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STATUS OF THE DOE (STOR)-SPONSORED NATIONAL PROGRAM  
ON HYDROGEN PRODUCTION FROM WATER VIA THERMOCHEMICAL CYCLES

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ABSTRACT

A pure thermochemical cycle is a system of linked regenerative chemical reactions which accepts only water and heat and produces hydrogen. Thermochemical cycles are potentially a more efficient and cheaper means of producing hydrogen from water than is the generating of electricity followed by electrolysis.

The Energy Storage Systems Division (STOR) of the Department of Energy is currently funding a national program on thermochemical hydrogen production. The National Aeronautics and Space Administration is responsible for the technical management of this program. The goal of this program is to develop a cycle which can potentially operate with an efficiency >40 per cent using a heat source providing a maximum available temperature of 1150K. A closed bench-scale demonstration of such a cycle would follow. This cycle would be labeled a "reference cycle" and would serve as a baseline against which future cycles would be compared.

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INTRODUCTION

The Energy Storage Systems Division (STOR), formerly in the Office of Conservation of the Energy Research and Development Administration (ERDA) but now part of the Department of Energy (DOE), is currently funding a national program on hydrogen energy storage. The National Aeronautics and Space Administration (NASA) is responsible for the technical management of the chemical-based portion of this program. One of the elements of this program involves the production of hydrogen from water using thermochemical cycles.

A pure thermochemical cycle is a system of linked regenerative chemical reactions which accepts only water and heat and produces hydrogen. Hybrids of these cycles may also include electrolytic or photochemical reactions. Thermochemical cycles are potentially a more efficient and cheaper means of producing hydrogen from water than is the generating of electricity followed by electrolysis. Both high-temperature nuclear reactors and solar concentrations are considered to be potential sources for the high-temperature process heat required by such systems.

The goal of this program is to develop a cycle which can potentially operate with an efficiency >40 per cent and produce hydrogen at a cost of <\$10/10<sup>6</sup>kJ, using a heat source providing a maximum available temperature of 1150K. A closed bench-scale demonstration of such a cycle would follow. This cycle would be labeled a "reference cycle" and would serve as a baseline against which future cycles would be compared. Bench-scale demonstration is defined here as the continuous operation of a complete thermochemical cycle in a

closed, integrated mode for several hundred hours. The scale for such a demonstration is somewhat greater than laboratory scale but much less than pilot plant scale.

The DOE (STOR) program on thermochemical cycles is broadly based with participation by the private sector (Westinghouse, General Atomic, and the Institute of Gas Technology), the academic community (University of Kentucky), the DOE National Laboratories (Los Alamos Scientific Laboratory and Lawrence Livermore Laboratory), and several NASA field centers (Lewis Research Center during FY 77 and the Jet Propulsion Laboratory). The overall goals and important achievements of these groups will be described including a description of the activities of the Thermochemical Hydrogen Production Review Panel. This panel was recently formed at the University of Kentucky to provide DOE with an independent review and evaluation of promising cycles.

#### THERMOCHEMICAL CYCLES PROGRAM STRUCTURE

The overall approach for achieving the program goal described in the INTRODUCTION may be summarized as follows: Work on the key reactions and problem areas of specific cycles judged to be of potential interest. When all the reactions of a cycle have been demonstrated individually in the laboratory (at least on a batch-scale basis) and an engineering flowsheet for the overall process has been prepared, obtain a preliminary assessment of the cycle's performance by an objective group. Using this information select two cycles for assembly into closed bench-scale demonstration. In parallel with this effort, conduct a supporting research and technology program emphasizing generic technologies.

In order to implement this overall program element approach, the activities of the thermochemical cycles program have been grouped according to the following categories: Specific Cycle Development, Supporting Research and Technology, and Cycle Evaluation. Specific objectives and status of on-going activities in each of these categories will be discussed in the sections that follow. In these discussions any statements pertaining to future activities should not be construed as a commitment on the part of DOE (STOR) or by the participating organization.

