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DEVELOPMENT OF A PREPROTOTYPE
SABATIER
CO₂ REDUCTION SUBSYSTEM

BY

GILBERT N. KLEINER
AND
DR. PHILIP BIRBARA

PREPARED UNDER CONTRACT NO. NAS 9-15470

BY

HAMILTON STANDARD
DIVISION OF UNITED TECHNOLOGIES CORPORATION
WINDSOR LOCKS, CONNECTICUT

FOR

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
LYNDON B. JOHNSON SPACE CENTER
HOUSTON, TEXAS

AUGUST, 1980
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ABSTRACT

A preprototype Sabatier CO₂ Reduction Subsystem was successfully designed, fabricated and tested. The lightweight, quick starting (<5 minutes) reactor utilizes a highly active and physically durable methanation catalyst composed of ruthenium on alumina. The use of this improved catalyst developed and fabricated by Hamilton Standard permits a single straight through plug flow design with an average lean component H₂/CO₂ conversion efficiency of over 99% over a range of H₂/CO₂ molar ratios of 1.8 to 5 while operating with flows equivalent to a crew size of one person steadystate to 3 persons cyclical (equivalent to 5 persons steady-state). The reactor requires no heater operation after start-up even during simulated 55 minute lightside/39 minute darkside orbital operation over the above range of molar ratios and crew loadings.

Subsystem performance was proven by parametric testing and endurance testing over a wide range of crew sizes and metabolic loadings. The subsystem's operation and performance is controlled by a microprocessor and displayed on a nineteen inch multi-colored cathode ray tube.
FOREWORD

This report has been prepared by the Hamilton Standard Division of United Technologies Corporation for the National Aeronautics and Space Administration's Lyndon B. Johnson Space Center in accordance with Contract NAS 9-13624, "Development of a Preprototype Sabatier CO₂ Reduction Subsystem."

Appreciation is expressed to the NASA Technical Monitor, Mr. Robert J. Cusick of the NASA, Johnson Space Center, for his guidance and advice.

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Figure 68 Sabatier Comparison Of Steadystate And Transient Bed Temperatures
Figure 69 Sabatier Comparison Of Steadystate And Transient Bed Temperatures
A development program of a Preprototype Sabatier CO\textsubscript{2} Reduction Subsystem was successfully completed at Hamilton Standard. The subsystem converts hydrogen and carbon dioxide to water and methane with an average demonstrated lean component efficiency of over 99\% for a range of H\textsubscript{2}/CO\textsubscript{2} molar ratios of 1.8 to 5.0 for a crew size range of one person steady-state to 3 persons cyclical operating with a simulated 55 minute light side/39 minute dark side orbital operation. The reactor starts up in less than five minutes, requires no heater operation after start-up and requires no active controls. Over 700 hours of on-line reactor test time over a wide range of operating conditions were accomplished during this program.

The primary feature of the reactor is the high activity catalyst developed and fabricated by Hamilton Standard and designated as UASC-151G. This catalyst, ruthenium on a 14-18 mesh granular alumina substrate, permitted a simple straight-through plug flow reactor design without complicated heat exchangers.

The subsystem was successfully integrated with a microprocessor based controller which permitted complete automatic control and a CRT display which provided a colored display of subsystem flow and key operating and performance parameters. All possible control and emergency shutdown provisions were demonstrated.

The test data obtained during this program was examined and successfully used as a basis for correlation of a Sabatier Thermal Computer Model. Steady-state conversion efficiencies agreement with test data were within 0.1\% for most test cases.
INTRODUCTION

Future extended mission manned spacecrafts will require regeneration of all possible to reduce the amount of expendables required for resupply. One of the most promising methods is to catalytically convert carbon dioxide and hydrogen in a Sabatier reactor to water and methane. The water would be used for crew consumption or electrolyzed to produce oxygen. The methane would be dumped to space.

A program to develop a preprototype Sabatier subsystem was undertaken by Hamilton Standard to demonstrate the performance and life characteristics of an efficient (>99%), simple lightweight design. This program is an outgrowth of Hamilton Standard's six previous Sabatier programs which included the Space Station Prototype (SSP) Sabatier program. Compared to the 98% efficient SSP reactor, the preprototype subsystem developed in this program is 1/5 the weight, 2/3 the size, uses 1/4 the catalyst, starts up in 1/20 the time and requires no heater operation after start-up. Operation of the subsystem is completely automatic by utilizing a microprocessor based controller.

Program Objective

The basic objective of this program was to develop a Sabatier CO Reduction Subsystem to be integrated with other individual technologies in the area of regenerative life support and evaluated as a part of a Regenerative Life Support Evaluation (RLSE) program at the NASA/JSC.

Program Duration

This final report encompasses all work performed during the period of April 1978 through June 1980.

The calculations in this report were made in US customary units and converted to SI metric units.
CONCLUSIONS

The following conclusions were reached as a result of this program activity:

1. The preprototype Sabatier subsystem successfully completed the development program requirements.

2. The reactor starts up in less than five minutes under all design conditions.

3. The catalytic Sabatier reaction is inherently self-limiting to a temperature of 593°C (1100°F).

4. Analytical computer techniques were shown to be accurate in predicting performance.

5. Once started, the reactor requires no active cooling or heating operation during a 55 minute lightside, 39 minute darkside orbital mission.

6. The subsystem was tested for a total of 720 hours with no degradation in performance. In fact performance improved.

7. The inlet dew point reactant from essentially dry to 21°C (70°F) and supply pressure variation from 1.2 to 1.34 atm (17.7 to 19.7 psia) had no detectable effect on the subsystem performance.

8. The preprototype design is directly applicable to a prototype system.

9. The controller and display, which is common to the TIMES (1) subsystem, requires no adjustments other than switching leads from one subsystem to another to provide complete automatic control with a display which illustrates flow paths and significant performance parameters.

10. The reactor efficiency is essentially over 99% efficient for H₂/CO₂ molar ratios in the range of 1.8 to 5.0.

11. The subsystem was operated successfully with 5% air (1% oxygen) mixed with the inlet gases. No adverse effects on the catalyst bed resulted as evidenced by subsequent baseline testing.

12. The reactor with adequate cooling can efficiently handle reactant flows equivalent to a crew size of up to 30 persons.

(1) Reference NASA Contract No. NAS9-15471
RECOMMENDATIONS

The following recommendations are a result of successful completion of this program.

1. Testing of an integrated system consisting of an electrolysis unit, a carbon dioxide concentrator and a Sabatier subsystem should be demonstrated to verify total air revitalization system operation and performance.

2. Since the reactor is capable, with adequate cooling, to handle reactant flows equivalent to a crew size of 30 persons, it is recommended that parametric testing be conducted to define the cooling required to achieve this increased capacity, the resultant reactor efficiencies, and the performance range with fixed cooling flows.

3. A prototype flight subsystem should be fabricated in order to demonstrate performance compliance on a simulated space mission and to be available for a possible flight evaluation.

4. If it is desired to operate the subsystem at reactant inlet pressures less than 1.2 atm (3 psig), it is recommended that the possibility of redesign of the water collection section be investigated.

5. In order to operate the Sabatier and TIMES subsystem concurrently it is recommended that an additional controller and display be fabricated or the controller capacity be increased to permit monitoring or operation of both systems concurrently using the same display and keyboard.
RESULTS

This Preprototype Sabatier Carbon Dioxide Reduction Subsystem Program resulted in the design fabrication, extensive testing and delivery to the NASA/JSC of a preprototype Sabatier Subsystem.

The preprototype Sabatier subsystem is shown schematically in Figure 1. Figure 2 is a photograph of the front and rear view of the subsystem package assembly. Figure 3 is a photograph of the Sabatier controller driver box assembly. Figure 4 shows the Sabatier subassembly integrated with the "common" TIMES controller. Figure 5 shows the "common" TIMES display and keyboard which is used to operate and monitor the Sabatier subsystem.

The subsystem was successfully integrated with the controller and display/keyboard from the TIMES program. Either subsystem, TIMES or Sabatier, can be operated by connecting the electrical leads from the subsystem and driver box of the subsystem to be operated to the controller. The electrical leads are common from the controller to the 19 inch, six color display and keyboard.

Over 700 hours of test time including a 120 hour continuous operation test run was accumulated during the development test program on the subsystem package assembly. Reactor steadystate performance was above 99% for all but two cases at a molar ratio of 4.0. The conversion efficiencies were calculated from gas chromatograph readings of outlet gas composition, and from flowmeter measurements. Table 1 shows the resultant performance data. An off design 10 person case at a molar ratio of 2.6 with the same cooling flow had a conversion effectiveness of 97.1%.

Cyclic operation of the subsystem to simulate a 55 minute on, 39 minute off orbital duty cycle also demonstrated an average conversion efficiency of 99%. Performance data obtained during this operation is shown in Table 2. As can be noted, subsequent testing after a catalyst treatment to remove additional residual chlorides resulted in improved performance for the cases rerun. During all these tests cooling flow was maintained at all times and no heater operation was required to initiate the reaction.

The effect of variation in total gas reactant inlet supply pressure of 1.2 atm to 1.34 atm (17.7 to 19.7 psia) showed that reactor performance is negligibly affected (<0.1%). The effect of reactant gas dewpoint from a dry condition to a dewpoint of 21.1°C (70°F) also showed that the hydrogen conversion efficiency is within 0.1%.
FIGURE 1
PREPROTOTYPE SABATIER SUBSYSTEM SCHEMATIC
FIGURE 2
PREPROTOTYPE SABATIER PACKAGE ASSEMBLY
FIGURE 3
SABATIER DRIVER BOX
FIGURE 4
SABATIER PACKAGE ASSEMBLY WITH DRIVER BOX AND CONTROLLER
### TABLE 1

Preprototype Sabatier Subsystem Performance
Conversion Efficiency During Steadystate Testing

<table>
<thead>
<tr>
<th>CO₂ Flow</th>
<th>H₂/CO₂ Molar Ratio</th>
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<tr>
<td></td>
<td>1.8</td>
</tr>
<tr>
<td>1 Man Continuous</td>
<td>99.8</td>
</tr>
<tr>
<td>1 Man Cyclic</td>
<td>99.7</td>
</tr>
<tr>
<td>2 Man Cyclic</td>
<td>----</td>
</tr>
<tr>
<td>3 Man Continuous</td>
<td>99.3</td>
</tr>
<tr>
<td>3 Man Cyclic</td>
<td>99.4</td>
</tr>
<tr>
<td>10 Man Continuous</td>
<td>----</td>
</tr>
<tr>
<td>(off design)</td>
<td></td>
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TABLE 2

Preprototype Sabatier Subsystem Performance
Average Conversion Efficiency During Cyclic Testing
(55 Minutes On - 39 Minutes Off)

<table>
<thead>
<tr>
<th>CO₂ Flow</th>
<th>H₂/CO₂ Molar Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.8</td>
</tr>
<tr>
<td>1 Man</td>
<td>99.6</td>
</tr>
<tr>
<td>2 Man</td>
<td>----</td>
</tr>
<tr>
<td>3 Man</td>
<td>99.6 (99.4)</td>
</tr>
</tbody>
</table>

( ) - Test results after completion of test program and catalyst treatment
Test results showed that for molar ratios above 4.06 no carbon dioxide was detected for the 3-man cyclic flow test condition. As a result, it appears that 100% conversion of the CO₂ lean component occurs at above a molar ratio of about 4.1.

A test conducted with 5.1% air (1% oxygen) mixed in with the inlet reactants showed no catalyst damage as a result of oxygen exposure.

During all start-up operations, the reaction was started in five minutes or less. Water production rates were usually <2.5% of the calculated value and water quality quickly improved during testing to a pH of 4.5-6.0, chlorides to barely detectable by the sensitive silver nitrate test and water conductivity to 10-20 μmhos.
**DISCUSSION**

The NASA Statement of Work (SOW) defined the major tasks for this program. The corresponding Hamilton Standard Work Breakdown Structure (WBS) and the detailed presentation of this report section is presented below:

<table>
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<th>SOW Paragraph</th>
<th>WBS No.</th>
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<tr>
<td>Subsystem Delivery</td>
<td>3.2.4</td>
<td>2.0, 3.0</td>
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<tr>
<td>Coordination with RLSE</td>
<td>3.2.5</td>
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<td>Documentation</td>
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<tr>
<td>Reliability</td>
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<td>3.0</td>
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<tr>
<td>Safety</td>
<td>8.0</td>
<td>1.0, 3.0</td>
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SUBSYSTEM DESIGN

The Sabatier subsystem schematic is shown in Figure 1. The carbon dioxide and hydrogen mixture enters the subsystem through a charcoal filter which protects the reactor from any trace amount of contaminant carryover from the upstream electrochemical carbon dioxide concentrator or the electrolysis subsystem. The mixture then passes to the reactor where it is converted to water vapor and methane. The water vapor, methane and excess reactant (either CO₂ or H₂) then flow to the air cooled condenser/separator, where the water vapor is condensed, separated from the gas stream and pumped out. The gases (methane and excess reactant and uncondensed water vapor) are then dumped overboard to space vacuum through a pressure regulator which also serves to regulate CO₂ and H₂ supply pressure. A bypass function for CO₂ and H₂ is provided for emergency shutdown and to permit maintenance on the Sabatier subsystem without interruption of the CO₂ Removal and O₂ Generation processes. The water is pumped out of the water separator by the pressure differential between the reactant pressure and a spring loaded accumulator which maintains a constant pressure drop across the porous plate separator. A positive displacement pump empties the accumulator when full. A fixed air cooling flow is supplied to the Sabatier Reactor and the condenser/separator by the fan. A controller is provided to control system operation, to monitor the instrumentation, provide status information to the display, activate bypass operating modes in response to out of tolerance conditions, provide warnings and instructions to the test operator. For all operating conditions and modes other than failure modes, the controller is not required to drive any thermal controls because the Sabatier Reactor requires no cooling modulation or heater operation (except at start-up) to meet the full range of performance requirements. The subsystem functions, capabilities, interface definition, schematic and operation are consistent with the RLSE system requirements.

The heart of the subsystem includes the reactor, the water condenser/separator, the accumulator and the water pump. These items, as further described in later paragraphs of this section, were developed on this program to the standards of space flight hardware, and will not require major modifications for flight use. The balance of the subsystem components are classified as ancillary equipment. High quality commercial items were employed for the ancillary items, with modifications as necessary to achieve the high quality and functional capabilities required of the pre-prototype unit.

The pump delivers water to the water management system at 2 atm (30 psia) which is the upper pressure limit defined by RLSE. The preprototype unit has its own cooling fan, however, the air cooling 3-ket at the reactor is designed to operate at low flow with the pressure drop available from normal Spacelab rack cooling air.
To limit touch temperature to 45°C (113°F) the front end of the reactor is insulated along the first 12.7 cm (5.0 inches) of length with min K type insulation. This insulation also retains more than adequate heat during the off period of cyclic operation to eliminate need for heater operation.

The remainder of the reactor has two air cooling jackets that direct flow air axially from the reactant exit end of the reactor toward the inlet end. Since jacket temperature can be quite high, an outer shield is used to limit temperature of exposed surfaces to 45°C (113°F).

The Sabatier reaction is self-limiting (a reverse endothermic reaction takes place) at about 593°C (1100°F). Therefore, there is no danger of the reactor overheating itself to failure under any load or molar flow ratio. For control and normal performance monitoring, a single thermocouple in the front end of the reactor bed is used. For preprototype performance analysis, the reactor was instrumented with 8 thermocouples running down the center of the bed and 3 thermocouples along the wall of the bed. Since the reactor radius is only 0.3 cm (0.72 in) centerline thermocouples and wall thermocouples reading were sufficient to map the temperature gradient. The reactor is sized to convert more than 99% of the lean reactant over a CO₂ flow range of from 0.91 kg/day (2.0 lb/day) at cyclic and continuous operation to 3.6 kg/day (7.9 avg lbs/day) at cyclic and continuous operation over a H₂/CO₂ molar ratio of from 1.8 to 5.0. This represents the maximum flow range considering a one to three-man crew and cyclic operation matched to a 94 minute orbit with 55 minute light side operation. The minimum flow is for one man, minimum metabolic, continuous operation and the maximum flow is for three men maximum metabolic cyclic operation.

