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DEVELOPMENT OF A PREPROTOTYPE SABATIER CO_2 REDUCTION SUBSYSTEM

BY

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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 CO_2 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 H_2/CO_2 conversion efficiency of over 99% over a range of H_2/CO_2 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 CO_2 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.

Hamilton Standard personnel responsible for the conduct of this program were Messrs. Harlan F. Brose, Program Manager, and Gilbert N. Kleiner, Program Engineering Manager. Appreciation is expressed to Dr. Philip Birbara, Technical Consultant, Messrs. Robert Moser and Edward O'Connor, Analysis, and Messrs. William Perkins and William Walters, Electrical Engineering.

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SUMMARY

A development program of a Preprototype Sabatier CO_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_2/CO_2 molar ratios of 1.8 to 5.0 for a crew size range of one person steadystate 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. Steadystate 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_2 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 H_2/CO_2 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.

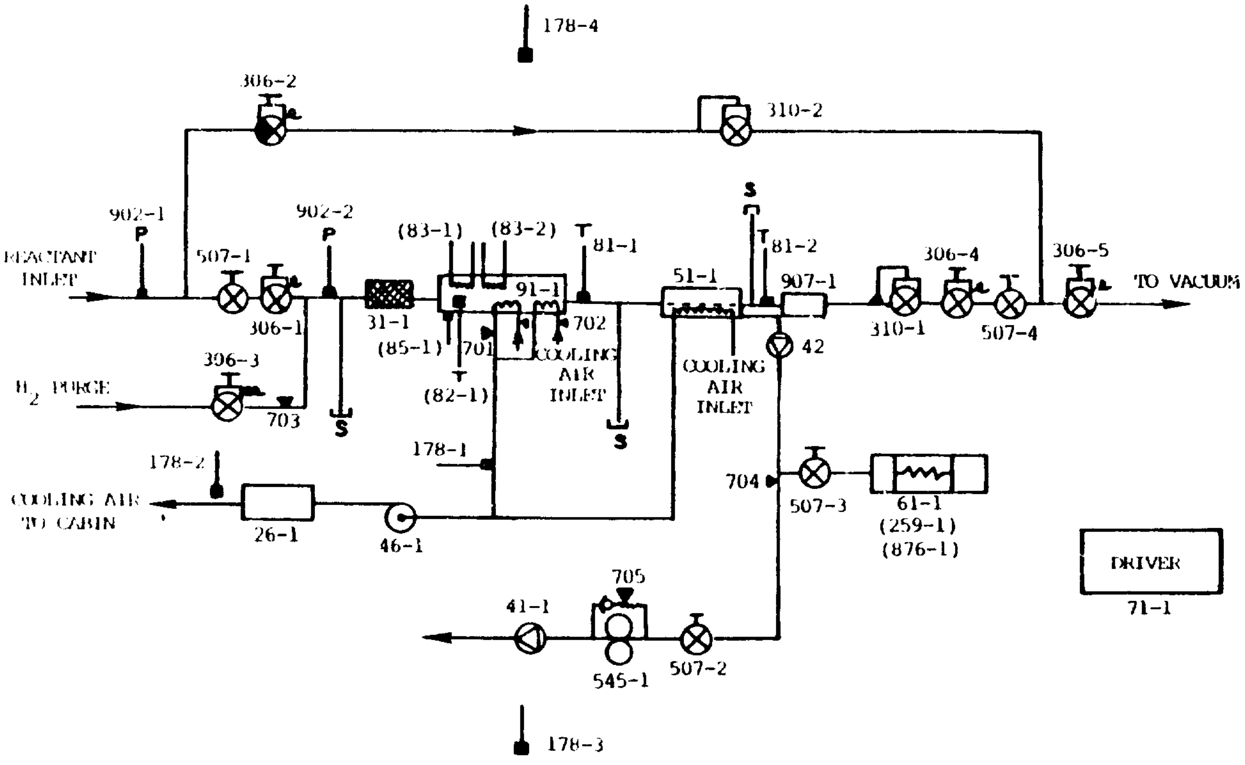
The preprototype Sabatier subsystem is shown schematically in Figure 1. Figure 2 is a photograph of the front and rear view of the subsystem package assembly. Figure 3 is a photograph of the Sabatier controller driver box assembly. Figure 4 shows the Sabatier subassembly integrated with the "common" 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%.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306-2
310-2
902-1
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902-2
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(83-1)
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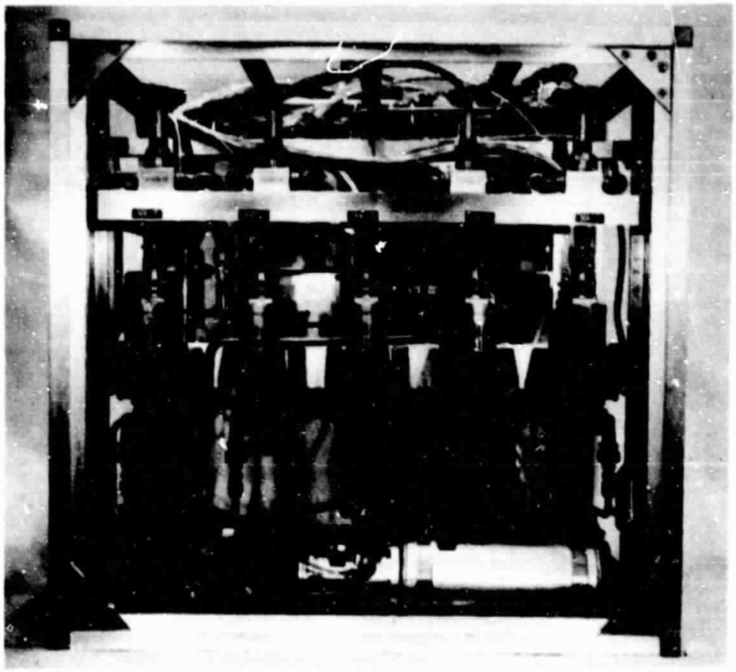
T 81-1
S
T 81-2
REACTANT INLET
507-1
306-1
31-1
(85-1)
701
91-1
702
T
(82-1)
COOLING AIR INLET
51-1
907-1
42
COOLING AIR INLET
306-4
310-1
507-4
306-5
TO VACUUM
H_2 PURGE
306-3
703
S
S
178-1
178-2
COOLING AIR TO CABIN
26-1
46-1
704
507-3
61-1
(259-1)
(876-1)
DRIVER
71-1
705
41-1
545-1
507-2
178-3

FIGURE 1
PREPROTOTYPE SABATIER SUBSYSTEM SCHEMATIC

ITEM NO.	PART NAME
ITEM 46	FAN, SABATIER AIR COOLING
ITEM 26	SILENCER, FAN
ITEM 61	ACCUMULATOR ASSEMBLY
ITEM 51	CONDENSER, SABATIER
ITEM 91	REACTOR, SABATIER
ITEM 31	CANISTER, CHARCOAL
ITEM 545	PUMP
ITEM 306	VALVE, ELECTRICAL S.O.
ITEM 310	REGULATOR, BACK PRESS.
ITEM 507	VALVE, MANUAL S.O.
ITEM 178	SENSOR-COMBUSTIBLE GAS
ITEM 178	SENSOR, MONITOR ASSEMBLY
ITEM 41	VALVE, CHECK
ITEM 42	VALVE, CHECK
ITEM 81-1	SENSOR, TEMPERATURE
ITEM 81-2	SENSOR, TEMPERATURE
ITEM 902-1	TRANSDUCER, PRESSURE-GAGE
ITEM 902-2	TRANSDUCER, PRESSURE-GAGE
ITEM 907	DETECTOR, LIQUID WATER
ITEM 82	SENSOR, TEMPERATURE
ITEM 83	HEATER—REACTOR
ITEM 85	SENSOR, TEMPERATURE
ITEM 86	THERMOCOUPLE, CHROMEL-ALUMEL
ITEM 259	ACCUMULATOR
ITEM 876	SENSOR, QUALITY-ACCUMULATOR
ITEM 87	THERMOCOUPLE, CHROMEL-ALUMEL
ITEM 701	ORIFICE, CONTROL
ITEM 702	ORIFICE CONTROL
ITEM 703	ORIFICE, CONTROL
ITEM 704	ORIFICE, CONTROL
ITEM 705	ORIFICE, CONTROL
ITEM 801	SAMPLE/PRESSURE PORT
ITEM 802	SAMPLE/PRESSURE PORT
ITEM 803	SAMPLE/PRESSURE PORT
ITEM 804	SAMPLE/PRESSURE PORT
ITEM 805	SAMPLE/PRESSURE PORT
ITEM 806	SAMPLE/PRESSURE PORT
ITEM 807	SAMPLE/PRESSURE PORT
ITEM 808	SAMPLE/PRESSURE PORT
ITEM 809	SAMPLE/PRESSURE PORT

FRONT VIEW



REAR VIEW

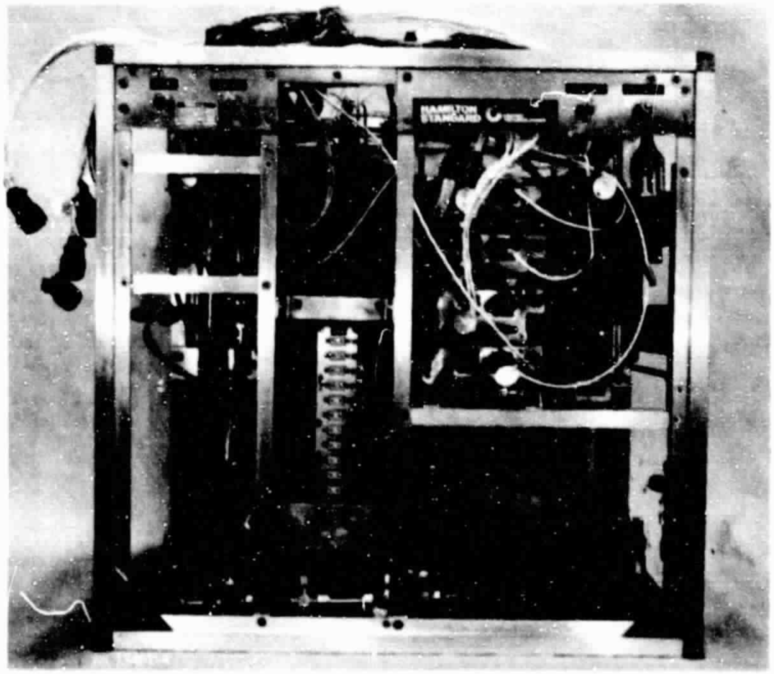
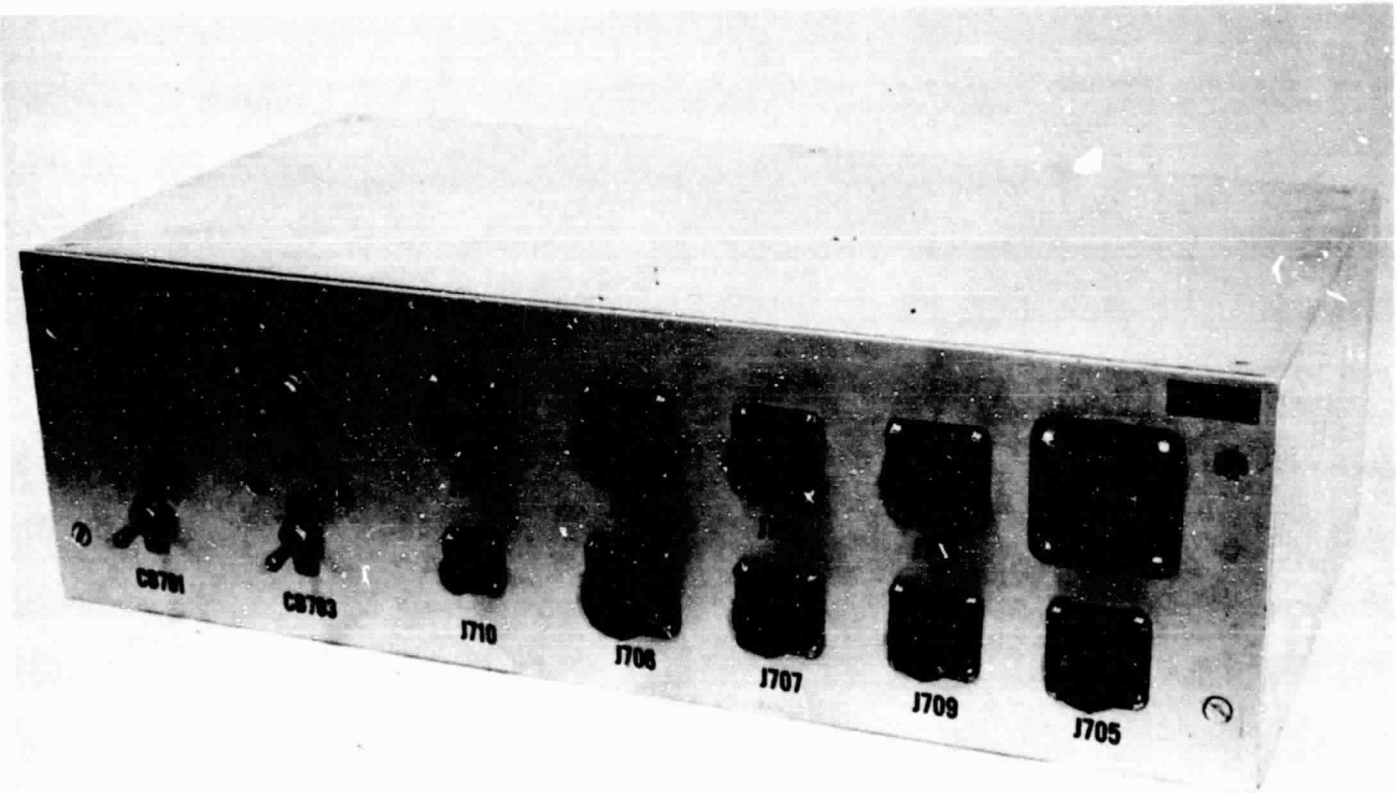


FIGURE 2
PREPROTOTYPE SABATIER PACKAGE ASSEMBLY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CB703
J710
J706
J707
J709
J705

FIGURE 3
SABATIER DRIVER BOX

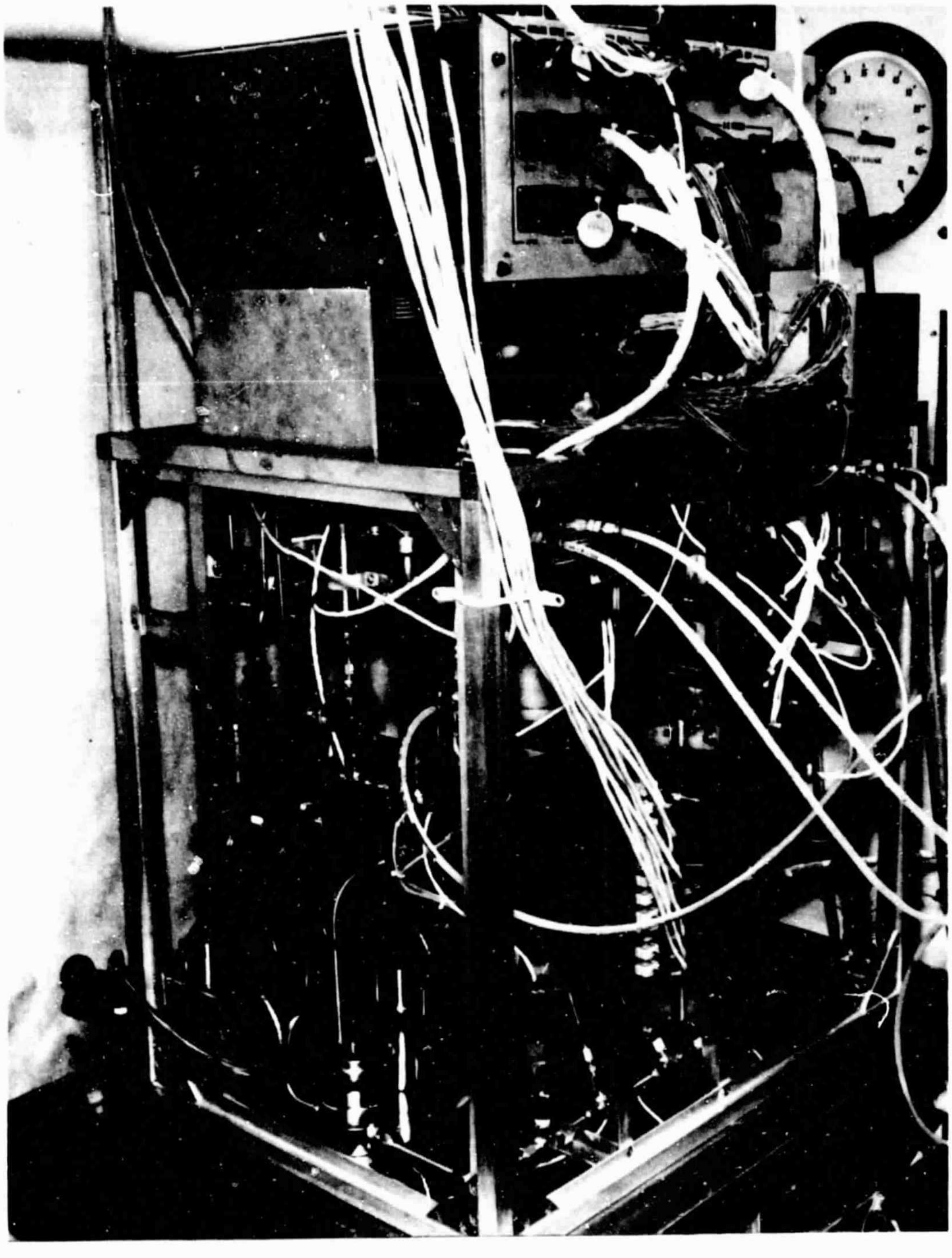

FIGURE 4
SABATIER PACKAGE ASSEMBLY WITH DRIVER BOX AND CONTROLLER

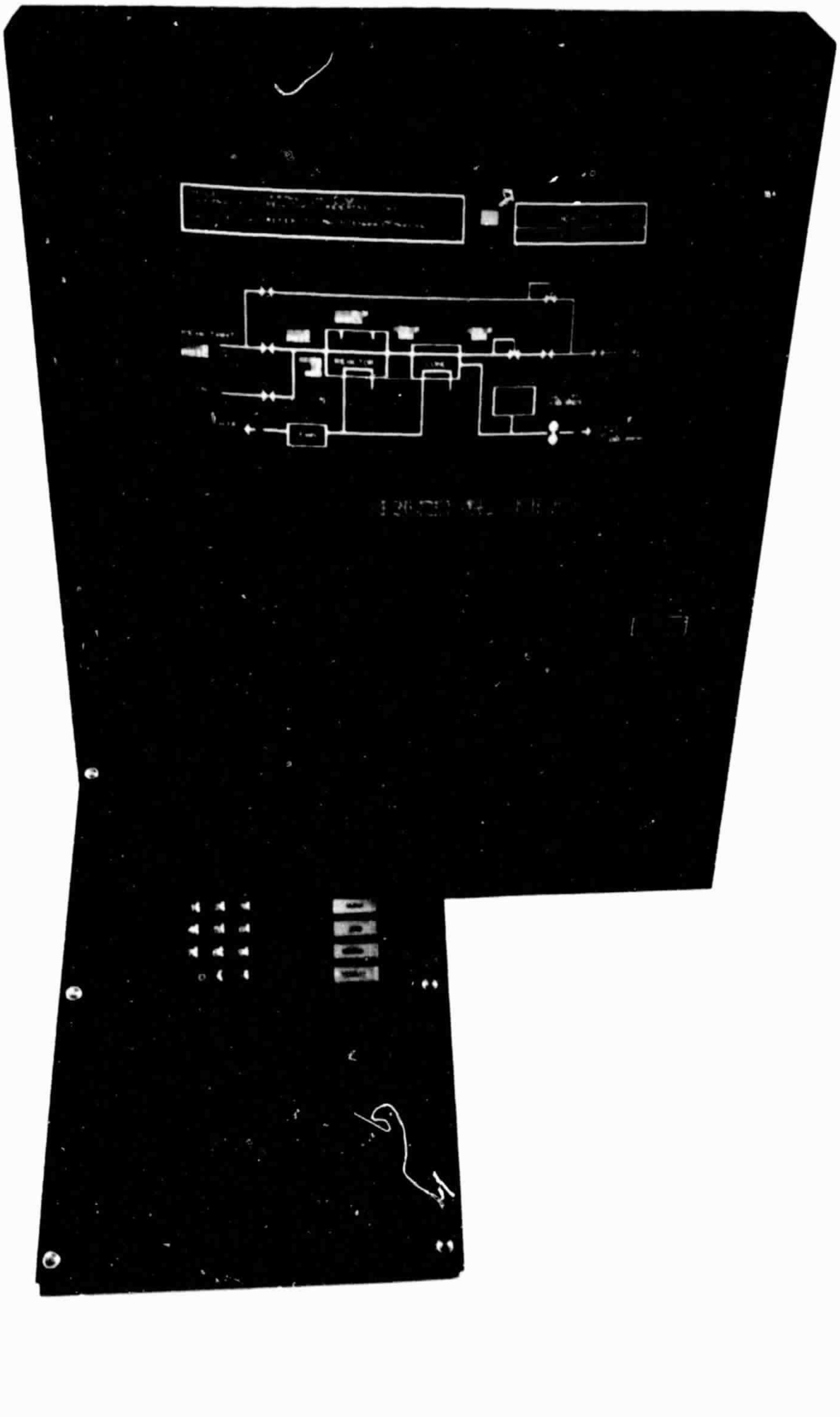

FIGURE 5
DISPLAY AND KEYBOARD

TABLE 1

Preprototype Sabatier Subsystem Performance Conversion Efficiency During Steadystate Testing

	H_2/CO_2 Molar Ratio				
CO_2 Flow	1.8	2.6	3.5	4.0	5.0
1 Man Continuous	99.8	99.8	99.6	99.1	100
1 Man Cyclic	99.7	99.7	99.2	98.2	100
2 Man Cyclic	----	99.7	----	----	----
3 Man Continuous	99.3	99.6	99.3	99.0	100
3 Man Cyclic	99.4	99.6	99.3	98.4	100
10 Man Continuous (off design)	----	97.2	----	----	----

TABLE 2

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

	H_2/CO_2 Molar Ratio				
CO_2 Flow	1.8	2.6	3.5	4.0	5.0
1 Man	99.6	99.6	99.4	98.6	100
2 Man	----	99.6	----	----	----
3 Man	99.6	98.8 (99.4)	98.1	97.4 (98.8)	100

(   ) - 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 CO_2 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 bearly detectable by the sensitive silver nitrate test and water conductivity to 10-20 μ mhos.