#### SPECIFIC CYCLE DEVELOPMENT

The tasks in this category will provide some of the laboratory data necessary for the subsequent evaluation of existing cycles prior to the selection of the two cycles for bench-scale demonstration. Operation of a single step of a thermochemical cycle in a bench-scale continuous-mode provides valuable data (contaminant build-up, work of separation, pumping work, heat transfer, etc.) which cannot be obtained from batch-reaction studies. These data will make it possible to develop more realistic engineering flowsheets which are required for each cycle before the cycle can be reviewed by the Evaluation Panel coordinated by the University of

Kentucky.

### Thermochemical Water Splitting - Sulfur Iodine Cycle (General Atomic)

The sulfur-iodine cycle is a pure thermochemical cycle consisting of the following three reactions:



where the  $\text{HI}_x$  represents a mixture of several polyiodides. A key feature of this cycle is that under proper conditions the products of the first reaction ( $\text{H}_2\text{SO}_4$  and  $\text{HI}_x$ ) separate under gravity into two phases because the two acids differ in density and are nearly immiscible. The upper phase contains most of the  $\text{H}_2\text{SO}_4$ , and the lower phase contains most of the  $\text{HI}_x$ . This cycle can be operated as an all-liquid and gas-phase process, which should offer considerable engineering advantage over cycles requiring solids handling.

The objectives of the program at General Atomic are to perform process engineering on this cycle and bench-scale testing of the individual steps of the cycle. Continued engineering is required to refine and improve the process design which already shows promise. Bench-scale testing of the individual process steps provides the data necessary for the preparation of a realistic engineering flowsheet, which is prerequisite to conducting a bench-scale demonstration of an entire cycle.

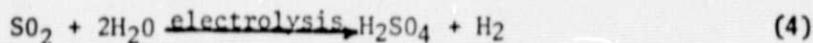
Bench-Scale Testing A bench-scale unit for the main solution reaction (reaction 1) has been designed, constructed, and tested for flow using simulated reactants. Trichloroethylene dyed with iodine was used to simulate molten iodine and nitrogen was used to simulate  $\text{SO}_2$ . The design for the sulfuric acid bench-scale unit has been completed. This system will concentrate the sulfuric acid produced in the main solution reaction and will then decompose the acid to produce  $\text{SO}_2$  and  $\text{O}_2$ . A recycle of undecomposed acid is incorporated. The next step will probably be the design and construction of a bench-scale model for iodine and water recovery from the  $\text{HI-H}_2\text{O-I}_2$  lower phase produced in reaction (1).

Process Engineering A redesign of the engineering flowsheet (3rd generation) for this cycle is currently being prepared with more than half the effort completed. A computer code (Design/2000 from the Chem Share Corp.) is being used to expedite the flowsheet design. This latest flowsheet will differ from the previous one in that it will show: (1) new operating conditions and a subsequent higher yield of the main solution reaction, (2) the use of  $\text{H}_3\text{PO}_4$  as dehydrating agent in the  $\text{HI-H}_2\text{O-I}_2$  separation section, (3) higher pressures in the  $\text{H}_2\text{SO}_4$  concentrating and decomposition section, and (4) possibly a lower temperature catalytic cracking of the  $\text{HI}$ .

These refinements in the flowsheet are expected to increase the process efficiency to the 45-50 per cent range, as compared to 41 per cent for the second-generation design. Additional details for the sulfur-iodine cycle can be found in reference (1).

Development of the Hybrid Sulfur Cycle (Westinghouse)

The objective of the program at Westinghouse is to assess the technical and economic feasibility of a hybrid (electrolytic/thermochemical) hydrogen generation process based on the electrolysis of sulfurous acid. This cycle (2) can be represented by the following two reactions:



The net reaction for this process is the decomposition of a molecule of water into hydrogen and oxygen. Because the theoretical cell voltage for sulfurous acid electrolysis (0.17 volts) is much smaller than the corresponding voltage for pure water (1.23 volts), this process offers the potential for producing hydrogen from water more cheaply than electricity generation followed by direct electrolysis. However, for this potential to be realized cell overvoltage must be minimized and an efficient and economic means for concentrating and decomposing the sulfuric acid produced by the electrolysis must be developed. In order to carry out a meaningful assessment of the potential for this cycle, the operating characteristics of the key process steps must be determined experimentally; these data can then be used in the engineering and economic analysis of the total system.

