT-MHR Ci per Fuel Element	Ci per Mw_e-yr GT-MHR	Ci per Mw_e-yr PWR
Am-241[41]	432.7	3.44	1597	2508	3518
Am-243	7370	0.20	0.145	0.23	0.60
C-14	5730	4.46	0.128 (100 ppm N)	0.20	8.34×10^{-3}
			0.043 (30 ppm N)	0.068	
Cs-137	30.2	86.5	1257	1973	3675
I-129	1.57×10^{7}	1.73×10^{-4}	3.32×10^{-4}	5.21×10^{-4}	1.26×10^{-3}
Np-237	2.14×10^{6}	7.05×10^{-4}	4.13×10^{-3}	6.48×10^{-3}	0.018
Pu-238	87.7	17.1	29.5	46.3	126
Pu-239	2.41×10^{4}	6.21×10^{-2}	2.15	3.38	11.0
Pu-240	6560	0.227	4.49	7.05	16.3
Pu-242	3.75×10^{5}	3.93×10^{-3}	0.035	0.055	0.047
Sr-90	29.1	137	1042	1636	2638
Tc-99	2.13×10^{5}	1.70×10^{-2}	0.17	0.27	0.49
U-235	7.04×10^{8}	2.16×10^{-6}	4.64×10^{-4}	7.28×10^{-4}	5.76×10^{-4}
U-236	2.34×10^{7}	6.47×10^{-5}	5.22×10^{-3}	8.20×10^{-3}	9.03×10^{-3}
U-238	4.47×10^{9}	3.36×10^{-7}	1.18×10^{-3}	1.86×10^{-3}	0.011

With the exception of C-14, Pu-242, and U-235, the GT-MHR inventories in Table 7-7 are significantly lower than the PWR inventories, when normalized with respect to the electrical energy generated by the spent fuel. The differences in discharge inventories arise from a number of factors:

1. The thermal efficiency of the GT-MHR is significantly higher than that of the PWR (47.5% vs. 32%).
2. There are significant differences in the fuel cycle. Because the PWR uses much lower enriched fuel, it requires 33.6 MTHM/Gw_e-yr, whereas the GT-MHR requires only 6.95

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[41] The discharge inventory for Am-241 includes the inventory of its parent nuclide, 14.4-yr Pu-241, since nearly all of the Pu-241 will decay to Am-241 within 100 years after emplacement of spent fuel into the repository.

MTHM/Gw_e-yr. The higher enriched fuel for the GT-MHR results in higher discharged quantities of U-235.

3. Because of its higher enrichment, high-burnup fuel cycle and higher thermal efficiency, the commercial GT-MHR produces much less plutonium than the PWR. Using the values in Table 7-7 and neglecting 14.4-yr Pu-241, the PWR produces about 2.5 times the plutonium produced by the GT-MHR (268 kg Pu/Gw_e-yr vs. 102 kg Pu/Gw_e-yr). The Pu in PWR spent fuel is also of higher quality than that in GT-MHR spent fuel (66% Pu-239 vs. 53% Pu-239).[42] The high burnup of GT-MHR spent fuel shifts the plutonium isotopics to higher mass numbers, which is why the Pu-242 inventory in GT-MHR spent fuel is slightly higher than that in PWR spent fuel.

There are also differences in the effective fission yields. Compared with the PWR, the GT-MHR neutron energy spectrum is less thermalized and, because of its lower plutonium inventory, the percentage of fissions occurring in plutonium isotopes is significantly lower for the GT-MHR

7.1.1.2 Radioactive Waste

No waste assessment beyond the above spent fuel assessment was performed for the commercial GT-MHR. The PC-MHR waste assessment was for a reactor complex consisting of four 600 MW(t) reactor modules and a Fuel Fabrication Facility (FFF) for plutonium fuel.[43,44] Each waste stream was classified as radioactive, hazardous, mixed, or non-radioactive, and as solid, liquid, or gas. These classifications are consistent with the waste definitions in DOE Order 5820.2A, as shown in Table 7-8. The significance of the waste stream is determined by its estimated volume or weight, frequency of generation, and activity. Some oil/grease wastes were classified as "mixed waste" because the EPA may classify oil as hazardous, and it may contain some radionuclides.

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[42] The proliferation resistance of GT-MHR spent fuel is discussed in detail in (Richards 2002).

[43] The reactor plant and fuel fabrication facility were assumed to be co-located on the same secure government site in the interest of safeguarding the weapons-grade Pu feedstock.

[44] The results for the Fuel Fabrication Facility are included here for completeness. Presumably, the fuel fabrication facility for the NGNP and commercial H2-MHRs will be located remotely from the reactor. plants. In addition, since these fuel plants will be processing LEU rather than WPu, their waste streams will be somewhat different and less toxic.

Table 7-8. Radioactive Waste Definitions based on DOE Order 5820.2A

Classification	Description
High-Level Waste (HLW)	The highly radioactive waste material that results from the reprocessing of spent nuclear fuel, including liquid waste produced directly in reprocessing and any solid waste derived from the liquid that contains a combination of transuranic waste and fission products requiring permanent isolation.
Spent Nuclear Fuel (SNF)	Fuel that has been withdrawn from a nuclear reactor following irradiation, but that has not been reprocessed to remove its constituent elements.
Transuranic Waste (TRU)	Without regard to form, waste that is contaminated with alpha-emitting transuranic radionuclides with half-lives greater than 20 years and concentrations greater than 100 nCi/g at the time of assay.
Low-Level Waste (LLW)	Waste that contains radioactivity and is not classified as HLW, SNF, TRU, or 1Ie(2) by-product material as defined by DOE Order 5820.2A.
Mixed Waste (MW)	Waste containing both radioactive and hazardous components as defined by the Atomic Energy Act and the Resource Conservation and Recovery Act, respectively.

The PC-MHR primarily produces the following radioactive wastes: (1) Fuel Fabrication Facility (FFF) wastes consisting of mostly low level waste (LLW) and some potential transuranic (TRU) wastes from the fuel fabrication process; (2) LLW generated by normal reactor operations and maintenance that is routed to the Radioactive Waste Management Building (RWMB), which is designed to service four reactor modules; and (3) spent fuel elements, which are stored temporarily on-site in Spent Fuel Storage and later shipped off-site as whole elements for permanent disposal.

The various systems in the RWMB treat solid, liquid, and gaseous radioactive wastes. Solid wastes are classified by activity and hazard and then packaged appropriately. High-level wastes (HLW) or spent nuclear fuel (SNF) must go to a HLW geologic repository, while LLW may be disposed of near the surface in a LLW repository. TRU waste must go to the Waste Isolation Pilot Plant (WIPP). Radioactive liquid wastes must be solidified before disposition. Radioactive gaseous waste contains non-condensable kryptons and xenons and must be filtered before release to the atmosphere. Gaseous effluents will pass through charcoal beds that hold up the short-lived species, releasing only small amounts of krypton-85.

The FFF waste management system operates independently from the RWMB. Fuel fabrication processes include scrap recovery steps to minimize plutonium losses. The conceptual design activities will include a waste minimization study that evaluates the recycling of coating gases and solvents.

The principal radioactive waste streams for the PC-MHR complex are defined in Figure 7-2 and summarized in Table 7-9. These waste streams were selected based upon their quantity and/or activity content (Curies). The waste streams represent fuel fabrication, reactor operation and maintenance, and spent fuel disposition. The reactor waste streams are elaborated below