The subsystem controls for normal operation are only the limit ranges in the water accumulator. The electric heater is used for startup and is turned on automatically when the subsystem is placed in the standby or process mode if the reactor temperature is below 177°C (350°F). The cooling air flow remains on at all times at a fixed flow condition during all operating modes. Since the reaction itself is self-limiting at 593°C (1100°F), all components are capable of operating while the reactor is at this condition. The Sabatier system can also withstand vacuum, or pressures far exceeding those that could be produced by the WVE or EDC. Although the reactor subsystem itself is inherently protected by design, there are some failures which could effect the interfacing subsystems. A controller and data processing unit is provided to detect such failures and take the necessary protective action. The control unit includes a multicolor display of subsystem flow, performance status and water production rate.
The Sabatier subsystem is not dependent on gravity and can be operated in any attitude in one G. The only components having more than a single fluid phase present are the reactor and the separator/condenser. Both of these component designs have been demonstrated at 1 G showing that capillary forces control the liquid gas interface.

General Design Philosophy

The design of the Sabatier CO\textsubscript{2} Reduction Subsystem was based on an extensive background of both experimental and analytical data with the actual catalyst used in the preprototype unit. One thousand hours of operating time has now been accumulated on this catalyst material. The subsystem is designed to meet the requirements specified in Table 3. These requirements include the requirements of the NASA work statement, RLSE design requirements, and other requirements necessary to ensure that the components comprising the heart of the subsystem are of flight design. The main feature of the concept is simplicity of both design and control. This was obtained by the use of a Hamilton Standard developed catalyst which permitted operation over a wide range of temperature, molar ratios and loads with no active control at high efficiency (99%+).

Due to the high activity catalyst used, the heat generated in a given volume is larger than its heat loss and the reaction is self-sustaining. As a result, the reactor "ignites" at under 177°C (350°F). Since the higher activity catalyst requires a smaller bed there is less heat loss and less thermal mass to heat and the reactor starts within five minutes.

The ability of the catalyst to operate effectively at lower temperatures allows reactor operation over a large range at conditions without active temperature control. Cooling flow is determined by performance at the maximum load conditions and remains constant. Although reactor temperatures are lower at low loads, substantial temperature margin for a self-sustaining reaction still exists. Electric heater or modulation of cooling flow are unnecessary even at minimum load conditions and intermittent cyclic operation, thus saving power, increasing the intrinsic reliability of the system, reducing weight and cost, and reducing the important parameter of total equivalent weight.

Two temperature measurements are sufficient to indicate reactor performance status and provide over-temperature protection. Although eleven thermocouples are provided in the preprototype to map the reactor performance, flight hardware systems will require only these two temperature measurements to monitor the health of the subsystem.
TABLE 3

DESIGN SPECIFICATION

| CO₂ FLOW RATE | NOMINAL | 3.0 kg/day (6.6 lb/day) |
|               | MINIMUM | 0.9 kg/day (2.0 lb/day) |
|               | MAXIMUM | 3.6 kg/day (7.92 lb/day) |

| H₂/CO₂ MOLAR RATIO | MINIMUM | 1.8 |
|                    | MAXIMUM | 5.0 |

| REACTOR EFFICIENCY | 99% |

| REACTANT SUPPLY PRESSURE | 1.4 ATM* (5 PSIG*) |
| REACTANT SUPPLY TEMPERATURE | 18-24°C (65-75°F) |
| REACTANT DEW POINT | SATURATED |
| TOUCH TEMPERATURE MAXIMUM | 45°C (113°F) |
| WATER DELIVERY PRESSURE | 2 ATM (30 PSIA) |
| START-UP TIME MAXIMUM | 5 MIN |
| GRAVITY | 0 TO + 1G |
| SUBSYSTEM DUTY CYCLE | CONTINUOUS OR CYCLIC |

* LATER REVISED TO 1.24 (3.5 PSIG)
Subsystem Analysis

Substantial analysis was conducted on the performance and operation of the Sabatier Subsystem and its subelements. In the case of all the active subelements, the analysis was verified by test data. In the computerized areas, the models were thoroughly verified by test data, at conditions required by the contract. The analysis techniques and computer programs were revised upon completion of the testing to reflect the actual performance obtained.

Maximum Reactor Temperature

The Sabatier reactor process is characterized by an exothermic gas phase reaction, catalyzed by a supported metal catalyst.

The maximum theoretical temperature which can be achieved in the reactor without external heat input was calculated by applying a successive approximation procedure to find the simultaneous solution of the standard equations of chemical equilibrium, conservation of mass and conservation of energy.

This calculated temperature is 593°C (1100°F) and was arrived at by the following procedure.

Thermodynamic gas equilibrium compositions were calculated in the computer program (NAS SP-273) for a wide range of operating conditions listed below:

- Reactant Gas Compositions - H₂/CO₂ molar ratios from 2.0 to 4.0 in 0.2 increments
- Dew Points - Bone dry, 27 ± 3°C (80°F and 100°F)
- Temperatures - 149°C to 816°C in 55°C increments (300 to 1500°F in 100°F increments)
- Total Gas Pressures - 1 and 1.4 atm (15 and 20 psia)

Based on the enthalpy of equilibrium gas products (obtained from Girdler Tabulations), it was determined that at a H₂/CO₂ molar ratio of 4.0, the adiabatic temperature was 552°C (f025°F), at a ratio of 2.6, the temperature is 593°C (1100°F).

The calculated adiabatic temperatures are in good agreement with the maximum experimentally measured bed temperatures. No temperatures in excess of 586°C (1087°F) were noted in the bed region under any design or off-design condition run.
The reactor's upper temperature level is regulated by a variation in the gas products' enthalpy via the reversible nature of the steam reforming reaction. Thus temperature greater than 593°C (1100°F) cannot be achieved without external heat input. This inherent self-control feature of the reaction is used in the subsystem to assure a safe system—one that the laws of chemical thermodynamics prevent from "running away".

Water Accumulator

The water accumulator is sized to hold 45 grams (0.1 lb). For 3-man operation at an H₂/CO₂ molar ratio of 2.6 it will cycle approximately every 41 minutes during continuous operation and about every 24 minutes during the on phase of cyclic operation.

Cooling Gas Flow Requirements

A constant cooling gas flow was selected to meet all requirements and is never changed during reactor operation. This capability increases system reliability by eliminating the need for active coolant controls. The cooling gas requirement is calculated from the change in enthalpy of the process stream (H₂ - H products - H reactants), and the inlet and exit coolant temperature requirements. For the Sabatier reactor, assuming an inlet temperature of 25°C (77°F) and an outlet temperature of 121°C (250°F); nominal three man flow conditions with 318 grams/day O₂ (0.7 lb/day O₂) leakage. The calculated volumetric flow rate is 0.52 m³/min (18.4 cfm). During testing fan flow was measured as 0.62 m³/min (22 cfm).

Charcoal Bed

There are no specific requirements for a charcoal sorbent bed upstream of the Sabatier reactor. However, there are the possibility of contaminants which may be released by the CO₂ removal system to the Sabatier reactor subsystem. Consistent with the RLSE baseline, a charcoal filter is provided. If in the future, the development of the CO₂ removal system obviates the need, the charcoal filter may be removed. The filter size at this time is the minimum required to prevent flow channeling.

Condenser/Separator Sizing

The full range of possible subsystem operation was considered when sizing the condenser/seperator. CO₂ flow rates of 1 man (at minimum metabolic rates) continuous to 3 man (maximum metabolic rate) cyclic operation and a H₂ to CO₂ molar ratio of 1.8 to 5.0 were considered. The sizing case occurred at the maximum CO₂ flow rate of 3 man cyclic and a H₂ to CO₂ molar ratio of 5.0. This design case has the highest water production rate and effluent flow.
A process gas inlet temperature of 100°C (210°F) was used in the design. This value is used because it is greater or equal to the highest reactor outlet temperature recorded in our tests and except for the off design cases, represents the most severe performance condition.

The cooling air stream is considered to be 0.71 m$^3$/in (25 cfm) at 24°C (75°F). The condenser/separator was found to require 0.04 m$^2$ (0.41 ft$^2$) of heat transfer area and 0.08 m$^2$ (.19 ft$^2$) of mass transfer area. The air stream flows over stainless steel fins 0.51 cm (0.2 in) high by 5.1 mm (0.002 in) thick, set at 5.5 fin per cm (14 fins per in).

The process gas passes over pin fins 25 percent open in four passes. The porous plate is the same material and construction as used in a Shuttle application, series A316 stainless steel 1.6 mm (0.0625 in) thick, and has a bubble point of 0.5 atm (7 psi).

Sabatier Reactor Catalyst

The Hamilton Standard catalyst used in the reactor is.

<table>
<thead>
<tr>
<th>Designation</th>
<th>UASC-151G</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composition</td>
<td>About 20% Ruthenium on alumina</td>
</tr>
<tr>
<td>Shape</td>
<td>14-18 mesh granules</td>
</tr>
</tbody>
</table>

This catalyst is highly active and structurally durable. The activity of UASC-151G is five times greater than that of UASC-150T, the catalyst supplied for the SSP Sabatier reactor. The improved reactor performance obtained is primarily due to the high activity of USAC-151G.

The specific surface area for a 3.8 cm (1.5 in) diameter bed of the 14-18 mesh granules is 300 percent greater than a bed of 0.3 cm X 0.3 cm (1/8 in X 1/8 in) tablets (SSP Sabatier catalyst) while the bed porosity is approximately 10 percent greater. The determination that the active Ruthenium is dispersed to a much greater extent on the granular support (4 to 5 times) is borne out by the hydrogen chemisorption measurements. Microprobe results indicate that Ruthenium deposition is uniform over the outer granular surface and throughout the cross-section of the UASC-151G granules.
Computer Program

The Hamilton Standard thermal math model of the Sabatier Reactor has been implemented for computer simulation using the H581 thermal analysis program. This program was merged with several subroutines which handle the chemical heat generation and chemical analysis.

H581 is a generic heat transfer program which solves a nodal heat transfer network. It was used to perform the thermal analysis of the Sabatier thermal model. The special chemical analysis routines calculate the chemical heat generated and provide the calculated heat as an input to the program. Also, the H581 provides the temperature distribution of the catalyst bed required by the chemical analysis routines, and so the calculations are iterative. Carbon dioxide and hydrogen flows into the reactor are determined by the chemical analysis routines from the mass flow heat capacity for hydrogen and carbon dioxide input to the program. Therefore, any reactant flow case is specified by inputting the appropriate values for the mass flow heat capacity and the reactant gas film coefficients.

Input for the Sabatier simulation is in four major sections: (1) a list of conductivities, (2) a list of thermal connections, (3) a description of each node, including thermal mass, and (4) data for the chemical reaction subroutines.

Hardware Description

The Sabatier subsystem, Figure 6, consists of the following assemblies.

- Sabatier, Package Assembly Figure 2
- Sabatier, Driver Box Figure 3
- TIMES, Controller Figure 7
- TIMES, Display and Keyboard Figure 5
- Interconnecting harnesses

The TIMES items are used to operate the Sabatier subsystem, to reduce program costs and to demonstrate the common capability of these items.
FIGURE 6
PREPROTOTYPE SABATIER SUBSYSTEM
FIGURE 8
CONTROLS AND DISPLAYS BLOCK DIAGRAM
The Sabatier package assembly, driver box and TIMES controller will be installed in the NASA test racks in close proximity to one another while the TIMES display and keyboard will be located remotely in the laboratory control center. A 10 meter transmission line is provided to permit the remote location. A 10 meter line is also provided to permit the NASA to install a remote discrete shutdown switch. The Sabatier electrical harness is defined by Hamilton Standard drawing SVSK 100140. An 0-5VDC analog output of all input parameter suitable for interfacing with the NASA Data Acquisition System is provided. A general purpose communication link for remote display, recording, or for transmitting information to other subsystems is also provided.

Controller and Display

Figure 8 is a block diagram of the control and display layout. This portion of the subsystem utilizes an advanced microprocessor-based controller and display that provides automatic control, 24 hour monitoring of subsystem water output, automatic shutdown, subsystem performance and flow monitoring, and maintenance servicing and checkout provisions.

A multi-colored Cathode Ray Tube (CRT) display format shown in Figure 9 provides a continuous readout of system mode, any subsystem anomalies or advice system status, and operations instructions. Any one of six visual displays of appropriate data can be selected. These are:

- Mode Selection Table (Figure 10)
- Operation Diagram (Figure 11)
- Performance Diagram (Figure 12)
- Performance Table With Limits
- Performance Plot of Water Production
- Maintenance Diagram

In addition, an anomaly readout together with an anomaly light, either white, yellow or red is displayed. White for a low level indication of abnormal occurrence, yellow for a caution and red for a warning and indicating the fact that the system is automatically being shutdown. An audible alarm accompanies the red anomaly light. In addition, the status of the electrical heaters, either on or off, is indicated by having the heater wire in the schematic glow red if on; and if off, blue. The status of the height of water in the accumulator is also visibly displayed in green in real time.

The display provides maximum essential information at a glance and requires minimum interpretation and training for monitoring or subsystem control. The microprocessor controller provides automatic sequencing, dynamic control, failure detection and isolation, processes instrumentation signals, calculates water production rate and provides ground test instrumentation interfaces.
Mode:  
Anomalies: ANOM LIGHT  
Advice:  

SABATIER  
Display Title  

Selected Display  

I/O,Echo, Computer Feedback  
Computer Options  

FIGURE 9  
SABATIER CRT DISPLAY FORMAT
## FIGURE 10

SABATIER MODE SELECTION TABLE

<table>
<thead>
<tr>
<th>MODE DECISION</th>
<th>ACTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>SHUTDOWN</td>
<td>ENTER '101 DISPLAY'</td>
</tr>
<tr>
<td>PURGE</td>
<td>ENTER '102 DISPLAY'</td>
</tr>
<tr>
<td>STANDBY</td>
<td>ENTER '103 DISPLAY'</td>
</tr>
<tr>
<td>PROCESS</td>
<td>ENTER '104 DISPLAY'</td>
</tr>
</tbody>
</table>

INPUT: 100J

FOR OPERATION DIAGRAM ENTER 'RETURN'
FIGURE 11
SABATIER OPERATION DIAGRAM
FIGURE 12
SABATIER PERFORMANCE DIAGRAM
Control of the subsystem is straightforward and requires minimal instruction for operator usage as control is experienced by inputting commands designated on the CRT display using the keyboard shown in Figure 13.

Four operating modes, shutdown, purge, standby and process, and a maintenance checkout mode are provided. The logic summary for these modes is shown in Table 4. Also shown are the malfunction shutdowns and the modes during which they are initiated. The maintenance checkout mode can only be entered after the system is completely shutdown, purged and by entering "107 DISPLAY" on the keyboard. This mode permits electrical operation of the electrical valves (Item 306) and operation of the pump (Item 545).

Operation of the pump, while clean filtered water is fed into the subsystem upstream of the condenser outlet (sample point 806) will permit purging of gas from the pump during the initial start-up of the subsystem. This pump operation will also permit observation of the accumulator fill and dump cycle diagrammatically on the screen. Caution—"Operation of the pump without an external supply of water will pump the water subsystem dry and result in the pump becoming airbound."

Operation of the subsystem automatically drives the valves to the proper position whether left in the wrong position, the maintenance mode, or if manually repositioned when the power was off.

Subsystem operating time is recorded by an elapsed timer mounted in the driver box. The timer is actuated upon subsystem power application and selection of a mode that requires fan operation. This prevents accumulation of "operating time" on a shutdown system when only power is supplied.