The experimental portion of the program at Westinghouse is concerned with sulfurous acid electrolysis, materials for handling high temperature sulfuric acid and SO<sub>3</sub>/SO<sub>2</sub>/O<sub>2</sub>/steam mixtures, and sulfur trioxide reduction. Process engineering for the cycle including flowsheet development and evaluation is also part of this program.

Sulfurous Acid Electrolysis The work in this area has concentrated on electrocatalysts, electrode configuration, and membranes for separating the cathode and anode compartments of the electrolyzer cell. These studies have been conducted at ambient temperature and pressure over a range of sulfuric acid concentrations and current densities. Electrocatalysts of the vanadium bronze and halide types as well as others are undergoing evaluation. To date no material has been found which is as catalytically active as platinum. The desirability of a non-noble catalyst for a commercial process is obvious. If candidate catalyst materials which compare favorably to platinum are found they will be dispersed in a carbon matrix and fabricated into anodes for testing in the single cell electrolyzer. If none of the catalysts tested appear promising, then a determination of the minimum platinum loading necessary for the desired cell

performance of a platinized carbon anode will be undertaken. The best anode for sulfurous acid electrolysis tested so far is a briquetted, liquid flow-through type constructed of carbon. The performance of this type anode (with a fixed platinum loading) will be measured as a function of current density (200-400mA/cm<sup>2</sup>), sulfuric acid concentration (50-80 weight per cent), temperature (50-70°C), and porosity. A commercially available microporous rubber was found to perform satisfactorily as the membrane separator; no further development work on the separator is currently underway. However, in the future, when the electrolyzer is operated at higher temperatures, pressures, and acid concentrations a different membrane may be required.

Table I presents the cell performance for sulfurous acid electrolysis that has been demonstrated to date along with the values that Westinghouse believes can be achieved with more development. This was a single-cell electrolyzer using briquetted carbon electrodes with platinum as the electrocatalyst. The cell operating conditions are also shown in the table. It is obvious that the most improvement in cell performance can be obtained by improving the anode catalyst and configuration. Only a small improvement in cell performance could be made by lowering the cell resistivity, which is primarily due to the resistivity of the membrane. It should be noted that the operating conditions shown in Table I do not correspond to the operating conditions desired for a commercial process. For this application pressures of 20 atmospheres, temperatures greater than 400K, and a sulfuric acid concentration in the 70-80 wgt. per cent range will probably be required.

Materials Studies are concentrated on finding materials of construction suitable for containment of sulfuric acid and its decomposition products at high temperatures and pressures (up to 1144K at 20 atm.). Current work involves static testing of compatibility of candidate materials with concentrated sulfuric acid. A test facility for exposing material samples to boiling sulfuric acid at temperatures to 725K has recently been put into operation. Some candidates for the acid vaporizer are: Dirion 51, Super Chlor, Hastelloy G and C4, SiC, Si<sub>3</sub>N<sub>4</sub>, and Aluminized Stainless Steel. Potential SO<sub>3</sub> reduction-reactor materials are being screened in a flowing system capable of exposing the materials samples to both anhydrous SO<sub>3</sub> and SO<sub>3</sub> containing H<sub>2</sub>O. Materials to be tested include: 300 Series Stainless Steel (both uncoated and aluminized), several Inconels, Incolloy 500, SiC, Si<sub>3</sub>N<sub>4</sub>, and Cermets.

Sulfur Trioxide Reduction Since sulfur trioxide decomposes very slowly (i) to sulfur dioxide and oxygen) unless catalyzed, a suitable catalyst must be found for this reaction if the overall process is to be economically feasible. The ideal catalyst would be cheap and its activity would not degrade substantially with time. The facility for screening SO<sub>3</sub> reduction has been modified to include the capability of flowing a stream of steam, SO<sub>3</sub>, and/or argon over the test catalyst in whatever portions are desired. So far both vanadium pentoxide and

