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Development of Advanced High Temperature Heat Exchangers: Proposal

University of Nevada, Las Vegas, Research Foundation

PROPOSAL

Development of Advanced High Temperature Heat Exchangers

to

U.S. Department of Energy
Office of Nuclear Energy, Science & Technology

from

University of Nevada, Las Vegas Research Foundation
4505 Maryland Parkway
Las Vegas, NV 89154

July 11, 2003

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1. Proposal Overview

A research team led by the University of Nevada, Las Vegas (UNLV) Research Foundation proposes a project to develop advanced high temperature heat exchangers (HTHX) for hydrogen production and electrical energy conversion from advanced nuclear reactor concepts. This project will also support the development of Generation IV reactors. The research team includes researchers from UNLV, General Atomics (GA), Sandia National Laboratories (SNL), The University of California, Berkeley UCB) and Oak Ridge National Laboratory (ORNL).

The proposed project will be administered by the University of Nevada Las Vegas Research Foundation (UNLVRF). UNLVRF will provide the overall contract administration and is the funding entity. Activities will include planning, budget and schedule reporting, collecting and organizing technical reports and team reviews. Quarterly progress reports will be delivered to DOE, including schedule and budget status. Review meetings will include a kick-off meeting and periodic meetings of the team. Other project management functions will include subcontracting and contracting as required and management and coordination of deliverables and schedules.

The main team members are:

UNLV Research Foundation:	Thomas Williams, Executive Director Robert F.D. Perret, Project Manager
GA:	Arkal Shenoy and Gottfried Besenbruch
ORNL:	William Corwin
SNL:	Paul Pickard
UCB:	Per Peterson
UNLV:	Denis Beller, Robert Boehm, Yitung Chen, William Culbreth, Anthony Hechanova, Samir Moujaes, Darrell Pepper, and Ajit Roy

The HTHX research and development program is divided into three major components:

1. High Temperature Heat Exchanger Thermal Systems Design
2. Materials Characterization and Testing
3. Scaled Heat Exchanger Demonstration Tests for Selected Technologies

This program is intended to establish a public-private partnership to develop and evaluate innovative high temperature heat exchangers for hydrogen production. The partnership will focus initially on engineering evaluation heat exchangers for two hydrogen production technologies (thermally assisted electrolysis and the sulfur-iodine thermochemical cycle) that couple with a nuclear reactor power source to split the water molecule into its constituent parts. However, advanced high temperature heat exchangers are important to nearly all hydrogen production concepts and the range of processes that the U.S. Department of Energy (DOE) will consider may be broadened in the next few years.

2. Introduction

Hydrogen has the potential to revolutionize the way Americans produce, store, and utilize energy. Hydrogen would be attractive as an energy carrier if it can be demonstrated that it could be produced cleanly and cost-effectively on a large scale. The evolution from the fossil fuel economy to a hydrogen economy could occur in this century if the technologies to bridge the gap are developed. Forsberg et al. (2003) point out that hydrogen is already used extensively in industry and that the development of hydrogen-fuel vehicles already justifies the development of advanced methods to produce hydrogen.

Although abundant on Earth, hydrogen is not an energy source that can be mined like coal and uranium or gathered like oil and natural gas. Hydrogen must be extracted by breaking molecules such as water or methane, which requires the input of large amounts of energy for large-scale production.

Nuclear energy provides an ample and economical source of energy that can be used to produce the high temperatures required in the water splitting technologies. The Generation IV project, a ten-nation international forum working together with the Department of Energy's (DOE) Nuclear Energy Research Advisory Committee (NERAC), identified the next generation nuclear reactor systems for producing new sources of power. The newly identified reactor concepts excel at meeting Generation IV goals for safety, sustainability, proliferation resistance and physical security, and economic operation. The Very High Temperature Gas Cooled Reactor was identified as uniquely suited for producing hydrogen without the consumption of fossil fuels or the emission of greenhouse gases. DOE has selected this system to demonstrate emissions-free nuclear-assisted hydrogen production by 2015.

Crosbie and Chapin (2003) offer three distinct advantages of using nuclear power to solve the problem of hydrogen production:

- Hydrogen production technologies powered with nuclear energy offer increases in efficiency and dramatic reductions in pollution.
- These advantages are available in each phase of the lifecycle of the energy carrier: collection, production, transmission and distribution, and end-use.
- Nuclear-based hydrogen production appears to be economically viable.

Two approaches for the efficient production of hydrogen using nuclear energy will be investigated in this project: thermally assisted electrolysis and thermochemical processes. These approaches are explained in the next two sections.

2.1 Electrolysis

Electrolysis is the splitting of water molecules using electricity, and is the best understood of the methods for producing hydrogen. It is considered a candidate for hydrogen production with nuclear energy because it may be combined with either existing nuclear electrical generating plants or with advanced high-temperature reactors.

The fundamental reactions of electrolysis are the half reactions of the water ions as follows:

$2H_3O^+ + 2e^- \rightarrow H_2 + 2H_2O$	cathode
$3H_2O \rightarrow ½\ O_2 + 2H_2O^+ + 2e^-$	anode
$H_2O \rightarrow H_2 + ½\ O_2$	

Because electrolysis uses electricity, the overall thermal efficiency of the process includes the efficiency of the electric power generation, as well as that of the electrolysis itself. The electrolysis process efficiency is generally very high, about 75%, but the efficiency of electric power generation is only about 33% in modern nuclear or coal plants. Therefore, the overall thermal efficiency for hydrogen generation from standard electrolysis technology is only about 25%. Newer nuclear plants operate at higher temperatures and have higher thermal efficiencies. Costs could be further reduced by using off peak electricity for electrolysis production and electrical power plant load leveling. Including higher thermal efficiencies from advanced high-temperature nuclear plants, the range of possible thermal efficiencies for electrolysis is 25-45% (Crosbie and Chapin, 2003).

