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THERMOCHEMICAL WATER-SPLITTING CYCLE, BENCH-SCALE INVESTIGATIONS AND PROCESS ENGINEERING

ANNUAL REPORT FOR THE PERIOD OCTOBER 1, 1978 THROUGH SEPTEMBER 30, 1979

by
PROJECT STAFF

Prepared under
Contract DE-AT03-76SF90351
for the San Francisco Operations Office
Department of Energy

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GENERAL ATOMIC COMPANY

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ABSTRACT

A program to investigate thermochemical water splitting has been under way at General Atomic Company (GA) since October 1972. This document is an annual progress report of Department of Energy (DOE) sponsored process development work on the GA sulfur-iodine thermochemical water splitting cycle. The work consisted of laboratory bench-scale investigations, demonstration of the process in a closed-loop cycle demonstrator, and process engineering design studies.

A bench-scale system, consisting of three subunits, has been designed to study the cycle under continuous flow conditions. The designs of subunit I, which models the main solution reaction and product separation, and subunit II, which models the concentration and decomposition of sulfuric acid, were presented in an earlier annual report. The design of subunit III, which models the purification and decomposition of hydrogen iodide, is given in this report. Progress on the installation and operation of subunits I and II is described.

A closed-loop cycle demonstrator was installed and operated based on a DOE request. Operation of the GA sulfur-iodine cycle was demonstrated in this system under recycle conditions.

The process engineering addresses the flowsheet design of a large-scale production process consisting of four chemical sections (I through IV) and one helium heat supply section (V). The completed designs for sections I through V are presented. The thermal efficiency of the process calculated from the present flowsheet is 47%.

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1. INTRODUCTION

Thermochemical water splitting potentially provides a nonfossil renewable source of hydrogen. It characteristically requires high-temperature heat input to achieve the necessary conditions for the chemical reactions to take place and appears to be compatible with heat characteristics projected for three important heat sources: the gas-cooled fission and fusion reactors and systems for concentrating solar energy.

General Atomic Company (GA) is working on the development of all three of these heat sources and in October 1972 began investigating thermochemical water splitting. The result of this initial work was the discovery of a promising cycle (called the sulfur-iodine cycle) that requires no solids handling. General Atomic is cooperating with the Department of Energy (DOE) and the Gas Research Institute (GRI) to develop the thermochemical water-splitting process to the point where it can be demonstrated as a commercially feasible source of hydrogen. Other participants in this effort have included the American Gas Association (whose sponsorship has been assumed by GRI), Northeast Utilities Service Company, Southern California Edison Company, and the University of California Los Alamos Scientific Laboratory.

The process can be described by the following three chemical equations:

$$2H_2O + xI_2 + SO_2 \rightarrow H_2SO_4(sol) + 2HI_x(sol) \qquad 370\ K \qquad (1)$$

$$H_2SO_4(sol) \rightarrow H_2O + SO_2 + 1/2\ O_2 \qquad 1144\ K \qquad (2)$$

$$2HI_x(sol) \rightarrow H_2 + xI_2 \qquad 393\ K \qquad (3)$$

where the x in the reactions represents the average of several polyiodides formed in the initial solution reaction. Although the cycle can be represented by the three above reactions, several processing steps are necessary to accomplish these reactions.

In February 1977, DOE [then Energy Research and Development Administration (ERDA)] began sponsoring process engineering design studies and laboratory bench-scale investigations under Contract EY-76-C-03-0167, Project Agreement 63. The general objective of the bench-scale work is to obtain better insight into the actual processing steps and their interaction by conducting key continuous flow reactions and separation steps that had previously been done on a batch basis. Bench-scale investigations will also give information on the handling of fluids involved, on the operational behavior of key pieces of equipment, and on the effects of incomplete physical separations and possible side reactions. In the later stages of the studies, the three subunits of the bench-scale system will be integrated and operated as one unit. This will provide additional valuable information for pilot plant design and operation. Process engineering efforts will show the energy efficiency that can be obtained, will give guidance to further chemical and bench scale investigations, and will become a basis for realistic cost estimates.

This document is a progress report on the DOE-sponsored work for the period October 1, 1978 through September 30, 1979. Section 2 describes the bench-scale investigations. Section 3 presents the closed-loop cycle demonstration effort, and Section 4 represents the process engineering effort. Detailed information related to the Work Plan and Activity Plan, program objectives, and engineering flowsheets is included as appendices.

2. BENCH-SCALE INVESTIGATIONS

Bench-scale studies are the logical first step in the scaleup of the sulfur-iodine water-splitting process. The design of the bench-scale system is based on the results of extensive chemistry studies of the three basic reactions described earlier. The main objective of the bench-scale unit is the study of the cycle under continuous flow conditions by modeling the main solution reaction, product separation, and concentration and decomposition of H_2SO_4 and HI. The bench-scale investigation effort was carried out in accordance with the approved FY-79 Work Plan (Appendix A). The unit is divided into three subunits: subunit I represents the main solution reaction, subunit II represents the sulfuric acid concentration and decomposition, and subunit III represents the hydrogen iodide concentration and decomposition. The designs of subunits I and II were presented in an earlier annual report (Ref. 2-1); design of subunit III is given in Section 2.1. Progress on the installation and operation of subunits I and II is described in Sections 2.2 and 2.3, respectively. When completed, the system will operate at a production rate of approximately 6.6×10^{-5} m^3/s ($\sim$4 liters/min).

The three subunits are described briefly as follows:

> Subunit I - The main solution reaction is carried out in this subunit. The H_2O and SO_2 are injected in a contact reactor where the two acid phases are formed. The products are then passed into a gas separator, where the excess SO_2 is removed for recycle, and eventually into a liquid-liquid separator, where the two phases are separated and collected.

Subunit II - The H_2SO_4 phase from subunit I is purified, concentrated, and pyrolized at temperatures up to 1144 K. Uncracked H_2SO_4 is recycled to the concentration column, and wet SO_2-O_2 product can then either be passed to a caustic scrub prior to metering and discharging or recycled to subunit I without removal of O_2.

Subunit III - This subunit separates HI from the lower phase product of the main solution reaction (containing HI, I_2, and H_2O) by a treatment with concentrated H_3PO_4. The HI is then catalytically decomposed at moderate temperature.

During FY-1979 several major accomplishments were made in the bench-scale effort. A new process equipment enclosure was completed which will eventually house all three subunits. Installation of the new enclosure in a separate laboratory provides the needed space for future integration of the three subunits. It also greatly improves the safety of the bench-scale operations. This new ventilated plexiglass enclosure provides good visibility of the process and permits easy access to the equipment.

Subunit I was removed from its old location in a laboratory hood and installed in the new enclosure. Information gathered during earlier operation of subunit I was used to improve the design of the system before reinstallation. Subunit II was also installed in the new enclosure. Subunits I and II have both undergone equipment and operational shakedown, and gathering of data was initiated. Design of subunit III was completed and all purchase orders were let. Installation of subunit III is scheduled for FY-1980.

Continued basic research in the chemistry area has resulted in process changes that represent improvements in the efficiency or cost of the process. Since design and installation of the bench-scale subunits preceded these process changes, they are not part of the present bench-scale system. However, it is anticipated that the improvements will be added to the bench-scale system at a later date in order to demonstrate their performance at bench-scale level before scaleup to pilot plant level.

2.1. DESIGN AND PROCUREMENT OF SUBUNIT III

2.1.1. Design Criteria for Subunit III

The overall design criteria for subunit III of the bench-scale process are substantially the same as those for subunits I and II:

1. The unit will reproduce the individual process operating steps of the large-plant conceptual flowsheet.

2. The process operating steps will occur at the temperature and pressure conditions of the conceptual flowsheet.

3. The bench-scale equipment will be designed and instrumented to facilitate the gathering of performance data useful for guiding scaleup and detailed design of pilot plant equipment.

Material and resource considerations made it impossible to strictly meet all the foregoing criteria. However, planned modifications to the system at a later date will make it possible to meet the design criteria. An example of the departure from the above design criteria is the HI decomposition reaction, which occurs at substantially ambient atmospheric pressure instead of 5.065×10^6 Pa (50 atm). This is due to the fact that the equipment for this process is presently designed from glass. An all-metal HI decomposition system is being designed and constructed under separate funding. It is expected that this system will eventually replace the glass apparatus in the bench-scale system.

The design criteria presented in Sections 2.1.1.1 through 2.1.1.7 define the functional subsections of subunit III as follows:

1. Feed system.
2. I_2 separation system.
3. HI distillation step.

4. H_3PO_4 concentration step.
5. HI decomposition step.
6. HI recycle system.
7. H_2 purification step.

2.1.1.1. Feed System. The feed system will provide a metered flow of heavy phase liquid effluent from subunit I at a rate of 0.7×10^{-6} m^3/s and a pressure of 600 Pa to a discharge pressure of ambient. The heavy phase from subunit I is assumed to have a mole ratio composition of $HI \cdot 3.8I_2 \cdot 5.5H_2O \cdot 0.01H_2SO_4$ at temperatures from ambient to 370 K.

The feed system will be capable of synthetic feed solution makeup in batches of 10^{-2} m^3 each, with a makeup time not exceeding 30 min. The synthetic feed solution composition is: 11.0 wt % HI, 81.1 wt % I_2, 7.8 wt % H_2O, and 0.1 wt % H_2SO_4.

The nominal H_2SO_4 content of actual or synthetic heavy phase represents a mixture of sulfur species that is not defined but which is probably predominately H_2SO_4. Molar equivalent amounts of SO_2 and of elemental sulfur may be substituted for undefined fractions of the H_2SO_4 specified for snythetic feed.

The feed system will provide metered synthetic feed for stored heavy phase from subunit I to the I_2 separation system at rates from 0.5×10^{-6} to 1.0×10^{-6} m^3/s. The storage volume in the feed system will accept a minimum of 4 hours flow of heavy phase from subunit I at 0.7×10^{-6} m^3/s.

The feed system will also meter HI vapor at a rate of 0.8×10^{-5} m^3/s at STP* to the HI decomposition step and have a N_2 purge capability for flushing H_2 gas from the HI decomposition step equipment and HI recycle system subsequent to completion of a period of operation.

*289 K and 1.013×10^{-5} Pa (60°F and 1 atm).

2.1.1.2. I_2 Separation System. The I_2 separation system will receive heavy phase from the feed system at a rate of 0.7×10^{-6} m^3/s and will separate the I_2 as liquid from the heavy phase by countercurrent contact with 100% H_3PO_4 at a rate sufficient to substantially remove all water from the liquid I_2 that is separated from the heavy phase. The H_3PO_4 flow rate into the I_2 separation system is expected to be in the range 4×10^{-4} to 8×10^{-4} kg/s.

The system will provide means of scrubbing with water substantially all entrained H_3PO_4 from the I_2 before the I_2 liquid leaves the I_2 separation system. The scrub water flow rate into the I_2 separation system is expected to be in the range 1×10^{-5} to 2×10^{-5} kg/s. Conditions in the scrubbing operation will be maintained such that both the water and the iodine are liquids. The raffinate of the water scrub operation will be introduced into the H_3PO_4-HI-H_2O phase of the I_2 separation operation and the combined flow conducted to the feed subsystem of the HI distillation step.

2.1.1.3. HI Distillation System. The HI distillation step will accept H_3PO_4-HI-H_2O solution from the I_2 separation step at a volumetric flow rate of approximately 0.5×10^{-6} to 0.8×10^{-6} m^3/s and will provide a gaseous effluent of HI vapor that is substantially free of water vapor at a rate of 0.25×10^{-3} kg/s. The HI may be accompanied by a variable amount of I_2 vapor flow, the amount of which is indefinite but probably of a magnitude of about 0.5×10^{-3} kg/s. Total volumetric vapor flow rate of HI-I_2 effluent from the HI distillation step is expected to be in the range 5×10^{-5} to 10^{-4} m^3/s at STP.

Approximately 85 wt % H_3PO_4 effluent substantially free of HI and at a temperature less than 350 K will leave the HI distillation step at a flow rate of approximately 0.7×10^{-6} m^3/s and will be conducted by gravity to the H_3PO_4 concentration step. The HI-H_2O separation will be accomplished by extractive distillation using H_3PO_4 as the extraction agent. Distillation overhead "reflux" will be 100% H_3PO_4 with a flow rate in the range 0.1×10^{-6} to 0.3×10^{-6} m^3/s.

2.1.1.4. H_3PO_4 Concentration Step. The 85 wt % H_3PO_4 effluent of the HI distillation step will be heated to sufficient temperature, up to 495 K, to substantially remove all water vapor from the H_3PO_4. The water vapor will be discarded and 100% H_3PO_4 will be recycled to the I_2 separation system and to the HI distillation step at the metered rates specified in the design criteria for those subsections of bench-scale subunit III. Effluent water vapor will be condensed before being discarded.

2.1.1.5. HI Decomposition Step. The HI and I_2 vapor effluent from the HI distillation step will be cooled to a temperature slightly exceeding the melting point of iodine, and condensed iodine will be separated from the residual vapor before the vapor is metered at a rate of approximately 0.5×10^{-3} m^3/s at STP into a vertical tubular heated chamber. Thermal decomposition of the HI vapor will occur in the heated chamber at a controlled temperature in the range 450 to 1200 K at substantially ambient atmospheric pressure. The controlled temperature volume for HI decomposition will be approximately 4×10^{-3} m^3 including catalyst volume, if any. Provision will be made for introducing and removing catalyst through a vapor-tight removable closure at the top of the decomposition chamber. Controlled heating capability will also be provided to prevent condensation of iodine from the decomposition chamber effluent.

2.1.1.6. HI Recycle System. The HI recycle system will accept the gaseous effluent HI decomposition products from the HI decomposition step at a volumetric rate of approximately 2.5×10^{-3} m^3/s at STP. The gas-vapor input will first be cooled to a temperature slightly above the melting point of iodine (387 K), and condensed iodine will be separated from the residual gas-vapor. The residual gas-vapor from the I_2 condensation will then be chilled with liquid nitrogen or dry ice to a sufficiently low temperature to remove substantially all condensable vapors from the H_2 product gas. Provision will also be made to revaporize the HI condensed at liquid nitrogen or dry ice temperature for recycle at metered rates of approximately 2×10^{-3} m^3/s at STP to the HI decomposition step. The capability of conducting a metered flow of approximately 1×10^{-6} m^3/s of residual gas from the I_2 condensation to output effluent hydrogen from the HI recycle system will be provided.

2.1.1.7. H_2 Purification Step. The H_2 purification step will provide countercurrent scrubbing with water to remove low concentrations of HI from the effluent H_2 of the HI recycle system. The H_2 purification system will accept and meter the H_2 effluent from the HI decomposition system at a rate of approximately 1.2×10^{-4} m^3/s and will accept and meter scrub water at a net average rate of approximately 0.01×10^{-6} m^3/s. Gas/liquid flow ratios in the countercurrent scrubbing operation will be maintained by recycle of aqueous raffinate to the water feed point of the scrubbing column. Provision will also be made for periodic transfer of aqueous scrub raffinate to the feed input of the HI distillation step.

2.1.1.8. Safety Criteria. Pressure relief will be provided for heated lines and equipment to safeguard against pressure buildup in the event of heater control failure. Pressure relief will be provided for cold traps to safeguard against pressure buildup in the event of loss of cooling. Positive displacement pumps will be provided with pressure relief to prevent pressure buildup in the event of discharge flow blockage.

Provision for nitrogen flushing before startup and following process operation, to prevent formation of air-hydrogen mixtures in the combustion and explosion ranges in the equipment, will be provided. Hydrogen product vented from the equipment will be immediately mixed with a large quantity of air in turbulent flow such that the air-hydrogen mixture is well below the explosive limit.

2.1.1.9. Instrumentation and Control Criteria. Flow, pressure, and level control will be manual. Sufficient surge capacity between unit operations will be provided to uncouple dynamic operating characteristics of individual operations. Heat and temperature control of equipment items will generally be automatic; heat and temperature control of line heat tracing will generally be manual. The choice of heat and temperature control is subject to exception for specific reasons.

2.1.1.10. Materials of Construction. Materials of construction will be resistant to corrosion, decomposition, and degradation of physical properties by exposure to HI, H_2O, I_2, H_2SO_4, S, H_2S, and H_2 under the pressure-temperature service conditions specified in Table 1. In general, glass and Teflon materials in contact with process materials will be preferred, unless some specific considerations supervene.

2.1.2. Flowsheet and Process Description

Figure 1 shows a detailed flowsheet for subunit III, the HI concentration and decomposition system. The basic functions of the principal equipment items are given in the following process description.

Degassed "heavy phase" from subunit I enters subunit III through positive displacement pump P-1. It is necessary to pump this liquid from subunit I because the output pressure from the degassing chamber of subunit I is approximately 600 to 6000 Pa (0.006 to 0.06 atm), whereas vessels V-1A and V-1B of subunit III are approximately at ambient atmospheric pressure. The heavy phase can be stored in either V-1A or V-1B while synthetic heavy phase makeup in the other feed vessel is occurring. Heavy phase from P-1 can be pumped directly to the processing portion of subunit III, bypassing the entire feed makeup and storage system. The feed makeup recirculation pumps P-2A and P-2B are of the centrifugal type and have two purposes: (1) to provide continuous recirculation stirring and temperature control of stored feed, and (2) to provide pressure head against feed flow control valves F-2A and F-2B. The magnitude of this pressure head is controlled mainly by bypass valves FC-1A and FC-1B and possibly, to a lesser extent, by partially closing shutoff valves VA-8A and VA-8B.

Feed from FC-2A or FC-2B is filtered in F-1 to remove adventitious crud before metering the flow with an orifice-manometer combination consisting of FI-2 and PI-2. The metered feed is then contacted with dry H_3PO_4 in packed column V-2. The H_3PO_4 strips H_2O and HI from the heavy

TABLE 1

EQUIPMENT LIST FOR HI CONCENTRATION AND PYROLYSIS BENCH-SCALE SYSTEM, SECTION III

Equipment Number	Equipment Name	Material of Construction	Normal Process Materials Exposure[a]	Normal Operating Conditions	
				Temperature °K	Pressure Pa×10^{-5}[b]
C-1	Wet H_3PO_4 Cooler	Glass	H_3PO_4,H_2O(S)	≤425	—
C-2	Dry H_3PO_4 Cooler	Glass	H_3PO_4	≤490	—
C-3	Waste Water Condenser	Glass	H_2O	≤373	—
C-4	HI Still I_2 Condenser	Glass	HI,I_2 (H_2O)	388	—
C-5	HI Decomposer I_2 Condenser	Glass	HI,I_2 (H_2O)	388	—
CF-1	Check-Float Valve for Surge Tank V-4	Glass	H_2O,H_3PO_4 (I_2,HI)	≤375	—
CF-2	Check-Float Valve for Surge Tank V-3	Glass	I_2 (H_3PO_4)	390	—
CF-3	Check-Float Valve for Surge Tank V-6	Glass	HI,H_3PO_4,H_2O (I_2,H_2SO_4)	390	—
CF-4	Check-Float Valve for Surge Tank V-16	Glass	H_3PO_4,H_2O	≤315	—
CF-5	Check-Float Valve for Surge Tank V-11	Glass	H_3PO_4 (H_2O)	≤315	—
CT-1	HI Decomp. Feed Press. Reg. Cold Trap	Glass	HI (I_2,H_2O)	78-300	—
CT-2	Product H_2 Cold Trap	Glass	H_2,HI(I_2,H_2O)	78-300	—
CT-3	Recycle HI Cold Trap	Glass	H_2,HI(I_2,H_2O)	78-300	—
CV-1	Nitrogen Purge Check Valve	Teflon	N_2 (HI,I_2,H_2O)	∿300	—
CV-2	HI Supply Check Valve	Teflon	HI (H_2O,I_2)	∿300	—
DI-1	Sample Port for Density Sample, V-8	Glass	H_3PO_4,H_2O	425	—
DI-2	Sample Port for Density Sample, V-11	Glass	H_3PO_4,H_2O	≤315	—
F-1	Feed Filter	Teflon	HI,H_2O,I_2 (H_2SO_4)	390	—
F-2	Sulfur Solids Filter	Teflon	H_3PO_4,H_2O (S)	<315	—
FC-1A	Feed Pump 2A Bypass	Teflon	HI,H_2O,I_2 (H_2SO_4)	390	∿1.3 max
FC-1B	Feed Pump 2B Bypass	Teflon	HI,H_2O,I_2 (H_2SO_4)	390	∿1.3 max
FC-2A	Feed Pump 2A Throttle	Glass-Teflon	HI,H_2O,I_2 (H_2SO_4)	390	∿1.3 max
FC-2B	Feed Pump 2B Throttle	Glass-Teflon	HI,H_2O,I_2 (H_2SO_4)	390	∿1.3 max
FC-3	Air Flow Control to C-5	Stainless Steel	Air	≤390	∿2.3
FC-4	I_2 Cleanup H_2O Input Flow Control	Teflon	H_2O (I_2)	∿300	∿2.0
FC-5	H_2O Scrub to V-13 Flow Control	Glass-Teflon	H_2O (HI)	∿300	∿2.0
FC-6	Conc. H_3PO_4 Pump P-6 Bypass	Teflon	H_3PO_4 (H_2O)	≤315	∿1.3 max
FC-7	Conc. H_3PO_4 Feed to V-2 Flow Control	Glass-Teflon	H_3PO_4 (H_2O)	≤315	∿1.3 max
FC-8	Conc. H_3PO_4 Feed to V-7 Flow Control	Glass-Teflon	H_3PO_4 (H_2O)	≤315	∿1.3 max

TABLE 1 (Continued)

Equipment Number	Equipment Name	Material of Construction	Normal Process Materials Exposure[a]	Normal Operating Conditions	
				Temperature °K	Pressure Pa×10^{-5}[b]
FC-9	Air Flow Control to C-4	Stainless Steel	Air	≤390	2.3
FC-10	HI Decomp. Feed Flow Control	Glass-Teflon	HI (I_2,H_2O)	∿390	--
FC-11	HI Decomp. Recycle Feed Flow Control	Glass-Teflon	HI	∿300	--
FC-12	Cold Trap CT-2 Bypass Flow Control	Glass-Teflon	H_2,HI,I_2 (H_2O)	∿300	--
FC-13	HI Makeup Feed Flow Control	Glass-Teflon	HI (I_2,H_2O)	∿300	--
FC-14	Auxiliary Boilup Water for V-8 Flow Control	Stainless Steel	H_2O (H_3PO_4)	∿300	--
FI-1	HI Makeup Supply Flow Rotameter	Kynar-Glass	HI (I_2,H_2O)	∿300	--
FI-2	Heavy Phase Feed ΔP Orifice	Teflon	HI,I_2,H_2O (H_2SO_4)	390	--
FI-3	H_2O Scrub Flow Rotameter for V-5	Kynar-Glass	H_2O (I_2,H_3PO_4)	∿300	1.7
FI-4	HI Distillation Column V-7 Feed Flow Rotameter	Kynar-Glass	H_3PO_4,HI,H_2O (I_2,H_2SO_4)	<390	--
FI-5	H_3PO_4 Distillation Column V-9 Feed Flow Rotameter	Kynar-Glass	H_3PO_4 (H_2O)	≤315	--
FI-6	Conc. H_3PO_4 Scrub Flow to V-7 Rotameter	Kynar-Glass	H_3PO_4 (H_2O)	≤315	--
FI-7	Conc. H_3PO_4 Scrub Flow to V-2 Rotameter	Kynar-Glass	H_3PO_4 (H_2O)	≤315	--
FI-8	HI Decomposer Feed Flow Rotameter	Kynar-Glass	HI (I_2,H_2O)	∿400	--
FI-9	HI Decomposer Recycle Feed Flow Rotameter	Kynar-Glass	HI	∿400	--
FI-10	Scrubbed H_2 Product Rotameter	Kynar-Glass	H_2 (H_2O)	∿300	--
FI-11	H_2 Feed Flow to V-13 Rotameter	Kynar-Glass	H_2,HI (I_2)	≤300	--
FI-12	H_2O Scrub Flow Rotameter to H_2 Scrub Column V-13	Kynar-Glass	H_2O (H_2,HI)	∿300	--
FI-13	Cold Trap CT-2 Bypass Flow Rotameter	Kynar-Glass	HI,H_2 (I_2)	∿390	--
FI-14	Auxiliary Boilup Water for V-8 Flow Rotameter	Kynar-Glass	H_2O (H_3PO_4)	∿300	--
H-1A	Feed Tank V-1A Circulation Line Heater	(c)	--	≥390	--
H-2B	Feed Tank V-1B Circulation Line Heater	(c)	--	≥390	--
H-2	I_2 Separation Column V-2 Heater	(c)	--	≥390	--
H-3	C-4, C-5, and V-3 Air Supply Heater	(c)	--	≥390	--
H-4	I_2 Scrub Column V-5 Heater	(c)	--	≥390	--
H-5	I_2 Scrub Aqueous Raffinate Recycle Feed to V-2 Heater	(c)	--	≥390	--
H-6	Conc. H_3PO_4 Feed to V-2 Heater	(c)	--	≥390	--
H-7	H_2O Scrub Feed to V-5 Heater	(c)	--	≥390	--
H-8	HI Distillation Column V-7 Feed Heater	(c)	--	∿400	--
H-9	HI Still Reboiler V-8 Heater	(c)	--	425	--
H-10	HI Distillation Column V-7 Heater	(c)	--	≥425	--
H-11	H_3PO_4 Concentration Column V-9 Feed Heater	(c)	--	425	--

TABLE 1 (Continued)

Equipment Number	Equipment Name	Material of Construction	Normal Process Materials Expcsure[a]	Normal Operating Conditions	
				Temperature °K	Pressure Pax10^{-5}[b]
H-12	H_3PO_4 Concentration Column V-9 Heater	(c)	--	490	--
H-13	Conc. H_3PO_4 Feed to HI Dist. Col. V-7 Heater	(c)	--	≥390	--
H-15	I_2-HI Phase Separator R-1 Heater	(c)	--	∿400	--
H-16	HI Decomposition Furnace	(c)	--	388	--
H-17	I_2 Condensation Prevention Heater for V-12	(c)	--	≤1000	--
H-18	HI Recycle Feed to V-12 Heater	(c)	--	400	--
H-19	I_2-HI Phase Separator R-2 Heater	(c)	--	400	--
H-21	HI Decomposition Vessel V-12 Feed Heater	(c)	--	≤500	--
H-22	Conc. H_3PO_4 Reboiler V-10 Heater	(c)	--	∿315	--
H-23	Product H_2 from V-13 Heater	(c)	--	315	--
LC-1	Column V-2 I_2-H_3PO_4 Interface Level Control	Glass-Teflon	I_2 (H_3PO_4)	390	--
LC-2	Column V-5 I_2-H_2O Interface Level Control	Glass-Teflon	I_2 (H_2O)	390	1.7
LC-3	HI Distillation Reboiler V-8 Level Control	Glass-Teflon	H_3PO_4,H_2O (S)	≥315	--
LC-4	Conc. H_3PO_4 Reboiler V-10 Level Control	Glass-Teflon	H_3PO_4 (H_2O)	≥315	--
LC-5	I_2 Level Control for Phase Separator R-1	Glass-Teflon	I_2 (HI,H_2O)	388	--
LC-6	I_2 Level Control for Phase Separator R-2	Glass-Teflon	I_2 (HI)	388	--
LC-7	Pump P-7 Bypass Valve for Level Control in V-14	Glass-Teflon	H_2O,HI	∿300	∿1.3 max
LC-8	Pump P-3 Bypass Valve for Level Control in V-4	Glass-Teflon	H_2O,H_3PO_4 (I_2)	<375	∿1.3 max
LI	All LI functions are by visual sight in glass equipment.	--	--	--	--
P-1	Feed Input Positive Displacement Pump	Carbon-alumina	HI,H_2,H_2O (H_2SO_4)	369	0.006 - 1013
P-2A	Tank V-1A Feed Output Pump	Polypropylene	HI,I_2,H_2O (H_2SO_4)	390	∿1.3 max
P-2B	Tank V-1B Feed Output Pump	Polypropylene	HI,I_2,H_2O (H_2SO_4)	390	∿1.3 max
P-3	I_2 Scrub Aqueous Raffinate Recycle Pump	Polypropylene	H_2O,H_3PO_4 (I_2)	<390	∿1.3 max
P-4	HI Distillation Column V-7 Feed Metering Pump	Carbon-alumina	HI,H_2PO_4,H_2O (I_2,H_2SO_4)	≤315	--
P-5	H_3PO_4 Concentration Column Feed Metering Pump	Carbon-alumina	H_3PO_4,H_2O	≤315	--
P-6	Conc. H_3PO_4 Recycle Pump	Polypropylene	H_3PO_4 (H_2O)	≤315	∿1.3 max

TABLE (Continued)

Equipment Number	Equipment Name	Material of Construction	Normal Process Materials Exposure[a]	Normal Operating Conditions	
				Temperature °K	Pressure Pa×10^{-5}[b]
P-7	H_2 Scrub Aqueous Raffinate Recycle Pump	Polypropylene	H_2O,HI	∿300	∿1.3 max
P-8	V-5 I_2 Positive Displacement Feed Pump	Carbon-alumina	I_2 (H_3PO_4)	390	1.0 - 1.7
PCV-1	HI Decomposer Feed System Pressure Control	Teflon	HI (I_2,H_2O)	390	(d)
PCV-2	I_2 Scrub Column V-5 Pressure Control	Teflon	H_2O,H_3PO_4 (I)	390	1.7
PCV-3	HI CT-2 Bypass Metering Pressure Control	Teflon	HI,H_2,I_2 (H_2O)	390	--
PI-1A	Makeup Tank V-1A Pressure Gauge	(e)	HI,N_2,H_2O,I_2	<390	--
PI-1B	Makeup Tank V-1B Pressure Gauge	(e)	HI,N_2,H_2O,I_2	<390	--
PI-2	Feed to I_2 Scrub Column V-2 Flow Manometer	Glass-Teflon	HI,I_2,H_2O (H_2SO_4)	390	ΔP∿0.15 m I_2(ℓ)
PI-3	I_2 Scrub Column V-5 Pressure Gauge	(e)	I_2 (H_3PO_4)	390	1.7
PI-4	HI Decomposer Feed Pressure Gauge	(e)	HI (I_2,H_2O)	390	--
PRV-1	Positive Displacement Pump P-1 Pressure Relief Valve	Teflon	HI,I_2,H_2O (H_2SO_4)	368	(f)
PRV-2A	Makeup Tank V-1A Pressure Relief Valve	Teflon	HI,I_2,H_2O	<390	(f)
PRV-2B	Makeup Tank V-1B Pressure Relief Valve	Teflon	HI,I_2,H_2O	<390	(f)
PRV-3	Metering Pump P-4 Pressure Relief Valve	Teflon	HI,H_3PO_4,H_2O (I_2 H_2SO_4)	<315	(f)
PRV-4	Metering Pump P-8 Pressure Relief Valve	Teflon	H_3PO_4,H_2O (S)	<315	(f)
PRV-5	Cold Trap CT-1 Pressure Relief Valve	Teflon	HI (I_2,H_2O)	∿300	(f)
PRV-6	Cold Trap CT-2 Pressure Relief Valve	Teflon	HI,H_2	∿300	(f)
PRV-7	Cold Trap CT-3 Pressure Relief Valve	Teflon	HI,H_2	∿300	(f)
PRV-8	Positive Displacement Pump P-8 Pressure Relief Valve	Teflon	I_2 (H_3PO_4)	390	1.7
PS-1	Pump P-4 Flow Pulsation Snubber	Teflon-Stainless Steel	H_3PO_4,H_2O	<315	--
PS-2	Pump P-5 Flow Pulsation Snubber	Teflon-Stainless Steel	H_3PO_4,H_2O	<315	--
R-1	I_2-HI Phase Separator for I_2 Condenser C-4	Glass	HI (I_2,H_2O)	388	--
R-2	I_2-HI-H_2 Phase Separator for I_2 Condenser C-5	Glass	HI,I_2,H_2 (H_2O)	388	--
TC-1A	H-1A Heater Controller, Makeup Tank 1-A	--	--	≥390	--
TC-1B	H-1B Heater Controller, Makeup Tank 1-B	--	--	≥390	--
TC-2	H-2 Heater Controller, I_2 Separation Column V-2	--	--	≥390	
TC-3	H-3 Heater Controller, I_2 Surge Tank V-3	--	--	≥390	--

TABLE 1 (Continued)

Equipment Number	Equipment Name	Material of Construction	Normal Process Materials Exposure[a]	Normal Operating Conditions	
				Temperature °K	Pressure $Pa \times 10^{-5}$[b]
TC-4	H-4 Heater Controller, I_2 Scrub Column V-5	--	--	≥390	--
TC-5	H-8 Heater Controller, HI Dist. Col. Feed V-7	--	--	~400	--
TC-6	H-9 Heater Controller, HI Dist. Reboiler V-8	--	--	≥425	--
TC-7	H-11 Heater Controller, H_3PO_4 Conc. Col. V-9 Feed	--	--	425	--
TC-8	Heater H-22 Controller, H_3PO_4 Conc. Reboiler V-10	--	--	≤500	--
TC-9	Heater H-13 Controller, HI Dist. Col. V-7 HI Output	--	--	≥390	--
TC-10	Heater H-10 Controller, HI Dist. Col. V-7 HI Output	--	--	≥425	--
TC-12	Heater H-15 Controller, I_2 Phase Separator R-1	--	--	~400	--
TC-13	Heater H-16 Controller, HI Decomp. Furnace	--	--	388	--
TC-15	Heater H-19 Controller, I_2 Phase Separator R-2	--	--	~400	--
TI-1	Feed to V-2 Temperature	(g)	--	390	--
TI-2	H_2O Raffinate of I_2 Scrub to V-2 Temperature	(g)	--	390	--
TI-3	Conc. H_3PO_4 Feed to V-2 Temperature	(g)	--	390	--
TI-4	H_2O Scrub to V-5 Temperature	(g)	--	390	--
TI-5	HI-H_3PO_4-H_2O Overflow from V-2 Temperature	(g)	--	390	--
TI-6	Wet H_3PO_4 Surge Tank V-16 Temperature	(g)	--	≤315	--
TI-7	Dry H_3PO_4 Surge Tank V-11 Temperature	(g)	--	≤315	--
TI-8	Feed Filter F-1 Temperature	(g)	--	390	--
TI-9	I_2 Condenser C-4 Air Supply Temperature	(g)	--	≥400	--
TI-10	Scrubbed H_2 Product Temperature, from V-13	(g)	--	~300	--
TI-11	HI Decomposition Temperature in V-12	(g)	--	390-1000	--
TI-12	HI Decomposition Feed Inlet Temperature to V-12	(g)	--	~400	--

TABLE 1 (Continued)