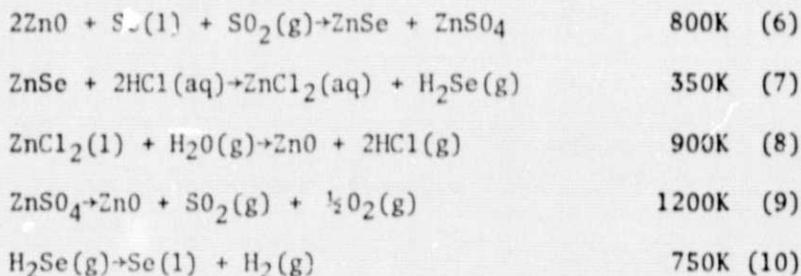
platinum have been tested as catalysts. Again, a non-noble metal is desirable. However, the migration of the non-noble metal catalysts downstream of the reactor zone because of hydroxide formation may be a problem with these catalysts. A test facility for SO<sub>3</sub> reduction catalyst screening capable of operating at pressures up to 20 atm. is being designed. This will simulate the conditions expected in a commercial unit. It can also be used to determine the effect of pressure on the reaction kinetics of SO<sub>3</sub> reduction.

Laboratory Model A working laboratory model of the hybrid sulfur cycle will be designed, constructed, and operated in a project jointly funded by DOE (STOR) and Westinghouse. This model will prove the scientific feasibility of water-splitting via thermochemical cycles. In addition, it will serve as a test bed for subsequent long-term testing of electrolyzer catalysts, electrodes, and SO<sub>3</sub> reduction catalysts and provide the capability for assessing interactions between various process steps. The model will operate at atmospheric pressure and will be heated electrically. The electrolyzer will be of the bi-polar, multicell type, consisting of about five cells in series, each with an area of 200-250 cm<sup>2</sup>. A hydrogen output of approximately two liters per minute is anticipated.

Process Engineering and Economics Recent economic studies by Westinghouse (2) indicate that their process has the potential of operating at an overall thermal efficiency of about 54 per cent in a plant sized to produce 10<sup>7</sup> standard cubic meters of hydrogen per day. However, these calculations were made on the basis of design conditions, not an operating conditions that have actually been achieved in the laboratory.

Engineering Development of the ZnSe Thermochemical Hydrogen Cycle (Lawrence Livermore Laboratory)

Under DOE (STOR) support LLL has completed a preliminary process design, flowsheet, and an economic analysis of an improved version of the ZnSe cycle for hydrogen production. This cycle can be described by the following major reaction steps:



Compared to an earlier version of the ZnSe Cycle, this improved cycle reduces by a factor of 2 the amount of ZnSO<sub>4</sub> to be decomposed at high temperatures, and spreads the cycle heat requirements out over a broad

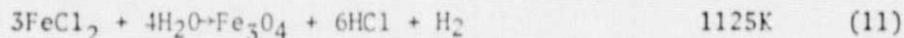
temperature range. From a design standpoint this both improves cycle efficiency and lowers equipment costs. For the analysis, they assumed a VHTR nuclear reactor heat source and developed special equipment designs for the critical steps in the cycle. An overall cycle efficiency of about 40 per cent and a hydrogen production cost of about \$13/GJ was obtained for a non-optimized analysis. LLL believes that these results are conservative at this point of cycle development because of the conservative nature of the input data. They would expect significant improvements in reaction rates and a consequent lowering of equipment costs if this cycle were to undergo engineering development. Results of this study were presented recently (3), and a final report is in preparation. Further DCE (STCR) support for experimental work on the ZnSe cycle is not expected until the cycle has been evaluated by the Thermochemical Hydrogen Review Panel. Availability of selenium and possible toxicity problems with H<sub>2</sub>Se are potential problem areas for this cycle.

#### SUPPORTING RESEARCH AND TECHNOLOGY

The specific objectives in this category will provide some of the data necessary for developing the technologies that are common to several thermochemical cycles or technology that may offer an alternative to existing approaches.

##### Cycle Efficiency Calculations and HBr Electrolysis (Institute of Gas Technology)

Load-Line Efficiency Calculations Under this task IGT has constructed preliminary process flowsheets for cycles which they designate B-1 and H-5. Cycle B-1 (4) is IGT's most developed cycle and can be represented by the following four reactions:



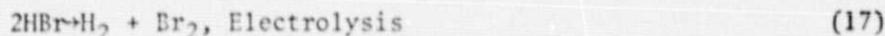
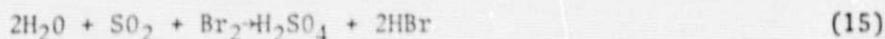
Cycle H-5 is a proprietary metal oxide-sulfurous acid cycle.