The Sabatier driver box which interfaces with the TIMES controller and display uses low voltage logic signals from the controller to control high voltage switches that in turn supply power to the various subsystem component motor and heaters. All main control relays are high quality military-type relays designed for 400 cycle use.

Sabatier Package Assembly

The Sabatier package assembly is packaged in a 0.18 m³ (6.3 ft³) volume 61 cm X 63.5 cm X 45.7 cm deep (24" X 25" X 18" deep). The cooling fan is included within this envelope. Components were grouped for the best compromise of simple plumbing, manual valve operation, and maintenance accessibility. Portions of the reactor are insulated and also thermally isolated from the structure. All interfaces terminate at the aft surface of the package. The structure is built within an aluminum frame with channel sections bolted together with simple support brackets and panels as required.
FIGURE 13
KEYBOARD
<table>
<thead>
<tr>
<th>Manually Selected Mode</th>
<th>Shut Down</th>
<th>Purge</th>
<th>Stand By</th>
<th>Process</th>
<th>Shut Down (Purge)</th>
<th>Shut Down (Post Purge)</th>
<th>Maintenance Shutdown</th>
<th>Trip Point</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control box selected</td>
<td>Select</td>
<td>Select</td>
<td>Stand By</td>
<td>Select</td>
<td>Malfunction</td>
<td>+10 Min. or 107 Display</td>
<td>All Modes</td>
<td>Applicable</td>
<td></td>
</tr>
<tr>
<td>Sub Mode Selection Parameter</td>
<td>Shuttle</td>
<td>Mode</td>
<td>Stand By</td>
<td>Process</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Function</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heaters On/Off</td>
<td>Off</td>
<td>Off</td>
<td>On</td>
<td>On</td>
<td>Off</td>
<td>Off</td>
<td>Off</td>
<td>Off</td>
<td></td>
</tr>
<tr>
<td>Condensate Delivery</td>
<td>Off</td>
<td>On</td>
<td>On</td>
<td>On</td>
<td>Off</td>
<td>Off</td>
<td>Off</td>
<td>Off</td>
<td></td>
</tr>
<tr>
<td>Fan</td>
<td>Off</td>
<td>on</td>
<td>on</td>
<td>on</td>
<td>Off</td>
<td>Off</td>
<td>Off</td>
<td>Off</td>
<td></td>
</tr>
<tr>
<td>Valve Sequence</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>106-1 (Process In)</td>
<td>Closed</td>
<td>Closed</td>
<td>Closed</td>
<td>Open</td>
<td>Closed</td>
<td>Closed</td>
<td>Closed</td>
<td>Closed</td>
<td></td>
</tr>
<tr>
<td>106-2 (Bypass)</td>
<td>Open</td>
<td>Open</td>
<td>Open</td>
<td>Open</td>
<td>Closed</td>
<td>Open</td>
<td>Open</td>
<td>Open</td>
<td></td>
</tr>
<tr>
<td>106-3 (Nitrogen)</td>
<td>Closed</td>
<td>Open</td>
<td>Closed</td>
<td>Closed</td>
<td>Open</td>
<td>Closed</td>
<td>Closed</td>
<td>Closed</td>
<td></td>
</tr>
<tr>
<td>106-4 (Process out)</td>
<td>Closed</td>
<td>Open</td>
<td>Open</td>
<td>Open</td>
<td>Closed</td>
<td>Closed</td>
<td>Closed</td>
<td>Closed</td>
<td></td>
</tr>
<tr>
<td>106-5 (System out)</td>
<td>Open</td>
<td>Open</td>
<td>Open</td>
<td>Open</td>
<td>Open</td>
<td>Open</td>
<td>Open</td>
<td>Open</td>
<td></td>
</tr>
<tr>
<td>Malfunction shutdowns</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>121</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>25%</td>
<td>Any one sensor</td>
</tr>
<tr>
<td>103-2</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>5.5 psig</td>
<td>Yellow warning</td>
</tr>
<tr>
<td>103-5</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>&gt;100°F</td>
<td>if below 4 psig</td>
</tr>
<tr>
<td>302</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>&lt;125°F</td>
<td>After 7 Min.</td>
</tr>
<tr>
<td>303</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>&gt;90%</td>
<td>Yellow warning</td>
</tr>
<tr>
<td>304</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>&gt;80%</td>
<td>Wet</td>
</tr>
<tr>
<td>307</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>&gt;1.0 amps</td>
</tr>
<tr>
<td>308</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>&gt;0.5 amps</td>
</tr>
<tr>
<td>(All 5)</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Wrong valve position</td>
</tr>
</tbody>
</table>

33
This package fits within the RLSE test area specified by the NASP. A flight experiment package of the same subsystem can be much smaller since improved packaging efficiency will be achieved, the cooling fan and muffler can be eliminated as well as the manual shutoff valves.

Weight and Volume

Total weight and weight breakdown are presented for the preprototype hardware in Table 5.

The package weight includes:

- Sabatier packaging assembly
- Sabatier Driver Box
- Ducts, tubes and fittings
- Frame and brackets
- Fasteners
- Wiring and all Sabatier electrical harnesses (5) between the subsystem package, driver box and the controller (TIMES)

Table 6 defines the Hamilton Standard part numbers and design comments for all component items in the subsystem.

Component Descriptions

The Sabatier subsystem components were selected for their demonstrated ability to meet Sabatier subsystem requirements. All components are backed by test data and are used here in less demanding requirements than they have demonstrated in the past. The main dynamic components—the reactor and the water condenser/seperator are new designs based on previous Hamilton Standard designs.

Sabatier Reactor: The catalyst bed weighs 460 gms (1.01 lbs) and is contained in a cylindrical tube, 34 cm (13.5 in) long, 3.6 cm (1.43 in) in diameter separated into two zones: the high temperature primary reaction zone; and the cooling or secondary reaction zone. Two heaters for redundancy are used to initially heat up the catalyst to start the reaction. The heaters are not required during normal cyclic operating modes, as there is sufficient thermal storage to restart the reaction.

The first or primary reaction zone is insulated to prevent heat loss to the cabin and to retain the heat of reaction during the "down" cycle of operation, eliminating power and time requirements for reheating of the catalyst. Two cooling jackets with a fixed rate of cabin air flowing through them surrounds the secondary zone.
### TABLE 5
PREPROTOTYPE SABATIER SUBSYSTEM WEIGHT

<table>
<thead>
<tr>
<th>DESCRIPTION</th>
<th>UNIT QTY.</th>
<th>UNIT WT. kgs.</th>
<th>TOTAL WT. lbs.</th>
<th>TOTAL WT. lbs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>VALVE, ELECTRICAL SHUT-OFF</td>
<td>5</td>
<td>0.82</td>
<td>4.08</td>
<td>1.8</td>
</tr>
<tr>
<td>VALVE, CHECK WATER</td>
<td>2</td>
<td>0.05</td>
<td>0.09</td>
<td>0.1</td>
</tr>
<tr>
<td>CANISTER, CHARCOAL</td>
<td>1</td>
<td>0.62</td>
<td>0.62</td>
<td>1.4</td>
</tr>
<tr>
<td>SABATIER REACTOR ASSEMBLY (INSTRUMENTED)</td>
<td>1</td>
<td>3.40</td>
<td>3.40</td>
<td>7.5</td>
</tr>
<tr>
<td>HEATER, ELECTRIC</td>
<td>2</td>
<td>(0.05)</td>
<td>(0.10)</td>
<td>(0.1)</td>
</tr>
<tr>
<td>CONDENSER/SEPARATOR (DRY)</td>
<td>1</td>
<td>1.32</td>
<td>1.32</td>
<td>2.9</td>
</tr>
<tr>
<td>SENSOR, TEMP.</td>
<td>2</td>
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**COMPONENT SUB-TOTAL**                         | 30.3      | 66.8          |
**PACKAGING (INCLUDES HARNESSES)**              | 19.3      | 42.6          |
**TOTAL WEIGHT (DRY)**                          | 49.6      | 109.4         |

* BETWEEN SUBSYSTEM PACKAGE, DRIVER BOX & CONTROLLER (TIMES)
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A platinum resistance temperature (PRT) sensor is located below the heater rod to indicate when the catalyst and reaction has reached a high or low temperature. Another PRT sensor located on the outside of the reactor underneath the insulation is used to monitor the temperature in the event that the bed temperature becomes too high due to failure to turn off the heaters.

A multi-point temperature sensor probe is included to take a temperature profile of the internal bed at 9 different points along the length. Three thermocouples are also located in the bed next to the outside wall.

The unit is of all stainless steel construction welded and bolted together with an aluminum perforated sheet outside shell for handling and touch temperature protection.

The catalyst bed is enclosed in a stainless steel tube with a welded cap on the inlet end with an opening for the reactant gas and the heater elements. The heater elements are enclosed in close fitting sheath for good heat transfer into the primary zone of the catalyst bed. The heaters can be removed and/or replaced without disturbing the bed. The exit end is flanged and bolted with provision for preloading the catalyst bed.

The primary zone is insulated with a High Temperature Min K (F 182) blanket. The cooling jacket consists of stainless steel serrated fins wrapped around the bed cylinder for good airflow and heat conduction, covered with a shell of stainless steel.

The unit is three-point mounted with the single point at the bottom mount for axial movement. Figure 14, 15 and 16 show the reactor internal configuration, outside configuration before insulation and heaters are installed and after insulation is installed.

Condenser/Separator: The condenser/seperator shown in Figure 17 is an all stainlesssteel plate and fin heat exchanger. The unit is made up of three adjacent layers. The first layer is a single pass 0.51 cm (0.200) inch) high plate and fin construction with a header on one end for avionics or cabin air flow. The water collection pass is a pin-fin plate that is the cold plate of the system and is on one side of the cold air pass. The top layer or hot pass consists of a stainless steel porous plate that is in contact on one side with the pin fin plate and on the other side with a 4 pass configuration of stainless steel serrated fins separated with stainless steel pass separators. The top plate is a solid stainless steel plate that is brazed to the top unit.
FIGURE 15
REACTOR BEFORE INSULATION INSTALLED
FIGURE 16
REACTOR ASSEMBLY (INSTRUMENTED)
FIGURE 17
CONDENSER/SEPARATOR

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Maintenance of the subsystem was considered in the design and layout of the hardware. No scheduled maintenance is required for any of the items except possibly for the charcoal filter, Item 31, depending on the quality of the inlet gases. All components items are considered line replaceable components and are easily removed as ample access to all items has been provided. Particular attention was made to facilitate removal of the reactor, Figure 18, the combustible gas monitors, Figure 19 and the heaters in the reactors Figure 20. In addition, a bolted flange in the charcoal canister and the Sabatier reactor permits replacing the charcoal or catalyst bed.

A special maintenance checkout mode in the controller logic has been provided which permits the electrical valves to be actuated independently to an open or close position, the pump to be operated, and the accumulator to be filled and emptied without resulting in an automatic system shutdown. The latter permits charging with water and purging of air from the system during initial (first time) start-up of the subsystem. A maintenance diagram can also be displayed which identifies and shows the location of all component items within the subsystem.

An Operating and Maintenance manual SVHSER 7222 provides more details for operating and maintenance of this subsystem.

SUBSYSTEM FABRICATION

Table 7 identifies the principal items in the preprototype Sabatier subsystem and shows whether they are make, buy or GFE items. The Sabatier subsystem package assembly was assembled using 1/4 inch and 1/2 inch stainless steel tubing, as appropriate, and Swagelok or equivalent stainless steel fittings. Components were located to facilitate maintenance, manual positioning and visual monitoring of the valves, to minimize line lengths and crossover points, and to provide all interface connectors on the back side of the package.

SUBSYSTEM TESTING AND RESULTS

The Sabatier test program was conducted in accordance with the Hamilton Standard Test Plan SVHSER 7196 Revision A (Appendix A).

The laboratory test system used for this test program is a Hamilton Standard rig constructed from commercial hardware. This rig permitted testing on a continuous basis over the full range of reactant compositions and flows required to determine the effects of variation in $\text{H}_2/\text{CO}_2$ molar ratios, reactant flow rates, reactant operating pressures and gas cooling flow rates on $\text{H}_2/\text{CO}_2$ conversion efficiencies and reactor temperature profiles.
FIGURE 18
REACTOR INSTALLATION
FIGURE 19
GAS MONITOR INSTALLATION
FIGURE 20
HEATER INSTALLATION
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VA — ITEM 721-005 | CRINCLE, CONTROL | MAKE |
VA — ITEM 801-009 | SAMPLE, PRESSURE PORT | MAKE |
SVSK 96117 | ITEM 51 | DRIVER BOX, SABATIER | MAKE |
Photographs of the test rig are shown in Figures 21 and 22. The facility consists of a reactant and cooling gas conditioning and supply section, the test hardware, product gas metering, product water collection, power supplies, instrumentation and data collection. The display and keyboard is shown in Figure 5.

During all testing a calibrated gas chromatograph shown in Figure 23 was used to record outlet gas composition and to verify inlet conditions when mixed gas flows were used and to verify the certified bottle blend when a new bottle was placed on line.

During all subsystem testing the data was recorded as noted in Table 8. The recording times were dependent on the type of test being conducted. A photograph of the data acquisition unit is shown in Figure 24. During cyclic runs at least one complete "off" and "on" cycle, temperature profiles were recorded every minute and an effluent gas sample was analyzed and plotted out every nine minutes during the on cycle. A typical sample raw data test summary sheet is shown in Figure 25.

Accuracy

All gas flows including CO₂, H₂, and N₂, were measured with Fischer-Porter flow meters calibrated at operating pressures and temperatures. The gas flow meters which were periodically calibrated with a wet test meter were accurate to +1% full scale. All effluent gas flow rates were measured by determining the quantity of flow with a wet test meter for a time interval measured by a stop watch. The accuracy of the product gas volume is +1% of the sample volume.

Pressure gages for the reactant, product, and cooling gases span a range of 0-2.0 atm (0-30 psia) and are capable of reading to 1.7 X 10⁻³ atm (+0.025 psia). All gages were calibrated prior to testing by the Hamilton Standard metrology laboratory.

The test rig permitted the option of humidifying the reactant gases to dewpoints up to room temperature. A Cambridge Systems Model 880 Dewpoint Hygrometer provided a measure of the humidity of the reactant gases prior to entry into the reaction chamber. Dewpoint readings were within +0.055°C (+0.1°F) for the 4.4°C (40°F) to 49°C (120°F) range.
FIGURE 21
TEST RIG - FRONT
FIGURE 23
GAS CHROMATOGRAPH

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FIGURE 24
DATA ACQUISITION UNIT
FIGURE 25
SAMPLE RAW DATA TEST SUMMARY SHEET
53
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<td>x</td>
</tr>
<tr>
<td>GAS COMPOSITION IN</td>
<td>x</td>
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</tr>
<tr>
<td>GAS COMPOSITION OUT</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>WATER OUT</td>
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<tr>
<td>GWP POINT IN</td>
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<td>x</td>
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<tr>
<td>T-REACTION COOLANT OUTLET (2)</td>
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<td>x</td>
</tr>
<tr>
<td>T-AMBIENT</td>
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<td>x</td>
</tr>
<tr>
<td>T-COOLANT OUT, MIXED</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>WATER PRODUCTION RATE</td>
<td>x</td>
<td>x</td>
</tr>
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</table>
The gas sampling system was capable of automatically sampling reactants at the inlet to the reactor, product gases at the outlet of the condenser, and calibration gases. A Hewlett Packard Model 5880A gas chromatograph analyzed for H₂, CO, CO₂, and CH₄. Gas composition together with the time of sample injection were automatically printed. Approximately nine minutes were required to analyze a gas sample. The gas chromatograph was programmed and calibrated to analyze for H₂, CH₄, CO, and CO quantitatively. Product gas accuracies of ±0.1% for H₂, CO₂, and CO and 0.5% CH₄ were obtained with this gas chromatograph unit for the expected partial pressure ranges. Certified premixed reactant blends were used in the test program to insure H₂ and CO₂ reactant gas accuracies of ±0.01%.