Equipment Number	Equipment Name	Materials of Construction	Normal Process Materials Exposure[a]	Normal Operating Conditions	
				Temperature °K	Pressure Pa×10^{-5}[b]
TI-13	I_2 Condenser C-5 Air Supply Temperature	(g)	--	≥400	--
TI-14	Waste Water Temperature, to V-15	(g)	--	≥315	--
V-1A	Feed Makeup and Storage Tank	Glass	HI,I_2,H_2O (H_2SO_4)	390	--
V-1B	Alternate Feed Makeup and Storage Tank	Glass	HI,I_2,H_2O (H_2SO_4)	390	--
V-2	I_2 Separation Column	Glass	HI,H_3PO_4,I_2,H_2O (H_2SO_4)	390	--
V-3	I_2 Surge Tank	Glass	I_2 (H_3PO_4)	390	--
V-4	H_2O Raffinate of I_2 Scrub Surge Tank	Glass	H_2O,H_3PO_4 (I_2)	∿375	1.7
V-5	I_2 Scrub Column	Glass	H_2O,I_2 (H_3PO_4)	390	--
V-6	Feed for HI Distillation Surge Tank	Glass	HI,H_3PO_4,H_2O (I_2,H_2SO_4)	≤390	--
V-7	HI Extractive Distillation Column	Glass	HI,H_3PO_4,H_2O (I_2,S)	≤425	--
V-8	HI Distillation Reboiler	Glass	H_3PO_4,H_2O (S)	425	--
V-9	H_3PO_4 Concentration Column	Glass	H_3PO_4,H_2O	≤490	--
V-10	H_3PO_4 Concentration Column Reboiler	Glass	H_3PO_4 (H_2O)	≤500	--
V-11	Concentrated H_3PO_4 Surge Tank	Glass	H_3PO_4 (H_2O)	≤315	--
V-12	HI Decomposer Vessel	Quartz	HI,H_2,I_2 (H_2O)	390-1000	--
V-13	H_2 Product Scrubbing Column	Glass	H_2O,H_2,HI	∿300	--
V-14	H_2 Scrubbing Column V-13 Surge Tank	Glass	H_2O,HI (H_2)	∿300	--
V-15	Waste H_2O Collection Vessel	Polypropylene	H_2O	≤315	--
V-16	H_3PO_4 Concentration Column Feed Surge Tank	Glass	H_3PO_4,H_2O	≤315	--
VA-1	N_2 Purge Shutoff Valve	Teflon	N_2 (HI)	∿300	--
VA-2	Heavy Phase Feed Bypass Valve	Teflon	HI,I_2,H_2O (H_2SO_4)	368	∿1.3 max
VA-3	Makeup Tanks V-1A and B Interconnection Valve	Teflon	HI,I_2,H_2O (H_2SO_4)	390	--
VA-4	Feed Sample Valve	Teflon	HI,I_2,H_2O (H_2SO_4)	390	--
VA-5A	Gases Feed Valve to Tank 1A	Teflon	HI,N_2 (I_2,H_2O)	<390	--
VA-5B	Gases Feed Valve to Tank 1B	Teflon	HI,N_2 (I_2,H_2O)	<390	--
VA-6A	Heavy Phase Inlet Valve to Tank 1A	Teflon	HI,I_2,H_2O (H_2SO_4)	≥368	--
VA-6B	Heavy Phase Inlet Valve to Tank 1B	Teflon	HI,I_2,H_2O (H_2SO_4)	≥368	--
VA-7A	Tank 1A Outlet Valve	Teflon	HI,I_2,H_2O (H_2SO_4)	390	--
VA-7B	Tank 1B Outlet Valve	Teflon	HI,I_2,H_2O (H_2SO_4)	390	--
VA-8A	Pump P-2A Discharge Throttle Valve	Teflon	HI,I_2,H_2O (H_2SO_4)	390	∿1.3 max
VA-8B	Pump P-2B Discharge Throttle Valve	Teflon	HI,I_2,H_2O (H_2SO_4)	390	∿1.3 max
VA-9	Filter F-1 Bypass Valve	Teflon	HI,I_2,H_2O (H_2SO_4)	390	--
VA-10A	Filter F-1 Outlet Valve	Teflon	HI,I_2,H_2O (H_2SO_4)	390	--
VA-10B	Filter F-1 Inlet Valve	Teflon	HI,I_2,H_2O (H_2SO_4)	390	

TABLE 1 (Continued)

Equipment Number	Equipment Name	Materials of Construction	Normal Process Materials Exposure[a]	Normal Operating Conditions	
				Temperature °K	Pressure Pa×10^{-5}[b]
VA-11	I_2 Scrub Raffinate Tank V-4 Drain Valve	Teflon	H_2O,H_3PO_4 (I_2)	<375	--
VA-12	HI Distillation Column Feed Sample Valve	Teflon	HI,H_3PO_4,H_2O (I_2,H_2SO_4)	∿400	--
VA-13	H_3PO_4 Concentration Columns Feed Tank V-16 Drain Valve	Teflon	H_3PO_4,H_2O	≤315	--
VA-14	H_3PO_4 Concentration Column V-9 Feed Sample Valve	Teflon	H_3PO_4,H_2O	≤315	--
VA-15	Conc. H_3PO_4 Surge Tank V-11 Sample Valve	Teflon	H_3PO_4 (H_2O)	≤315	--
VA-16	Conc. H_3PO_4 Pump P-6 Discharge Drain Valve	Teflon	H_3PO_4 (H_2O)	≤315	--
VA-17	HI Decomposer V-12 Feed Sample Valve	Teflon	HI (I_2,H_2O)	390	--
VA-18	HI Decomposer V-12 Product Sample Valve	Glass	HI,H_2,I_2 (H_2O)	<460	--
VA-19	Pump P-7 to V-6 Discharge Valve	Teflon	H_2O,HI	∿300	1.3 max
VA-20	CT-1 HI Output Valve to Scrubbing	Teflon	H_2 (HI)	78-300	--
VA-21	CT-2 Transfer to CT-3 Valve	Teflon	HI,H_2 (I_2,H_2O)	78-300	--
VA-22	H_2 Product from CT-2 Outlet Valve	Teflon	H_2 (HI)	78-300	--
VA-23	CT-2 HI Output Recycle Valve	Teflon	HI (I_2,H_2O)	∿300	--
VA-24	CT-3 HI Output Recycle Valve	Teflon	HI (I_2,H_2O)	∿300	--
VA-25	HI Decomposer V-12 Fresh and Recycle Feed Mixing Valve	Teflon	HI (I_2,H_2O)	390	--
VA-26	H_2 Product from CT-3 Outlet Valve	Teflon	H_2 (HI)	78-300	--
VA-27	H_2 Scrub Raffinate from V-14 Sample Valve	Teflon	H_2O,HI (H_2)	∿300	--
VA-28	Sulfur Filter F-2 Bypass Valve	Teflon	H_3PO_4,H_2O (S)	≤315	--
VA-29	Sulfur Filter F-2 Outlet Valve	Teflon	H_3PO_4,H_2O	≤315	--
VA-30	Sulfur Filter F-2 Inlet Valve	Teflon	H_3PO_4,H_2O (S)	≤315	--
VA-31	Recycle HI Sample Valve	Teflon	HI (I_2,H_2O)	∿300	--
VA-32	H_2 Product Outlet-Sample Valve, before Scrubbing	Teflon	H_2 (HI)	>78	--
VA-33	H_2 Product Feed Shutoff Valve to Scrubbing	Teflon	H_2 (HI)	>78	--
VA-34	Scrubbing Column V-13 Raffinate Recirculation valve	Teflon	H_2O,HI (H_2O)	∿300	1.3 max
VA-35	N_2 Purge Valve to HI Decomposition Feed Stream	Teflon	N_2,HI (I_2,H_2O)	<390	--
VA-36	N_2 Purge Shutoff Valve to H_3PO_4 Portion of System	Teflon	HI,N_2 (I_2,H_2O)	≤390	--
VA-37	H_2O Supply-Shutoff Valve to H_2 Scrubber V-13	Teflon	H_2O	∿300	∿2.0
VA-38	Condensed I_2 in R-1 Recycle Valve to V-2	Teflon	I_2 (HI,H_2O)	390	--

TABLE 1 (Continued)

Equipment Number	Equipment Name	Materials of Construction	Normal Process Materials Exposure[a]	Normal Operating Conditions	
				Temperature °K	Pressure Pa×10^{-5}[b]
VA-39	Condensed I_2 in R-2 Recycle Valve to V-2	Teflon	I_2 (HI,H_2O)	390	--
VA-40	Air Supply Shutoff Valve	Stainless Steel	Air	∿300	∿2.3
VA-41	CT-1 HI Output Recycle Valve	Teflon	H_2 (HI)	∿300	--

(a) Constituents present only in small amounts are shown parenthetically.

(b) Unless otherwise specified, pressure is ambient to ambient plus a liquid head of a few centimeters to no more than 1/2meter.

(c) Heaters are on the exterior of equipment and do not contact process materials; heater materials of construction are not specified.

(d) Pressure is set empirically at the minimum amount above ambient that will afford pressure control, e.g., PCV-1, probably on the order of 0.1×10^5 Pa, gauge.

(e) Gauges are steel bourdon-tube type filled with silicone oil and are protected from contact with process materials by a Teflon diaphragm.

(f) Pressure relief valves are adjustable and will be set to relieve at pressures somewhat in excess of working pressure, which in most cases is slightly above ambient pressure.

(g) Temperatures are measured in glass or teflon thermowells or on the exterior of the equipment and does not contact process materials; thermocouple materials in temperature measurement service is not specified.

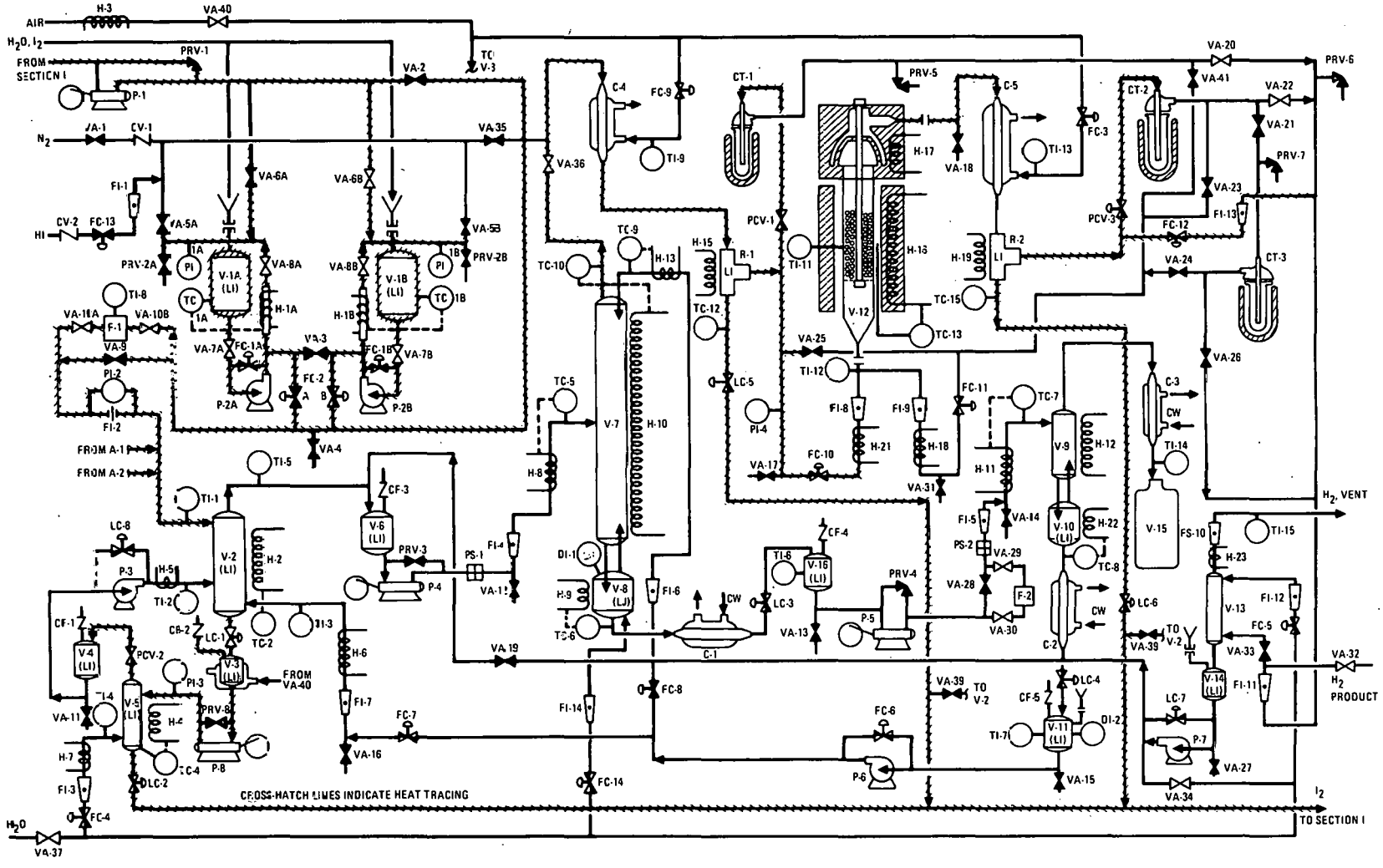


Fig. 1. Subunit III, HI concentration and decomposition system

phase, leaving nearly all the iodine as a heavy liquid, which flows from the bottom of V-2 by gravity into surge tank V-3. H_3PO_4-H_2O-HI solution overflows from the top of V-2 into surge tank V-6. The interface level between liquid I_2 and the H_3PO_4 solution in V-2 is controlled manually by valve LC-1. Liquid iodine from V-3 is metered by positive displacement pump P-8 into pressurized packed column V-5, where the iodine is contacted with water to remove entrained H_3PO_4. The scrub is done at about 1.7×10^5 Pa instead of ambient atmospheric pressure so that water will be liquid at a temperature a little above the melting point of iodine (386.7 K). The interface level between liquid I_2 and water in V-5 is controlled manually by valve LC-2. The pressure drop between V-5 and vapor disengagement tank V-4 is controlled by PCV-2. From V-4 the dilute H_3PO_4 solution is pumped into V-2 at a suitable feed point somewhat above the lower outlet of V-2. HI not removed from the I_2 in V-2 is removed in V-5.

It is not certain whether the subsystem consisting of V-4, P-3, and H-5 is necessary. It may be possible to connect PCV-2 directly to the dilute H_3PO_4 solution recycle feed point on V-2, or directly through a single line cooler. The practicality of making the direct connection will depend on the operational "touchiness" of column V-2 in relation to the steadiness of the operating conditions attainable in V-5 under practical operating conditions. The overflow subsystem for V-5 shown in Fig. 1 is conservative; it positively uncouples the dynamic output behavior of V-5 from the conditions at the dilute H_3PO_4 recycle feed point on V-2.

The H_3PO_4-HI-H_2O overflow in V-6 is metered by positive displacement pump P-4 into packed distillation column V-7 at a temperature that is controlled to be approximately the boiling point of the feed mixture. Dry H_3PO_4 is introduced into the top of V-7 as a water extraction agent and acts as the overhead reflux condensate stream of an ordinary distillation. The feed/reflux ratio is adjusted so that HI-H_2O azeotrope of the binary vapor-liquid equilibrium does not occur. HI is prevented from leaving the bottom column of V-7 by boilup of H_2O vapor from V-8, the still reboiler.

If there is no water flow into V-8 via FC-12 and FI-12, the boilup rate from V-8 is not an independent variable. It is set by the feed/reflux ratio that is required to keep H_2O out of the HI effluent and by the need to keep the H_3PO_4 concentration in the liquid phase above 85.0%, below which concentration an HI-H_2O azeotrope can occur. In order to ensure that there will be sufficient vapor boilup to keep HI out of V-8, an auxiliary water input to V-8 was specified, although it may not be necessary to use it.

Hot H_3PO_4 solution leaving V-8 by gravity flow is cooled in C-1 to protect downstream plastic parts from heat softening and swelling attack. The cool solution is then pumped through filter F-2 to remove any elemental sulfur that may have formed in V-7.

F-2 of the flowsheet is representative of the need to provide a purge point in the system for the removal of sulfur species. Actual heavy phase normally contains a small amount of sulfur, probably mostly as H_2SO_4. The inevitable process upset and operational control problems that are typical of new experimental bench-scale continuous processing systems will occasionally lead to a high sulfur content in the heavy phase. The introduction of F-2 into the flowsheet provides a means to purge sulfur species from the system.

Filtered H_3PO_4 solution from F-2 is then fed to a packed distillation column (V-9) where water is vaporized. Liquid of approximately 100% H_3PO_4 leaves at the bottom.

In principle, reboiler V-10 is not needed, but in practice it seems appropriate to have backup H_2O vaporization capability to allow for possible operational touchiness and short circuit flows. Hot 100% H_3PO_4 flows by gravity from V-10 through C-2, where it is cooled to protect downstream plastic parts. Cooled 100% H_3PO_4 is collected in surge tank V-11 and is then pumped by P-6 for use in V-2 and V-7.

The HI vapor leaving the top of V-7 is cooled in C-4 to slightly above the melting point of I_2 to condense as much as possible any I_2 that may be present. The I_2 that condenses in C-4 will probably originate mainly from the separation step in V-2 not being perfect; however, some of it may originate in premature HI decomposition in V-7. Condensed $I_2(\ell)$ is then separated from the HI vapor in R-4, and the vapor is metered into the bottom of the HI decomposer (V-12). The HI feed system for V-12 is fairly elaborate in order to permit careful control during experiments for accurately defining the kinetics of the HI decomposition.

Heat input and temperature control for the HI decomposition are provided by furnace H-16. Heater H-17 guards against condensation of I_2, which could drip back into the catalyst bed.

Iodine from the decomposition of HI in V-12 is condensed as liquid in C-5 and is separated from the remaining HI vapor - H_2 gas mixture in R-2. The HI vapor is then frozen out of the H_2 gas in liquid nitrogen cold trap CT-2. A small amount of residual I_2 vapor, along with any adventitious H_2O vapor and volatile sulfur species (probably SO_2 and/or H_2S), will also freeze out with the HI. Virtually pure hydrogen then leaves the system through valve VA-22, flowmeter FI-11, and valve VA-32.

Liquid nitrogen cold traps CT-1, CT-2, and CT-3 are interconnected so as to permit continuous recycle of undecomposed HI back to V-12 even though the traps are of the batch type, with the freezeout occurring as solids instead of as liquid condensation. In order to model the proposed final water scrub of HI from the H_2 product in the base plant conceptual flowsheet, a metered bypass of CT-2, via FC-12 and FI-13, is provided, and a final water scrub of the H_2 product can be introduced by opening valve VA-33 and closing valve VA-32. The H_2 product stream is then scrubbed with water in packed column V-13. Dilute HI solution flows by gravity from the bottom of V-13 into surge tank V-14, from which it is then pumped to surge tank V-6, the feed supply of the HI extractive distillation column V-7.

2.1.3. Equipment Listing

The equipment for subunit III is listed in Table 1.

2.2. INSTALLATION AND OPERATION OF SUBUNIT I

2.2.1. Subunit I Design Changes

The work on subunit I in 1979 began with an assessment of the design of this system as it existed at the end of 1978. The purpose of the assessment was to determine practicable design changes for improving the operability, control, and energy utilization of this system. The assessment drew heavily from actual operating experience acquired during 1978. The assessment resulted in the proposal of several specific changes, which are described in Table 2. Implementation of these changes resulted in the system shown schematically in Figs. 2 and 3.

The revised system differed from the original design (Ref. 2-1) in the following ways:

1. The revised system temporarily has no capability for recycling $SO_2(g)$ from the first phase separator (R-102) to the reactor (R-101).

2. The revised system temporarily has no capability for recycling reactor (R-101) product as mixed liquid phases from R-102 to R-101 inlet.

3. The revised system originally had no capability to degas the heavy phase from the second phase separator (R-103). This capability has now been provided by a vacuum degassing column.

4. The iodine melt vessels (V-101A and V-101B) were removed from heated, insulated boxes and provided with electrical heating mantles.

TABLE 2
WATER-SPLITTING BENCH-SCALE INVESTIGATION, SUBUNIT I DESIGN ASSESSMENT

Section	Description of Change	Reason for Change
I_2 fusion and injection	1. Insulate vessels V-1A and V-1B with Fibrefax. Provide heating mantles.	1. Existing vessels use external heating coils without insulation. Difficult to keep I_2 fused.
	2. Use glass I_2 transfer line with minimum 4-mm i.d. Operating pressure approximately 30 psig max.	2. Existing 1/4-in.-o.d. Teflon tube plugged.
	3. Modify I_2 injection at reactor R-1. Use jet nozzle concept per Sketch 3260005-R1-1.	3. Prevent I_2 solidification and plugging at point of contact with H_2O and SO_2.
	4. Replace F1-3B with a direct-readout calibratable, non-plugging flowmeter. (Example: rotameter with Teflon-coated metal tube and float and magnetic follower.)	4. Existing small-bore glass tube plugs and has an uncalibrated manometer readout.
SO_2 injection	1. Wrap the SO_2 transfer line with heating tape; heat to approximately 120°C.	1. Prevent cooling and solidification of of I_2 at point of contact with SO_2.
	2. Repair FC-1. Transistor needs to be replaced.	2. Controller does not work.
	3. Install SO_2 recycle loop and wrap recycle line with heating tape.	3. Present subunit I cannot recycle SO_2 from separator R-2 per original design.
H_2O injection	1. Wrap H_2O transfer line with heating tape; heat to approximately 120°C.	1. Prevent cooling and solidification of I_2 at point of contact with H_2O.

TABLE 2 (Continued)

Section	Description of Change	Reason for Change
Mixed phases	1. Install R-1 product recycle loop. Add new check valve.	1. Increase mixing and conversion in reactor R-1.
	2. Install FC-6 downstream and close to separator R-2.	2. Improve level control in R-2 due to quicker response.
SO_2 stripping	1. Install SO_2 stripping loop, including V-2, V-3, V-4, and associated valves, tubing, and instruments.	1. This loop is presently not installed.
General	1. Replace the following four Teflon valves with glass valves: FC-4, FC-6, FC-8, and FC-9.	1. Teflon valves tend to leak.
	2. Add sample connections and valves at R-2 inlet, SO_2 from R-2, mixed phase from R-2.	2. Required to allow complete chemical analysis of unit performance.
	3. Modify insulated hot boxes to allow access to components from back of panel.	3. Existing boxes are mounted on aluminum panels with no access from rear. Heating tape without hot boxes is not adequate.
	4. Mount all hardware on Unistrut and Flexframe.	4. Required to provide maintenance access and to eliminate heat sink.

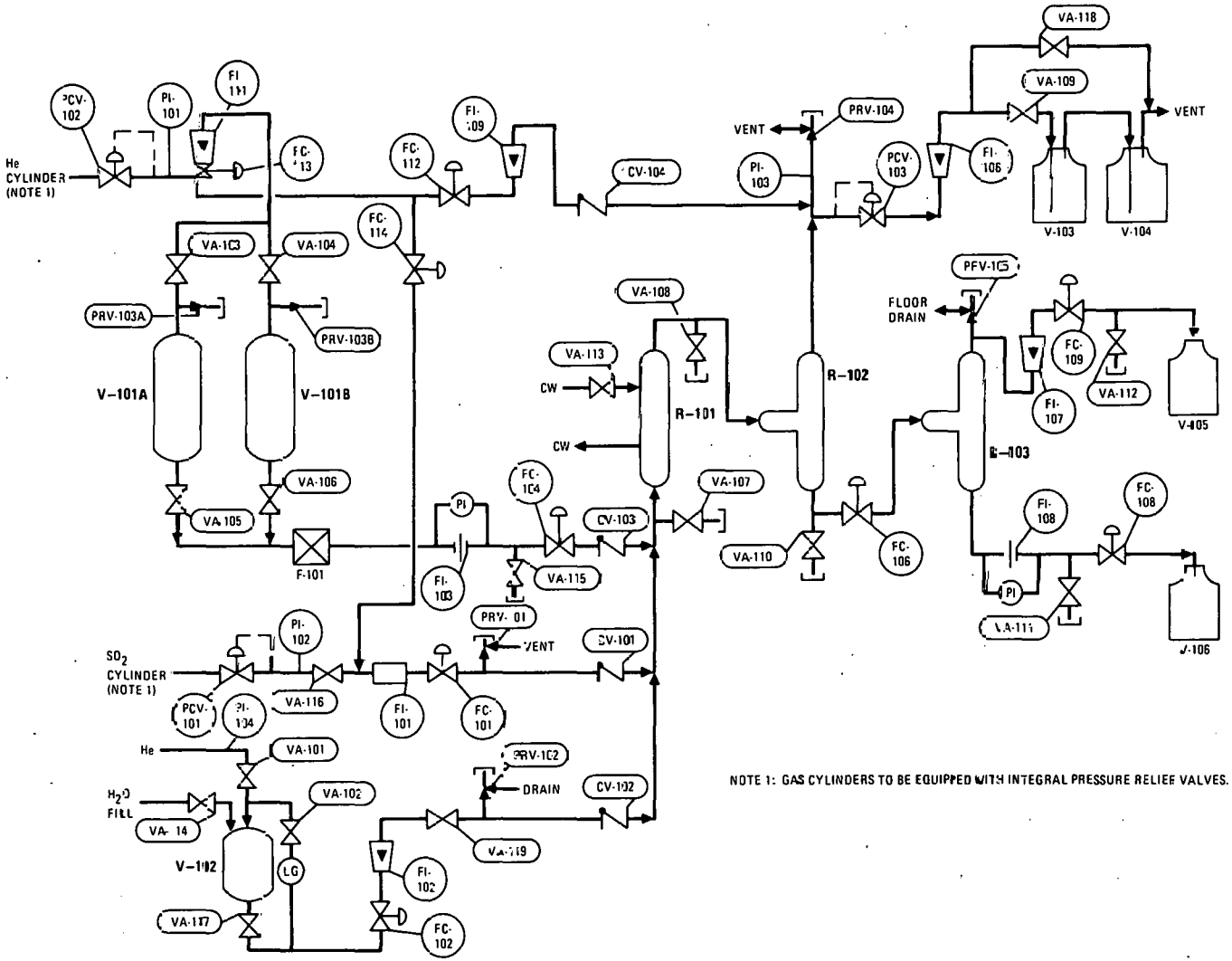
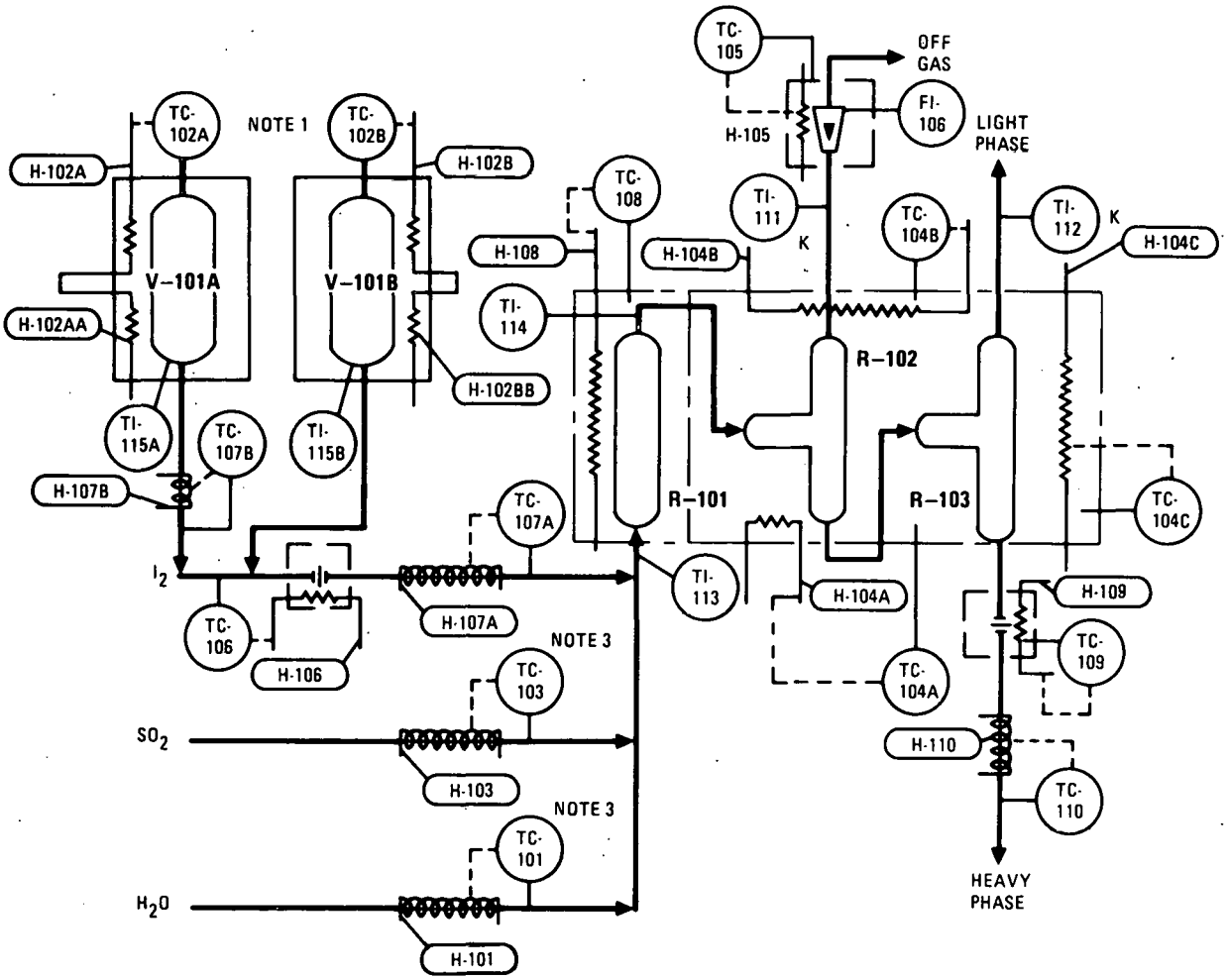


Fig. 2. Subunit I - vessels, piping, and controls



NOTES

1. INSTALL REDUNDANT THERMOCOUPLES. ONLY ONE CONNECTED TO RECORDER.
2. ALL THERMOCOUPLES TYPE J EXCEPT TI-111 AND TI-112 (TYPE K)
3. GLAS-COL CONTROLLERS. ALL OTHERS ARE BARBER-COLMAN.

Fig. 3. Subunit 1 - heaters, controllers, and thermocouples

5. The $I_2(\ell)$ injection port at reactor R-101 was modified as shown in Fig. 4.

This redesign of subunit I and issue of purchase orders for all new parts were completed by March 30, 1979.

A significant amount of thought and effort also went into the possibility of replacing some of the glass equipment of subunit I with metal equipment. This would result in a more easily operable system and would allow gathering of valuable materials corrosion data under actual operating conditions. Several areas of subunit I were identified for possible replacement of glass with metal vessels.

2.2.2. Construction of Subunit I

Construction of subunit I started on March 1 and was completed on May 29. Equipment shakedown, including leak-testing, instrument calibration, and verification of functional operability with water and inert gas, was completed by June 18.

No fundamental process design problems were discovered during shakedown. Several minor equipment design problems were uncovered. For example, the iodine flow sensing device (FI-103) did not function as required and iodine flow rates could not be accurately measured. An armored rotameter with remote readout has been ordered to replace the capillary manometer.

2.2.3. Shakedown and Operation of Subunit I

Operational shakedown of subunit I began in early July. The initial objective was to verify the ability of the system to melt and transport iodine to the reactor (R-101) in a reasonable time. The initial melting of approximately 9 kg of fresh crystals (bulk density approximately

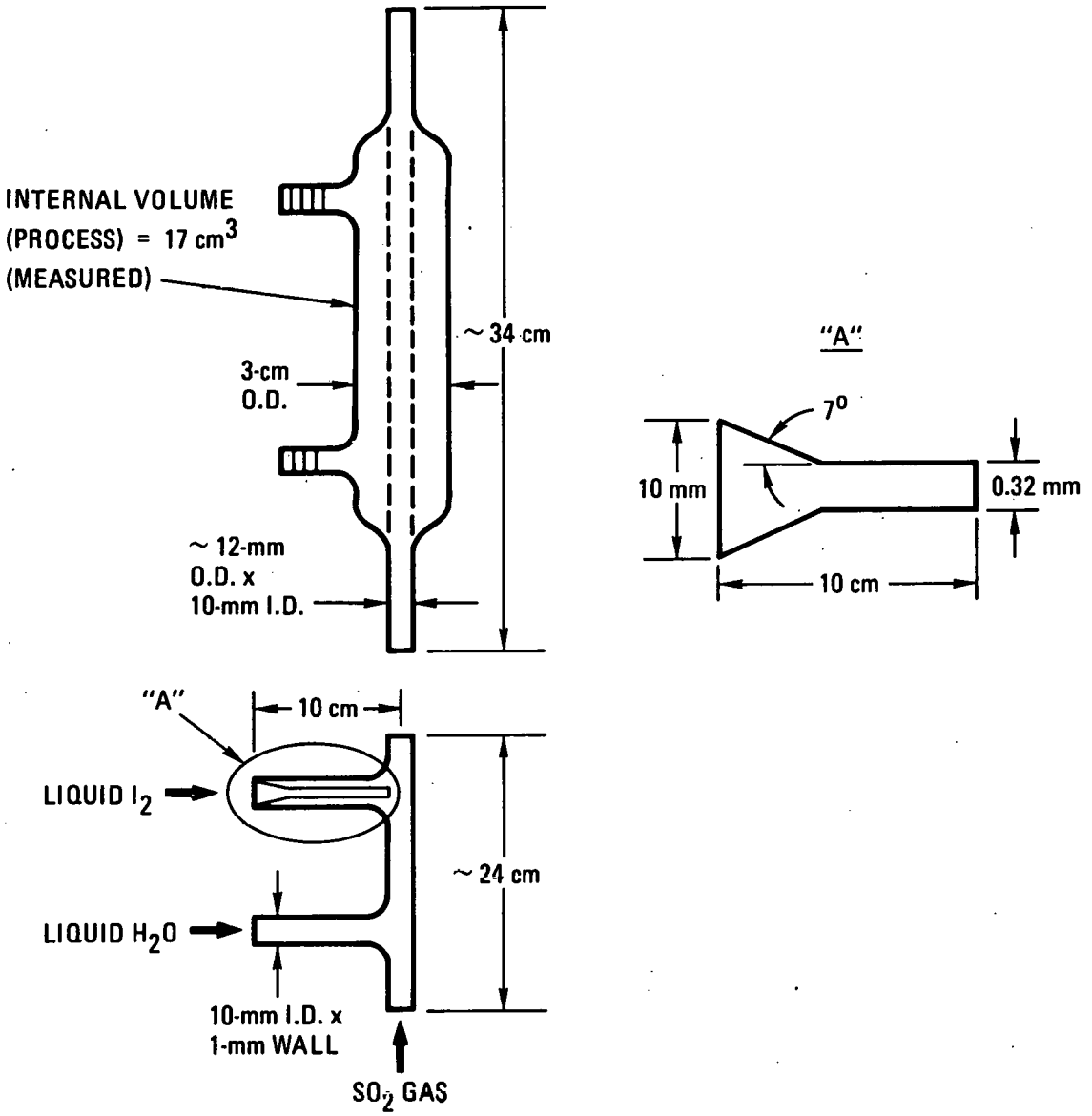


Fig. 4. Subunit I R-101 mixing entry

2.2 g/m^3) in a glass vessel was accomplished in 30 min with a 1-kW external electrical heating mantle. Resolidified iodine with a higher bulk density took somewhat longer to melt.

Several solid plugs occurred at cold spots in the heat-traced iodine feed line and prevented flow of the molten iodine. Numerous attempts to keep the system hot and to free these plugs failed. As a result of this experience, most of the glass parts in the iodine feed system were replaced with Hastelloy B tube and Hastelloy C valves (Whitey "NB" series). The main melt vessel is still glass but a melt vessel fabricated of Hastelloy C-276 has been designed and will be installed if funding is sufficient. The revised system is shown in Fig. 5.

Several experiments yielding useful data have been conducted with subunit I. The first experiment produced separable light and heavy acid phases over a 90-min period. Analysis of 73 g of light phase after degassing indicated an H_2SO_4 concentration of approximately 42 wt %, whereas the design concentration is 50 wt % without a "boost" reaction. Approximately 3.8 kg of heavy phase was also collected but not analyzed. These quantities resulted from the reaction of approximately 3 kg of purified liquid iodine with 1.2 liters of water. The average I_2/H_2O ratio was 2.5/1 (weight basis) as compared to 7/1 (design). A later experiment produced approximately 34 g of light phase with an H_2SO_4 concentration of approximately 48 wt % after degassing. This is very close to flowsheet design conditions. The heavy phase collected was very viscous, and the volume ratio of light-to-heavy phases was much lower than before. Approximately 3 kg of resublimed iodine reacted with 160 ml of water in a 40-min period, giving an average I_2/H_2O weight ratio of 19/1. The experiments up to this time were all of short duration and were conducted without benefit of adequate iodine or SO_2 flow indicators. Therefore, complete material balances were not obtainable for estimation of throughput in terms of equivalent hydrogen. After installation of the iodine flowmeter, quantitative experiments will be carried out to verify flowsheet conditions. These earlier qualitative experiments indicate that flowsheet conditions can be met without great difficulty.