2.2. Sulfur-Iodine Thermochemical Cycle

The Sulfur-Iodine process is a thermochemical water splitting cycle developed at General Atomics and first described in the mid 1970's. The process consists of three chemical reactions, which sum to the dissociation of water. These reactions are as follows:

$I_2 + SO_2 + 2H_2O \rightarrow 2HI + H_2SO_4$	(120°C min.)
$H_2SO_4 \rightarrow H_2O + SO_2 + ½\ O_2$	(800°C min.)
$2HI \rightarrow H_2 + I_2$	(450°C min.)
$H_2O \rightarrow H_2 + ½\ O_2$	

Theoretically, only water and heat need to be added to the cycle. Heat energy enters a thermochemical cycle through one or more endothermic high-temperature chemical reactions. Heat is rejected via exothermic low temperature reactions. All of the reactants, other than water, are regenerated and recycled. Figure 1 shows a schematic of the system.

A great deal of the necessary input energy is used in the separation steps. In addition, the process steps occur in various phase states that include mostly liquids, gases, and even a two-phase liquid process. Complex modeling is necessary to determine the predicted cycle efficiency. Brown et al (2002) suggest that a thermal efficiency of hydrogen production of greater than 50% is realistic. Since the constituents of the cycle are highly reactive, they must be safely contained while maintaining the challenging reaction conditions.

Accordingly, choice of materials and component fabrication techniques for the chemical process, especially the heat exchangers, will provide interesting challenges.

Figure 1 shows a concept for driving the Sulfur-Iodine process using process heat from a Modular Helium Reactor (MHR). The intermediate heat exchanger (IHX) would consist of helium-to-helium heat-exchanger modules housed within a vessel, along with the primary-coolant circulator. The chemical reactions shown in Figure 1 would each be driven in multiple, parallel trains of process equipment. Alternatively, the intermediate heat transfer fluid could be a high-temperature, low-pressure molten salt liquid, depending upon tradeoffs between pumping power, heat-exchanger mechanical design, and materials performance. Figure 2 shows a concept for a MHR demonstration plant for (a) producing electricity using a gas turbine, (b) producing hydrogen using the Sulfur-Iodine process, and (c) producing hydrogen using high-temperature electrolysis.

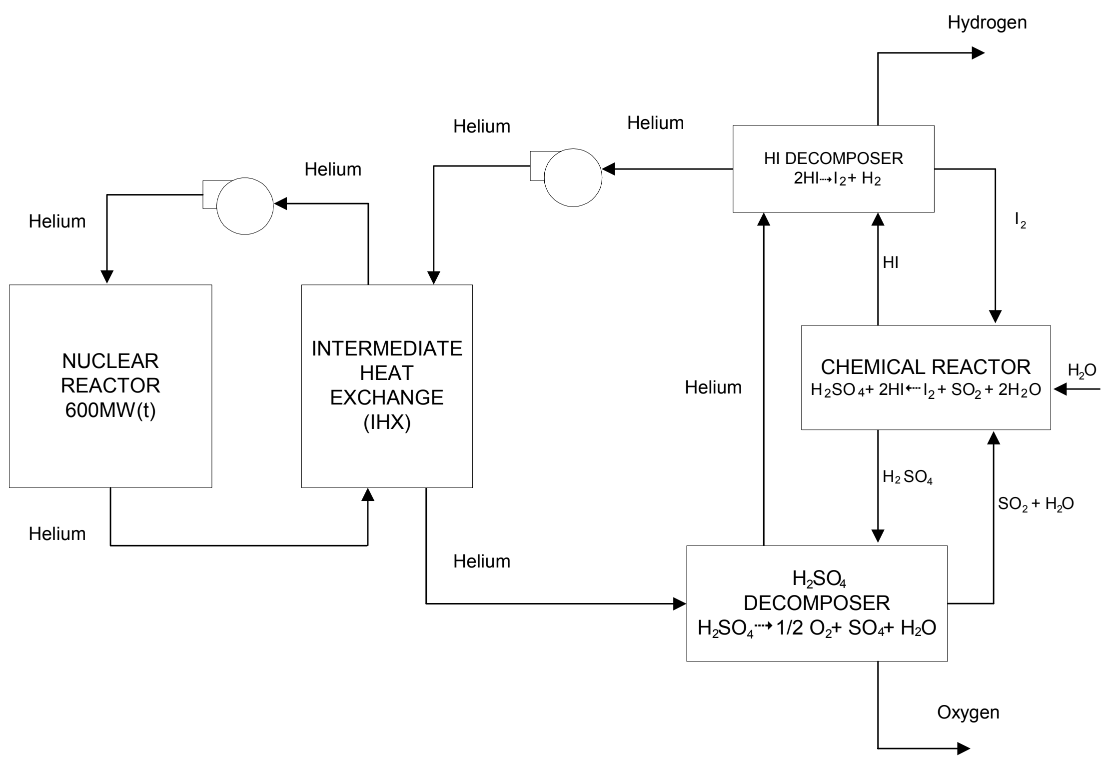

Figure 1. Concept for using an intermediate heat exchanger to interface a Modular Helium Reactor with a Sulfur-Iodine hydrogen production plant.

Figure 2. Concept for a Modular Helium Reactor Demonstration Plant, showing the molten-salt intermediate loop option (Courtesy of INEEL)

3. Scope and Emphasis of Proposed Research

Research teams involved in the project will cooperate on the components. A brief description of the research scope and emphasis for each component are given below.

3.1 High Temperature Heat Exchanger Design Studies

- Work with the U.S. Department of Energy Office of Nuclear Energy, Science and Technology (DOE NE) nuclear hydrogen research and development program elements on high temperature systems studies for hydrogen production.
- Identify the range of HTHX applications for Gen IV hydrogen production .
- Develop thermal systems concepts/designs and overall heat/mass balances for the range of Gen IV power conversion and hydrogen production concepts.
- Develop design specifications for the intermediate heat exchanger and other HTHXs used in the conceptual designs.
- Undertake thermal hydraulic systems numerical modeling to establish and analyze temperature, pressure, and flow rate requirements.
- Perform thermal, thermal hydraulic, and structural analyses for selected advanced HTHX concepts for hydrogen production.
- Deliver detailed design for candidate intermediate heat exchanger concepts and materials for hydrogen production requirements.