All thermocouples used were type K chromel-alumel thermocouples. The temperature readings were accurate to within ±0.5%.

Hydrogen conversion efficiencies for H₂/CO₂ molar ratios < 4.0 were calculated by substituting experimentally measured values into the following equation:

\[
\% \text{ Hydrogen Efficiency} = \frac{R_{H_2 \text{ in}} - x(R_{Tout})}{R_{H_2 \text{ in}}} \times 100
\]

Where
\[
\begin{align*}
x & = \% \text{ H}_2 \text{ in dry product sample} \\
R_{Tout} & = \text{measured dry product flow-out, cc/min} \\
R_{H_2 \text{ in}} & = \text{measured H}_2 \text{ reactant flow cc/min}
\end{align*}
\]

Similarly, carbon dioxide conversion efficiencies for H₂/CO₂ molar ratios >4.0 were calculated by substitution, experimentally measured values into the following equation:

\[
\% \text{ Carbon Dioxide Efficiency} = \frac{R_{CO_2 \text{ in}} - y(R_{Tout})}{R_{CO_2 \text{ in}}} \times 100
\]

Where
\[
\begin{align*}
y & = \% \text{ CO}_2 \text{ in dry product sample} \\
R_{Tout} & = \text{measured dry product flow-out, cc/min} \\
R_{CO_2 \text{ in}} & = \text{measured CO}_2 \text{ reactant flow cc/min}
\end{align*}
\]

The calculated H₂ and CO₂ conversion efficiencies are accurate to within ±0.05%. Table 9 summarizes test data tolerances.
### TABLE 9

**TEST DATA TOLERANCES**

<table>
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<tr>
<th>Item</th>
<th>Tolerance</th>
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<tr>
<td>Product Gas Compositions:</td>
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<tr>
<td>H₂ and CO₂</td>
<td>-0.5% full scale</td>
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<td>CH₄</td>
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<td>Reactant Compositions (Certified Mixtures):</td>
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<td>±1% of sample volume</td>
</tr>
<tr>
<td>Product Liquid Volume</td>
<td>±1% of sample volume</td>
</tr>
<tr>
<td>Temperature</td>
<td>±0.5% of reading</td>
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<tr>
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<tr>
<td>Gas Coolant Flows</td>
<td>±2% full scale</td>
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</table>
Subsystem Changes

During the test program the following subsystem changes were incorporated to improve subsystem operation.

Two orifices, Item 705 around the water pump and Item 704 downstream of the accumulator were installed because the pump emptied the accumulator so fast that a suction pressure was induced across the porous plate resulting in gas breakthrough and the pump becoming gas bound. This resulted in a loss of pumping capacity. The orifices prevent this from happening by permitting water flow around the pump and regulating the rate of water discharge from the accumulator. As a result, extensive pressure drop across the porous plate does not occur.

A check valve Item 42 was installed downstream of the condenser/separator outlet to prevent emptying of the water from the subsystem when it is shut down or when the subsystem is dried out by purging for long periods of time with dry nitrogen. The check valve also permits charging of the downstream lines and accumulator with water to reduce start-up time and, more important, to purge the pump of gas during initial subsystem start-up operations. Subsystem operation on a day-to-day basis after the initial gas purge start-up does not require charging of the subsystem.

Subsystem controller logic was established so that the nitrogen purge valve, Item 306-3, is closed if an excessive pressure (<1.4 atm (6.0 psig)) is sensed upstream of the reactor. This provides overpressure protection in the event the nitrogen supply pressure is too high to be controlled to an acceptable level by the Item 703 orifice. Overpressure protection from the reactant supply is sensed by Item 902-1 pressure sensor which closes Item 306-1 and opens Item 306-2.

Eight sample ports were provided (Item 801 thru 809) to facilitate testing, charging of the subsystem, or to provide instrumentation or sampling ports.

Calibration Curves

Calibration curves for the following items were determined or are provided as noted on the following page:
Accumulator Assembly - Figure 26
Item 61

- This curve is typical, as the original quantity sensor failed due to the use of the wrong test equipment. A calibration curve for the shipment item was not run.

Pressure Transducer - Figure 27
Item 901-1

- This item was converted from an absolute pressure transducer to a gage pressure transducer.

Pressure Transducer - Figure 28
Item 901-2

- This item was converted from an absolute pressure transducer to a gage pressure transducer.

Temperature Sensor - Table 10
Items 902-1, 85-1, 81-1 and 81-2

Combustible Gas Sensor Per SVSK TR 84456
Item 178

Test Time

A total of over 720 hours of test time (versus 324 hours required by the contract) with reactant flow through the reactor was accumulated during this program. Since the catalyst used in the reactor had been previously used for breadboard testing, the catalyst now has over 1000 hours of test time on it. No degradation in performance has been experienced, in fact performance has improved over this time.

Table 11 defines the test time required, the actual test time accumulated, whether certified premixed reactant blend gases were required, and when actual certified premixed reactant blends were used. A check in the later columns indicates that as a minimum, the required test item was accumulated using the certified blend. As can be noted, a good portion of the testing was accomplished using certified blend gases.

When certified gas blends were not used, the gas supply consisted of mixing a shop hydrogen gas supply with a bottled supply of carbon dioxide at 1.7 atm (25 psia) in the proper proportions as measured by calibrated flow meters and verified by the gas chromatograph to obtain the desired molar ratio.
Figure 26
Accumulator Calibration Curve
Figure 27
Sabatier I 902-1 Pressure Transducer Calibration

Rosemount 1331 AA8  S/N 308
HS P/N  SVSK 84522  Ref.
Conversion To Gage Transducer
60
Figure 28
Sabatier I 902-2 Pressure Transducer
Rosemount 1310A8 S/N 309
HS P/N SVSK 84522 Ref.

Pressure (psi)
Output Voltage (VDC)

Before Mod. (ABS)
(Gage)
After Mod.

New Part No. SVSK 101128-2
**TABLE 10**

| T°C | R1/R2 | T°C | R1/R2 | T°C | R1/R2 | T°C | R1/R2 | T°C | R1/R2 | T°C | R1/R2 | T°C | R1/R2 | T°C | R1/R2 |
|-----|--------|-----|--------|-----|--------|-----|--------|-----|--------|-----|--------|-----|--------|-----|--------|-----|--------|
| 0   | 1      | 100 | 1.0245 | 200 | 1.0245 | 300 | 1.0245 | 400 | 1.0245 | 500 | 1.0245 | 600 | 1.0245 | 700 | 1.0245 |
| 1   | 1      | 200 | 1.0245 | 300 | 1.0245 | 400 | 1.0245 | 500 | 1.0245 | 600 | 1.0245 | 700 | 1.0245 | 800 | 1.0245 |

The values of R1/R2 are given at the rate of 0.0245% per °C. If the resistance is low due to welding or dust, the data may not be accurate.
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TABLE 10 (CONTINUED)
## Table 11

### SABATIER TEST LOG

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Test Description</th>
<th>Molar Ratio H₂/CO₂</th>
<th>Test Time Req'd Hrs.</th>
<th>Actual Test Time Hrs.</th>
<th>Certified Premixed Gas Req'd</th>
<th>Test</th>
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| Total    | 238                   | 388.3              |                      |                       |                            |      |
### Table 11 (Continued)  
**SABATIER TEST LOG**

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Test Description</th>
<th>Molar Ratio H₂/CO₂</th>
<th>Test Time Req'd Hrs.</th>
<th>Actual Test Time Hrs.</th>
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<td>113.75</td>
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</table>

* Reactor "On" Time
Cooling Flows

Reactor cooling flow was determined by installing various diameter orifice (Item 701 and 702) sizes in each reactor cooling circuit line until a reasonable reactor temperature profile was obtained. The coolant flow was measured by installing a wet gas meter downstream of each orifice, one leg at a time, and using the cooling fan, Item 46, to draw cooling flow over the reactor. The cooling flows selected at room ambient conditions are:

- Middle section (Item 701) - 3600 cc/min (0.092 cfm)
- End section (Item 702) - 6000 cc/min (0.212 cfm)

The cabin flow at room ambient conditions is 623,000 cc/min (22 cfm).

Power Consumption

The power consumed was measured using the Hamilton Standard Power Supply Rig 135B. Component powers were:

- Fan, Item 46: 53 watts
- Pump, Item 545: 33 watts
- Heater, Item 83: 100 watts (each)

Effects of Pressure

The effects of variation in total pressure on the reactor hydrogen conversion was theoretically and experimentally determined. Equilibrium hydrogen concentrations and the resulting hydrogen conversion efficiencies at 260°C (500°F) for H₂/CO₂ reactant molar ratios varying from 2.0 to 4.0, total pressures of 1 and 1.4 atm (15 and 20 psia), and various inlet dew points (dry, 80°F 80 and 100°F) were calculated as shown in Table 12.

The program, NASA SP-273, was utilized to calculated hydrogen equilibrium compositions at the various operating conditions. The equilibrium composition and temperature of a reacting mixture is obtained by applying a successive approximation procedure to find the simultaneous solution of the standard equations of chemical equilibrium, conservation of (atomic) mass, and conservation of energy for specified values of pressure and either temperature, enthalpy or entropy.
### TABLE 12

**CALCULATED EFFECT OF TOTAL PRESSURE AND DEWPOINT ON CONVERSION EFFICIENCY**

<table>
<thead>
<tr>
<th>(\text{H}_2) Molar Ratio</th>
<th>Equilibrium Temperature °C (°F)</th>
<th>Pressure atm (psia)</th>
<th>Dry</th>
<th>26.7°C (80°F)</th>
<th>38°C (100°F)</th>
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<tbody>
<tr>
<td>2.0</td>
<td>260 (500)</td>
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<td>99.4</td>
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</tr>
<tr>
<td>2.0</td>
<td>260 (500)</td>
<td>1.4 (20)</td>
<td>99.5</td>
<td>99.5</td>
<td>99.5</td>
</tr>
<tr>
<td>2.6</td>
<td>260 (500)</td>
<td>1.0 (15)</td>
<td>99.4</td>
<td>99.4</td>
<td>99.4</td>
</tr>
<tr>
<td>2.6</td>
<td>260 (500)</td>
<td>1.4 (20)</td>
<td>99.5</td>
<td>99.5</td>
<td>99.5</td>
</tr>
<tr>
<td>3.0</td>
<td>260 (500)</td>
<td>1.0 (15)</td>
<td>99.4</td>
<td>99.3</td>
<td>99.3</td>
</tr>
<tr>
<td>3.0</td>
<td>260 (500)</td>
<td>1.4 (20)</td>
<td>99.4</td>
<td>99.4</td>
<td>99.4</td>
</tr>
<tr>
<td>4.0</td>
<td>260 (500)</td>
<td>1.0 (15)</td>
<td>99.0</td>
<td>99.0</td>
<td>99.0</td>
</tr>
<tr>
<td>4.0</td>
<td>260 (500)</td>
<td>1.4 (20)</td>
<td>99.1</td>
<td>99.1</td>
<td>99.1</td>
</tr>
</tbody>
</table>
As indicated by Table 12, increasing the total pressure from 1.0 atm (15 psia) to 1.4 atm (20 psia) results in an increased hydrogen conversion of 0.1%. Table 13 tabulated results of pressure variation from 1.20 to 1.37 atm (19.7 to 17.7 psia). It should be noted that low hydrogen conversions of 99.2% are attributable to catalyst chloride contamination which was subsequently clarified to give conversions of 99.5% for similar operating circumstances. Based on the results of Table 12, it has been experimentally demonstrated that reactor performance is negligibly impacted for a 0.14 atm (2 psia) difference in total reactor pressure.

It should be noted that from a subsystem standpoint there is a minimum level at which the subsystem can be operated with automatic water removal and no resetting of the pressure regulator to operate over the crew loading and molar ratios required. This pressure is 1.2 atm (3 psig) at the 3 man continuous condition with a molar ratio of 2.6. At this setting the operating pressure will vary from 1.26 atm (3.8 psig) to 1.18 atm (2.6 psig) depending on the crew size and molar ratio. Operation below 1.2 atm (3 psig) is marginal and not recommended as it can result in the inability to delivery water automatically which will result in water carryover in the discharge line and a reduced water production rate. The minimal pressure is a function of the pressure drop in the porous plate, the water check valve, the accumulator spring rate, line height, and the pressure regulator tolerance.

The operating pressure can be lowered to approximately 1.1 atm (1.5 to 1.6 psig) by completely bypassing the automatic water removal system. However, since the porous plate requires a driving pressure equivalent to this pressure, operation is considered marginal.

Effect Of Reactant Dew Point

Table 14 tabulates the theoretical H₂ conversion efficiencies for three dewpoints at various operating conditions based on gaseous equilibrium at 260°C (500°F). A negligible decline in H₂ conversion efficiency results from an increase in inlet humidity from a dry condition to a dewpoint of 37.8°C (100°F).

Similarly, the experimental results as shown in Table 12 agree with the theoretical predictions. The H₂ conversion efficiency is within 0.1% for when the inlet humidity is varied from a dry condition to a dewpoint 21.1°C (70°F).
TABLE 13

EFFECT OF PRESSURE ON H₂ CONVERSION

<table>
<thead>
<tr>
<th>Run #</th>
<th>Date</th>
<th>CO₂ Flow</th>
<th>Molar Ratio</th>
<th>Pressure atm (psia)</th>
<th>% H₂ Conversion</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>1/31/80</td>
<td>3 Man Cont.</td>
<td>2.52</td>
<td>1.34 (19.7)</td>
<td>99.2</td>
</tr>
<tr>
<td>4</td>
<td>1/31/80</td>
<td>3 Man Cont.</td>
<td>2.52</td>
<td>1.29 (18.2)</td>
<td>99.2</td>
</tr>
<tr>
<td>5</td>
<td>2/01/80</td>
<td>3 Man Cont.</td>
<td>2.52</td>
<td>1.20 (17.7)</td>
<td>99.2</td>
</tr>
</tbody>
</table>
### TABLE 14

**EFFECT OF REACTANT DEW POINT**

<table>
<thead>
<tr>
<th>Run #</th>
<th>Date</th>
<th>Flow</th>
<th>Molar Ratio</th>
<th>Dew Point</th>
<th>% H₂ Conversion</th>
</tr>
</thead>
<tbody>
<tr>
<td>18</td>
<td>2/12/80</td>
<td>3 Man Cyclic</td>
<td>2.6</td>
<td>dry</td>
<td>99.5</td>
</tr>
<tr>
<td>18</td>
<td>2/20/80</td>
<td>3 Man Cyclic</td>
<td>2.6</td>
<td>21.1 (70)</td>
<td>99.6</td>
</tr>
</tbody>
</table>
Effect Of H₂/CO₂ Molar Ratios - Steadystate

Table 15 summarizes both H₂ and CO₂ steadystate conversion efficiencies for H₂/CO₂ molar ratios varying from 1.8 to 5.0 and CO₂ flows varying from 1 man continuous to 3 man cyclic. As a rule of thumb, H₂ conversion efficiency declines slightly for a given CO₂ flow as the H₂/CO₂ molar ratio is increased from 1.8 to 4.0. Similarly, CO₂ conversion efficiency increases for a given CO₂ flow as the H₂/CO₂ molar ratio is increased from 4.0 to 5.0. It should be noted that tests have demonstrated near complete conversion of the lean component CO₂ when the H₂/CO₂ molar ratio is increased beyond 4.1. The raw data test summary sheets for these cases are contained in Appendix B.

CO₂ Conversion Efficiencies

All testing at a H₂/CO₂ molar ratio of 5.0 resulted in 100% conversion of the CO led in component. A 3 man cyclic flow test, was conducted which varied the H₂/CO₂ ratios from 4.2 to 4.0 in order to determine the presence of CO₂ in the effluent flow. At molar ratios of 4.2 and 4.1 no CO₂ was detected in the outlet flow. CO₂ conversion efficiencies less than 100% were first observed at a molar ratio of 4.06.