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:

Tasks	SOW Paragraph	WBS No.
Subsystem Design	3.2.1	1.0
Subsystem Fabrication	3.2.2	2.0
Subsystem Testing	3.2.3	3.0
Subsystem Delivery	3.2.4	2.0, 3.0
Coordination with RLSE	3.2.5	4.0
Documentation	4.6	5.0
Support Requirements	5.0	2.0
Quality Assurance	6.0	2.0
Reliability	7.0	3.0
Safety	8.0	1.0, 3.0

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 CO_2 or H_2) 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 CO_2 and H_2 supply pressure. A bypass function for CO_2 and H_2 is provided for emergency shutdown and to permit maintenance on the Sabatier subsystem without interruption of the CO_2 Removal and O_2 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 preprototype 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 jacket 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 CO_2 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 H_2/CO_2 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_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 permited 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

CO_2 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)
H_2/CO_2 MOLAR RATIO		
MINIMUM	1.8	1.8
MAXIMUM	5.0	5.0
REACTOR EFFICIENCY	99%	99%
REACTANT SUPPLY PRESSURE	1.4 ATM*	(5 PSIG*)
REACTANT SUPPLY TEMPERATURE	18-24°C	(65-75°F)
REACTANT DEW POINT	SATURATED	SATURATED
TOUCH TEMPERATURE MAXIMUM	45°C	(113°F)
WATER DELIVERY PRESSURE	2 ATM	(30 PSIA)
START-UP TIME MAXIMUM	5 MIN	5 MIN
GRAVITY	0 TO ± 1G	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 - H_2/CO_2 molar ratios from 2.0 to 4.0 in 0.2 increments

Dew Points - Bone dry, 27 and 38°C (80° and 100°F)

Temperatures - 149° 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 H_2/CO_2 molar ratio of 4.0, the adiabatic temperature was 552°C (1025°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 H_2/CO_2 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 reliabiity by eliminating the need for active coolant controls. The cooling gas requirement is calculated from the change in enthalpy of the process stream (H - 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 O_2 (0.7 lb/day O_2) leakage. The calculated volumetric flow rate ≐ 0.52 m^3/min (18.4 cfm). During testing fan flow was measured as 0.62 m^3/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 CO_2 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 CO_2 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/separator. CO_2 flow rates of 1 man (at minimum metabolic rates) continuous to 3 man (maximum metabolic rate) cyclic operation and a H_2 to CO_2 molar ratio of 1.8 to 5.0 were considered. The sizing case occurred at the maximum CO_2 flow rate of 3 man cyclic and a H_2 to CO_2 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 0.04m^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.

Designation	-	UASC-151G
Composition	-	About 20% Ruthenium on alumina
Shape	-	14-18 mesh granules

This catalyst is highly active and structually 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.

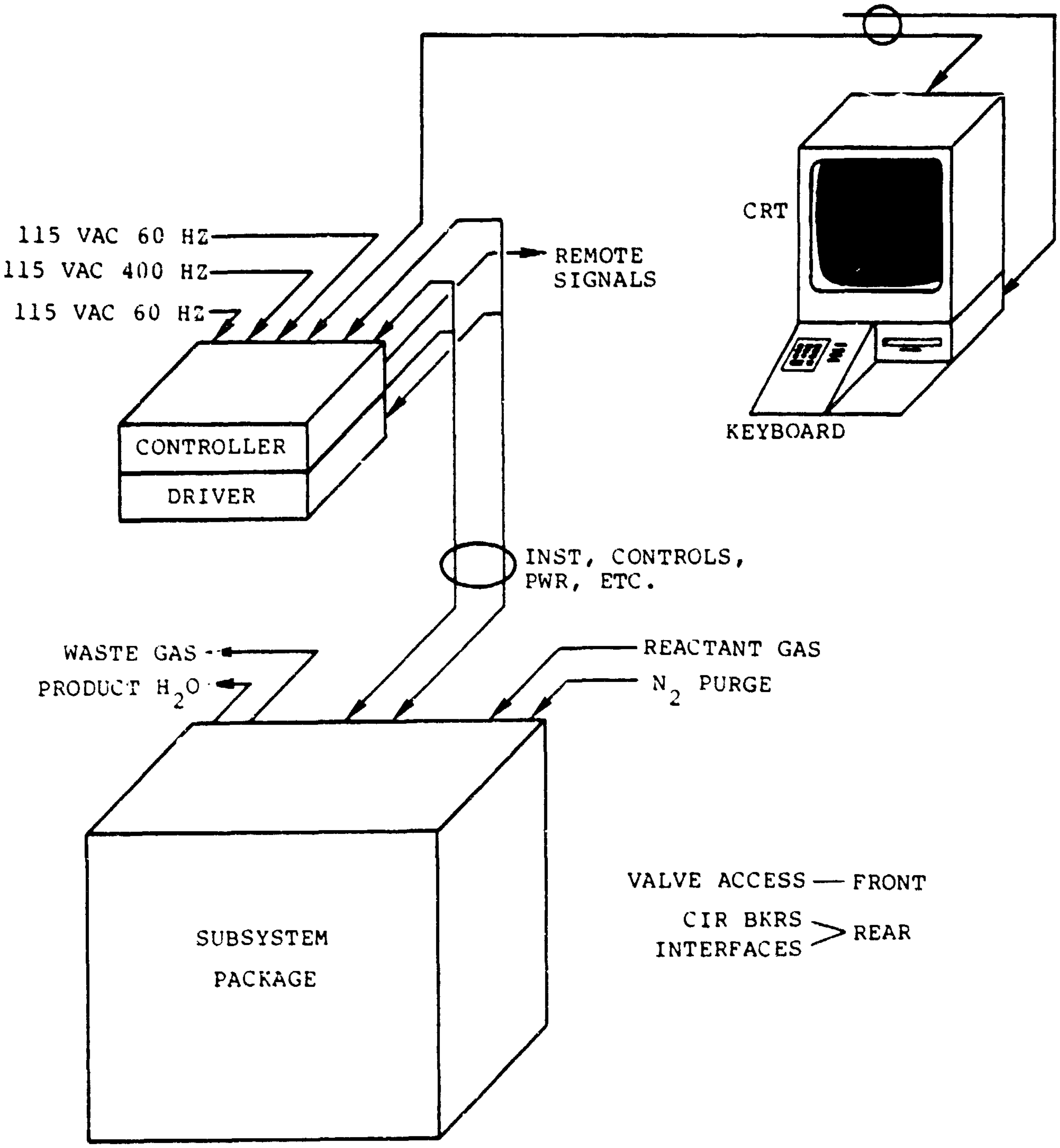
115 VAC 60 HZ
115 VAC 400 HZ
115 VAC 60 HZ
REMOTE SIGNALS
CRT
KEYBOARD
CONTROLLER
DRIVER
INST, CONTROLS, PWR, ETC.
WASTE GAS
PRODUCT H_2O
REACTANT GAS
N_2 PURGE
SUBSYSTEM PACKAGE
VALVE ACCESS — FRONT
CIR BKRS
INTERFACES
REAR

FIGURE 6

PREPROTOTYPE SABATIER SUBSYSTEM

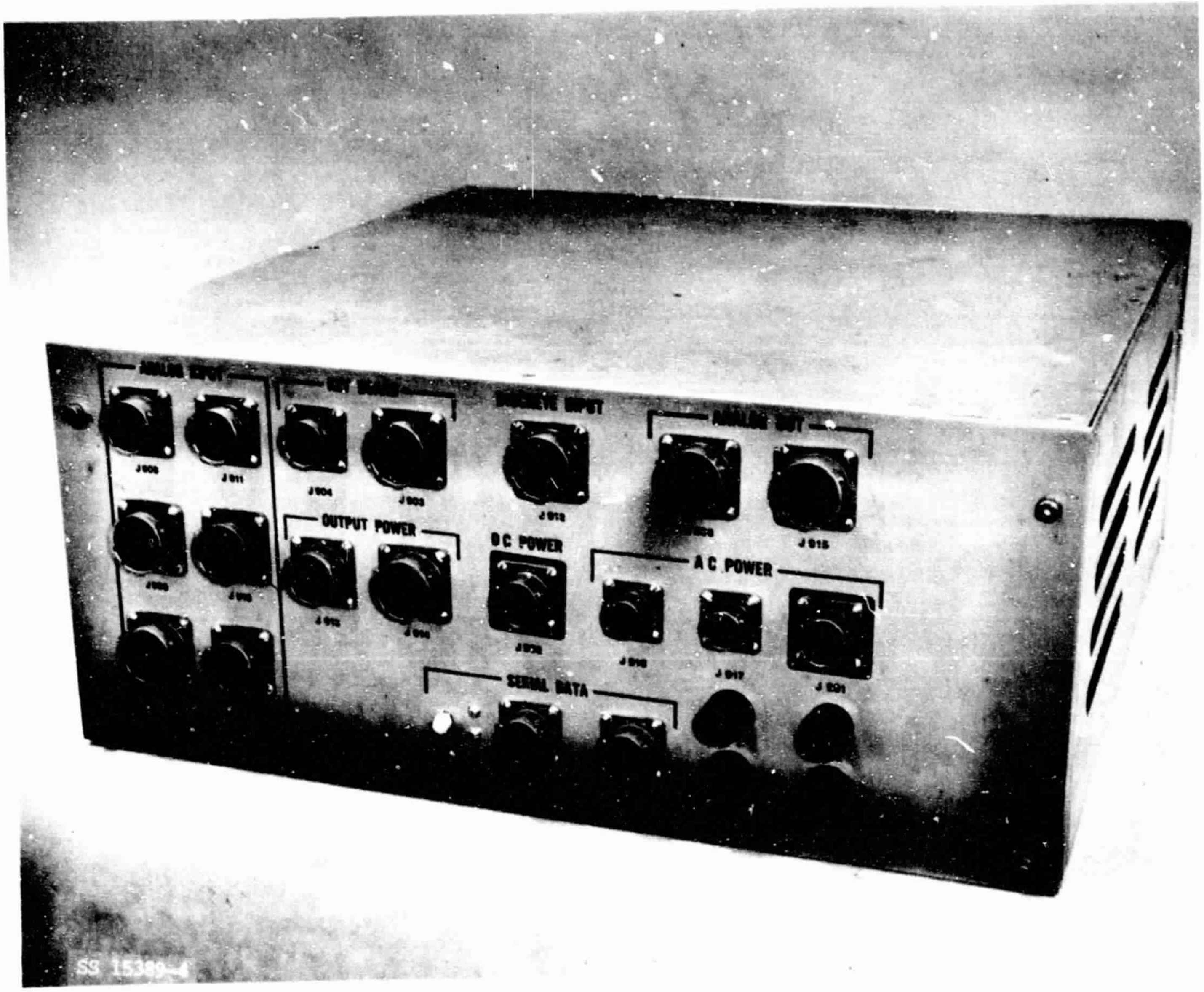
ANALOG INPUT
DISCRETE INPUT
ANALOG OUT
OUTPUT POWER
D C POWER
A C POWER
SERIAL DATA
J 915
SS 15389-4

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FIGURE 7
TIMES CONTROLLER

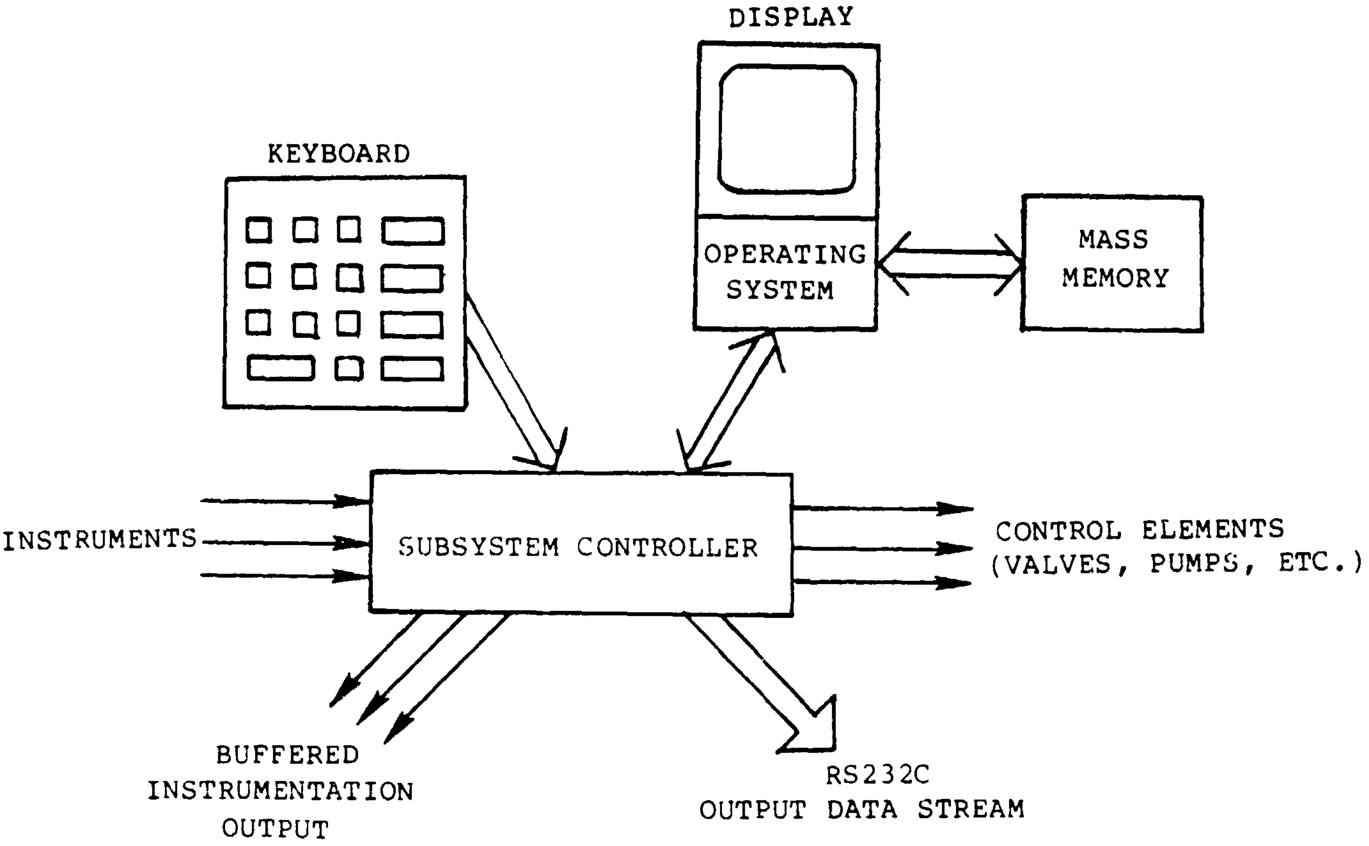

DISPLAY
KEYBOARD
OPERATING SYSTEM
MASS MEMORY
INSTRUMENTS
SUBSYSTEM CONTROLLER
CONTROL ELEMENTS (VALVES, PUMPS, ETC.)
BUFFERED INSTRUMENTATION OUTPUT
RS232C OUTPUT DATA STREAM

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 anomolies 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.

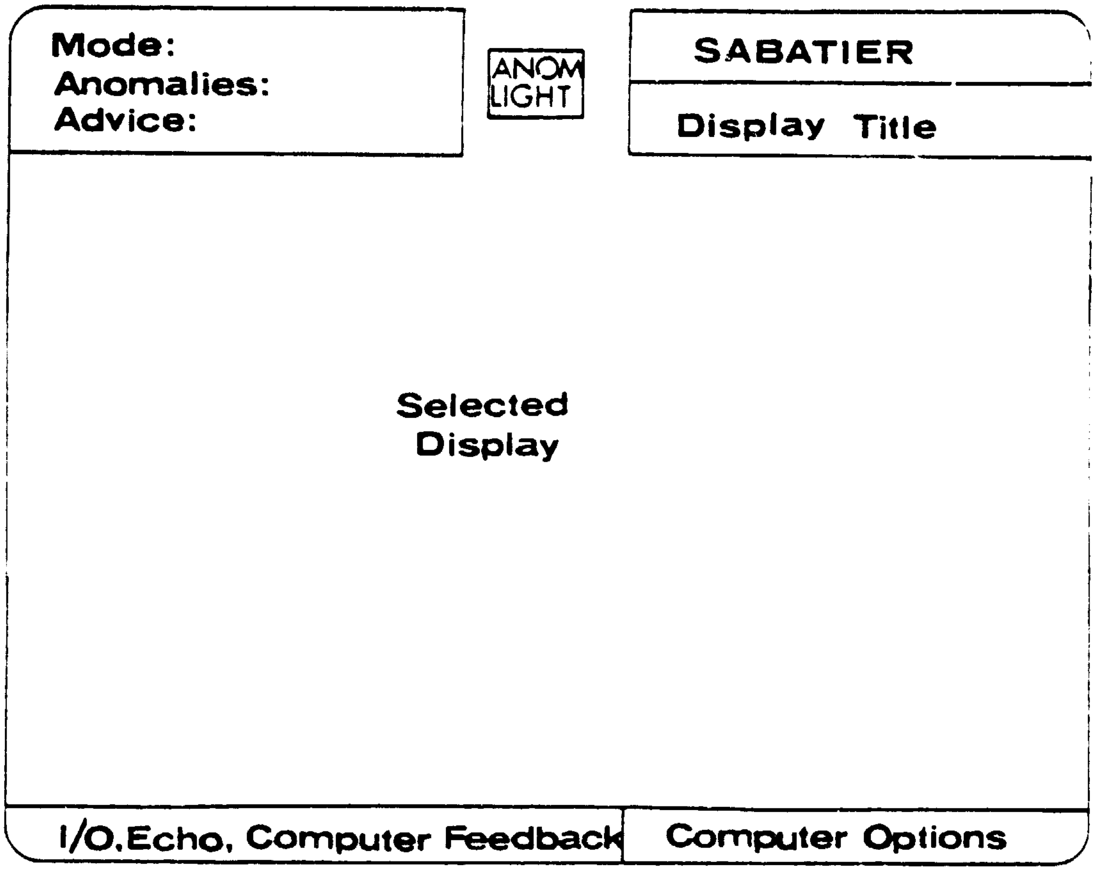
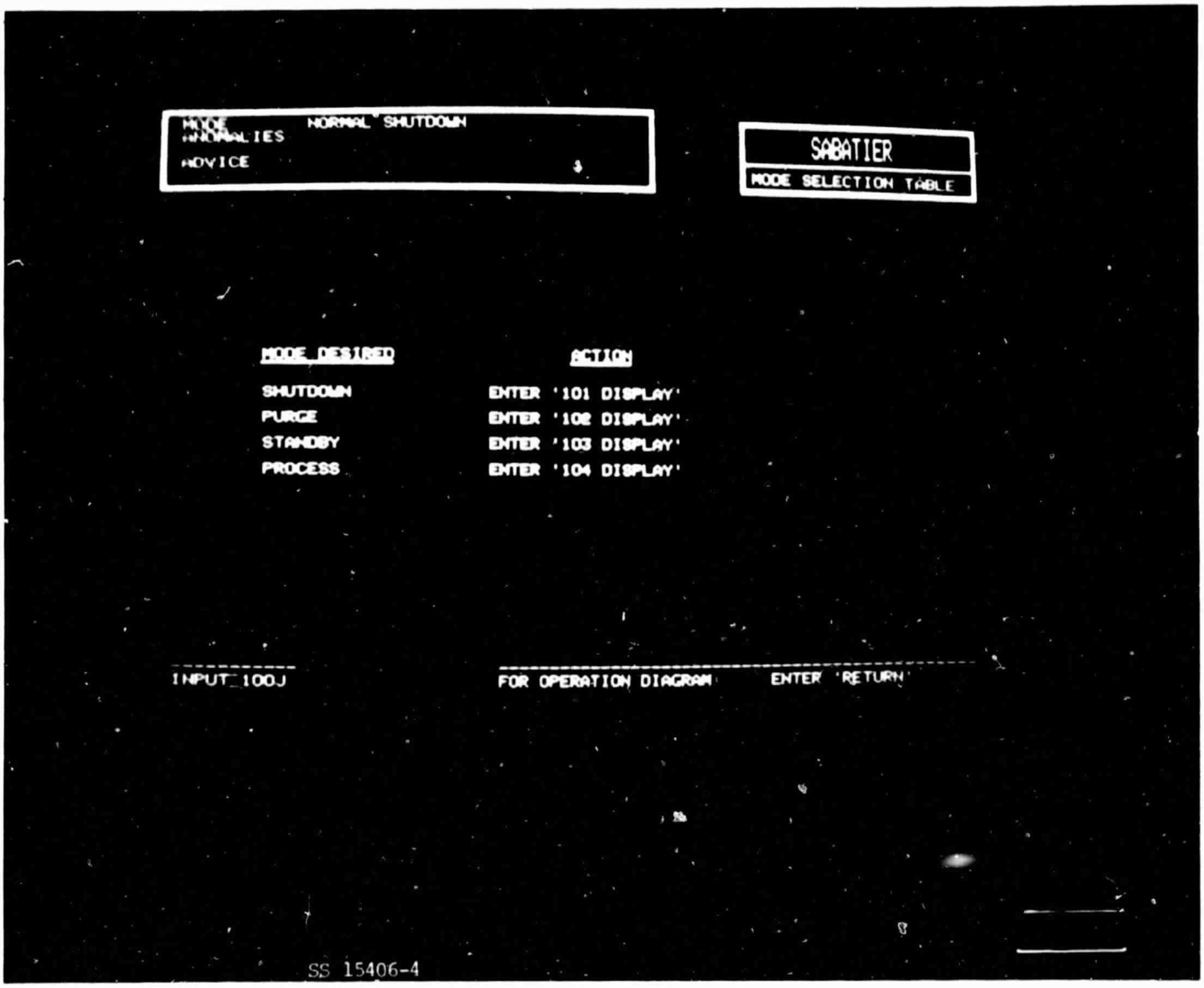

Mode:
Anomalies:
Advice:
ANOM LIGHT
SABATIER
Display Title
Selected Display
I/O.Echo, Computer Feedback
Computer Options

FIGURE 9
SABATIER CRT DISPLAY FORMAT



```
MODE        NORMAL SHUTDOWN                          SABATIER
ANOMALIES                                       MODE SELECTION TABLE
ADVICE

        MODE DESIRED            ACTION
        SHUTDOWN          ENTER '101 DISPLAY'
        PURGE             ENTER '102 DISPLAY'
        STANDBY           ENTER '103 DISPLAY'
        PROCESS           ENTER '104 DISPLAY'

INPUT 100J           FOR OPERATION DIAGRAM      ENTER 'RETURN'
```