The purpose of these calculations is to identify the portion of the overall process that will benefit most from concentrated research and development effort. The most energy intensive elements in the B-1 flowsheet have been identified and mass and energy balance calculations have begun. The two areas that will most benefit from intensive engineering analysis

are the HCl-H<sub>2</sub>O separation scheme and the steam-rich conditions for the FeCl<sub>2</sub> hydrolysis (reaction (11), which is the hydrogen producing step in the cycle). IGT has investigated physical adsorption and pressurized distillation as alternative HCl-H<sub>2</sub>O separation schemes. They are doubtful that better overall thermal efficiency will be obtained with physical adsorption processes than with distillation. Enough data has been acquired to evaluate high-pressure distillation. It appears that the separation of HCl-H<sub>2</sub>O mixtures can be made more complete by pressurized distillation.

In order to interface with projected hydrogen transmission lines which will operate at 70 to 100 atm., the hydrogen-producing FeCl<sub>2</sub>-hydrolysis reaction must be operated at elevated pressures. This will necessitate a higher reaction temperature because the equilibrium mole fraction of hydrogen falls off rapidly with increasing pressure.

Maximum Attainable Thermal Efficiency Calculation The maximum attainable thermal efficiency of a cycle is defined by IGT as the upper limit that could be attained through a process flow sheet calculation if heat exchange is optimized and capital costs for equipment are ignored. IGT will calculate this efficiency for the following three-step sulfur-bromine hybrid cycle:



This calculation will incorporate some elements of realistic operating conditions including: (1) the heat required for endothermic reactions; (2) an approximation for the work required for endoergic reactions and for the separation of reactant/product mixtures; (3) an approximation of the limits of recovering heat from exothermic reactions and from the product streams of high temperature reactions; and (4) the effects of performing reactions at actual temperatures of proven laboratory operability rather than at thermodynamically optimum temperatures.

Hydrogen Bromide Electrolysis Hybrid electrochemical cycles may operate more efficiently and produce hydrogen at less cost than either a pure thermochemical or a pure electrolytic process. The purpose of the electrolysis subtask is to study the decomposition of HBr which is recognized as the key problem area for the sulfur-bromine hybrid cycle. If an efficient process for decomposing HBr could be found, then this cycle would represent an alternative to the hybrid cycle currently being emphasized, the sulfur cycle, which utilizes electrolysis of sulfurous acid. However, the H<sub>2</sub>SO<sub>4</sub> produced in the electrolysis of sulfurous acid is relatively dilute and must be concentrated prior to its decomposition. In contrast, the sulfur-bromine cycle avoids this

costly concentration process because the  $H_2SO_4$  produced in the first step of this cycle is already concentrated. Another feature that makes the HBr Hybrid Cycle attractive is that it should be possible to separate HBr relatively cleanly in the first step of the cycle (reaction 15) because the HBr will vaporize and entrain only small amounts of  $SO_2$  and  $H_2O$ .

The work of Schuetz (5) and others on the electrolysis of HBr and on the HBr- $H_2O$  system has been reviewed. The principal difficulty in the electrolysis has been the inability to achieve high anode current densities. Cathode efficiencies are reported to be quite good, with high current densities obtained at elevated temperatures and pressures on platinum electrodes.

Presently, electrode materials for this process are limited to the very expensive noble metals. IGT will initiate laboratory experiments to evaluate candidate low-cost electrodes. Platinum, "porous carbon," and vitreous carbon will be tested as anodes. Operating cell voltages at selected bath concentrations, room temperatures, and atmospheric pressures will be measured as a function of current density over a 50 to 200 mA/ $cm^2$  range.

#### Thermochemical Processes for Hydrogen Production (Los Alamos Scientific Laboratory)

The primary role of the Los Alamos Scientific Laboratory (LASL) in the overall thermochemical hydrogen program sponsored by DOE (STOR) is to provide supporting research and technology in problem areas common to a number of thermochemical cycles. New techniques for solution concentration and thermochemical decomposition of HBr are examples of such activities. Technology developed in these studies will be continuously transferred to industry.