Effect Of Air Addition To The Sabatier Reactants

A test was designed and conducted to observe the effects on reactor operation resulting from the addition of 5.1% air to the inlet reactants for 7.5 hours. This test was run at a 3 man continuous flow and a H₂/CO₂ molar ratio of 2.46. Subsequent testing confirmed that no catalyst damaged resulted from this exposure to 1% oxygen.

The reaction between H₂ and O₂ resulted in increased heat generation and a less desirable temperature profile within the bed. As a result, hydrogen conversion efficiency dropped from 99.1% to 98.7% with the 5.1% air addition.

Figure 29 shows a comparison of the temperature profile with and without air addition.
Reactor Bed Temp. Profile
3-Man Continuous Flow
H$_2$/CO$_2$ Molar Ratio 2.46

(o) With 5.1% air - H$_2$ Conversion Efficiency = 98.7
(-) Without Air - H$_2$ Conversion Efficiency = 99.1

Figure 29
Comparison of Reactor Performance
With and Without Air Addition
Table 15

Steady-state Conversion Efficiency Test Results

<table>
<thead>
<tr>
<th>CO₂ Flow</th>
<th>1.8</th>
<th>2.6</th>
<th>3.5</th>
<th>4.0</th>
<th>5.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Man Continuous</td>
<td>99.8</td>
<td>99.8</td>
<td>99.6</td>
<td>99.1</td>
<td>100</td>
</tr>
<tr>
<td>1 Man Cyclic</td>
<td>99.7</td>
<td>99.7</td>
<td>99.2</td>
<td>98.2</td>
<td>100</td>
</tr>
<tr>
<td>2 Man Cyclic</td>
<td>—</td>
<td>99.7</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>3 Man Continuous</td>
<td>99.3</td>
<td>99.6</td>
<td>99.3</td>
<td>99.0</td>
<td>100</td>
</tr>
<tr>
<td>3 Man Cyclic</td>
<td>99.4</td>
<td>99.6</td>
<td>99.3</td>
<td>98.4</td>
<td>100</td>
</tr>
<tr>
<td>10 Man Cyclic</td>
<td>—</td>
<td>97.2</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>
Sabatier Cyclic Operation

Subsystem cyclic tests to simulate light side (55 minutes on) and dark side (39 minutes off) operation were conducted. Nearly all cyclic tests were conducted without use of the TIMES controller. Automatic cycling was accomplished by using a Agastat Programmer which cycled the Item 306-1 valve and the Item 306-2 valve to direct reactant into or around the reactor. Cooling flow was maintained during the whole cycle. Water was removed from the subsystem accumulator by a breadboard controller which emptied the accumulator by starting the pump based on a signal from the quantity sensor Item 876 in the accumulator in the same manner as the TIMES controller. The Sabatier reactor was capable of starting without heater assistance over a range of operating conditions listed in Table 18.

Table 16 summarizes the test results for cyclic operation with a 55 min reactant flow period followed by a no-flow period of 39 min. Improved performance was obtained for the 3-man CO flow conditions after completion of the test program due to removal of the catalyst chlorides from the aft portion of the reactor bed. Thus, it is thus anticipated that conversion efficiencies of the lean component will exceed 99.0% except at the stoichiometric ratio of 4.0 where conversion efficiencies at the higher CO2 flows will be greater than 98.5%.

These tests were conducted without cessation of reactor cooling during the no reactant flow period. However, it is expected that restart of the Sabatier reactor without heater assistance will be marginal for 1 man flows with H2/CO2 molar ratios less than 1.8.

During the no reactant flow period of cyclic operation, it was observed that the reactor pressure decreased to less than ambient in approximately 10 minutes. The pressure decay as shown in Figure 30 results from residual hydrogen reacting with carbon dioxide and the condensation of product water vapor in a locked up volume caused by closing the Item 306-1 valve and the pressure regulator Item 310 acting as a check valve. The reduced pressure tended to suck water (estimated to be approximately 15 ml) from in the condenser back into the reactor discharge line. When the reactant flow was cycled back on, some of the liquid water was expelled through the condenser and into the overload dump line reducing the water production rate. This was particularly noticeable on some of the one man cases. A test run by shutting off the reactant gas supply showed a reduced pressure effect (Figure 30) depending on the volume of the upstream line.

It should be noted that hydrogen within the reactor is essentially consumed after reactor shutdown. Thus, the requirement to purge hydrogen from the reactor by an inert gas is not necessary. All cyclic runs were conducted without purging after flowing reactants through the catalytic bed.
Pressure decay with humidifier overhead volume (gas supply shut off upstream of humidifier unit)

Pressure decay without humidifier overhead volume (gas supply shut off downstream of humidifier unit)

$\text{H}_2/\text{CO}_2$ Molar Ratio = 2.6
3 Man Cyclic Flow
Duty Cycle = 55 Min On & 39 Min Off

Note: Gas supply shut-off to simulate no flow during dark side operation.

Figure 30

Pressure vs. Elapsed Time During Off Cycle Of
*Cyclical Operational Mode
TABLE 16

AVERAGE CONVERSION EFFICIENCY DURING CYCLIC TESTING
(55 MINUTES ON—39 MINUTES OFF)

<table>
<thead>
<tr>
<th>CO₂ Flow</th>
<th>H₂/CO₂ Molar Ratio</th>
<th>1.8</th>
<th>2.6</th>
<th>3.5</th>
<th>4.0</th>
<th>5.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Man</td>
<td>99.6</td>
<td>99.6</td>
<td>99.4</td>
<td>98.6</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>2 Man</td>
<td>—</td>
<td>99.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 Man</td>
<td>99.6 (99.4)</td>
<td>98.8</td>
<td>98.1</td>
<td>97.4</td>
<td>100</td>
<td></td>
</tr>
</tbody>
</table>

( ) — Test results after completion of basic test program and catalyst treatment
### TABLE 17

**CYCLE OPERATING RANGE WITHOUT HEATER ASSISTANCE**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂ Flow</td>
<td>1-10 man</td>
</tr>
<tr>
<td>H₂/CO₂ Molar Ratio</td>
<td>1.8 - 5.0</td>
</tr>
<tr>
<td>Duty Cycle</td>
<td>55 min on/39 min off</td>
</tr>
<tr>
<td>Dew Point</td>
<td>Dry - 21.1°C (70°F)</td>
</tr>
</tbody>
</table>
Water Production

Water production for steadystate operation as a function of reactant flow is quite predictable. Experimentally measured water production was usually <2.5% the calculated value. Water production rates averaged over long periods of time (>2 hrs) were quite predictable. However, water production rates experimentally determined for short periods often varied widely due to operational variations in the water removal system; i.e., air bubbles in the accumulator, variations in accumulator volumes, etc.

Problems in accurate measurement of water production rates for cyclic operation were introduced by the vacuum anomaly discussed in the previous section. The vacuum created in the reactant off flow period of cyclic operation results in water (approximately 15 ml) collecting in the product gas exit lines. Thus the quantity of water as determined by accumulator volume displacement will provide erroneous readings which are greater for the nominal low water production situations; i.e., lower CO₂ flows and H₂/CO₂ molar ratios.

Water Quality

Product water was periodically analyzed for pH conductivity and chloride content. Water quality improved significantly during the course of this program. For example, pH values improved from 2.0-4.0 at the very start of the test to 4.5-6.0, chloride content to levels barely detectable by the sensitive silver nitrate test from readily apparent, and conductivity from 300-500 mhos to 20-30 mhos. The improved water quality was obtained during most of the Sabatier test program.

Subsystem Malfunctions

During the 720 hours of testing some equipment malfunctions occurred. These were:

- Heater, Item 83--This item failed after approximately 600 hours of testing (estimated). Failure was not detected until operation with the controller and display which showed that one heater was not operating at start-up. Start-up times with one heater were slightly longer but just within five minutes so malfunction went undetected earlier. The cause of the malfunction was not determined.

- Reactor overtemperature sensor, Item 85,--This item failed shortly after testing began. Failure was caused by the vendor inadvertently using low temperature lead wires.
Check valve, Item 41—This item periodically tended to stick open apparently due to calcium or dirt deposits on the valve seat. The valve was replaced and filtered water used to charge the subsystem and the problem did not reoccur.

Air in the Item 545 pump—If the pump becomes air bound it will not pump; as a result, the lines must be charged initially with water and the air removed. Once this is done there is no further problem.

Water liquid detector, Item 907—The initial design did not have a sheath on the probes. As a result, moisture wicked up the probe and bridged across to the other probe resulting in a water carryover malfunction indication and an automatic system shutdown. The design was changed per SVSK 101129 and no further problems have been encountered.

Accumulator quantity sensor, Item 876—electrical checkout of the sensor using a conventional voltmeter resulted in burn-out of the control pot. Any electrical checkout of the quantity sensor must be done with a standard high importance digital meter.

Analysis And Correlation Of Test Data

The development Sabatier reactor was extensively tested as discussed above. Data from this testing was examined and used as a basis for the correlation of the Sabatier computer program.

Table 18 shows steadystate conversion efficiencies for actual test results composed to simulated computer model predictions. These test conversion efficiencies were calculated from gas chromatograph readings of outlet gas composition, and from flowrator measurements. The raw data test summary sheets for each test condition appear in Appendix B.
<table>
<thead>
<tr>
<th>Molar Ratio</th>
<th>CO₂ Flow</th>
<th>% H₂ Conversion</th>
<th>% CO₂ Conversion</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1.8</td>
<td>2.6</td>
</tr>
<tr>
<td>1 Man</td>
<td>2.2 lbm/day</td>
<td>99.8</td>
<td>99.8</td>
</tr>
<tr>
<td>Continuous</td>
<td></td>
<td>99.7</td>
<td>99.7</td>
</tr>
<tr>
<td>3 Man</td>
<td>3.74 lbm/day</td>
<td>99.7</td>
<td>99.4</td>
</tr>
<tr>
<td>Cyclic</td>
<td></td>
<td>99.7</td>
<td>98.9</td>
</tr>
<tr>
<td>2 Man</td>
<td>6.6 lbm/day</td>
<td>99.7</td>
<td>99.6</td>
</tr>
<tr>
<td>Continuous</td>
<td></td>
<td>99.7</td>
<td>98.5</td>
</tr>
<tr>
<td>3 Man</td>
<td>11.28 lbm/day</td>
<td>99.4</td>
<td>98.4</td>
</tr>
<tr>
<td>Cyclic</td>
<td></td>
<td>99.8</td>
<td>98.5</td>
</tr>
</tbody>
</table>

**KEY**

- Test Results
- Simulation Results
In addition, catalyst bed temperatures and outlet coolant temperatures were measured. These appear on the data sheets in Appendix B. Measured temperatures at the head of the bed, however, do not reflect actual bed temperatures because of the fin effect of the thermocouple probe. This only affects the first two thermocouples. Also, coolant temperature measurements are inherently low because of thermocouple fin effect, and because the thermocouple is located several inches downstream of the coolant outlet. It is estimated that the low flow temperature reading is approximately 70% of the actual and the high flow temperature reading is 84% of the actual (referenced to ambient). Measured bed temperature profiles are shown for all steadystate cases in Figures 31 to 51. Corrected coolant temperatures are also depicted on these figures.

This test data was used to correlate the Sabatier Thermal Model discussed in the Design section of this report. Simulations of all the tests described above were analyzed using the correlated model, with results appearing in Table 18 and Figures 31 to 51. Simulation reactor temperature profiles reflect the temperature of the thermocouple probe, so they should match the test data. Simulation coolant temperatures indicate actual coolant temperatures so they should be compared to corrected test temperatures.

Simulated steadystate conversion efficiencies agree with test data with deviations of less than 0.1% for most cases. Also, steadystate temperature profiles are in good agreement with test, except for the very end of the bed in the lower flow conditions. This is attributed to condensation in the end of the bed. Coolant and outlet temperatures do not agree very well with test; however, the thermocouple fin effect and location as noted above on these temperature measurements should be sufficient to account for this. Also, the high flow coolant temperature is affected by condensation in the aft portion of the bed.

Table 19 contains a summary of the average conversion efficiencies for actual testing compound to the simulated computer model predictions for the duty cycle of 55 minutes on and 39 minutes off, which simulates normal light side/dark side operation. The improved efficiency values shown in parenthesis were obtained after completion of the test program and after catalyst treatment to remove additional residual chlorides.
<table>
<thead>
<tr>
<th>Conversion Efficiency</th>
<th>Test Data (○)</th>
<th>Simulation (→)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>°C (°F)</td>
<td>°C (°F)</td>
</tr>
<tr>
<td>Low Flow Coolant</td>
<td>84°C (183°F)</td>
<td>102°C (216°F)</td>
</tr>
<tr>
<td>High Flow Coolant</td>
<td>51°C (123°F)</td>
<td>32°C (90°F)</td>
</tr>
</tbody>
</table>

FIGURE 31
SABATIER STEADY STATE BED TEMPERATURES
1 MAN CONTINUOUS
MOLAR RATIO = 1.8
82
FIGURE 32
SABATIER STEADY STATE BED TEMPERATURES
1 MAN CONTINUOUS
MOLAR RATIO = 2.6
<table>
<thead>
<tr>
<th></th>
<th>°C</th>
<th>°F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Flow Coolant</td>
<td>118</td>
<td>245</td>
</tr>
<tr>
<td>High Flow Coolant</td>
<td>73</td>
<td>164</td>
</tr>
<tr>
<td>Conversion Efficiency</td>
<td>99.6</td>
<td>99.3</td>
</tr>
</tbody>
</table>

**FIGURE 33**
SABATIER STEADY STATE BED TEMPERATURES
1 MAN CONTINUOUS
MOLAR RATIO = 2.5
FIGURE 34
SABATIER STEADY STATE BED TEMPERATURES
1 MAN CONTINUOUS
MOLAR RATIO = 4.0
**FIGURE 35**

SABATIER STEADY STATE BED TEMPERATURES

1 MAN CONTINUOUS

MOLAR RATIO = 5.0

---

**Test Data (o) Simulation (—)**

<table>
<thead>
<tr>
<th>Condition</th>
<th>°C</th>
<th>°F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Flow Coolant</td>
<td>136</td>
<td>276</td>
</tr>
<tr>
<td>High Flow Coolant</td>
<td>71</td>
<td>159</td>
</tr>
<tr>
<td>Conversion Efficiency</td>
<td>100</td>
<td></td>
</tr>
</tbody>
</table>

---

**Temperature**

- Insulated: -17.8°C
- First Cooling Jacket: 38°C
- Second Cooling Jacket: 1200°C

---

**Position Along Bed Length**
| Low Flow Coolant | 110°C (230°F) | 102°C (216°F) |
| High Flow Coolant | 66°C (150°F) | 33°C (91°F) |
| Conversion Efficiency | 99.7 | 99.7 |

Test Data (○) Simulation (→)

**Figure 36**

SABATIER STEADY STATE BED TEMPERATURE

1 MAN CYCLIC

MOLAR RATIO = 1.8

87
Test Data (O) Simulation (—)

<table>
<thead>
<tr>
<th></th>
<th>°C (°F)</th>
<th>°C (°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Flow Coolant</td>
<td>136°C (277°F)</td>
<td>147°C (297°F)</td>
</tr>
<tr>
<td>High Flow Coolant</td>
<td>71°C (160°F)</td>
<td>80°C (180°F)</td>
</tr>
<tr>
<td>Conversion Efficiency</td>
<td>99.7</td>
<td>99.4</td>
</tr>
</tbody>
</table>