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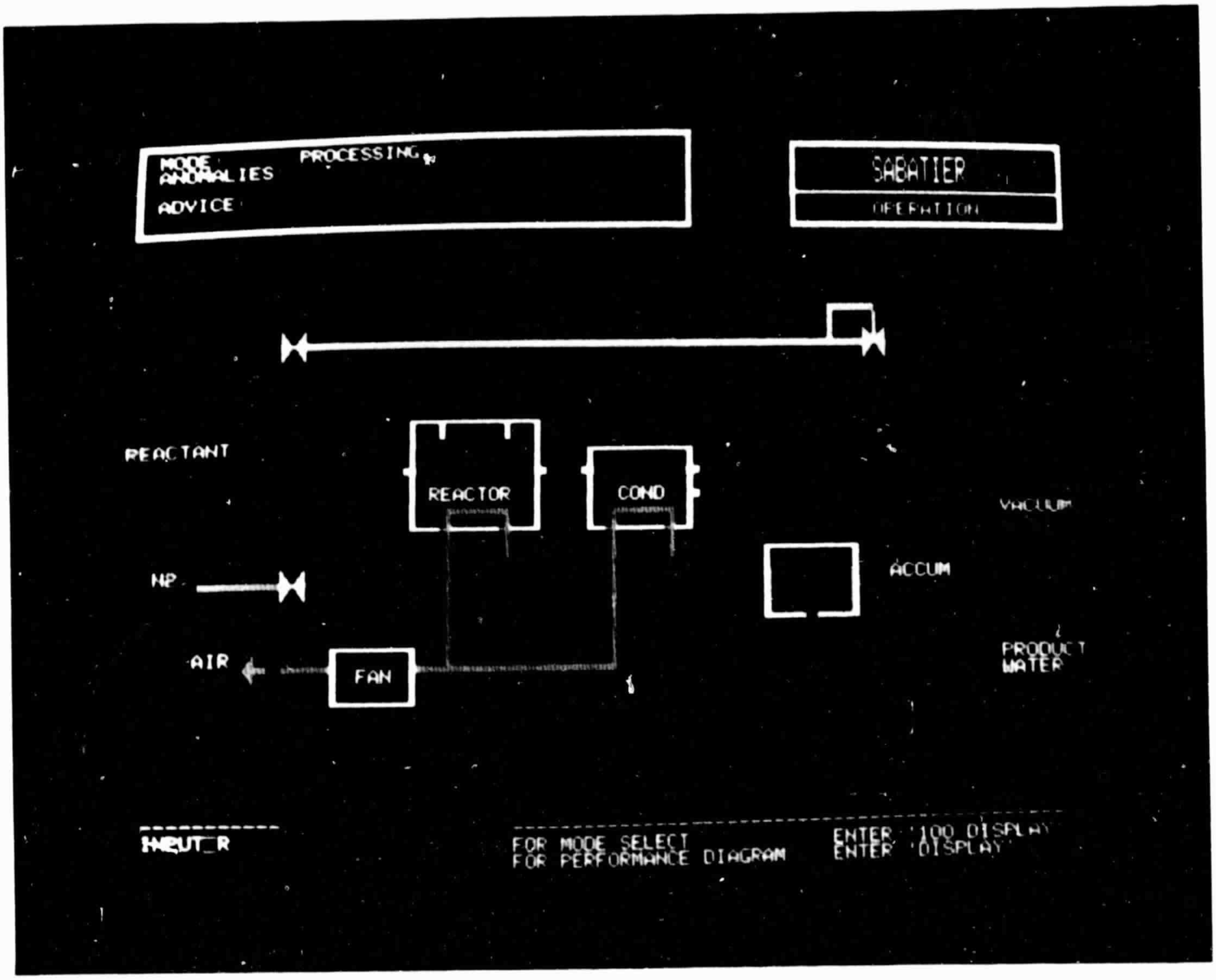
FIGURE 10
SABATIER MODE SELECTION TABLE



MODE PROCESSING
ANOMALIES
ADVICE

INPUT R

FOR MODE SELECT ENTER '100 DISPLAY'
FOR PERFORMANCE DIAGRAM ENTER 'DISPLAY'

SABATIER
OPERATION
REACTANT
REACTOR
COND
VACUUM
ACCUM
NP
AIR
FAN
PRODUCT WATER

FIGURE 11
SABATIER OPERATION DIAGRAM

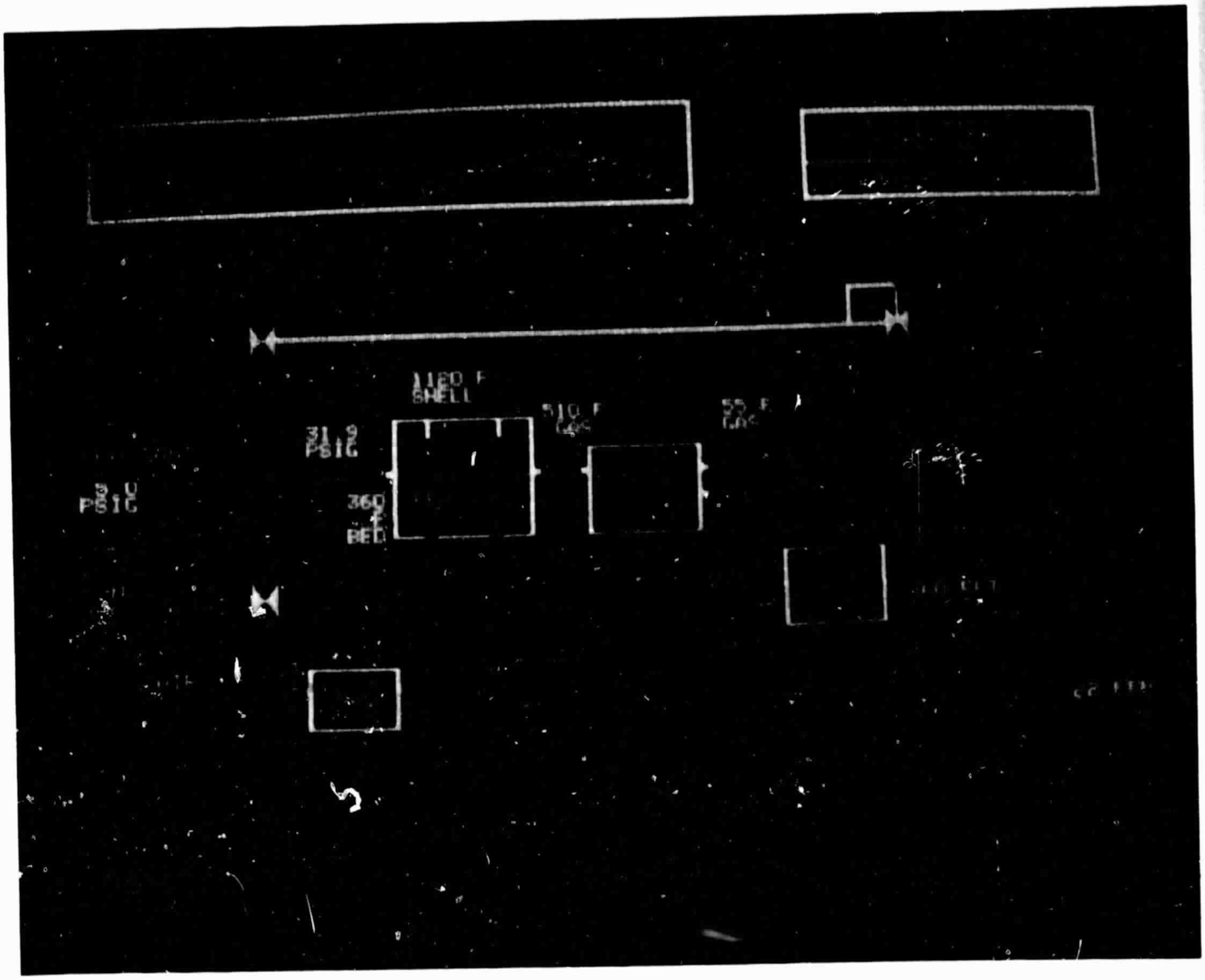

1120 F
SHELL
510 F
GAS
55 F
GAS
31.9
PSIG
5.0
PSIG
360
F
BED

FIGURE 12
SABATIER PERFORMANCE DIAGRAM

Control of the subsystem is straight forward 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 diagramatically 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 m^3 (6.3 ft^3) 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 accessibilty. 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.

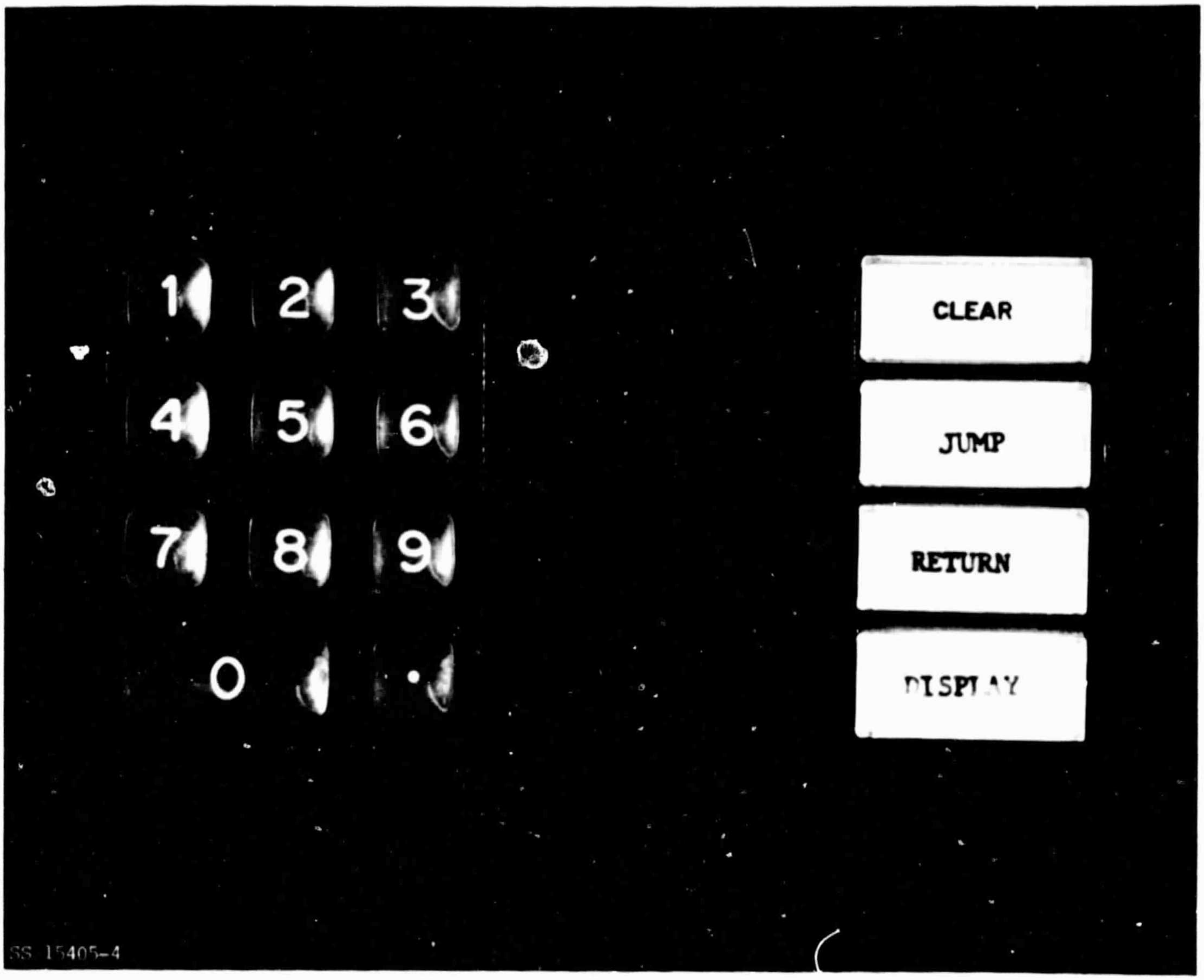

1
2
3
4
5
6
7
8
9
0
.
CLEAR
JUMP
RETURN
DISPLAY
SS 15405-4

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FIGURE 13
KEYBOARD

TABLE 4
CONTROL LOGIC

		Modes								
	Manually Selected Mode Controller-Selected Sub-Mode	Shutdown	Purge	Standby	Process	Shutdown (Purge)	Shutdown (Post Purge)	Maintenance Shutdown	Trip Point	Comments
	Sub-Mode Selection Parameter		-Select Shutdown -Select Standby or Process			Malfunction	+10 Min. or	107 Display	All Modes Applicable	
	Functions									
	. Heater Logic	Off	Off	On	On	Off	Off	Off		
	. Condensate Delivery	Off	On	On	On	On	Off	Off		
	. Fan	Off	On	On	On	On	Off	Off		
	. Valve Sequence									
	306-1 (Process In)	Closed	Closed	Closed	Open	Closed	Closed	Closed		
	306-2 (Bypass)	Open	Open	Open	Closed	Open	Open	Open		
	306-3 (N_2)	Closed	Open	Closed	Closed	Open	Closed	Closed		
	306-4 (Process Out)	Closed	Open	Open	Open	Open	Closed	Closed		
	306-5 (System Out)	Open	Open	Open	Open	Open	Open	Open		
	Malfunction Shutdowns									
Item	Name									
178	Combustible Gas Indication (4)	Yes	Yes	Yes	Yes	No	No	Yes	25%	Any one sensor
306-5	Outlet Valve (306-5) Closed (Discrete)	↓	↓	↓	↓	Yes	Yes	No	Valve Closed	
902-1	Reactant Over Pressure	↓	↓	↓	↓	No	No	Yes	>5.5 psig	Yellow warning if below 2psig
902-2	Purge Over Pressure	↓	↓	↓	↓	↓	↓	Yes	>5.5 psig	
81-2	High Condenser Output Temperature	↓	↓	↓	↓	↓	↓	Yes	>100°C	
82-1	Low Reactor Temperature	No	No	↓	↓	↓	↓	No	<325°F	After 7 Min. on start up only
61	Accumulator Level	Yes	Yes	↓	↓	↓	↓	No	>90%	Yellow warning if > 80%
907	Liquid Sensor Wet (Discrete)	↓	↓	↓	↓	↓	↓	Yes	Wet	
46	High Fan Current	↓	↓	↓	↓	↓	↓	Yes	>1.0 amps	
545	High Pump Current	↓	↓	↓	↓	↓	↓	Yes	>0.5 amps	
85-1	Reactor Over Temperature	Yes	↓	↓	↓	Yes	Yes	Yes	>1100°F	
306 (all 5)	Electrical Valves Wrong Position	Yes	Yes	Yes	Yes	↓	↓	No	Wrong valve position	

This package fits within the RLSE test area specified by the NASA. 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/separator 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

			PREPROTOTYPE		
DESCRIPTION	QTY.	UNIT WT. kgs.	TOTAL WT. kgs.	UNIT WT. lbs.	TOTAL WT. lbs.
VALVE, ELECTRICAL SHUT-OFF	5	0.82	4.08	1.8	9.0
VALVE, CHECK WATER	2	0.05	0.09	0.1	0.2
CANISTER, CHARCOAL	1	0.62	0.62	1.4	1.4
SABATIER REACTOR ASSEMBLY (INSTRUMENTED)	1	3.40	3.40	7.5	7.5
HEATER, ELECTRIC	2	(0.05)	(0.10)	(0.1)	(0.2)
CONDENSER/SEPARATOR (DRY)	1	1.32	1.32	2.9	2.9
SENSOR, TEMP.	2	0.05	0.09	0.1	0.2
SENSOR, LIQUID	1	0.09	0.09	0.2	0.2
REGULATOR BACK PRESSURE	2	1.13	2.27	2.5	5.0
VALVE, MANUAL SHUT-OFF	4	0.23	0.91	0.5	2.0
FAN, COOLING/MUFFLER ASSEMBLY	1	1.91	1.91	4.2	4.2
ACCUMULATOR ASSEMBLY	1	1.13	1.13	2.5	2.5
PUMP	1	1.81	1.81	4.0	4.0
SENSOR, COMBUSTIBLE GAS SENSING ELEMENT	4	0.14	0.56	0.3	1.2
CONTROLLER, COMBUSTIBLE GAS SIGNAL COND.	4	1.31	5.24	2.9	11.5
DRIVER BOX	1	6.53	6.53	14.4	14.4
SENSOR, PRESSURE	2	0.14	0.28	0.3	0.6
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)

TABLE 6
DESIGN DEFINITION

PART NO.	ITEM NO.	PART NAME	DESIGN COMMENTS
SVSK 96500	—	SABATIER PACKAGE ASSEMBLY	HAMILTON STANDARD DESIGN, SEE DESCRIPTION IN TEXT
SVSK 96467	ITEM 46	FAN, SABATIER AIR COOLING	BUY ITEM
SVSK 96471	ITEM 26	SILENCER, FAN	MODIFIED COMMERCIAL ITEM
SVSK 99752	—	ADAPTER, FAN HOUSING	HAMILTON STANDARD DESIGN
SVSK 96490	ITEM 61	ACCUMULATOR ASSEMBLY	GFE, SHUTTLE ITEM
SVSK 96349	ITEM 51	CONDENSER, SABATIER	HAMILTON STANDARD DESIGN
SVSK 96482	ITEM 91	REACTOR, SABATIER	HAMILTON STANDARD DESIGN
SVSK 96470	ITEM 31	CANISTER, CHARCOAL	HAMILTON STANDARD DESIGN
SVSK 86329	ITEM 545	PUMP	GFE, SSP ITEM
SVSK 84424	ITEM 306	VALVE, ELECTRICAL S.O.	GFE, SSP ITEM
SVSK 84412	ITEM 310	REGULATOR, BACK PRESS.	GFE, SSP ITEM
SVSK 84530	ITEM 507	VALVE, MANUAL S.O.	GFE, SSP ITEM
SVSK 84456-100	ITEM 178	SENSOR-COMBUSTIBLE GAS	GFE, SSP ITEM
SVSK 84456-200	ITEM 178	SENSOR, MONITOR ASSEMBLY	GFE, SSP ITEM
SVSK 96466	ITEM 41	VALVE, CHECK	CATALOG ITEM
SVSK 101124	ITEM 42	VALVE, CHECK	CATALOG ITEM
SVSK 101126	—	FILTER, CONDENSER INLET	HAMILTON STANDARD DESIGN
SVSK 96465-1	ITEM 81-1	SENSOR, TEMPERATURE	CATALOG ITEM
SVSK 96465-2	ITEM 81-2	SENSOR, TEMPERATURE	CATALOG ITEM
SVSK 101128-1	ITEM 902-1	TRANSDUCER, PRESSURE-GAGE	GFE, MODIFIED SSP
SVSK 101128-2	ITEM 902-2	TRANSDUCER, PRESSURE-GAGE	GFE, MODIFIED SSP
SVSK 101129	ITEM 907	DETECTOR, LIQUID WATER	HAMILTON STANDARD DESIGN
SVSK 100140	—	HARNESS, ELECTRICAL	HAMILTON STANDARD DESIGN
SVSK 101127	—	TUBING, FLEXIBLE	CATALOG ITEM
SVSK 99753	—	HOUSING, SENSOR	HAMILTON STANDARD DESIGN
SVSK 101130	—	FRAME, SABATIER PACKAGE	HAMILTON STANDARD DESIGN
SVSK 101125-1	—	BRACKET, REACTOR, MOUNTING	HAMILTON STANDARD DESIGN
SVSK 101125-2	—	BRACKET, REACTOR, MOUNTING	HAMILTON STANDARD DESIGN
SVSK 96499	ITEM 82	SENSOR, TEMPERATURE	HAMILTON STANDARD DESIGN
SVSK 96486	ITEM 83	HEATER - REACTOR	HAMILTON STANDARD DESIGN
SVSK 96465	ITEM 85	SENSOR, TEMPERATURE	CATALOG ITEM
SVSK 96497	ITEM 86	THERMOCOUPLE, CHROMEL-ALUMEL	HAMILTON STANDARD DESIGN
SVSK 96492	ITEM 259	ACCUMULATOR	GFE, MODIFIED SHUTTLE ITEM
SVSK 764179	ITEM 876	SENSOR, QUALITY-ACCUMULATOR	GFE, SHUTTLE ITEM
—	ITEM 87	THERMOCOUPLE, CHROMEL-ALUMEL	CATALOG ITEM
—	ITEM 701-705	ORIFICE, CONTROL	HAMILTON STANDARD DESIGN
—	ITEM 801-809	SAMPLE/PRESSURE PORT	CATALOG ITEM

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 8 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/separator 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.