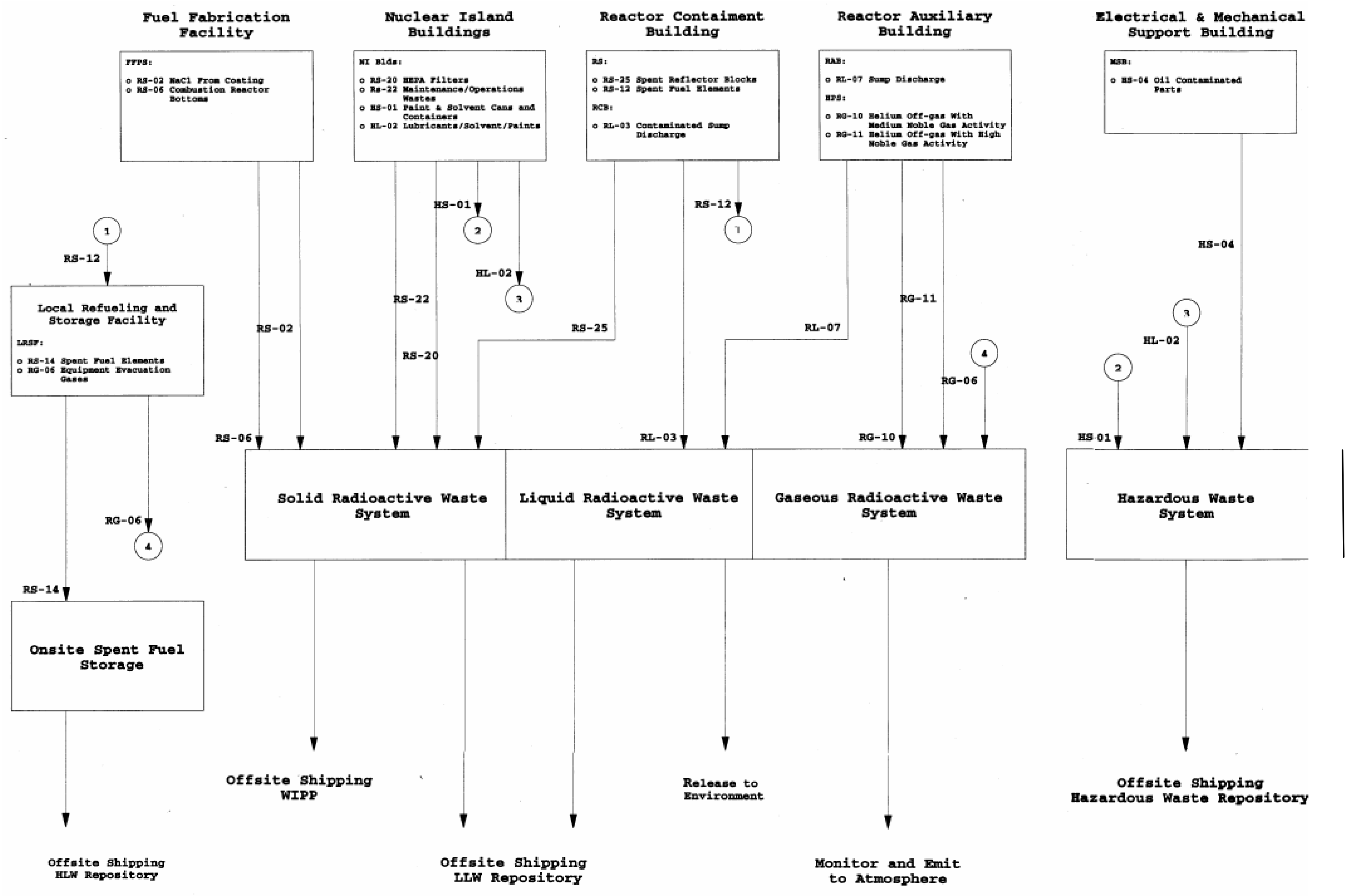

Figure 7-2. Waste Stream Flow Diagram

Table 7-9. Principal Radioactive Waste Streams

Waste Stream	Description	Form	Volume (per year)	Class	Disposition
Fuel Fabrication					
RS-04	SiC Hulls	Solid	0. 18 m^3	LLW	LLW Repository
RS-07	Process HEPA Filters	Solid	0.004 m^3	LLW	LLW Repository
RS-01	Purification Residues	Solid	0.68 m^3	TRU	TRU Repository
RS-02	NaCl from Coating	Solid	9.2 m^3	LLW	LLW Repository
RS-06	combustion reactor bottoms	Solid	1.0 m^3	TRU	TRU Repository
Reactor Operation/Maintenance					
RG-10	CO_2 Regeneration	Gas	8,000 scm		Controlled Emission
RG-11	LTA Regeneration	Gas	2,300 scm		Controlled Emission
RG-06	Equipment Evacuation Gases	Gas	3,000 scm		Controlled Emission
RS-20	Building HEPA Filters	Solid	17.0 m^3	LLW	LLW Repository
RS-22	Oper/Maintenance Wastes	Solid	14.2 m^3	LLW	LLW Repository
RS-19	Spent HPS Filters	Solid	0.4 m^3/5yrs	LLW	LLW Repository
RS-25	Spent Reflector Blocks	Solid	60.0 m^3	LLW	LLW Repository
RS-28	Turbomachine Maintenance /Replacement	Solid	5.6 m^3/7yrs	LLW	LLW Repository
Spent Fuel Disposition					
RS-12	spent fuel elements	Solid	128 M^3	SNF	HLW Repository

The following estimates for the levels of radioactive waste for the PC-MHR are expected to be an order of magnitude higher than those anticipated for the commercial GT-MHR because very conservative design criteria were adopted for the PC-MHR to account for the large uncertainties in the performance of high-burnup, TRISO-coated Pu fuel compared to the performance of LEU fuel. Consequently, the design margins for the PC-MHR were chosen to be a factor of 10 greater than those for other MHR designs, including the NP-MHTGR and the commercial GT-MHR (PC-MHR 1994). By inference, the levels of radioactive waste for the NGNP and commercial H2-MHR are also expected to an order of magnitude lower.

7.1.1.2.1 Radioactive Gases

A small fraction of the fission products are released from the core during reactor operation. Condensable fission products that escape from fuel particles deposit ("plate out") on the graphite reflector elements and other helium-wetted surfaces in the primary circuit. Calculations have been performed to determine the circulating and plateout activity in the PC-MHR, and the results were used to quantify the reactor operation radioactive gaseous waste streams.

The fission gases are collected in the Helium Purification System by CO_2 absorbers located immediately upstream of the Low Temperature Absorbers (LTAs). Regeneration of the CO_2 absorbers results in large quantities of helium and carbon dioxide that are slightly contaminated with trace amounts of krypton and xenon (RG-1O).[45] The estimated quantity of off-gas for 4 modules is about 8,000 scm/yr, which is directed to the Gaseous Radwaste System.

The LTAs in the HPS condense krypton and xenon radionuclides from the helium coolant. An LTA will be regenerated after three months on line, before its sorptive capacity is reached. Regeneration liberates a large volume of helium and nitrogen with high activity gaseous fission products (RG-11). Most of the radioisotope levels in the LTA reach steady state, but the longer-lived krypton-85 builds up with time. Table 7-10 shows the inventory after three months of operation. The table also shows the reduction of activity from decay. For example, the activity in the LTA drops by half if it is allowed to decay for several days before release. With proper delay in the gaseous radioactive waste management system, only a small amount of krypton-85 gas will be released to the atmosphere (or bottled for long-term storage). The estimated quantity of off-gas from LTA regeneration is about 2,300 scm/yr.

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[45] Waste stream identifier defined in Figure 7-2.

Table 7-10. Activities in LTA after 3 Months Operation[46]

Radionuclide	Activity (Ci) after N Days Decay			
	N = 0	1	3	60
Kr-85	28	28	28	27
Kr-85m	114	3	0	0
Kr-87	*55*	0	0	0
Kr-88	167	0	0	0
Kr-89	1	0	0	0
Xe-131m	67	63	*56*	2
Xe-133m	106	77	42	0
Xe-133	4640	4070	3132	2
Xe-135m	0.17	0	0	0
Xe-135	823	134	4	0
Total	6019	4376	3261	31

Other principal gaseous waste streams consist of purge/evacuation gases from refueling equipment operations (RG-06). These gases consist of helium slightly contaminated with fission gases. The estimated quantity of equipment purge gases is 3,000 scm/yr. Radioactive gases are collected and piped to the Gaseous Radwaste System, where they are held up in charcoal delay beds and released as controlled and monitored emissions to the atmosphere.

7.1.1.2.2 Radioactive Liquids

With the design change to the gas turbine-based plant (versus the earlier steam-cycle designs, including the NP-MHTGR), the expected quantity of liquids contaminated with radioisotopes was drastically curtailed. Steam-cycle plants contained numerous liquid waste streams composed of leakage from the steam/water systems which either have radioisotopes entrained directly from the leakage out of the primary system (generally referred to as "high" purity wastes), or radioisotopes coming from pickup of surface contamination after the liquid has collected in a nuclear island building sump (generally referred to as "low" purity wastes). The gas turbine plant has less potential for leakage because of the absence of a steam generator. However,

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[46] These radionuclide inventories for the PC-MHR are an order of magnitude higher than the design inventories for the commercial GT-MHR.

some aqueous radwaste will be generated from leakage of water systems for the PCS heat exchangers, although only at fractions of that for the steam cycle design. Also, unlike the steam cycle plant, helium can leak into the waterside during most normal operating conditions. Virtually all of this aqueous waste can be cleaned up through the ion exchange system and reused in the plant. Hence, there is minimal radioactive liquid effluent stream from the plant.

7.1.1.2.3 Radioactive Solids

Principal waste streams in the form of solids (other than spent fuel) mainly consist of spent resins, high temperature absorber (HTA) filters from the HPS, replaceable reflectors, spent HEPA filters, and maintenance wastes, including turbomachinery replacement parts and hotel wastes. Contaminated spent resins come primarily from the Liquid Radwaste System, which uses ion exchange resins to cleanup radioactive liquids. These resins are slurried over to the Solid Radwaste System where they are "fixed" in 55 gal drums in the solidification plant and disposed of off-site in a LLW repository. The waste quantity from this source has not been estimated, but it is expected to be very low compared to other nuclear facilities since the volume of water leaks is much lower.

The HTA filter in the HPS removes condensable fission products from the helium stream before it gets to the CO_2 absorber or the LTA (RS-19). These filters would be sized for replacement from once every five years to possibly once in the life of the plant. Their Curie content is on the order of thousands of curies when initially removed from the system, decaying down to hundreds of Curies after one year. The estimated volume (based on the five year filter life design) is 0.4 m^3. These filters would be handled by the Solid Radwaste system and disposed of as LLW in a burial site.

Reflector blocks (RS-25) immediately adjacent to fuel elements are designed to be replaced every 6th refueling outage (the replacement is staggered with approximately one-sixth of the reflector blocks replaced during each refueling outage). All other reflector blocks are designed to remain in the core for the plant life. The reflector elements are disposed of as LLW, as was done for Fort St. Vrain (FSV), in 30 gal drums after being immobilized via the solidification system or by some other means. The estimated quantity for this stream is 166 reflectors per refueling per module including half blocks, resulting in ~60 m^3/yr of discarded reflector blocks for a four module plant.

Spent HEPA filters (RS-20) come from the HVAC systems of the various nuclear island buildings, but principally from the Reactor Containment and Reactor Service Building systems. These filters are compacted and then fixed by the solidification system and shipped as LLW drums for off-site disposal in a repository. The quantity of filters has been estimated as ~200 m^3/yr. The average volume reduction from compaction is estimated, based on experience in the decommissioning of the GA fuel fabrication facility in San Diego, as 12:1. Hence, the volume to be drummed is ~17 m^3/yr.

Routine maintenance operations (RS-22) will generate LLW wastes consisting of "hotel" wastes (e.g., anti-C clothing, gloves, booties, etc.), and seals, 0-rings, miscellaneous small parts, etc. These items will be sorted as combustible or noncombustible, compactable or non-compactable, and packaged accordingly for off-site disposal as LLW. The estimated volume of maintenance waste is based upon the commercial GT-MHR design requirement of 14.2 m^3/yr for a four-module plant. This value, which is founded on current PWR experience, is considered conservatively high since maintenance and leakage from steam cycle systems represent a larger contribution to the contamination of the plant. A conservative calculation of PC-MHR "hotel" wastes gave a nominal annual waste production of less than 11 m^3. The operation of Fort St. Vrain also supports these figures. During the period from 1979 through 1991 the average total solid waste volume from the FSV site was 26.5 m^3/yr including both HEPA filters and discarded reflector blocks (FSV was a 842 MW(t) HTGR that operated at ≤70% power for most of its lifetime).

Other maintenance wastes include replaceable parts from the turbomachine consisting mainly of discarded rotor blades and seals (RS-26). It is assumed that the turbomachine will be pulled out of the PCS vessel for maintenance every 7 years. The turbine rotor blades and stator vanes, which are assumed to be highly radioactive from fission product contamination (e.g., Cs-134/-137 and Ag-110m), will be dismantled remotely and disposed of as LLW to the Solid Radwaste System. Similarly, all sliding seals and instrumentation will be replaced during turbocompressor maintenance. The estimated total volume is ~5.6 m^3 per maintenance for four turbocompressors.

Summing the above sources of solid waste yields (0.4/5 + 17 + 11 + 5.6/7) = ~29 m^3/yr. The specific activities of the solid waste from the NGNP and H2-MHR should be an order of magnitude lower than for the PC-MHR, but the volumes should be similar.

7.1.1.3 Waste Heat

The plant design will be optimized to use the nuclear process heat to the fullest extent that is economical; however, given fundamental thermodynamic limitations, some fraction of the nuclear heat will be non-useful. This residual waste heat will be rejected to the environment. For the SI-Based H2-MHR plant, waste heat is rejected primarily from Section 1 of the Hydrogen Production System (sulfuric acid decomposition). For a 600 MW(t) plant, the total heat rejection rate is 336 MW(t) (Richards 2006a). For the HTE-based plant, 246 MW(t) of waste heat is rejected from the precooler and intercooler modules of the PCS (Richards 2006b). For both plants, it is expected that dry cooling towers will be used to reject heat to the atmosphere (although wet cooling could also be used if a particular site favored it). This system is sized to provide a margin of 15% above the expected maximum heat duty.