**FIGURE 37**

SABATIER STEADY STATE BED TEMPERATURES
MAN CYCLIC
MOLAR RATIO = 2.5
<table>
<thead>
<tr>
<th></th>
<th>°C (°F)</th>
<th>°C (°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Flow Coolant</td>
<td>171°C (340°F)</td>
<td>228°C (442°F)</td>
</tr>
<tr>
<td>High Flow Coolant</td>
<td>77°C (170°F)</td>
<td>53°C (128°F)</td>
</tr>
<tr>
<td>Conversion Efficiency</td>
<td>99.1</td>
<td>98.9</td>
</tr>
<tr>
<td>Low Flow Coolant</td>
<td>Test Data (○)</td>
<td>Simulation (—)</td>
</tr>
<tr>
<td>------------------</td>
<td>---------------</td>
<td>----------------</td>
</tr>
<tr>
<td></td>
<td>°C (°F)</td>
<td>°C (°F)</td>
</tr>
<tr>
<td>224°C (436°F)</td>
<td>233°C (452°F)</td>
<td></td>
</tr>
<tr>
<td>High Flow Coolant</td>
<td>80°C (176°F)</td>
<td>54°C (130°F)</td>
</tr>
<tr>
<td>Conversion Efficiency</td>
<td>98.4</td>
<td>99.0</td>
</tr>
</tbody>
</table>

FIGURE 39
SABATIER STEADY STATE BED TEMPERATURES
1 MAN CYCLIC
MOLAR RATIO = 4.0
90
Test Data (○) Simulation (→)

<table>
<thead>
<tr>
<th></th>
<th>°C (°F)</th>
<th>°C (°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Flow Coolant</td>
<td>227°C (441°F)</td>
<td>236°C (456°F)</td>
</tr>
<tr>
<td>High Flow Coolant</td>
<td>82°C (180°F)</td>
<td>60°C (140°F)</td>
</tr>
<tr>
<td>Conversion Efficiency</td>
<td>100</td>
<td>99.8</td>
</tr>
</tbody>
</table>

**FIGURE 40**

SABATIER STEADY STATE BED TEMPERATURES
1 MAN CYCLIC
MOLAR RATIO = 5.0

91
Test Data (o) Simulation (→)
°C (°F)     °C (°F)
Low Flow Coolant 253°C (488°F)  298°C (569°F)
High Flow Coolant 171°C (189°F)  82°C (180°F)
Conversion Efficiency 99.7     99.6

FIGURE 41
SABATIER STEADY STATE BED TEMPERATURES
2 MAN CYCLIC
MOLAR RATIO = 2.6
FIGURE 42
SABATIER STEADY STATE BED TEMPERATURES
3 MAN CONTINUOUS
MOLAR RATIO = 1.8
Test Data (O) Simulation (—)

<table>
<thead>
<tr>
<th></th>
<th>°C (°F)</th>
<th>°C (°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Flow Coolant</td>
<td>232°C (450°F)</td>
<td>267°C (513°F)</td>
</tr>
<tr>
<td>High Flow Coolant</td>
<td>183°C (339°F)</td>
<td>69°C (156°F)</td>
</tr>
<tr>
<td>Conversion Efficiency</td>
<td>99.6</td>
<td>99.5</td>
</tr>
</tbody>
</table>

FIGURE 43
SABATIER STEADY STATE BED TEMPERATURES
3 MAN CONTINUOUS
MOLAR RATIO = 2.6

94
Test Data (o) Simulation (→)°C (°F) °C (°F)
Low Flow Coolant 285°C (545°F) 349°C (660°F)
High Flow Coolant 107°C (224°F) 109°C (229°F)
Conversion Efficiency 99.3 99.5

FIGURE 44
SABATIER STEADY STATE BED TEMPERATURES
3 MAN CONTINUOUS
MOLAR RATIO = 3.5

95
Test Data (O) Simulation (→)

°C (°F)  °C (°F)
Low Flow Coolant 308°C (586°F) 360°C (680°F)
High Flow Coolant 132°C (270°F) 129°C (265°F)
Conversion Efficiency 99.0 99.1

FIGURE 45
SABATIER STEADY STATE BED TEMPERATURES
3 MAN CONTINUOUS
MOLAR RATIO = 4.0

96
Test Data (O) Simulation (—)

<table>
<thead>
<tr>
<th></th>
<th>°C (°F)</th>
<th>°C (°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Flow Coolant</td>
<td>332°C (630°F)</td>
<td>356°C (673°F)</td>
</tr>
<tr>
<td>High Flow Coolant</td>
<td>147°C (296°F)</td>
<td>136°C (277°F)</td>
</tr>
<tr>
<td>Conversion Efficiency</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>

FIGURE 46
SABATIER STEADY STATE BED TEMPERATURES
3 MAN CONTINUOUS
MOLAR RATIO = 5.0

97
Test Data (O) Simulation (→)

<table>
<thead>
<tr>
<th>Temperature °C (°F)</th>
<th>°C (°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Flow Coolant</td>
<td>262°C (503°F)</td>
</tr>
<tr>
<td>High Flow Coolant</td>
<td>100°C (212°F)</td>
</tr>
<tr>
<td>Conversion Efficiency</td>
<td>99.4</td>
</tr>
</tbody>
</table>

FIGURE 47
SABATIER STEADY STATE BED TEMPERATURES
3 MAN CYCLIC
MOALR RATIO = 1.8

98
Test Data (o) Simulation (—)

<table>
<thead>
<tr>
<th></th>
<th>°C (°F)</th>
<th>°C (°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Flow Coolant</td>
<td>303°C (578°F)</td>
<td>378°C (712°F)</td>
</tr>
<tr>
<td>High Flow Coolant</td>
<td>134°C (274°F)</td>
<td>151°C (304°F)</td>
</tr>
<tr>
<td>Conversion Efficiency</td>
<td>99.6</td>
<td>99.7</td>
</tr>
</tbody>
</table>

**FIGURE 48**
SABATIER STEADY STATE BED TEMPERATURES
3 MAN CYCLIC
MOLAR RATIO = 2.6

99
Test Data (○) Simulation (→)

<table>
<thead>
<tr>
<th></th>
<th>°C (°F)</th>
<th>°C (°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Flow Coolant</td>
<td>337°C (638°F)</td>
<td>418°C (784°F)</td>
</tr>
<tr>
<td>High Flow Coolant</td>
<td>191°C (376°F)</td>
<td>236°C (457°F)</td>
</tr>
<tr>
<td>Conversion Efficiency</td>
<td>99.3</td>
<td>99.4</td>
</tr>
</tbody>
</table>

FIGURE 49
SABATIER STEADY STATE BED TEMPERATURES
3 MAN CYCLIC
MOLAR RATIO = 3.5

100
Test Data (o) Simulation (—)

\begin{tabular}{c|c|c}
\hline
& \text{\(^\circ\)C (\(^\circ\)F)} & \text{\(^\circ\)C (\(^\circ\)F)} \\
\hline
Low Flow Coolant & 349\(^\circ\)C (660\(^\circ\)F) & 434\(^\circ\)C (813\(^\circ\)F) \\
High Flow Coolant & 226\(^\circ\)C (438\(^\circ\)F) & 271\(^\circ\)C (520\(^\circ\)F) \\
Conversion Efficiency & 98.6 & 98.5 \\
\hline
\end{tabular}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure50}
\caption{SABATIER STEADY STATE BED TEMPERATURES 3 MAN CYCLIC MOLAR RATIO = 4.0}
\end{figure}
**Test Data (○) Simulation (—)**

<table>
<thead>
<tr>
<th></th>
<th>°C (°F)</th>
<th>°C (°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Flow Coolant</td>
<td>356°C (673°F)</td>
<td>417°C (783°F)</td>
</tr>
<tr>
<td>High Flow Coolant</td>
<td>196°C (384°F)</td>
<td>282°C (540°F)</td>
</tr>
<tr>
<td>Conversion Efficiency</td>
<td>100</td>
<td>99.7</td>
</tr>
</tbody>
</table>

**FIGURE 51**

**SABATIER STEADY STATE BED TEMPERATURES**

3 MAN CYCLIC

MOLAR RATIO = 5.0

102
<table>
<thead>
<tr>
<th>Molar Ratio</th>
<th>CO\textsubscript{2} Flow</th>
<th>% H\textsubscript{2} Conversion</th>
<th>% CO\textsubscript{2} Conversion</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.8</td>
<td>2.6</td>
<td>3.5</td>
</tr>
<tr>
<td>1 Man</td>
<td>Continuous</td>
<td>99.6</td>
<td>99.6</td>
</tr>
<tr>
<td></td>
<td>2.2 lbm/day</td>
<td>99.5</td>
<td>99.5</td>
</tr>
<tr>
<td>2 Man</td>
<td>Cyclic</td>
<td>99.6</td>
<td>99.5</td>
</tr>
<tr>
<td></td>
<td>7.48 lbm/day</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 Man</td>
<td>Continuous</td>
<td>99.6</td>
<td>98.8</td>
</tr>
<tr>
<td></td>
<td>6.6 lbm/day</td>
<td>*(99.4)</td>
<td>*(98.8)</td>
</tr>
</tbody>
</table>

*Value obtained after completion of test program. Improved performance attributable to catalyst treatment to remove additional residual catalyst chlorides. It is expected that current performance for all points will be due to predicted values for all points.

**KEY**
- Test Results
- Simulation Results
Bed temperature profiles at the end of the shutdown and 25 minutes into the warm-up are shown in Figures 52 to 63 for several transient cases. Also, conversion efficiencies as a function of time into warm-up are presented for these runs. Note that for the 2 and 3 man cases a large dip in performance occurs about 25 minutes into the warm-up. The cause of the reduced performance can be seen by superimposing the steady-state profile over the profile at 25 minutes into warm-up (Figures 67 to 69). In the profiles at 25 minutes, the transition from the hot to cold section of the bed is much faster, so that gas residence time in the 260-316°C (500-600°F) area, where final scrubbing occurs, is short. Also notice that some sections of the bed are warmer at 25 minutes than in steady-state, contributing to the steeper profile.

Transient cool down computer simulation shows good agreement with test data as can be seen in plots of reactor profiles at the end of the cool down period (Figures 52, 55, 58, and 61). However, warm-up is not as well correlated with test as is seen in reactor temperature profiles and conversion efficiency plots (Figures 33, 56, 59, and 62). This discrepancy is due to the warm-up anomaly mentioned above.
FIGURE 52
SABATIER TRANSIENT BED TEMPERATURES
1 MAN CYCLIC
MOLAR RATIO = 1.8

Time Into Warmup = 0.0

(0) Test Data
(→) Simulation

Position Along Bed Length

Temperature °C

649
593
538
482
427
371
316
260
204
149
93
38
-17.8

0 3 6 9 12 15
Insulated First Cooling Jacket Second Cooling Jacket
Time Into Warmup = 27

(o) Test Data
(—) Simulation

FIGURE 53
SABATIER TRANSIENT BED TEMPERATURES
1 MAN CYCLIC
MOLAR RATIO = 1.8

Position Along Bed Length

Insulated | First Cooling Jacket | Second Cooling Jacket
FIGURE 54
SABATIER WARM UP CONVERSION EFFICIENCY HISTORY
1 MAN CYCLIC
MOLAR RATIO = 1.8
Time Into Warmup = 0.0

(○) Test Data
(—) Simulation

FIGURE 55
SABATIER TRANSIENT BED TEMPERATURES
2 MAN CYCLIC
MOLAR RATIO = 2.6
Time Into Warmup = 27.0

Test Data
Simulation

FIGURE 56
SABATIER TRANSIENT BED TEMPERATURES
2 MAN CYCLIC
MOLAR RATIO = 2.6

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FIGURE 57
SABATIER WARM UP CONVERSION EFFICIENCY HISTORY
2 MAN CYCLIC
MOLAR RATIO = 2.6
FIGURE 58
SABATIER TRANSIENT BED TEMPERATURES
MAN CYCLIC
MOLAR RATIO = 2.6
Time Into Warmup = 24.0

(○) Test Data
(—) Simulation

FIGURE 59
SABATIER TRANSIENT BED TEMPERATURES
3 MAN CYCLIC
MOLAR RATIO = 2.6
FIGURE 60
SABATIER WARM UP CONVERSION EFFICIENCY HISTORY
3 MAN CYCLIC
MOLAR RATIO = 2.6
Time Into Warmup = 0.0

(C) Test Data
(—) Simulation

Insulated Jacket, First Cooling Jacket, Second Cooling Jacket

Position Along Bed Length

FIGURE 61
SABATIER TRANSIENT BED TEMPERATURES
3 MAN CYCLIC
MOLAR RATIO = 4.0
Time Into Warmup = 25.0

FIGURE 62
SABATIER TRANSIENT BED TEMPERATURES
3 MAN CYCLIC
MOLAR RATIO = 4.0
FIGURE 63
SABATIER WARM UP CONVERSION EFFICIENCY HISTORY
3 MAN CYCLIC
MOLAR RATIO = 4.0
FIGURE 64
SABATIER WARM UP CONVERSION EFFICIENCY HISTORY
1 MAN CYCLIC
MOLAR RATIO = 2.6
FIGURE 65
SABATIER WARM UP CONVERSION EFFICIENCY HISTORY
1 MAN CYCLIC
MOLAR RATIO = 3.5
FIGURE 66
SABATIER WARM UP CONVERSION EFFICIENCY HISTORY
MAN CYCLIC
MOLAR RATIO = 3.5
Time Into Warmup = 27.0

(o) Test Data
(-) Simulation

FIGURE 67
SABATIER COMPARISON OF STEADY STATE AND TRANSIENT BED TEMPERATURES
2 MAN CYCLIC
MOLAR RATIO = 2.6
SABATIER COMPARISON OF STEADY STATE AND TRANSIENT BED TEMPERATURES
3 MAN CYCLIC MOLAR RATIO = 2.6
FIGURE 69
SABATIER COMPARISON OF STEADY STATE AND TRANSIENT BED TEMPERATURES
3 MAN CYCLIC
MOLAR RATIO = 4.0
SUBSYSTEM DELIVERY

The following hardware was shipped under this contract to NASA/JSC.

Sabatier Package Assembly        SVSK 96500
Sabatier Driver Box              SVSK 97813
Connectors, Electrical (1 each)
  >901 - PT06A-12-105
  >700 - PT06A-12-105
  >701 - PT06A-8-4S
  Mating miniature thermocouple connectors (11) (Item 86)

Prior to delivery of this hardware, the Sabatier Package Assembly was refurbished. This consisted of:

- Replacing heater, SVSK 96486 (Item 83)
- Replacing overtemperature probe SVSK 96465 (item 85)
- Catalyst treatment, to remove additional residual chlorides
- Installation of name tags and component item numbers
- Tie down of electrical leads and harnesses.

Reactor cooling air temperature sensors, Items 87-1 and 87-2, although not on the subsystem parts list, were left installed in order to facilitate testing at NASA/JSC.

After refurbishment the subsystem was setup and tested to verify proper function and performance and various failure modes. Performance was improved as discussed previously. Water was drained and then the subsystem purged for 24 hours with dry nitrogen. Inlet and outlet ports were capped and double bagged and the unit delivered to the shipping department where it was crated and subsequently delivered to NASA/JSC by a North American air ride van.
COORDINATION WITH RLSE

The Sabatier CO₂ Reduction Subsystem schematic is shown in Figure 1. The subsystem closely matches the RLSE program Sabatier CO₂ Reduction Subsystem and provides the same interfaces, functions, and internal componentry to be fully compatible with the overall RLSE System requirements. The Sabatier package assembly, driver box, and TIMES controller will fit into the space provided in the NASA/JSC Advanced ECS laboratory. The TIMES controller and display is installed in a standard NASA supplied electronic rack for use in the NASA laboratory. Ten meters of leads wire is provided by the TIMES program to permit this remote location. A lead (10 meters long) for an external remote discrete shutdown switch was also provided as part of the Sabatier subsystem harness.