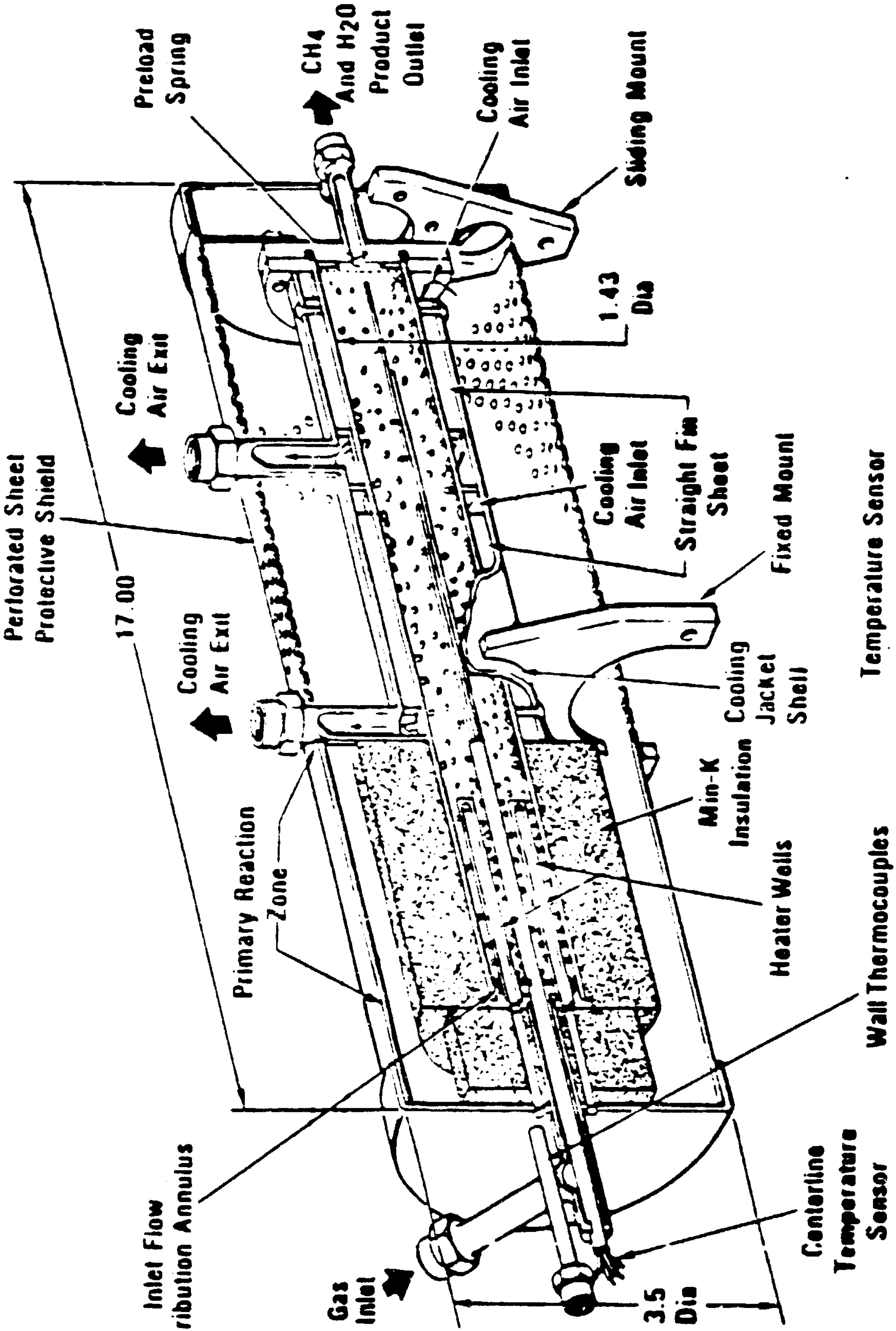
Preload Spring
CH4 And H2O Product Outlet
Cooling Air Inlet
Sliding Mount
Cooling Air Exit
1.43 Dia
Perforated Sheet Protective Shield
17.00
Cooling Air Exit
Cooling Air Inlet
Straight Fin Sheet
Fixed Mount
Temperature Sensor
Cooling Jacket Shell
Primary Reaction Zone
Min-K Insulation
Heater Wells
Wall Thermocouples
Inlet Flow Distribution Annulus
Gas Inlet
3.5 Dia
Centerline Temperature Sensor

FIGURE 14
SABATIER REACTOR - CROSS SECTION

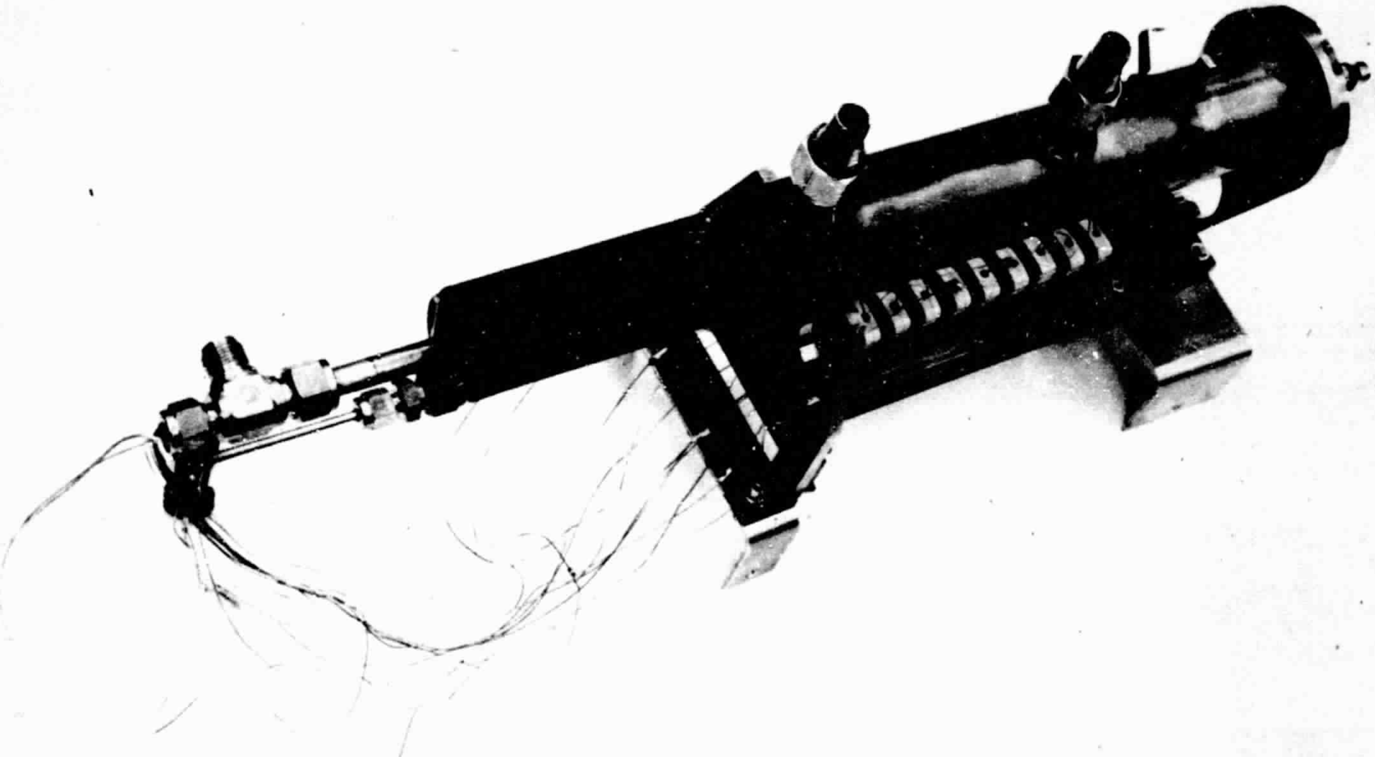

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FIGURE 15
REACTOR BEFORE INSULATION INSTALLED

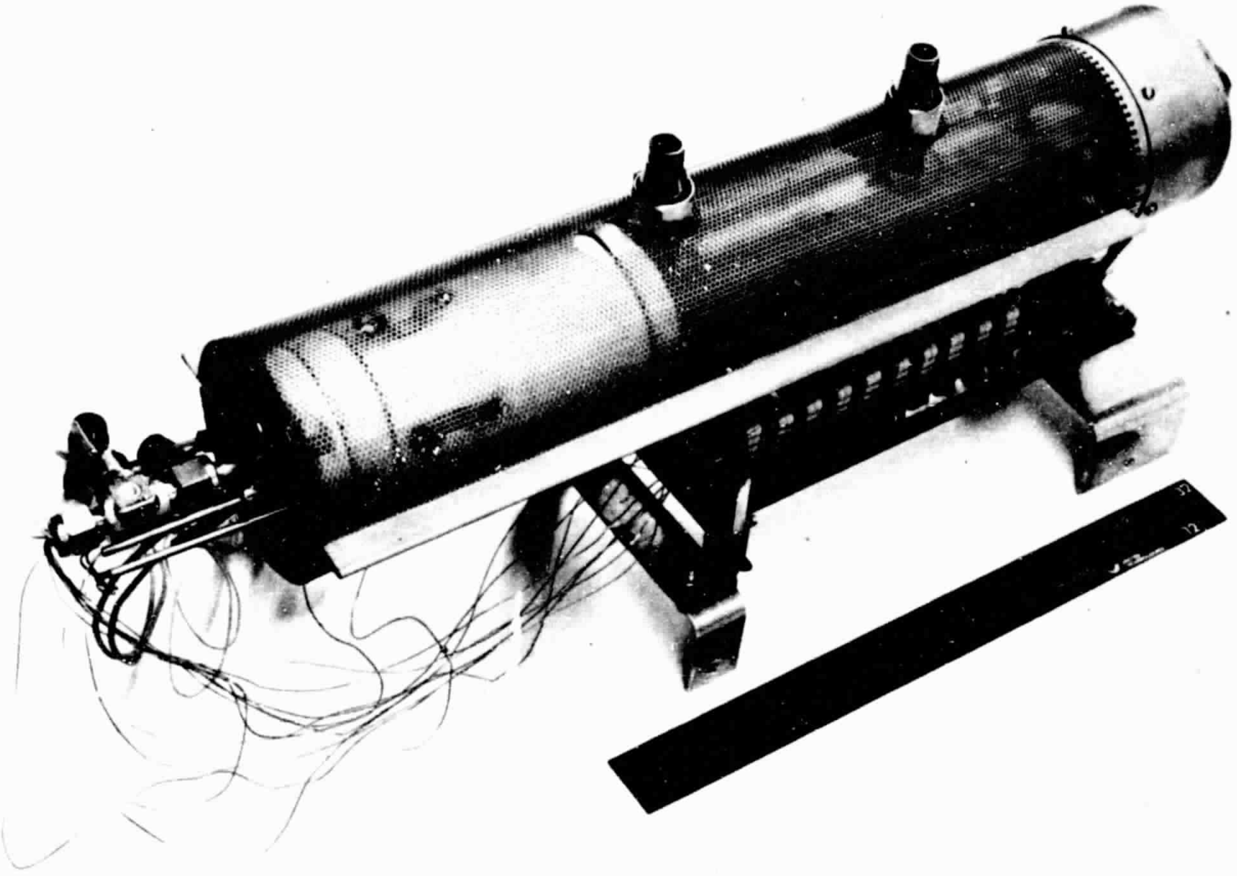

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FIGURE 16
REACTOR ASSEMBLY (INSTRUMENTED)

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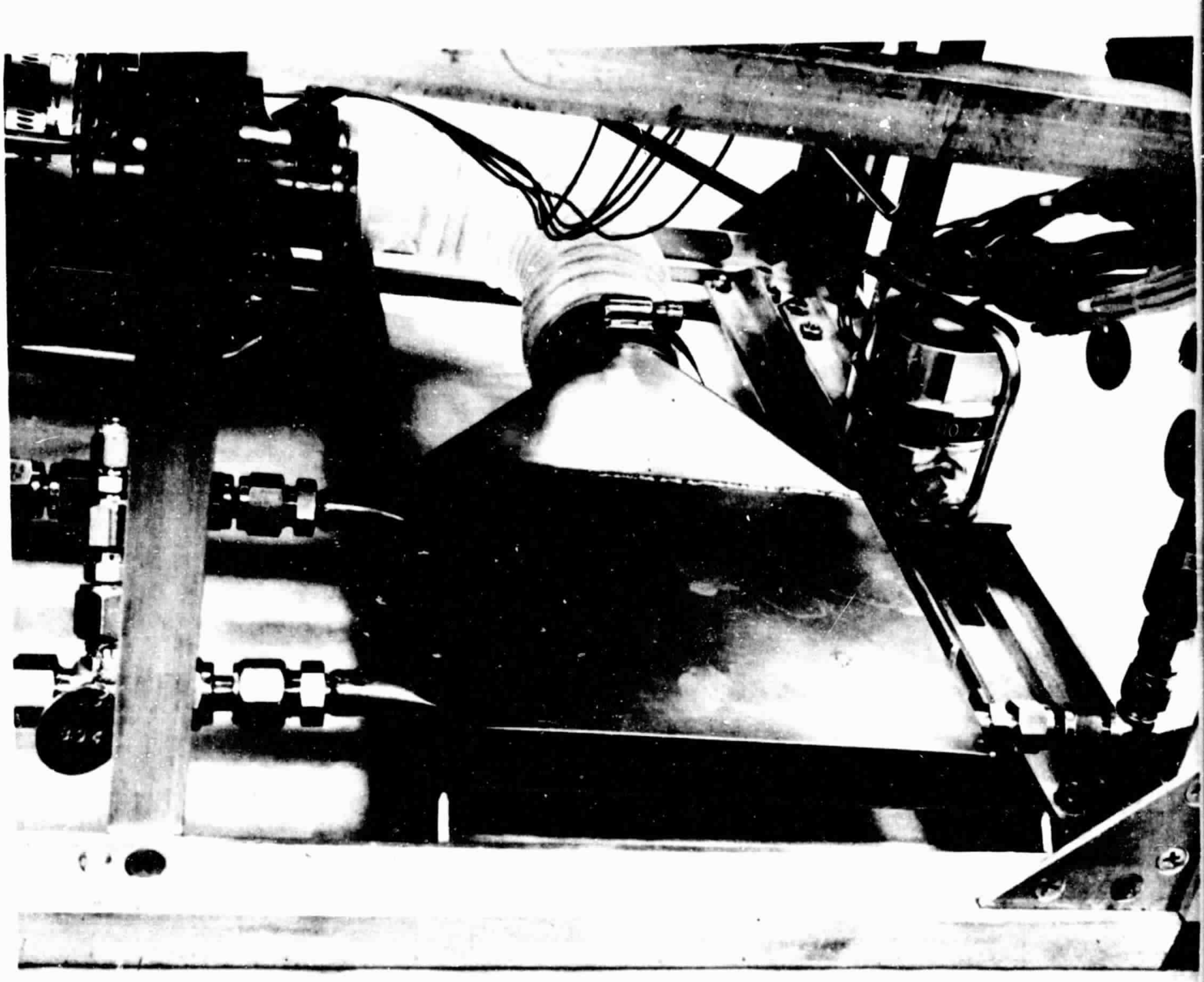

FIGURE 17
CONDENSER/SEPERATOR

Maintenance

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 H_2/CO_2 molar ratios, reactant flow rates, reactant operating pressures and gas cooling flow rates on H_2/CO_2 conversion efficiencies and reactor temperature profiles.

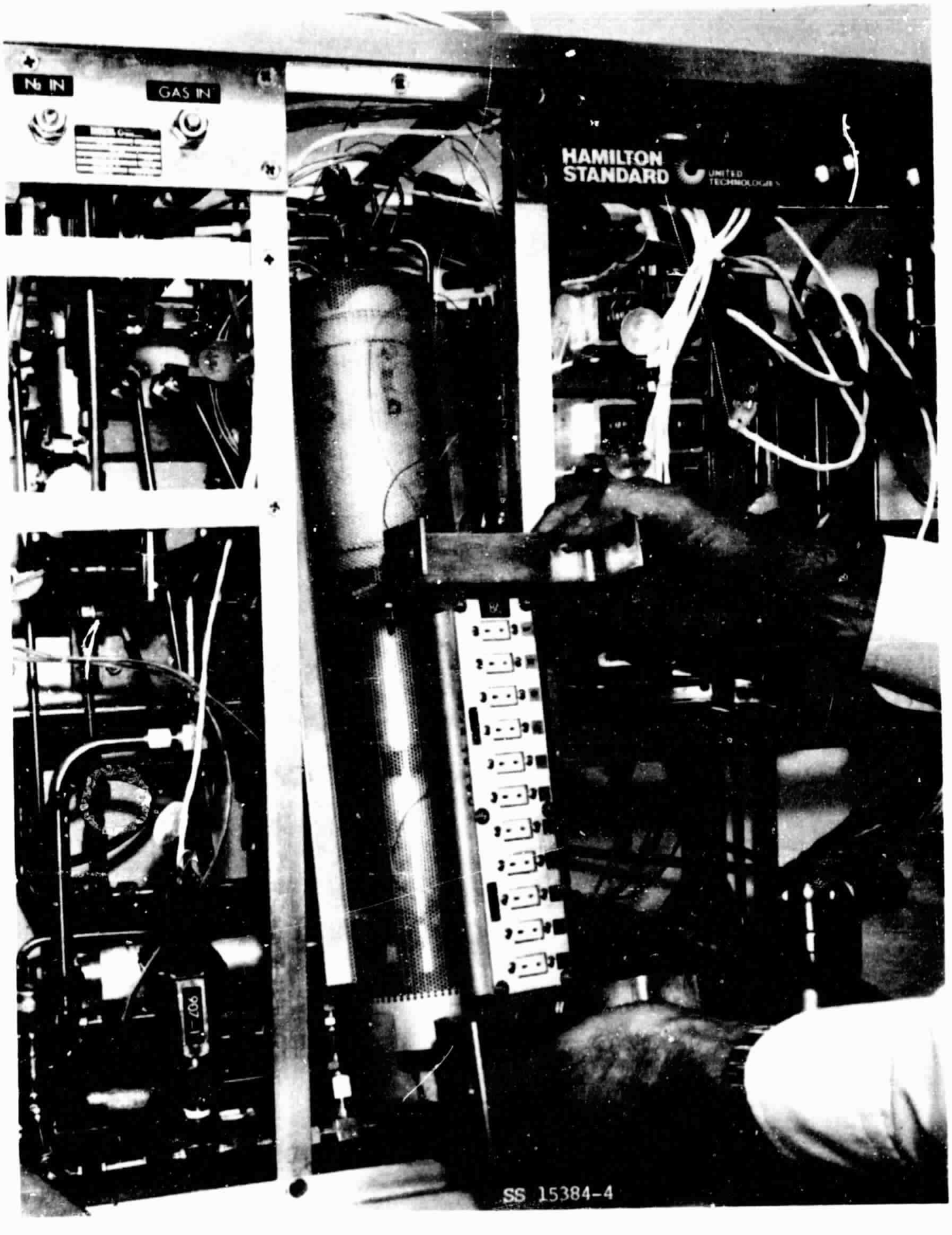
N2 IN
GAS IN
HAMILTON STANDARD UNITED TECHNOLOGIES
SS 15384-4

FIGURE 18
REACTOR INSTALLATION

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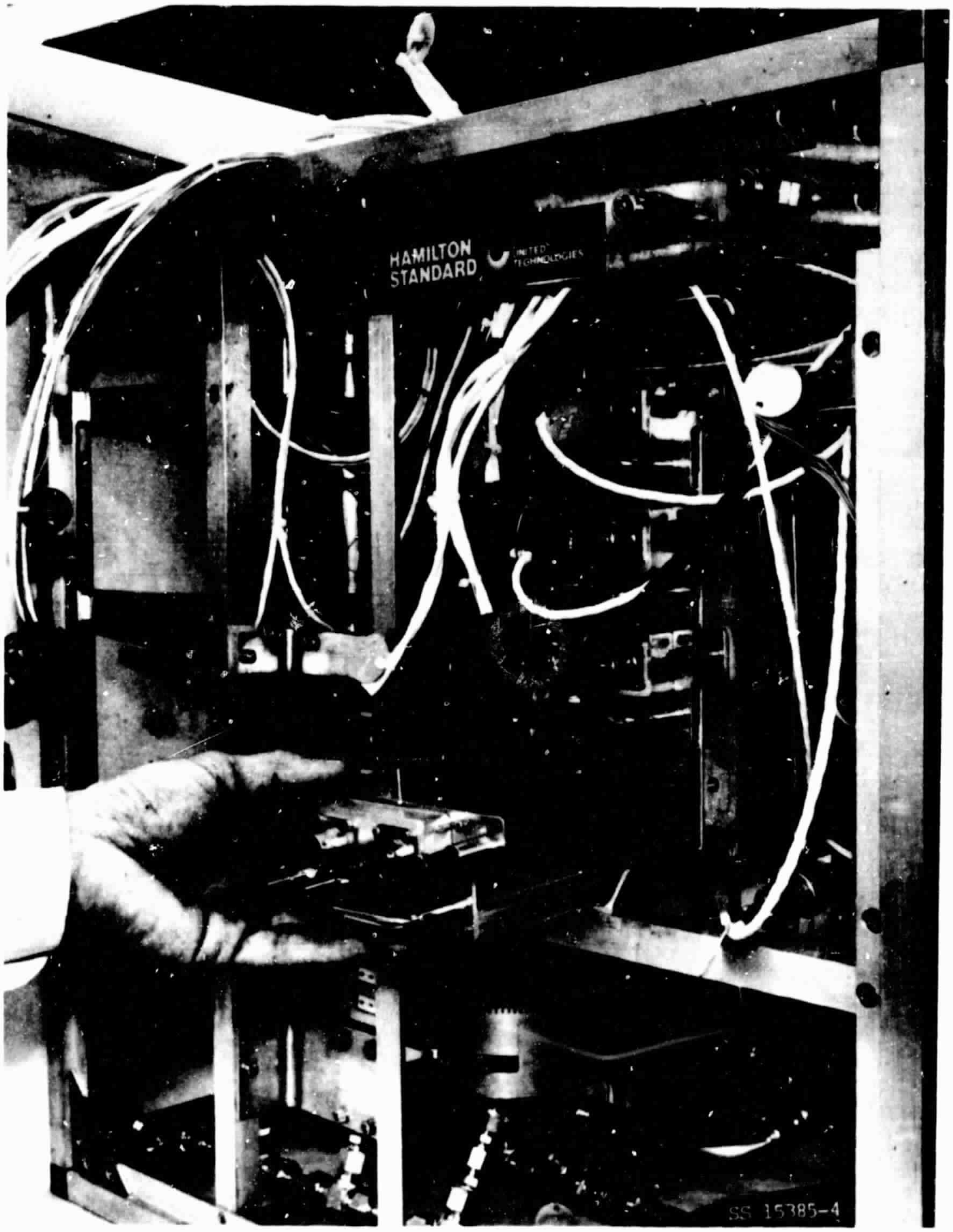
HAMILTON STANDARD
UNITED TECHNOLOGIES
SS 15385-4