3.1.1 Introduction

Heat exchangers are the key energy conversion components for thermally-driven hydrogen production. The success of the Gen IV project relies critically on the design and performance of these system components.

Heat exchangers are used in many commercial applications, and numerous types of units can be purchased from a large number of manufacturers. The performance requirements and component designs for these commercial applications are straightforward.

However, commercial units and standard designs will almost certainly be inadequate for the applications anticipated in the Gen IV reactor project. For example, highly reactive and corrosive chemicals at very high temperature, and possibly high pressure, will require specialized materials and fabrication processes to assure safety and durability over long periods and many process cycles.

The analysis of heat exchangers that will be required for Gen IV system concept design will rely, in part, on conventional heat exchanger design. Determination of heat transfer coefficients as well as effectiveness assessments will be required. The first of these aspects can be pursued with CFD modeling. However, the effects of thermal radiation must be assessed to determine its importance. Moreover, unconventional designs and fabrication processes may be required to accommodate special materials and process environments.

Heat transfer augmentation in a pipe has been studied and reported in numerous papers, many of which deal with rough surfaces where promotion of turbulence kinetic energy is caused by separation of flows. While researchers have contributed significant efforts in this field, there is still relatively poor understanding of the processes of these flows. It is because the flow is so complex and presently existing turbulence models still have many limitations in predicting a wide range of parameters in separating, reattaching, recirculating and chemically reacting flows. Insertions in a flow passage such as coils, wings, orifices, plates, cylinders, etc., have been used to increase heat transfer rates in the design of a heat exchanger. Also, using non-straight channels or ducts, such as channels with corrugated walls or micro-fins or ducts with a backward facing step, and elbow flows have been considered to attain high heat transfer rates. The flow phenomena analysis is more complex and difficult because it may have a profound influence on the heat transfer results. It has been substantiated that turbulent flows could cause substantial enhancement over laminar flows in heat transfer rates between the fluid and the heat exchanger wall. Therefore, it is very important to select an appropriate methodology to calculate turbulent flows in obtaining reasonable results and for better understanding of heat transfer mechanisms due to turbulent effects.

The Nevada Center for Advanced Computational Methods (NCACM) will investigate mathematical models, numerous turbulence models and simulation techniques for computing heat transfer and flow behaviors in chemically reacting duct flows. It is desirable to obtain correlations of phenomenological turbulence heat transfer mechanisms. Although the large-eddy simulation (LES) and the direct numerical simulation (DNS) techniques have demonstrated several advantages over turbulence modeling, these simulations have disadvantages in computations of three-dimensional flow problems and/or flows in industrial applications with complicated geometrical shapes due to their excessive demands for CPU time and memory. The turbulence models of both the Boussinesq viscosity concepts, such as the k-ε model, k-ω model, and the Reynold-stress closure model which consists of the second-order turbulence modeling will be studied for their advantages and disadvantages for HTHX design. The near-wall turbulence phenomena and turbulence eddies will be carefully examined by using computational fluid dynamics and heat transfer analysis with h-adaptation mesh.

3.1.2 High-Temperature Coolants and Materials

There are three primary classes of high-temperature coolants that are needed for these applications, as well as high-temperature materials that can be used with these coolants. Additionally, process fluids for thermochemical hydrogen production require consideration. These coolants and process fluids are:

- Helium. Helium is the required primary coolant for near-term demonstration of combined hydrogen and electricity production. Helium is also the most desirable power cycle fluid for molten salt waste transmuters, and molten salt fusion blanket systems. Helium is inert, but must be used at very high pressures, and thus primary issues for high-temperature use of helium relate to high-strength, high-temperature materials.
- Molten salts. Various fluoride-based molten salts have highly desirable properties as high-temperature coolants, due to their high heat capacity, low pumping power, and very low pressures (sufficiently low to be compatible with fusion plasmas). Molten salts are highly inert if proper chemistry control is maintained. They provide a logical, low risk choice for use as high-temperature intermediate heat transfer fluids for thermochemical hydrogen production, where chemistry control is easy and flow velocities are modest. More interesting materials and chemistry issues require research for applications where chemistry control is complicated by neutron transmutation (e.g. fusion/fission neutron effects) and where contaminants must be recovered (e.g. debris from inertial fusion targets, fission products for molten-salt transmutation).
- Lead-bismuth. The most attractive liquid metal for high-temperature heat transfer due to its high boiling temperature compared to sodium, and with similar properties and corrosion issues to the tin-lithium liquid metal that has been studied for fusion systems, this is the best candidate for spallation targets for accelerator-based neutron sources and for cooling fast-neutron-spectrum cores for actinide management. Heat transfer, fluid mechanics, and materials compatibility are already under study at UNLV.
- Sulfuric acid. The primary candidate process fluid for the thermochemical production of hydrogen, sulfuric acid and its high-temperature thermal decomposition products create aggressively oxidizing conditions that require special

approaches to create passivating surface layers and provide high corrosion resistance.

- Hydrogen Iodide. Whereas decomposition temperatures of this solution are lower than those required for sulfuric acid decomposition, they are very high and the material interactions of this acid at elevated temperatures must be accommodated in heat exchanger designs.
- Hydrogen. Hydrogen embrittlement of materials used for heat exchangers, flow channels and gas containers under pressure must also be considered.

At least three major classes of high-temperature materials provide promising candidates for these applications:

- High-temperature nickel-based alloys (e.g. Hastelloy). Good materials compatibility potential for helium and molten salts up to temperatures in the range of 750°C. Also a candidate material for sulfuric acid thermal decomposition. Limited capability under fusion neutron irradiation.
- High-temperature ferritic steels (particularly oxide-dispersion ferritic steels). Good performance under fusion and fission neutron irradiation, to temperatures around 750°C. Good potential for compatibility with lead/bismuth under appropriate chemistry control. Demonstrating compatibility with molten salts would have substantial value for the fusion application. Silica bearing steels provide a candidate material for sulfuric acid thermal decomposition.
- Advanced carbon and silicon carbide composites. With excellent mechanical strength to temperatures exceeding 1000°C, these are now used for high-temperature rocket nozzles to eliminate the need for nozzle cooling and for thermal protection of the space shuttle nose and wing leading edges. Many options are available that trade fabrication flexibility and cost, neutron irradiation performance, and coolant compatibility. Can potentially be used with helium and molten salt coolants. Silicon carbide is also compatible with sulfur-iodine thermochemical hydrogen production. Major opportunities and research challenges exist to apply these materials to high-temperature heat transport applications.