7.1.2 H_2 Production Plant – SI Process

The SI-based hydrogen plant, which is described in Section 2.3.2, is designed to minimize the generation of chemical waste streams and to maximize the utilization of the high-temperature heat delivered by the reactor via the IHX. Nevertheless, the SI process employs a number of high-temperature, high-pressure unit operations, many of which also contain process streams with high concentrations of hydrogen which is not easily contained quantitatively; consequently, the potential for generating gaseous and liquid waste streams is not trivial.

The design of the SI plant is in the pre-conceptual design stage. Potential waste streams have been identified for the various unit operations, but they have not, in general, been quantified at this writing. The available information is summarized below.

7.1.2.1 Chemical Waste

The SI hydrogen plant will be designed to minimize releases of chemicals to the environment. During routine operation there are no designed liquid wastes from the hydrogen plant proper and only minimal losses as vapors. Phosphoric acid has a very low vapor pressure, even at elevated temperatures, and the acid concentration step is not expected to produce a waste stream requiring treatment. A small amount of sulfur dioxide may be lost, but it is likely to be well within EPA guidelines.

The oxygen product stream may contain trace quantities of sulfur dioxide. For the NGNP demonstration plant, the oxygen may be vented to the atmosphere. Any resulting sulfur dioxide emissions will likely be well within legal limits. If not, the sulfur dioxide can be scrubbed from the oxygen using a caustic scrubber containing a dilute solution of sodium hydroxide. This operation would generate a small aqueous sodium sulfate waste stream, which would be solidified and disposed as solid waste.

Small amounts of liquid wastes may be produced during maintenance activities but every effort will be made to recover and recycle the process chemicals. The only routine chemical wastes expected are those produced during process water purification and cooling water blowdown. These wastes have not been quantified. If aqueous waste streams do not meet local discharge limits, they will be treated as required, solidified and disposed of as solid hazardous waste.

Extensive testing has been done on the engineering materials expected to be used in the hydrogen plant to minimize corrosion; however, it is expected that some corrosion will occur over the lifetime of the plant. Corrosion products (chiefly sulfates of the metals used) will re-circulate with the process streams and are expected to collect in the sulfuric acid boiler section of the plant. It is not expected that corrosion products will appear in waste streams. One component of periodic plant maintenance will be to examine the boiler surfaces for evidence of these corrosion products and to clean the surfaces as necessary. Any hazardous waste produced by structural materials corrosion will be treated as required, packaged, and disposed of as solid waste in accordance with applicable state and federal regulations.

7.1.2.2 Waste Heat

As indicated in Section 7.1.1.3, with the SI process, waste heat is rejected primarily from Section 1 of the Hydrogen Production System (sulfuric acid decomposition).

7.1.3 H_2 Production Plant – HTE Process

As described in Section 2.3.3, a pre-conceptual design for an HTE-based demonstration plant for the NGNP has been proposed by Toshiba (Hoashi 2006). This demonstration plant would produce hydrogen at a rate of 6000 Nm^3/hr. The design uses the tubular SOE cells being developed by Toshiba (see Tables 7.11 and 7.12); the composition of the Toshiba electrodes are different from that assumed in the NERI study.

Table 7-11. Composition of Toshiba SOEC Components

Component	Composition
Tubular substrate	NiO-8YSZ*
Hydrogen electrode	NiO-8YSZ*
Electrolyte	8YSZ*
Middle layer	SDC**
Oxygen electrode	LSC***
Hydrogen electrode current feeder	Ag
Oxygen electrode current feeder	Ag punting metal

* 8YSZ: 8 mol % yttria doped zirconia
** SDC: samaria doped ceria
***LSC: lanthanum strontium cobaltite

Table 7-12. Dimensions of Toshiba SOEC Components

Component	Dimensions
Tubular substrate	1.5mm
Hydrogen electrode	20 μm
Electrolyte	20 μm
Middle layer	10 μm
Oxygen electrode	20 μm
Hydrogen electrode current feeder	20 μm
Oxygen electrode current feeder	~36 μm

7.1.3.1 Chemical Waste

As introduced in Section 5.2, very little chemical waste is expected to be produced during plant operation (beyond some hotel wastes). However, the SOE cells will need to be replaced after reaching their effective lifetime (5-10 years). Toshiba has estimated the masses of spent SOEC that would have to be disposed of every five years (see Table 7.13)

Table 7-13. Quantity of Spent HTE SOE Cells

Component	Quantity (Every 5 Years) - Kg
Tubular substrate	12,755
Hydrogen electrode	1,275
Electrolyte	1,275
Middle layer	638
Oxygen electrode	1,275
Hydrogen electrode current feeder	25
Oxygen electrode current feeder	906
Total Mass	18,149

Certain of the SOEC materials, including the LSC anodes, are classified as hazardous materials;[47] therefore, rather large quantities of spent SOEC would need be disposed in hazardous waste landfills licensing by the federal government. The future availability of hazardous waste landfill is uncertain, and the disposal costs are significant and increasing. The practicality of recovery and recycle of these materials will need to be investigated.

7.1.3.2 Waste Heat

For the HTE-based H2-MHR plant, 246 MW(t) of waste heat from the reactor plant is rejected from the precooler and intercooler modules of the PCS (Richards 2006b). Low-grade waste heat from the HTE plant will be rejected to the atmosphere via dry cooling towers.

7.2 Waste Management

As described above, the NGNP and a commercial H2-MHR will inevitably generate certain waste streams that will have to be managed. Waste minimization is a fundamental component of waste management that must be addressed during conceptual and preliminary design. The topic will likely receive considerable attention during the licensing process.

It is anticipated that a comprehensive waste minimization program in accordance with DOE Order 5400.1, General Environmental Protection Program, and the Resource Conservation and Recovery Act, will be required for the NGNP as it was for the NP-MHTGR and for other DOE projects.[48]

As described for the PC-MHR program (Olsen 1995), the objective of a waste minimization program is to design, construct, operate, decontaminate, and decommission the facilities with the fundamental goals of:

Minimizing waste generation through source elimination, reduction, and recycling, and
Reducing pollutant discharges to levels that are as low as reasonably achievable (ALARA).
The scope of the waste minimization program for the PC-MHR was to include all solid, liquid, and gaseous wastes generated in the Reactor Complex and Fuel Fabrication Facility including radioactive wastes, hazardous wastes, mixed wastes (radioactive and hazardous), and non-hazardous wastes.

Waste minimization constitutes elimination or minimization of wastes expected to be generated by identifying source reduction activities to minimize or eliminate the source and recovery and

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[47] Per Material Safety Data Sheets (MSDS, http://raider.muc.edu/~habeckjc/msdsmain.htm)

[48] DOE Order 5400.1 is not cited explicitly in the SRM but numerous requirements therein mandate waste minimization.

recycle activities to use or reuse a material from waste stream. Source reduction is the preferred approach, followed by recycling. Source reduction can be particularly effective when addressed during facility design, especially when it is done early in the design process when system and component requirements are being defined.

While a commercial H2-MHR would, in principle, not be designed to explicitly meet DOE orders, there are numerous analogous EPA regulations and federal laws, including the Resource Conservation and Recovery Act (RCRA) that mandate waste minimization programs. Consequently, the discussion below should apply equally well to the commercial plant.

7.2.1 Reactor Plant

As for all nuclear power plants, the most important waste management issue for the MHR nuclear heat source will be the disposition of spent nuclear fuel. The amount of spent fuel generated per unit electrical output or mass of hydrogen generated will be minimized by maximizing the fuel burnup (SRM, PLT 3.1.8); nevertheless, very substantial quantities of spent nuclear fuel will be generated during the plant operational lifetime. In contrast, the reactor designer has much greater opportunity to optimize the reactor plant design to minimize the generation of radioactive waste streams; once regulatory compliance is assured, the management of radioactive streams ultimately becomes a benefit/cost issue.[49] These two topics are elaborated below and should apply to both the NGNP and commercial H2-MHR.

7.2.1.1 Spent Fuel Disposition

The characteristics of the spent fuel from the commercial GT-MHR were summarized in Section 7.1.1.1. As discussed previously, the spent fuel from the NGNP and a commercial H2-MHR should be quite similar (with the possible exception of the initial NGNP core which may use TRISO-coated LEU UO_2 particles with a lower enrichment and irradiated to a lower burn up and fast fluence). The spent fuel management strategy adopted for the PC-MHR and the commercial GT-MHR is as follows. Spent fuel is removed from the core and first placed for interim storage in the Local Refueling and Storage Facility (LRSF). The fuel is loaded into inert dry wells, which are submersed in water pools for decay heat removal. After a one-year cooling period, the spent fuel is loaded into multipurpose canisters (MPC) which are then placed in concrete dry storage casks on pads in the on-site, spent fuel storage facility and stored there for approximately nine more years. Each storage cask holds one MPC, which contains 42 fuel elements. The unprocessed, whole fuel elements contained within the MPC are then shipped to a “Yucca Mountain-like” geological repository for permanent disposal.

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[49] This design philosophy is codified in the “As Low As Reasonably Achievable (ALARA)” provisions of 10CFR20.1[c].

The performance of unprocessed, spent MHR fuel elements in a geological repository has been evaluated (Richards 2002). This evaluation of commercial GT-MHR spent fuel disposal was based in large measure on a previous evaluation of disposal of spent fuel from a weapons Pu-fueled PC-MHR (Richards 1994). Based upon the PC-MHR evaluation in FY93 through FY95 and on an earlier assessment of commercial HTGR spent fuel disposal options by ORNL, it was concluded that the preferred option for HTGR spent fuel is the direct disposal of unprocessed spent fuel elements in a geologic repository. In fact, unprocessed HTGR spent fuel elements are a nearly ideal waste form for permanent geologic disposal; the ceramic coated-particle fuel, encapsulated in nuclear graphite blocks, represents a far smaller proliferation risk and a far more robust radionuclide containment system than Zircaloy clad, commercial LWR spent fuel.

The commercial GT-MHR spent fuel disposal evaluation (Richards 2002) resulted in the following conclusions and recommendations, which closely parallel the earlier ones for the PC-MHR (Richards 1994):

1. The TRISO coatings provide a barrier that is highly resistant to groundwater attack. Based on the available data, the fuel particles should remain intact over geologic time scales, even if the repository were to become permanently flooded with groundwater.

2. The nuclear-grade graphite blocks provide a structural container for the spent fuel that is also highly resistant to groundwater attack. Because of their very low impurity content, the graphite blocks with the fuel compacts removed would be classified as Class C, low-level waste. Leaching of the activation-product inventory from the graphite, including C-14, poses essentially zero near-term or long-term radiological risk.