FIGURE 19
GAS MONITOR INSTALLATION

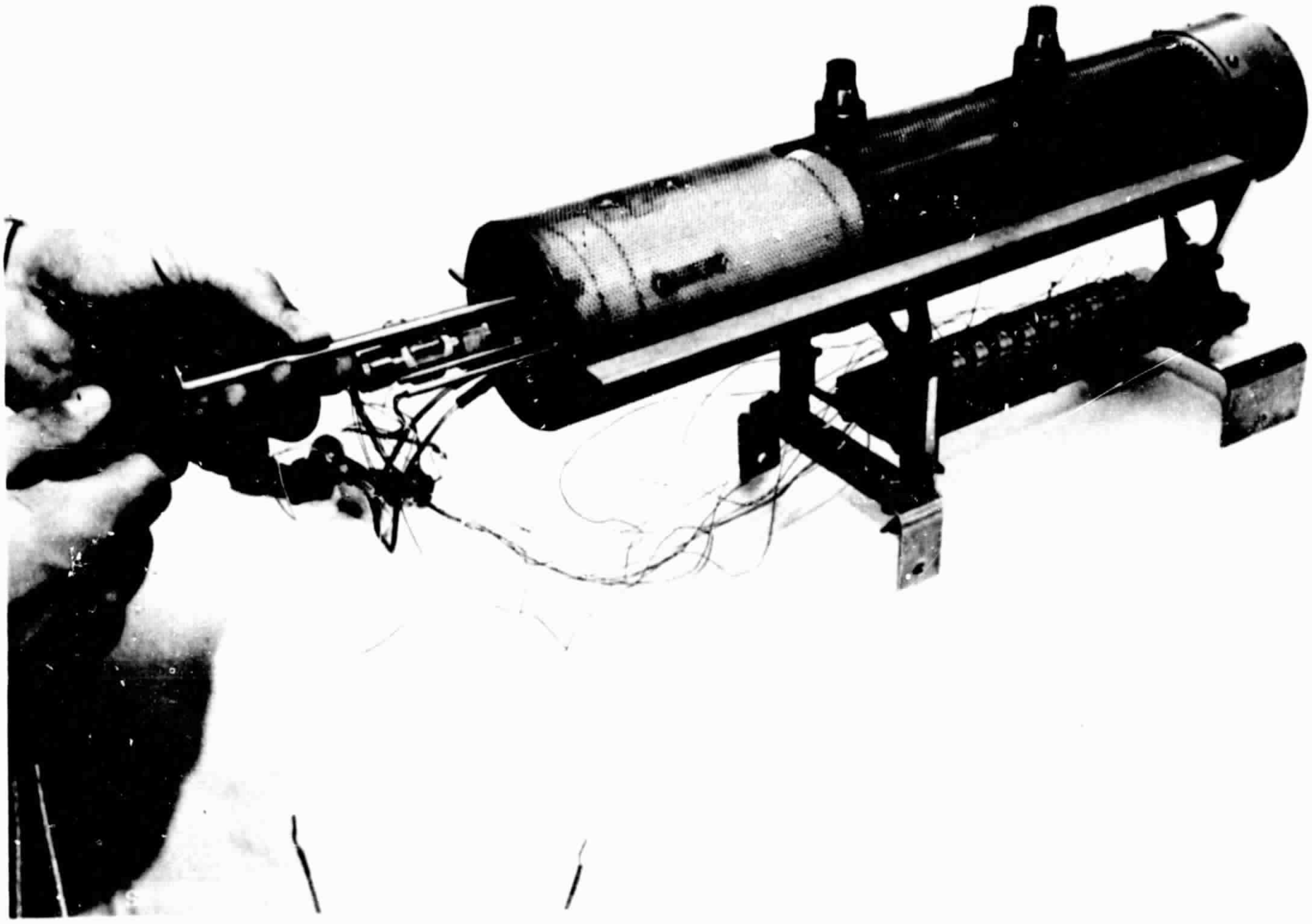

FIGURE 20
HEATER INSTALLATION

TABLE 7
PREPROTOTYPE SABATIER SUBSYSTEM
MAKE/BUY LIST

QTY. PER ASSY.	PART NO.	ITEM NO.	PART NAME	REMARKS
1	SVSK 96500	—	SABATIER PACKAGE ASSEMBLY	MAKE
1	SVSK 96467	ITEM 46	FAN, SABATIER AIR COOLING	BUY
1	SVSK 96471	ITEM 26	SILENCER, FAN	MODIFIED BUY
1	SVSK 99752	—	ADAPTER, FAN HOUSING	MAKE
1	SVSK 96490	ITEM 61	ACCUMULATOR ASSEMBLY	MODIFIED GFE
1	SVSK 96349	ITEM 51	CONDENSER, SABATIER	MAKE
1	SVSK 96482	ITEM 91	REACTOR, SABATIER	MAKE
1	SVSK 96470	ITEM 31	CANISTER, CHARCOAL	MAKE
1	SVSK 86329	ITEM 545	PUMP	GFE
5	SVSK 84424	ITEM 306	VALVE, ELECTRICAL S.O.	GFE
2	SVSK 84412	ITEM 310	REGULATOR, BACK PRESS.	GFE
4	SVSK 84530	ITEM 507	VALVE, MANUAL S.O.	GFE
4	SVSK 84456-100	ITEM 178	SENSOR-COMBUSTIBLE GAS	GFE
4	SVSK 84456-200	ITEM 178	SENSOR, MONITOR ASSEMBLY	GFE
1	SVSK 96466	ITEM 41	VALVE, CHECK	BUY
1	SVSK 101124	ITEM 42	VALVE, CHECK	BUY
1	SVSK 101126	—	FILTER, CONDENSER INLET	MAKE
1	SVSK 96465-1	ITEM 81-1	SENSOR, TEMPERATURE	BUY
1	SVSK 96465-2	ITEM 81-2	SENSOR, TEMPERATURE	BUY
1	SVSK 101128-1	ITEM 902-1	TRANSDUCER, PRESSURE-GAGE	MODIFIED GFE
1	SVSK 101128-2	ITEM 902-2	TRANSDUCER, PRESSURE-GAGE	MODIFIED GFE
1	SVSK 101129	ITEM 907	DETECTOR, LIQUID WATER	MAKE
1	SVSK 100140	—	HARNESS, ELECTRICAL	MAKE
1	SVSK 101127	—	TUBING, FLEXIBLE	BUY
1	SVSK 99753	—	HOUSING, SENSOR	MAKE
1	SVSK 101130	—	FRAME, SABATIER PACKAGE	MAKE
1	SVSK 101125-1	—	BRACKET, REACTOR, MOUNTING	MAKE
1	SVSK 101125-2	—	BRACKET, REACTOR, MOUNTING	MAKE
1	SVSK 96499	ITEM 82	SENSOR, TEMPERATURE	BUY
1	SVSK 96486	ITEM 83	HEATER - REACTOR	BUY
1	SVSK 96465	ITEM 85	SENSOR, TEMPERATURE	BUY
11	SVSK 96497	ITEM 86	THERMOCOUPLE, CHROMEL-ALUMEL	BUY
1	SVSK 96492	ITEM 259	ACCUMULATOR	MODIFIED GFE
1	SVSK 764179	ITEM 876	SENSOR, QUALITY-ACCUMULATOR	GFE
1	—	ITEM 87	THERMOCOUPLE, CHROMEL-ALUMEL	BUY
1 EA	—	ITEM 701-705	ORIFICE, CONTROL	MAKE
1 EA	—	ITEM 801-809	SAMPLE/PRESSURE PORT	BUY
1	SVSK 97813	ITEM 71	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 CO_2, H_2 and N_2 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 1.7×10^{-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 ±.055°C (±0.1°F) for the 4.4°C (40°F) to 49°C (120°F) range.

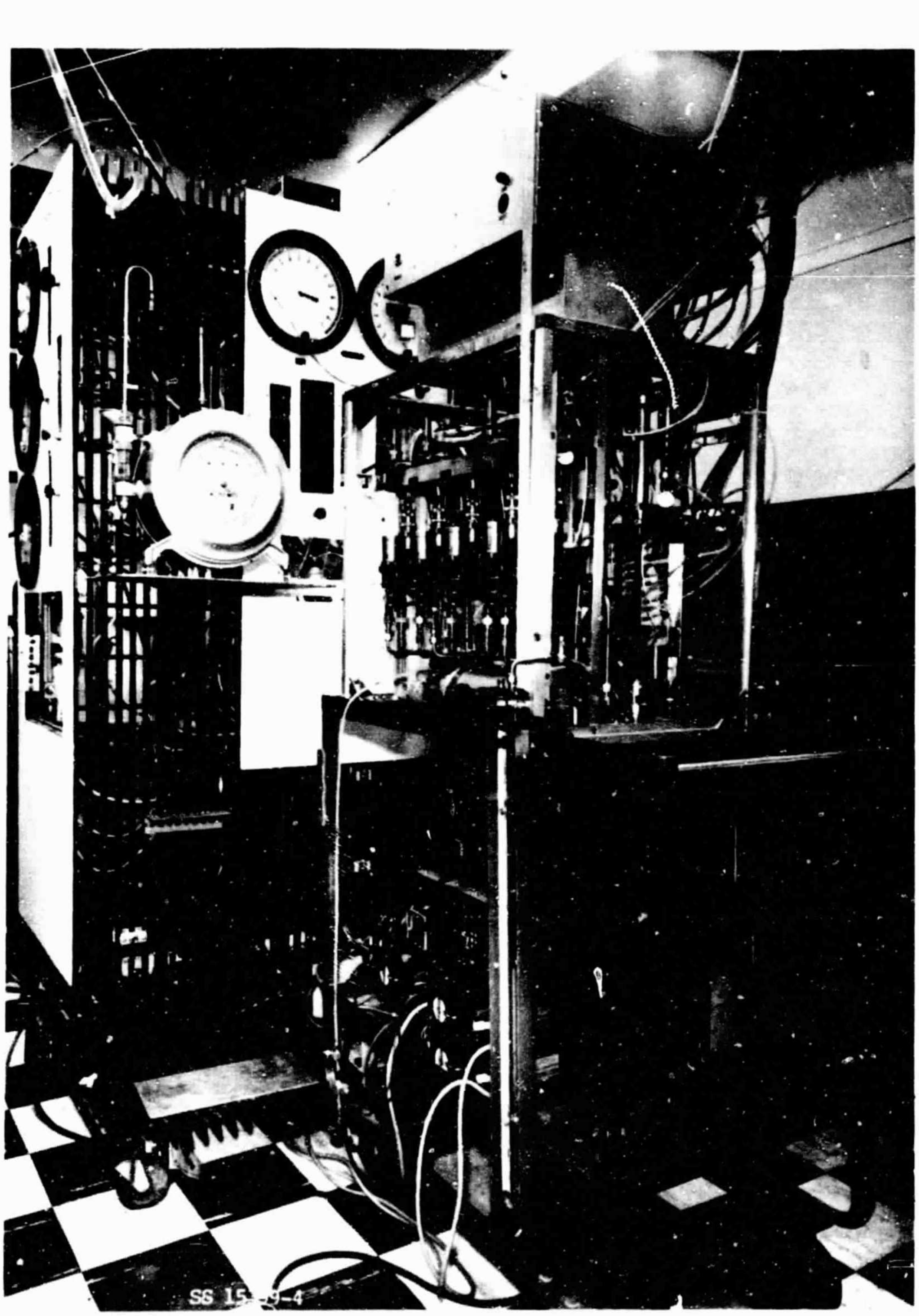

FIGURE 21
TEST RIG - FRONT

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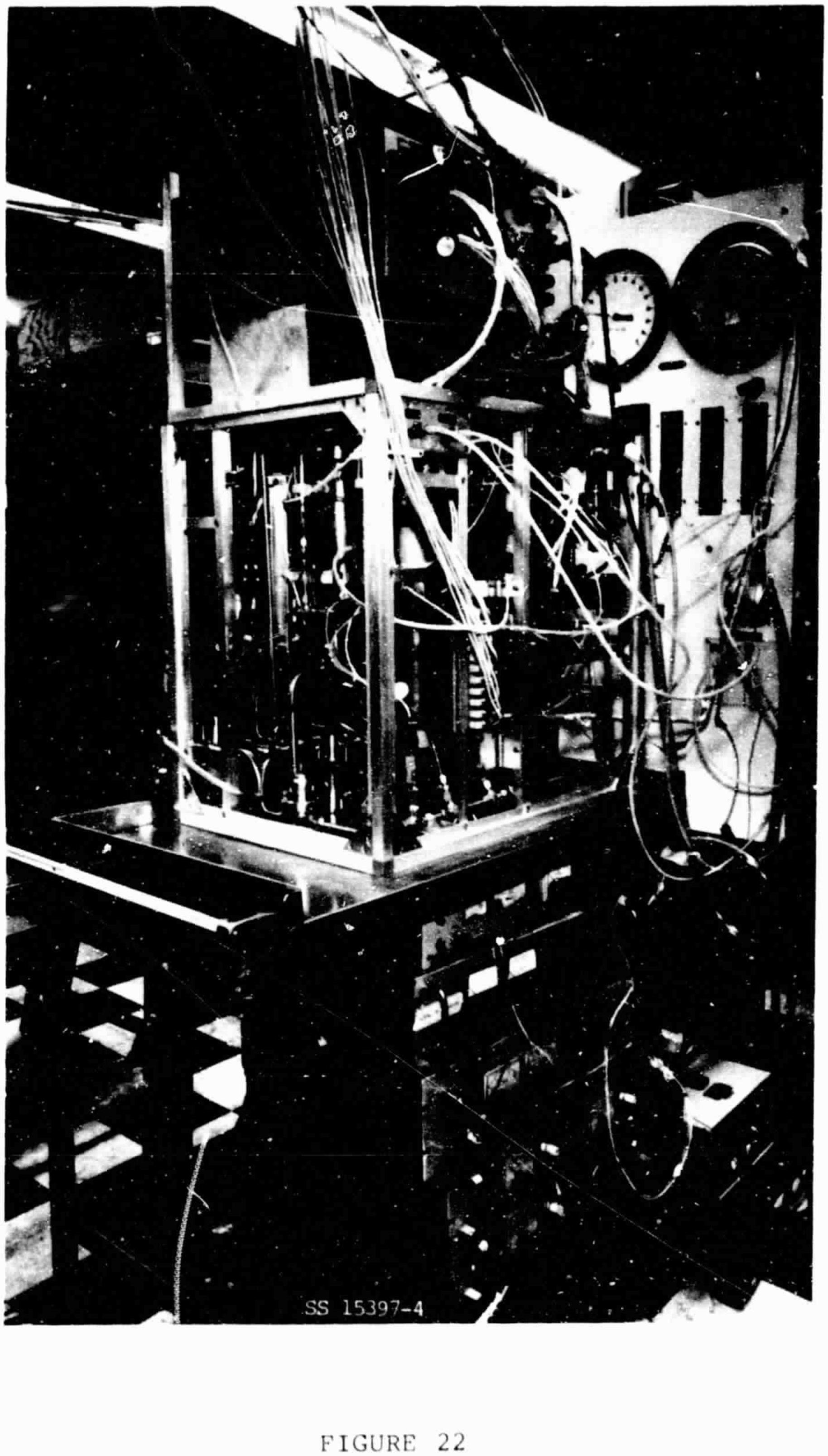

FIGURE 22
TEST RIG - REAR

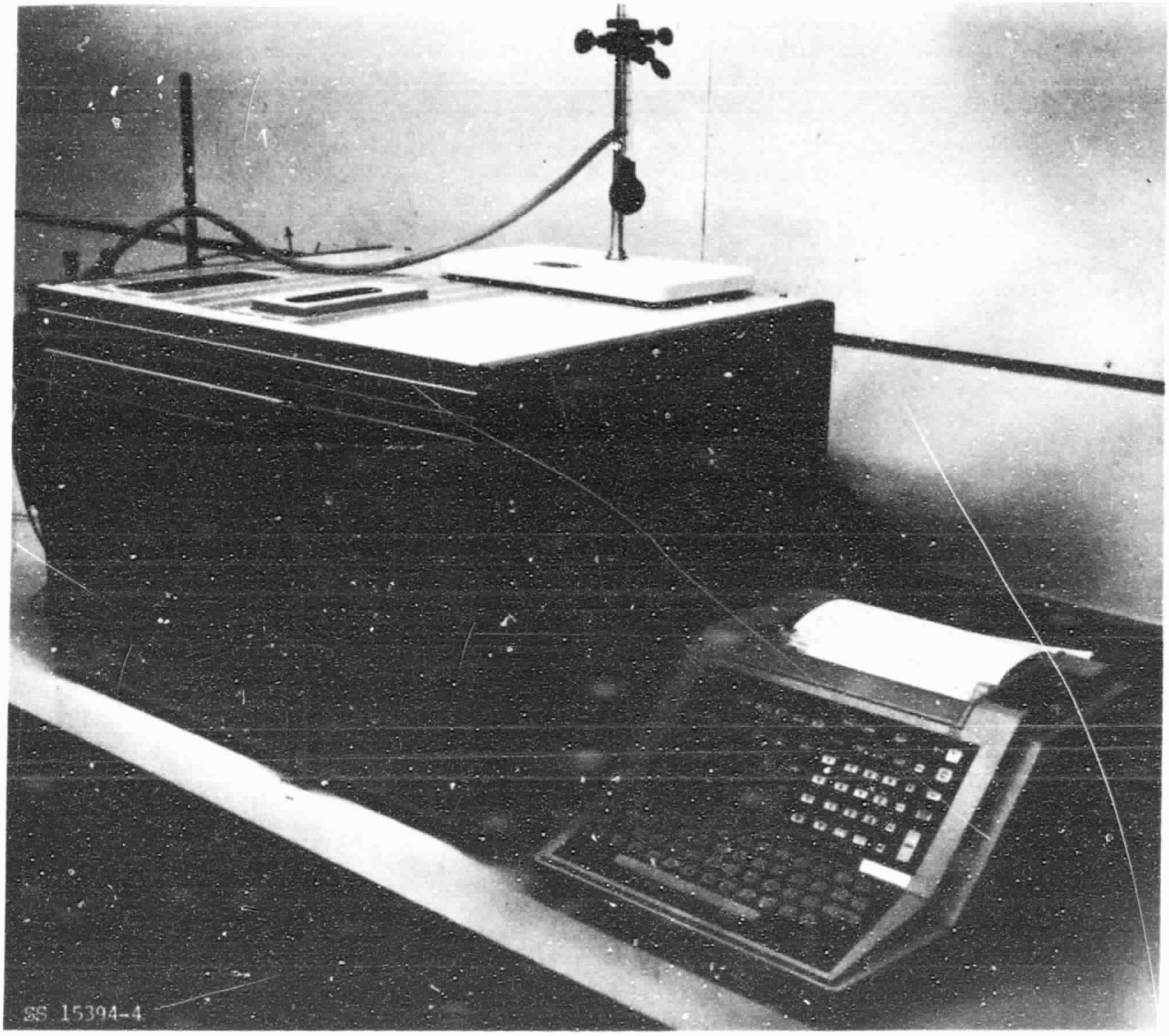

FIGURE 23
GAS CHROMATOGRAPH

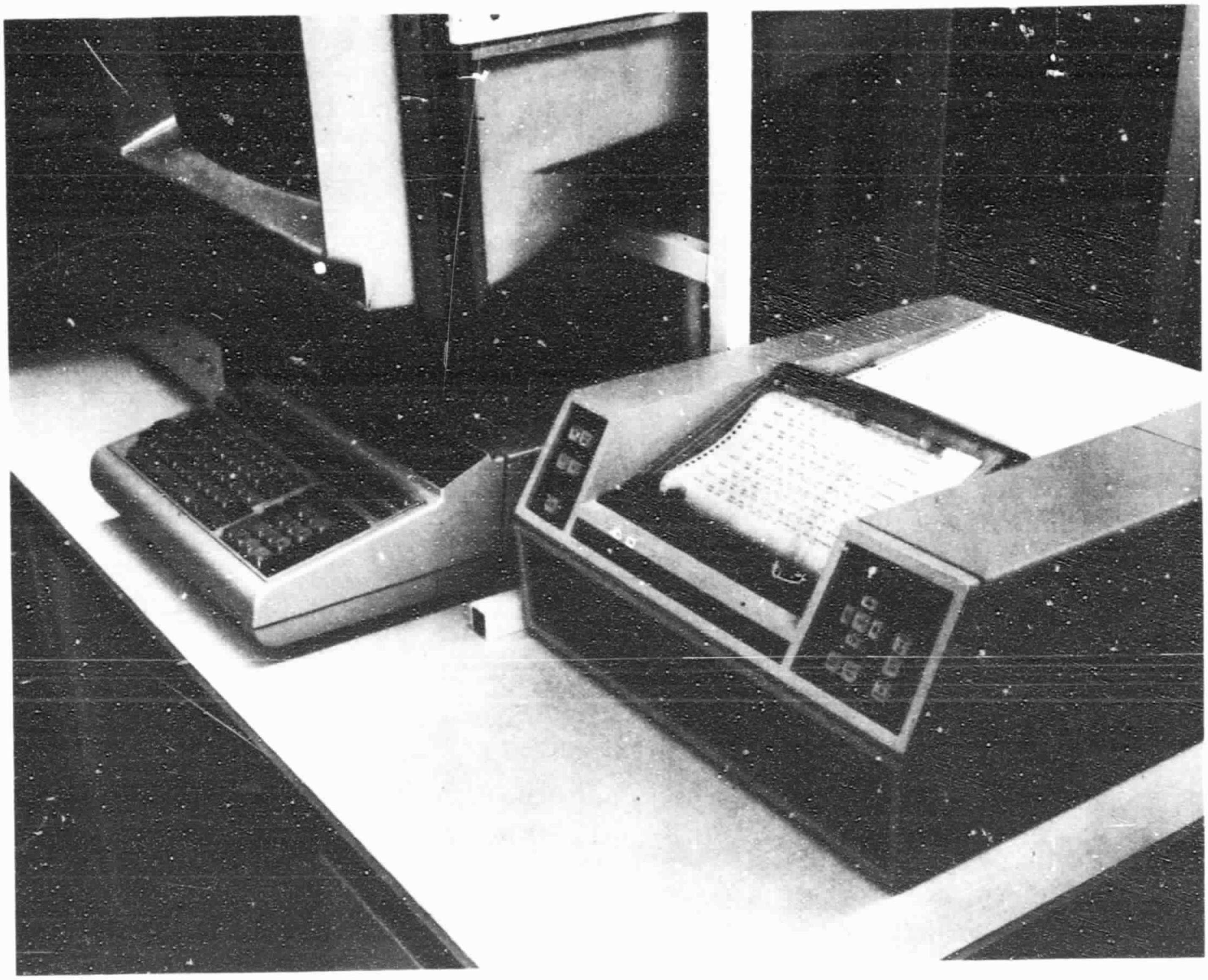

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FIGURE 24
DATA AQUISITION UNIT