3.1.3 Capabilities Available at UNLV

UNLV has significant expertise (6 experienced faculty) and engineering tools available for the necessary analysis. Included are a vast array of CFD software including STAR-CD, FLUENT, FIDAP, ANSYS, FEMLAB, CFX, and a variety of other codes, several of which have been developed at the NCACM.

A great deal of computer equipment is also available to researchers ranging from the extremely powerful machines that are found in the National Supercomputing Center for Energy and the Environment: SGI® Onyx® 3800 with InfiniteReality3 Graphics; Sun Fire[tm] 6800 Server; Sun Enterprise[tm] 5500 Server; Sun Enterprise[tm] 450 Server; RackSaver® RS-1100 Cluster; and a new Internet2 Graphics Visualization Lab. Storage equipment includes: StorageTek PowderHorn® 9310 Automated Cartridge System; L180 Tape Library; SGI® Total Performance 9400 (TP9400) Storage Subsystem; and a Sun

StorEdge[tm] T3 Disk Array

NCACM also has a variety of computer resources, including hardware and software, to conduct its research. All systems are directly networked to the larger UNLV network backbone. These items include 20 high-end PCs in use throughout the facility, two SGI workstations, and an 18-node PC-clustering beowulf system.

3.1.4 Tasks and Timeline

First, the heat transfer requirements will be given in terms of the energy transport from each of the chemical streams to their corresponding wetted surfaces. These can be determined by the use of standard (usually empirical) convective/phase change correlations, the use of CFD modeling, as well as by the performance of specific tests designed to determine the demonstrated performance. All three of these approaches will be used in this study. The importance of thermal radiation in the overall heat transfer process will be assessed. Flat plate, tube-type and baffled heat exchanger concepts will be evaluated.

Direct contact heat transfer processes will also be considered for application to the general requirements of this project. Although it is not obvious that a clear path for this application exists, the possibility will be examined. These devices have the beauty of high heat transfer rates and no intervening surfaces. The limitations of the units will be assessed for the applications required. UNLV has a great deal of expertise in the design and analysis of these devices.

The other element of this study is to incorporate the heat transfer information determined with the various possibilities of overall heat exchanger configurations. Of critical importance to this portion of the study are the flow rates required, the contact time, and fluid pressures. In this study, 1-D energy balance solutions will be used first to determine possible overall performance. When the results of these studies are completed, the promising designs will then be analyzed in more detail using appropriate CFD modeling. Attempts will be initiated with 2-D analysis, but full 3-D analysis may have to be used on the selected designs. A three-year schedule is shown in Table 1.

Table 1. HTHX Design Studies Three-year Research Plan

Dates (Starts July 2003)												
Time (Months)	3	6	9	12	15	18	21	24	27	30	33	36
Lit. survey and collaborator mtgs.												
Identify candidate concepts and specs												
Identify CFD analytical tools												
Develop HTHX analyses												
HTHX preliminary characterizations												
HTHX final design analyses												
Follow-up Proposal												
Final Report												
Quarterly Reports												

3.2 Materials characterization and testing

- Work with DOE NE nuclear hydrogen research and development program elements on materials for hydrogen production.
- Identify candidate materials and performance requirements for nuclear hydrogen production candidate technologies.
- Based on DOE R&D priorities, initiate materials characterization testing activities (e.g., fabrication of test samples, physical property characterization tests, materials compatibility tests as function of temperature and environment for candidate HTHX materials, and fabricability/formability tests for HTHX design studies).

3.2.1 Introduction

The selection of materials for developing advanced high temperature heat exchangers (HTHX) will depend on the ability of prospective materials to meet design and service requirements, and to be fabricated and assembled according to design and performance specifications. The capability of the selected material to meet these requirements is determined by its mechanical, physical and corrosion properties, as well as its susceptibility to forming, shaping and bonding by feasible means. The mechanical properties of metal/alloy components are highly dependent on the chemical composition, thermal treatment and the resultant metallurgical microstructures (grain size, phase distribution and crystal structure). For advanced fiber-reinforced ceramic composites, mechanical properties are highly dependent upon the fiber material characteristics and assembly, machining and bonding, matrix infiltration, and surface coating methods.

Mechanical properties of ductile metallic materials are described as the relationship between forces (or stresses) acting on a material and the resistance of the material to deformation (i.e., strains). Strength and ductility are the two key metallurgical parameters that can influence the workability of metals and alloys and the quality of their fabricated products. These two parameters can be determined by tensile testing using cylindrical specimens both at ambient and elevated temperatures. The strength of a material can be quantified by the yield strength (YS), ultimate tensile strength (UTS), and breaking stress (σ_f) from the stress-strain diagram obtained during the tensile testing. Two traditional and common measures of ductility are the percent elongation (%El) and percent reduction in area (%RA) at the gage section of the cylindrical specimen used in tensile testing. Since the heat exchanger (HX) materials will be subjected to a significantly high operating temperature range (800-1000^{o}C), it appears appropriate to initially perform short-term tensile testing at elevated temperatures to evaluate the strength and ductility parameters of candidate materials. Subsequently, long-term tests of creep deformation (deformation at a constant stress) can also be performed at elevated temperatures using similar type of test specimen.

For advanced fiber reinforced ceramics, like those used in the Space Shuttle tiles, mechanical strength and creep resistance can be readily maintained in the 800 to 1000°C range, but the very small strains required to induce brittle failure required specialized design approaches, and approaches to providing the very low permeability required to confine high-pressure helium are more challenging than with ductile metallic materials. Liquid silicon infiltrated (LSI) carbon-fiber reinforced composites appear potentially promising for this application. Because LSI structures can be fabricated in relatively complex geometries and individual components are readily bonded together to form yet more complex structures, the potential exists for the fabrication of extremely compact heat exchangers, with high surface area to volume ratios, if mechanical design and materials compatibility issues can be successfully resolved.