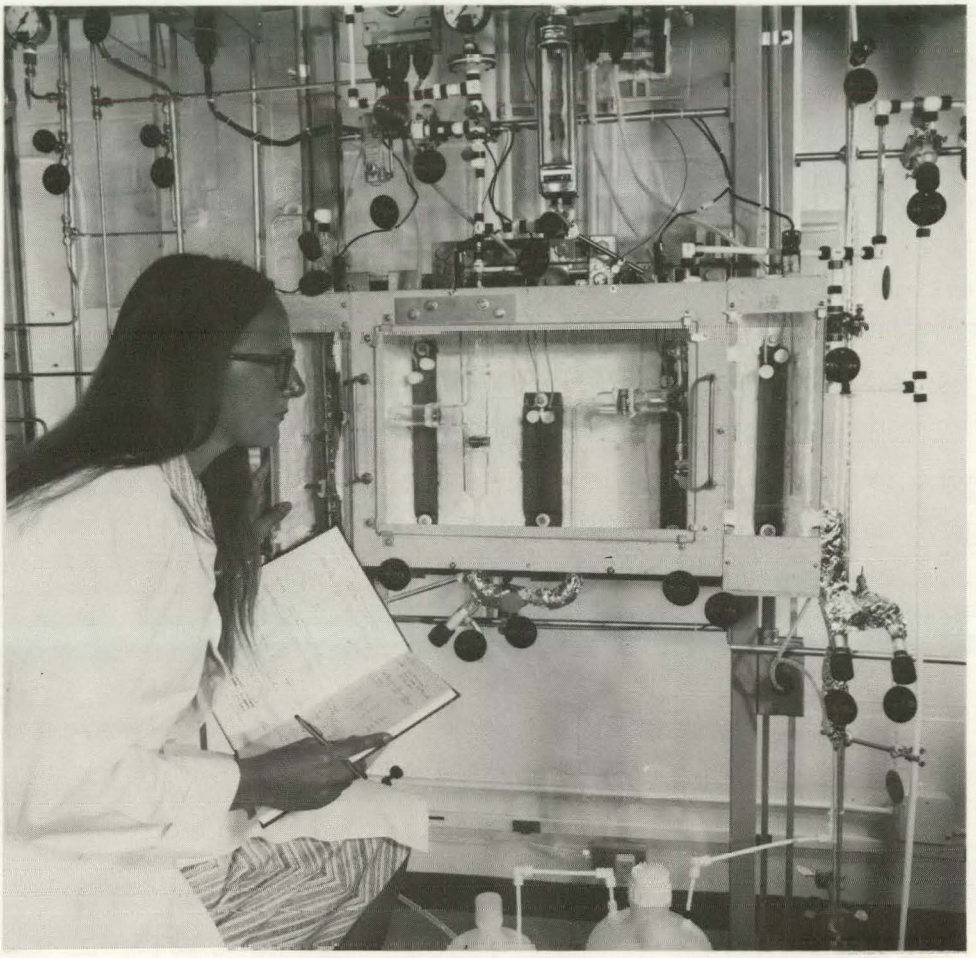


Fig. 5. Present design of subunit I

2.2.4. Iodine Supply

Early experiments in subunit I were done with iodine that had been purified by distillation. Although this procedure eliminated plugging of the mixing entry capillary with organic or mineral impurities, it was labor intensive; available equipment for distilling the iodine limited the purification rate to 6 to 7 kg/day. As an alternative to purification of the iodine on-hand, purchase of resublimed iodine from another supplier was investigated. Comparative analysis of resublimed iodine from Spectrum Chemical Manufacturing Corporation (Redondo Beach, Calif.), iodine crystals already on-hand, and distilled iodine showed the resublimed iodine to be superior (i.e., fewer impurities). Therefore, subsequent experiments were conducted with the resublimed iodine [assay: 99.8% I (minimum), nonvolatile impurities 0.010%, chloride and bromide (as Cl) 0.003%, balance uncharacterized organic material]. No plugging problems due to impurities were experienced.

2.3. INSTALLATION AND OPERATION OF SUBUNIT II

2.3.1. Construction of Subunit II

Construction of subunit II started on March 1 and was completed on May 14. Equipment shakedown, including leak-testing, instrument calibration, and verification of functional operability with water and inert gas, was completed by June 18.

As with subunit I, no fundamental process design problems were discovered during shakedown. Several minor equipment design problems, such as pump air lock and inoperable flow-indicators, were uncovered. The changes recommended to resolve these problems are described in more detail in Table 3. The system was subsequently modified to incorporate these changes. The design of subunit II is shown schematically in Fig. 7.

TABLE 3
SUBUNIT II MODIFICATIONS

Description of Change	Justification
1. Install vent valves on V-201A and V-201B recirculation lines between vessels and first shut-off valves. Order: 2-1/4-in. valves Mace Part No. 911-234-0	1. Pressure (or vacuum) builds up in V-201A and V-201B as level changes and reduces P-201 and P-202 flow capacity. Difficult to relieve gas through downflowing liquid from R-204.
2. Install vent valves on discharge side of pumps P-201 and P-202 as close to impeller housing as possible. Order: 2-1/4-in. valves Mace Part No. 911-234-0	2. It is difficult to vent air from system and pumps frequently airlock.
3. Replace orifice manometers FI-201 and FI-202 with rotameters. Use infrared scanner, as required, to find float. Order: Brooks Model 1355, Meter Size 2, Tube R-2-15-D, both glass and tantalum floats, anodized aluminum housing, 150-mm scale.	3. See Table 1, item 1.
4. Revise V-201A and V-201B fill lines: a. Replace with 5/8-in.-o.d. x 16-in. wall x 1/2-in.-long lines b. Provide funnel, 4-in. diameter x 4-in. cone height with 3/8-in. o.d. x 1/16-in. wall x 4-in. long stem. Support funnel with ring support.	4. Existing fill line makes spillage (of corrosive acid) unavoidable.
5. Remove F-201.	5. Not needed if FI-201 replaced (item 3).

TABLE 3 (Continued)

Description of Change	Justification
6. Fuse V-203.	6. Gasketed flange seal leaks and cannot be tightened further.
7. Relocate FC-203 downstream of PI-210.	7. Cannot measure P-202 discharge pressure in present location.
8. Install pressure gauges and control valves on discharge side of P-203 and P-204 pumps; valves to be located downstream of FI-203 and FI-206, respectively. (Relocate PI-204 upstream of new control valve.) Order: (a) 2-1/4-in. valves, Mace Part No. 911-234-0; (b) one Ashcraft pressure gauge, 0 to 30 psi, 1-psi increments, 2-1/2-in. dial; (c) gauge protector, Mace Part No. 966-2142-1-1-1.	8. Pressure gauges integral with pulse dampeners PS-201 and PS-202 do not function below 10 psig (actual system pressure approximately 3 to 6 psig). Presently, flow adjustment to concentrator and decomposer requires piston (cam) adjustment at pump. This is undesirable during operation. Outlet valves are acceptable to pump supplier.
9. Install higher power (400 W) minimum) heating mantle on V-206 Order: Cal-Glass, Inc., spherical heating mantle, Size No. 0-108-3, Part No. LG-8820.	9. Existing mantle (250 W) covers less than 30% of volume of V-206 and is not adequate to provide required boilup at 1.2 slpm H_2 (equivalent).
10. Provide miscellaneous spare fittings.	10. None exist. Required for configuration changes.
11. Fuse V-209.	11. See item 6.
12. Provide Teflon sleeves to seal glass joints. Order: ACE Glass, Inc., Vineland, N.J., Teflon sleeve 28/15.	12. Better seal and easier to install than hand-made sleeves.

TABLE 3 (Continued)

Description of Change	Justification
13. Modify decomposer furnace tube according to Sketch 326005-V8-2 (Fig. 6).	13. Required to facilitate loading and unloading of catalyst and catalyst support.
14. Install cooler between R-202 and LC-203/FI-204. Order: Liebig condensor Part No. LG-5180 Lab-Glass with 200-mm jacket length and 28/15 ball joint at one end and socket joint at other.	14. Required to protect LC-203 valve and FI-204 rotameter from excessive temperature (∿225°C). Temperature of recycle acid limited to 200°F by Teflon rotameter seals.
15. Order tantalum floats for six Brooks rotameters, Model 1355, Meter Size 2. Order: one float for tube R-2-15-A and five floats for tube R-2-14-D.	15. Required to extend range from 1.2 to 4.0 slpm H_2.

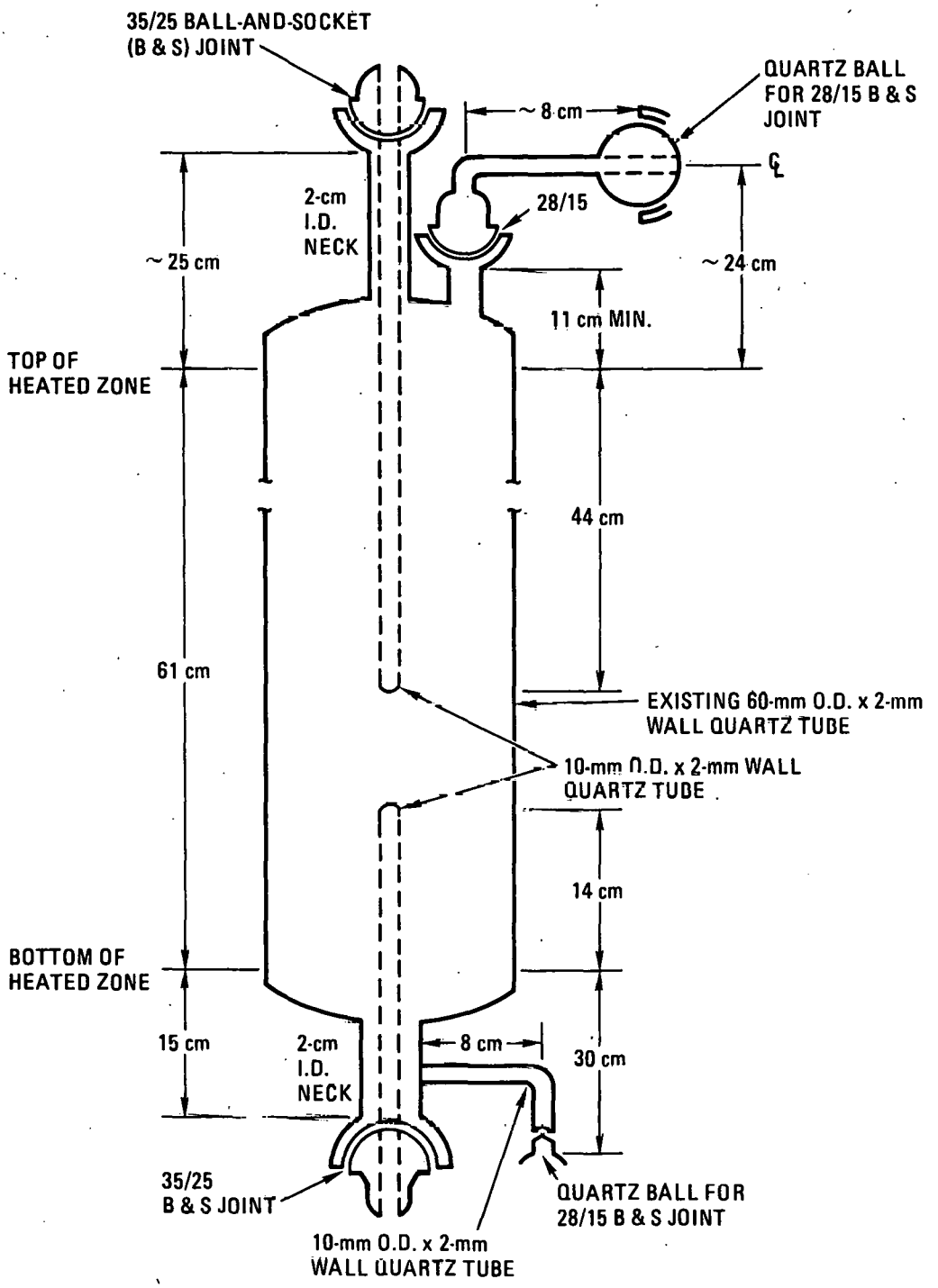


Fig. 6. Decomposer furnace tube

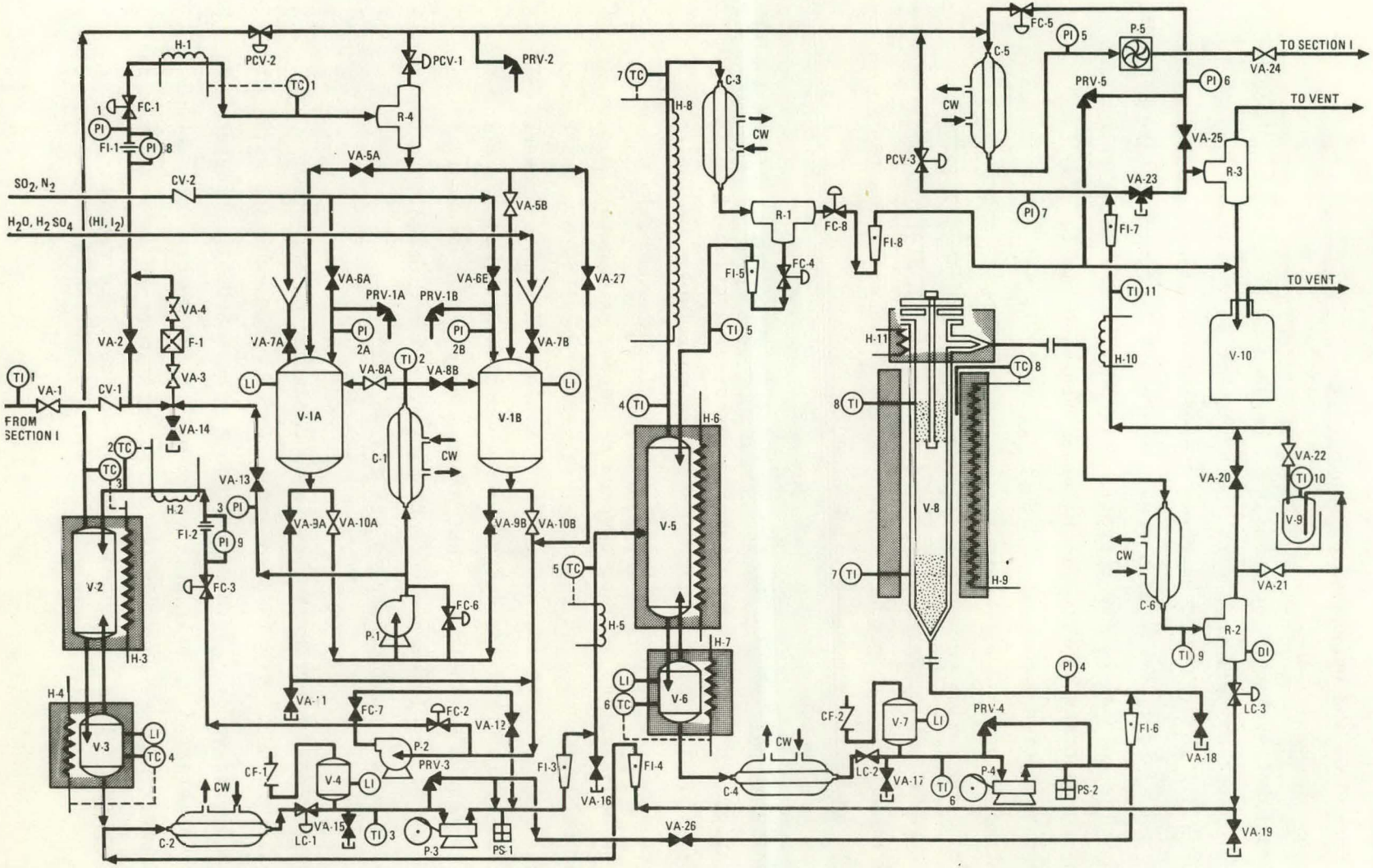


Fig. 7. Flowsheet of subunit II, bench-scale H_2SO_4 concentration and decomposition

2.3.2. Shakedown and Operation of Subunit II

Operational shakedown of subunit II began in October with a batch stripping operation performed with the HI-I_2 stripper column. This column, packed with 3.2 mm (1/8 in.) diameter spherical glass beads, was operated at 1.013×10^{-5} Pa (1 atm) and a steady-state reboiler temperature of 125° to 130°C. The column was fed approximately 300 ml of a "synthetic" feed solution representing expected light phase from subunit I. The feed solution composition was 53 wt % H_2SO_4, 1.2 wt % HI, and 0.2 wt % I_2 at room temperature. Qualitatively, the steam-stripping operation was successful. Operation was straightforward, and no leakage occurred. Stripper product was clear and appeared to contain no HI-I_2 impurities. Analysis of acid in the product showed an H_2SO_4 concentration (60 to 65 wt %) well above the flowsheet value of 60%.

Subsequent attempts to run the HI-I_2 stripper column at higher iodine concentrations in the feed were thwarted by precipitation of solid iodine from supersaturated feed solution. Separate correlation of iodine solubility in sulfuric acid with temperature indicates that only 0.2 wt % iodine can be dissolved at room temperature and approximately 0.4 wt % iodine at 66°C, the present limiting equipment temperature. The design conditions are 0.8 wt % iodine at 95°C. Evaluation of the present limitations to reaching the design feed composition, i.e., operating the feed system at 95°C, indicates that program objectives (Appendix B) can still be met at the lower concentration; future integration of subunits I and II will permit an increase to the design value.

Two shakedown experiments have been conducted on the H_2SO_4 concentrator column. The feed solution to the column was approximately 60 wt % H_2SO_4 in water, the normal product from the HI-I_2 stripper. The reboiler was started up half full of 96 wt % H_2SO_4 to simulate actual bottom product composition. In the first experiment an improperly wired temperature controller prevented reaching the required reboiler temperature

of 275° to 300°C. During a subsequent trial run, one of the glass feed lines broke and forced shutdown of the experiment. The system has been repaired and additional runs will be made in the future.

2.4. FUTURE WORK

The main emphasis in the bench-scale effort during FY-80 will be focused on the installation and functional testing of subunit III and gathering of data in subunits I and II.

The experimental work will be geared toward meeting the bench-scale objectives described in Appendix B and will be carried out in accordance with the phased approach described in the Activity Plan (Appendix C).

2.5. REFERENCE

2-1. "Thermochemical Water-Splitting Cycle, Bench-Scale Investigations and Process Engineering, Annual Report for the Period February through December 31, 1977," DOE Report GA-A14950, General Atomic Company, April 1978.

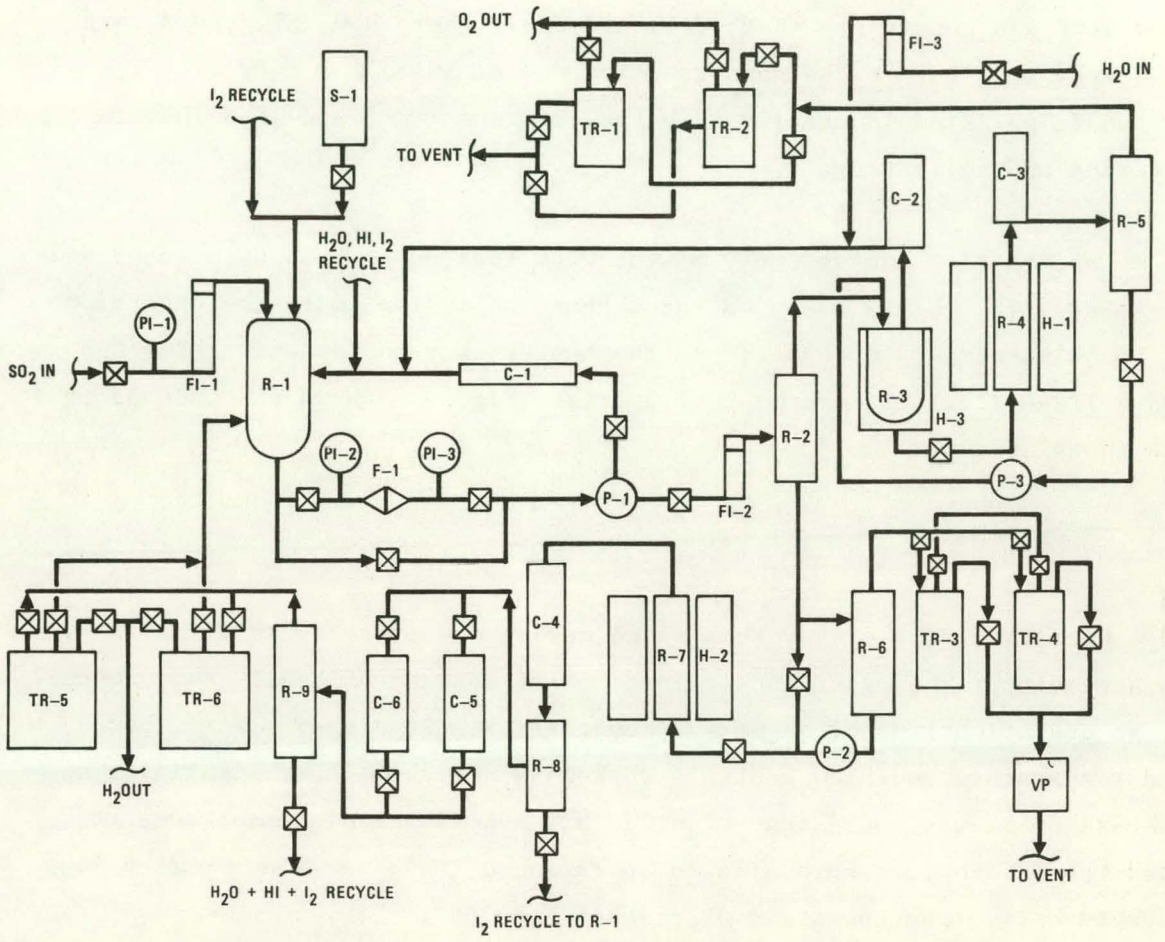
3. CLOSED LOOP-CYCLE DEMONSTRATOR

During the latter part of FY-79, DOE requested that GA demonstrate the sulfur-iodine cycle in a closed loop using recycled materials. Work on design of such a system [the closed-loop cycle demonstrator (CLCD)] started in September 1978 and construction was completed in December.

3.1. DESIGN AND CONSTRUCTION

The CLCD was not designed to duplicate the conditions of the process engineering flowsheet, but rather to provide an early demonstration of the feasibility of the cycle under recycle conditions. A schematic diagram of the system is shown in Fig. 8.

H_2O, I_2, and SO_2 are fed into a main reaction vessel (R-1) and continuously recirculated, by means of a pump (P-1), in a loop where temperature control can be obtained through the cooler (C-1)(or heater). Some of the products are intermittently fed to the liquid-liquid separator (R-2), where the two acid phases are separated. The upper H_2SO_4 phase is purified by boiling in R-3 and then decomposed in a quartz cracker containing FeO catalyst. The product gas is first cooled in a condenser (R-5), the condensed phase (unreacted H_2SO_4) is recycled to R-3, and the gas phase (SO_2 and O_2) is fed to the purification system. (TR-1 and TR-2 are two CO_2-acetone traps in parallel.) The lower phase from R-2 ($HI-I_2-H_2O$ containing SO_2) goes to an off-gas reactor (R-6), where SO_2 is extracted under vacuum at 370 K and trapped in the liquid nitrogen traps (TR-3 and TR-4). Again, intermittently, the degassed lower phase is sent to a cracker (R-7), where some of the HI is thermally decomposed into H_2 and I_2. The product gases are first cooled in C-4 and then fed to a series of



COMPONENT DESIGNATION

C-1	PRIME REACTION RECIRCULATING PRODUCT COOLER
C-2	UPPER PHASE OFF GAS COOLER
C-3	H_2SO_4 POST-CRACK PRODUCT COOLER
C-4	HI POST-CRACK PRODUCT COOLER
C-5	HYDROGEN PURIFICATION LOOP PRE-COOLER
C-6	HYDROGEN PURIFICATION LOOP PRE-COOLER
F-1	PRIME REACTION MAIN-LOOP FILTER
FI-1	SO_2 INPUT FLOW INDICATOR
FI-2	MAIN LOOP OUTPUT FLOW INDICATOR
FI-3	WATER SUPPLY INPUT FLOW INDICATOR
H-1	H_2SO_4 CRACKING FURNACE
H-2	HI DECOMPOSITION FURNACE
H-3	UPPER PHASE PURIFICATION HEATER
P-1	MAIN LOOP CIRCULATING PUMP
P-2	LOWER PHASE CIRCULATING AND FEED PUMP
P-3	H_2SO_4 RECYCLE PUMP
R-1	MAIN REACTION VESSEL
R-2	MAIN REACTION PRODUCT LIQUID-LIQUID SEPARATOR
R-3	H_2SO_4 PURIFICATION BOILER
R-4	H_2SO_4 DECOMPOSITION REACTOR
R-5	UPPER PHASE POST-DECOMPOSITION GAS-LIQUID SEPARATOR
R-6	LOWER PHASE OFF-GAS REACTOR
R-7	LOWER PHASE DECOMPOSITION REACTOR
R-8	LOWER PHASE POST-DECOMPOSITION GAS-LIQUID SEPARATOR
R-9	HYDROGEN PURIFICATION LOOP GAS-LIQUID SEPARATOR
S-1	IODINE SUPPLY VESSEL
TR-1	OXYGEN PURIFICATION LOOP CO_2 - ACETONE TRAP
TR-2	OXYGEN PURIFICATION LOOP CO_2 - ACETONE TRAP
TR-3	LOWER PHASE SO_2 OFF-GAS LN_2 TRAP
TR-4	LOWER PHASE SO_2 OFF-GAS LN_2 TRAP
TR-5	HYDROGEN PURIFICATION LOOP LN_2 TRAP
VP	LOWER PHASE OFF-GAS SYSTEM VACUUM PUMP

Fig. 8. Closed-loop cycle demonstrator

separator and condensers (R-8, C-5, and C-6), where H_2O, HI, and I_2 are separated and sent to the main reaction vessel (R-1) for recycle. The H_2 gas is purified in the liquid nitrogen traps (TR-5 and TR-6) before metering and collecting.

Construction and assembly of the CLCD took place between October and December 1978. Glass was used throughout the system, with the exception of the high-temperature portions [the two cracker-cooler units (R-4/C-3 and R-7/C-4)], which were made of quartz. Figure 9 shows the CLCD as it was installed.

3.2. OPERATION

Operation of the CLCD took place during the first weeks of January. As a result of the experience gained during testing of bench-scale subunit I, no operational problems were encountered. All valves, joints, pumps, and temperature and flow controls worked as designed. For simplicity of operation, it was found convenient to add a small displacement pump to feed the HI cracker; this allowed operation of the degassing P-2/R-6 loop independently from operation of cracker R-7.

Operation of the CLCD started by introducing 3 kg of iodine and 1 kg of water at room temperature into the main reaction vessel (R-1). SO_2 was bubbled through at a rate of 3 liters/min until there was evidence of formation of two separate liquid phases (20 min). The prime reaction products were kept circulating through the filter (F-1) and the cooler (C-1) by means of the pump (P-1). Since the temperature had risen to only 45°C, no cooling was necessary. Intermittently, the liquid was fed to the phase separator (R-2) and allowed to rest 5 min to complete the separation; the upper phase was then sent ot the H_2SO_4 purification boiler (R-3) and the lower phase to the degasser (R-6).

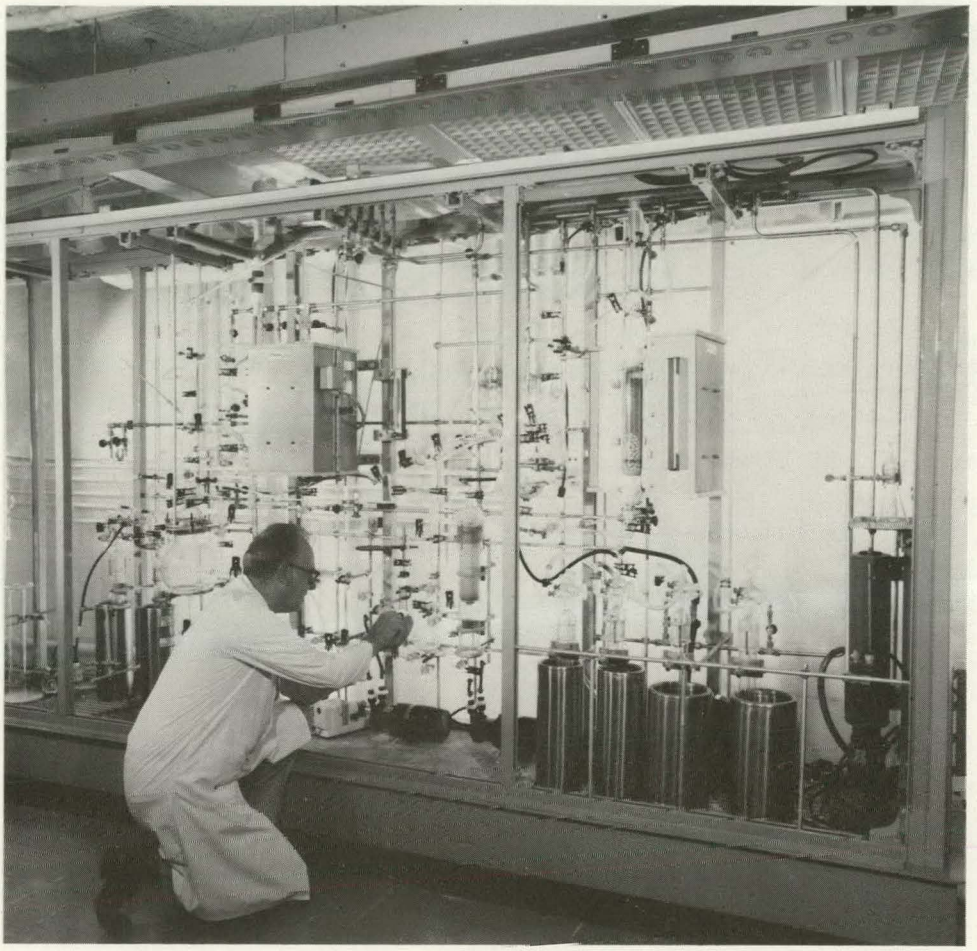


Fig. 9. Installation of closed-loop cycle demonstrator

The H_2SO_4 was concentrated from an initial 30% to approximately 95% and all of the water and traces of I_2 and HI were cooled in C-2 and recycled into the main loop. The concentrated, purified H_2SO_4 was fed to the cracker (R-4), filled with pellets of Fe_2O_3 catalyst kept at 850°C, at a rate of approximately 5 cm^3/min. The product gases were condensed in C-3, recycling the uncracked H_2SO_4 to the boiler and sending the resulting SO_2-O_2 mixture directly to the main loop for recycle or to the trap system for separation and analysis. The lower phase was degassed (SO_2 removal) under vacuum in R-6 for 10 min before it was sent to the HI cracking step.

Since, for simplicity, the CLCD was designed without the HI purification step, the lower phase (HI-I_2-H_2O) was fed directly to the HI cracker and no catalyst was used.

The feeding rate was approximately 4 cm^3/min and the temperature was held at 900°C. Before operating the HI cracker, the system was flushed with He.

The product gases from the cracker (R-7) were cooled and all condensed phases (H_2O, I_2, and unreacted HI) were recycled to the main loop. The cooled gas was purified in the liquid nitrogen traps (TR-5 and TR-6) and the product H_2 was collected in a graduated cylinder. The rate of H_2 production was approximately 20 cm^3/min.

Operation of the loop was accomplished subsequently in a complete recycle mode: the main reaction products were formed by reacting the recycled I_2 from the HI decomposition system with the SO_2 obtained from the H_2SO_4 cracker. No differences were observed.

During operation of the loop small quantities of sulfur were observed in the recycled liquids after the HI cracking coolers and small amounts of H_2S collected in the H_2 purification traps. This was due to incomplete separation of the sulfur-containing species (SO_2 and H_2SO_4) from the lower

phase prior to decomposition. The lower phase concentration and purification step (H_3PO_4 treatment), which is an integral part of the cycle, will eliminate this problem. The step will be tested in subunit III.

Complete operation of the CLCD confirmed the feasibility of the GA water-splitting cycle and provided laboratory personnel with information useful for the detailed construction and operation of the bench-scale unit.

A motion picture was made of the operating CLCD and distributed to the various funding agencies.

4. ENGINEERING STUDIES

The process engineering design effort for the water-splitting cycle at GA was based on the following objectives and constraints:

1. Energy is supplied by a process heat high-temperature gas-cooled reactor (HTR) having a helium inlet temperature of 772 K and an outlet temperature of 1265 K.

2. Process power is supplied from the helium loop and from a low-temperature, process-bottoming cycle.

3. The temperature match-up of the helium heat delivery line and the process heat demand line must be good to maintain efficiency.

4. Heat must be reused within the process until its quality is so low that it must be rejected.

5. Reasonable estimates are used for unavailable thermochemical data.

During FY-79, a revision of the total flowsheet was carried out. In this revised version, several of the new process improvements were incorporated in the flowsheet. The result of this revision was a significantly improved efficiency of 47% (from 42%). The main process improvements included in the design were:

1. A higher temperature in the main solution reaction.
2. An increase in sulfuric acid concentraiton to 57% (from 50%).
3. Utilization of phosphoric acid of lower concentration in the hydrogen iodide purification system.
4. Decomposition of hydrogen iodide in the liquid phase instead of the gas phase.

These process improvements were mainly responsible for the increased thermal efficiency of the process. A simplified schematic flow diagram of the sulfur iodine process conceptually showing product mass flows and recycle streams is given in Fig. 10. Figures 11 through 15 are simplified versions of the five detailed engineering flowsheets.

A description of the sulfur-iodine process via process flowsheet sections I through V is given below. For reasons of simplicity, the descriptions are keyed to the simplified flow diagrams (Figs. 11 through 15). Detailed flowsheets for sections I through V, including mass and energy balances, are included as Appendix D.

4.1. FLOWSHEET SECTION I - H_2SO_4-HI PRODUCTION AND SEPARATION; O_2 PURIFICATION

The main solution reaction is carried out in section I of the flowsheet together with the purification of the product oxygen. Figure 11 shows a simplified version of the detailed flowsheet for this section.

In the main reaction, recycle iodine from sections III and IV reacts with water and SO_2 from a mixture of gaseous SO_2-O_2 in a countercurrent reactor (C-101). The reaction results in the formation of the two acids, H_2SO_4 and HI, in solution. The discovery of the formation of two phases and the natural separation of these phases made the sulfur-iodine cycle feasible. The lower density phase (upper phase) contains all the H_2SO_4 at a concentration of approximately 50 wt % with traces of iodine and a small amount of dissolved SO_2. The higher density phase (lower phase) contains all the HI with considerable amounts of iodine in an H_2O solution. A small quantity of SO_2 and a trace of H_2SO_4 are also present.