3. Because of the GT-MHR's high-burnup fuel cycle and high thermal efficiency, GT-MHR spent fuel contains significantly lower inventories of fission products and transuranic actinides than commercial LWR spent fuel on a per unit electrical energy basis. These lower inventories translate to a lower Ingestion Hazard Index (IHI) and a lower decay-heat load for GT-MHR spent fuel (see Figure 7-3).

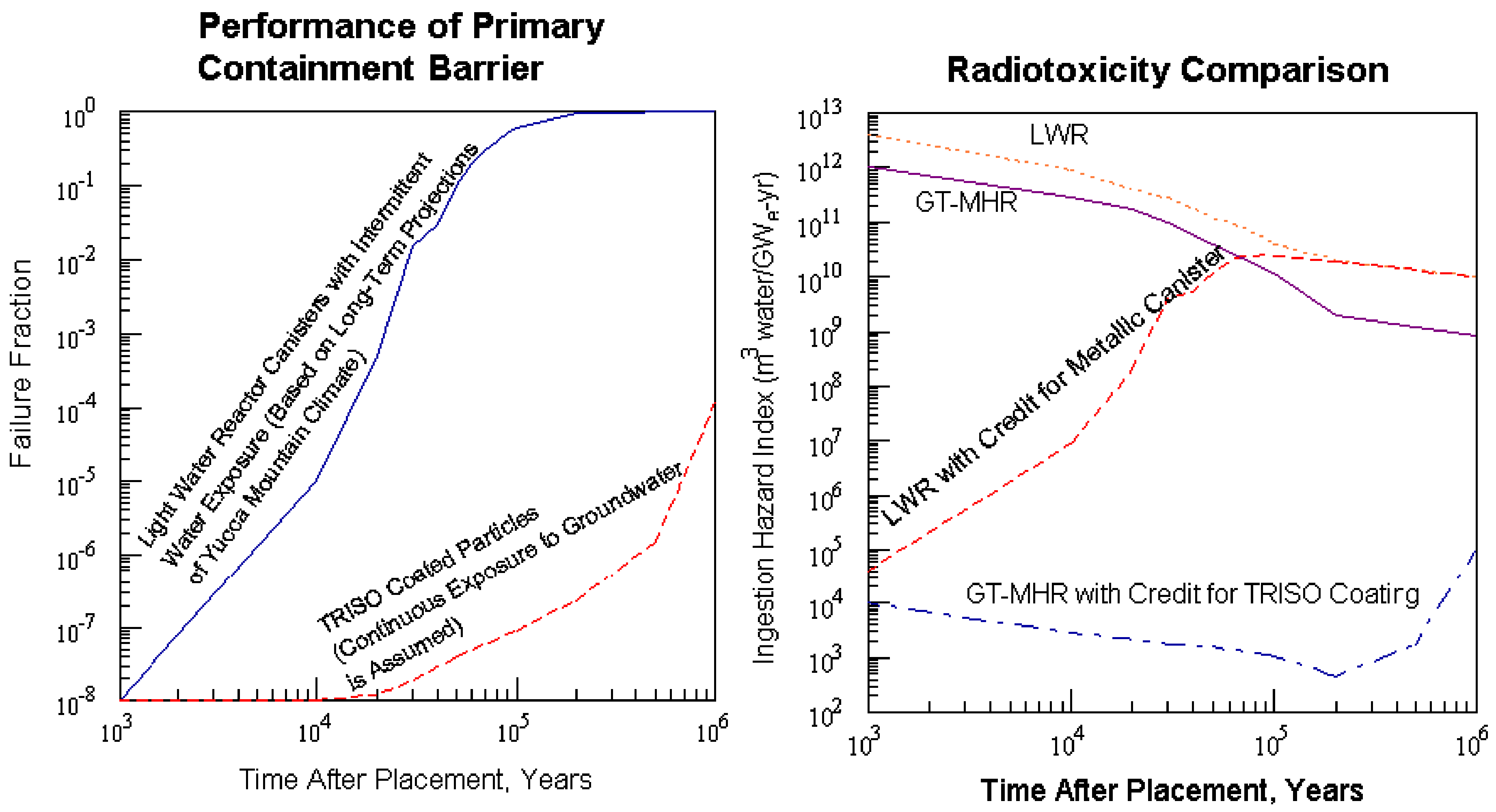

Figure 7-3. Comparison of GT MHR and LWR Spent Fuel Performance

4. GT-MHR spent fuel is highly resistant to proliferation and its characteristics are less favorable for recycle than commercial LWR spent nuclear fuel (CSNF). A GT-MHR MPC would contain only 2.7 kg of plutonium, which is a factor of 30 less than that for a typical PWR canister. Also, the plutonium isotopics in GT-MHR spent fuel are more degraded than those in CSNF.

5. Because of the low power density and low fissile material content of GT-MHR spent fuel, its MPC design is relatively straightforward and inexpensive. Also, because of the robustness and high corrosion resistance of the spent fuel itself, there is very little reliance on the GT-MHR MPC for long-term radionuclide containment. In contrast, the CSNF waste packages require the addition of neutron poison for criticality control and must include jackets of Alloy 22 and titanium drip shields to provide defense in depth from groundwater corrosion.

6. The repository-loading strategy for GT-MHR MPCs is also relatively simple and straightforward. Up to 77 GT-MHR MPCs can be loaded per repository acre, and the MPCs can be surrounded with a low-permeability, highly retarding overpack without compromising thermal design limits. In contrast, only 6 to 7 typical PWR waste packages could be loaded per repository acre, and even this sparse loading requires the drift tunnels to be actively cooled for 50 years after emplacement. Because of this active-cooling requirement, CSNF waste packages cannot be surrounded by an overpack, and an expensive titanium shield is required to provide additional resistance to corrosion and protection from rock fall.

In the process of performing the above assessments of coated-particle fuel performance and radionuclide transport in a repository environment, it became apparent that certain additional experimental data, primarily related to the long-term stability of coated-particle fuel, would serve to increase the confidence in the predictions; consequently, a confirmatory test and analysis plan defining experimental programs to generate such data was prepared (Hanson 2002a).

7.2.1.2 Radioactive Waste

7.2.1.2.1 Radionuclide Control Philosophy

The most effective means of minimizing radioactive waste streams from a nuclear power plant is source reduction. The dominant source of radionuclides in an MHR is the fission product inventory in the reactor core. For modular HTGR designs, a hallmark philosophy has been adopted since the early 1980s to design the plant such that the radionuclides would be retained in the core during normal operation and postulated accidents (e.g., PSID 1992). The key to achieving this safety goal is the reliance on TRISO-coated fuel particles for primary fission product containment at their source, along with passive cooling to assure that the integrity of the coated particles is maintained even if the normal cooling systems were permanently disrupted.

In response to that goal, a radionuclide containment system for an MHR, which reflects a defense-in-depth philosophy, has been designed to limit radionuclide release from the core to the environment to insignificant levels during normal operation and a spectrum of postulated accidents. Nevertheless, a small fraction of TRISO fuel particles have as-manufactured defects or fail in-service (e.g., PSID 1992), resulting in fission product release from the core and attendant contamination of the primary coolant circuit. A fundamental design requirement is to establish allowable limits on allowable core releases during normal operation and postulated accidents.

7.2.1.2.2 Radionuclide Design Criteria

Standard GA design practice is to define a two-tier set of radionuclide design criteria, - referred to as "Maximum Expected" and "Design" criteria, - (or allowable core releases for normal operation and Anticipated Operational Occurrences); this practice has been followed since the design of the Peach Bottom 1 prototype U.S. HTGR up through the current commercial GT-MHR (e.g., Hanson 2002b). The "Design" criteria are derived from externally imposed requirements, such as the site-boundary dose limits, occupational exposure limits, etc.; in principle, any of these radionuclide control requirements could be the most constraining for a given reactor design. The off-site PAG dose limits proved to be the most constraining for the 350 MW(t) steam-cycle MHTGR, and they will probably be the most constraining for the commercial H2-MHR as well although occupational exposures are anticipated to take on added importance for a direct-cycle plant compared to a steam-cycle plant.

Once the "Design" criteria have been derived from the radionuclide control requirements, the corresponding "Maximum Expected," criteria are derived by dividing the "Design" criteria by an uncertainty factor, or design margin, to account for uncertainties in the design methods. This uncertainty factor is typically a factor of four for the release of fission gases from the core and a factor of 10 for the release of fission metals.[50] The fuel and core are to be designed such that there is at least a 50% probability that the fission product release will be less than the "Maximum Expected" criteria and at least a 95% probability that the release will be less than the "Design" criteria. This GA approach to implementing such radionuclide design criteria is illustrated in Figure 7-4. (No particular scale is implied in this figure; it is simply a conceptual illustration of the approach.)

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[50] For the PC-MHR, the design margins were increased by a factor of 10 to 40x and 100x to account for the large uncertainties in the performance of high-burnup Pu fuels; in retrospect, those margins were perhaps excessive as discussed in (PC-MHR 1994).