Environment can have a profound influence on the performance of the HX materials. Depending on the type of environment, a material may undergo destruction or deterioration due to its reaction with the environment. Since hydrogen will be generated in this program by splitting of water molecules resulting from either high-temperature electrolysis or the thermal decomposition of sulfuric acid (H_2SO_4) to produce oxygen and sulfur oxides, different types of corrosion-related damage can be experienced by the candidate HX materials. Three most prominent forms of environment-induced degradations can be categorized as general corrosion, localized corrosion, and stress corrosion cracking (SCC) and/or hydrogen embrittlement (HE). General corrosion refers to damage dominated by uniform thinning that proceeds without appreciable localized attack. In case of localized corrosion, corrosion damage produced is localized rather than spread uniformly over the exposed material surface. The two most common types of localized corrosion are pitting and crevice corrosion for which the sites of corrosive attack are relatively smaller compared to the overall exposed surface. The environment-induced cracking (EIC) such as SCC and HE is the result of the combined and synergistic interaction of mechanical stress (applied or residual) and corrosive environment. Thus, the subject of EIC is multidisciplinary involving metallurgy, chemistry/electrochemistry, fractography and fracture mechanics. The general corrosion behavior is commonly evaluated by exposing metallic or ceramic coupons in prototypical chemical and thermal environments of interest for a desired period. General corrosion can be assessed through weight-loss measurements. The localized corrosion behavior is generally determined by electrochemical polarization methods. The susceptibility of metals to SCC/HE can be determined by using constant-load, constant-displacement, and slow-strain-rate (SSR) testing techniques as functions of environmental (temperature and pH) and metallurgical (composition, heat-treatment and microstructure) variables.

Metallographic and fractrographic evaluations using optical microscopy and scanning electron microscopy (SEM), respectively are commonly used to analyze the metallurgical microstructures, and failure modes of the tested specimens. While the optical microscopy is capable of analyzing the grain size and microstructures, the extent and morphology of failure (ductile versus brittle, intergranular versus transgranular) can be determined by SEM. Further, the deformation characteristics (imperfections such as voids and dislocations) during high-temperature tensile testing can be analyzed by transmission electron microscopy (TEM).

The Materials Performance Laboratory (MPL) at UNLV's Mechanical Engineering Department is well-equipped to perform the metallographic and corrosion studies of numerous engineering materials. Further, the Materials Testing Laboratory (MTL) is capable of conducting high-temperature tensile testing in the presence of an inert gas. UNLV's Geoscience Department has a state-of-the-art SEM facility. Further, a TEM is being installed at the Harry Reid Center of UNLV. The overall research capabilities at UNLV are given below.

3.2.2 Research Capabilities at UNLV

Materials Performance Laboratory and Materials Testing Laboratory

- Twelve Cortest Constant Load Testing Fixtures (Proof Rings – 7,500 lb Load Capacity)
- Four Cortest SSR Test Frames (Constant Extension Rate Test Fixture - 7,500 lb Load Capacity)
- Twelve High-Temperature (120^{o}C) Corrosion-Resistant Test Vessels (Hasteloy C-276)
- One High-Temperature (500^{o}C) Corrosion-Resistant Autoclave (Hasteloy C-276) with Lid having Electrochemical Connections
- Two EG&G Model 273A Potentiostats, and one EG&G eight-channel multiple potentiostat
- One Blue-M 1200^{o}C Heat Treatment Furnace
- High – Temperature Water Bath and Mettler Electronic Balance, one each
- Twelve Custom Luggin Probes for Polarization under Controlled Electrochemical

Potential

- One 1000X Resolution Leica Optical Microscope with Digital Image Capture
- Buehler Sample Preparation Accessories – Isomet 4000 Linear Precision Saw, Abrasimet 2 Abrasive Cutter, Ecomet 6 Variable Speed Grinder/Polisher with Automet 2 Power Head
- One High-Temperature (1000^{o}C) Inert Gas Chamber for Tensile Properties Evaluation in Association with an MTS unit

Additional Heat Treatment Facilities

Two high temperature furnaces are available:

1) Lindberg Furnace
The maximum temperature is 1200 ^{o}C (2200 ^{o}F). The working dimensions are 15” x 7.5” x 5.5”.

2) Thermodyne Furnace
The maximum temperature is 1200 ^{o}C (2200 ^{o}F). The working dimensions are 6.5” x 4.5” x 4.5”.

Machine Shop

The UNLV College of Engineering has a machine shop with a Haas 3-axis CNC vertical mill, two vertical mills, two lathes, a welding station, and a variety of band saws, shear breaks, and drill presses. None of this equipment is automated so we have developed good working relationships with several local machine shops. There are several good local shops with CNC, EDM, water jet, and laser cutting capabilities that can be contracted at reasonable rates.

Microstructural Analysis

The UNLV Mechanical Engineering Department has a photomicroscopy lab with two 3-wheel sample polishing stations along with a sample potting machine and sanding wheels. The lab has a Unimet Unitron 8644 Inverted Metallurgical Microscope with 800X magnification equipped with a digital camera and computer for recording micrographs. The lab also has a Leco M-400A microhardness tester, several Wilson and Clark Rockwell hardness testers, and a Beuler sample mounting press.

More recently, one 1000X resolution Leica optical microscope with digital image capturing capability has been installed in the MPL. The necessary sample preparation accessories including Buehler Isomet-4000 linear precision saw, Abrasimet-2 abrasive cutter, Ecomet-6 variable speed grinder/polisher with Automet-2 power head have also been added to this facility.

Scanning Electron Microscopy

The UNLV Geosciences Department has a JEOL-5600 Scanning Electron Microscope. It is optimized for imaging micron to millimeter scale topographic detail of solid materials. Resolution of up to 50 nm at 100,000 times magnification is possible. The SEM is equipped with a BSE detector and an Oxford ISIS energy dispersive spectrometer (EDS) system, capable of semi-quantitative analysis (± 10%). The topographic and compositional images can be processed directly on the screen to show pseudo-color and critical point measurement of features. The images can also be combined, allowing for easy comparison of samples or different magnifications. The manual stage can accommodate four 1-cm diameter samples or one sample up to 3.2-cm diameter. The SEM and EDS are controlled by two networked Windows 95 operating systems allowing for intuitive, simple operation.