The phases are separated (S-101), and the sulfuric acid phase is reacted with molten iodine and SO_2. This increases the H_2SO_4 concentration to approximately 57 wt % and generates additional reaction product HI. The

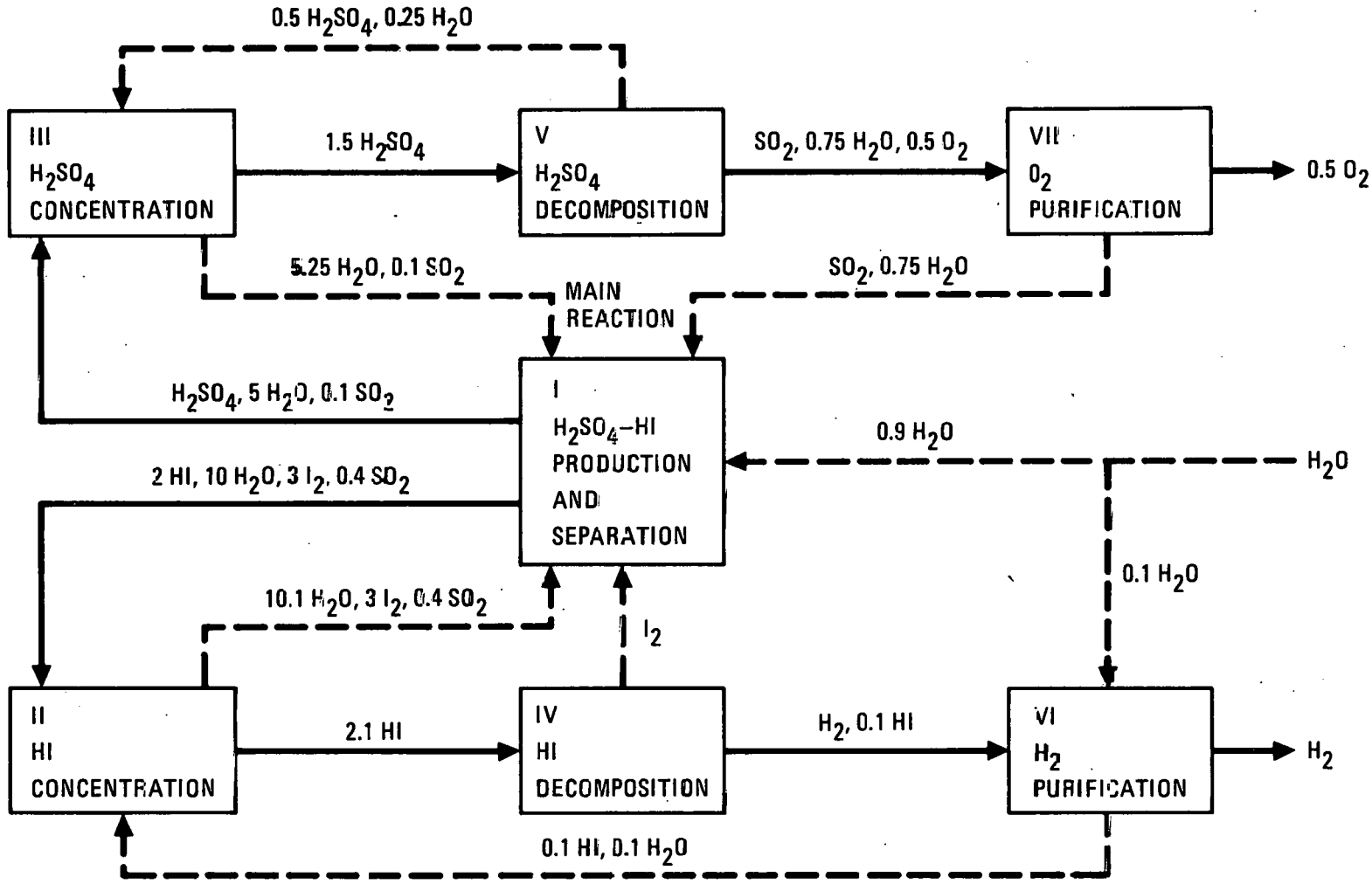


Fig. 10. Simplified schematic flow diagram of sulfur-iodine cycle

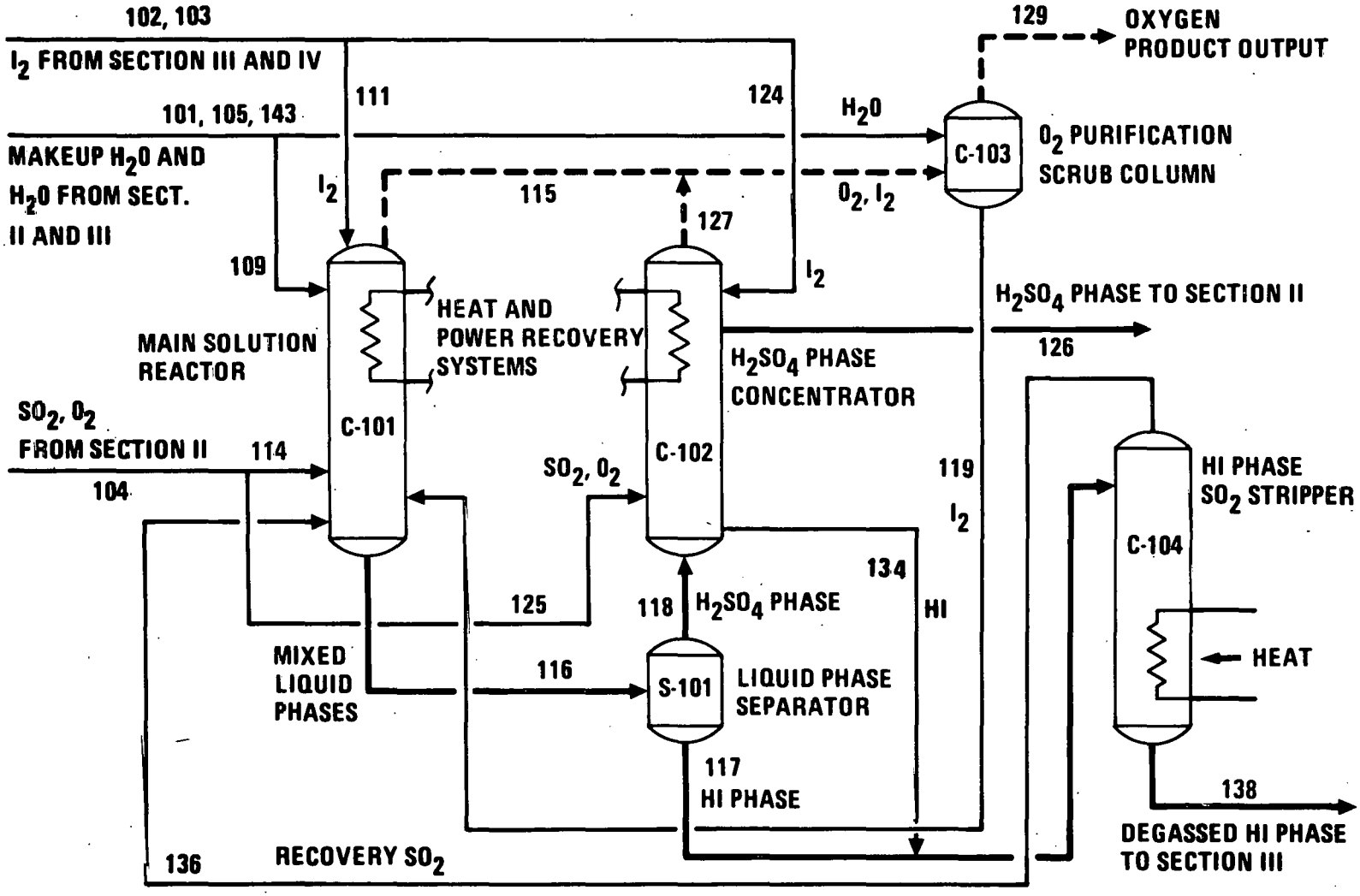


Fig. 11. Simplified flowsheet for section I

57% sulfuric acid is transferred to section II for concentration and decomposition. The lower phase goes through a degassing step, which removes practically all the SO_2 (C-104). This lower phase containing HI, H_2O, and I_2 is then transferred to section III for purification and HI separation.

The SO_2 entering the main reaction (C-101) and the H_2SO_4 boost reaction (C-102) is a mixture of SO_2 and O_2 coming directly from the SO_3 decomposition reaction of section II. As this gas mixture passes through the reactor, SO_2 is removed by reaction with I_2 and H_2O, and the gas leaving the top of the main solution reactor is practically pure oxygen with small amounts of iodine. The iodine is removed in a scrub column (C-103), and pure oxygen leaves the system as a product.

All reactions in section I have been demonstrated in the laboratory and the yields quoted in the material balance sheets of Appendix D are based on actual experimental data. The engineering design of section I is based on GA experiments and available thermodynamic literature data.

4.2. FLOWSHEET SECTION II - H_2SO_4 CONCENTRATION AND DECOMPOSITION

Concentration and decomposition of sulfuric acid are carried out in this section, which fulfills one part of the recycle requirement by generating the needed SO_2 for the main reaction from the H_2SO_4 decomposition. Figure 12 shows a simplified version of the detailed flowsheet for this section.

Dilute sulfuric acid (57 wt %) from section I is concentrated in a series of flash evaporators (V-201 through V-212). The concentrated H_2SO_4 is decomposed (E-221) to H_2O and SO_3, and the sulfur trioxide is decomposed (E-214) to sulfur dioxide and oxygen. The SO_3 decomposition is the highest temperature step in the total process, with operating temperatures of up to 870°C (1600°F). The gaseous mixture of SO_2 and O_2 is separated from the water and unreacted H_2SO_4 and transferred to the main solution reactor in section I. The condensate from this separation is recycled to the first flash evaporator.

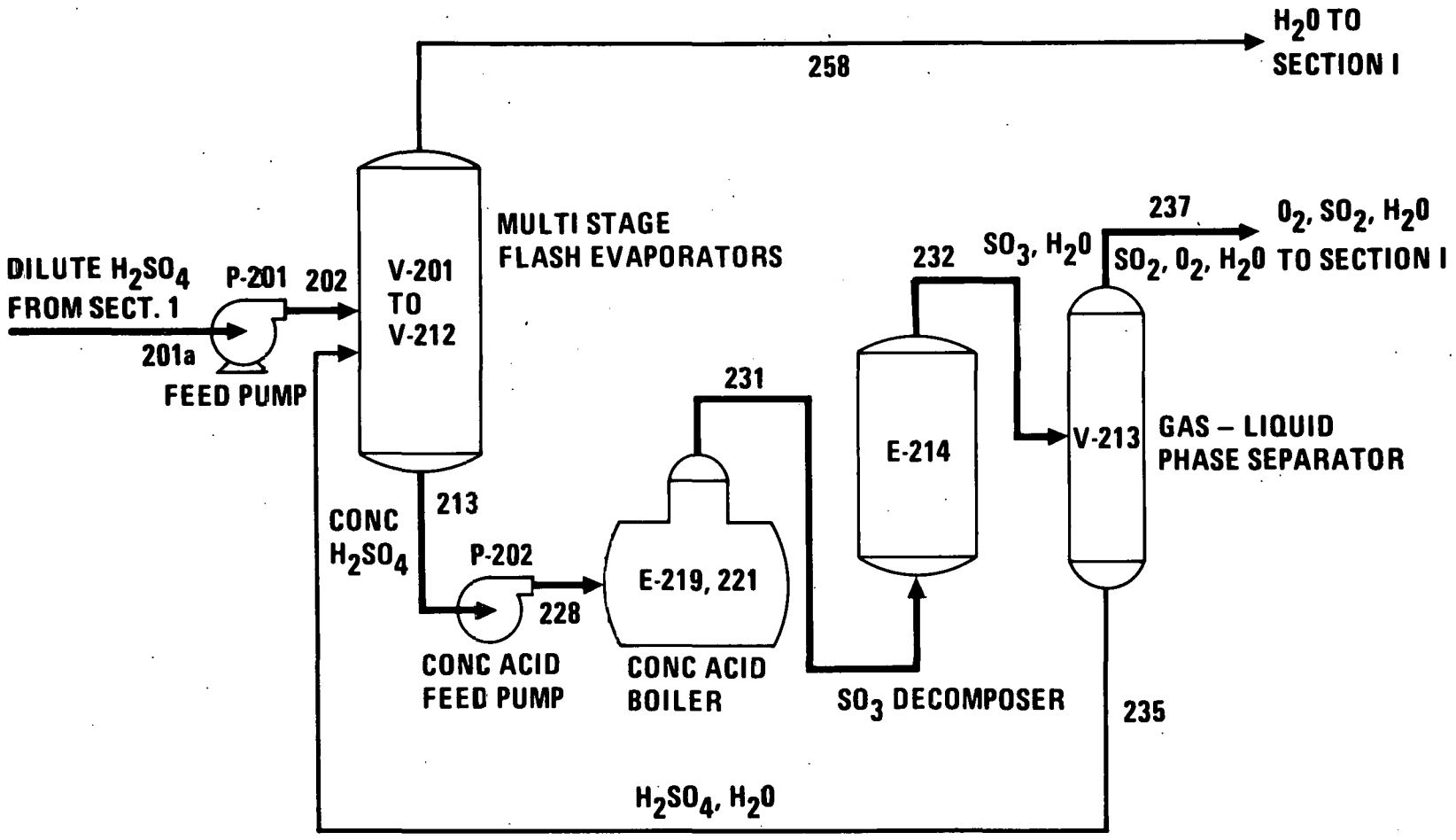


Fig. 12. Simplified flowsheet for section II

The concentration and decomposition of H_2SO_4 are common to a number of water-splitting cycles and have been evaluated in several laboratories. General Atomic has developed proprietary catalysts and processes, which have been demonstrated at the quoted temperature. The engineering design of section II is based on GA experimental data and available thermodynamic literature data.

4.3. FLOWSHEET SECTION III - HI SEPARATION

Hydrogen iodide is separated from the components of the $HI-I_2-H_2O$ solution (lower phase) in this section. Figure 13 shows a simplified version of the detailed flowsheet for this section.

Lower phase from section I containing approximately 4 moles of iodine and 5 moles of water for each mole of HI is treated with concentrated phosphoric acid (C-302) and a major portion of the iodine (~95%) is separated from the solution. This iodine is scrubbed with water to remove small amounts of HI and H_3PO_4 (C-301) and returned to the main solution reaction of section I. The overhead solution containing HI, H_2O, H_3PO_4, and some I_2 is subjected to an extractive distillation (C-303), where most of the water (99%) remains with the phosphoric acid and the HI and I_2 are removed as overhead vapor. Minor amounts of H_2S may be formed in these steps from a reaction of trace quantities of H_2SO_4 with HI. The dilute phosphoric acid is concentrated in a series of concentrators (E-318 through E-321) and reused for the iodine separation as discussed above. The overhead containing HI, some I_2, and a very small amount of water is cooled (E-305) to condense and separate (S-301) some of the iodine and then subjected to another distillation (C-313). Here the HI is purified to a level where it can be sent to section IV for decomposition after compression to 5.065×10^6 Pa (50 atm).

The engineering design of the HI purification system is based on laboratory data collected at GA. Design of the phosphoric acid concentration section is based on available thermodynamic data from the literature.

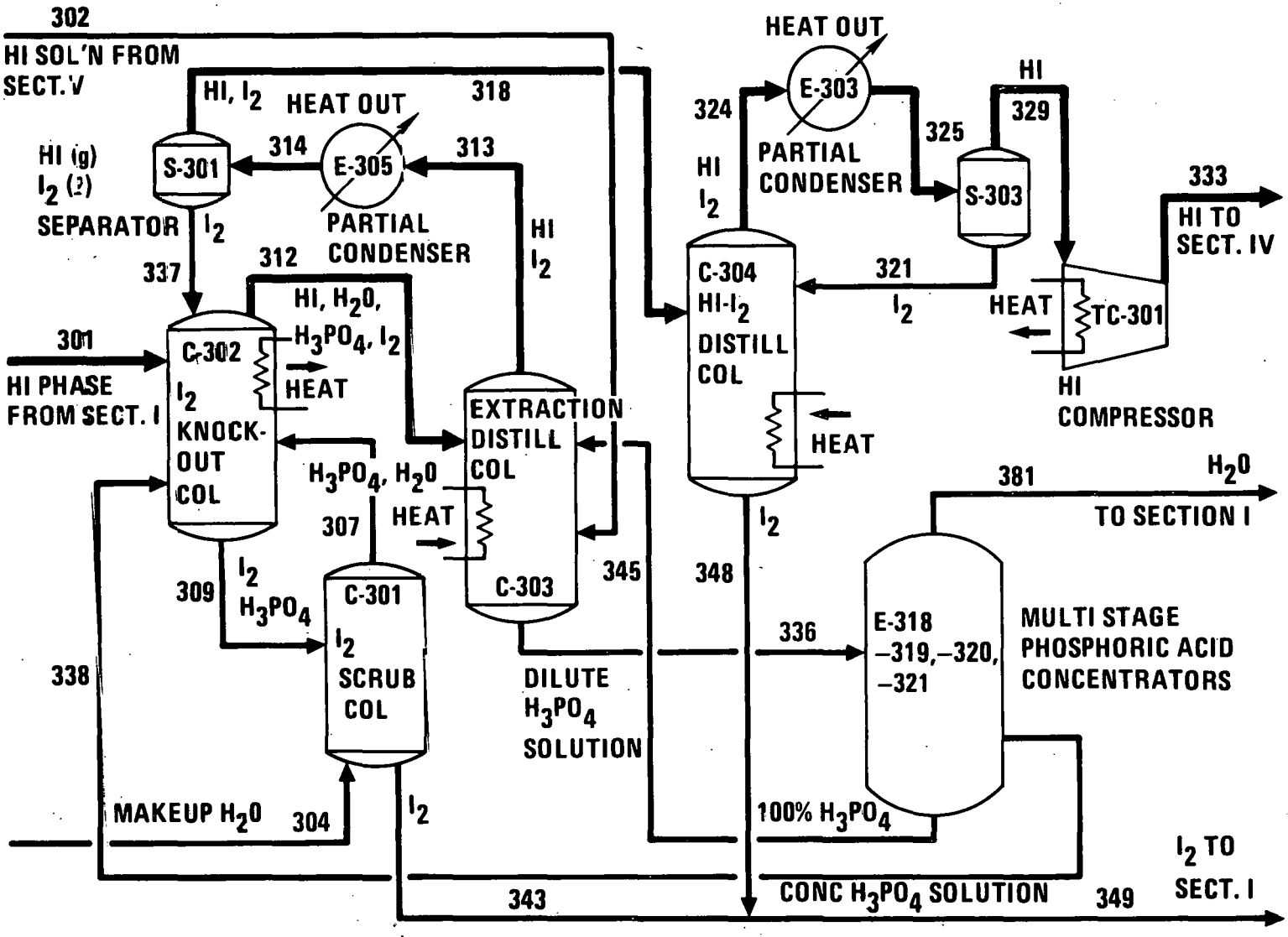


Fig. 13. Simplified flowsheet for section III

4.4. FLOWSHEET SECTION IV - HI DECOMPOSITION

The decomposition of hydrogen iodide is carried out in this section. Figure 14 shows a simplified version of the detailed flowsheet for this section.

Purified liquid HI [5.065×10^6 Pa (50 atm)] from section III is catalytically decomposed at approximately 120°C (R-401). The degree of decomposition is only approximately 30% in one pass. Therefore, the recycle step has to be used in this section. The hydrogen product is separated from most of the I_2 and some HI in a liquid gas separator (S-401). This gas is then cooled (E-408, E-409, and E-410) to condense out most of the HI, which is recycled to the HI decomposer (R-401). The gaseous H_2 product is scrubbed with H_2O, and pure hydrogen is the resulting end product. The liquid from the gas-liquid separator (S-401) contains mostly iodine and HI. The HI is removed by distillation (C-401) and returned to the HI decomposer (R-401). The iodine is returned to the main solution reaction in Section I.

The engineering design of section IV is based on experimental laboratory data collected at GA. The catalysts for the liquid HI decomposition have been developed and demonstrated. General Atomic has filed for a patent for the decomposition of liquid HI. The decision to design the system for 5.065×10^6 Pa (50 atm) pressure was based on existing pipeline pressures for natural gas transmission.

4.5. FLOWSHEET SECTION V - POWER GENERATION AND HEAT TRANSFER

Section V of the flowsheet describes the generation of heat and power needed in some of the processing sections. The basic assumption has been that a high-temperature gas-cooled nuclear reactor, similar to the one designed by GA, would be available. Figure 15 shows a simplified block diagram of the detailed flowsheet for this section.

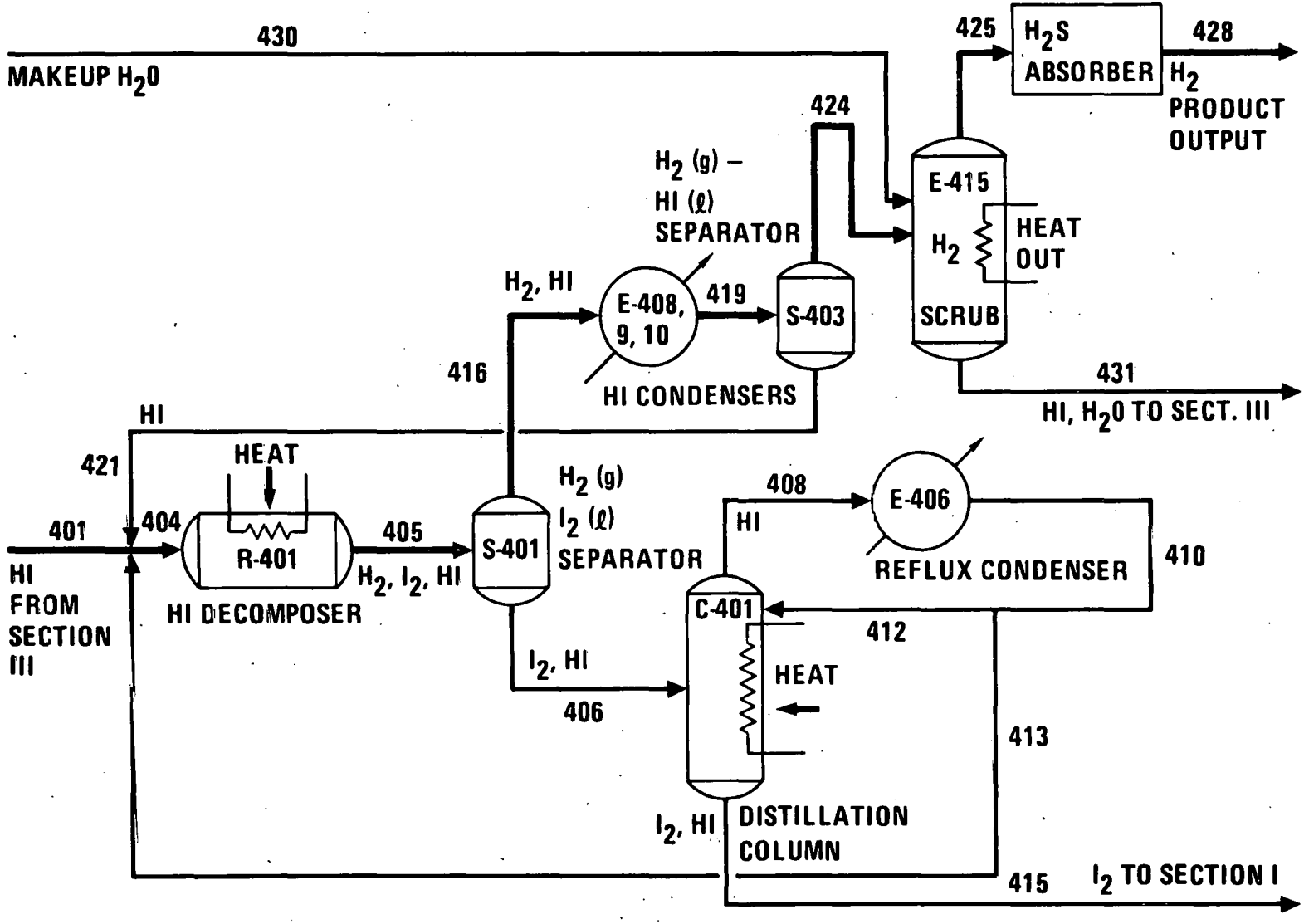


Fig. 14. Simplified flowsheet for section IV

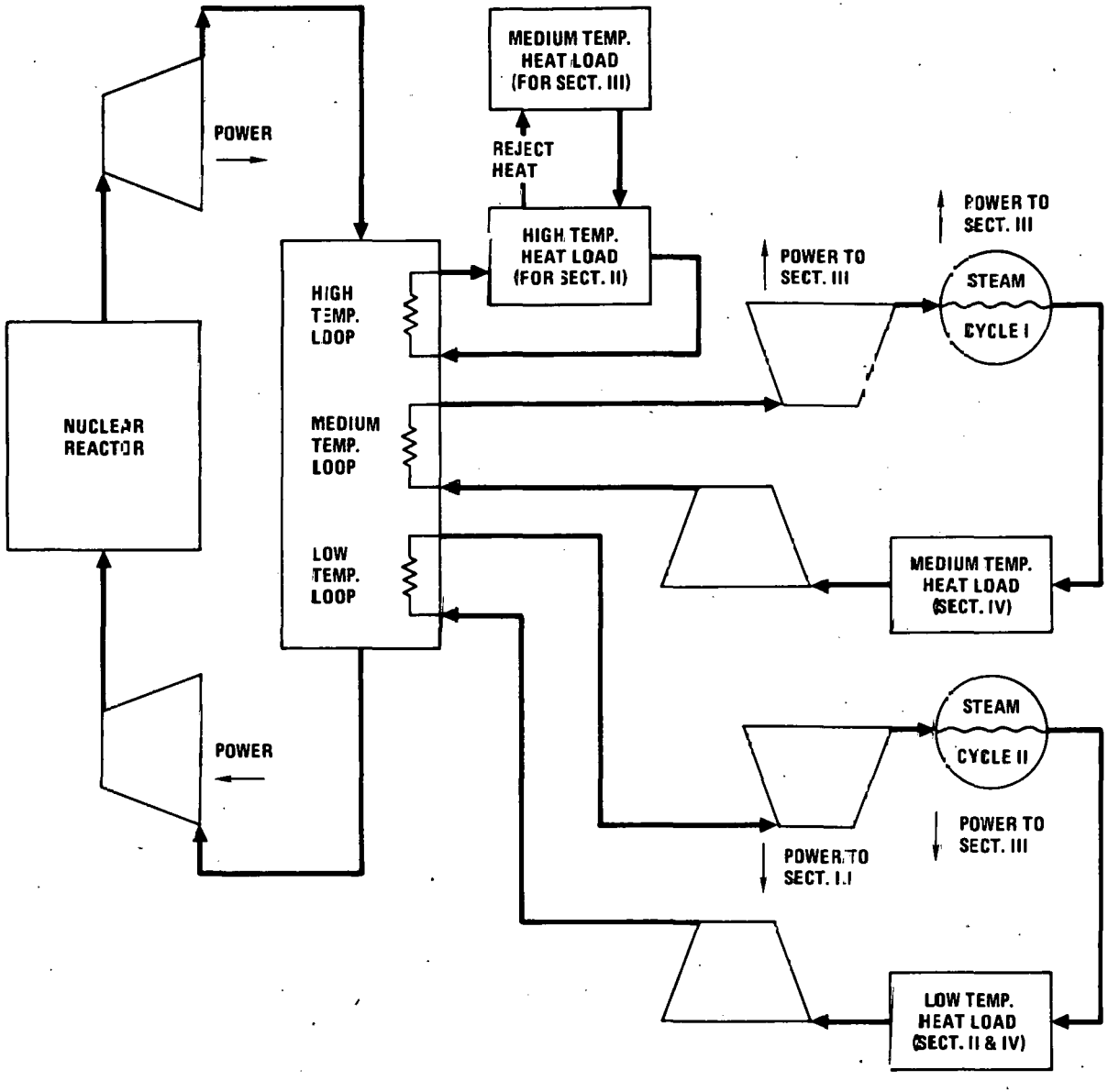


Fig. 15. Simplified flowsheet for section V

Helium from the primary loop transfers its heat to three secondary helium loops through heat exchangers that operate at high, intermediate, and low temperatures. The high-temperature loop provides the heat for the sulfuric acid decomposition reaction of flowsheet section II. Recovered heat from section II is utilized to provide heat for the HI distillation and phosphoric acid concentration of flowsheet section III. The intermediate-temperature loop provides the heat for flowsheet section IV, HI decomposition. Power for flowsheet section III is generated through a helium turbine and a steam cycle. The low-temperature loop provides low value heat to flowsheet sections II and IV, sulfuric acid concentration and HI distillation. Additional power for flowsheet section III is generated through a helium turbine and a second low-temperature steam cycle. Section I is heat self-sufficient and exports power to other sections.

The design of section V is based on available thermodynamic data and good engineering practice.

APPENDIX A
WORK PLAN FOR FY-79
WATER-SPLITTING BENCH-SCALE INVESTIGATIONS
(PREPARED FEBRUARY 1979)

Contract No. DE-AT03-76SF90851
Project 3260 - Thermochemical Water Splitting
Task 005 - Bench Model
Work Order 001 - Bench-Scale Investigations

A.1. OJBECTIVE

The objective of this task is to verify the chemical concepts which together constitute the GA thermochemical water-splitting process. This process basically involves three chemical reactions: (1) the oxidation of sulfur dioxide (SO_2) by an aqueous solution of iodine to form sufluric acid (H_2SO_4) and hydriodic acid (HI); (2) the thermal decomposition of sulfuric acid to form water, sulfur dioxide, and oxygen; and (3) the catalytic decomposition of hydrogen iodide to form iodine and hydrogen. Thus, the overall result of the process is to create hydrogen and oxygen from water. The verification of this process is aimed at developing engineering approaches to each of these reactions and to their associated separation processes. These processes have heretofore been carried out only in the laboratory using traditional chemical investigative methods.

A.2. PURPOSE

General Atomic is presently conducting a comprehensive program sponsored by the Gas Research Institute (GRE), the Department of Energy (DOE), and others to develop the sulfur-iodine cycle as the basis for a thermochemical process that creates hydrogen and oxygen from water. This is a long-term program leading to the operation of a large-scale

demonstration plant. The benefits of this research will be a process that provides a nonfossil, renewable source of hydrogen for the gas industry (Ref. A-1).

The purpose of the bench-scale investigations is to carry out extensive testing on a larger-than-laboratory scale of the three subunits that comprise the water-splitting process. At a later date the bench-scale subunits will be operated as a continuous chemical process with addition of water feed, removal of hydrogen and oxygen products, and conversion and recycle of all other chemicals (H_2SO_4, HI, SO_2, and I_2). Subunit I carries out the main solution reaction, which produces the acids H_2SO_4 and HI out of SO_2, H_2O, and I_2. Subunit II concentrates and decomposes H_2SO_4, and the decomposition products are separated. Subunit III concentrates and decomposes HI, and the decomposition products are separated.

The bench-scale investigations will consist of four overlapping phases of work: design assessments and improvements, fabrication and installation, shakedown testing, and data acquisition. During FY-79 the emphasis will be on completing the first three phases for subunits I and II. Data acquisition for subunits I and II may begin after July 1, 1979, if the budget allows. Procurement of equipment for subunit III will be completed by the end of FY-79.

A.3. CURRENT STATUS

General Atomic has done development of the thermochemical water-splitting process, based on the sulfur iodine cycle, over the past 4 or 5 years. The results of this work are reported by Russell (Ref. A-2), Schuster (Ref. A-3), Norman (Ref. A-4), and others. The first bench-scale work based on earlier process design studies (Ref. A-5) was done in 1978; subunit I was built, installed, and operated. After operational problems were encountered, tests were stopped and subunit I was modified. Subunit I is presently inactive; operation is scheduled to resume during FY-79 after the design modifications are complete and the equipment are reinstalled in a new location.

The design of subunit II was completed in 1978 and is discussed by McCorkle (Ref. A-6). Procurement of equipment for subunit II was started at the same time and must be completed during FY-79. Data acquisition from this unit must start by July 1, 1979.

The design of subunit III was also completed in 1978 and is discussed by McCorkle (Ref. A-7). Procurement of equipment for subunit III has not started but must be completed by the end of FY-79. Operation of this unit is not scheduled during FY-79.

A.4. SCOPE OF ACTIVITY

A.4.1. Design Assessment and Improvement

An assessment of the most recent "as modified" design of subunit I will be made to determine if specific improvements can be incorporated without slipping FY-79 milestones or exceeding the FY-79 budget. This assessment will focus on operability, control, and energy utilization.

A.4.2. Procurement and Fabrication

Specifications will be compiled to allow procurement or fabrication of equipment for subunits I, II, and III that is not already "on-hand" or "on-order." Items will be fabricated at GA whenever lower costs or improved schedule result.

A.4.3. INSTALLATION

Subunits I and II will be installed during FY-79. Subunit III will be installed later. Installation of subunits I and II will be carried out as dictated by equipment availability and a critical path schedule that reflects equipment delivery schedules, installation-manpower availability, and the optimum sequencing of installation activities.

A.4.4. Shakedown Testing

Sufficient testing of bench-scale subunits I and II will be done to ensure the physical integrity and functional operability of each equipment item and the system as a whole. The functional performance of the equipment will not be tested during shakedown.

A.4.5. Data Acquisition

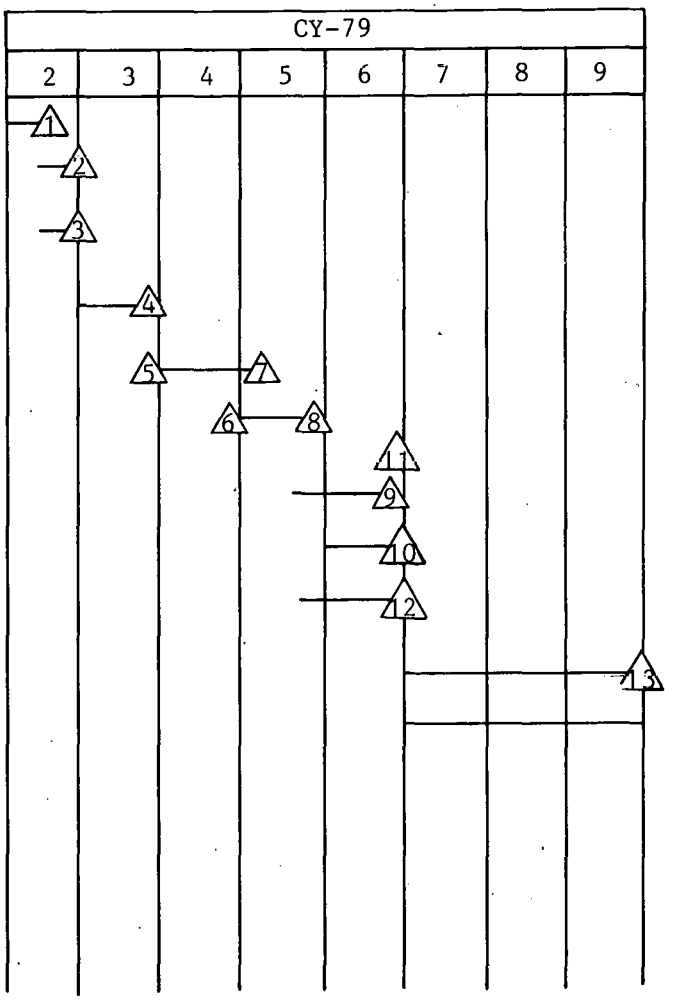
The acquisition of performance data from subunits I and II will be done in accordance with accepted experimental-design techniques as described in Activity Plans for these units. These data will be evaluated statistically whenever possible and used to verify the chemical concepts and engineering approaches that constitute the current design of the flowsheet for thermochemical water splitting.

A.5. MILESTONES

		Scheduled	Actual
1.	Complete and issue FY-79 Work Plan.	2/9/79	2/8/79
2.	Complete design assessment of subunit I and issue memorandum.	2/28/79	2/24/79
3.	Compile procurement/fabrication specifications for subunit II. Initiate procurement through Purchasing.	2/28/79	2/28/79
4.	Compile procurement/fabrication specifications for subunit I. Initiate procurement through Purchasing.	3/30/79	3/30/79
5.	Start installation of subunit II.	4/1/79	3/1/79
6.	Start reinstallation of subunit I.	5/1/79	3/1/79
7.	Complete installation of subunit II.	5/15/79	5/15/79
8.	Complete installation of subunit I.	6/1/79	5/29/79
9.	Complete shakedown of subunit II.	6/30/79	6/18/79

		Scheduled	Actual
10.	Complete shakedown of subunit I.	6/30/79	6/18/79
11.	Start operation and data acquisition for subunit II.	6/30/79	Delayed pending design changes
12.	Issue Activity Plans for subunits I and II.	6/30/79	6/29/79
13.	Complete purchase of equipment for subunit III. (Deliver all approved Purchase Requests to Purchasing.)	9/30/79	8/16/79

A.6. SCHEDULE



Activity

1. Prepare FY-79 Work Plan
2. Subunit I design assessment
3. Compile subunit II procurement/fabrication specifications
4. Compile subunit I procurement/fabrication specifications
5. Install subunit II
6. Reinstall subunit I
7. Shakedown of subunit II
8. Shakedown of subunit I
9. Prepare subunit I and II Activity Plans
10. Purchase subunit III equipment
11. Operate subunits I and II (if FY-79 budget allows)

A. 7. REFERENCES

A-1. "Thermochemical Water Splitting for Hydrogen Production: 1979 Program," Proposal GACP 83-004 (Rev.) to the Gas Research Institute, November 30, 1978.