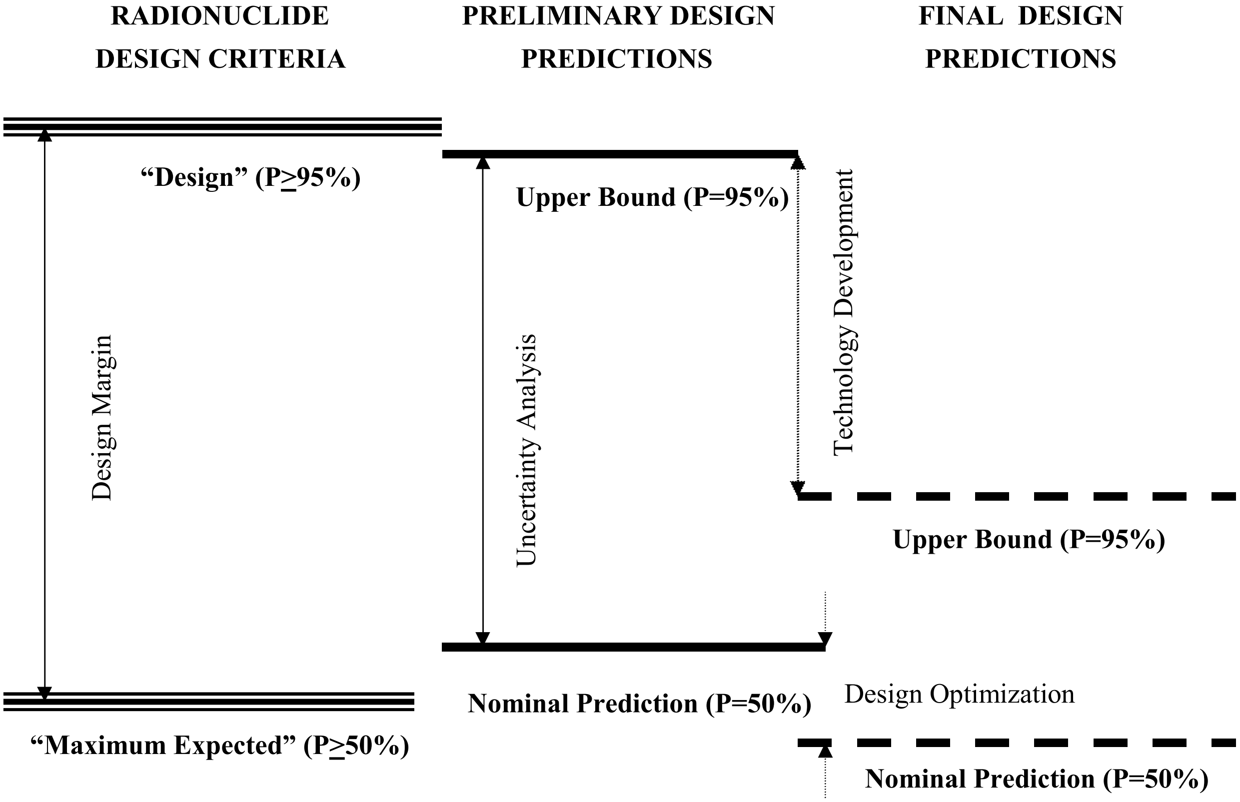

Figure 7-4. Radionuclide Design Criteria

In the example given in Figure 7-4, the Preliminary Design predictions (solid lines) slightly exceed the criteria (triple lines) at the 50% confidence level: i.e., the nominal (50% confidence) prediction is slightly higher than the "Maximum Expected" criterion, but 95% confidence prediction meets the "Design" criterion, primarily because a large design margin was chosen to accommodate the considerable uncertainties in the current design methods at the Preliminary Design stage. This example was chosen because it is anticipated to roughly reflect the current prediction of Ag-110m release from a GT-MHR core, based upon previous GA analysis of PC-MHR operating with a 850 °C core outlet temperature. Silver release is of concern because it can be diffusively released from intact TRISO particles at high temperatures and preferentially deposit on the turbine, where it is predicted to be a dominant contributor to O&M dose rates (it is only a minor contributor to off-site dose rates because of its low effectivity).

There are several candidate options for resolving this design issue. The first option is simply to relax the "Maximum Expected" criterion and to design the plant to accommodate the currently predicted levels of 250-day Ag release and the large uncertainties in the predictive methods; however, this option implies high O&M dose rates and the attendant requirements for fully remote turbine maintenance, etc. Another option is to develop and qualify efficient decontamination protocols to reduce the dose rates from the turbine prior to refurbishment to levels permitting hands-on maintenance. A third option (dashed lines) is to reduce the predicted Ag release and the uncertainties therein by a combination of design optimization (primarily to reduce the nominal prediction) and technology development (primarily to reduce the uncertainty in the prediction).

Since diffusive release from intact particles is the dominant source of Ag release, the most effective design changes to reduce Ag release are those that reduce the peak fuel temperatures in the core. Some reduction in peak temperatures can be achieved by improved fuel zoning to optimize the core power distribution for minimum Ag release, and further reductions are possible with various fuel shuffling schemes. Larger fuel temperature reductions require more dramatic changes in the fuel-block design and/or in-core operating conditions (e.g., power density); such changes have broad implications for the overall plant design and fuel cycle costs.

A comprehensive trade study would be required to identify the optimal combination of the above options to resolve the plateout issue. In any case, it might be prudent to design a first-of-a-kind, direct-cycle HTGR to permit fully remote turbomachine maintenance should the actual gamma dose rates prove to be higher than predicted. Furthermore, the option of having a spare turbomachine to permit extended delay times prior to turbomachine refurbishment should also be evaluated during conceptual design.[51]

7.2.2 H_2 Production Plant – SI Process

Waste minimization will be a high-priority goal for the design of the SI hydrogen plant. Water is the only feedstock, and hydrogen and oxygen are the only products produced in quantity. In principle, it should be possible to design the SI plant to be a nearly “zero-discharge” facility. A formal waste minimization plan for the SI plant should be prepared.

7.2.3 H_2 Production Plant – HTE Process

Waste minimization will also be a high-priority goal for the design of the HTE hydrogen plant. Water is the only feedstock, and hydrogen and oxygen are the only products produced in quantity. In principle, it should be possible to design the HTE plant to be a nearly “zero-discharge” facility during plant operation.

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[51] After five years, only 0.6% of 250-d Ag-110m would remain; however, 19% of 2.1-yr Cs-134 would remain, and 30-yr Cs-137 would be effectively unchanged. Nevertheless, there is reason to believe that the Cs isotopes can be efficiently removed by standard decontamination protocols (e.g., Hanson 2002b).

However, as discussed in Section 7.1.3.1, the SOE cells will need to be replaced after reaching their effective lifetime (5-10 years). Certain of the SOEC materials, including the LSC anodes, are classified as hazardous materials; therefore, rather large quantities of spent SOEC would need be disposed in hazardous waste landfills licensing by the federal government. Although beyond the scope of this study, the practicality of recovery and recycle of these materials will need to be investigated. A formal waste minimization plan for the HTE plant should be prepared.

8. TRITIUM CONTROL

Tritium (H-3) will be produced in an H2-MHR by various nuclear reactions. Given its high mobility, especially at high temperatures, some tritium will permeate through the IHX and the hydrogen plant process heat exchangers, contaminating the product hydrogen (e.g., Gainey 1976, Hanson 2006). This tritium contamination will contribute to public and occupational radiation exposures; consequently, stringent limits on tritium contamination in the product hydrogen are anticipated to be imposed by regulatory authorities. Design options are available to control tritium in an H2-MHR, but they can be expensive so an optimal combination of mitigating features must be implemented in the design.

8.1 Tritium Behavior in HTGRs

The following sources of tritium production have been identified, primarily from early surveillance programs at operating HTGRs (steam-cycle plants), and they can be reasonably quantified for a H2-MHR: (1) ternary fission (yield $\approx 10^{-3}$), (2) neutron activation of He-3 in the primary He coolant (He-3 abundance = 2×10^{-7}), (3) neutron activation of lithium impurities in fuel-compact matrix and core graphite, and (4) neutron capture reactions in boron control materials. Ternary fission will be the dominant source of tritium production, but much of this tritium will be retained in the TRISO-coated fuel particles. He-3 activation will generate a relatively modest fraction of the total tritium production in the reactor; however, since it is born in the primary coolant, it will likely be the dominant source of tritium in the primary helium and, hence, the dominant source of product contamination as well.

Tritium strongly chemisorbs on irradiated nuclear graphite at elevated temperatures. Consequently, a large fraction of the tritium entering the primary helium will be sorbed on the huge mass of graphite in the core. In operating HTGRs, including Fort St. Vrain, the core graphite was a far more important sink for tritium removal than the HPS. However, a large fraction of this stored tritium can be released if water is introduced into the primary coolant (a low-probability event for an H2-MHR with an IHX and/or direct-cycle gas turbine).

Tritium will permeate through the heat exchangers and process piping in an H2-MHR and will contaminate the product hydrogen. Surface films will play a critically important role in establishing the in-reactor, tritium permeation rates. Oxide films can reduce H-3 permeability by orders of magnitude. However, normal plant operating transients (e.g., startup/shutdown, etc.) may compromise film integrity and result in increased H 3 permeation rates.

Design methods are available to estimate H-3 production, distribution, and release, but they are rudimentary and characterized by large uncertainties (Hanson 2006). The current design methods appear adequate for conceptual design, but they will need to be upgraded for preliminary design and independently validated prior to completion of final design. Some technology development will be necessary to provide the basis for these design methods improvements and validation.

8.2 Product Contamination

Given the behavior of tritium summarized above, tritium will be produced in an H2-MHR and will migrate, to some degree, throughout the plant, including the hydrogen production plant. Consequently, the primary helium coolant and the process streams, including the hydrogen product stream, will likely contain measurable quantities of tritium. Since tritium is a radiological hazard, especially when ingested into the human body, this tritium contamination represents a potential dose contributor for both occupational and public exposure. Of particular significance for an H2-MHR is the tritium contamination of the product hydrogen, which may be consumed by the general public (e.g., in fuel-cell powered transportation vehicles).

The fundamental issue is not whether tritium will contaminate the product hydrogen because it almost certainly will, based on past operating experience with steam-cycle HTGRs. The fundamental issues are the allowable levels of tritium contamination in the product hydrogen and the design features that will need to be implemented to assure that these limits are met with the required design margin.

The tritium production rates and its transport behavior in the primary coolant circuit of an H2-MHR can be conservatively estimated with reasonable confidence, given the available design methods for predicting tritium transport and its observed behavior in operating steam-cycle HTGRs. The unique design challenge for the H2-MHR will be predicting the rates of H-3 transport into the hydrogen production plant and its migration behavior in the various process streams. The possible H-3 contamination pathways in the SI process are shown schematically in Figure 8-1 (Richards 2006a).[52]

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[52] A comparable evaluation of the tritium distribution in an HTE plant has not yet been reported.