The UNLV Geosciences Department also has the JEOL-8900 Electron Probe Microanalyzer (EPMA). It is optimized for quantitative, non-destructive chemical analysis of solid materials on a micron scale. Four fully automated wavelength dispersive spectrometers (WDS) are equipped with 2 crystals each and are capable of quantifying elements ranging from boron to uranium. Concentrations of at least 0.10 wt % can be measured to within ±1% of the measured abundance. In addition, elements present in smaller concentrations can be measured with somewhat less precision. The energy dispersive spectrometer collects a full spectrum of x-rays at once and is capable of rapidly qualifying up to 8 elements at one time. Both EDS and WDS can also be used to obtain high-precision x-ray maps and line scans of spatial variation in chemical composition. The instrument is also equipped with backscattered electron, secondary electron, and cathodoluminescence detectors capable of producing "real time" images, or automated images in tandem with x-ray mapping to further characterize the area of interest. A fully automated stage, capable of holding up to nine one-inch round samples (or six petrographic sections) has reproducibility of less than one micron. Unmounted samples up to 15 cm in diameter can also be accommodated. The EPMA is controlled by a graphical user interface on a HP-UX UNIX workstation.

Transmission Electron Microscopy

A transmission electron microscope (TEM) has recently been procured from FEI, and is in the process of being installed at the Harry Reid Center (HRC) at UNLV. The anticipated date for the establishment of the TEM facility is in the fall of 2003.

3.2.3 Proposed Work Scope and Timeline

The first task under this component is to identify the performance requirements of materials and then potential candidate materials for nuclear hydrogen production technologies.

Nickel base alloys

Based on the prior working knowledge and experience of Prof. Roy, it appears that nickel (Ni) base alloys such as Waspaloy, Alloy C-22 and Alloy C-276 may provide the desired metallurgical and corrosion properties in the temperature range of 800-950^{o}C. However, it is necessary to perform literature review as soon as possible on these nickel-chromiummolybdenum-tungsten (Ni-Cr-Mo-W) alloys with respect to their high-temperature tensile properties, and resistance to general/localized corrosion and SCC/HE in acidic, oxidizing aqueous environments at elevated temperatures.

Subsequently, efforts will be made to melt some experimental heats of candidate materials by vacuum induction melting (VIM)/argon oxygen decarburization (AOD) at an offsite manufacturing facility. These materials will then be processed (forged and rolled) to produce the desired shapes (round bars/plates) followed by the appropriate heat-treatments at the vendor's location. Tensile specimens and electrochemical polarization specimens will be machined from these heat-treated materials.

Upon availability of these specimens, the following tests will be performed:

- Tensile testing at ambient temperature to determine YS, UTS, σ_f, %El and %RA
- Tensile testing at elevated temperatures (100-700^{o}C) in the presence of nitrogen to determine the tensile properties including ductility parameters as a function of test temperature
- Metallographic evaluation of specimens before and after tensile testing using optical microscopy
- TEM evaluation of the tested specimens to characterize the deformation mechanism
- General corrosion and localized corrosion studies (coupons) using high-temperature autoclaves, in sulfuric-acid tests to be performed by Sandia National Laboratory, and in molten-salt flow loop tests performed by Oak Ridge National Laboratory
- Localized corrosion (pitting/crevice) studies using potentiostats at elevated temperatures to determine the corrosion potential and the critical pitting potential
- SCC tests using constant-load and SSR techniques at elevated temperatures with and without controlled cathodic potentials to determine the effect of hydrogen
- Fractographic evaluation of broken tensile specimens used in SCC/HE testing by SEM to determine the extent and morphology of cracking
- Evaluation of general/localized corrosion test specimens by optical microscopy
- Determine fabricability/formability of the HX materials to accommodate the desired design

<u>LSI fiber reinforced composites</u>

Liquid silicon infiltrated (LSI) carbon-fiber composites are a new class of relatively inexpensive and easily fabricated composite materials capable of maintaining high mechanical strength in the desired range of 800 to 1000°C. Viability studies of these materials therefore will be focused on verifying the compatibility of LSI composites with the three principal fluids considered for thermochemical hydrogen production: helium, the baseline reactor coolant for thermochemical hydrogen production; molten fluoride salt, a candidate high heat capacity, low pressure intermediate heat transfer fluid for thermochemical hydrogen production; and high-temperature sulfuric acid and its thermal decomposition products, for the principal high-temperature reaction in the sulfur-iodine hydrogen production process. The specific experimental test activities will then be:

- Helium. Thermal and mechanical analysis, design and procurement of small helium permeation test samples for helium leak testing, and leak testing under helium pressures of 7 MPa and temperatures between 800 and 1000°C.

- Sulfuric acid. Corrosion model development and design of sample coupons of LSI composite with protective oxidation-resistant coating, sample testing with high-temperature sulfuric acid as a part of the SNL HX materials test program, and sample characterization and analysis.

- Molten salt. Corrosion model development and design of sample coupons of LSI composite with protective graphitic coating, sample testing with flowing zirconium-based molten salt in the ORNL molten-salt test loop, and sample characterization and analysis.

<u>Prioritization</u>

Prioritization and level of effort for these tests will depend on DOE research and development priorities, therefore, significant efforts will be made to interact with collaborators from DOE NE nuclear hydrogen R&D program, and participants from ORNL, SNL and GA. The resultant data will be presented to a HTHX working group on a periodic basis. Effort will also be made to present these data at technical society conferences, and subsequently publish in relevant journals. In addition, quarterly and annual reports will be prepared as usual. A three-year schedule is shown in Table 2.