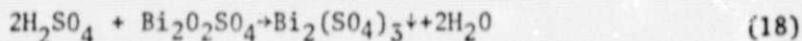
Cycles presently under investigation that include sulfuric acid as an intermediate are the hybrid sulfur cycle being investigated at Westinghouse and the sulfur-iodine cycle undergoing development at General Atomic. Both these cycles incur large heat penalties (and thus a loss in efficiency) in drying sulfuric acid solutions prior to sulfuric acid decomposition. LASL work is aimed at reducing this heat penalty by either avoiding the drying step in changing the cycle's chemistry or by precipitating an insoluble, non-hydrated metal sulfate from the acid solution. In either case, preliminary analysis shows a significant increase of approximately 10 per cent in the efficiency on meeting design goals.

The sulfur-bromine cycle shown in reactions (15-17) eliminates the need for acid concentration as the products of reaction (15) are 100 wt per cent sulfuric acid and anhydrous hydrogen bromide (gas). Investigations are proceeding to explore means of successfully carrying out reaction (16) other than by electrolysis. Subcycles involving the intermediate substances  $VBr_2$ - $VBr_3$  as well as  $CrBr_2$  and  $CrBr_3$  have worked, however the reaction of hydrogen bromide with the lower bromide to evolve hydrogen

has been too slow in both these cases.

The second approach to "drying" sulfuric acid solutions involves the formation of a metal sulfate that decomposes readily to sulfur trioxide. The sulfur trioxide gas can be decomposed more easily and at less of a thermal requirement than sulfuric acid (anhydrous).

A survey and assessment of the literature was made and showed that the sulfates of bismuth and antimony satisfy the criteria for insolubility as well as non-hydrate formation. Bismuth additionally forms a series of oxysulfates that decompose over a wide temperature range to lower sulfates and eventually to the oxide. Los Alamos has proposed the following precipitation scheme for concentrating H<sub>2</sub>SO<sub>4</sub> solutions:



where the downward-pointing arrow indicates precipitate formation and the upward arrow indicates gas evolution. Experiments are currently being run to measure SO<sub>3</sub> pressures over bismuth sulfates both with and without catalytic substances present to increase the rate of SO<sub>3</sub> formation.

#### CYCLE EVALUATION

Continued evaluation of promising cycles will be required before a reference cycle can be designated. To accomplish this, a group is needed that can provide an independent, unbiased, standardized review and evaluation of promising thermochemical cycles designated by DOE/NASA.

#### Evaluation of Thermochemical Hydrogen Production Processes (University of Kentucky)

To carry out these reviews, the University of Kentucky has established a Thermochemical Hydrogen Review Panel with financial support from DOE. Representatives of industry, the academic community, the DOE National Laboratories, and private industry have been included on this panel. A member of a chemical engineering design organization has been included on the panel to assist in the economic analysis of these cycles. In order for a cycle to be a candidate for evaluation by the panel, all the individual chemical reactions in the cycle must have been demonstrated in the laboratory (at least on a batch-reaction basis) and an engineering flowsheet for the process must be available. A report in a standardized format will be prepared by the panel for each cycle that is reviewed and is expected to constitute the best appraisal of the current status of the cycle. This information will be extremely useful to DOE/NASA

technical management when they select the cycles for bench-scale demonstration.

Areas of Concern Each report will include a review and evaluation in the following areas:

- (1) Chemistry
- (2) Flowsheet and Efficiency (Heat Penalty Analysis)
- (3) Materials
- (4) Economics

The membership of the panel was chosen so that an expert in each of the above areas is included. Information in these areas required to accomplish the cycle review will be furnished to the panel by the process developer. Some details as to the report content in each of the areas of concern will now be given:

(1) Chemistry

The reactions comprising a thermochemical process may range from speculative to industrially proven. An evaluation will be made of the status of the experimental data for particular reactions. Important points which will be covered include:

- Experimental evidence that the reaction proceeds as written and an evaluation of the experimental techniques used to obtain such evidence (i.e. batch vs. flow, fresh reactants vs. recycled reactants)
- Side reactions and how they might be avoided
- Effect of operating conditions including temperature and pressure on the yield of the reaction, approach to equilibrium conditions, and effect on equipment size
- Reaction kinetics and possible catalytic improvements
- Availability of thermodynamic data for the reactants