Interfaces for the Sabatier subsystem are as defined in NASA’s RLSE study. A mixture of hydrogen and carbon dioxide is received from the EDC. A charcoal bed in the Sabatier subsystem will protect the Sabatier reactor if there are trace amounts of contaminant carryover from the EDC or WVE. CO₂ concentrator pressure is controlled to 1.2 atms (3.5 psig) by pressure regulators contained within the Sabatier reactor system. If the primary regulator fails closed, a bypass valve (Item 306-2) will be automatically activated diverting flow to a bypass regulator thus protecting upstream equipment.

A pump is provided to deliver water to the water management system at 2 atms (30 psia) which is the upper pressure limit defined by RLSE. The preprototype unit has its own cooling fan, however, the air cooling jacket at the reactor is designed to operate at low flow with the pressure drop available from normal Spacelab rack cooling air. Air cooling is used to simplify integration of the subsystem, consistent with RLSE guidelines.

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DOCUMENTATION

Table 20 defines the contract documentation required and the documents submitted in response to the data requirements for this program test by Hamilton Standard.
<table>
<thead>
<tr>
<th>DRL Item No.</th>
<th>Name</th>
<th>Document</th>
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<tbody>
<tr>
<td>1</td>
<td>Report, Monthly Progress</td>
<td>Submitted Monthly</td>
</tr>
<tr>
<td>2</td>
<td>Program Plan</td>
<td>Sabatier-04 dated June 13, 1978</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sabatier-10 dated August 18, 1978</td>
</tr>
<tr>
<td>3</td>
<td>Plan, Master Test</td>
<td>Sabatier-EM-13 dated January 12, 1979</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SVHSER 7196</td>
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<tr>
<td>4</td>
<td>Report Final</td>
<td>Sabatier-EM-21 dated August 1980</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SVHSER 7221</td>
</tr>
<tr>
<td>5</td>
<td>Technical Information Release</td>
<td>Submitted Quarterly - (No items were reported)</td>
</tr>
<tr>
<td>6</td>
<td>Report Financial Management</td>
<td>Submitted Monthly</td>
</tr>
<tr>
<td>7</td>
<td>Drawings, Engineering and</td>
<td>Sabatier-72 dated July 17, 1980</td>
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<tr>
<td></td>
<td>Associated Lists</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Manual, Familiarization and</td>
<td>Sabatier-</td>
</tr>
<tr>
<td></td>
<td>Operation</td>
<td>SVHSER 7222</td>
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<tr>
<td>9</td>
<td>FMEA</td>
<td>Sabatier-EM-19 dated June 22, 1980</td>
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<tr>
<td>10</td>
<td>Manual, Maintenance and Repair</td>
<td>Combined with DRL Item No. 8</td>
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<tr>
<td>11</td>
<td>Lists, Nonmetallic Materials</td>
<td>Sabatier-EM-03 dated October 20, 1978</td>
</tr>
</tbody>
</table>
SUPPORT REQUIREMENTS

Below is a list of Government Furnished Property (GFP) made available by the NASA/JSC in support of this contract. Items not used were returned to the Government after the preprototype Sabatier subsystem was shipped.

<table>
<thead>
<tr>
<th>Quantity Supplied</th>
<th>Delivered With Subsystem</th>
<th>Description</th>
</tr>
</thead>
</table>
| 5                 | 4                        | SSP Item 178 Combustible Gas Sensor  
SVSK 84456-100 Sensing Assy.  
SVSK 84456-200 Monitor Assy.  
With Elec Harness |
| 6                 | 5                        | SSP Item 306 Valve, Elec Shutoff, Manual Override  
SVSK 84424-100  
With Elec Harness |
| 1                 | -                        | SSP Item 368 Backpressure Regulator Valve  
SVSK 84519 |
| 5                 | 4*                       | SSP Item 507 Manual Shutoff Valve  
SVSK 84530-1 |
| 1                 | 1                        | SSP Item 545 Water Pump  
SVSK 96329-2 |
| 2                 | 2*                       | SSP Item 902 Pressure Transducer  
SVSK 86339-3 (Ref:  
SVSK 84522-3)  
With Elec Harness |
| 2                 | -                        | SSP Item 907 Water Detector Sensor  
SVSK 86587  
With Elec Harness |
| 1                 | 1*                       | Space Shuttle Assembly  
Accumulator Assy.  
SV755518-1  
With Spare Parts |

*Items modified for use in Sabatier subsystem
QUALITY ASSURANCE

The objective of the Quality Assurance Program was to search out quality weakness and provide appropriate corrective actions. Quality assurance considerations were included during the CO₂ Reduction Subsystem Design, engineering evaluations, procurement and fabrication activities. All vendor-supplied items were checked out and inspected per engineering instructions prior to assembly into the subsystem. Prior to delivery of the hardware, a First Article System Inspection (FASI) was held. The review committee consisted of senior engineering, reliability and quality personnel. Only minor quality deficiencies consisting mostly of electrical wiring harness locations were identified and required corrections.
RELIABILITY

The CO Reduction Subsystem, as concepted, has a high inherent reliability. The Sabatier reactor and the water separator are passive devices. In the flight configuration, cooling is provided by a constant supply of avionics cooling air flow. The addition of a charcoal filter in the process line minimizes the sensitivity of the reactor to upsets in upstream subsystems.

The water quantity measurement and delivery equipment consists of a pump and a calibrated accumulator. The cyclic operative of the accumulator is estimated at 1500 cycles per month. This results in a pump on-time of only 25-50 hours. At this low usage rate, this equipment would not be considered limited life.

The backpressure regulator is backed up by an in-line shutoff valve which provides isolation, and automatic switchover to a second regulator. The automatic switchover function, activated by an inlet pressure sensor, permits uninterrupted operation and venting of upstream subsystems.

Equipment safety is enhanced through design simplification, and automatic failure detection and shutdown. All components which contain H₂ or CH₄ are of a welded construction and incorporate static seals. Safety critical parameters, such as pressure, temperature, and external gas leakage, have redundant sensing and shutdown capability.

The Failure Mode and Effects Analysis (FMEA) completed as a part of this program is contained in Appendix C of this report.
SAFETY

Safety was a prime consideration in design of the CO₂ Reduction Subsystem because of the presence of hydrogen gas in the subsystem. During the design of the subsystem safety was enhanced by incorporating the following safety features in the hardware and/or subsystem:

1. Utilization of a catalyst that has a low start temperature and a reaction that is temperature limited regardless of flow.

2. Incorporates a dedicated overtemperature sensor to initiate automatic subsystem shutdown.

3. A single failure in one component will not cause successive failures in other components.

4. All manual valves and manual overrides in electrical valves are readily accessible from the front face of the subsystem.

5. The controller provides automatic hands-off operation and automatically purges with nitrogen the subsystem during any shutdown.

6. A visual and audio alarm is provided during any abnormal condition.

7. Four combustible gas detectors are provided in the subsystem.

8. All interfaces and connectors are clearly labeled.

9. Circuit breakers are incorporated to protect electrical equipment.

10. In all connectors, the hot connector is a female socket.

11. Overpressure of the subsystem is presented by design (reactor is sent straight through tube design), by a flow limiting orifice in the nitrogen line, by pressure regulators, and pressure sensors which will signal the controller to bypass inlet flow or shutoff nitrogen flow if the pressure level exceeds a predetermined value.
APPENDIX A
HAMLET STANDBD

DIVISION OF UNITED TECHNOLOGIES CORPORATION

JANUARY, 1979.

MASTER TEST P. 11

FOR

PREPROTOTYPE SABATIER SUBSYSTEM

CONTRACT NAS 9-15470

PREPARED BY: 

VINCENT A. CELINO
PROJECT ENGINEER

APPROVED BY: 

HARLAN F. BROSE
PROGRAM MANAGER

*REVISED JANUARY, 1980
1.0 INTRODUCTION

Testing for the Preprototype Sabatier Subsystem shall be performed at the component and subsystem levels. Each component shall be tested as described herein to assure critical performance and operational characteristics as required prior to subsystem testing. Subsystem level testing shall be performed to verify subsystem design features, startup and shutdown characteristics, operating pressure level capabilities, failure mode characteristics and parametric Sabatier Reactor and subsystem performance under steady state, cyclic and transient conditions.

Tables I and II show the specific component tests to be run; Tables III and IV show specific subsystem tests to be run.

2.0 TEST DESCRIPTIONS

2.1 Examination of Product - Each specified component in Table I shall be examined to determine that the material and workmanship requirements have been met and that all external devices such as flanges, mounting provisions, and connector locations are as specified.

2.2 Base Point Calibration - Each specified component will be operated to demonstrate that the unit meets specified functional and baseline performance requirements, including startup and shutdown.

2.3 Proof Pressure - A proof pressure test will be conducted on fluid system pressure carrying components and assemblies. The pressure will be 1.5 times maximum operating pressure and will be held for a period of five minutes at room temperature. At the conclusion of the proof pressure test, the components will be examined to verify that no damage or permanent deformation has occurred.

2.4 Leakage - Fluid system components will be subjected to an external and an internal leakage test, as applicable.

2.5 Performance - Each component shall be subjected to a performance test except where a base point calibration is sufficient prior to subsystem testing. Performance tests are categorized in four ways:

2.5.1 Operational Check - This test demonstrates that the component operates when it is subjected to the appropriate stimuli. This test is primarily for commercially available components.

2.5.2 Performance Map - These are more extensive tests to be conducted on the reactor and condenser in the subsystem. These tests are described in more detail in Section 4.0.
<table>
<thead>
<tr>
<th>ITEM NO.</th>
<th>DESCRIPTION</th>
<th>P/N</th>
<th>EOP</th>
<th>BASE POINT</th>
<th>PROOF PRESS</th>
<th>LEAKAGE</th>
<th>PERFORM</th>
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<tbody>
<tr>
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<td>SILENCER</td>
<td>SVSK96471-1</td>
<td>X</td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
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<tr>
<td>31</td>
<td>CHARCOAL CANISTER</td>
<td>SVSK96470-1</td>
<td>X</td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>41</td>
<td>CHECK VALVE</td>
<td>SVSK96466-1</td>
<td>X</td>
<td></td>
<td></td>
<td>X</td>
<td>OP</td>
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<td>42</td>
<td>CHECK VALVE</td>
<td>SVSK101124</td>
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<tr>
<td>46</td>
<td>FAN</td>
<td>SVSK96462-1</td>
<td>X</td>
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<td>OP</td>
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<td>51</td>
<td>CONDENSER/SEP</td>
<td>SVSK96349-1</td>
<td>X</td>
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<td>ACCUMULATOR</td>
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<td>71</td>
<td>DRIVER BOX</td>
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<td>81</td>
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<td>X</td>
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<tr>
<td>82</td>
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<td>X</td>
<td></td>
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<tr>
<td>83</td>
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<td>SVSK96486-1</td>
<td>X</td>
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<td>X</td>
<td>X</td>
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<tr>
<td>178</td>
<td>COMB GAS DETECTOR</td>
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<td>306</td>
<td>ELEC S.O. VALVE</td>
<td>SVSK84424-100</td>
<td>X</td>
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<tr>
<td>310</td>
<td>BACK PRESS. REG</td>
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<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
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<tr>
<td>507</td>
<td>MAN S.O. VALVE</td>
<td>SVSK84530-1</td>
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<td>X</td>
<td></td>
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<td>X</td>
<td>X</td>
<td>X</td>
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<td>SV764179-1</td>
<td>X</td>
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<td>X</td>
<td></td>
<td></td>
<td>X</td>
<td>CAL</td>
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<tr>
<td>907</td>
<td>LIQUID WATER DETECTOR</td>
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<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
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<td>259</td>
<td>ACCUMULATOR</td>
<td>SVSK96492*</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
</tbody>
</table>

**CODE:**
- OP - OPERATIONAL CHECK
- MAP - PERFORM MAP
- CAL - CALIBRATION OVER RANGE
- ACCEPT - ACCEPTANCE TEST

*REFERENCE SABATIER PACK*
**SUMMARY**

<table>
<thead>
<tr>
<th>LEAKAGE</th>
<th>PERFORM</th>
<th>POWER CONSUMPT</th>
<th>CONTINUITY</th>
<th>ENDUR</th>
<th>FAIL MODE CHECKOUT</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>OP</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>X</td>
<td>OP</td>
<td></td>
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</tr>
<tr>
<td>X</td>
<td>CAL</td>
<td></td>
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<td></td>
<td></td>
</tr>
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<td>X</td>
<td>CAL</td>
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<tr>
<td>X</td>
<td>CAL</td>
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<tr>
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<td>CAL</td>
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<td></td>
</tr>
<tr>
<td>X</td>
<td>CAL</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>OP</td>
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<td>X</td>
<td>CAL</td>
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</tr>
<tr>
<td>X</td>
<td>MAP</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**FOLDOUT FRAME**

2
2.5.3 Calibration - Components as indicated in Table I shall be calibrated over the operational range. These components are limited to those generating signals for use in the controller.

2.5.4 Acceptance Tests - This is a series of tests to be conducted at the subsystem level and are described in more detail in Section 5.0.

2.6 Power Consumption - Electrically operated items will be cycled and the power consumption measured.

2.7 Continuity - All specified electrical components will be examined to assure proper wiring.

2.8 Endurance Testing - Shall be performed as part of subsystem tests. These tests are described in Section 5.0.

2.9 Failure Mode Identification - The principal failure modes for each component or assembly will be identified and the effect determined. Identification of safety hazards will also be noted. These tests shall be conducted on the controller and the subsystem.

3.0 LABORATORY TEST SYSTEM SCHEMATICS

The tests indicated in Table II will be run with the test rig shown in Figure 1. The effects of variation in total pressure and air cooling flow rates on \( \text{H}_2/\text{CO}_2 \) conversion will be determined with this setup. These tests will establish the cooling flow rate to be used for all subsequent reactant process rates.

Figure 2 shows the flow schematic to be employed for measuring Sabatier reactor cooling flow. The existing test rig will be modified to accommodate integrated subsystem testing.

Test equipment shall permit testing on a continuous basis over the full range of reactant compositions and flows currently anticipated in order to determine the effects of variation in \( \text{H}_2/\text{CO}_2 \) molar ratios, reactant flow rates, reactant operating pressures and gas cooling flow rates on \( \text{H}_2/\text{CO}_2 \) conversion efficiencies and reactor temperature profiles.

3.1 Reactant Gas Supplies - Certified premixed reactant blends shall be used for test points 1 through 10 in Table II and for test points 12, 15, 17, 21, 24 and 27 in Table III. The premixed reactant flowmeter shall be calibrated with the reactant mix. at the flowmeter pressure to be used during test. The reactant mixtures for the remaining test points in Tables III and IV shall be established by metering hydrogen and carbon dioxide individually and mixing them.
### TABLE II

**SABATIER REACTOR AND CONDENSER/SEPARATOR**

**COMPONENT TESTS**

<table>
<thead>
<tr>
<th>H₂/CO₂ MOLAR RATIO</th>
<th>1.8</th>
<th>NOMINAL FLOW 2.6</th>
<th>5.0</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TEST # FLOW ON (HRS)</td>
<td>TEST # FLOW ON (HRS)</td>
<td>TEST # FLOW ON (HRS)</td>
</tr>
<tr>
<td>CO₂ MAN FLOW</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>7</td>
<td>2</td>
<td>9</td>
</tr>
<tr>
<td>3</td>
<td>(2) 1</td>
<td>2</td>
<td>(2) 2</td>
</tr>
<tr>
<td>3</td>
<td>(2) 3</td>
<td>2</td>
<td>(2) 3</td>
</tr>
<tr>
<td>(1) 3 CYCLIC</td>
<td>8</td>
<td>2</td>
<td>(3) 4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(3) 5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(3) 6</td>
</tr>
<tr>
<td>TOTAL HOURS</td>
<td>4</td>
<td>+</td>
<td>12</td>
</tr>
</tbody>
</table>

20 hrs total

(1) Flow is 1.71 times steady state flow

(2) Tests 1, 2 and 3 establish effect of air cooling flows thereby permitting selection of constant air cooling flow for all process reactant flows.