A-2. Russell, J. L., Jr., et al., "Development of Thermochemical Water Splitting for Hydrogen Production at General Atomic Company," General Atomic Report GA-A14050, September 30, 1976.

A-3. Schuster, J. R., et al., "Development of a Sulfur-Iodine Thermochemical Water Splitting Cycle for Hydrogen Production," General Atomic Report GA-A14307, May 1077.

A-4. Norman, J. H., et al., "Water Splitting - The Chemistry of the I_2SO_2-H_2O Reaction and the Processing of H_2SO_4 and HI Products," General Atomic Report GA-A14746, December 1977.

A-5. "Thermochemical Water-Splitting Cycle Bench-Scale Investigations and Process Engineering, Annual Report for the Period February through December 31, 1977," General Atomic Report GA-A14950, April 1978.

A-6. McCorkle, K. H., "Design of Bench-Scale System Section II, Sulfuric Acid Concentration and Decomposition," General Atomic unpublished data, March 28, 1978.

A-7. McCorkle, K. H., "Design of Bench-Scale System Section III, HI Concentration and Decomposition," General Atomic unpublished data, April 24, 1978.

APPENDIX B
OBJECTIVE OF BENCH-SCALE EXPERIMENTS
(PREPARED NOVEMBER 2, 1979)

The objectives for experimental work on the bench-scale system have been established. At present details are only given for bench-scale subunits I and II. Details for subunit III will be provided later. The following objectives have been agreed upon:

Subunit I

1. Demonstration of Flowsheet Conditions (for June 1979 flowsheet)

   a. Verify 50% sulfuric acid concentration of main reaction at 95°C, I_2/H_2O = 7/1 (wt), and enough SO_2 to agitate reactants with excess SO_2 in off-gas.

   b. Verify 4 liters/min of hydrogen equivalent production rate.

   c. Verify lower phase SO_2 stripping [flowsheet value (or less) of SO_2 in heavy phase after stripping].

   d. Verify good liquid phase separation (upper-lower).

   Future Work

   e. Verify SO_2/O_2 flowsheet separation in newly designed and constructed reactor. (O_2 purification will be demonstrated in the pilot plant.)

2. Improvement of Flowsheet Operating Conditions

   a. Improve areas where flowsheet conditions cannot be met.

   b. Increase SO_2 pressure for main reaction (up to 2 atm now, higher pressure later when metal vessels are used).

   c. Increase main reaction temperature (>95°C).

   d. Verify H_2SO_4 boost reaction (later, after reactor has been installed).

3. Improvement of Process Yield

   a. Evaluate possibilities for lowering H_2O requirements.

   b. Same as 2b, 2c, and 2d.

4. Verification of Materials Compatibility

   a. Evaluate materials compatibility by inserting material coupons into process flowstream.

   b. Design and construct process vessels from candidate materials and use in bench-scale system.

5. Generation of Engineering Data for Pilot Plant Design

   a. Carry out experiments that provide data required for pilot plant (engineering-scale) equipment design.

6. Integration of Subunit I with Other Subunits

   a. Integrate subunit I with subunits II and III and operate as a single unit after individual subunits have been operated extensively.

7. Evaluation of Potential Process Control Equipment

   a. Evaluate control equipment and make part of bench-scale system if possible.

8. Demonstration Runs

   a. Carry out three demonstration runs of 6-hours duration each at steady-state conditions of 1 above.

Subunit II

1. Demonstration of Flowsheet Conditions (for June 1979 flowsheet)

   a. Verify iodine removal.

   b. Verify 4 liters/min of hydrogen equivalent production rate.

   c. Verify H_2SO_4 decomposition ratio (98% of equilibrium) and catalyst performance; catalyst = Pt on Zr, SO_3 residence time 1/2 s.

   d. Evaluate catalyst life.

2. Improvement of Flowsheet Operating Conditions

   a. Improve areas where flowsheet conditions cannot be met.

3. Verification of Materials Compatibility

   a. Evaluate materials compatibility by inserting material coupons into process flowstream.

   b. Design and construct process vessels from candidate materials and use in bench-scale system.

4. Generation of Engineering Data for Pilot Plant Design

   a. Carry out experiments that provide data required for pilot plant (engineering-scale) equipment design.

5. Integration of Subunit II with Other Subunits

   a. Integrate subunit II with subunit I and operate as single unit after extensive operation of individual units.

6. Evaluation of Potential Process Control Equipment

   a. Evaluate control equipment and make part of bench-scale system if possible.

7. Demonstration Runs

   a. Carry out three demonstration runs of 6-hours duration each at steady-state conditions of 1 above.

Subunit III

Objectives will be established after installation of this subunit.

APPENDIX C
ACTIVITY PLAN FOR BENCH-SCALE MODEL: SUBUNITS I, II, AND III

1.0 SCOPE

This document describes the activities and experimental work to be conducted with the bench-scale model of the thermochemical water-splitting cycle from FY-79 through FY-83.

Initially this work will only encompass individual operation of Subunit I (H_2SO_4-HI Production and Separation) and Subunit II (H_2SO_4 Concentration and Decomposition). Later, after construction of Subunit III (HI Concentration and Decomposition), the work will continue with the separate operation of this subunit. Finally, the work will conclude with the integrated operation of all three subunits.

2.0 OBJECTIVES

The overall objective of the bench-scale model is to develop engineering approaches to the thermochemical water-splitting process steps that have been previously carried out in the laboratory with traditional chemical investigative methods (Ref. 9.1).

The following two goals are established to meet this objective:

1. Demonstrate the technical feasibility of the thermochemical water-splitting process concepts in bench-scale equipment.

2. Obtain the process information required to design and build an engineering-scale model (pilot plant) of the thermochemical water splitting cycle.

In order to meet these goals, information will be gathered on the following technical issues.

Subunit I Technical Issues

I. SO_2 Feed Gas Injection
   A. Control
II. H_2O Feed & Injection
   A. Control
III. I_2 Fusion & Injection
   A. Control
   B. Fusion Efficiency
IV. Main Solution Reaction
   A. H_2SO_4 Yield
   B. Boost-Reaction Yield (later)
   C. Reactor Design
   D. Materials [(1) Zr, (2) elastomer, (3) plastic] (later)
V. Phase Separation
   A. Gas-Liquid Separator Performance (i.e., Product Quality)
   B. Liquid-Liquid Separator Performance (i.e., Product Quality)
   C. Materials [(1) Zr, (2) elastomer, (3) plastic]
VI. SO_2 Recovery (later)
   A. SO_2 Recycle
   B. Heavy-Phase Stripper Performance
VII. General
   A. Subunit capacity/limiting equipment
   B. Operability/Control

C. Flow Turndown

D. Sampling

E. Flow Measurement

Subunit II Technical Issues

I. I_2 Removal

A. Product Purity

B. Boilup

C. Temperature and Temperature Gradient

D. Operability/Control

E. Capacity

F. Flow Turndown

G. Sampling

H. Flow Measurement

I. Materials [Hastelloy C Tubing for $H_2SO_4+I_2$(trace)] (later)

II. H_2SO_4 Concentration

A. Product Purity

B. Temperature and Temperature Gradient

C. Operability/Control

D. Capacity

E. Flow Turndown

F. Sampling

G. Flow Measurement

III. $H_2 SO_4$ Decomposer

A. Conversion (SO_2 Yield)

B. Catalyst Studies

C. Operability/Control

D. Capacity

E. Materials (aluminized Incoloy 800H test coupons) (later)

Subunit III Technical Issues

(later)

3.0 EXPERIMENTAL DESIGN

Separate documents will be issued detailing the design of experiments for Subunits I, II and III, and for the integrated bench model. The intent of the design will be to obtain the greatest amount of information from the least number of tests. This can be accomplished with established statistical methods (Ref. 9.2, 9.3, 9.4, 9.5), particularly to determine the effects of several variables on a given design parameter.

4.0 TEST DESCRIPTION

The test program for each subunit will be implemented in five phases:

Phase	Type of Operation	Feed	Principal Objective
I	Equipment shakedown	Water, N_2	Verify structural integrity & functional operability.
II	Operational shakedown	Makeup	Verify total system operability with actual process fluids.

Phase	Type of Operation	Feed	Principal Objective
III	Parametric studies of isolated subunits.	Makeup	Determine component characteristics, performance, and limitations.
IV	Capacity tests of isolated subunits.	Makeup	Determine subunit capacity, performance, and efficiency.
V	Integrated operation	Recycle SO_2 & I_2	Verify subunit interface compatibility and total cycle performance.

A brief description of the tests within each phase follows:

Phase I - Equipment Shakedown

The purpose of this phase is to verify the structural integrity and functional operability of each subunit. In general, shakedown will consist of equipment preparation, operator training, leak-testing, calibration of instruments, and functional testing of each component. Details of the shakedown procedure for Subunits I and II are given in References 9.6 and 9.7 (Subunit III shakedown procedure to be issued later).

Phase II - Operational Shakedown

The purpose of this phase is to verify the operability of each subunit with actual process fluids. Experiments of limited scope will be conducted to ensure that process fluids can be adequately conditioned

and transported, that required chemical reactions occur, and that products of chemical reactions or process operations can be isolated.

Phase III - Parametric Studies

The purpose of this phase is to determine the operating characteristics, performance, and capacity limitations of major components. The effects of temperature, flowrate (residence time), pressure, and composition on yield and product purity are typical of the kind of information sought. Specific series of tests will be performed as described in Table I. During this Phase, various materials will be investigated for chemical compatibility.

Phase IV - Capacity Tests

The purpose of this phase is to determine the flow capacity of each subunit and to find the flow-limiting component(s). In addition, tests will be conducted to study general issues of operability and control. Specific series of tests will be performed as described in Table II. As in Phase III, various materials will be investigated for chemical compatibility.

Phase V - Integrated Operation

The purpose of this phase is to verify the interface compatibility of Subunits I, II and III, and to evaluate overall cycle performance. Attention will focus on overall cycle flow capacity, utilization of internal recycle streams, operability at system interfaces, materials,

Table I

Parametric Studies

Test Series	Subunit	Component	Test Results
1	1	Reactor	1. H_2SO_4 yield as a function of: a. Temperature b. I_2/H_2O c. SO_2/H_2O d. Flowrate (residence time) e. Pre-mixing tube design 2. Boost-reaction (later) yield as a function of a. Stoichiometry b. Control 3. H_2SO_4 yield as a function of reactor design (later) at optimum process conditions. 4. Corrosion resistance of Zr.
2	1	Gas-Liquid Separator	1. Purity of gas and liquid products as functions of:

Table 1 (continued)

Test Series	Subunit	Component	Test Results
2 (cont'd.)	1	Gas-Liquid Separator	a. Temperature b. Flowrate (residence time) c. I_2/H_2O d. SO_2/H_2O e. Interface - level control method f. Impurities 2. Separation Efficiency
3	1	Liquid-Liquid Separator	1. Purity of gas and liquid products as functions of: a. Temperature b. Flowrate (residence time) c. I_2/H_2O d. SO_2/H_2O e. Interface-level control method f. Impurities 2. Separation Efficiency

Table I (continued)

Test Series	Subunit	Component	Test Results
3 (cont'd)	I	Liquid-Liquid Separator	3. Corrosion resistance of Zr.
4. (later)	I	Heavy-Phase Stripper	1. Performance (SO_2 concentration in bottom product) as a function of: a. Feedrate b. Temperature c. Reflux
5	II	I_2-Removal Column	1. Vapor and liquid product purities as a function of: a. Boilup b. Flow turndown c. Temperature and temperature gradient d. Feed composition 2. Corrosion resistance of Hastelloy C.

Table I (continued)

Test Series	Subunit	Component	Test Results
6	II	H_2SO_4 Concentrator	1. Vapor and liquid product purities as a function of: a. Temperature and temperature gradient. b. Flow turndown c. Feed composition d. Reflux e. Boilup
7	II	H_2SO_4 Decomposer	1. Conversion (SO_2 Yield) as a function of: a. Temperature b. Flowrate (residence time) c. Catalyst i. Type ii. Amount iii. Activation method iv. Regeneration method

Table 1 (continued)

Test Series	Subunit	Component	Test Results
7 (cont'd)	II	H_2SO_4 Decomposer	2. Corrosion resistance of aluminized Incoloy 800 H near or in catalyst.
8, etc. (later)	III	TBD	TBD

Table II

Capacity Tests

Test Series	Subunit	Test Results
1	I	1. Develop SO_2 feed gas flow and temperature control.
		2. Develop H_2O feed flow and temperature control.
		3. Develop I_2 fusion method and I_2 flow and temperature control.
2	I	1. Investigate materials in the liquid-liquid separator (Zr; elastomer; plastic).
3 (later)	I	1. Develop SO_2 recycle operability and control
4	I	1. Determine subunit flow capacity.
		2. Determine subunit flow turndown.
5	I	1. Develop sampling and analysis methods.
6	II	1. Develop operability and control of:
		a. I_2 - Removal System
		b. H_2SO_4 - Concentration System

Table II (continued)

Test Series	Subunit	Test Results
6 (cont'd.)	II	c. H_2SO_4 - Decomposer System
7	II	1. Determine subunit flow capacity.
		2. Determine subunit flow turndown.
8.	II	1. Develop sampling and analysis methods.
9	II	1. Obtain data on catalyst activity, life, and attrition.
10 etc. (later)	III	TBD

and overall control. Specific series of tests will be performed as described in Table III.

Table III
Integrated Operation

Test Series	Test Results
1	1. SO_2 recycle stream utilization - Operation of Subunits I and II
2	1. I_2 recycle stream utilization - Operation of Subunits I and III
3	1. Integrated operation of Subunits I, II, and III: a. Flow capacity b. Recycle stream utilization c. Evaluation of control methods

5.0 ACCEPTANCE CRITERIA

The tests performed on the bench-scale model are designed to achieve the objectives listed in Section 2.0. The validity of the tests will, therefore, be judged against those objectives. In general, the "acceptance" of this thermochemical cycle will be established by the following criteria:

1. Flow capacity of each subunit and of the integrated cycle equivalent to 1-4 standard liters per minute of product hydrogen.
2. Full utilization of internal recycle streams.
3. Low losses of I_2 and SO_2 (or their equivalents).
4. Low impurity levels in product hydrogen.

6.0 QUALITY ASSURANCE REQUIREMENTS

Experimental test procedures shall be documented separately to describe the detailed activities planned for Subunits I, II and III, and for the integrated bench model. A controlled marked-up copy of each test procedure shall be maintained to show the actual procedure used.

All test results and other pertinent technical information derived from operation of the bench model shall be recorded in a registered GA laboratory notebook. This notebook shall be maintained in accordance with the GA Policies & Procedures Manual, "Maintenance of Notebooks," and with Recycle Development Department procedure DP-143-11, "Experimental Data Recording, Identification, and Retrieval."

Instruments used to record reportable data shall be calibrated in accordance with Recycle Development Department procedure DP-143-3, "Test Equipment and Instrumentation - Calibration and Maintenance."

7.0 SAFETY REQUIREMENTS

Prior to operation of the bench model, a review of the safety of its design shall be conducted with the GA Plant Safety Department and Industrial Hygiene.

The operation of the bench model shall be conducted in accordance with the GA Accident Prevention Program Manual and in a manner which ensures that the following safety requirements are met:

1. The laboratory exhaust system shall be operated at all times when toxic chemicals are present in the laboratory in order to prevent

exceeding safe limits. NOTE: Safe limits for SO_2 and I_2 in air are 5 ppm(v) (8-hour average exposure) and 1 mg/m^3 (short-time exposure), respectively.

2. The exhaust system shall be activated, the enclosure louvers opened, and the room evacuated and isolated after any accidental release of toxic vapors.

3. Pressure relief valves shall be used to protect personnel and to prevent equipment damage from overpressure.

4. All hot surfaces shall be insulated to protect personnel.

5. Safety glasses shall be worn during all tests. Enclosure doors shall be closed whenever possible during testing.

6. High-pressure gas cylinders shall be properly identified and stored in a safe area outside the laboratory.

7. Interim liquid chemical wastes shall be collected and stored in corrosion-resistant containers. The maximum capacity of these containers shall be 5 gallons for light phase (H_2SO_4 solutions) and 3 gallons for heavy phase (HI_x solutions). Handling of these materials shall be done in accordance with safe procedures for toxic and corrosive chemicals (Ref. 9.8).

8. An eye-wash fountain and safety shower shall be available for emergency use.

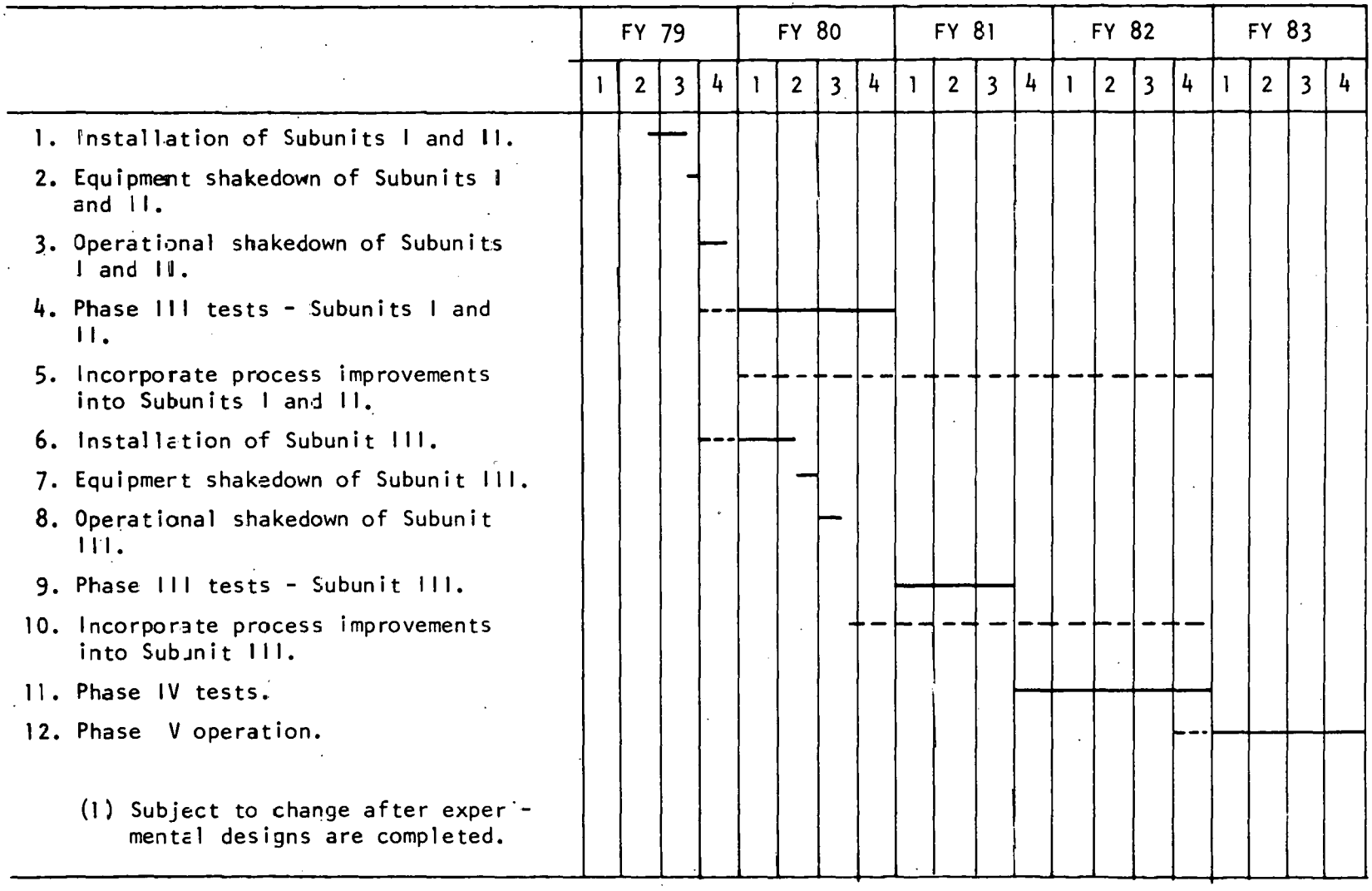
9. Equipment, including tubing, which contains iodine, iodides, or any other halides under pressure shall not be constructed of austenitic stainless steel.

8.0 SCHEDULE

The activities described herein shall be carried out in accordance with the following approximate schedule:

Thermochemical Water-Splitting Cycle
Bench Model

Work Schedule[1]



(1) Subject to change after experimental designs are completed.

9.0 REFERENCES

9.1 "Thermochemical Water Splitting for Hydrogen Production, 1979 Program", Proposal to the Gas Research Institute, GACP 83-004 (Ref.), November 30, 1978.

9.2 Box, G. E. P. and J. S. Hunter, "The 2^{k-p} Fractional Factorial Designs," Part I and Part II Technometrics, Vol. 3, 1961.

9.3 Cochran, W. G. and G. M. Cox, Experimental Designs, 2nd Edition, John Wiley & Sons, 1966.

9.4 Davies, O., Design and Analysis of Industrial Experiments, 2nd Edition, Hafner, 1956.

9.5 Johnson, N. L. and F. C. Leone, Statistics and Experimental Design, John Wiley & Sons, 1964.

9.6 Rode, J. S., "Project 3260: Subunit I Shakedown Procedure", SDB:JSR:95:79, May 18, 1979.

9.7 Rode, J. S., "Project 3260: Subunit II Shakedown Procedure", SDB:JSR:89:79, May 10, 1979.

9.8 General Atomic Accident Prevention Program Manual, Revised 1975.

APPENDIX D
DETAILED FLOWSHEETS, INCLUDING MASS AND ENERGY BALANCES, FOR SECTIONS I THROUGH V

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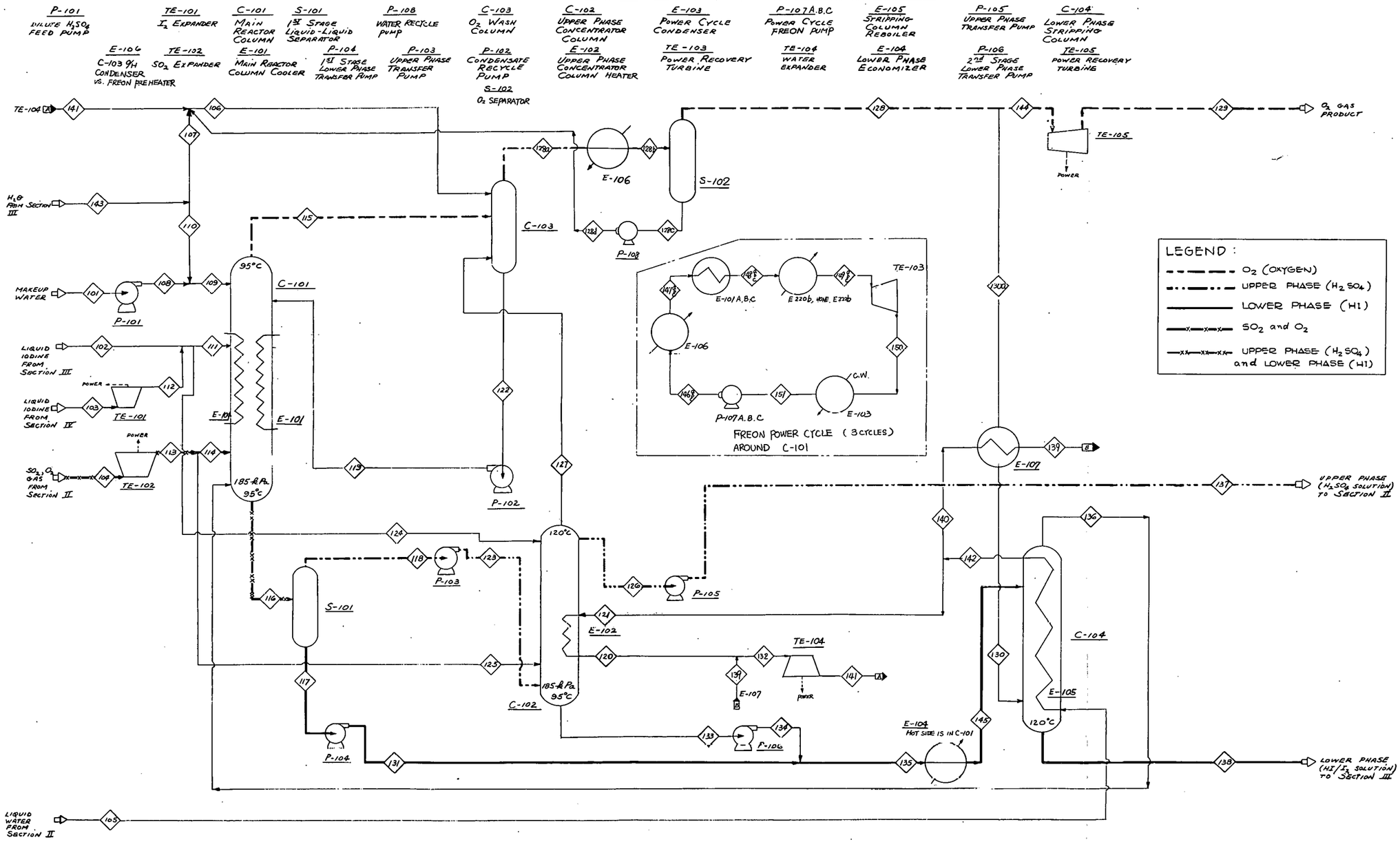

Fig. D-1. Section I - H_2SO_4-HI production and separation; O_2 purification

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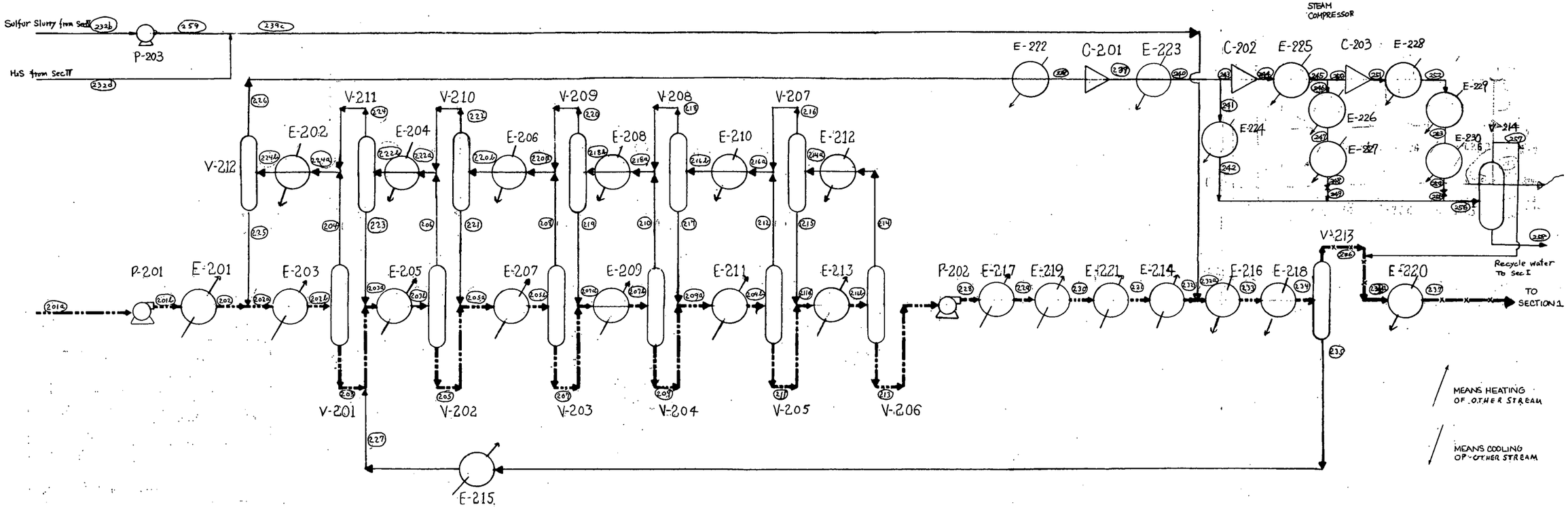
P-201 Feed Pump
V-212 1st Stage H_2SO_4 Separator
E-202 1st Stage H_2SO_4 Condenser
V-211 2nd Stage H_2SO_4 Separator
E-204 2nd Stage H_2SO_4 Condenser
V-210 3rd Stage H_2SO_4 Separator
E-206 3rd Stage H_2SO_4 Condenser
V-209 4th Stage H_2SO_4 Separator
E-208 4th Stage H_2SO_4 Condenser
V-208 5th Stage H_2SO_4 Separator
E-210 5th Stage H_2SO_4 Condenser
V-207 6th Stage H_2SO_4 Separator
E-212 6th Stage H_2SO_4 Condenser
P-202 Conc. H_2SO_4 Pump
C-201 First Stage Steam Compressor
E-222 Precooler
C-202 Second Stage Steam Compressor
E-223,5,8. After Cooler
E-224,6,9. Condenser
C-203 Third Stage Steam Compressor
E-227,230 Sub Cooler
V-214 SO_2 Separator



E-201 1st Stage H_2SO_4 Flash Preheater
E-203 1st Stage H_2SO_4 Flash Heater
P-203 Sulfer Slurry Pump
V-201 1st Stage H_2SO_4 Flash Drum
E-205 2nd Stage H_2SO_4 Flash Heater
E-215 Recycle H_2SO_4 Preheater
V-202 2nd Stage H_2SO_4 Flash Drum
E-207 3rd Stage H_2SO_4 Flash Heater
V-203 3rd Stage H_2SO_4 Flash Drum
E-209 4th Stage H_2SO_4 Flash Heater
V-204 4th Stage H_2SO_4 Flash Drum
E-211 5th Stage H_2SO_4 Flash Heater
V-205 5th Stage H_2SO_4 Flash Drum
E-213 6th Stage H_2SO_4 Flash Heater
V-206 6th Stage H_2SO_4 Flash Drum
E-217 Concentrated H_2SO_4 Preheater
E-219 Concentrated H_2SO_4 Boiler
E-221 H_2SO_4 Decomposer
E-214 SO_3 Decomposer
E-216 SO_3 Decomposer Product Cooler
E-218 SO_3 Decomposer Product Condenser
V-213 SO_3 Decomposer Product Separator
E-220 SO_2-O_2 Cooler

LEGEND :
- UPPER PHASE (H_2SO_4)
- SO_2 and O_2 (OXYGEN)

Fig. D-2. Section II - H_2SO_4-H_2O separation and H_2SO_4 decomposition

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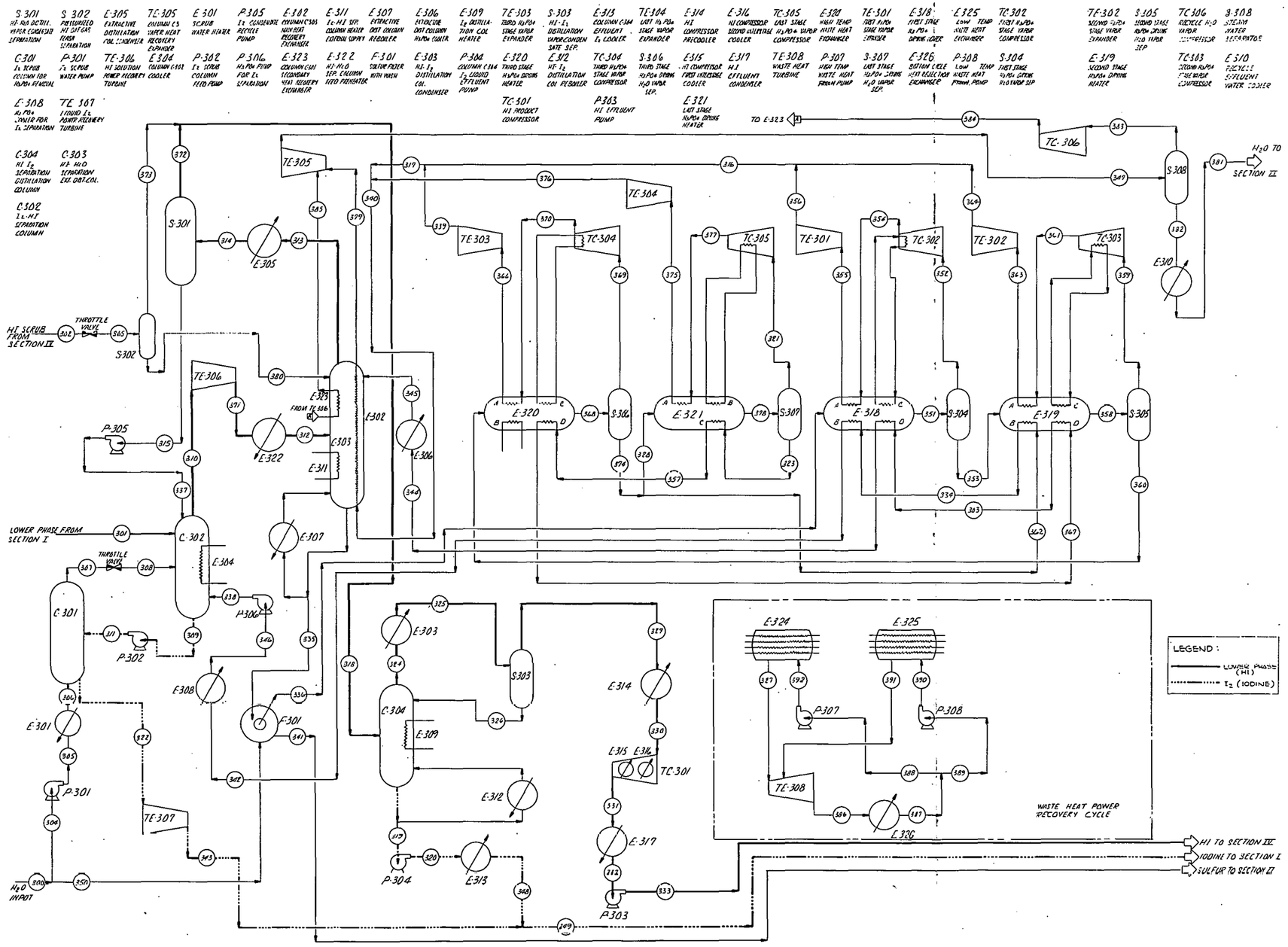