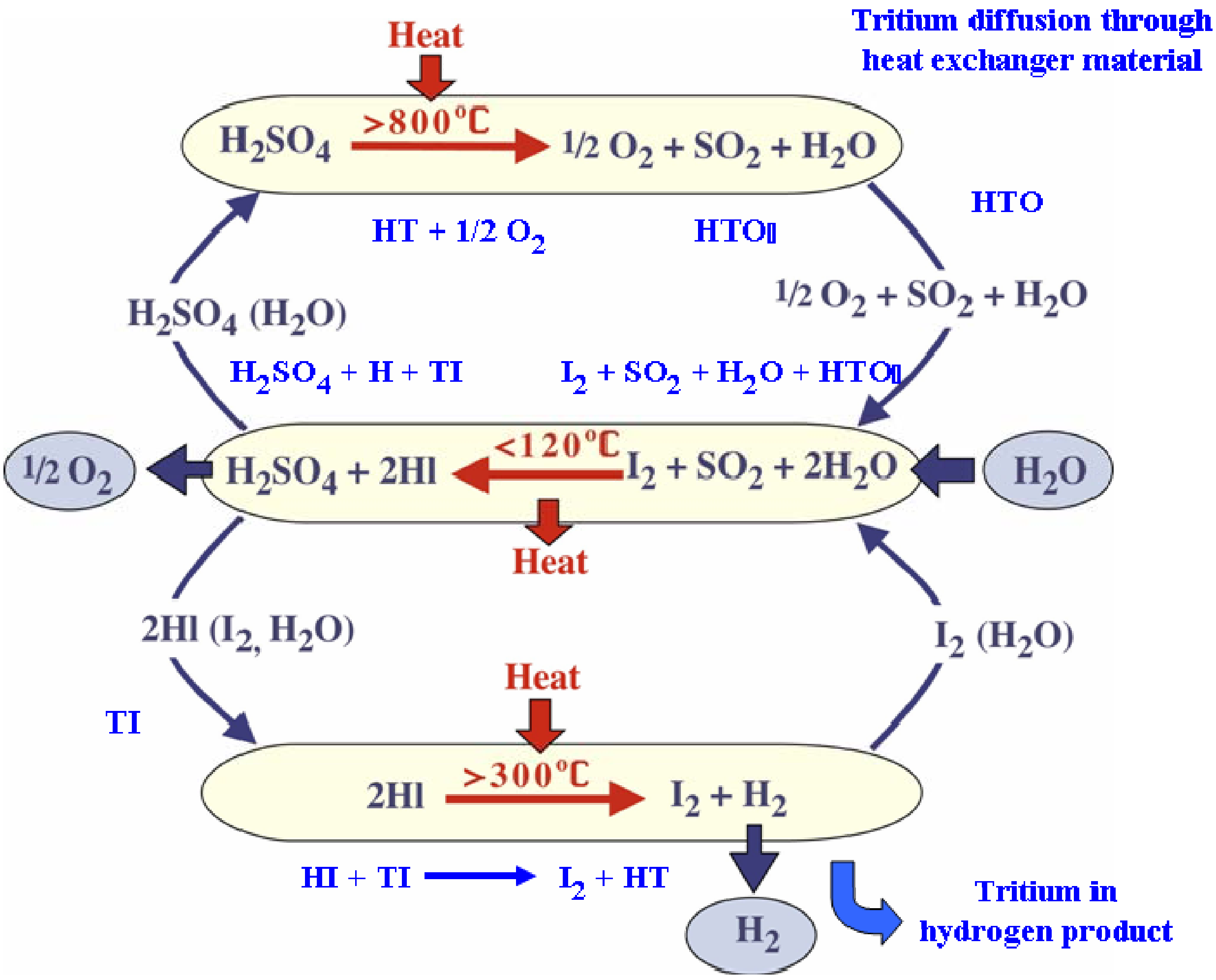

Figure 8-1. H-3 Contamination Pathways in SI Process

8.3 Contribution to Radionuclide Source Terms

In addition to contaminating the product hydrogen stream, tritium will likely be present at some concentration in the gaseous and liquid effluent streams released from the plant into the surrounding environment (Hanson 2006). While compliance with the various national regulations on public radiation exposure from nuclear plants (e.g., 10CFR50, Appendix I) was not a problem, tritium was nevertheless the dominant dose contributor to off-site doses during normal operation for previous steam-cycle HTGRs. Moreover, for those operating HTGRs that solidified the tritiated water removed by their HPSs, tritium was a major contributor to the total radionuclide inventories disposed of as a solid waste as well.

In contrast, tritium has consistently been predicted to be an insignificant dose contributor for postulated accidents for operating HTGRs and for proposed advanced HTGR designs. For postulated accidents in advanced HTGR designs, the dominant off-site dose contributors are consistently predicted to be the radioiodines, especially I-131 (e.g., PSID 1992); the H-3 inventories in an HTGR are too small to be significant compared to the radioiodines and noble gases (the exception being the tritium-producing New Production Reactor). It is anticipated that the same results will be obtained when dose assessments for normal plant operation and postulated accidents are made for the H2-MHR.

With an H2-MHR, the majority of the waste heat is rejected through evaporation of a small fraction of the circulating water. A makeup water system replenishes water lost to evaporation and is also used to control the water chemistry in the circulating water. Excess makeup water is blown down from the cooling tower basin to the receiving water body. The water released from evaporation and blow down are potential sources of tritium release to the environment and these sources are factored into the design of the HPS. Radionuclide releases, including H-3 release, via this pathway will need to be quantified for both normal operation and a spectrum of postulated accidents.

8.4 Design Options For H-3 Control in HTGRs

While there are uncertainties in the H-3 production rates and distribution throughout an H2-MHR, especially with regard to the expected levels of H-3 contamination in the product hydrogen, there are a number of design options for H-3 control in HTGRs. Once limits on the allowable H-3 levels in the product hydrogen are established and a comparison with the expected H-3 contamination levels has been made, a study can be conducted to determine which design option for H-3 control, or combinations thereof, is optimal for the reference H2-MHR plant design. These design options are summarized below; they will be given further definition and quantified as the plant design evolves.

Realistic Limits on H-3 Contamination of Product Hydrogen. While perhaps more of a prerequisite than a design option, realistic limits on allowable H-3 contamination in the product hydrogen are nevertheless critically important. H-3 contamination limits proposed by the design organizations early in the design and licensing process may set precedents that could prove difficult to change in the future. Therefore, it is prudent to propose realistic limits initially and to demonstrate compliance with large safety margins to accommodate uncertainties in the predicted contamination levels rather than to adopt ultraconservative limits initially simply because they appear achievable based upon early scoping assessments.

As an example of an ultraconservative limit on H-3 contamination of nuclear-derived commercial products, the German PNP project in the early 1980s adopted a provisional limit of 10 pCi H-3/g of synthetic natural gas derived from coal gasification; this contamination level corresponds to a radiation dose of only 20 μrem/year to the critical population group (Steinwarz 1984).

Obviously, this radiation dose is of no consequence compared to natural background radiation which is about four orders-of-magnitude higher.

There are established H-3 contamination limits for both occupational and public exposures that have been set by national and international regulatory agencies, including the US NRC and the US EPA. They include allowable limits on H-3 concentrations in air (e.g., 100 pCi/l, NRC) and in drinking water (e.g., 20,000 pCi/l, EPA). The dose limits corresponding to these concentration limits should be carefully considered when proposing a H-3 contamination limit for nuclear-derived hydrogen. The allowable contamination limits, and the corresponding dose limits, for other radionuclides in commercial products and/or public use commodities may also provide guidance (e.g., the dose equivalent to allowable radon in natural gas or drinking water).

The allowable H-3 contamination limits may be dependent upon the assumed commercial scenario. For example, the limit derived upon assumption that nuclear-derived hydrogen will be become the dominant transportation fuel in the future may be more stringent than the limit derived upon assumption that nuclear hydrogen will used for manufacture of liquid-ammonia fertilizer or to sweeten sour crude oil. Establishment of accepted H-3 contamination limits may well involve a protracted negotiation with regulatory authorities.

Stringent Limits on Li Impurities in Core Materials. The most fundamental way to control H-3 in HTGRs is to limit its production to the fullest extent practical. Obviously, it is impractical to reduce the production of H-3 by ternary fission or by neutron activation of He-3 in the primary helium coolant.[53] However, H-3 production from activation of Li impurities in core materials can be, and should be, controlled. Since Li is an effective neutron poison, stringent limits (e.g., <~50 ppb) are typically set for the allowable Li impurity levels in the components that constitute the active core, including the fuel-compact matrix and fuel-element graphite in a prismatic core. However, it is important to also limit the Li impurity levels in the permanent graphite structures in the reactor system. In the case of the German AVR, the “carbon brick” (Koehlestein) used for the permanent side reflector had an unusually high Li impurity level estimated to be ~4 ppm (Cordewiner 1979); consequently, Li activation was the dominant source of H-3 production in that pebble-bed HTR.

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[53] The concentration of He-3 in helium extracted from natural gas wells is generally much lower than the concentration of He-3 in atmospheric helium; however, gas wells are the commercial source of helium in any case so the point is moot.

Coated B_4C Granules in Control Materials. The B-10 used in HTGR cores as a neutron absorber is typically present as B_4C granules, which have been pressed into pellets with a carbonaceous binder. The production of H-3 in these control materials is typically predicted to be a minor contributor to the total H-3 production in the plant. Nevertheless, should release of H-3 from control materials become a significant contributor to the total H-3 present in the primary coolant, the B_4C granules can be encapsulated with dense pyrocarbon and/or SiC coatings that will dramatically decrease the H-3 release rates from them.

Increased He Purification Rate in Primary Loop. The typical He purification system design that utilizes oxidizer beds/dryers for control of H-3 and hydrogen efficiently removes H-3 from the processed primary coolant. Thus, the H-3 concentration in the primary coolant can, in principle, be reduced by increasing the mass flow rate through the HPS. However, as the mass flow rate is increased, the HPS becomes increasingly more expensive. In addition, based upon HTGR operating experience, the H-3 removal rate from the primary coolant by sorption on the core graphite is expected to be much larger than the removal rate by purification. Consequently, the mass flow rate through the HPS would have to be increased substantially before it would effect a dramatic reduction in the circulating H-3 level. Therefore, this option is probably less attractive than adding a purification system to the heat transport loop (see below).

Purification System for Secondary Loop. A simplified purification system can be added to the secondary loop (assuming that the secondary heat transport fluid is also helium rather than molten salt). The secondary-loop HPS might be dedicated to H-3 removal although some control of chemical impurities might be desirable as well. It is likely that the liquid nitrogen-cooled charcoal beds could be eliminated from the design. It is expected that adding a simplified HPS to the secondary loop would be much more cost effective than large increases in the primary loop purification rate.

Customized Coolant Chemistry in the Secondary Loop. It may well be possible to control the helium chemistry in the secondary loop such that coherent oxide films are produced on the heat exchanger surfaces in the IHX, thereby reducing the H-3 permeation rates through the walls separating the primary and secondary loops. The presence of coherent oxide films can reduce the H-3 permeation rates by several orders of magnitude. However, the in-reactor effectiveness is not well known. There is evidence that thermal cycling as a result of transient reactor operations (e.g., startup/shutdown, loading following, etc.) can cause cracking of oxide films resulting in increased H-3 permeation rates. Custom tailoring of the coolant chemistry to limit core corrosion in the British CO_2-cooled Advanced Gas Reactors (AGRs) has proven practical (e.g., Faircloth 1981), and, of course, it is extensively practiced in water-cooled reactors to control “crud” formation and to protect the fuel rod cladding. Buchkremer (1984) described how the coolant chemistry in an HTR could be adjusted to produce coherent oxide films on high-temperature alloys that would serve as tritium permeation barriers.

Permeation Resistant Coatings on Heat Exchanger Surfaces. There are coatings, especially aluminum oxide-based coatings, that can be applied to heat exchanger tubes to dramatically reduce the H-3 permeation rates. However, as with oxide layers, the long-term in-reactor effectiveness of such coatings is unknown. Thermal cycling as a result of transient reactor operations may again compromise their long-term performance. In addition, it is straightforward to add such protective coatings to the exteriors of the metal tubes that are used in shell-and-tube heat exchangers; it would be more difficult, if not impractical, to incorporate permeation-barrier coatings with printed-circuit heat exchanger designs (e.g., Heatrix-type).