(2) Flowsheet Development and Efficiency

The chemical engineering required to commercialize the process is embodied in the process flowsheets. These flowsheets describe the mass and energy flows as well as the process conditions. They provide the basis for efficiency estimates, equipment specification and cost estimation. Important points that will be covered include:

- An assessment of the flowsheets as to whether they are adequate for detailed calculations of equipment sizes, etc.
- An estimation of the irreversibilities, or heat penalties,

associated with the flowsheet. (The heat penalty associated with each major step in the process will be estimated. The total thermal energy requirement is the sum of the theoretical heat requirement and all the heat penalties. These values determine the process efficiency.)

- Assessment of the difficulty of separating the products from one another and from the reactants, and estimates of the actual heat equivalent of the separation work
- The nature of the interface between the primary heat source and the process
- An identification of those aspects of the process which require the development of new technology - The time required to develop this technology will be assessed.

### (3) Materials

An estimate will be made of construction materials required based on the operating temperatures and pressures and chemical compounds. The availability and relative costs of these required materials will be discussed. Design alternatives which may affect material considerations will be identified where possible.

### (4) Economics

A reasonably firm flowsheet based on a standard plant thermal input must be available before equipment cost estimates can be made. If such a flowsheet is available, a standard costing procedure will be used for these estimates. If a satisfactory flowsheet is not available, rough estimates of equipment cost will be made from preliminary data. Particular attention will be paid to the relationship among heat penalties, efficiencies, capital costs, and production costs. Using this information, a plot of hydrogen production cost vs. reciprocal efficiency will be prepared for the process.

It is expected that each report will point out the individual steps of the process which have the greatest effect on cycle efficiency and cost of the hydrogen produced. The development effort on the cycle should then be concentrated on these steps in order to make the greatest improvements in the cycle.

Current Status The hybrid sulfur cycle was the first cycle chosen by DOE for review. The first meeting of the review panel was held in the fall of 1977; a second panel meeting is scheduled for January 1978. The report containing the evaluation and recommendations for this first cycle is expected to be completed by the end of March 1978.

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## OTHER PROGRAMS ON THERMOCHEMICAL HYDROGEN

In order to place the DOE (STOR) program on thermochemical hydrogen in its proper perspective, other programs on thermochemical hydrogen, both in this country and abroad, should be mentioned. It is beyond the scope of this paper to discuss these programs in any detail.

### Division of Basic Energy Sciences

The Division of Basic Energy Sciences, part of DOE's Office of Research, is currently sponsoring a program on thermochemical hydrogen which includes the participation of five DOE National Laboratories, two universities, and a research institute. This program supports fundamental chemistry studies leading to the improvement of and/or innovation of new chemical cycles for thermochemical dissociation of water.

### American Gas Association

The AGA is currently supporting programs at the Institute of Gas Technology and at General Atomic. The objective of the project at IGT is to identify and develop efficient practical processes for producing hydrogen from water and nuclear heat. This hydrogen could, of course, be used as a replacement for natural gas. The project at GA involves studying processes necessary for the development of the sulfur-iodine cycle.

### Foreign Programs

There are large continuing efforts on thermochemical hydrogen at EURATOM, Ispra, Italy, at the Julich Nuclear Research Center in West Germany. Both these programs are currently emphasizing the development of sulfur-based cycles. There are smaller programs in France and Japan. An international Energy Agreement between most of the countries working on thermochemical hydrogen was signed in October 1977. This agreement should facilitate the exchange of research results, progress reports, etc., between participating countries.

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TABLE I

CELL PERFORMANCE-SULFUROUS ACID ELECTROLYSIS

	<u>ACHIEVED</u>	<u>PROJECTED</u>
ANODE POTENTIAL.....	460 mV	300 mV
CATHODE POTENTIAL.....	10 mV	10 mV
CELL RESISTIVITY.....	130 mV	100 mV
CELL OPERATING POTENTIAL.....	600 mV	410 mV

OPERATING CONDITIONS

- SULFURIC ACID CONCENTRATION-50 WGT. PERCENT
- CURRENT DENSITY-200 mA/CM<sup>2</sup>
- ATMOSPHERIC PRESSURE
- TEMPERATURE-523K

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