Fig. D-3. Section III - HI separation

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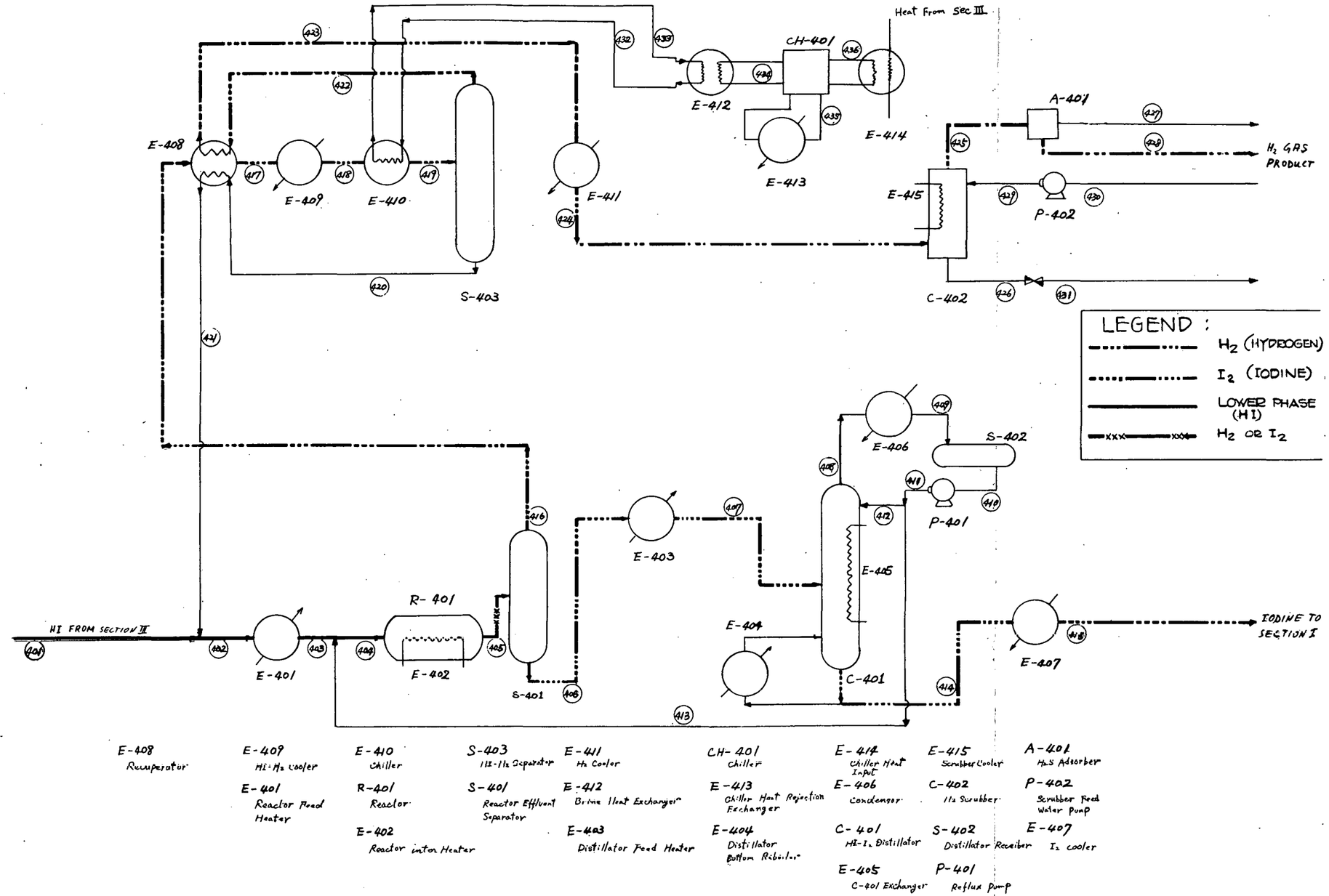

Fig. D-4. Section IV - HI decomposition

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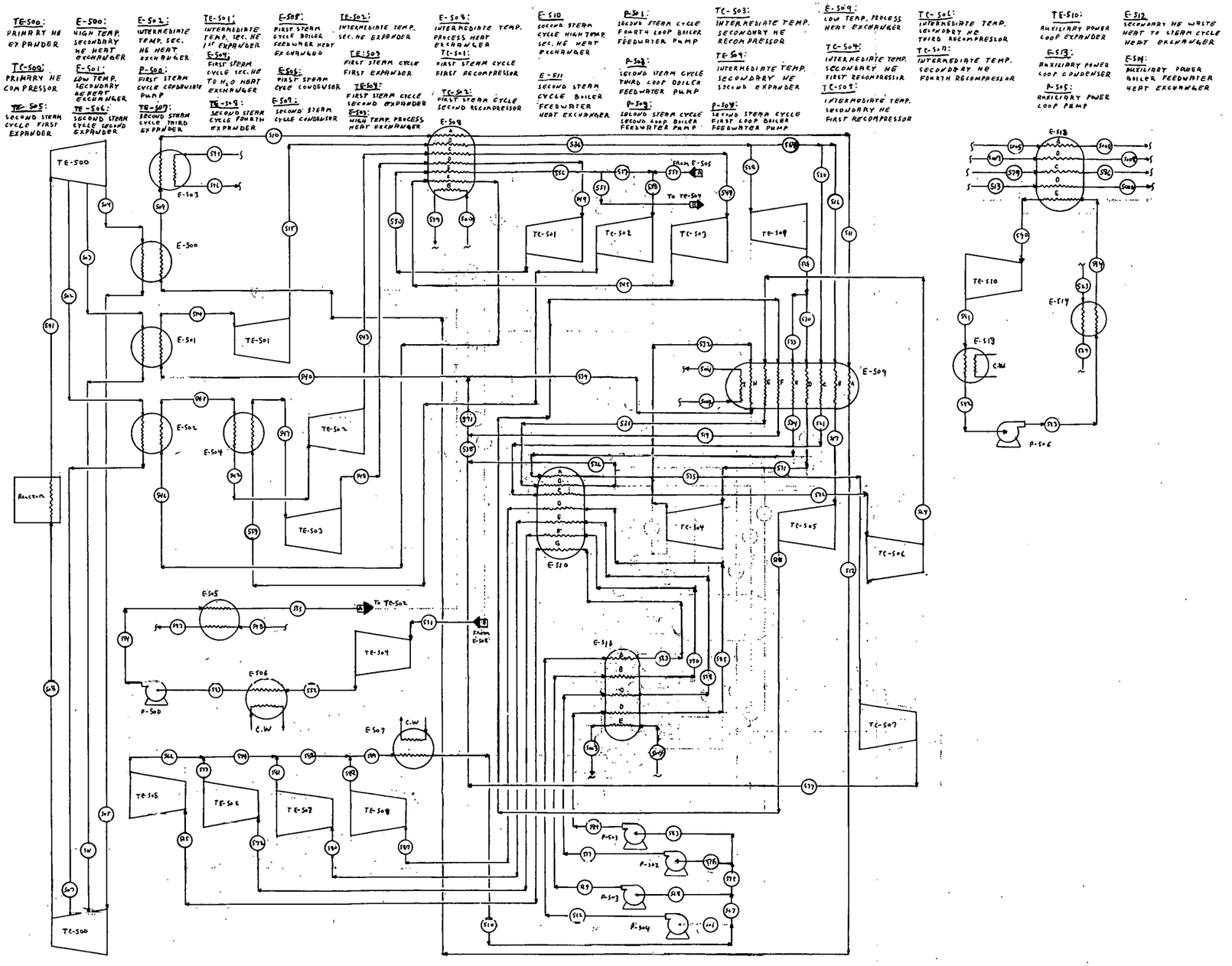

Fig. D-5. Section V - power generation and heat transfer

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ENERGY BALANCE

kJ/0.993 mole H_2	Section I	Section II	Section III	Section IV	Process Sections Subtotal	Section V *	Overall Total
Gross Power Load	0.50	31.32	126.53	0.01	158.79	239.27	-
Power Recovery	23.53	0	22.90	0	46.43	351.97	-
Net External Power Demand	-23.03	31.32	104.06	0.01	112.36	112.70	-
Gross Heat Load	191.24	792.47	1087.18	98.26	2169.15	558.29	608.47
Heat Recovery	186.19	512.74	944.20	77.39	1720.52	33.70	-
Heat from Other Sections	5.05	0	151.43	8.45	164.93	0	-
Net External Heat Demand	0	421.29	0	27.34	448.63	495.54	608.47
Net External Energy Demand	-23.03	452.61	104.06	27.35	560.99	608.47	608.61
Heat to Other Sections	0	141.56	8.45	14.92	164.93	461.05	285.63
Reject Heat	116.18	0	140.86	18.18	275.22	81.89	322.98
Enthalpy Δ	-134.16	311.05	106.18	2.70	285.77	608.47	608.47

* The redesign of Section V needs to be completed since Section I has recently been modified. The given values in this table will change only slightly and the effect on the overall process efficiency will be insignificant.

$$\text{Thermal efficiency} = \left[\Delta H - \left(\frac{\Delta H}{\Delta G}\right) W\right] / Q = [285.77 - 1.2 \times 0]/608.47 = 0.47\ (47\%)$$

SECTION I
MAIN SOLUTION REACTION
MATERIAL BALANCE

Basis: 0.993 Mole H_2

Stream Number	Component Molar Flow Ratios							Total Flow Ratios		Phase	Pressure $Pa \times 10^5$	Temp °K	Comments
	H_2SO_4	HI	I_2	H_2O	SO_2	O_2	R-11	Mole	Weight				
101	0	0	0	0.84806	0	0	0	0.84806	7.6321	ℓ	1.01	298	H_2O input from environment
102	0	0.01000	7.75966	0.13180	0	0	0	7.90146	985.75	ℓ	1.85	393	I_2 from Section III
103	0	0	0.99400	0.00200	0	0	0	0.99600	126.06	ℓ	50.66	393	I_2 from Section IV
104	0	0	0	0.38953	1.00515	0.49650	0	1.89118	43.607	g	2.00	368	SO_2, O_2 from Section II
105	0	0	0	4.71137	0	0	0	4.71137	42.400	ℓ	5.02	425	
106	0	0	0	7.69382	0	0	0	7.69382	69.241	ℓ	1.85	370	
107	T	0	0	2.49854	0	0	0	2.49854	22.486	ℓ	1.85	368	
108	0	0	0	0.84806	0	0	0	0.84806	7.6321	ℓ	1.85	298	
109	0	0	0	8.99232	0	0	0	8.99232	80.926	ℓ	1.85	361	
110	T	0	0	8.14426	0	0	0	8.14426	73.294	ℓ	1.85	368	
111	0	0.00923	8.11102	0.12399	0	0	0	8.24424	1030.2	ℓ	1.85	393	
112	0	0	0.99400	0.00200	0	0	0	0.99600	126.06	ℓ	1.85	393	
113	0	0	0	0.38953	1.00515	0.49650	0	1.89118	43.607	g	1.85	362	
114	0	0	0	0.34496	0.89139	0.44100	0	1.67735	38.678	g	1.85	362	
115	0	0	0.02455	0.40816	0	0.46717	0	0.89988	14.254	g	1.85-	368	
116	0.92899	1.86924	7.19908	14.89721	0.21605	0	0	25.11057	1218.8	ℓ	1.85	368	
117	0.00186	1.86924	7.11908	9.89430	0.20118	0	0	19.16566	1127.9	ℓ	1.85-	368	
118	0.92713	0	0	5.00291	0.01487	0	0	5.94491	90.921	ℓ	1.85-	368	
119	0.03773	0.07546	0	7.57446	0	0	0	7.68765	74.837	ℓ	1.85+	379.5	
120	0	0	0	3.40455	0	0	0	3.40455	30.639	ℓ	5.02	377.5	
121	0	0	0	3.40455	0	0	0	3.40455	30.639	ℓ	5.02	400	
122	0.03773	0.07546	0	7.57446	0	0	0	7.68765	74.837	ℓ	1.85	379.5	
123	0.92713	0	0	5.00291	0.01487	0	0	5.94491	90.921	ℓ	1.85+	368	
124	0	0.00073	0.64265	0.00983	0	0	0	0.65321	81.623	ℓ	1.85	393	
125	0	0	0	0.04457	0.11376	0.05629	0	0.21462	4.9412	g	1.85	362	
126	0.99900	0	0	4.09350	0.00375	0	0	5.09625	85.902	ℓ	1.85-	393	
127	0	0	0.01316	0.05360	0.03773	0.05629	0	0.16080	4.2607	g	1.85-	393	
128	0	0	0	0.02175	0	0.52267	0	0.54442	8.5506	g	1.85-	313	
128a	0	0	0	0.50566	0	0.52267	0	1.02833	12.906	g	1.85	370	
128b	0	0	0	0.50566	0	0.52267	0	1.02833	12.906	g+ℓ	1.85	313	
128c	0	0	0	0.48391	0	0	0	0.48391	4.3550	ℓ	1.85-	313	
128d	0	0	0	0.48391	0	0	0	0.48391	4.3550	ℓ	1.85+	313	
129	0	0	0	0.02066	0	0.49650	0	0.51716	8.1224	g+ℓ	1.01	290.7-	O_2 output-H_2O vapor 0.01000
130	0	0	0	0.00109	0	0.02617	0	0.02726	0.42813	g	1.85-	378	H_2O liquid 0.01066

SECTION I
MAIN SOLUTION REACTION
MATERIAL BALANCE
(Continued)

Stream Number	Component Molar Flow Ratios							Total Flow Ratios		Phase	Pressure Pa×10^5	Temp °K	Comments
	H_2SO_4	HI	I_2	H_2O	SO_2	O_2	R-11	Mole	Weight				
130a	0	0	0	0.00109	0	0.02617	0	0.02726	0.42813	g	1.85	313	
131	0.00186	1.86924	7.19908	9.89430	0.20118	0	0	19.16566	1127.9	g	1.85+	368	
132	0	0	0	4.71137	0	0	0	4.71137	42.400	ℓ	5.02	377.5	
133	0.00014	0.14476	0.55746	0.76618	0.01514	0	0	1.48368	87.323	ℓ	1.85-	368	
134	0.00014	0.14476	0.55746	0.76618	0.01514	0	0	1.48368	87.323	ℓ	1.85+	368	
135	0.00200	2.01400	7.75654	10.66048	0.21632	0	0	20.64934	1215.2	ℓ	1.85+	368	
136	0	0.00200	0.00388	0.05217	0.21592	0.02617	0	0.30014	8.4170	g	1.85	393	
137	0.99900	0	0	4.0935	0.00375	0	0	5.09625	85.902	ℓ	1.85+	393	Upper phase to Section II
138	0.00200	2.01200	7.75266	10.60940	0.00040	0	0	20.37646	1207.2	ℓ	1.85	393	Lower phase to Section III
139	0	0	0	1.30682	0	0	0	1.30682	11.761	ℓ	5.02	377.5	
140	0	0	0	1.30682	0	0	0	1.30682	11.761	ℓ	5.02	400	
141	0	0	0	4.71137	0	0	0	4.71137	42.400	ℓ	1.85	377.5	
142	0	0	0	4.71137	0	0	0	4.71137	42.400	ℓ	5.02	400	
143	0	0	0	10.64280	0	0	0	10.64280	95.780	ℓ	1.85	368	H_2O from Section III
144	0	0	0	0.02066	0	0.49650	0	0.51716	8.1224	g	1.85-	313	
145	0.00200	2.01400	7.75654	10.66048	0.21632	0	0	20.64934	1215.2	ℓ	1.85	390.8	
146a	0	0	0	0	0	0	1.36462	1.36462	93.648	ℓ	7.00	300	R-11 MW=137.38 ($c\,cl_3F$)
146b	0	0	0	0	0	0	1.28574	1.28574	88.234	ℓ	8.80	300	
146c	0	0	0	0	0	0	2.05860	2.05860	141.27	ℓ	10.60	300	
147a	0	0	0	0	0	0	1.36462	1.36462	93.648	ℓ	7.00	340.1	R-11
147b	0	0	0	0	0	0	1.28574	1.28574	88.234	ℓ	8.80	340.1	Power cycle
147c	0	0	0	0	0	0	2.05860	2.05860	141.27	ℓ	10.60	340.1	
148a	0	0	0	0	0	0	1.36462	1.36462	93.648	g+ℓ	6.42	363.1	
148b	0	0	0	0	0	0	1.28574	1.28574	88.234	g	8.18	373.1	
148c	0	0	0	0	0	0	2.05860	2.05860	141.27	g+ℓ	10.12	383.1	
149a	0	0	0	0	0	0	1.36462	1.36462	93.648	g	6.39	363.1	
149b	0	0	0	0	0	0	1.28574	1.28574	88.234	g	8.18	373.1	
149c	0	0	0	0	0	0	2.05860	2.05860	141.27	g	10.08	383.1	
150	0	0	0	0	0	0	4.70896	4.70896	323.15	g	1.13	300	
151	0	0	0	0	0	0	4.70896	4.70896	323.15	ℓ	1.13	300	

SECTION I
MAIN SOLUTION REACTION
HEAT LOADS

Heat Exch. Number	Energy Load, kJ	Hot-Side In		Hot-Side Out		Cold-Side In		Cold-Side Out		Comments
		Stream Number	Stream Temp.,°K	Stream Number	Stream Temp.°K	Stream Number	Stream Temp.°K	Stream Number	Stream Temp.°K	
E-101A	29.409	-	379	-	368	147a	340.1	148a	363.1	Hot side is in C-101
B	31.231	-	389	-	368	147b	340.1	148b	373.1	Hot side is in C-101
C	49.010	-	398	-	368	147c	340.1	148c	383.1	Hot side is in C-101
E-102	5.880	121	400	120	377.5	-	368	-	393	Cold side is in C-102
E-103	116.178	150	300	15	300	C.W.	-	-	-	
E-104	36.403	-	398	-	383	135	368	145	390.8	Hot side is in C-101
E-105	9.103	105	425	142	400	-	390.8	-	393	Cold side is in C-104
E-106	22.903	128a	370	128b	313	146 a,b,c	300	147 a,b,c	340.1	
E-107	2.257	140	400	139	377.5	130a	313	130	378	
E-220b	2.974	-	410	-	368	148a	363.1	149a	363.1	
E-222b	2.071	-	405	-	393	148c	383.1	149c	383.1	

SECTION I

MAIN SOLUTION REACTION
POWER LOADS

Power Device Number	Energy Load kJ	Input Stream No.	Input Stream Pressure, Pax10^5	Output Stream No.	Output Stream Pressure, Pa x 10^5	Comments
P-101	0.001	101	1.01	108	1.85	
P-102	negligible	122	1.85-	119	1.85+	
P-103	negligible	118	1.85-	123	1.85+	
P-104	negligible	117	1.85-	131	1.85+	
P-105	negligible	126	1.85-	137	1.85+	
P-106	negligible	133	1.85-	134	1.85+	
P-107A	0.108	151	1.13	146a	7.00	
107B	0.127	151	1.13	146b	8.80	
107C	0.262	151	1.13	146C	10.60	
P-108	negligible	128c	1.85-	128d	1.85+	
TE-101	0.287	103	50.66	112	1.85	
TE-102	0.497	104	2.00	113	1.85	
TE-103	21.916	149a,b,c	6.39,8.18,10.08	150	1.13	
TE-104	0.023	132	5.02	141	1.85	
TE-105	0.809	144	1.85-	129	1.01	

SECTION II

H_2SO_4 CONCENTRATION AND DECOMPOSITION

MATERIAL BALANCE

Basis: .0993 mole H_2 Product

Stream No.	Component Molar Flow Ratios							Total Flow Ratio		Phase	Pressure $Pa \times 10^5$	Temp. °K	Comments
	H_2SO_4	SO_3	SO_2	H_2O	O_2	S	H_2S	Mole	Weight				
201a	0.9990	0	0.0038	4.0935	0	0	0	5.0963	85.194	ℓ	1.85	393	
201b	0.9990	0	0.0038	4.0935	0	0	0	5.0963	85.194	ℓ	2.00	393	
202	0.9990	0	0.0038	4.0935	0	0	0	5.0963	85.194	ℓ	2.00	425	
202a	0.9999	0	0.0038	4.0973	0	0	0	5.1010	85.992	ℓ	2.00	425	
202b	0.9999	0	0.0038	4.0973	0	0	0	5.1010	85.992	ℓ+g	2.00	470	
203	0.9995	0	0	2.1161	0	0	0	3.1156	68.017	ℓ	2.00	470	
203a	1.3688	0	0	2.9024	0	0	0	4.2712	93.189	ℓ	2.00	470	
203b	1.3688	0	0	2.9024	0	0	0	4.2712	93.189	ℓ+g	2.00	502	
204	0.0004	0	0.0038	1.9812	0	0	0	1.9854	17.975	g	2.00	470	
205	1.3660	0	0	1.8608	0	0	0	3.2268	83.676	ℓ	2.00	502	
205a	1.3983	0	0	1.9048	0	0	0	3.3031	85.654	ℓ	2.00	502	
205b	1.3982	0.0001	0	1.9049	0	0	0	3.3032	85.654	ℓ+g	2.00	536	
206	0.0028	0	0	1.0416	0	0	0	1.0444	9.513	g	2.00	502	
207	1.3838	0	0	1.2263	0	0	0	2.6101	78.836	ℓ	2.00	536	
207a	1.4704	0	0	1.3031	0	0	0	2.7735	83.770	ℓ	2.00	536	
207b	1.4683	0.0021	0	1.3052	0	0	0	2.7756	83.770	ℓ+g	2.00	573	
208	0.0144	0.0001	0	0.6786	0	0	0	0.6931	6.818	g	2.00	536	
209	1.4157	0	0	0.7294	0	0	0	2.1451	75.926	ℓ	2.00	573	
209a	1.6362	0	0	0.8430	0	0	0	2.4792	87.752	ℓ	2.00	573	
209b	1.6019	0.0343	0	0.8773	0	0	0	2.4792	86.380	ℓ+g	2.00	613	
210	0.0526	0.0021	0	0.5758	0	0	0	0.6305	7.844	g	2.00	573	
211	1.4193	0	0	0.3009	0	0	0	1.7202	72.245	ℓ	2.00	613	
211a	1.6561	0	0	0.3510	0	0	0	2.0071	84.298	ℓ	2.00	613	
211b	1.5578	0.0983	0	0.4493	0	0	0	2.1054	84.298	ℓ+g	2.00	634	
212	0.1826	0.0343	0	0.5764	0	0	0	0.7933	15.506	g	2.00	613	
213	1.3610	0	0	0.1547	0	0	0	1.5157	68.073	ℓ	2.00	634	
214	0.1968	0.0983	0	0.2946	0	0	0	0.5897	16.225	g	2.00	634	
214a	0.2859	0.0092	0	0.2055	0	0	0	0.5006	16.225	ℓ+g	2.00	613	
215	0.2368	0	0	0.0501	0	0	0	0.2869	12.053	ℓ	2.00	613	
216	0.0491	0.0092	0	0.1554	0	0	0	0.2137	4.173	g	2.00	613	
216a	0.2317	0.0435	0	0.7318	0	0	0	1.0070	19.679	g	2.00	613	
216b	0.2731	0.0021	0	0.6904	0	0	0	0.9656	19.679	ℓ+g	2.00	573	
217	0.2205	0	0	0.1136	0	0	0	0.3341	11.826	ℓ	2.00	573	
218	0.0526	0.0021	0	0.5768	0	0	0	0.6315	7.853	g	2.00	573	
218a	0.1052	0.0042	0	1.1526	0	0	0	1.2620	15.697	g	2.00	573	
218b	0.1092	0.0002	0	1.1486	0	0	0	1.2580	15.697	ℓ+g	2.00	536	

SECTION II
H_2SO_4 CONCENTRATION AND DECOMPOSITION
MATERIAL BALANCE
(CONTINUED)

Stream No.	Component Molar Flow Ratios							Total Flow Ratio		Phase	Pressure $Pa \times 10^5$	Temp. °K	Comments
	H_2SO_4	SO_3	SO_2	H_2O	O_2	S	H_2S	Mole	Weight				
219	0.0866	0	0	0.0768	0	0	0	0.1634	4.934	ℓ	2.00	536	
220	0.0226	0.0002	0	1.0718	0	0	0	1.0946	10.763	g	2.00	536	
220a	0.0370	0.0003	0	1.7504	0	0	0	1.7877	17.581	g	2.00	536	
220b	0.0372	0.0001	0	1.7502	0	0	0	1.7875	17.581	ℓ+g	2.00	502	
221	0.0323	0	0	0.0440	0	0	0	0.0763	1.979	ℓ	2.00	502	
222	0.0049	0.0001	0	1.7042	0	0	0	1.7092	15.584	g	2.00	502	
222a	0.0077	0.0001	0	2.7478	0	0	0	2.7556	25.116	g	2.00	502	
222b	0.0078	0	0	2.7477	0	0	0	2.7555	25.116	ℓ+g	2.00	470	
223	0.0073	0	0	0.0137	0	0	0	0.0210	0.481	ℓ	2.00	470	
224	0.0005	0	0	2.7340	0	0	0	2.7345	24.635	g	2.00	470	
224a	0.0009	0	0.0038	4.7152	0	0	0	4.7199	42.610	g	2.00	470	
224b	0.0009	0	0.0038	4.7152	0	0	0	4.7199	42.610	ℓ+g	2.00	425	
225	0.0009	0	0	0.0038	0	0	0	0.0047	0.078	ℓ	2.00	425	
226	0	0	0.0038	4.7114	0	0	0	4.7152	42.531	g	2.00	425	
227	0.3620	0	0	0.7726	0	0	0	1.1346	24.690	ℓ	2.00	470	
228	1.3610	0	0	0.1547	0	0	0	1.5157	68.073	ℓ	8.60	635	
229	1.3610	0	0	0.1547	0	0	0	1.5157	68.073	ℓ	8.60	686	
230	0.8269	0.5341	0	0.6888	0	0	0	2.0498	68.073	g	8.60	686	
231	0.1966	1.1644	0	1.3191	0	0	0	2.6801	68.073	g	7.80	800	
232	0.0005	0.3615	0.9990	1.5152	0.4995	0	0	3.3757	68.073	g	5.20	1144	
232a	0.0005	0.3615	1.0014	1.5236	0.4965	0	0	3.3835	68.183	g	5.20	1144	
232b	0	0	0	0.0072	0	0.0012	0	0.0084	0.084	ℓ+s	1.013	303	Slurry pump.
232c	0	0	0	0.0072	0	0.0012	0	0.0084	0.084	ℓ+s	5.2	303	
232d	0	0	0	0	0	0	0.0012	0.0012	0.020	g	5.2	400	
233	0.3484	0.0136	1.0014	1.1757	0.4965	0	0	3.0356	68.183	g	2.40	579	
234	0.3620	0	1.0014	1.1621	0.4965	0	0	3.0220	68.183	ℓ+g	2.00	418	
235	0.3620	0	0	0.7726	0	0	0	1.1346	24.690	ℓ	2.00	418	
236	0	0	1.0014	0.3895	0.4965	0	0	1.8874	43.492	g	2.00	418	
236a	0	0	1.0052	0.3895	0.4965	0	0	1.8912	43.614	g	2.00	418	
237	0	0	1.0052	0.3895	0.4965	0	0	1.8912	43.614	g	2.00	368	
238	0	0	0.0038	4.7114	0	0	0	4.7152	42.531	g	2.00	425	
239	0	0	0.0038	4.7114	0	0	0	4.7152	42.531	g	5.02	499	
240	0	0	0.0038	4.7114	0	0	0	4.7152	42.531	g	5.02	425	
241	0	0	0.0011	1.3163	0	0	0	1.3174	11.884	g	5.02	425	
242	0	0	0.0011	1.3163	0	0	0	1.3174	11.884	ℓ	5.02	425	
243	0	0	0.0027	3.3951	0	0	0	3.3978	30.648	g	5.02	425	

SECTION II
H_2SO_4 CONCENTRATION AND DECOMPOSITION
MATERIAL BALANCE
(Continued)

Stream No.	Component Molar Flow Ratios							Total Flow Ratio		Phase	Pressure $Pa \times 10^5$	Temp. °K	Comments
	H_2SO_4	SO_3	SO_2	H_2O	O_2	S_2	H_2S	Mole	Weight				
244	0	0	0.0027	3.3951	0	0	0	3.3978	30.648	g	9.35	496	
245	0	0	0.0027	3.3951	0	0	0	3.3978	30.648	g	9.35	450	
246	0	0	0.0012	1.4459	0	0	0	1.4471	13.054	g	9.35	450	
247	0	0	0.0012	1.4459	0	0	0	1.4471	13.054	ℓ	9.35	450	
248	0	0	0.0012	1.4459	0	0	0	1.4471	13.054	ℓ	9.35	425	
249	0	0	0.0012	1.4459	0	0	0	1.4471	13.054	ℓ	5.02	425	
250	0	0	0.0015	1.9492	0	0	0	1.9507	17.594	g	9.35	450	
251	0	0	0.0015	1.9492	0	0	0	1.9507	17.594	g	17.95	533	
252	0	0	0.0015	1.9492	0	0	0	1.9507	17.594	g	17.95	480	
253	0	0	0.0015	1.9492	0	0	0	1.9507	17.594	ℓ	17.95	480	
254	0	0	0.0015	1.9492	0	0	0	1.9507	17.594	ℓ	17.95	425	
255	0	0	0.0015	1.9492	0	0	0	1.9507	17.594	ℓ	5.02	425	
256	0	0	0.0038	4.7114	0	0	0	4.7152	42.531	ℓ	5.02	425	
257	0	0	0.0038	0	0	0	0	0.0038	0.121	g	5.02	425	
258	0	0	T	4.7114	0	0	0	4.7114	42.409	ℓ	4.90	425	

SECTION II
H_2SO_4 CONCENTRATION AND DECOMPOSITION
HEAT AND POWER LOADS

Heat Exch. Number	Energy Load, kJ	Hot-Side Input		Hot-Side Output		Cold-Side Input		Cold-Side Output		Comments
		Stream Number	Stream Temp, °K	Stream Number	Stream Temp, °K	Stream Number	Stream Temp, °K	Stream Number	Stream Temp, °K	
E-201	15.113	(a)	(a)	(a)	(a)	201b	393	202	425	
E-202	3.854	224a	470	224b	425	(a)	(a)	(a)	(a)	
E-203	103.162	(a)	(a)	(a)	(a)	202a	425	202b	470	
E-204	4.632	222a	502	222b	470	(a)	(a)	(a)	(a)	
E-205	63.546	(a)	(a)	(a)	(a)	203a	470	203b	502	
E-206	5.979	220a	536	220b	502	(a)	(a)	(a)	(a)	
E-207	49.390	(a)	(a)	(a)	(a)	205a	502	205b	536	
E-208	12.303	218a	573	218b	536	(a)	(a)	(a)	(a)	
E-209	43.984	(a)	(a)	(a)	(a)	207a	536	207b	573	
E-210	25.195	216a	613	216b	573	(a)	(a)	(a)	(a)	
E-211	61.130	(a)	(a)	(a)	(a)	209a	573	209b	613	
E-212	25.113	214a	634	214b	613	(a)	(a)	(a)	(a)	
E-213	44.058	(a)	(a)	(a)	(a)	211a	613	211b	614	
E-214	172.119	(a)	(a)	(a)	(a)	231	800	232	1144	
E-215	5.120	(a)	(a)	(a)	(a)	235	418	227	470	
E-216	123.561	232	1144	233	579	(a)	(a)	(a)	(a)	
E-217	13.531	(a)	(a)	(a)	(a)	228	635	229	686	
E-218	93.326	233	579	234	418	(a)	(a)	(a)	(a)	
E-219	132.401	(a)	(a)	(a)	(a)	229	686	230	686	
E-220	3.591	236	418	237	368	(a)	(a)	(a)	(a)	
E-221	82.540	(a)	(a)	(a)	(a)	230	686	231	800	
E-222	5.518	226	425	238	393	(b)	(b)	(b)	(b)	Heat generated by compression of steam.
E-223	13.805	239	499	240	425	(b)	(b)	(b)	(b)	
E-224	50.001	241	425	242	425	(b)	(b)	(b)	(b)	
E-225	6.653	244	496	245	450	(b)	(b)	(b)	(b)	
E-226	52.775	246	450	247	450	(b)	(b)	(b)	(b)	
E-227	2.843	247	450	248	425	(b)	(b)	(b)	(b)	
E-228	4.849	251	533	252	480	(b)	(b)	(b)	(b)	
E-229	67.193	252	480	253	480	(b)	(b)	(b)	(b)	
E-230	8.544	253	480	254	425	(b)	(b)	(b)	(b)	

(a): See Table - 4 for first heat load match up

(b): See Table - 5 for heat load match up (utilization of heat generated by compression of steam)

SECTION II
H_2SO_4 CONCENTRATION AND DECOMPOSITION
HEAT AND POWER LOADS
(Continued)

Power Device	Energy Load kJ	Input Stream Number	Input Stream Pressure, Pax 10^5	Output Stream Number	Output Stream Pressure, Pax 10^5	Comments
P-201	0.003	201a	1.85	201b	2.00	
P-202	0.067	213	2.00	228	8.60	
P-203	Negligible	232b	1.013	232c	5.20	Slurry pump.
C-201	17.362	238	2.00	239	5.02	
C-202	8.280	243	5.02	244	9.35	
C-203	5.608	250	9.35	251	17.95	

SECTION II
H_2SO_4 CONCENTRATION AND DECOMPOSITION
HEAT LOAD MATCHUP

BASIS: 0.993 mole H_2 Product

Hot - Side			Cold - Side			Heat Load	Comments
Heat Exch. Number	Input Temp. °K	Output Temp. °K	Heat Exch. Number	Input Temp. °K	Output Temp. °K	k_J	
(a)	(a)	(a)	E214a	1130	1144	7.005	
E-216a	1144	810	E214b1	800	1130	73.043	E214 load total 172.119
(a)	(a)	(a)	E214b2	800	1130	92.071	
E-216b	810	706.9	E221A	686	800	22.553	E221 load total 81.540
(a)	(a)	(a)	E221B	686	800	58.987	
(a)	(a)	(a)	E219	686	686	132.401	
E-216C	706.9	645	E217	635	686	13.531	
E-216d	645	628	E213A	613	634	3.718	E213 load total 44.058
(a)	(a)	(a)	E213B	613	634	40.340	
E-216e	628	579	E211A	573	613	10.716	
E-212	634	613	E211B	573	613	26.113	E211 load total 61.130
(a)	(a)	(a)	E211C	573	613	24.301	
E-210	613	573	E209A	536	573	26.195	
E-218a	579	546	E209B	536	573	19.129	E209 load total 48.984
(a)	(a)	(a)	E209C	536	573	3.660	
E-208	573	536	E207A	502	536	12.303	
E-218b	546	512	E207B	502	536	19.709	E207 load total 49.390
(a)	(a)	(a)	E207C	502	536	17.378	
(a)	(a)	(a)	E205a	497	502	9.929	
E-206	536	502	E205b	493.49	497	6.979	
E-218C	512	495	E205C	488.5	493.49	9.854	E205 load total 63.546
E-218d	495	480	E205d1	470	488.5	8.695	
(a)	(a)	(a)	E205d2	473.6	488.5	22.584	
(b)	(b)	(b)	E205e	470	473.6	5.505	
E-204a	502	485.7	E203A	425	470	2.366	
E-218e	480	435	E203B	425	470	26.085	E203 load total 103.162
(b)	(b)	(b)	E203C	425	470	63.455	
(a)	(a)	(a)	E203D	425	470	11.256	
E-218f	435	418	E201a	404.1	425	9.854	
E-220a	418	410	E201b	402.8	404.1	0.617	E201 load total 15.113
(b)	(b)	(b)	E201c	393	402.8	4.642	
E-204b	485.7	470	E215a	450.7	470	2.266	E215 load total 6.120
E-202	470	425	E215b	418	450.7	3.854	
E-220b	410	368	-	-	-	2.974	Cold side is in power cycle of Section 1

(a): Heat supplied from Section V (Helium Section)
(b): See Table - 5 for heat load match up (Heat generated by steam compression)

SECTION II
H_2SO_4 CONCENTRATION AND DECOMPOSITION
HEAT LOAD MATCHUP
(Continued)