HAMILTON STANDARD UNITED TECHNOLOGIES

SVHSER 7221

DATE: 2-19-80

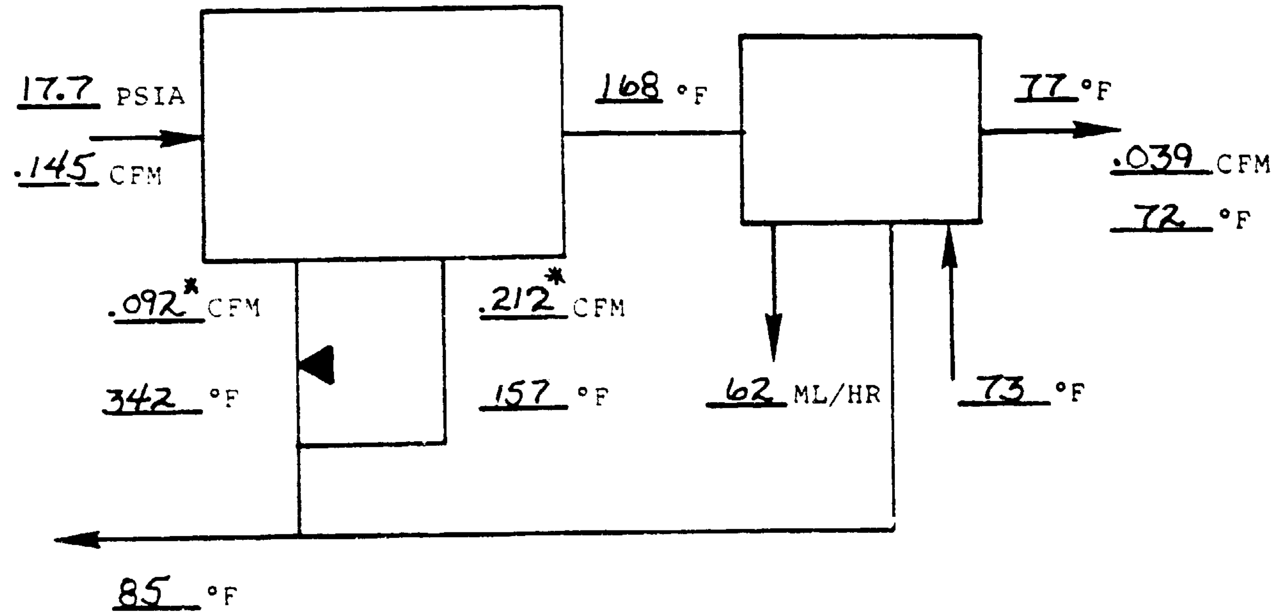
RUN NO. 53

TEST NO. 17

SABATIER

3 MAN CONT

M.R. 2.60


17.7 PSIA
.145 CFM
168 °F
77 °F
.039 CFM
72 °F
.092* CFM
342 °F
.212* CFM
157 °F
62 ML/HR
73 °F
85 °F

946 °F CONTROL

848 961 855 532 338 209 192 192 °F

925 704 391 °F

______ °F OVERTEMP

$\mathcal{E} = 99.6$

G.C. RUN NO. 22

H_2 1.02

CH_4 64.73

CO_2 34.02

* AT ROOM TEMPERATURE

FIGURE 25

SAMPLE RAW DATA TEST SUMMARY SHEET

TABLE 8

DATA RECORD METHOD

PARAMETER	WITHOUT CONTROLLER & DISPLAY			WITH CONTROLLER & DISPLAY			
	DATA ACQUISITION PRINTOUT	HAND TAB	CHROMATOGRAPH PRINTOUT	DATA ACQUISITION PRINTOUT	HAND TAB	CHROMATOGRAPH PRINTOUT	DISPLAY
TIME	x	x	x	x			
P-SUPPLY	x	x					x
P-IN	x	x			x		x
P_{N_2} WATER BACK PRESSURE	x	x			x		
REACTOR TEMPERATURES (11)	x			x			
T-REACTOR CONTROL	x						x
T-REACTOR OVERTEMPERATURE	x						x
T-CONDENSER IN	x						x
T-CONDENSER OUT	x						x
FLOW IN—FLOWRATOR		x			x		
FLOW OUT—WET GAS METER		x			x		
P BAROMETER		x			x		
GAS COMPOSITION IN		x	x		x	x	
GAS COMPOSITION OUT			x			x	
WATER OUT		x				x	
DEW POINT IN		x				x	
T-REACTOR COOLANT OUTLET (2)	x			x			
T-AMBIENT		x		x			
T-COOLANT OUT, MIXED	x			x			
WATER PRODUCTION RATE		x			x		x

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 H_2, CO, CO_2 and CH_4. 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 H_2, CH_4, CO_2 and CO quantitatively. Product gas accuracies of ±0.1% for H_2, CO_2 and CO and 0.5% CH_4 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 H_2 and CO_2 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 H_2/CO_2 molar ratios ≤ 4.0 were calculated by substituting experimentally measured values into the following equation:

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

Where x = % H_2 in dry product sample

R_{Tout} = measured dry product flow-out, cc/min

R_{H_2} in = measured H_2 reactant flow cc/min

Similarly, carbon dioxide conversion efficiencies for H_2/CO_2 molar ratios >4.0 were calculated by substitution, experimentally measured values into the following equation:

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

Where y = % CO_2 in dry product sample

R_{Tout} = measured dry product flow-out, cc/min

R_{CO_2} in = measured CO_2 reactant flow cc/min

The calculated H_2 and CO_2 conversion efficiencies are accurate to within ±0.05%. Table 9 summarizes test data tolerances.

TABLE 9

TEST DATA TOLERANCES

Item	Tolerance
Product Gas Compositions:	
H_2 and CO_2	±0.1% full scale
CH_4	±0.5% full scale
Reactant Compositions (Certified Mixtures):	
H_2 and CO_2	±0.02% full scale
Product Gas Volume	±1% of sample volume
Product Liquid Volume	±1% of sample volume
Temperature	±0.5% of reading
Pressure	±0.025 psia
Gas Coolant Flows	±2% full scale

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 Item 61	- Figure 26	- 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 Item 901-1	- Figure 27	- This item was converted from an absolute pressure transducer to a gage pressure transducer.
Pressure Transducer Item 901-2	- Figure 28	- This item was converted from an absolute pressure transducer to a gage pressure transducer.
Temperature Sensor Items 902-1, 85-1, 81-1 and 81-2	- Table 10	-
Combustible Gas Sensor Item 178	Per SVSK TR 84456	

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.

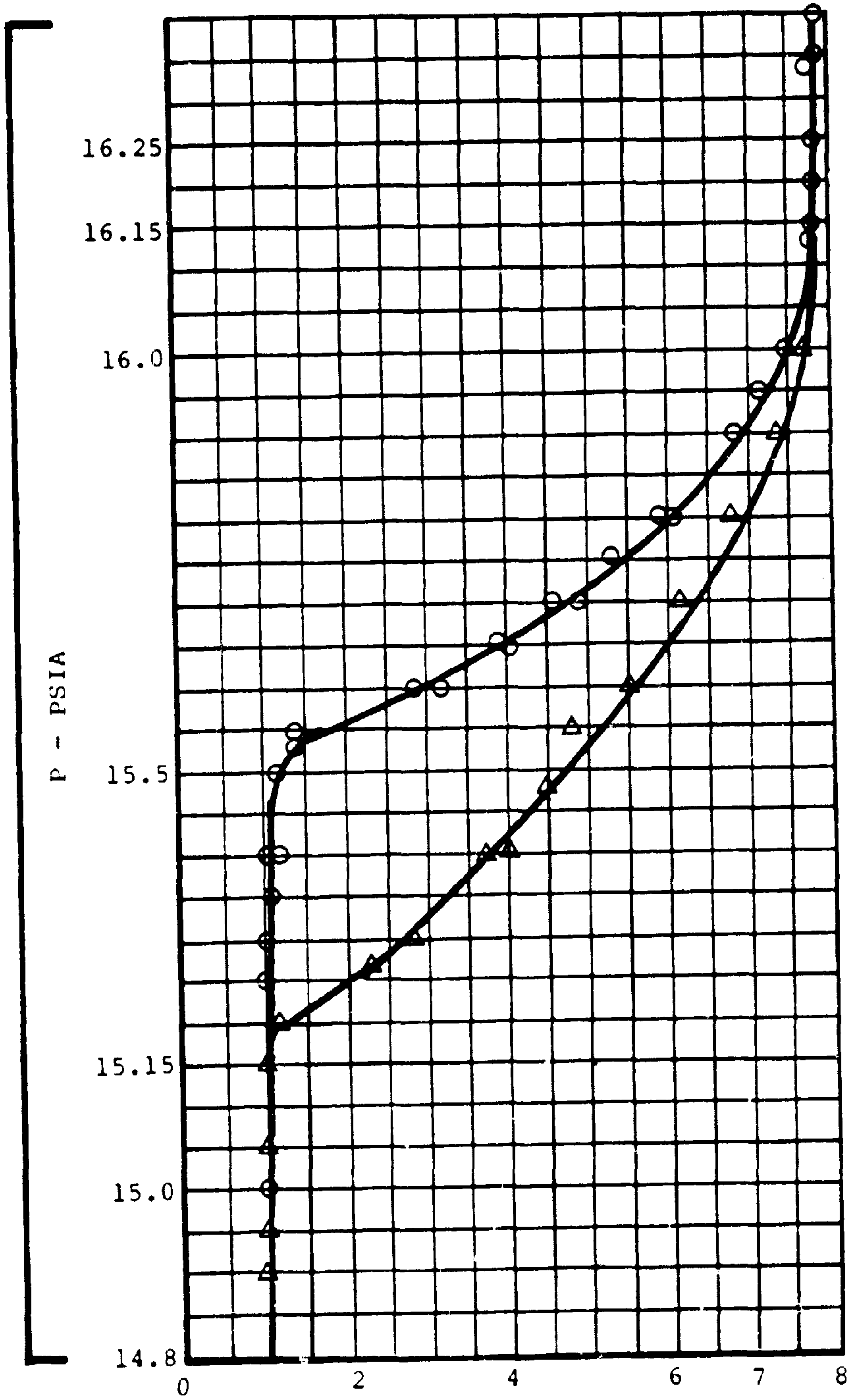


Figure 26

Accumulator Calibration Curve

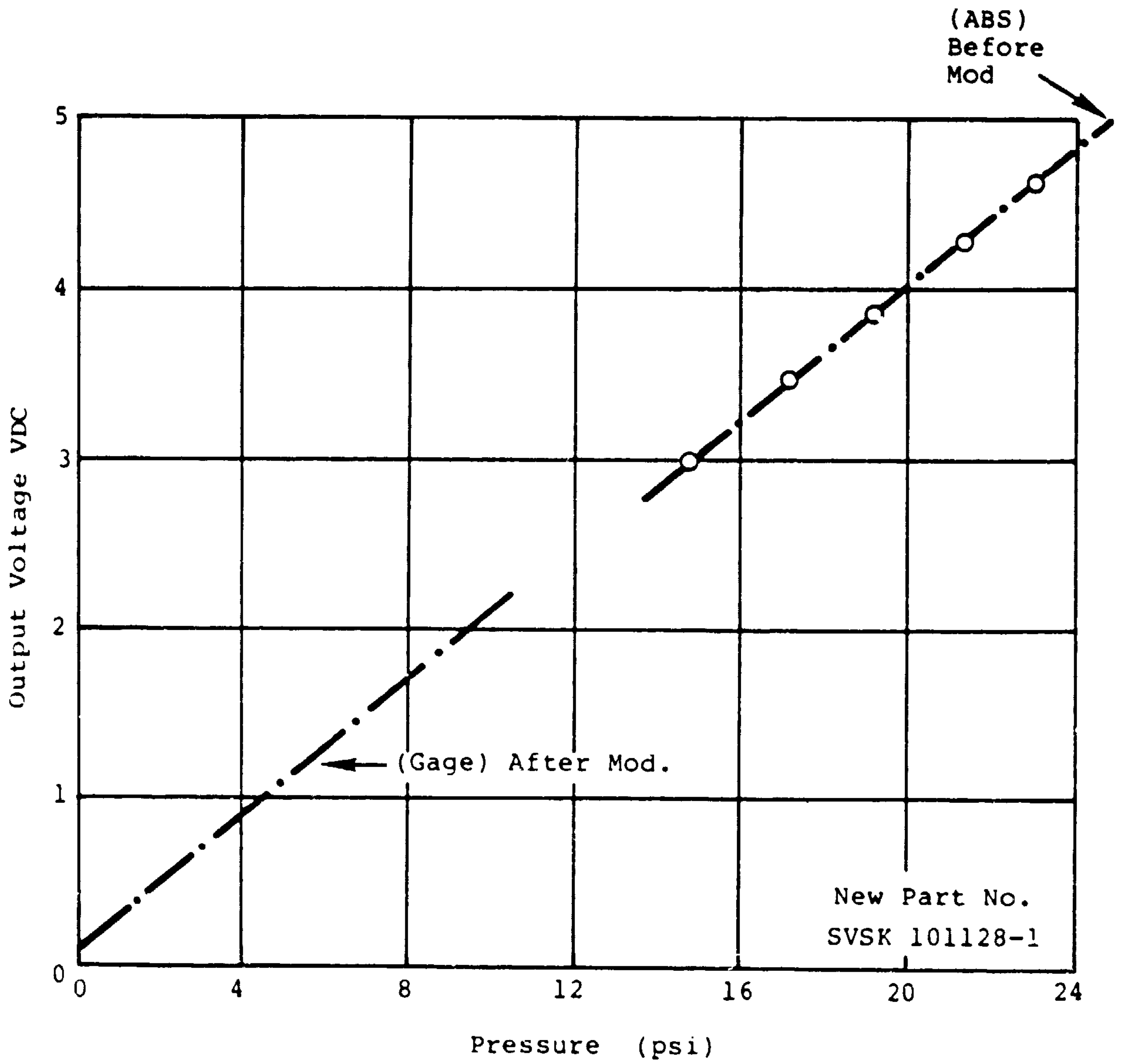


Figure 27

Sabatier I 902-1 Pressure Transducer Calibration

Rosemount 1331 AA8 S/N 308
HS P/N SVSK 84522 Ref.

Conversion To Gage Transducer

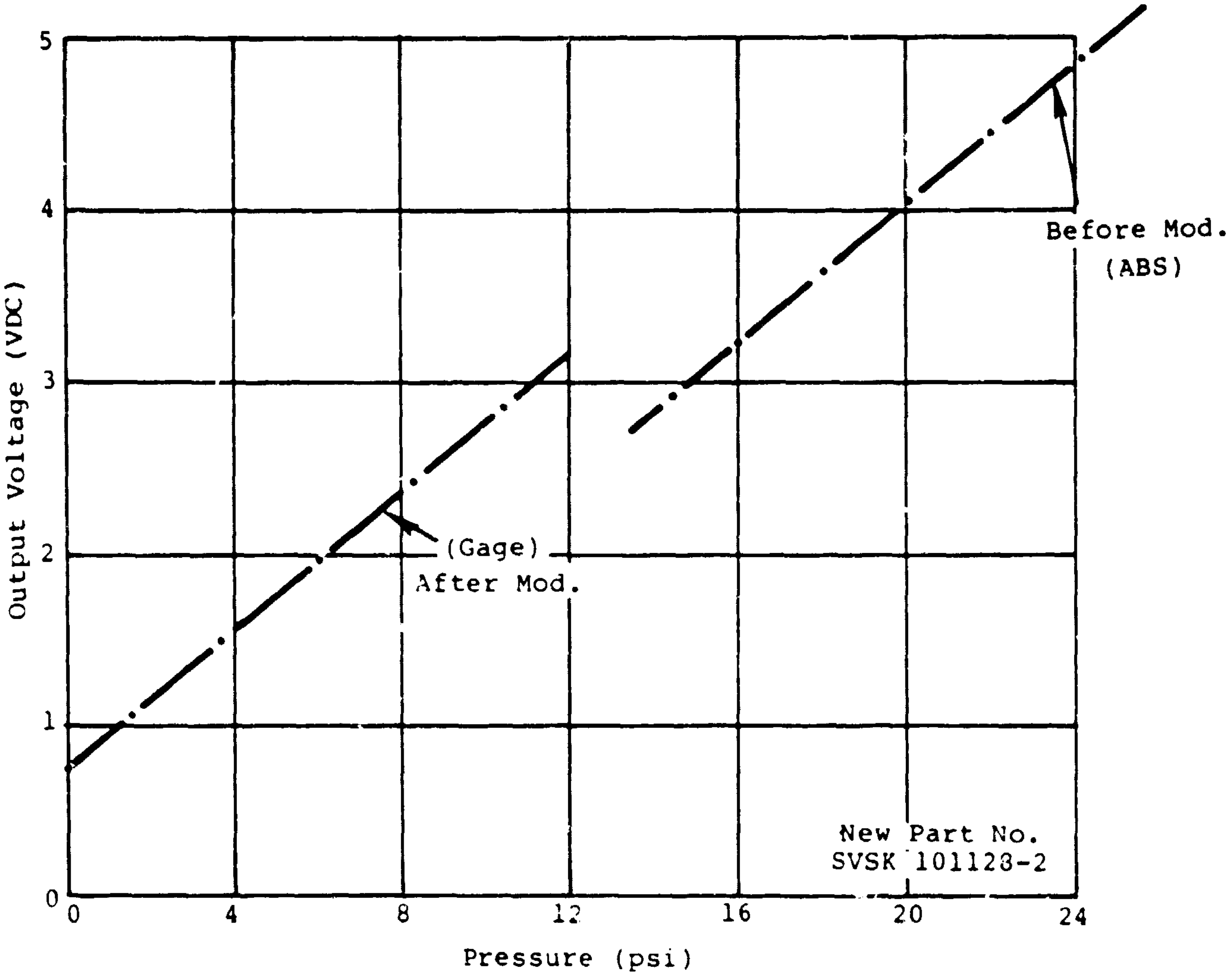


Figure 28

Sabatier I 902-2 Pressure Transducer

Rosemount 1310A8		S/N 309
HS P/N	SVSK 84522	Ref.

TABLE 10

TABLE IV R_T/R_0 vs TEMPERATURE (°F) FOR TYPICAL PURE, ANNEALED, STRAIN-FREE PLATINUM RESISTANCE TEMPERATURE SENSOR (-436 to +1500° F)

The last digit of R_T/R_0 is usually not smooth but the next-to-last is within 1 of being smooth in most parts of the table.