9. DECONTAMINATION AND DECOMMISSIONING

The NGNP will be designed to have a 60-year lifetime (SRM, PLT 3.0.9), and a commercial H2-MHR is expected to have a comparable design lifetime (Richards 2006a and Richards 2006b). At the end of its operational lifetime, the physical plant will represent the ultimate "by-product" of electricity and hydrogen production, and both the reactor plant and the hydrogen plant will have to decontaminated and decommissioned (SRM, PLT 3.1.11.14). The specific decontamination and decommissioning (D&D) requirements will be determined during the licensing process and by the prevailing regulatory climate at the plant end-of-life. Nevertheless, D&D requirements need to be considered during design, and D&D costs need to be included in the economic assessment of a commercial H2-MHR.

9.1 Reactor Plant D&D

A comprehensive discussion of the D&D of the NGNP and future H2-MHR reactor plants is beyond the scope of the present study. Nevertheless, it is noteworthy that the D&D of future MHRs was addressed in some detail in 2005, and the results of that evaluation, including a cost estimate for the D&D of a GT-MHR, are summarized below (Hanson 2005).

The primary motivation for performing the subject evaluation was a 2003 NEA report on the decommissioning costs for various types of nuclear power reactors, based upon a survey of its member countries. The report (NEA 2003) concluded: "…decommissioning cost estimates reported remain below 500 USD/kW$_e$ for nearly all water reactors but are significantly higher for gas-cooled reactors (around 2500 USD/kW$_e$)." The report raised concern that this conclusion might be taken to reflect negatively upon future development and deployment of advanced MHRs. In response, the past experience with D&D of gas-cooled reactor was reviewed, and the "lessons learned" to guide future MHR D&D, including projected costs, were determined.

Three types of gas-cooled, graphite-moderated nuclear reactors have been used for electrical power generation: CO_2-cooled MAGNOX reactors, CO_2-cooled AGRs, and He-cooled HTGRs (the latter category includes both prismatic core and pebble-bed core HTGRs). Reactors of each type are now in various stages of decontamination and decommissioning. Since these gas-cooled reactors share certain common features, notably graphite moderation, the D&D experience with each type is of some relevance to the eventual D&D of future MHRs.

While regulations and terminology differ somewhat internationally, there are three basic decommissioning options (along with combinations and variants thereof); using US terminology and criteria, they can be summarized as follows:

"DECON" (Decontamination): In DECON, all radioactive components and structures are decontaminated or dismantled, packaged and shipped to a low-level waste (LLW) disposal site (they may be first stored temporarily on site). Once this task is completed and the NRC terminates the plant's license, that portion of the site can be reused for other purposes.

"SAFSTOR" (Safe Storage): In SAFSTOR, the nuclear plant is kept intact and placed in protective storage for up to 60 years. This method, which involves securing and safeguarding that part of the plant, which contains radioactive materials, allows time for radioactive decay to reduce the in-plant radiation fields and the inventories of radionuclides that must be transported and dispositioned off-site. Once the radionuclides have decayed to lower levels, the unit is dismantled similar to the DECON option.

"ENTOMB" (Entombment): This option involves encasing the radioactive structures, systems and components in a stabilizing medium, such as concrete, to provide shielding and isolation. The encased plant would be appropriately maintained, and surveillance would continue until the radioactivity decays to a level that permits termination of the plant's license.

The data in the NEA report provide little or no insight into the projected D&D costs for advanced HTGRs, including the GT-MHR, because no He-cooled reactor was included in their data base. In fact, data from the successful D&D of the Fort St. Vrain HTGR, which cost <$573/kW$_e$, suggest that the D&D costs for future MHRs should be comparable to that for water reactors. This extrapolation is supported by a 1993 Bechtel study, which estimated that the D&D costs for a four-module 600 MW$_t$ GT-MHR at $243/kW$_e$ in 1992 dollars, which escalates to about $350/kW$_e$ in 2003 dollars. The cost data presented in the NEA report for MAGNOX reactor D&D are summarized in Table 9-1 along with the Bechtel cost estimates for future MHRs.

The D&D cost data presented in Table 9-1 need to be used with some caution. In particular, they are difficult to compare on a common basis because the work scopes can be quite different (e.g., some D&D cost estimates include the substantial cost of spent fuel storage and disposal, and other estimates do not). An important consideration is that for most of the gas-cooled reactors that have been decommissioned, or that are currently being decommissioned, the plant owners have chosen a variant of the SAFSTOR option; consequently, the final D&D of some of these units has been postponed by as long as ~135 years. In such cases, the ultimate total project costs are highly speculative. In this context, the completed D&D of the FSV HTGR - which led to a free release of the site and its subsequent reuse as a gas-fired power plant - is particularly significant and encouraging. A further complication is that permanent repositories for the final disposition of spent nuclear fuel (or reprocessed HLW) are not yet available in any industrialized country; obviously, projecting the eventual costs of spent fuel disposal under these circumstances is also speculative.

Given the complexity of a D&D project for a nuclear power plant, it should be anticipated that numerous licensing issues could arise for any such project. Many of these licensing issues will be largely specific to the particular project and to the particular site and country of residence. However, the potential licensing issues of interest in the present context are those that are more generic in nature and, hence, that might arise during the D&D of future MHRs. The following licensing issues related to D&D were judged to have the potential to negatively impact the prospects for the construction of a future commercial MHR (i.e., they are potential feasibility issues):

The assured availability of off-site, long-term interim storage facilities and/or a permanent repository for the spent fuel generated throughout the plant operating lifetime is essential for viability of any new nuclear power plant construction.

Unprocessed, coated-particle spent fuel – whether in the form of prismatic blocks or spherical fuel elements – must be determined to be an acceptable waste form for disposal in a permanent repository. In particular, the fuel-element graphite and fuel-compact matrix (or pebble matrix) must be classified as a "non-combustible" material (Hanson 2002a).

The core graphite – or at least the vast bulk of it – should qualify as low-level waste. The graphite components would likely have to be surveyed to determine their radionuclide inventories, and it is conceivable that the most contaminated components (e.g., the replaceable reflector blocks at the core exit of a prismatic MHR) might need to be partially decontaminated or classified as intermediate level waste. In fact, all of the FSV core graphite was disposed of as Class A LLW, the lowest classification (Fisher 1998).

The assured availability of future LLW repositories that will accept the full spectrum of wastes generated by the D&D of an MHR.

9.2 Hydrogen Plant D&D

The D&D of the SI-based and HTE-based hydrogen plants has not yet been addressed, but the D&D of chemical plants at the of their useful lifetimes is established industry practice.

Table 9-1. Nuclear Power Plant D&D Experience

Reactor	Net Plant Efficiency (%)	Current D&D Status	Final D&D Option54	Average D&D Cost55 ($/kWe)	Comments
NEA Survey					
PWRs	~32	Various	DECON	320	Range of 200 – 500 $/kW$_e$; “extreme” data sets excluded (e.g. a PWR @ 909 $/kW$_e$)
BWRs	~32	Various	DECON	420	Range of 300 – 550 $/kWe; “extreme” data sets excluded. (e.g. a BWR @ 2300 $/kW$_e$)
GCRs	~25[56]	Various	DECON	2500	MAGNOX data only (11 units); no data sets excluded (“insufficient” statistical basis)
HTGR D&D Data					
Dragon	N/A	SAFSTOR	?	?	No turbine-generator
Peach Bottom	35	SAFSTOR	DECON	?	Prototype; plant efficiency not optimized. DECON with Peach Bottom 2&3 in ~2030.
AVR	33	SAFSTOR	DECON	?	Prototype; plant efficiency not optimized
THTR	40	SAFSTOR	DECON	?	Demonstration plant
FSV	39	Complete	DECON	573	Demonstration plant
Bechtel 1992 D&D Cost Study[57]					
4 x 450 MW$_t$ MHTGR	38.5	Planned	DECON	456	Steam-cycle MHR
4 x 600 MW$_t$ GT-MHR	48	Planned	DECON	311	Direct-cycle MHR

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[54] Other D&D options, particularly ENTOMB or ENTOMB in combination with partial DECON, could be considered if regulatory & political climates change.

[55] All costs in 2003 dollars (the escalation factor from 2003 to 2007 is 1.10)

[56] The plant efficiencies for MAGNOX reactors vary from 22% for the oldest units to 28% for the newest units.

[57] Bechtel cost estimate of July, 1993, escalated by 28% to September, 2003, dollars for consistency with the NEA cost data.

10. CONCLUSIONS AND RECOMMENDATIONS

The conclusions and recommendations resulting from this evaluation are summarized below. Some of the conclusions and many of the recommendations are tentative for several reasons. The NGNP and the commercial H2-MHR are in the pre-conceptual design phase. Consequently, a number of assumptions had to be made in order to make the evaluation. Moreover, the results of this evaluation feed into the broader economic assessment for the commercial H2-MHR. Other factors subsequently identified during that evaluation but not considered here may alter perspectives (e.g., different primary markets for commercial hydrogen). On-going technology programs may identify significant problems (e.g., SI process yields under prototypical plant conditions, SOEC service lifetimes, etc.) Finally, forecasting the market values of commodities and the licensing and political climate well into the future is always speculative (as natural gas prices have dramatically demonstrated during the past five or so years).

10.1 Conclusions

The following conclusions apply to both the NGNP and to commercial H2-MHRs unless otherwise noted.

Commercial Products

1. The primary commercial products (commodities) produced by the NGNP and commercial H2-MHRs will be electricity and hydrogen. Hydrogen is perceived to be primarily a future replacement for fossil fuels although it is also used extensively in petroleum refining, chemical processing, and ammonia production.
2. The future market value of hydrogen can reasonably be correlated with the future cost of natural gas, the real cost of which the authors believe will increase significantly in future decades because of supply-and-demand forces as well as an anticipated carbon penalty.
3. The levelized price of electricity in the 2020 – 2060 timeframe is projected to be about 55 mil/kw-hr in Idaho and 106 mil/kw-hr in the TX-LA Gulf coast area. The levelized price of natural gas in the 2020 – 2060 timeframe is projected to be about \$12/MMBtu in both locations.
4. The H2-MHR plants will also produce large quantities of high purity oxygen (8 kg of O_2/kg of H_2). There is a significant industrial market for high purity oxygen, but the real future market value will probably remain stable because it is economically produced by cryogenic distillation of air.
5. The excess electricity produced by the NGNP (beyond that needed for hydrogen production) can be sold to the local grid in the vicinity of the plant site at the Idaho National Laboratory. An attractive end use for the NGNP hydrogen (and, perhaps, for some of the excess electricity as well) would be for the production of ammonia to supply the large agricultural fertilizer market in the region. Conceivably, the hydrogen might also be transported for use

at refineries in northern Utah. As a last resort, the NGNP hydrogen could be simply vented to the atmosphere (or flared).