Hot - Side			Cold - Side				
Heat Exch. Number	Input Temp. °K	Output Temp. °K	Heat Exch. Number	Input Temp. °K	Output Temp. °K	Heat Load k_J	Comments
E-228	533	480	E205e1	470.4	473.6	4.849	
E-225a	496	491.5	E205e2	470	470.4	0.656	
E-223a	499	480	E203C1	467.5	470	3.545	
E-225b	491.5	480	E203C2	466.3	467.5	1.658	
E-229A	480	480	E203C3	449.3	466.3	23.946	
E-225C	480	450	E203C41	438.98	449.3	4.339	
E-223b	480	450	E203C42	438.98	449.3	5.596	
E-230a	480	450	E203C43	438.98	449.3	4.660	
E-226A	450	450	E203C5	425	438.98	19.711	
E-229B	480	480	E320	461.38	465	38.567	
E-229C	480	480	E312	457.5	457.5	2.375	
E-229D	480	480	E309B	430.85	457.5	2.305	
E-226B	450	450	E307	430.85	430.85	5.061	
E-226C	450	450	E311A11	423.17	430.85	28.003	
E-223C	450	432.55	E311A12	422.28	423.17	3.225	
E-230b	450	445.23	E309B1	422.28	430.85	0.742	
E-230C	445.23	441.92	E309C12	407.16	413.09	0.513	
E-227A	450	425	E322A121	412.79	413.09	1.306	
E-227B	450	425	E311B21	412.79	413.09	1.537	
E-230C1	441.92	425	E322A122	412.51	412.79	1.207	
E-230C2	441.92	425	E311B22	412.51	412.79	1.422	
E-223d1	432.55	425	E322A123	412.36	412.51	0.647	
E-223d2	432.55	425	E311B23	412.36	412.51	0.762	
E-224A	425	425	E322A124	407.16	412.36	22.415	
E-224B	425	425	E311B24	407.16	412.36	26.391	
E-224C	425	425	E201C1	399.7	402.8	1.195	
E-222a	425	405	E201C2	393	399.7	3.447	
E-222b	405	393	-	-	-	2.071	Cold side is in power cycle in Section 1

Basis: 0.99300 g-mole H_2 Product
T = "Trace"

SECTION III
HI Separation
Material Balance

Stream Number	Component Molar Flow Ratios								Total Flow Ratio		Phase	Pressure k Pa$^{\times}$10^{-2}	Temp. °K	Comments
	H_2SO_4	HI	I_2	H_2O	SO_2	S	H_2S	H_3PO_4	Moles	Weight				
300	0	0	0	0.08440	0	0	0	0	0.08440	0.076	ℓ	1.013	298.15	Net input from the environment
301	0.00200	2.01200	7.75266	10.60940	0.00040	T	T	0	20.46646	1207.204	ℓ	1.850	393.15	Input from Sec. I, H_2SO_4-HI Synthesis
302	0	0.08120	T	0.08120	0	0	T	0	0.16240	5.920	ℓ	50.663	303.00	Input from Section IV, HI Decomposition
303	T	0	0	T	0	T	0	1.06604	1.06604	52.186	ℓ	1.013	457.75	
304	0	0	0	0.07000	0	0	0	0	0.07000	0.630	ℓ	1.013	298.15	
305	0	0	0	0.07000	0	0	0	0	0.07000	0.630	ℓ	2.026	298.15	
306	0	0	0	0.07000	0	0	0	0	0.07000	0.630	ℓ	2.026	381.57	
307	T	0.01240	0.01240	0.03100	0	0	0	0.06200	0.11780	5.679	ℓ	2.026	393.15	
308	T	0.01240	0.01240	0.03100	0	0	0	0.06200	0.11780	5.679	ℓ	1.850	393.15	
309	T	0.01240	7.56836	0.02480	0	0	0	0.06200	7.66756	963.721	ℓ	1.850	393.15	
310	0.00200	2.02450	0.53970	14.72583	0.00040	T	T	14.26942	31.65185	1028.978	ℓ	1.850	393.15	
311	T	0.01240	0.01240	0.02480	0	0	0	0.06200	7.66756	963.721	ℓ	2.026	393.15	
312	0.00200	2.02450	0.53970	14.72583	0.00040	T	T	14.26942	31.65185	1028.978	ℓ	1.013	418.00	
313	0	2.08535	0.54770	0.09500	T	T	0.00120	0	2.72925	203.585	g	1.013	401.00	
314	0	2.08535	0.54770	0.09500	T	T	0.00120	0	2.72925	203.586	g&ℓ	1.013	387.00	[0.01250 HI·0.34300 I_2· 0.02500 H_2O] (ℓ) plus a trace of S(s).
315	0	0.01250	0.34300	0.02500	T	T	T	0	0.38050	44.516	ℓ	1.013	387.00	
316	0	0	0	7.74113	0	0	0	0	7.74113	69.666	g&ℓ	6.786	436.85	1.14003 H_2O (g)
317	0	0	0	10.33761	0	0	0	0	10.33761	93.033	g&ℓ	6.786	436.85	1.39315 H_2O (g)
318	0	2.07720	0.20470	0.07000	T	0	0.00120	0	2.35310	159.347	g	1.013	387.00	
319	0	0.01000	0.20370	0.06800	0	0	0	0	0.28170	2.708	ℓ	1.013	457.50	
320	0	0.01000	0.20370	0.06800	0	0	0	0	0.28170	2.708	ℓ	1.850	457.51	
321	0	0	0	0.30519	0	0	0	0	0.30519	2.747	g	1.013	534.15	
322	0	T	7.55596	0.06380	0	0	0	0	7.61976	958.672	ℓ	2.026	393.15	
323	T	0	0	T	0	0	0	1.06604	1.06604	52.186	ℓ	1.013	534.15	
324	0	2.21820	0.05140	0.26900	0	0	0.00120	0	2.53980	150.710	g	1.013	377.60	
325	0	2.21820	0.05140	0.26900	0	0	0.00120	0	2.53980	150.710	g&ℓ	1.013	368.15	[2.06720 HI+0.00100 I_2+ 0.00200 H_2O+0.00120 H_2S](g)
326	0	0.15100	0.05040	0.26700	0	0	T	0	0.46840	18.443	ℓ	1.013	368.15	

SECTION III
HI Separation
Material Balance
(Continued)

Stream Number	Component Molar Flow Ratios								Total Flow Ratio		Phase	Pressure k Pa×10⁻²	Temp. °K	Comments
	H_2SO_4	HI	I_2	H_2O	SO_2	S	H_2S	H_3PO_4	Moles	Weight				
327	0	0	0	0	0	0	0	3.05102	3.05102	419.15	g	9.480	380.00	
328	T	0	0	0.30519	0	T	0	1.06604	1.37123	52.186	ℓ	1.013	476.65	
329	0	2.06720	0.00100	0.00200	0	0	0.00120	0	2.07140	132.267	g	1.013	368.15	
330	0	2.06720	0.00100	0.00200	0	0	0.00120	0	2.07140	132.267	g	1.013	300.00	
331	0	2.06720	0.00100	0.00200	0	0	0.00120	0	2.07140	132.267	g	8.268	373.24	
332	0	2.06720	0.00100	0.00200	0	0	0.00120	0	2.07140	132.267	ℓ	8.268	300.00	
333	0	2.06720	0.00100	0.00200	0	0	0.00120	0	2.07140	132.267	ℓ	50.663	300.41	HI output to Section IV.
334	T	0	0	4.08523	0	T	0	14.26942	18.35465	735.300	ℓ	1.013	457.75	
335	T	0	0	14.72083	0	0.00120	0	15.33546	30.05749	883.221	ℓ	1.013	430.85	
336	T	0	0	14.72803	0	T	0	15.33546	30.06349	883.266	ℓ	1.013	430.85	
337	0	0.01250	0.34300	0.02500	T	T	T	0	0.38050	44.516	ℓ	1.850	387.01	
338	T	0	0	4.08523	0	T	0	14.26942	18.35465	735.300	ℓ	1.850	393.15	
339	0	0	0	2.59648	0	0	0	0	2.59648	23.367	g&ℓ	6.786	436.85	0.25312 H_2O(g)
340	0	0	0	10.64280	0	0	0	0	10.64280	95.780	g&ℓ	6.786	436.85	1.45639 H_2O(g)
341	0	0	0	0.00720	0	0.00120	0	0	0.00840	0.084	ℓ&s	1.013	300.00	0.00120 S(s) Output to Section II.
342	T	0	0	4.08523	0	T	0	14.26942	18.35465	735.300	ℓ	1.013	438.85	
343	0	T	7.55596	0.06380	0	0	0	0	7.61976	958.672	ℓ	1.850	393.15	
344	T	0	0	T	0	0	0	1.06604	1.06604	52.186	ℓ	1.013	438.85	
345	T	0	0	T	0	0	0	1.06604	1.06604	52.186	ℓ	1.013	401.00	
346	T	0	0	4.08523	0	T	0	14.26942	18.35465	735.00	ℓ	1.013	393.15	
347	0	0	0	11.14230	0	0	0	0	11.14230	100.275	g&ℓ	1.850	391.01	0.49950 H_2O(g)
348	0	0.01000	0.20370	0.06800	0	0	0	0	0.28170	2.708	ℓ	1.850	389.80	
349	0	0.01000	7.75966	0.13180	0	0	0	0	7.90146	985.752	ℓ	1.850	393.15	Iodine Output to Section I
350	0	0	0	0.01440	0	0	0	0	0.01440	0.130	ℓ	1.013	298.15	
351	T	0	0	14.72803	0	T	0	15.33546	30.06349	883.266	g&ℓ	1.013	446.11	4.33285 H_2O(g)
352	0	0	0	4.33285	0	0	0	0	4.33285	38.994	g	1.013	446.11	
353	T	0	0	10.39518	0	T	0	15.33546	25.73064	844.272	ℓ	1.013	446.11	
354	0	0	0	4.33285	0	0	0	0	4.33285	38.994	g	10.252	454.11	
355	0	0	0	4.33285	0	0	0	0	4.33285	38.994	g&ℓ	10.252	454.11	0.31583 H_2O(g)
356	0	0	0	4.33285	0	0	0	0	4.33285	38.994	g&ℓ	6.786	436.85	0.45110 H_2O(g)
357	T	0	0	T	0	T	0	1.06604	1.06604	52.186	ℓ	1.013	488.65	
358	T	0	0	10.39518	0	T	0	15.33546	25.73064	844.272	g&ℓ	1.013	461.38	3.40828 H_2O(g)
359	0	0	0	3.40828	0	0	0	0	3.40828	30.673	g	1.013	461.38	
360	T	0	0	6.98690	0	T	0	15.33546	22.32236	813.600	ℓ	1.013	461.38	

SECTION III
HI Separation
Material Balance
(continued)

Stream Number	Component Flow Molar Ratios								Total Flow Ratio		Phase	Pressure k Pax10^{-2}	Temp. °K	Comments
	H_2SO_4	HI	I_2	H_2O	SO_2	S	H_2S	H_3PO_4	Moles	Weight				
361	0	0	0	3.40828	0	0	0	0	3.40828	30.673	g	14.348	469.38	
362	T	0	0	4.08523	0	T	0	14.26942	18.35465	735.300	ℓ	1.013	476.65	
363	0	0	0	3.40828	0	0	0	0	3.40828	30.673	g&ℓ	14.348	469.38	0.52105 H_2O(g)
364	0	0	0	3.40828	0	0	0	0	3.40828	30.673	g&ℓ	6.786	436.85	0.68893 H_2O(g)
365	0	0.08120	T	0.08120	0	0	T	0	0.16240	5.920	g&ℓ	1.013	288.94	[0.00435 HI+trace H_2O](g)
366	0	0	0	2.59648	0	0	0	0	2.59648	23.367	ℓ	19.666	484.65	
367	T	0	0	T	0	0	0	1.06604	1.06604	52.186	ℓ	1.013	469.38	
368	T	0	0	6.98690	0	T	0	15.33546	22.32236	813.600	g&ℓ	1.013	476.65	2.59648 H_2O(g)
369	0	0	0	2.59648	0	0	0	0	2.59648	23.367	g	1.013	476.65	
370	0	0	0	2.59648	0	0	0	0	2.59648	23.367	g	19.666	484.65	
371	0	2.02450	0.53970	14.72583	0.00040	T	T	14.26942	31.65185	1028.978	ℓ	1.013	393.15	
372	0	2.07285	0.20470	0.07000	T	T	0.00120	0	2.34875	15.907	g	1.013	387.00	
373	0	0.00435	0	T	0	0	T	0	0.00435	0.278	g	1.013	288.94	
374	T	0	0	4.39042	0	T	0	15.33546	19.72588	790.233	ℓ	1.013	476.65	
375	0	0	0	0.30519	0	0	0	0	0.30519	2.747	ℓ	52.519	540.15	
376	0	0	0	0.30519	0	0	0	0	0.30519	2.747	g&ℓ	6.786	436.85	0.06324 H_2O(g)
377	0	0	0	0.30519	0	0	0	0	0.30519	2.747	g	52.519	540.15	
378	T	0	0	0.30519	0	T	0	1.06604	1.37123	54.933	ℓ	1.013	534.15	0.30519 H_2O(g)
379	0	0	0	10.64280	0	0	0	0	10.64280	95.780	ℓ	1.850	415.00	
380	0	0.07685	T	0.08120	0	0	T	0	0.15805	5.642	ℓ	1.013	288.94	
381	0	0	0	10.64280	0	0	0	0	10.64280	95.780	ℓ	1.850	368.15	H_2O Output to Section I
382	0	0	0	10.64280	0	0	0	0	10.64280	95.780	ℓ	1.850	391.01	
383	0	0	0	0.49950	0	0	0	0	0.49950	4.495	g	1.850	391.01	
384	0	0	0	0.49950	0	0	0	0	0.49950	4.495	g	3.396	463.92	
385	0	0	0	0.49950	0	0	0	0	0.49950	4.495	ℓ	3.396	413.00	
								R-11*						
386	0	0	0	0	0	0	0	3.96034	3.96034	544.07	g	1.130	300	
387	0	0	0	0	0	0	0	3.96034	3.96034	544.07	ℓ	1.130	300	
388	0	0	0	0	0	0	0	3.05102	3.05102	419.15	ℓ	1.130	300	
389	0	0	0	0	0	0	0	0.90932	0.90923	124.92	ℓ	1.130	300	
390	0	0	0	0	0	0	0	0.90932	0.90932	124.92	ℓ	7.000	300	
391	0	0	0	0	0	0	0	0.90932	0.90932	124.92	g	6.390	363.1	
392	0	0	0	0	0	0	0	3.05102	3.05102	419.15	ℓ	10.000	300	

*FREON-11

Section III
HI Separation
Heat Exchanger Loads and Operating Temperatures

Basis: 0.993 g-mole H_2

Heat Exch. Number	Energy Load, kJ	Hot-Side In.		Hot-Side Out		Cold-Side In		Cold-Side Out		Comments
		Stream Number	Stream Temp, K	Stream Number	Stream Temp, K	Stream Number	Stream Temp, K	Stream Number	Stream Temp, K	
E-301	0.4400	[Heat Recovered with Section III]				305	298.15	306	381.57	
E-302	72.2842	340	436.85	379	415.00	(C-303)	401.00	(C-303)	430.85	54.2347 kJ is isothermal at 436.85K on warm side
E-303	21.5858	324	377.60	325	368.15	[See Section III Heat Recovery Table]				
E-304	41.2642	(C-302)	393.15	(C-302)	393.15	[See Section III Heat Recovery Table]				
E-305	4.5295	313	401.00	314	387.00	[See Section III Heat Recovery Table]				
E-306	8.0996	344	438.85	345	401.00	[See Section III Heat Recovery Table]				
E-307	5.0611	[Heat from Section II]				-	430.85(-)	-	430.85(+)	See Section II for heat supply temperature
E-308	136.2974	342	438.85	346	393.15	[See Section III Heat Recovery Table]				
E-309	6.9204	[See Comments]				(C-304)	377.50	(C-304)	457.50	3.5605 kJ demand is supplied from Section II; the remainder is recovered within Section III.
E-310	18.4793	382	391.00	381	368.15	[See Section III Heat Recovery Table]				
E-311	108.8309	[See Comments]				(C-303)	405.78	(C-303)	430.85	61.3702 demand is supplied from Section II; the remainder is recovered within Section III.
E-312	2.3750	[Heat from Section II]				-	457.50(-)	-	457.50(+)	See Section II for heat supply temperature.
E-313	1.5130	320	457.51	348	389.80	[See Section III Heat Recovery Table]				
E-314	4.1025	329	368.15	330	300.00	[See Section III Heat Recovery Table]				
E-315	4.1975	(TC-301)	373.23	(TC-301)	300.00	[See Section III Heat Recovery Table]				
E-316	4.1975	(TC-301)	373.23	(TC-301)	300.00	[See Section III Heat Recovery Table]				
E-317	41.1935	331	373.23	332	300.00	[See Section III Heat Recovery Table]				36.9950 kJ is isothermal at 300.00K on warm side
E-318A	145.2961	354	454.11	355	454.11	Shell Side	430.85	Shell Side	446.11	
E-318B	60.2526	334	457.75	342	438.85	Shell Side	430.85	Shell Side	446.11	
E-318C	42.8573	(TC-302)	454.11	(TC-302)	454.11	Shell Side	430.85	Shell Side	446.11	
E-318D	4.0444	303	457.75	344	438.85	Shell Side	430.85	Shell Side	446.11	
E-319A	101.5068	361	469.38	363	469.38	Shell Side	446.11	Shell Side	461.38	
E-319B	60.3627	362	476.65	334	457.75	Shell Side	446.11	Shell Side	461.38	
E-319C	41.1041	(TC-303)	469.38	(TC-303)	469.38	Shell Side	446.11	Shell Side	461.38	
E-319D	0.5706	367	469.38	303	457.75	Shell Side	446.11	Shell Side	461.38	
E-320A	88.4231	370	484.65	366	484.65	Shell Side	465.01	Shell Side	476.65	
E-320B	38.5672	[Heat from Section II]				Shell Side	465.01	Shell Side	461.38	See Section II for heat supply temperature
E-320C	35.4359	(TC-304)	484.65	(TC-304)	484.65	Shell Side	465.01	Shell Side	476.65	
E-320D	4.1236	357	488.65	367	469.38	Shell Side	461.38	Shell Side	476.65	
E-321A	8.9001	377	540.15	375	540.15	Shell Side	499.17	Shell Side	519.76	
E-321B	6.2228	(TC-305)	540.15	(TC-305)	540.15	Shell Side	519.76	Shell Side	534.15	
E-321C	9.7365	323	534.15	357	488.65	Shell Side	476.65	Shell Side	499.17	

Section III
HI Separation
Heat Exchanger Loads and Operating Temperatures
(Continued)

Heat Exch. Number	Energy Load, kJ	Hot-Side In		Hot-Side Out		Cold-Side In		Cold-Side Out		Comments
		Stream Number	Stream Temp, K	Stream Number	Stream Temp, K	Stream Number	Stream Temp, K	Stream Number	Stream Temp, K	
E-322	107.0491	[Heat Recovered within Section III]				371	393.15	312	418.00	See Section III Heat Recovery Table
E-323	20.7363	384	463.92	385	423.00	(C-303)	401.00	(C-303)	405.78	
E-324	90.0754	[Heat Recovered within Section III&IV]				392	300.00	327	380.00	See Section III Heat Recovery Table
E-325	26.0012	[Heat Recovered within Section III]				390	300.00	391	363.10	See Section III Heat Recovery Table
E-326	97.7397	336	300.00	387	300.00	CW				

Section III
Detailed Heat Matchup

	Heat Exch. No.	Max. Temp. K	Min. Temp. K	Heat Exch. No.	Max. Temp K	Min. Temp. K	Heat Load kJ	Comments
1	E-301 A_1	381.57	377.50	E-313S	398.09	397.98	0.0001	
2	E-301 A_2	381.57	377.50	E-308Q	398.09	397.98	0.0198	
3	E-301 A_3	381.57	377.50	E-305E	398.09	397.98	0.0016	
4	E-301 B_1	377.50	298.15	E-313T	397.98	397.85	0.0029	
5	E-301 B_2	377.50	298.15	E-308R	397.98	397.85	0.3857	
6	E-301 B_3	377.50	298.15	E-305F	397.98	397.85	0.0297	
7	E-303 A	377.60	376.94	E-325B_1	363.15	363.15	1.5112	
8	E-303 B	376.94	373.23	E-414	-	-	8.4480	
9	E-303 C_1	373.23	371.15	E325B_2	363.15	363.15	4.7605	
10	E-303 C_2	371.15	368.15	E-324E_2	363.07	338.00	6.8661	
11	E-304	393.15	393.15	E-324G_4	380	380	41.2642	
12	E-305 A	401.00	393.39	E-309J_3	395.13	393.13	0.0121	
13	E-305 B	401.00	398.39	E-322F_3	395.13	393.15	0.6056	
14	E-305 C	398.39	398.09	E-309K_3	393.15	381.57	0.0712	
15	E-305 D	398.09	397.98	E-309L_3	381.57	377.50	0.0251	
16	E-305 E	398.09	397.98	E-301A_3	381.57	377.50	0.0016	
17	E-305 F	397.98	397.85	E-301B_3	377.50	298.15	0.0297	
18	E-305 G	397.85	393.15	E-324C	380.00	380.00	41.2642	
19	E-305 H	393.15	387.00	E-325B	365.00	365.00	1.9897	
20	E-306 A	438.85	419.59	E-309D_3	426.28	418.00	0.4432	
21	E-306 B	438.85	419.59	E-311B_3	426.28	418.00	22.2371	
22	E-306 C	438.85	419.59	E-309E_3	418.00	413.71	0.3441	
23	E-306 D	438.85	419.59	E-322A_3	418.00	413.71	17.1376	
24	E-306 E	438.85	419.59	E-311D_3	418.00	413.71	17.2699	
25	E-306 F	419.59	415.54	E-309G_3	407.27	405.78	0.0092	
26	E-306 G	419.59	415.54	E-322C_3	407.27	405.78	0.4576	
27	E-306 H	419.59	415.54	E-311F_3	407.27	405.78	0.4606	
28	E-306 I	415.54	409.02	E-309H_3	405.78	401.00	0.0293	
29	E-306 J	415.54	409.02	E-322D_3	405.78	401.00	1.4633	
30	E-306 K	409.02	401.00	E-309I_3	401.00	395.13	0.0361	
31	E-306 L	409.02	401.00	E-323E_3	401.00	395.13	1.7975	
32	E-307	430.85	430.85	-	-	-	5.0611	Heat Supplied from Section II. See Section II Heat Exchanger Tables for Matchup
33	E-308 A	438.85	419.59	E-309D_2	426.28	418.00	0.0316	
34	E-308 B	438.85	419.59	E-311B_2	426.28	418.00	1.5955	
35	E-308 C	438.85	419.59	E-309E_2	418.00	413.71	0.0247	

Section III
Detailed Heat Matchup
(Continued)

	Heat Exch. No.	Max. Temp. K	Min. Temp. K	Heat Exch. No.	Max. Temp. K	Min. Temp. K	Heat Load kJ	Comments
36	E-308 D	438.85	419.59	$E-322A_2$	418.00	413.71	1.2296	
37	E-308 E	438.85	419.59	$E-311D_2$	418.00	413.71	1.2392	
38	E-308 F	419.59	415.54	$E-309G_2$	407.27	405.78	0.1190	
39	E-308 G	419.59	415.54	$E-322C_2$	407.27	405.78	5.9297	
40	E-308 H	419.59	415.54	$E-311F_2$	407.27	405.78	5.9755	
41	E-308 I	415.54	409.02	$E-309H_2$	405.78	401.00	0.3813	
42	E-308 J	415.54	409.02	$E-322D_2$	405.78	401.00	18.9857	
43	E-308 K	409.02	401.00	$E-309I_2$	401.00	395.13	0.4684	
44	E-308 L	409.02	401.00	$E-322E_2$	401.00	395.13	23.3216	
45	E-308 M	401.00	398.39	$E-309J_2$	395.13	393.15	0.1578	
46	E-308 N	401.00	398.39	$E-322F_2$	395.13	393.15	7.8580	
47	E-308 O	398.39	398.09	$E-309K_2$	393.15	381.57	0.9236	
48	E-308 P	398.09	397.98	$E-309L_2$	381.57	377.50	0.3246	
49	E-308 Q	398.09	397.98	$E-301A_2$	381.57	377.50	0.0198	
50	E-308 R	397.98	397.85	$E-301B_2$	377.50	298.15	0.3859	
51	E-308 S	397.85	393.15	$E-324G_3$	380.00	380.00	14.0146	
52	E-309 A	457.50	430.85	-	-	-	2.3053	Heat Supplied from Section II. See Section II Heat Exchanger Tables for Matchup.
53	E-309 B	430.85	426.62	-	-	-	0.6252	Heat Supplied from Section II. See Section II Heat Exchanger Tables for Matchup.
54	E-309 C	426.62	426.28	E-313A	457.51	438.85	0.0081	
55	$E-309D_1$	426.28	418.00	E-313C	438.85	419.59	0.0033	
56	$E-309D_2$	426.28	418.00	E-308A	438.85	419.59	0.0318	
57	$E-309D_3$	426.28	418.00	E-306A	438.85	419.59	0.4432	
58	$E-309E_1$	418.00	413.71	E-313E	438.85	419.59	0.0026	
59	$E-309E_2$	418.00	413.71	E-308C	438.85	419.59	0.0247	
60	$E-309E_3$	418.00	413.71	E-306C	438.85	419.59	0.3441	
61	E-309F	413.71	407.27	-	-	-	0.5566	Heat Supplied from Section II. See Section II Heat Exchanger Tables for Matchup.
62	$E-309G_1$	407.27	405.78	E-313H	419.59	415.54	0.0009	
63	$E-309G_2$	407.27	405.78	E-308F	419.59	415.54	0.1190	
64	$E-309G_3$	407.27	405.78	E-306F	419.59	415.54	0.0092	
65	$E-309H_1$	405.78	401.00	E-313K	415.54	409.02	0.0029	
66	$E-309H_2$	405.78	401.00	E-308I	415.54	409.02	0.3813	
67	$E-309H_3$	405.78	401.00	E-306I	415.54	409.02	0.0293	
68	$E-309I_1$	401.00	395.13	E-313M	409.02	401.00	0.0035	

Section III
Detailed Heat Matchup
(Continued)

	Heat Exch. No.	Max. Temp. K	Min. Temp. K	Heat Exch. No.	Max. Temp. K	Min. Temp. K	Heat Load kJ	Comments
69	E-309I$_2$	401.00	395.13	E-308K	409.02	401.00	0.4684	
70	E-309I$_3$	401.00	395.13	E-306K	409.02	401.00	0.0361	
71	E-309J$_1$	395.13	393.15	E-313O	401.00	398.39	0.0012	
72	E-309J$_2$	395.13	393.15	E-308M	401.00	398.39	0.1578	
73	E-309J$_3$	395.13	393.15	E-305A	401.00	398.39	0.0121	
74	E-309K$_1$	393.15	381.57	E-313Q	398.39	398.09	0.0069	
75	E-309K$_2$	393.15	381.57	E-308O	398.39	398.09	0.9236	
76	E-309K$_3$	393.15	381.57	E-305C	398.39	398.09	0.0712	
77	E-309L$_1$	381.57	377.50	E-313R	398.09	397.98	0.0024	
78	E-309L$_2$	381.57	377.50	E-308P	398.09	397.98	0.3246	
79	E-309L$_3$	381.57	377.50	E-305D	398.09	397.98	0.0251	
80	E-310A	391.00	389.21	E-324G$_1$	380.00	380.00	1.4455	
81	E-310B	389.21	386.08	E-324F$_1$	380.00	363.07	2.5275	
82	E-310C	386.08	370.30	E-325B$_3$	363.15	363.15	12.7565	
83	E-310D	370.30	368.15	E-324E$_1$	363.07	338.00	1.7498	
84	E-311A	430.85	426.26	-	-	-	31.3748	Heat Supplied from Section II. See Section II Heat Exchanger Tables for Matchup.
85	E-311B	426.62	426.28	E-313B	457.51	438.85	0.4089	
86	E-311C$_1$	426.28	418.00	E-313D	438.85	419.59	0.1666	
87	E-311C$_2$	426.28	418.00	E-308B	438.85	419.59	1.5955	
88	E-311C$_3$	426.28	418.00	E-306B	438.85	419.59	22.2371	
89	E-311D$_1$	418.00	413.71	E-313G	438.85	419.59	0.1294	
90	E-311D$_2$	418.00	413.71	E-308E	438.85	419.59	1.2392	
91	E-311D$_3$	418.00	413.71	E-306E	438.85	419.59	17.2699	
92	E-311E	413.71	407.27	-	-	-	27.9286	Heat Supplied from Section II. See Section II Heat Exchanger Tables for Matchup.
93	E-311F$_1$	407.27	405.78	E-313J	419.59	415.54	0.0448	
94	E-311F$_2$	407.27	405.78	E-308H	419.59	415.54	5.9755	
95	E-311F$_3$	407.27	405.78	E-306H	419.59	415.54	0.4606	
96	E-312	457.50	457.50	-	-	-	2.3750	Heat Supplied from Section II. See Section II Heat Exchanger Tables for Matchup.
97	E-313A	457.51	438.85	E-309C	426.62	426.28	0.0081	
98	E-313B	457.51	438.85	E-311B	426.62	426.28	0.4089	
99	E-313C	438.85	419.59	E-309D$_1$	426.28	418.00	0.0033	
100	E-313D	438.85	419.59	E-311B$_1$	426.28	418.00	0.1666	
101	E-313E	438.85	419.59	E-309E$_1$	418.00	413.71	0.0026	
102	E-313F	438.85	419.59	E-322A$_1$	418.00	413.71	0.1284	
103	E-313G	438.85	419.59	E-311D$_1$	418.00	413.71	0.1294	
104	E-313H	419.59	415.54	E-309G$_1$	407.27	405.78	0.0009	

Section III
Detailed Heat Matchup
(Continued)

	Heat Exch. No.	Max. Temp. K	Min. Temp. K	Heat Exch. No.	Max. Temp. K	Min. Temp. K	Heat Load kJ	Comments
105	E-313I	419.59	415.54	$E-322C_1$	407.27	405.78	0.0444	
106	E-313J	419.59	415.54	$E-311F_1$	407.27	405.78	0.0448	
107	E-313K	415.54	409.02	$E-309H_1$	405.78	401.00	0.0029	
108	E-313L	415.54	409.02	$E-322D_1$	405.78	401.00	0.1423	
109	E-313M	409.02	401.00	$E-309I_1$	401.00	395.13	0.0035	
110	E-313N	409.02	401.00	$E-322E_1$	401.00	395.13	0.1747	
111	E-313O	401.00	398.39	$E-309J_1$	395.13	393.15	0.0012	
112	E-313P	401.00	398.39	$E-322F_1$	395.13	393.15	0.0589	
113	E-313Q	398.39	398.09	$E-309K_1$	393.15	381.57	0.0069	
114	E-313R	398.09	397.98	$E-309L_1$	381.57	377.50	0.0024	
115	E-313S	398.09	397.98	$E-301A_1$	381.57	377.50	0.0001	
116	E-313T	397.98	397.85	$E-301B_1$	377.50	298.15	0.0029	
117	E-313U	397.85	389.80	$E-324G_6$	380.00	380.00	0.1798	
118	E-314A	368.23	335.00	$E-324D_1$	338.00	325.82	1.9975	
119	E-314B	335.00	313.00	$E-324C_2$	325.82	300.00	1.3224	
120	E-314C	313.00	300	C.W.	-	-	0.7826	
121	E-315A	373.23	335.00	$E-324D_3$	338.00	325.82	2.1913	
122	E-315B	335.00	313.00	$E-324C_3$	325.82	300	1.2610	
123	E-315C	313.00	300.00	C.W.	-	-	0.7452	
124	E-316A	373.23	312.4	$E-325A_1$	363.15	300.00	3.4865	
125	E-316B	312.4	300.00	C.W.	-	-	0.7110	
126	E-317A	373.23	312.4	$E-325A_2$	363.15	300.00	3.4865	
127	E-317B	312.4	300.00	C.W.	-	-	37.7070	
128	E-320B	465.01	461.38	-	-	-	38.5672	Heat Supplied from Section II. See Section II Heat Exchanger Tables for Matchup.
129	$E-322A_1$	418.00	413.71	E-313F	438.85	419.59	0.1284	
130	$E-322A_2$	418.00	413.71	E-308D	438.85	419.59	1.2296	
131	$E-322A_3$	418.00	413.71	E-306D	438.85	419.59	17.1376	
132	E-322B	413.71	407.27	-	-	-	27.7148	Heat Supplied from Section II. See Section II Heat Exchanger Tables for Matchup.
133	$E-322C_1$	407.27	405.78	E-313I	419.59	415.54	0.0444	
134	$E-322C_2$	407.27	405.78	E-308G	419.59	415.54	5.9297	
135	$E-322C_3$	407.27	405.78	E-306G	419.59	415.54	0.4570	
136	$E-322D_1$	405.78	401.00	E-313L	415.54	409.02	0.1423	
137	$E-322D_2$	405.78	401.00	E-308J	415.54	409.02	18.9857	
138	$E-322D_3$	405.78	401.00	E-306J	415.54	409.02	1.4633	

Section III
Detailed Heat Matchup
(Continued)

	Heat Exch. No.	Max. Temp. K	Min. Temp. K	Heat Exch. No.	Max. Temp. K	Min. Temp. K	Heat Load kJ	Comments
139	E-322E$_1$	401.00	395.13	E-313N	409.02	401.00	0.1747	
140	E-322E$_2$	401.00	395.13	E-308L	409.02	401.00	23.3216	
141	E-322E$_3$	401.00	395.13	E-306L	409.02	401.00	1.7975	
142	E-322F$_1$	395.13	393.15	E-313P	401.00	398.39	0.0589	
143	E-322F$_2$	395.13	393.15	E-308N	401.00	398.39	7.8580	
144	E-322F$_3$	395.13	393.15	E-305B	401.00	398.39	0.6056	
145	E-324A	373.00	300.00	E-411A	383.00	315.00	2.2577	
146	E-324B	380.00	373.00	E-305G	397.85	387.00	0.2165	
147	E-324C$_1$	325.82	300.00	E-409A	335.70	313.00	6.2920	
148	E-324C$_2$	325.82	300.00	E314B	335.00	313.00	1.3224	
149	E-324C$_3$	325.82	300.00	E-315B	335.00	313.00	1.2610	
150	E-324D$_1$	338.00	325.82	E314A	368.23	335.00	1.9975	
151	E-324D$_2$	338.00	325.82	E-315A	373.33	335.00	2.1913	
152	E-324E$_1$	363.07	338.00	E-310D	370.30	368.15	1.7498	
153	E-324E$_2$	363.07	338.00	E-303C$_2$	371.15	368.15	6.8661	
154	E-324F$_1$	380.00	363.07	E-310B	389.21	386.08	2.5275	
155	E-324F$_2$	380.00	363.07	E-305H	397.85	387.00	3.2935	
156	E-324G$_1$	380.00	380.00	E-310A	391.00	389.21	1.4455	
157	E-324G$_2$	380.00	380.00	E-407A	403.00	393.00	0.8120	
158	E-324G$_3$	380.00	380.00	E-308S	397 85	393.15	14.0146	
159	E-324G$_4$	380.00	380.00	E-304	393.15	393.15	41.2642	
160	E-324G$_5$	380.00	380.00	E-406C	393.90	393.00	2.3840	
161	E-324G$_6$	380.00	380.00	E-313U	397 85	389.80	0.1798	
162	E-325A$_1$	363.15	300.00	E-316A	373.23	312.40	3.4865	
163	E-325A$_2$	363.15	300.00	E-317A	373.23	312.40	3.4865	
164	E-325B$_1$	363.15	363.15	E-303A	377.60	376.94	1.5112	
165	E-325B$_2$	363.15	363.15	E-303C$_1$	373.23	371.15	4.7605	
166	E-325B$_3$	363.15	363.15	E-310C	386.08	370.30	12.7565	
167	E-406C	393.9	393.00	E-324G$_5$	380.00	380.00	2.3840	
168	E-407C	403.00	393.00	E-324G$_2$	380.00	380.00	0.8120	
169	E-409A	335.70	313.00	E-324C$_1$	325.82	300.00	6.2920	
170	E-409B	313.00	300.00	C.W.			2.7720	
171	E-411A	383.00	315.00	E-324A	373.00	300.00	2.2577	
172	E-411B	315.00	300.00	C.W.			0.4003	
173	E-414	-	-	E-303B	376.94	373.23	8.4480	
174	E-326	300.00	300.00	C.W.			97.7397	