T (°F)	R_T/R_0	T (°F)	R_T/R_0	T (°F)	R_T/R_0	T (°F)	R_T/R_0	T (°F)	R_T/R_0	T (°F)	R_T/R_0	T (°F)	R_T/R_0	T (°F)	R_T/R_0	T (°F)	R_T/R_0
-452.1	.0007107																
436	.0014353	-220	.4279531	-4	.9200994	+212	1.3925068	+428	1.8480455	+644	2.2867114	+860	2.7085035	+1076	3.1134216	+1292	3.5014686
434	.0017054	218	.4326411	2	.9245407	214	1.3968012	430	1.8521846	646	2.2906941	862	2.7123302	1078	3.1170929	1294	3.5049807
432	.0020481	216	.4373261	0	.9289914	216	1.4010951	432	1.8563223	648	2.2946757	864	2.7161554	1080	3.1207612	1296	3.5084933
430	.0024733	214	.4420080	+2	.9334406	218	1.4053876	434	1.8604584	650	2.2986556	866	2.7199791	1082	3.1244287	1298	3.5120047
428	.0029899	212	.4466867	4	.9378883	220	1.4096787	436	1.8645932	652	2.3026342	868	2.7238014	1084	3.1280947	1300	3.5155144
426	.0035070	210	.4513625	6	.9423348	222	1.4139682	438	1.8687265	654	2.3066112	870	2.7276222	1086	3.1317594	1302	3.5190229
424	.0043356	208	.4560352	8	.9467792	224	1.4182563	440	1.8728584	656	2.3105869	872	2.7314416	1088	3.1354226	1304	3.5225298
422	.0051559	206	.4607048	10	.9512224	226	1.4225430	442	1.8769890	658	2.3145611	874	2.7352596	1090	3.1390842	1306	3.5260353
420	.0061645	204	.4653714	12	.9556641	228	1.4268282	444	1.8811179	660	2.3185338	876	2.7390761	1092	3.1427446	1308	3.5295393
418	.0072788	202	.4700353	14	.9601043	230	1.4311120	446	1.8852454	662	2.3225052	878	2.7428911	1094	3.1464034	1310	3.5330419
416	.0085344	200	.4746960	16	.9645431	232	1.4353943	448	1.8893715	664	2.3264751	880	2.7467047	1096	3.1500609	1312	3.5365431
414	.0099344	198	.4793537	18	.9689803	234	1.4396753	450	1.8934962	666	2.3304435	882	2.7505170	1098	3.1537167	1314	3.5400427
412	.0114814	196	.4840085	20	.9734161	236	1.4439547	452	1.8976194	668	2.3344104	884	2.7543277	1100	3.1573712	1316	3.5435411
410	.0131773	194	.4886608	22	.9778504	238	1.4482326	454	1.9017412	670	2.3383758	886	2.7581368	1102	3.1610243	1318	3.5470378
408	.0150244	192	.4933106	24	.9822832	240	1.4525093	456	1.9058614	672	2.3423400	888	2.7619446	1104	3.1646758	1320	3.5505332
406	.0170217	190	.4979563	26	.9867145	242	1.4567843	458	1.9099804	674	2.3463026	890	2.7657512	1106	3.1683260	1322	3.5540270
404	.0191875	188	.5025994	28	.9911444	244	1.4610580	460	1.9140977	676	2.3502638	892	2.7695562	1108	3.1719747	1324	3.5575195
402	.0214612	186	.5072403	30	.9955729	246	1.4653303	462	1.9182137	678	2.3542236	894	2.7733596	1110	3.1756219	1326	3.5610105
400	.0239018	184	.5118786	32	1.0000000	248	1.4696010	464	1.9223283	680	2.3581818	896	2.7771617	1112	3.1792678	1328	3.5645001
398	.0264561	182	.5165137	34	1.0044255	250	1.4738703	466	1.9264413	682	2.3621387	898	2.7809623	1114	3.1829122	1330	3.5679881
396	.0292115	180	.5211461	36	1.0088495	252	1.4781381	468	1.9305530	684	2.3660941	900	2.7847614	1116	3.1865551	1332	3.5714748
394	.0320703	178	.5257759	38	1.0132722	254	1.4824045	470	1.9346632	686	2.3700480	902	2.7885591	1118	3.1901964	1334	3.5749601
392	.0350580	176	.5304030	40	1.0176935	256	1.4866695	472	1.9387719	688	2.3740005	904	2.7923554	1120	3.1938367	1336	3.5784440
390	.0381689	174	.5350274	42	1.0221132	258	1.4909330	474	1.9428792	690	2.3779516	906	2.7961501	1122	3.1974751	1338	3.5819263
388	.0414004	172	.5396490	44	1.0265315	260	1.4951951	476	1.9469849	692	2.3819012	908	2.7999435	1124	3.2011122	1340	3.5854072
386	.0447421	170	.5442682	46	1.0309483	262	1.4994557	478	1.9510895	694	2.3858492	910	2.8037355	1126	3.2047479	1342	3.5888866
384	.0481912	168	.5488846	48	1.0353637	264	1.5037150	480	1.9551924	696	2.3897961	912	2.8075260	1128	3.2083822	1344	3.5923646
382	.0517439	166	.5534986	50	1.0397776	266	1.5079727	482	1.9592939	698	2.3937413	914	2.8113150	1130	3.2120150	1346	3.5958412
380	.0553932	164	.5581098	52	1.0441903	268	1.5122290	484	1.9633939	700	2.3976851	916	2.8151026	1132	3.2156463	1348	3.5993163
378	.0591346	162	.5627186	54	1.0486014	270	1.5164838	486	1.9674926	702	2.4016275	918	2.8188887	1134	3.2192762	1350	3.6027899
376	.0629677	160	.5673247	56	1.0530110	272	1.5207372	488	1.9715896	704	2.4055684	920	2.8226734	1136	3.2229047	1352	3.6062622
374	.0668756	158	.5719285	58	1.0574192	274	1.5249892	490	1.9756854	706	2.4095079	922	2.8264566	1138	3.2265317	1354	3.6097330
372	.0708627	156	.5765296	60	1.0618260	276	1.5292397	492	1.9797797	708	2.4134459	924	2.8302384	1140	3.2301573	1356	3.6132023
370	.0749241	154	.5811283	62	1.0662313	278	1.5334888	494	1.9838725	710	2.4173825	926	2.8340187	1142	3.2337813	1358	3.6166701
368	.0790527	152	.5857215	64	1.0706352	280	1.5377364	496	1.9879639	712	2.4213177	928	2.8377977	1144	3.2374040	1360	3.6201366
366	.0832443	150	.5903184	66	1.0750375	282	1.5419826	498	1.9920539	714	2.4252512	930	2.8415751	1146	3.2410251	1362	3.6236015
364	.0874929	148	.5949097	68	1.0794385	284	1.5462273	500	1.9961424	716	2.4291835	932	2.8453512	1148	3.2446449	1364	3.6270651
362	.0917955	146	.5994987	70	1.0838381	286	1.5504705	502	2.0002293	718	2.4331144	934	2.8491257	1150	3.2482633	1366	[illegible]
360	.0961473	144	.6040853	72	1.0882360	288	1.5547125	504	2.0043150	720	2.4370437	936	2.8528988	1152	3.2518801	1368	[illegible]
358	.1005454	142	.6086695	74	1.0926327	290	1.5589527	506	2.0083990	722	2.4409716	938	2.8566705	1154	3.2554957	1370	[illegible]
356	.1049872	140	.6132515	76	1.0970278	292	1.5631917	508	2.0124818	724	2.4448981	940	2.8604406	1156	3.2591096	1372	3.6408947
354	.1094896	138	.6178308	78	1.1014217	294	1.5674292	510	2.0165630	726	2.4488231	942	2.8642095	1158	3.2627221	1374	[illegible]
352	.1139881	136	.6224079	80	1.1058139	296	1.5716653	512	2.0206429	728	2.4527467	944	2.8679768	1160	3.2663332	1376	3.6478105
350	.1185135	134	.6269829	82	1.1102047	298	1.5758999	514	2.0247212	730	2.4566688	946	2.8717427	1162	3.2699428	1378	3.6512693
348	.1231313	132	.6315555	84	1.1145941	300	1.5801329	516	2.0287981	732	2.4605895	948	2.8755071	1164	3.2735510	1380	3.6547212
346	.1277485	130	.6361258	86	1.1189821	302	1.5843647	518	2.0328735	734	2.4645087	950	2.8792701	1166	3.2771578	1382	3.6581717
344	.1323929	128	.6406938	88	1.1233686	304	1.5885950	520	2.0369475	736	2.4684266	952	2.8830316	1168	3.2807631	1384	3.6616207
342	.1370604	126	.6452597	90	1.1277535	306	1.5928237	522	2.0410201	738	2.4723428	954	2.8867916	1170	3.2843668	1386	3.6650683
340	.1417476	124	.6498233	92	1.1321373	308	1.5970511	524	2.0450914	740	2.4762578	956	2.8905503	1172	3.2879693	1388	3.6685146
338	.1464523	122	.6543847	94	1.1365193	310	1.6012771	526	2.0491609	742	2.4801712	958	2.8943075	1174	3.2915703	1390	3.6719592
336	.1511730	120	.6589438	96	1.1409001	312	1.6055014	528	2.0532292	744	2.4840831	960	2.8980634	1176	3.2951698	1392	3.6754020
334	.1559061	118	.6635009	98	1.1452794	314	1.6097244	530	2.0572960	746	2.4879937	962	2.9018176	1178	3.2987679	1394	3.6788444
332	.1606508	116	.6680557	100	1.1496570	316	1.6139461	532	2.0613613	748	2.4919028	964	2.9055706	1180	3.3023646	1396	3.6822848
330	.1654063	114	.6726085	102	1.1540332	318	1.6181661	534	2.0654252	750	2.4958104	966	2.9093220	1182	3.3059597	1398	3.6857238
328	.1701725	112	.6771590	104	1.1584085	320	1.6223848	536	2.0694877	752	2.4997166	968	2.9130719	1184	3.3095534	1400	3.6891613
326	.1749489	110	.6817075	106	1.1627812	322	1.6266021	538	2.0735486	754	2.5036214	970	2.9168205	1186	3.3131457	1402	3.6925974
324	.1797298	108	.6862538	108	1.1671539	324	1.6308180	540	2.0776081	756	2.5075247	972	2.9205675	1188	3.3167365	1404	3.6960321
322	.1845210	106	.6907981	110	1.1715245	326	1.6350323	542	2.0816663	758	2.5114265	974	2.9243132	1190	3.3203259	1406	3.6994650
320	.1893158	104	.6953404	112	1.1758936	328	1.6392451	544	2.0857230	760	2.5153270	976	2.9280573	1192	3.3239138	1408	3.7028967
318	.1941253	102	.6998806	114	1.1802613	330	1.6434567	546	2.0897781	762	2.5192259	978	2.9318001	1194	3.3275004	1410	3.7063269
316	.1989373	100	.7044187	116	1.1846278	332	1.6476666	548	2.0938320	764	2.5231234	980	2.9355414	1196	3.3310854	1412	3.7097557
314	.2037543	98	.7089547	118	1.1889927	334	1.6518753	550	2.0978842	766	2.5270196	982	2.9392812	1198	3.3346691	1414	3.7131831
312	.2085760	96	.7134889	120	1.1933557	336	1.6560822	552	2.1019351	768	2.5309142	984	2.9430196	1200	3.3382511	1416	3.7166090
310	.2134059	94	.7180210	122	1.1977177	338	1.6602878	554	2.1059845	770	2.5348074	986	2.9467565	1202	3.3418317	1418	3.7200335
308	.2182261	92	.7225510	124	1.2020780	340	1.6644922	556	2.1100325	772	2.5386991	988	2.9504920	1204	3.3454111	1420	3.7234566
306	.2230689	90	.7270792	126	1.2064371	342	1.6686949	558	2.1140791	774	2.5425894	990	2.9542261	1206	3.3489890	1422	3.7268783
304	.2279053	88	.7316053	128	1.2107946	344	1.6728962	560	2.1181241	776	2.5464782	992	2.9579587	1208	3.3525654	1424	[illegible]
302	.2327443	86	.7361296	130	1.2151508	346	1.6770961	562	2.1221678	778	2.5503656	994	2.9616897	1210	3.3561402	1426	[illegible]
300	.2375797	84	.7406519	132	1.2195054	348	1.6812945	564	2.1262099	780	2.5542316	996	2.9654196	1212	3.3597137	1428	[illegible]
298	.2424182	82	.7451724	134	1.2238587	350	1.6854915	566	2.1302508	782	2.5581360	998	2.9691479	1214	3.3632857	1430	[illegible]
296	.2472596	80	.7496907	136	1.2282104	352	1.6896870	568	2.1342900	784	2.5620192	1000	2.9728748	1216	3.3668564	1432	[illegible]
294	.2520855	78	.7542073	138	1.2325607	354	1.6938813	570	2.1383279	786	2.5659007	1002	2.9766000	1218	3.3704255	1434	[illegible]
292	.2568871	76	.7587220	140	1.2369096	356	1.6980738	572	2.1423642	788	2.5697810	1004	2.9803240	1220	3.3739931	1436	[illegible]
290	.2617049	74	.7632348	142	1.2412570	358	1.7022650	574	2.1463993	790	2.5736597	1006	2.9840464	1222	3.3775594	1438	[illegible]
288	.2665184	72	.7677458	144	1.2456030	360	1.7064547	576	2.1504328	792	2.5775370	1008	2.9877674	1224	3.3811241	1440	[illegible]
286	.2713279	70	.7722549	146	1.2499476	362	1.7106430	578	2.1544648	794	2.5814128	1010	2.9914871	1226	3.3846875	1442	[illegible]
284	.2761334	68	.7767622	148	1.2542907	364	1.7148299	580	2.1584954	796	2.5852872	1012	2.9952052	1228	3.3882495	1444	[illegible]
282	.2809349	66	.7812676	150	1.2586324	366	1.7190153	582	2.1625245	798	2.5891601	1014	2.9989218	1230	3.3918099	1446	[illegible]
280	.2857314	64	.7857713	152	1.2629725	368	1.7231993	584	2.1665522	800	2.5930316	1016	3.0026371	1232	3.3953691	1448	[illegible]
278	.2905261	62	.7902732	154	1.2673113	370	1.7273818	586	2.1705785	802	2.5969016	1018	3.0063509	1234	3.3989264	1450	[illegible]
276	.2953134	60	.7947731	156	1.2716486	372	1.7315628	588	2.1746034	804	2.6007702	1020	3.0100632	1236	3.4024836	1452	[illegible]
274	.3001026	58	.7992714	158	1.2759845	374	1.7357423	590	[illegible]	806	2.6046373	1022	3.0137742	1238	3.4060391	1454	[illegible]
272	.3048937	56	.8037680	160	1.2803189	376	1.7399207	592	[illegible]	808	2.6085031	1024	3.0174837	1240	3.4095932	1456	[illegible]
270	.3096616	54	.8082628	162	1.2846518	378	1.7440974	594	[illegible]	810	2.6123673	1026	3.0211917	1242	3.4131457	1458	[illegible]
268	.3144562	52	.8127558	164	1.2889833	380	1.7482727	596	[illegible]	812	2.6162301	1028	3.0248983	1244	3.4166972	1460	[illegible]
266	.3192361	50	.8172470	166	1.2933135	382	1.7524466	598	[illegible]	814	2.6200915	1030	3.0286034	1246	3.4202470	1462	[illegible]
264	.3239737	48	.8217365	168	1.2976422	384	[illegible]	600	[illegible]	816	2.6239514	1032	3.0323070	1248	3.4237952	1464	[illegible]
262	.3287169	46	.8262244	170	[illegible]	386	[illegible]	602	[illegible]	818	2.6278099	1034	3.0360093	1250	[illegible]	1466	[illegible]
260	.3334944	44	.8307104	172	[illegible]	388	[illegible]	604	[illegible]	820	2.6316669	1036	3.0397100	1252	[illegible]	1468	[illegible]
258	.3382531	42	.8351948	174	[illegible]	390	[illegible]	606	[illegible]	822	2.6355224	1038	3.0434094	1254	[illegible]	1470	[illegible]
256	.3430044	40	.8396777	176	[illegible]	392	[illegible]	608	[illegible]	824	[illegible]	1040	3.0471073	1256	[illegible]	1472	[illegible]
254	.3477530	38	.8441587	178	[illegible]	394	[illegible]	610	[illegible]	826	[illegible]	1042	3.0508037	1258	[illegible]	1474	[illegible]
252	.3524981	36	.8486381	180	[illegible]	396	[illegible]	612	[illegible]	828	[illegible]	1044	3.0544987	1260	[illegible]	1476	[illegible]
250	.3572314	34	.8531158	182	[illegible]	398	[illegible]	614	[illegible]	830	[illegible]	1046	3.0581923	1262	[illegible]	1478	[illegible]
248	.3619776	32	.8575920	184	[illegible]	400	[illegible]	616	[illegible]	832	[illegible]	1048	3.0618844	1264	[illegible]	1480	[illegible]
246	.3667110	30	.8620663	186	[illegible]	402	[illegible]	618	[illegible]	834	[illegible]	1050	[illegible]	1266	[illegible]	1482	[illegible]
244	.3714425	28	.8665392	188	[illegible]	404	[illegible]	620	[illegible]	836	[illegible]	1052	[illegible]	1268	[illegible]	1484	[illegible]
242	.3761703	26	.8710104	190	[illegible]	406	[illegible]	622	[illegible]	838	[illegible]	1054	[illegible]	1270	[illegible]	1486	[illegible]
240	.3808946	24	.8754798	192	[illegible]	408	[illegible]	624	[illegible]	840	[illegible]	1056	[illegible]	1272	[illegible]	1488	[illegible]
238	.3856142	22	[illegible]	194	[illegible]	410	[illegible]	626	[illegible]	842	[illegible]	1058	[illegible]	1274	[illegible]	1490	[illegible]
236	[illegible]	20	[illegible]	196	[illegible]	412	[illegible]	628	[illegible]	844	[illegible]	1060	[illegible]	1276	[illegible]	1492	[illegible]
234	[illegible]	18	[illegible]	198	[illegible]	414	[illegible]	630	[illegible]	846	[illegible]	1062	[illegible]	1278	[illegible]	1494	[illegible]
232	[illegible]	16	[illegible]	200	[illegible]	416	[illegible]	632	[illegible]	848	[illegible]	1064	[illegible]	1280	[illegible]	1496	[illegible]
230	[illegible]	14	[illegible]	202	[illegible]	418	[illegible]	634	[illegible]	850	[illegible]	1066	[illegible]	1282	[illegible]	1498	[illegible]
228	[illegible]	12	[illegible]	204	[illegible]	420	[illegible]	636	[illegible]	852	[illegible]	1068	[illegible]	1284	[illegible]	1500	[illegible]
226	[illegible]	10	[illegible]	206	[illegible]	422	[illegible]	638	[illegible]	854	[illegible]	1070	[illegible]	1286	[illegible]		
224	[illegible]	8	[illegible]	208	[illegible]	424	[illegible]	640	[illegible]	856	[illegible]	1072	[illegible]	1288	[illegible]		
222	[illegible]	6	[illegible]	210	[illegible]	426	[illegible]	642	[illegible]	858	[illegible]	1074	[illegible]	1290	[illegible]		

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OF POOR QUALITY

TABLE 10 (CONTINUED)

TABLE 10 R_T/R_0 = TEMPERATURE (°C) FOR TYPICAL PURE, ANNEALED, STRAIN-FREE PLATINUM RESISTANCE TEMPERATURE SENSOR [illegible]

[illegible]

T (°C)	R_T/R_0	T (°C)	R_T/R_0	T (°C)	R_T/R_0	T (°C)	R_T/R_0	T (°C)	R_T/R_0	T (°C)	R_T/R_0	T (°C)	R_T/R_0	T (°C)	R_T/R_0	T (°C)	R_T/R_0	T (°C)	R_T/R_0
-258.95	[illegible]																		
[illegible]	[illegible]	-152	.3771136	-44	.8235319	+64	[illegible]	+172	[illegible]	+280	[illegible]	+388	[illegible]	+496	[illegible]	+604	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	151	[illegible]	43	.8275704	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	150	[illegible]	42	.8316075	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	149	[illegible]	41	.8356433	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	148	[illegible]	40	.8396777	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	147	[illegible]	39	.8437108	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	146	[illegible]	38	.8477426	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	145	[illegible]	37	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
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Table 11

SABATIER TEST LOG

Test No.	Test Description	Molar Ratio H_2/CO_2	Test Time Req'd Hrs.	Actual Test Time Hrs.	Certified Premixed Gas	
					Req'd	Test
1	3 Man Cont.	2.6	2	2.25	✓	✓
2	" " "	2.6	2	2.0	✓	✓
3	" " "	2.6	2	5.0	✓	✓
4	3 Man Cyclic	2.6	2	2.25	✓	✓
5	" " "	2.6	2	4.75	✓	✓
6	" " "	2.6	2	3.75	✓	✓
7	1 Man Cont.	1.8	2	2.8	✓	✓
8	3 Man Cyclic	1.8	2	4.0	✓	✓
9	1 Man Cont.	5.0	2	2.0	✓	✓
10	3 Man Cyclic	5.0	2	3.0	✓	✓
11	1 Man Cont.	1.8	2	3.25		✓
12	3 Man Cont.	1.8	2	4.7	✓	✓
13	3 Man Cyclic	1.8	2	4.0		✓
14	1 Man Cont.	2.6	50	57.0		✓
15	3 Man Cont.	2.6	8	12.75	✓	✓
16	" " "	2.6	120	120.0		
17	" " "	2.6	8	84.85	✓	✓
18	3 Man Cyclic	2.6	10	38.75		
19	10 Man Cont.	2.6	10	12.25		
20	1 Man Cont.	3.5	2	5.25		
21	3 Man Cont.	3.5	2	8.7	✓	✓
22	3 Man Cyclic	3.5	2	5.0		
			238	388.3		

Table 11 (Continued)

SABATIER TEST LOG

Test No.	Test Description	Molar Ratio H_2/CO_2	Test Time Req'd Hrs.	Actual Test Time Hrs.	Certified Premixed Gas	
					Req'd	Test
23	1 Man Cont.	4.0	2	7.5		✓
24	3 Man Cont.	4.0	2	12.5	✓	✓
25	3 Man Cyclic	4.0	2	7.25		
26	1 Man Cont.	5.0	2	2.5		✓
27	3 Man Cyclic	5.0	2	4.0	✓	✓
28	3 Man Cyclic	5.0	2	3.0		✓
29	1 Man Cyclic	1.8	4*	18.0*		✓
30	3 Man Cyclic	1.8	4*	14.5*		
31	1 Man Cyclic	2.6	20*	25.4*		
32	2 Man Cyclic	2.6	10*	39.0*		
33	3 Man Cyclic	2.6	20*	41.75*		
34	1 Man Cyclic	3.5	2*	2.75*		
35	3 Man Cyclic	3.5	2*	2.2*		
36	1 Man Cyclic	4.0	2*	3.6*		✓
37	3 Man Cyclic	4.0	2*	15.95*		
38	1 Man Cyclic	5.0	4*	5.4*		✓
39	3 Man Cyclic	5.0	4*	13.4*		
Other	Miscellaneous	-	-	113.75		
			324	720.75		

* 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 H_2/CO_2 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 EFFORT OF TOTAL PRESSURE AND DEWPOINT ON CONVERSION EFFICIENCY

H_2 Molar Ratio	Equilibrium Temperature °C (°F)	Pressure atm(psia)	H_2 Conversion Inlet Reactant Dew Points		
			Dry	26.7°C(80°F)	38°C(100°F)
2.0	260 (500)	1.0 (15)	99.4	99.4	99.4
2.0	260 (500)	1.4 (20)	99.5	99.5	99.5
2.6	260 (500)	1.0 (15)	99.4	99.4	99.4
2.6	260 (500)	1.4 (20)	99.5	99.5	99.5
3.0	260 (500)	1.0 (15)	99.4	99.3	99.3
3.0	260 (500)	1.4 (20)	99.4	99.4	99.4
4.0	260 (500)	1.0 (15)	99.0	99.0	99.0
4.0	260 (500)	1.4 (20)	99.1	99.1	99.1

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 H_2 conversion efficiencies for three dewpoints at various operating conditions based on gaseous equilibrium at 260°C (500°F). A negligible decline in H_2 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 H_2 conversion efficiency is with in 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 H_2 CONVERSION

Run #	Date	CO_2 Flow	Molar Ratio	Pressure atm (psia)	% H_2 Conversion
4	1/31/80	3 Man Cont.	2.52	1.34 (19.7)	99.2
4	1/31/80	3 Man Cont.	2.52	1.29 (18.2)	99.2
5	2/01/80	3 Man Cont.	2.52	1.20 (17.7)	99.2

TABLE 14

EFFECT OF REACTANT DEW POINT					
Run #	Date	Flow	Molar Ratio	Dew Point °C (°F)	% H_2 Conversion
18	2/12/80	3 Man Cyclic	2.6	dry	99.5
18	2/20/80	3 Man Cyclic	2.6	21.1 (70)	99.6

Effect Of H_2/CO_2 Molar Ratios - Steadystate

Table 15 summarizes both H_2 and CO_2 steadystate conversion efficiencies for H_2/CO_2 molar ratios varying from 1.8 to 5.0 and CO_2 flows varying from 1 man continuous to 3 man cyclic. As a rule of thumb, H_2 conversion efficiency declines slightly for a given CO_2 flow as the H_2/CO_2 molar ratio is increased from 1.8 to 4.0. Similarly, CO_2 conversion efficiency increases for a given CO_2 flow as the H_2/CO_2 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 CO_2 when the H_2/CO_2 molar ratio is increased beyond 4.1. The raw data test summary sheets for these cases are contained in Appendix B.

CO_2 Conversion Efficiencies

All testing at a H_2/CO_2 molar ratio of 5.0 resulted in 100% conversion of the CO_2 lean component. A 3 man cyclic flow test, was conducted which varied the H_2/CO_2 ratios from 4.2 to 4.0 in order to determine the presence of CO_2 in th effluent flow. At molar ratios of 4.2 and 4.1 no CO_2 was detected in the outlet flow. CO_2 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 H_2/CO_2 molar ratio of 2.46. Subsequent testing confirmed that no catalyst damaged resulted from this exposure to 1% oxygen.

The reaction between H_2 and O_2 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.

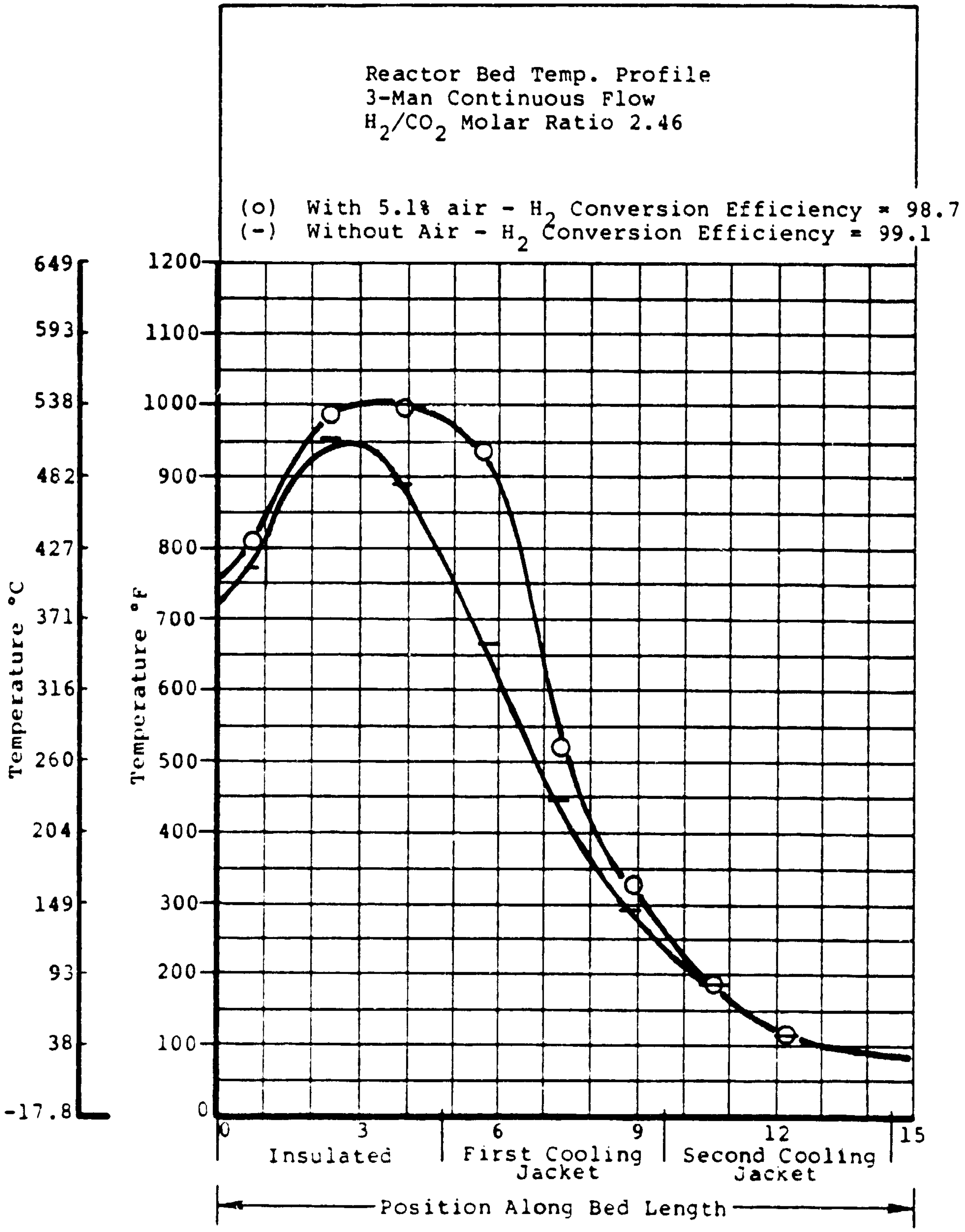


Figure 29

Comparison of Reactor Performance
With and Without Air Addition

Table 15

Steadystate Conversion Efficiency Test Results

	H_2/CO_2 Molar Ratio				
CO_2 Flow	1.8	2.6	3.5	4.0	5.0
1 Man Continuous	99.8	99.8	99.6	99.1	100
1 Man Cyclic	99.7	99.7	99.2	98.2	100
2 Man Cyclic	—	99.7	—	—	—
3 Man Continuous	99.3	99.6	99.3	99.0	100
3 Man Cyclic	99.4	99.6	99.3	98.4	100
10 Man Cyclic	—	97.2	—	—	—

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_2 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 CO_2 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 H_2/CO_2 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.