6. The NGNP oxygen can be vented to the atmosphere unless a “green” oxygen consumer can be co-located at the site; any such oxygen consumer (e.g., a cement plant) should not generate significant air emissions, especially not carbon dioxide.
7. The primary market for hydrogen and electricity from commercial H2-MHRs, at least for the first units, appears to be petroleum refineries to provide hydrogen for sweetening crude feedstock and for hydrocracking. Such an application may well include the supply of process steam as well. The supply of hydrogen and electricity for ammonia production for fertilizer and other industrial applications also appears potentially attractive.
8. Commercial H2-MHRs will produce large quantities of high-purity oxygen. A suitable consumer of this oxygen needs to be identified and co-located at the plant site. This oxygen consumer should not generate significant air emissions, especially not carbon dioxide or other GHGs.

Waste Products

1. The NGNP and commercial H2-MHRs will generate certain waste streams. As with all nuclear power plants, the most significant waste stream will be the spent fuel elements from the nuclear heat source.
2. The plants will also generate radioactive and chemical waste streams. Past operating experience with HTGRs and past design experience with advanced MHRs indicate radioactive waste streams can be reduced to below current LWR practice.
3. In general, the most effective means of waste minimization is source reduction, especially during the design phase.
4. The key to minimizing radioactive waste is the use of high quality, high performance TRISO-coated fuel to retain the fission products in the reactor core to the fullest extent practical during normal operation and postulated accidents.
5. The SI-based hydrogen plant can be designed to limit the gaseous and liquid, chemical waste streams to very low levels. The only feedstock is water, and the only products are hydrogen and oxygen; the most hazardous process materials (e.g., sulfuric acid) are fully contained and recycled.
6. The oxygen product stream will likely contain traces of sulfur dioxide, which may require polishing by caustic scrubbing. A small quantity of corrosion products (mainly metal sulfates from reaction of sulfuric acid with structural metals) will also be generated.
7. The HTE-based hydrogen plant will generate very little chemical waste as a result of plant operation. The primary waste stream will be spent solid oxide electrolyzer cells which will need to be replaced periodically since they are expected to have a maximum design life of 5-10 years. These spent SOE cells will be produced in quantity and will contain hazardous materials, which cannot be disposed of municipal landfills.

Tritium Control

1. Tritium will be produced in the NGNP and commercial H2-MHR by various nuclear reactions. Ternary fission will produce the largest inventory of tritium, but that tritium will be largely retained in the TRISO fuel particles. The major source of tritium in the primary coolant will likely be the neutron activation of the He-3 in the primary coolant helium.
2. Given its high mobility, especially at high temperatures, some tritium will permeate through the intermediate heat exchanger and the hydrogen plant process vessels, contaminating the product hydrogen.
3. This tritium contamination of the hydrogen will contribute to public and occupational radiation exposures; consequently, stringent limits on tritium contamination in the product hydrogen are anticipated to be imposed by regulatory authorities.
4. Realistic limits on allowable tritium contamination of the product hydrogen need to adopted early in the design process.
5. Design options are available to control tritium in an H2-MHR, but they can be expensive so an optimal combination of mitigating features must be implemented in the design.
6. The most cost-effective means of controlling tritium contamination appears to be the addition of a helium purification system to the secondary loop which transfers heat from the primary coolant loop containing the reactor to the hydrogen production plant.

Spent Fuel Disposition

1. Unprocessed, spent MHR fuel elements are a nearly ideal waste form for geological disposal, far superior to zircaloy-clad LWR fuel bundles.
2. The TRISO coatings provide a barrier that is highly resistant to groundwater attack. Based on the available data, the fuel particles should remain intact over geologic time scales, even if the repository were to become permanently flooded with groundwater.
3. The nuclear-grade graphite blocks provide a structural container for the spent fuel that is also highly resistant to groundwater attack. Because of their very low impurity content, the graphite blocks with the fuel compacts removed would likely be classified as Class C, low-level waste. Leaching of the activation-product inventory from the graphite, including C-14, poses essentially zero near-term or long-term radiological risk.
4. Because of the GT-MHR's high-burnup fuel cycle and high thermal efficiency, GT-MHR spent fuel contains significantly lower inventories of fission products and transuranic actinides than commercial LWR spent fuel on a per unit electrical energy basis.
5. GT-MHR spent fuel is highly resistant to proliferation and its characteristics are less favorable for recycle than commercial LWR spent nuclear fuel. Also, the plutonium isotopics in GT-MHR spent fuel are more degraded than those in CSNF.
6. Because of the robustness and high corrosion resistance of the spent MHR fuel itself, there is very little reliance on the MHR MPC for long-term radionuclide containment.

7. The repository-loading strategy for GT-MHR MPCs is relatively simple and straightforward. Up to 77 MHR MPCs can be loaded per repository acre, and the MPCs can be surrounded with a low-permeability, highly-retarding overpack without compromising thermal design limits.

Plant D&D

1. The NGNP will be designed to have a 60-year lifetime, and a commercial H2 MHR is expected to have a comparable design lifetime. At the end of its operational lifetime, the physical plant will represent the ultimate "by-product" of electricity and hydrogen production, and both the reactor plant and the hydrogen plant will have to be decontaminated and decommissioned.
2. Based upon the past D&D experience with gas-cooled reactors, especially the successful D&D of the Fort St. Vrain HTGR, the D&D costs for both the NGNP and commercial H2-MHR reactor plants should be comparable to that for a LWR on a per MW(e) basis.
3. An important component of the above conclusion is that the core graphite – or at least the vast bulk of it – should qualify as low-level waste. In fact, all of the FSV core graphite qualified as Class A low-level waste (the lowest level classification).
4. The D&D of the hydrogen plants has not yet been addressed, but there are established industry practices for the D&D of chemical plants at the end of their useful lifetimes.

10.2 Recommendations

1. The following recommendations apply to both the NGNP and to commercial H2-MHRs unless otherwise noted.

Commercial Products

1. The NGNP should be designed such that excess electricity produced by the NGNP (beyond that needed for H_2 production) can be sold to the local utility grid.
2. The prospect of using the NGNP hydrogen (and, perhaps, some of the excess electricity as well) for the production of ammonia to supply the large agricultural fertilizer market in the region should be aggressively pursued.
3. A "green" oxygen consumer should be co-located at the plant site; any such oxygen consumer (e.g., a cement plant) should not generate significant air emissions, especially not carbon dioxide.
4. The value of and options for supplying a portion of the process heat as process steam rather than as high temperature helium should be evaluated.
5. As the requisite resources become available, a more comprehensive market survey of the potential future customers for hydrogen, oxygen, high-temperature, process heat, and process steam should be performed for a variety of sites.

Waste Products

1. The fuel burnup should be maximized to the fullest extent practical to minimize the amount of spent fuel per unit electrical production and unit mass of hydrogen production.
2. Every effort should be made to minimize the radioactive and chemical waste streams. To that end, stringent radionuclide design criteria should be adopted to limit the fission release from the core to the fullest extent practical.
3. A design goal for the SI plant should be "zero-discharge" of pollutants to the environment.
4. The recovery and potential recycle of hazardous constituents from spent SOECs should be a high-priority R&D task.

Tritium Control

1. An overall H-3 mass balance for the H2-MHR should be made using the available design methods. The emphasis should be on estimating the degree of product contamination. The results will provide guidance on sizing the helium purification systems for the primary and secondary circuits.
2. The international radiological regulations should be reviewed to provide a logical basis for setting limits on the allowable H-3 contamination in the product hydrogen.
3. Realistic design goals for allowable H-3 contamination in the product hydrogen should adopted early in the conceptual design of the commercial H2-MHR and a legal limit negotiated with regulatory authorities during preliminary design.
4. The extensive literature on H-3 permeation through heat exchanger materials should be acquired, reviewed, and evaluated as a basis for selecting the best available correlations for predicting H-3 permeation from the primary to secondary loops and from the secondary loop to the SI process streams.
5. The extensive literature on H-3 permeation barrier coatings should be acquired, reviewed, and evaluated for possible application in an H2-MHR. A feasibility study should be made to determine if there is a practical means of applying such coatings to a printed-circuit type IHX.
6. Trade studies should be performed to identify the optimal combination of design options for assuring tritium contamination levels will be well below anticipated regulatory limits.

Spent Fuel Disposition

1. The confirmatory testing and analysis tasks defined in (Hanson 2002a) to qualify spent MHR fuel elements as a suitable waste form for disposal in a geologic repository and to assess the transport of radionuclides from spent fuel elements in the repository to the environment should be conducted. In particular, the following tasks are the highest priority:
2. Measure the crush strength of irradiated coated particles that have been stored for long time periods (decades) to determine the effect of storage time upon the crush strength.

3. Demonstrate that the irradiated, reference fuel-element graphite and fuel-compact matrix are noncombustible according to the criteria outlined in ASTM Standard E-136.
4. Measure the corrosion rates of SiC coatings of irradiated TRISO-coated fuel particles under groundwater-ingress conditions as a function of temperature and water chemistry.
5. Measure the N-14 content in as-manufactured matrix and graphite from archival specimens and the C-14 content of irradiated H-451 graphite to permit a more reliable quantification of the C-14 content of irradiated matrix and graphite.

<u>Plant D&D</u>

1. The contamination of the reactor plant by long-lived radionuclides (e.g., 30-yr Cs-137, 28-yr Sr-90, etc.) should be minimized by adopting stringent limits on fission product release from the core during operation.
2. The cobalt content of structural metals subjected to significant neutrons fluxes should be minimized to the extent practical to minimize the amount of neutron activation.
3. The reactor plant should be properly instrumented (i.e., plateout probes) such that the plateout inventories in the primary circuit can be accurately monitored throughout the operating lifetime.
4. A reactor surveillance program should be planned and conducted to determine the radionuclide inventories of components changed out of the reactor during plant operation. In particular, replaceable reflector blocks should surveyed to determine their radionuclide inventories and LLW classification.

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ACKNOWLEDGEMENTS

The authors gratefully acknowledge the contributions and assistance provided by the following individuals and their respective organizations. The foundation of this study was the two 2006 NERI reports on SI-based and HTE-based H2-MHRs prepared by Matt Richards of General Atomics and his colleagues at GA, INL and Texas A&M; the subject study could not have even been initiated without these seminal reports. Bob Buckingham of General Atomics contributed information on the SI-based NGNP demonstration plant. Masaru Fukuie and his colleagues at Toshiba Corporation of Yokohama, Japan, contributed information on the HTE-based NGNP demonstration plant. The guidance on market forecasting provided by Malcolm Labar of General Atomics was particularly helpful.

This report is a work in progress which will require updating and embellishment as the designs for the NGNP and the H2-MHRs mature. It is anticipated that the able assistance of forenamed individuals will be solicited again in the near future.

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