Table 2. HTHX Materials Characterization and Testing Three-year Research Plan

Dates (Starts July 2003)												
Time (Months)	3	6	9	12	15	18	21	24	27	30	33	36
Lit. survey and collaborator mtgs.												
Identify candidate materials and reqs.												
Develop testing capabilities												
Fabricate test specimens												
Materials testing campaign												
Data Analysis												
Follow-up Proposal												
Final Report												
Quarterly Reports												

3.3 Scaled demonstration testing for selected HX systems

- Work with DOE NE R&D program to identify highest priority candidates for HTHX designs for Gen IV hydrogen production.
- Design and fabricate scaled HTHX section designs.
- Conduct heat transfer and performance testing of HTHX components for lab-scale and pilot plant conditions.
- Interface with Very High Temperature Reactor demonstration project.

3.3.1 Introduction

As a famous researcher once said, "in experimentation there is knowledge." This is certainly called for in determining the heat transfer performance of the heat exchangers planned for this study. Ultimately the evaluation of the full-scale equipment will determine the degree of success. However, in a project of the current type, where the states of both the art and science are being pushed, evaluations are wisely started on more elemental forms of the final design.

In the course of this study, basic heat transfer phenomena as well as overall heat exchanger performance will need to be evaluated. Primarily studies of these issues are motivated because of the potentially out-of-the-ordinary designs required for the equipment that are a result of high temperatures and unusual materials used. It is not unreasonable that some atypical geometries might have to be applied in order to accomplish the fabrication constraints for the device(s).

An experimental evaluation protocol will be used that starts from bench-scale to focus on detailed information and works up to prototypical devices. This is complicated by the temperatures and fluids being used. The information found in the experiments will be used to calibrate the CFD/HEX codes used for the ultimate design.

3.3.2 Facilities Available

UNLV has two laboratories where work of the type required for the heat transfer quantification and heat exchanger performance evaluations can take place. The first of these is the Thermal Engineering Laboratory within the Mechanical Engineering Department. This laboratory has a variety of thermal instrumentation and appropriate locations to perform testing. Devices ranging from a variety of temperature measuring elements (from thermocouples to infrared meters) to actual flow systems are available. Included in the locations available for evaluations is one where a high power bus is located. Hoods and other kinds of necessary facilities can be used for the types of tests required.

Various types of data acquisition hardware and software are also available. Included are LabView systems of significant sizes. Several computers with the appropriate data acquisition elements are also available.

Also available are the facilities of the Center for Energy Research. Numerous devices are available for achieving very high temperatures as a result of using high concentrations of solar energy.

One of the critical elements in an experimental program is the availably of production facilities to develop the experimental test sections. We have access to excellent facilities of the UNLV Machine Shop as well as a good relationship with a highly qualified and excellently outfitted shop at Kell's Automotive in Las Vegas.

3.3.3 Tasks and Timeline

After the literature survey noted in section 3.3.1 (above), as well as one being done for this set of tasks are completed, a determination will be made about the need for detailed heat transfer studies. We anticipate that these will have to be performed on the phase change and single-phase gaseous heat transfer processes. The determination how this will impact the overall design will be made by examining the effect of the heat transfer uncertainty on the overall process. For example, in the heat transfer through a heat exchanger wall can be represented as an energy rate of flow from one fluid to another through a separating wall where three thermal resistances may limit the heat transfer. If the heat transfer resistance to one of the fluids is known with high certainty to be quite high and resistance to the other fluid is known with less certainty but is expected to be low, the latter uncertainty may not impact the design that much. As a result of this analysis, at most two studies of fundamental heat transfer processes will be made. In some situations, this might be accomplished by a lumped-mass transient approach. In others, an actual flow loop will have to be developed to assess the heat transfer rates demonstrated. Data taken from these tests will be determined over as wide an operating range as is reasonably accomplished and reported in a form that will be useful in design codes.

At this point, fabrication and assembly feasibility of potentially unique heat exchangers will be examined. This information will be developed from the materials section of this work. Of particular concern is the possibility that the materials used, combined with high temperatures and potentially high pressures, may require configurations that are different from conventional heat exchanger design. Any truly anomalous passage geometries may have to be subjected to heat transfer evaluations.

In the later phases of the project, scale model heat exchangers will be subjected to evaluation under circumstances typical of what might occur in the actual plant design. Some difficulty will be encountered in trying to accomplish this. This is because while the geometry can be scaled, the scaling parameters involve fluid properties. The same fluids as are used in the actual design will be used.

Ultimately, the test of a prototype heat exchanger will be performed. This will be quite large in scale and will involve the input from the various project participants. A three-year schedule is shown in Table 3.

Table 3. Scaled HTHX Tests Three-year Research Plan

Dates (Starts July 2003)												
Time (Months)	3	6	9	12	15	18	21	24	27	30	33	36
Lit. survey and collaborator mtgs.												
Develop HTHX conceptual design												
Perform heat transfer tests												
Perform initial small HTHX tests												
HTHX prototype design and testing												
Final design for actual unit												
Follow-up Proposal												
Final Report												
Quarterly Reports												

4. Structure and Cooperating Partners

The main coordinators for the overall project and each component are presented. Students and post-doctoral researchers are not included. For each component and subcomponent, qualitative descriptions of work anticipated in each year and important decision points of the project are also presented.

Overall Project Coordinators

Programmatic Principal Investigator: Thomas Williams (UNLV Research Foundation)
Project Manager: Robert F.D. Perret
Technical Interface: Anthony Hechanova (UNLV) and Paul Pickard (SNL)
Technical Coordinators:

- Component 1. High Temperature Heat Exchanger Thermal Systems Design
  - GA: Arkal Shenoy (IHX), and Gottfried Besenbruch (Process Heat Exchangers)
  - UNLV: Anthony Hechanova (Component 1 Principal Investigator), Denis Beller, Robert Boehm, Yitung Chen, William Culbreth, Samir Moujaes, and Darrell Pepper
- Component 2. Materials Characterization and Testing
  - ORNL: William Corwin
  - UNLV: Ajit Roy (Component 2 Principal Investigator)
- Component 3. Scaled Heat Exchanger Demonstration Tests for Selected Technologies
  - GA: Arkal Shenoy (IHX), and Gottfried Besenbruch (Process Heat Exchangers)
  - ORNL: William Corwin
  - UNLV: Anthony Hechanova (Component 3 Principal Investigator), Denis Beller, Robert Boehm, Yitung Chen, William Culbreth, Samir Moujaes, and Darrell Pepper

5. Milestones and Deliverables

Project Manager Robert Perret of the UNLV Research Foundation will perform overall management of all research components. Although some work will be conducted at locations outside of Nevada, UNLV will play the role of clearinghouse for record-keeping and deliverable production and dissemination including the assembly and distribution of monthly and quarterly progress reports and annual technical reports.