(3) Tests 4, 5, and 6 determine effect of reactor pressure on H₂ conversion efficiency.
3.2 Laboratory Gas Analysis - Product gas mixture analysis shall be determined by gas chromatographic tests. Accuracies shall be as follows:

<table>
<thead>
<tr>
<th>Concentration</th>
<th>Range</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂</td>
<td>0 - 5%</td>
<td>± 0.1%</td>
</tr>
<tr>
<td>CO₂</td>
<td>0 - 5%</td>
<td>± 0.1%</td>
</tr>
<tr>
<td>CH₄</td>
<td>0 - 25%</td>
<td>± 0.5%</td>
</tr>
</tbody>
</table>

4.0 SABATIER REACTOR AND CONDENSER/SEPARATOR TESTS

The test sequence in Table II shall be performed on the Reactor-Condenser group in the rig setup shown in Figure 1. Reactor coolant air flows shall be measured as shown in Figure 2.

5.0 SUBSYSTEM TESTING

Subsequent to component testing, the subsystem shall be operated at baseline conditions both at the beginning and at the end of the test program to determine the effect of operating time on system performance. The contractor shall demonstrate the Sabatier subsystem capability of satisfying an off-nominal requirement by operating at the one-man rate for two days. A 120 hour continuous endurance test shall also be conducted. System power and H₂/CO₂ conversion efficiency shall be recorded during this operation. An acceptance test shall then be conducted and witnessed by the NASA technical monitor. This testing shall include a subsystem shutdown after the off-nominal operation and system startup and operation at baseline conditions. Cyclic operational performance shall also be demonstrated. The parametric tests shall include conditions comparable to 1, 2, and 3 man loadings. In addition, off-design testing shall be conducted which exhibits H₂ conversion efficiencies of approximately 90% and 80%.

The subsystem test program shall be conducted as shown in Figure 1 and shall include a minimum of 304 hours of reactant flow in the conduct of parametric, endurance, and acceptance testing as defined in Tables III and IV.

6.0 TEST REPORTS

The data from each test will be recorded on Hamilton Standard Log Sheets. This data will consist of the rig operational parameters as well as the results of gas, chemical and physical analysis performed. The performance data calculated from each test will be plotted and compared with performance predicted by computer models. A test report shall be prepared and included in the final report.
*TEST ONE LEG AT A TIME

FIGURE 2
REACTOR COOLING AIR FLOW TEST SETUP
<table>
<thead>
<tr>
<th>${\text{H}_2/\text{CO}_2}$ Molar Ratio</th>
<th>1.0</th>
<th>2.6</th>
<th>3.5</th>
<th>4.0</th>
<th>5.0</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CO}_2 Man Flow</strong></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>11 2 (P)</td>
<td>14 50 (E)</td>
<td>20 2 (P)</td>
<td>23 2 (P)</td>
<td>26 2 (P)</td>
</tr>
<tr>
<td>3</td>
<td>12 2 (P)</td>
<td>(4) 15 8 (A)</td>
<td>21 2 (P)</td>
<td>24 2 (P)</td>
<td>27 2 (P)</td>
</tr>
</tbody>
</table>

| **(2) 3 Cyclic** | | | | | |
| 13 2 (P) | 18 10 (P) | 22 2 (P) | 25 2 (P) | 28 2 (P) |

| **(3) 10** | | | | | |
| 19 10 (P) | | | | | |

| TOTAL HOURS | 6 | + | 206 | + | 6 |

(1) - All runs @ constant air cooling flow and reactor pressure determined in Table II

(2) - Flow is 1.71 times steady state flow

(3) - High bed loading run to satisfy 80-90% $\text{H}_2$ conversion efficiency requirement

(4) - Acceptance (Baseline) Test

A = Acceptance Testing

F = Endurance Testing

P = Parametric Testing
<table>
<thead>
<tr>
<th>$\text{H}_2/\text{CO}_2$ Molar Ratio</th>
<th>1.8</th>
<th>2.6</th>
<th>3.5</th>
<th>4.0</th>
<th>5.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>TEST NO.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FLOW ON (HRS)</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NOMINAL FLOW</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TEST NO.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FLOW ON (HRS)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 CYCLIC CO$_2$ MAN FLOW</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>29</td>
<td>4 (P)</td>
<td>31</td>
<td>20 (E)</td>
<td>34</td>
</tr>
<tr>
<td>2</td>
<td>32</td>
<td>10 (E)</td>
<td>+</td>
<td></td>
<td>+</td>
</tr>
<tr>
<td>3</td>
<td>30</td>
<td>4 (P)</td>
<td>33</td>
<td>20 (E)</td>
<td>35</td>
</tr>
<tr>
<td>TOTAL HOURS</td>
<td>8</td>
<td>50</td>
<td>+</td>
<td>4</td>
<td>+</td>
</tr>
</tbody>
</table>

(1) - All runs at constant air cooling flow and reactor pressure determined in Table I.

(2) - Flow is 1.71 times steady state value.

P = Parametric Testing
E = Endurance Testing
DATE: 3-7-10
RUN No. 9
TEST No. 7

SABATIER
1 MAN CONT.
M.R. 1.8

16.4 PSI
0.038 CFM

85°F

0.092 CFM

157°F

0.212 CFM

124°F

78°F

553°F CONTROL
597 568 323 193 174 158 133 102 °F

499 252 178 °F

--- °F Overtemp

G.C. RUN No. 7C
H2 32
CH4 44.77
CO2 53.72

\[ \varepsilon = 99.8 \]

* AT ROOM TEMP
** RUN ONLY 2.5 HOURS
** DUMPS PVC CUMULATOR DID NOT
DATE: 3-7-80
RUN No. 4
TEST No. 12

SABATIER

3 MAN CONT.

M.R. I.D

17.5 PSIA

113 CFM

153°F

.092* CFM

269°F

.212* CFM

147°F

5/6 ml/hr

79°F

0.36 CFM

73°F

75°F

77°F

866°F CONTROL

761 423 702 371 232 185 163 181°F

834 543 250 °F

°F OVERTEMP

G.C. RUN No. 4A

H2 1.34

CH4 43.91

CO2 53.73

\[ \varepsilon = 99.3 \]

*AT ROOM TEMP.
SABATIER

1 MAN CONT.

M.R. 2.6

17.4 psia

0.049 CFM

83°F

77°F

0.092 CFM

160°F

129°F

19.2 ml/hr

73°F

105°F

193 187 169 163

598°F CONTROL

641 615 544 183 187 173 169 105°F

544 284 180 °F

°F OVERTEMP

G.C. RUN NO. 8

H₂ .44

CH₄ 62.75

CO₂ 36.63

ζ = 99.8

* AT ROOM TEMP.
SABATIER

3 MAN CONT.

M.R. 2.60

17.7 PSIA

.145 CFM

168°F

77°F

.092 CFM

.218 CFM

342°F

157°F

62 ml/hr

73°F

85°F

946°F CONTROL

848 961 455 582 330 209 192 192 °F

425 704 391 °F

°F OVERTEMP

G.C. RUN NO. 22

H₂ 1.02

CH₄ 64.93

CO₂ 34.02

E = 99.6

* AT ROOM TEMP.
DATE: 3-25-80
RUN No. 9
TEST No. 20

SABATIER
1 MAN CONT.
M.R. 35

ORIGINAL PAGE IS
OF POOR QUALITY
DATE: 3-24-80
RUN No. 11
TEST No. 21

SABATIER
3 MAN CONT.
M.R. 3.5

17.9 PSIA
\[ \frac{0.181 \text{ CFM}}{184^\circ F} \]
\[ \frac{0.092 \text{ CFM}}{410^\circ F} \]
\[ \frac{0.212 \text{ CFM}}{201^\circ F} \]
\[ \frac{81 \text{ ml/h}}{79^\circ F} \]
\[ \frac{44^\circ F}{979^\circ F \ \text{CONTROL}} \]
848 998 937 700 534 373 200 200 \( ^\circ \text{F} \)
974 623 562 \( ^\circ \text{F} \)

\[ E = 99.3 \]

* AT ROOM TEMP.
DATE: 3-21-80
RUN No. 6
TEST No. 23

SABATIER

1 MAN CONT.

M.R. 40

17.3 PSIA

.067 CFM

152°F

.092 CFM

246°F

.212 CFM

157°F

33 ml/hr

79°F

86°F

860°F CONTROL

644 697 631 284 200 200 197 144°F

524 480 234 °F

°F OVERTEMP

E = 99.1

*AT ROOM TEMP.
DATE: 3-27-80
RUN No. 11
TEST No. 24

SABATIER

3 MAN CONT.

M.R. 4.0

179 PSIA

.201 CFM

.092 CFM

439 °F

189 °F

.212 CFM

240 °F

101 ml/hr

78 °F

25 °F

.038 CFM

75 °F

96 °F

993 °F CONTROL

630 1007 969 814 649 492 352 152 °F

997 869 656 °F

°F OVERTEMP

G.C. RUN No. 16

H2 5.39

CH4 930.9

CO2 1.39

\[ \varepsilon = 99.0 \]

* AT ROOM TEMP
DATE: 4/2-80
RUN No. 6
TEST No. 9 26

SABATIER

1 MAN CONT.

M.R. 5.0

17.5 PSIA

138°F

138°F

79°F

0.081 CFM

0.092 CFM

0.212 CFM

219°F

416°F

31 ml/hr

76°F

73°F

84°F

464°F CONTROL

154 122 53 241 187 185 181 132 °F

822 406 191 °F

°F OVERTEMP

G.C. RUN No. 9

H2 493

CH4 50.49

CO2 0

\[ \varepsilon_{CO2} = 100.0 \]

* AT ROOM TEMP
SABATIER
3 MAN CONT.
M.R. 5.0

18.0 psia
.242 CFM

178°F

.092 CFM
.212 CFM

471°F

261°F

93°F

108 ml/hr
78°F

40°F

.089 CFM
74°F

1004°F control

G.C. RUN No. 2106
H2 46.7
CH4 49.9
CO2 0

°F overtemp

E = 100.0

* AT ROOM TEMP.

ORIGINAL PAGE IS OF POOR QUALITY.
DATE: 2-8-80
RUN No. 21
TEST No. 19

SABATIER
10 MAN Cont.
M.R. 2.6

18.8 PSIA
.49 CFM

113 °F

498 °F
.092 CFM

443 °F
.212 CFM

79 °F
148 CFM
74 °F

228 ml/hr
75 °F

974 °F Control
694 150 103 950 940 891 873 718 °F

1020 966 847 °F

°F Overtemp

G.C. RUN No. 6
H2 7.18
CH4 5.5.21
CO2 34.61

E = 97.2

* AT ROOM TEMP
DATE: 3-16-80
RUN No. 5
TEST No. 29

SABATIER
1 man cyclic
M.R. 1.8

G. C. RHN No. 5
H₂ .55%
CH₄ 44.95%
CO₂ 54.89%

\[ E = 99.7 \]

* AT ROOM TEMP.
SAFATIER

3 MAN CYCLIC

M.R. 1.8

DATE: 3-13-80
RUN No. 3
TEST No. 6/13

G.C. RUN No. 6
H₂ 1/1
CH₄ 42.53
CO₂ 57.07

\[ E = 99.4 \]

* AT ROOM TEMP.

INITIAL PAGE 2
* POOR QUALITY

E-13
SABATIER

1 MAN CYCLIC

M.R. 2.6

17.6 psia

0.081 CFM

135°F

77°F

0.022 CFM

72°F

81°F

826°F CONTROL

804 844 876 964 192 192 186 181 °F

780 781 199 °F

°F OVERTEMP

6 = 99.7

* AT ROOM TEMP

DATE: 2-28-90
RUN No. 31
TEST No. 6
SABATIER

2 MAN CYCLIC

M.R. 2.6

17.9 PSIA
.165 CFM

87 °F

370 °F

174 °F

212 °C FM

172 °F

77 mL/hr

74 °F

79 °F

.044 CFM
72 °F

953 °F CONTROL

823 842 854 855 874 889 174 195 °F

940 765 469 °F

°F OVERTEMP

E = 99.7

* AT ROOM TEMP.

G.C. RUN NO. 10

H2 .86

CH4 65.57

CO2 33.47

DATE: 3-4-80
RUN NO. 6
TEST NO. 32
DATE: 2-20-80
RUN No. 18
TEST No. 18

SABATIER

3 MAN CYCLIC

M.R. 2.6

18.0 PSIA

180°F

78°F

0.069 CFM

72°F

G.C. RUN No. 4

H₂ 1.08

CH₄ 60.95

CO₂ 37.76

95°F CONTROL

783 571 946 819 658 484 356 195 °F

966 849 655 °F

— °F OVERTEMP

ɛ = 99.6

* AT ROOM TEMP.
DATE: 3-25-80
RUN No. 12
TEST No. 34

SABATIER
/ MAN CYCLIC
M.R. 3.5

17.6 PSIA
.101 CFM

162°F

.092 CFM
.212 CFM

264°F
156°F

81°F
.022 CFM

76°F

50 ml/hr
78°F

86°F

903°F CONTROL
865 920 709 197 168 195 141°F

870 549 198°C

°F OVERTEMP

G.C. RUN No. 12
H2 3.10
CH4 84.60
CO2 12.00

E = 99.2

* AT ROOM TEMP
DATE: 3-26-50
RUN NO. 7
TEST NO. 22

SABATIER
3 MAN CYCLIC
M.R. 3.5

18.1 PSIA
.310 CFM

190°F
.092*CFM
.212*CFM
329°F
150 ml/hr
77°F

316°F
9/76°F

.068*CFM
74°F

59°F

996°F CONTROL
777 1010 1006 928 K20 697 556 240°F

1021 933 736 °F

°F OVER TEMP

G.C. RUN NO. 7
H2 2.33
CH4 46.26
CO2 10.41

ε = 99.3

* AT ROOM TEMP
SABATIER

1 MAN CYCLIC

M.R. 4.0

17.5 PS14

.112 CFM

177°F

.092* CFM

333 °F

161 °F

.212* CFM

57 ml/hr

79 °F

51 °F

949 °F CONTROL

870 964 638 487 201 200 200 133 °F

929 684 347 °F

°F OVERTEMP

G.C. RUN NO. 12

Ha 8.24

CH₄ 69.25

CO₂ 2.02

ε = 98.2

*AT ROOM TEMP

DATE: 5-26-30

RUN NO. 9

TEST NO. 36
SABATIER
3 MAN CYCLIC
M.R. 4/0

\[ 18.3 \text{ PSIA} \]
\[ 0.344 \text{ CFM} \]
\[ 210^\circ F \]
\[ 78^\circ F \]
\[ 0.70 \text{ CFM} \]
\[ 72^\circ F \]
\[ 180 \text{ ml/hr} \]
\[ 75^\circ F \]

\[ 101^\circ F \]
\[ 497^\circ F \text{ CONTROL} \]
\[ 745 \ 1012 \ 1024 \ 973 \ 893 \ 798 \ 694 \ 347^\circ F \]
\[ 1037 \ 564 \ 145^\circ F \]
\[ -^\circ F \text{ OVERTEMP} \]

\[ E = 98.4 \]

\* AT ROOM TEMP.

G.C. RUN NO. 1942
\[ H_2 \ 6.71 \]
\[ CH_4 \ 89.22 \]
\[ CO_2 \ 2.52 \]
SABATIER

1 MAN CYCLIC

M.R. 5.0

17.5 PSIA

.135 CFM

164 °F

.092 CFM

336 °F

.212 CFM

164 °F

79 °F

.048 CFM

73 °F

57 ml/hr

71 °F

87 °F

983 °F CONTROL

869 999 889 452 301 240 221 136 °F

964 694 346 °F

°F OVERTEMP

G.C. RUN NO. 136

H2 49.52

CH4 56.30

CO2 0

ɛ = 100.0

NT ROOM TEMP

DATE: 4-3-80

RUN NO. 4

TEST NO. 38

B-21
End Date
2/81