SECTION III
Power Machinery

Basis: 0.993 g-moles H_2 Product

Power Equipment Number	Work Load k J	Input		Output	
		Stream Number	Pressure k Pa$\times 10^{-2}$	Stream Number	Pressure k Pa$\times 10^{-2}$
P-301	0.0001	304	1.013	305	2.026
P-302	0.0093	309	1.850	311	2.026
P-303	0.5464	332	8.268	333	50.663
P-304	0.0014	319	1.013	320	1.850
P-305	0.0021	315	1.013	337	1.850
P-306	0.0844	346	1.013	338	1.850
P-307	0.3633	388	1.13	392	10.00
P-308	0.0718	389	1.13	390	7.00
TC-301	12.5925	330	1.013	331	8.268
TC-302	39.4051	352	1.013	354	10.252
TC-303	35.8200	359	1.013	361	14.348
TC-304	31.3214	369	1.013	370	19.666
TC-305	5.0616	321	1.013	377	52.519
TC-306	1.6831	383	1.850	384	3.396
TE-301	-0.5630	355	10.252	356	6.786
TE-302	-1.4768	363	14.348	364	6.786
TE-303	-0.5435	366	19.666	339	6.786
TE-304	-0.2746	375	52.519	376	6.786
TE-305	-1.1723	379	6.786	347	1.850
		385	3.396		
TE-306	-0.0945	310	1.850	371	1.013
TE-307	-0.0074	322	2.026	343	1.850
TE-308	-18.7719	327	9.480		
		391	6.390	386	1.13

Basis: 0.993 g mole H_2 product
T = "Trace"

SECTION IV
HI DECOMPOSITION
Material Balance

Stream Number	Component Molar Flow Ratios					Total Flow Ratios		Phase	Pressure Pa x 10^5	Temp. °K	Comments
	HI	I_2	H_2O	H_2S	H_2	Mole	Weight				
401	2.0672	0.0010	0.0020	0.0012	0	2.0714	132.24	ℓ	(a)	300.41	
402	3.1776	0.0045	0.0021	0.0012	0.0252	3.2106	203.65	ℓ	(a)	342.2	
403	3.1776	0.0045	0.0021	0.0012	0.0252	3.2106	203.65	ℓ	(a)	393	
404	3.9914	0.0051	0.0021	0.0012	0.0281	4.0279	255.73	ℓ	(a)	393	
405	2.0054	0.9981	0.0021	0.0012	1.0211	4.0279	255.73	ℓ	(a)	393	
406	0.8138	0.9946	0.0020	0	0.0029	1.8133	178.11	ℓ	(a)	393	
407	0.8138	0.9946	0.0020	0	0.0029	1.8133	178.11	ℓ	(a)	420	
408	1.9531	0.0014	0	0	0.0069	1.9614	124.97	g	(a)	403	
409	1.9531	0.0014	0	0	0.0069	1.9614	124.97	ℓ	(a)	393	
410	1.9531	0.0014	0	0	0.0069	1.9614	124.97	ℓ	(a)	393	
411	1.9531	0.0014	0	0	0.0069	1.9614	124.97	ℓ	51.663	393	
412	1.1393	0.0008	0	0	0.0040	1.1441	72.895	ℓ	(a)	393	
413	0.8138	0.0006	0	0	0.0029	0.8173	52.075	ℓ	(a)	393	
414	T	0.9940	0.0020	0	0	0.9960	126.04	ℓ	(a)	713	
415	T	0.9940	0.0020	0	0	0.9960	126.04	ℓ	(a)	393	
416	1.1916	0.0035	0.0001	0.0012	1.0182	2.0527	77.621	g	(a)	393	
417	1.1916	0.0035	0.0001	0.0012	1.0182	2.0527	77.621	g&ℓ	(a)	335.7	
418	1.1916	0.0035	0.0001	0.0012	1.0182	2.0527	77.621	g&ℓ	(a)	303	
419	1.1916	0.0035	0.0001	0.0012	1.0182	2.0527	77.621	g&ℓ	(a)	273	
420	1.1104	0.0035	0.0001	0	0.0252	1.1392	71.413	ℓ	(a)	273	
421	1.1104	0.0035	0.0001	0	0.0252	1.1392	71.413	ℓ	(a)	383	
422	0.0812	0	0	0.0012	0.9930	1.0754	6.2081	g	(a)	273	
423	0.0812	0	0	0.0012	0.9930	1.0754	6.2081	g	(a)	383	
424	0.0812	0	0	0.0012	0.9930	1.0754	6.2081	g&ℓ	(a)	303	
425	0	0	0.0008	0.0012	0.9930	0.9950	1.0276	g	(a)	303	
426	0.0812	0	0.0812	0	0	0.1624	5.9189	ℓ	(a)	303	
427	0	0	0	0.0012	0	0.0012	0.0205	g	(a)	400	
428	0	0	0.0008	0	0.9930	0.9938	1.0070	g	(a)	303	
429	0	0	0.0812	0	0	0.0812	0.7308	ℓ	(a)	298.15	
430	0	0	0.0812	0	0	0.0812	0.7308	ℓ	1.01325	298.15	
431	0.0812	0	0.0812	0	0	0.1624	5.9189	ℓ	1.01325	303	
432	0	--	--	--	--	--	--	ℓ	--	275.74(b)	Brine loop output from chiller.
433	0	--	--	--	--	--	--	g&ℓ	--	275.74(b)	Brine loop input to chiller.
434	0	--	--	--	--	--	--	g&ℓ	--	263.74(b)	
435	0	--	--	--	--	--	--	g&ℓ	--	303(b)	
436	0	--	--	--	--	--	--	g&ℓ	--	361.15(b)	

(a) Pressure is 50.663 x 10^5 Pa. (50 atm)
(b) These are mean temperatures.

SECTION IV
HI DECOMPOSITION
HEAT AND POWER LOADS

Basis: 0.993 g mole H_2 Product

Heat Exch. Number	Energy Load kJ	Hot Side In		Hot Side Out		Cold Side In		Cold Side Out		Comments
		Stream Number	Temp. °K	Stream Number	Temp. °K	Stream Number	Temp. °K	Stream Number	Temp. °K	
E-401	16.151	(a)	(a)	(a)	(a)	402	342.2	403	393	
E-402	8.075	(a)	(a)	(a)	(a)	--	393	--	393	
E-403	4.619	(a)	(a)	(a)	(a)	406	393	407	420	
E-404	4.786	(a)	(a)	(a)	(a)	--	713	--	713	
E-405	43.079	(a)	(a)	(a)	(a)	--	403	--	713	
E-406	26.610	408	403	409	393	(a)	(a)	(a)	(a)	
E-407	25.960	414	713	415	393	(a)	(a)	(a)	(a)	
E-408	13.103	416	393	417	335.7	420 & 422	273 & 273	421 & 423	383 & 383	
E-409	9.064	417	335.7	418	303	--	--	--	--	Cold side is in power cycle in Section III
E-410	6.758	418	303	419	273	432	~275.74	433	~275.74	Cold side temperature is a log mean average for heat transfer.
E-411	2.658	423	383	424	303	--	--	--	--	Cold side is in power cycle Section III
E-412	6.758	433	~275.74	432	~275.74	434(b)	~263.74	434(b)	~263.74	Temperatures are log mean average.
E-413	15.206	435	~303	435	~303	--	C.W.	--	C.W.	
E-414	8.448	--	377	--	373	436(b)	361.5	436(b)	361.5	Heat source is Sec. III.
E-415	2.979	--	303	--	303	--	C.W.	--	C.W.	

(a) See Table 3 for heat match up.

(b) Flow direction, amount and composition are not defined.

SECTION IV
HI DECOMPOSITION
HEAT AND POWER LOADS

Power Device Number	Energy Load	Input Stream Number	Input Pressure Pa x 10^5	Output Stream Number	Output Pressure Pa x 10^5	Comments
P-401	Negligible	410	50.663	411	51.663	
P-402	0.208	430	1.01325	429	50.663	

Special Equipment Number	Heat Effect kJ	Power Demand kJ	Comment
A-401	C.0004 In	0	Isothermal at 393°F

SECTION IV
HI DECOMPOSITION
HEAT RECUPERATION MATCH UP

Basis: 0.993 g mole H_2 Product

Hot Side			Cold Side			Heat Load kJ	Comments
Heat Exch. Number	Input Temp. °K	Output Temp. °K	Heat Exch. Number	Input Temp. °K	Output Temp. °K		
Sec. V	-	-	E-404	713	713	4.786	
Sec. V	-	-	E-405A	705	713	1.112	Total 27.336 kjoul should be applied from Sec. V
Sec. V	-	-	E-405B	403	705	21.438	
E-407A	713	459.95	E-405C	403	705	20.529	
E-407B	459.95	403	E-403	393	420	4.619	
E-406A	403	400	E-402	393	393	8.075	
E-406B	400	393.9	E-401	342.2	393	16.151	
E-406C	393.9	393	-	-	-	2.384	Cold side is in power power cycle in Sec. III
E-407C	403	393	-	-	-	0.812	

SECTION V

Power Generation and Helium Heat Transfer
Material Balance

Basis: 0.993 g-mol H_2 Product

Stream Number	Molar Flow Ratio		Mass Flow Ratio	Temp. K	Pressure Pa × 10^5	Phase	Comments
	Helium	(H_2)					
500	-	-	-	686.00	-	-	Intermediate temperature process heat lowest temperature stream input; see detailed matchup table of Section V.
501	60.71023	-	121.3969	1255.40	49.041	g	
502	21.11470	-	42.2212	1226.86	46.000	g	
503	23.51088	-	47.0126	934.29	21.245	g	
504	16.03465	-	32.1631	1214.56	44.726	g	
505	16.03465	-	32.1631	742.27	44.726	g	
506	23.51088	-	47.0126	536.51	21.245	g	
507	21.11470	-	42.2212	751.56	46.000	g	
508	60.71023	-	121.3969	773.20	49.041	g	
509	16.03465	-	32.1631	1159.00	51.676	g	
510	16.03465	-	32.1631	728.00	51.676	g	
511	16.03465	-	32.1631	696.00	51.676	g	
512	16.03465	-	32.1631	686.71	51.675	g	
513	-	-	-	368.15	-	-	Waste heat from Section III input; see detailed matchup table of Section V.
514	23.51088	-	47.0126	878.73	51.675	g	
515	23.51088	-	47.0126	728.00	30.445	g	
516	7.42623	-	14.8496	696.00	30.445	g	
517	7.42623	-	14.8496	480.95	30.445	g	
518	7.42623	-	14.8496	606.79	51.675	g	
519	7.42623	-	14.8496	480.95	51.675	g	
520	7.42623	-	14.8496	696.00	30.445	g	
521	7.42623	-	14.8496	606.79	30.445	g	
522	7.42623	-	14.8496	544.30	30.445	g	
523	-	-	-	368.15	-	-	Waste heat from Section III input; see detailed matchup table of Section V.

SECTION V
Power Generation and Helium Heat Transfer
Material Balance
(Continued)

Stream Number	Molar Flow Ratio		Mass Flow Ratio	Temp. K	Pressure Pa x 10^5	Phase	Comments
	Helium	H_2O					
524	7.42622	-	4.8496	686.71	51.675	g	
525	7.42622	-	4.8496	616.73	51.675	g	
526	7.42622	-	4.8496	480.95	51.675	g	
527	-	-	-	311.00	-	-	Waste heat from Section III output; see detailed matchup table of Sec. V.
528	8.65483	-	29.6992	696.00	30.455	g	
529	8.65483	-	29.6992	686.71	29.328	g	
530	8.04233	-	16.0815	686.71	29.328	g	
531	8.04233	-	16.0815	480.95	29.328	g	
532	8.04233	-	16.0815	616.73	51.675	g	
533	0.61610	-	1.2320	686.71	29.328	g	
534	0.61610	-	1.2320	616.73	29.328	g	
535	0.61610	-	1.2320	375.07	29.328	g	
536	23.51088	-	47.0726	696.00	30.445	g	
537	0.61610	-	1.2328	480.95	51.675	g	
538	8.04232	-	16.0815	480.95	51.675	g	
539	8.04233	-	16.0815	480.95	51.675	g	
540	23.51088	-	47.0126	480.95	51.675	g	
541	21.11470	-	42.2212	1171.30	51.675	g	
542	21.11470	-	42.2212	755.00	51.675	g	
543	21.11470	-	42.2212	728.00	46.691	g	
544	21.11470	-	42.2212	696.00	46.691	g	
545	21.11470	-	42.2212	728.00	51.675	g	
546	21.11470	-	42.2212	696.00	51.675	g	
547	-	7.05705	63.5099	1159.30	379.210	g	
548	-	7.05705	63.5099	976.94	156.945	g	
549	-	7.05705	63.5099	696.00	156.945	g	
550	-	7.05705	63.5099	728.00	189.510	g	
551	-	1.01643	2.0325	696.00	189.510	g	
552	-	1.01643	2.0325	300.00	0.035	g+ℓ	0.28664 $H_2O(\ell)$
553	-	1.01643	2.0325	300.00	0.035	ℓ	

SECTION V
Power Generation and Helium Heat Transfer
Material Balance
(Continued)

Stream Number	Molar Flow Ratio		Mass Flow Ratio	Temp. K	Pressure Pa x 10^5	Phase	Comments
	Helium	H_2O					
554	-	1.01643	2.0325	300.85	189.50	ℓ	
555	-	1.01643	2.0325	391.00	189.50	ℓ	
556	-	7.05705	63.5099	696.00	189.50	g	
557	-	6.04062	12.0789	696.00	189.50	g	
558	-	7.05705	63.5099	644.02	189.50	g	
559	-	7.05705	63.5099	743.00	379.210	g	
560	-	0.79590	7.1527	300.00	0.035	ℓ	
561	-	0.07007	0.6306	300.00	0.035	ℓ	
562	-	0.07007	0.6306	300.10	24.978	ℓ	
563	-	0.07007	0.6306	368.00	24.978	ℓ	
564	14.85245	-	29.6992	696.00	30.455	g	
565	-	0.07007	0.6306	524.82	24.978	g	
566	-	0.07007	0.6306	300.00	0.035	g+ℓ	0.01536 $H_2O(\ell)$
567	-	0.72583	6.5321	300.00	0.035	ℓ	
568	-	0.17772	1.5994	300.00	0.035	ℓ	
569	-	0.17772	1.5994	300.15	40.906	ℓ	
570	-	0.17772	1.5994	368.00	24.978	ℓ	
571	15.46855	-	30.9311	480.95	51.675	g	
572	-	0.17772	1.5994	552.59	40.906	g	
573	-	0.17772	1.5994	300.00	0.035	g+ℓ	0.04242 $H_2O(\ell)$
574	-	0.24779	2.2300	300.00	0.035	g+ℓ	0.05778 $H_2O(\ell)$
575	-	0.54811	4.9327	300.00	0.035	ℓ	
576	-	0.27343	2.4607	300.00	0.035	ℓ	
577	-	0.27343	2.4607	300.26	63.652	ℓ	
578	-	0.27343	2.4607	368.00	63.652	ℓ	
579	-	-	-	383.00	-	-	Waste heat from Section IV input; see detailed matchup table of Section V.
580	-	0.27343	2.4607	580.73	63.652	g	
581	-	0.27343	2.4607	300.00	0.035	g+ℓ	0.07053 $H_2O(\ell)$
582	-	0.52122	4.6907	300.00	0.035	g+ℓ	0.12831 $H_2O(\ell)$
583	-	0.27468	2.4720	300.00	0.035	ℓ	

SECTION V
Power Generation and Helium Heat Transfer
Material Balance
(Continued)

Stream Number	Molar Flow Ratio		Mass Flow Ratio	Temp. K	Pressure Pa x 10^5	Phase	Comments
	Helium	H_2O					
5002	-	-	-	403	-	-	Low temperature process heat lowest temperature input; see detailed matchup table of Section V.
5003	-	-	-	311.00	-	-	Waste heat recovery from Sec. II & III
5004	-	-	-	410.00	-	-	Waste heat recovery from Sec. II & III
5005	-	-	-	378.00	-	-	Waste heat from Section
5006	-	-	-	368.00	-	-	Waste heat from Section
5007	-	-	-	394.90	-	-	Waste heat from Section
5008	-	-	-	393.00	-	-	Waste heat from Section

SECTION V
Power Generation and Helium Heat Transfer
Material Balance
(Continued)

Stream Number	Molar Flow Ratio		Mass Flow Ratio	Temp. K	Pressure Pa x 10^5	Phase	Comments
	Helium	H_2O					
584	-	0.27468	2.4720	300.28	94.989	ℓ	
585	-	0.27468	2.4720	360.00	94.989	ℓ	
586	-	-	-	358.00	-	-	Waste heat from Section IV output; see detailed matchup table of Section V.
587	-	0.27468	2.4720	608.15	94.989	g	
588	-	0.27468	2.4720	300.00	0.035	g+ℓ	0.07630 H_2O(g)
589	-	0.79550	7.1627	300.00	0.035	g+ℓ	0.20461 H_2O(ℓ)
590	-	0.25056	2.2585	350.00	0.411	g	
591	-	0.25056	2.2585	300.00	0.035	g+ℓ	0.02311 H_2O(ℓ)
592	-	0.25056	2.2585	300.00	0.035	ℓ	
593	-	0.25056	2.2585	300.00	0.411	ℓ	
594	-	0.25056	2.2585	350.00	0.411	ℓ	
595	-	-	-	713	-	-	High temperature process heat lowest temperature input; see detailed matchup table of Section V.
596	-	-	-	1144	-	-	High temperature process heat highest temperature output; see detailed matchup table of Sec. V.
597	-	-	-	311.00	-	-	Waste heat recovery from Sec. II & III.
598	-	-	-	410.00	-	-	Waste heat recovery from Sec. I & III.
599	-	-	-	713	-	-	Intermediate temperature process heat highest temperature output; see detailed matchup table of Section V.
5000	-	-	-	358.00	-	-	Waste heat from Section I & II output; see detailed table of Section V.
5001	-	-	-	686	-	-	Low temperature process heat highest temperature output; see detailed matchup table of Sec. V.

SECTION V

Power Generation and Helium Heat Transfer
Energy Transfer, Overall Table

Basis: 0.993 g-mol H_2 Product

Heat Exchanger No.	Heat Load, kJ	Warm Side				Cool Side				Comments
		Inlet Stream No.	Inlet Stream Temp., K	Outlet Stream No.	Outlet Stream Temp., K	Inlet Stream No.	Inlet Stream Temp., K	Outlet Stream No.	Outlet Stream Temp., K	
E-500	157.396	504	1214.56	505	742.27	512	686.71	509	1159.00	
E-501	194.185	503	934.29	506	536.51	540	480.95	514	878.73	
E-502	208.595	502	1226.86	507	751.56	546	696.00	541	1171.30	
E-503	144.892	509	1159.00	510	728.00	-	713.00	-	1144.00	High temperature process heat loads; see detailed matchup table of Section V.
E-504	182.701	541	1171.30	542	755.00	559	743.00	547	1159.30	
E-505	6.844	598	410.00	597	311.00	554	368.15	555	311.00	Waste heat from Sec. II and III see detailed matchup table for Section V.
E-506	32.052	552	300.00	553	300.00	CW	-	-	-	
E-507	25.548	589	300.00	560	300.00	CW	-	-	-	
E-508	169.612	-	728.00	-	696.00	-	686.00	-	713.00	Intermediate temperature process heat loads; see heat exchanges matchup summary table.
E-509	138.281	-	696.00 to 606.79		480.95	-	403.00	-	686.00	Low temperature process head heat loads, see heat exchanger matchup summary table.
E-510	33.697	-	696.00	-	686.71 to 480.95	-	686.71 to 606.79	-	616.73 to 480.95	See heat exchanger matchup summary table.
E-511	5.952	5003	410.00	5004	311.00	-	~300.00	-	368.00	See heat exchangers matchup table for warm side and see detailed matchup table for cool side.
E-512	10.454	-	410 to 378	-	394.9 to 368.00	594		590		
E-513	9.999	591	300.00	592	300.00	CW	-	-	-	
E-514	0.994	523	311.00	527	350.00	593	300.00	554	350.00	Waste heat from Section III, see detailed matchup table for Section V.

SECTION V

Power Generation and Helium Heat Transfer
Energy Transfer, Overall Table
(Continued)

Power Equipment No.	Work Load kJ	Inlet Stream No.	Inlet Stream Pressure Pa x 10^5	Outlet Stream No.	Outlet Stream Pressure Pa x 10^5	Comments
P-500	0.385	553	0.035	554	189.510	
P-501	0.052	583	0.035	584	94.989	
P-502	0.035	576	0.035	577	63.652	
P-503	0.015	568	0.035	569	40.906	
P-504	0.004	561	0.035	562	24.978	
P-505	negligible	592	0.035	593	0.6212	
TC-500	135.503	*	*	508	49.041	*Streams 505 (44.726x10^5Pa), 506(21.245x10^5Pa) and 507(46.000x10^5Pa)
TC-501	8.830	549	156.945	550	189.510	
TC-502	18.938	558	189.510	559	379.210	
TC-503	12.044	544	46.619	545	51.675	
TC-504	22.696	531	29.328	532	51.675	
TC-505	19.423	517	30.445	518	51.675	
TC-506	21.982	522	30.445	524	51.675	
TC-507	1.356	535	29.328	537	51.675	
TE-500	183.100	501	49.041	+	+	+streams 502(46.000x10^5Pa), 503(21.245x10^5Pa) and 504(44.726x10^5Pa)
TE-501	73.660	514	51.675	515	30.445	
TE-502	11.850	542	51.679	543	46.691	
TE-503	45.964	547	379.210	548	156.945	
TE-504	23.494	551	189.510	552	0.035	
TE-505	1.094	565	24.978	566	0.035	
TE-506	2.965	572	40.906	573	0.035	
TE-507	4.738	580	63.652	581	0.035	
TE-508	4.970	587	94.989	588	0.035	
TE-509	1.672	528	30.455	529	29.328	
TE-510	1.313	590	0.621	591	0.035	

SECTION V

Power Generation and Heat Transfer
Heat Exchangers Matchup Summary Table

Basis: 0.993 g-mole H_2 Product

		Heat Load, kJ	Warm Side				Cool Side				Comments
			Inlet Stream No.	Inlet Stream Temp., K	Outlet Stream No.	Outlet Stream Temp., K	Inlet Stream No.	Inlet Stream Temp., K	Outlet Stream No.	Outlet Stream Temp., K	
E-508	A	10.698	510	728.00	511	696.00	-	-	-	-	
	B	15.638	515	728.00	536	696.00	-	-	-	-	
	C	14.044	543	728.00	544	696.00	-	-	-	-	See detailed matchup table for cool side heat exchangers.
	D	99.574	548	976.94	549	696.00	-	-	-	-	
	E	15.614	550	728.00	556	696.00	-	-	-	-	
	F	14.044	545	728.00	546	696.00	-	-	-	-	
	G	169.612	-	-	-	-	500	686	599	713	Intermediate temperature process heat demand.
E-509	A	3.136	511	696.00	512	686.71	-	-	-	-	
	B	33.193	516	696.00	517	480.95	-	-	-	-	
	C	13.770	520	696.00	521	606.97	-	-	-	-	
	D	34.395	530	686.71	531	480.95	-	-	-	-	See detailed matchup table for cool side heat exchangers.
	E	0.896	533	686.71	534	616.73	-	-	-	-	
	F	19.423	518	606.79	519	480.95	-	-	-	-	
	G	10.802	524	686.71	525	616.73	-	-	-	-	
	H	22.696	532	616.73	539	480.95	-	-	-	-	
	I	138.281	-	-	-	-	5002	403	5001	686	Low temperature power heat demand.
E-510	A	3.055	534	616.73	535	375.07	-	-	-	-	
	B	20.957	525	616.73	526	480.95	-	-	-	-	
	C	9.645	521	606.97	522	544.30	-	-	-	-	
	D	11.985	-	-	-	-	585	360.00	587	608.15	
	E	11.368	-	-	-	-	578	410.00	580	580.73	
	F	7.395	-	-	-	-	570	410.00	572	552.59	
	G	2.949	-	-	-	-	563	410.00	565	524.82	
E-511	A	0.543	562	300.10	563	410.00	-	-	-	-	
	B	1.493	569	300.15	570	410.00	-	-	-	-	See detailed matchup table for cool side exchangers.
	C	2.289	577	300.26	578	410.00	-	-	-	-	
	D	1.633	584	300.28	585	360.00	-	-	-	-	
	E	5.963	5003	410.00	5004	311.00	-	≈ 300	-	360.00	Waste heat recovery for second steam cycle.

SECTION V

Power Generation and Heat Transfer
Heat Exchangers Matchup Summary Table
(Continued)

	Heat Load, kJ	Warm Side				Cool Side				Comments
		Inlet Stream No.	Inlet Stream Temp., K	Outlet Stream No.	Outlet Stream Temp., K	Inlet Stream No.	Inlet Stream Temp., K	Outlet Stream No.	Outlet Stream Temp., K	
E-512 A	3.566	5005	378.00	5006	368.00	-	-	-	-	Higher temperature waste heat recovery for auxiliary power cycle.
B	4.982	5007	394.90	5008	393.00	-	-	-	-	
C	0.831	578	383.00	536	358.00	-	-	-	-	
D	1.085	513	368.15	5000	358.00	-	-	-	-	
E	10.464	-	-	-	-	594	350.00	590	350.00	Auxiliary power cycle heat demand

Detailed Matchup of Processing Sections
High Temperature Heat Demand
from Section V

Easis: 0.993 g-mol H_2 Product

Cool Side				Warm Side		
Heat Exchanger No.	Heat Load kJ	Input Temperature, K	Output Temperature, K	Heat Exchanger No.	Input Temperature, K	Output Temperature K
E-205 a_1	2.379	499.00	502.00	E-509B$_{21232}$	542.28	526.33
E-205 a_2	2.573	499.00	502.00	E-509D$_{2232}$	542.28	526.33
E-205 a_3	2.377	499.00	502.00	E-509F$_{232}$	542.28	526.33
E-205 a_4	2.563	499.00	502.00	E-509G$_{232}$	542.28	526.33
E-205 d_{21}	5.411	473.60	488.50	E-509B$_{21252}$	525.39	488.73
E-205 d_{22}	5.853	473.60	488.50	E-509D$_{2252}$	525.39	488.73
E-205 d_{23}	5.406	473.60	488.50	E-509F$_{252}$	525.39	488.73
E-205 d_{24}	5.853	473.60	488.50	E-509H$_{252}$	525.39	488.73
E-207 C_1	4.207	502.00	530.00	E-509B$_{21221}$	573.25	542.28
E-207 C_2	4.550	502.00	530.00	E-509D$_{2222}$	573.25	542.28
E-207 C_3	4.203	502.00	530.00	E-509F$_{222}$	573.25	542.26
E-207 C_4	4.550	502.00	530.00	E-509H$_{222}$	573.25	542.28
E-209 C_1	0.877	530.00	573.00	E-509B$_{21212}$	582.90	573.25
E-209 C_2	0.949	530.00	573.00	E-509D$_{2212}$	582.90	573.25
E-209 C_3	0.876	530.00	573.00	E-509G$_{212}$	582.90	573.25
E-209 C_4	0.949	530.00	573.00	E-509H$_{212}$	582.90	573.25
E-211 C_1	5.389	573.00	613.00	E-509B$_{2111}$	625.21	582.90
E-211 C_2	2.519	573.00	613.00	E-509C$_{21}$	625.21	606.97
E-211 C_3	6.324	573.00	613.00	E-509D$_{211}$	625.21	582.90
E-211 C_4	0.107	573.00	613.00	E-509E$_{21}$	625.21	616.73
E-211 C_5	1.171	573.00	613.00	E-509G$_{21}$	625.21	616.73
E-211 C_6	3.288	573.00	613.00	E-509F$_{11}$	606.77	582.90
E-211 C_7	5.053	573.00	613.00	E-509H$_{11}$	616.73	582.90

Detailed Matchup of Processing Sections
High Temperature Heat Demand
from Section V
(Continued)

Cool Side				Warm Side		
Heat Exchanger No.	Heat Load kJ	Input Temperature, K	Output Temperature, K	Heat Exchanger No.	Input Temperature, K	Output Temperature K
E-213 B_1	3.106	613.00	636.00	E-509A	696.00	625.21
E-213 B_2	5.742	613.00	636.00	E-509B_{II}	662.43	625.21
E-213 B_3	10.952	613.00	636.00	E-509C_{II}	696.00	625.21
E-213 B_4	10.275	613.00	636.00	E-509D_I	686.71	625.21
E-213 B_5	0.776	613.00	636.00	E-509E_I	686.71	625.21
E-213 B_6	9.489	613.00	636.00	E-509G_I	686.71	625.21
E-214 a	7.005	1300.00	1144 00	E-503 I	1159.00	1138.05
E-214 b_2	92.071	800.00	1130.00	E-503 II	1138.05	862.49
E-219 A	78.356	686.00	686.00	E-508 DVI	917.08	696.00
E-219 B_1	10.698	686.00	686.00	E-508 A	728.00	696.00
E-219 B_2	15.638	686.00	686.00	E-508 B	728.00	696.00
E-219 B_3	14.044	686.00	686.00	E-508 C	728.00	696.00
E-219 B_4	15.614	686.00	686.00	E-508 E	728.00	696.00
E-219 B_5	14.044	686.00	686.00	E-508 F_2	728.00	696.00
E-221 B_I	45.017	713.00	800.00	E-503 III	862.49	728.00
E-221 B_2	4.139	705.00	713.00	E-508 DII	963.37	951.76
E-221 B_3	9.831	686.00	705.00	E-508 DIV	948.62	920.88
E-404	4.786	713.00	713.00	E-508 DI	976.54	963.37
E-405 A	1.112	705.00	713.00	E-508 DIII	951.76	948.62
E-405 B_{II}	1.349	686.00	705.00	E-508 DV	920.88	917.08
E-405 B_2	3.691	634.00	686.00	E-509 B_{1} I	696.00	672.08
E-405 B_3	1.491	613.00	634.00	E-509 B_{1} II	672.08	662.43
E-405 B_{41}	0.682	573.00	613.00	E-509 B_{2112}	625.21	582.90
E-405 B_{42}	0.294	573.00	613.00	E-509 C_{22}	625.21	606.97

Detailed Matchup of Processing Sections
High Temperature Heat Demand
from Section V
(Continued)

Cool Side				Warm Side		
Heat Exchanger No.	Heat Load kJ	Input Temperature, K	Output Temperature, K	Heat Exchanger No.	Input Temperature, K	Output Temperature K
E-405 B_{43}	0.739	573.00	613.00	E-509 D_{2112}	625.21	582.90
E-405 B_{44}	0.119	573.00	613.00	E-509 E_{2}	625.21	616.73
E-405 B_{45}	0.137	573.00	613.00	E-509 D_{212}	625.21	616.73
E-405 B_{46}	0.384	573.00	613.00	E-509 F_{12}	606.77	582.90
E-405 B_{47}	0.590	573.00	613.00	E-509 H_{12}	616.73	582.90
E-405 B_{51}	0.629	530.00	573.00	E-509 B_{21211}	582.90	573.25
E-405 B_{52}	0.680	530.00	573.00	E-509 D_{2211}	582.90	573.25
E-405 B_{53}	0.628	530.00	573.00	E-509 F_{211}	582.90	573.25
E-405 B_{54}	0.680	530.00	573.00	E-509 H_{211}	582.90	573.25
E-405 B_{61}	0.578	502.00	530.00	E-509 B_{21221}	573.25	542.28
E-405 B_{62}	0.625	502.00	530.00	E-509 D_{2221}	573.25	542.28
E-405 B_{63}	0.578	502.00	530.00	E-509 F_{221}	573.25	542.28
E-405 B_{64}	0.626	502.00	530.00	E-509 H_{221}	573.25	542.28
E-405 B_{71}	0.085	499.00	502.00	E-509 B_{21231}	542.28	526.33
E-405 B_{72}	0.092	499.00	502.00	E-509 D_{2231}	542.28	526.33
E-405 B_{73}	0.085	499.00	502.00	E-509 F_{231}	542.28	526.33
E-405 B_{74}	0.092	499.00	502.00	E-509 H_{231}	542.28	526.33
E-405 B_{81}	0.144	488.50	499.00	E-509 B_{2124}	526.33	525.39
E-405 B_{82}	0.156	488.50	499.00	E-509 D_{224}	526.33	525.39
E-405 B_{83}	0.145	488.50	499.00	E-509 F_{24}	526.33	525.39
E-405 B_{84}	0.156	488.50	499.00	E-509 H_{24}	526.33	525.39
E-405 B_{91}	0.253	473.60	488.50	E-509 B_{21251}	525.39	488.73
E-405 B_{92}	0.274	473.60	488.50	E-509 D_{2251}	525.39	488.73
E-405 B_{93}	0.253	473.60	488.50	E-509 F_{251}	525.39	488.73
E-405 B_{94}	0.274	473.60	488.50	E-509 H_{251}	525.39	488.73
E-405 B_{101}	1.201	403.00	473.60	E-509 B_{2126}	488.73	480.95
E-405 B_{102}	1.299	403.00	473.60	E-509 D_{226}	488.73	480.95
E-405 B_{103}	1.201	403.00	473.60	E-509 F_{26}	488.73	480.95
E-405 B_{104}	1.299	403.00	473.60	E-509 H_{26}	488.73	480.95

Detailed Matchup of Processing Sections Waste Heat
in Section V

Basis: 0.993 g-mol H_2 Product

Warm Side						Cool Side				
Heat Exchanger No.	Heat Load kJ	Input Stream No.	Input Temperature K	Output Stream No.	Output Temperature K	Heat Exchanger No.	Input Stream No.	Input Temperature K	Output Stream No.	Output Temperature K
E-106	3.566	5005	378.00	5006	368.00	E-512 A	594	350.00	590	350 00
E-220 b_1	2.000	5004(A)	410.00	5003(A)	368.00	E-511-I	-	300.00	-	360.00
E-220 b_2	0.974	598(A)	410.00	597(A)	368.00	E-505-I	554	300.00	555.00	391.00
E-222 b_1	1.909	598(B)	405.00	597(B)	311.00	E-505-II	554	300.00	555.00	391.00
E-222 b_2	0.162	-	311.00	-	300.00	CW	-		-	-
E-314 A	3.365	5004(E)	368.15	5003(B)	311.00	E-511-II	-	300.00	-	360.00
E-314 B	0.738	-	311.00	-	300.00	CW	-	-	-	-
E-315 B_1	0.598	5004(C)	368.15	5003(C)	311.00	E-511-III	-	300.00	-	360.00
E-315 B_2	2.677	598(C)	368.15	597(C)	311.00	E-505-III	554	300.00	555.00	391.00
E-315 B_3	0.630	-	311.00	-	300.00	CW	-	-		-
E-316 B_1	0.406	598(D)	368.15	597(D)	311.00	E-505-IV	554	300.00	555.00	391.00
E-316 B_2	0.503	513(A)	368.15	5000(A)	358.00	E-512D-I	594	350.00	590.00	350.00
E-316 B_3	0.944	-	368.15	-	311.00	E-514	593	300.00	594	350.00
E-316 B_4	1.422	-	368.15	-	311.00	CW	-	-	-	-
E-316 B_5	0.630	-	311.00	-	300.00	CW	-	-	-	-
E-317 B_1	0.582	513(3)	368.15	5000(B)	358.00	E-512D-II	594	350.00	590.00	350.00
E-317 B_2	3.324	-	358.00	-	303.00	CW	-	-	-	-
E-406 C_1	0.066	598(E)	394.90	597(E)	393.00	E-505-V	554	300.00	555	391.00
E-406 C_2	0.498	5007	394.90	5008	393.00	E-512 B	594	350.00	590	350.00
E-407 C	0.812	598(F)	403.00	597 (F)	393.00	E-505-VI	554	300.00	555	391.00
E-411 A	0.831	597	383.00	586	358.00	E-512 C	594	350.00	590	350.00
E-411 B	1.827	-	358.00	-	303.00	CW	-	-	-	-

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