In addition to quarterly progress reports, annual technical reports, and annual meetings held in Las Vegas, NV, results from the project will also be submitted to publications and presented at conferences and incorporated into the UNLV website for dissemination to the scientific community.

5.1 Year 1 Milestones

5.1.1 High Temperature Heat Exchanger Design Studies

- Quantify range of parameters for HTHX applications

- Estimate IHX design requirements and specifications
- Develop thermal systems concepts and preliminary designs
- Develop thermal systems modeling

5.1.2 Materials Characterization and Testing

- Identify performance requirements and candidate materials
- Develop testing matrices
- Fabricate test samples
- Initiate planning for
    - physical properties tests
    - materials compatibility tests
    - fabricability/formability tests

5.1.3 Scaled Demonstration Testing for Selected Heat Exchanger Systems

- Identify high priority candidates for the HTHX
- Develop program for design and fabrication

5.2 Year 2 Milestones

5.2.1 High Temperature Heat Exchanger Design Studies

- Investigate thermal systems concepts and designs
- Update IHX design specification and prepare design specifications for process-side HTHXs
- Initiate thermal systems modeling to establish temperature, pressure, flow rate requirements
- Define candidate IHX concepts and materials for these hydrogen production requirements
- Perform thermal, thermal hydraulic, and structural analyses for selected advanced HTHX concepts for hydrogen production

5.2.2 Materials Characterization and Testing

- Update performance requirements
- Select candidate materials
- Fabricate test samples
- Initiate physical properties tests
- Initiate materials compatibility tests
- Initiate fabricability/formability tests

5.2.3 Scaled Demonstration Testing for Selected Heat Exchanger Systems

- Define demonstration test conditions
- Initiate design and fabrication activities
- Initiate advanced heat exchanger test program

- Interface with VHTR demonstration project

5.3 Year 3 Milestones

5.3.1 High Temperature Heat Exchanger Design Studies

- Complete initial designs and modeling
- Complete thermal, thermal hydraulic, and structural analyses
- Finalize IHX and process-side HTHX Design Specifications

5.3.2 Materials Characterization and Testing

- Complete testing matrices

5.3.3 Scaled Demonstration Testing for Selected Heat Exchanger Systems

- Complete design and fabrication
- Complete advanced heat exchanger test program

6. Requested Budget

	Year 1	Year 2	Year 3	Total
PERSONNEL:				
Res. Prof/Sci (7.5 mo, Year 1)	$ 75,000	$ 100,000	$ 125,000	$ 300,000
Prof. (3 summer mo, Year 1)	$ 30,000	$ 60,000	$ 60,000	$ 150,000
Post Doc (0.5 FTE, Year 1)	$ 35,000	$ 52,500	$ 52,500	$ 140,000
Financial Oversight	$ 2,500	$ 5,000	$ 5,000	$ 12,500
Classified Salaries	$ 10,000	$ 10,000	$ 10,000	$ 30,000
Graduate Assistants (4, Year 1)	$ 52,000	$ 78,000	$ 78,000	$ 208,000
Undergrad Student Wages	$ 12,000	$ 18,000	$ 18,000	$ 48,000
TOTAL SALARIES:	**$ 216,500**	**$ 323,500**	**$ 348,500**	**$ 888,500**
FRINGE:	$ 35,250	$ 49,200	$ 54,700	$ 139,150
Tuition	$ 12,000	$ 18,000	$ 18,000	$ 48,000
TOTAL DIRECT:	**$ 263,750**	**$ 390,700**	**$ 421,200**	**$ 1,075,650**
***MTD COST:**	$ 251,750	$ 372,700	$ 403,200	$ 1,027,650
INDIRECT COST:	$ 123,358	$ 182,623	$ 197,568	$ 503,549
TOTAL UNLV	**$ 387,108**	**$ 573,323**	**$ 618,768**	**$ 1,579,199**
PROGRAM MANAGEMENT				
Technical Program Mgmt	$ 46,800	$ 62,400	$ 62,400	$ 171,600
Project Administration	$ 5,200	$ 10,400	$ 10,400	$ 26,000
Finance/Budget Mgmt	$ 12,000	$ 24,000	$ 24,000	$ 60,000
Legal Services	$ 12,250	$ 16,500	$ 16,500	$ 45,250
TRAVEL	$ 20,000	$ 20,000	$ 20,000	$ 60,000
SUBTOTAL PROGRAM MGMT	**$ 96,250**	**$ 133,300**	**$ 133,300**	**$ 362,850**
SUBCONTRACTS:				$ -
Subcontract 1	$ 150,000	$ 200,000	$ 200,000	$ 550,000
Subcontract 2	$ 88,500	$ 130,000	$ 130,000	$ 348,500
Subcontract 3		$ 100,000	$ 100,000	$ 200,000
SUBTOTAL SUBCONTRACTS	**$ 238,500**	**$ 430,000**	**$ 430,000**	**$ 1,098,500**
EQUIPMENT:	$ 9,000	$ 84,000	$ 39,000	$ 132,000
SUPPLIES:	$ 9,142	$ 9,377	$ 8,932	$ 27,451
OTHER:				
Analytical Services	$ 10,000	$ 20,000	$ 20,000	$ 50,000
TOTAL COST:	**$ 750,000**	**$ 1,250,000**	**$ 1,250,000**	**$ 3,250,000**

Level of Effort

Task Area	Year 1	Year 2	Year 3	Total
HTHX Design Studies	$250,000	$400,000	$300,000	$950,000
Materials Testing	$400,000	$475,000	$400,000	$1,275,000
Scaled HTHX Tests	$100,000	$375,000	$550,000	$1,025,000
Total (year)	$750,000	$1,250,000	$1,250,000	$3,250,000

7. References

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