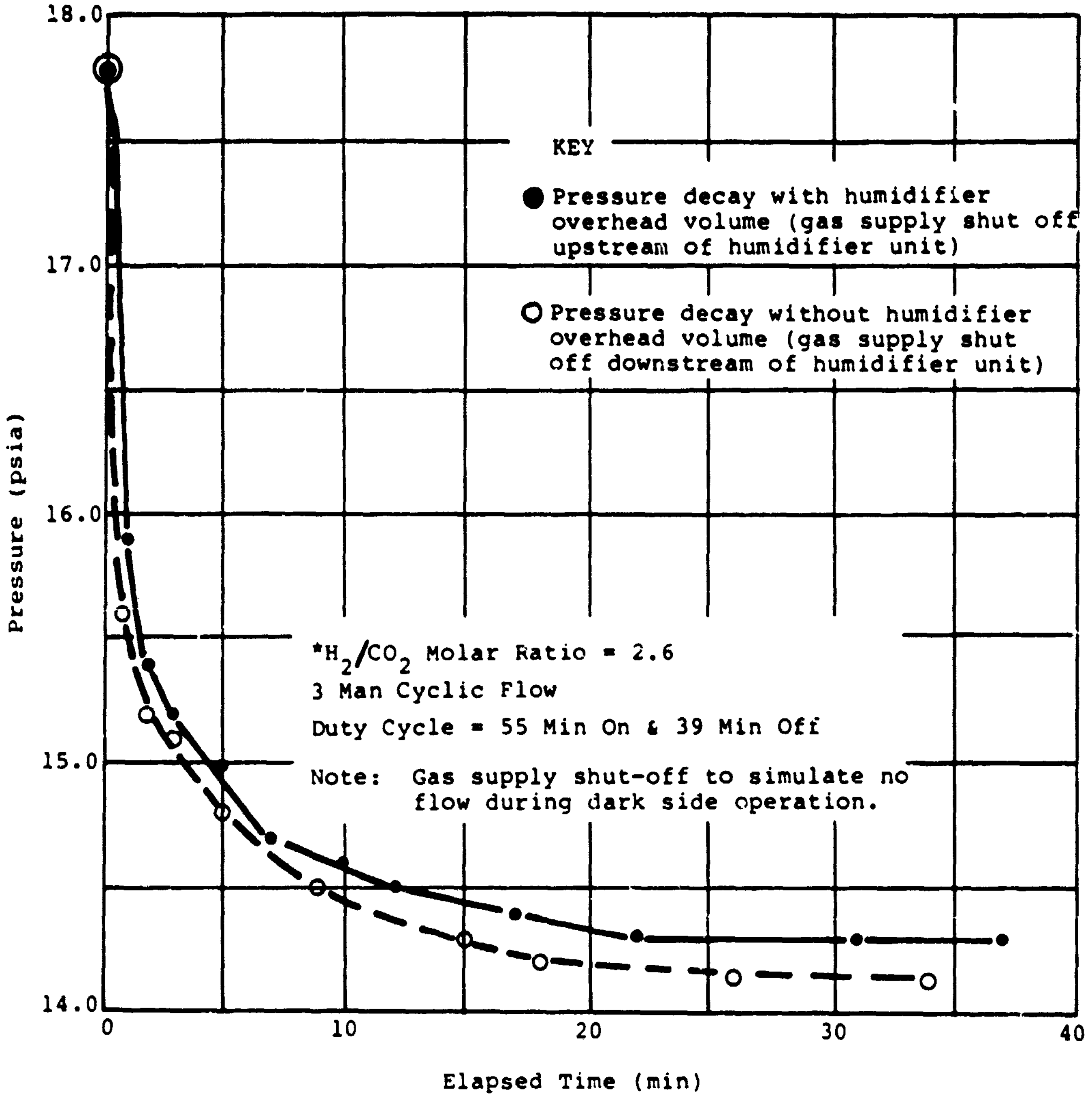


Figure 30

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)

	H_2/CO_2 Molar Ratio				
CO_2 Flow	1.8	2.6	3.5	4.0	5.0
1 Man	99.6	99.6	99.4	98.6	100
2 Man	—	99.6	—	—	—
3 Man	99.6	98.8 (99.4)	98.1	97.4 (98.8)	100

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

TABLE 17

CYCLE OPERATING RANGE WITHOUT HEATER ASSISTANCE

CO_2 Flow	-	1-10 man
H_2/CO_2 Molar Ratio	-	1.8 - 5.0
Duty Cycle	-	55 min on/39 min off
Dew Point	-	Dry - 21.1°C (70°F)

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 CO_2 flows and H_2/CO_2 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 18

STEADYSTATE TEST AND SIMULATION CONVERSION EFFICIENCIES

	% H_2 Conversion				% CO_2 Conversion
Molar Ratio CO_2 Flow	1.8	2.6	3.5	4.0	5.0
1 Man Continuous 2.2 lbm/day	99.8 99.7	99.8 99.7	99.6 99.3	99.1 98.9	100.0 99.8
1 Man Cyclic 3.74 lbm/day	99.7 99.7	99.7 99.4	99.2 98.9	98.2 99.0	100.0 99.8
2 Man Continuous 6.6 lbm/day	99.7 99.6				
3 Man Continuous 6.6 lbm/day	99.3 99.5	99.6 99.5	99.3 99.5	99.0 99.1	100.0 100.0
3 Man Cyclic 11.28 lbm/day	99.4 99.8	99.6 99.7	99.3 99.4	98.4 98.5	100.0 99.7

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 effects 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.

	Test Data (o) °C (°F)	Simulation (—) °C (°F)
Low Flow Coolant	84°C (183°F)	102°C (216°F)
High Flow Coolant	51°C (123°F)	32°C (90°F)
Conversion Efficiency	99.8	99.7

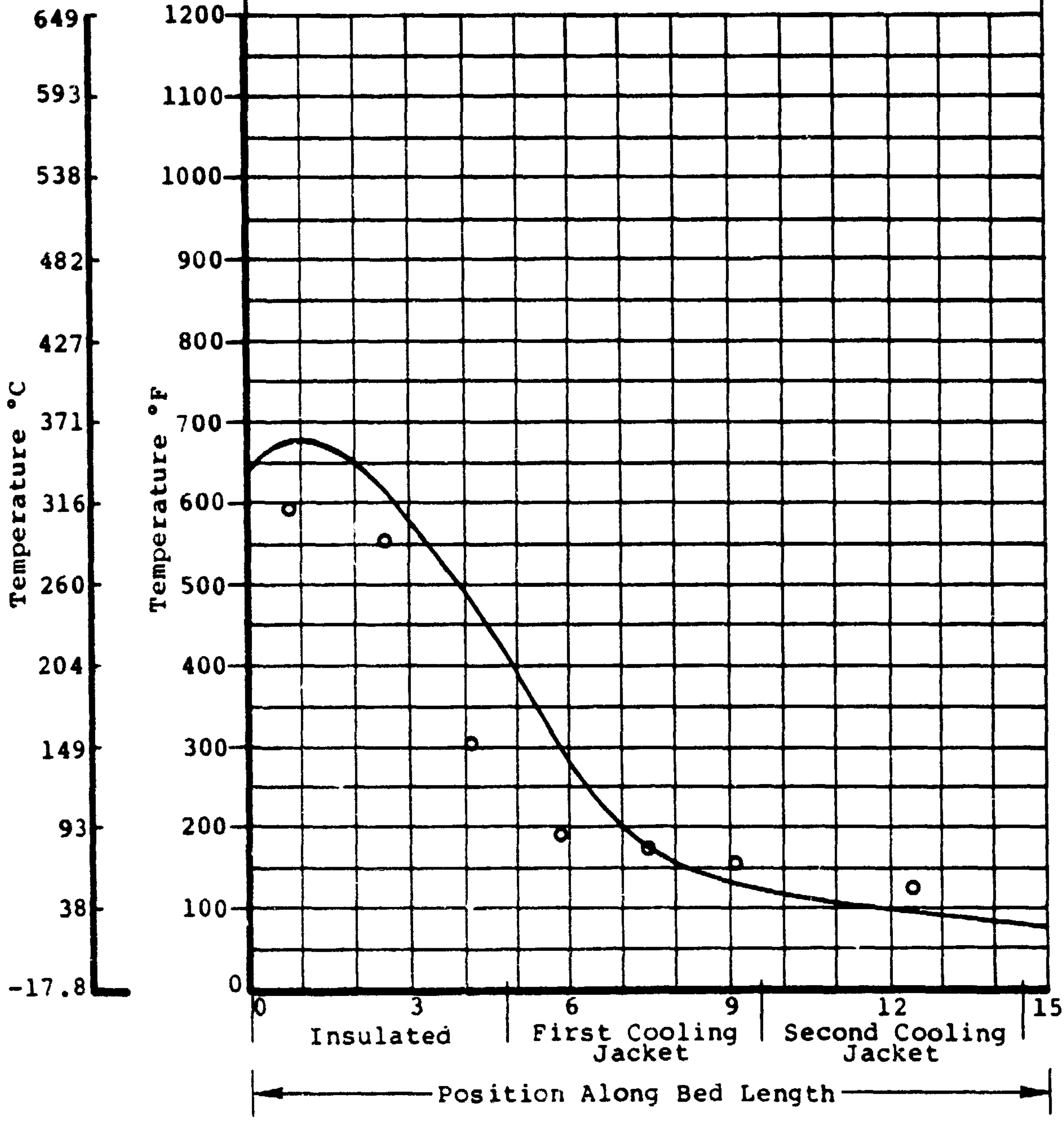


FIGURE 31

SABATIER STEADY STATE BED TEMPERATURES

1 MAN CONTINUOUS

MOLAR RATIO = 1.8

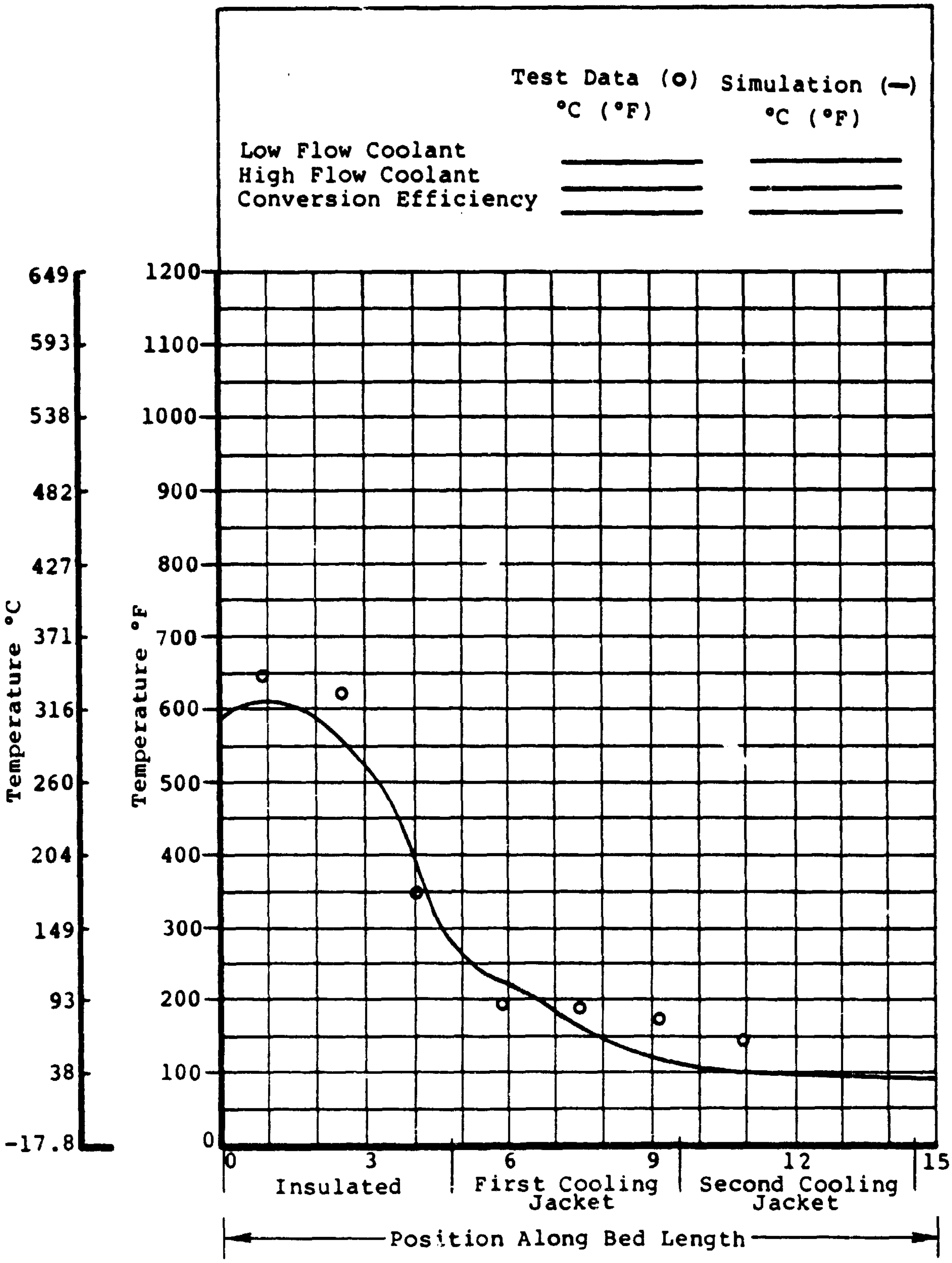
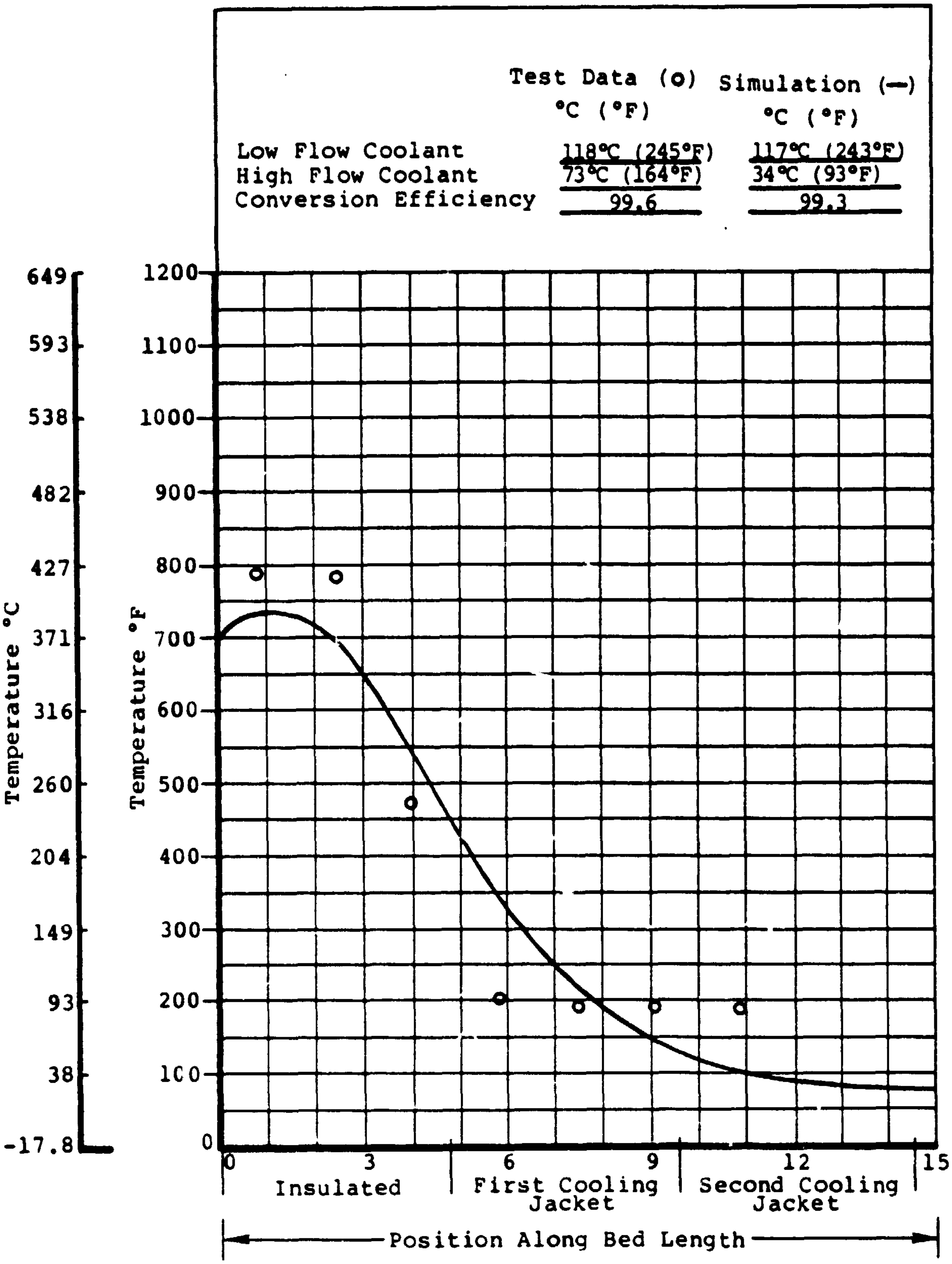
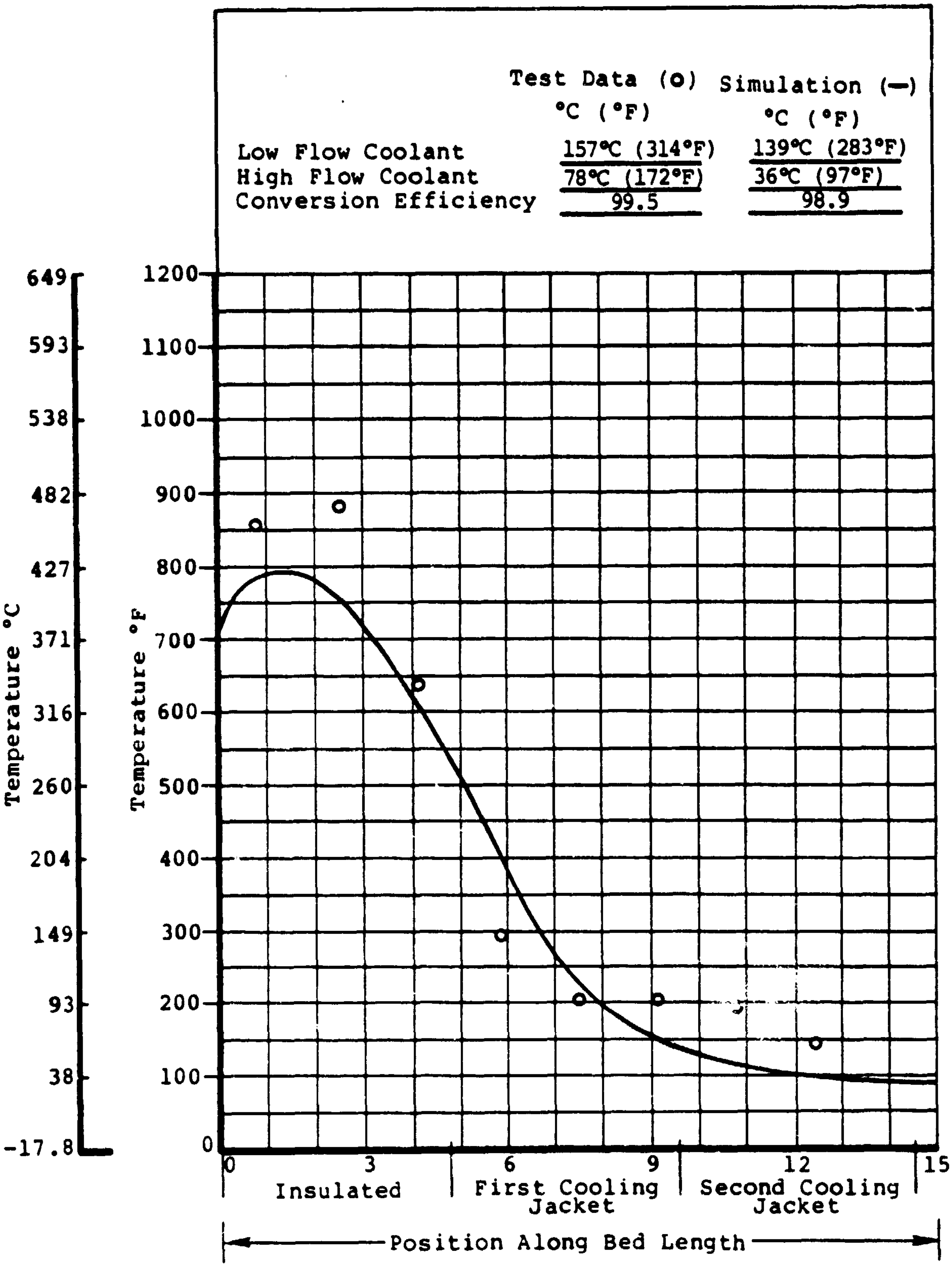


FIGURE 32
SABATIER STEADY STATE BED TEMPERATURES
1 MAN CONTINUOUS
MOLAR RATIO = 2.6



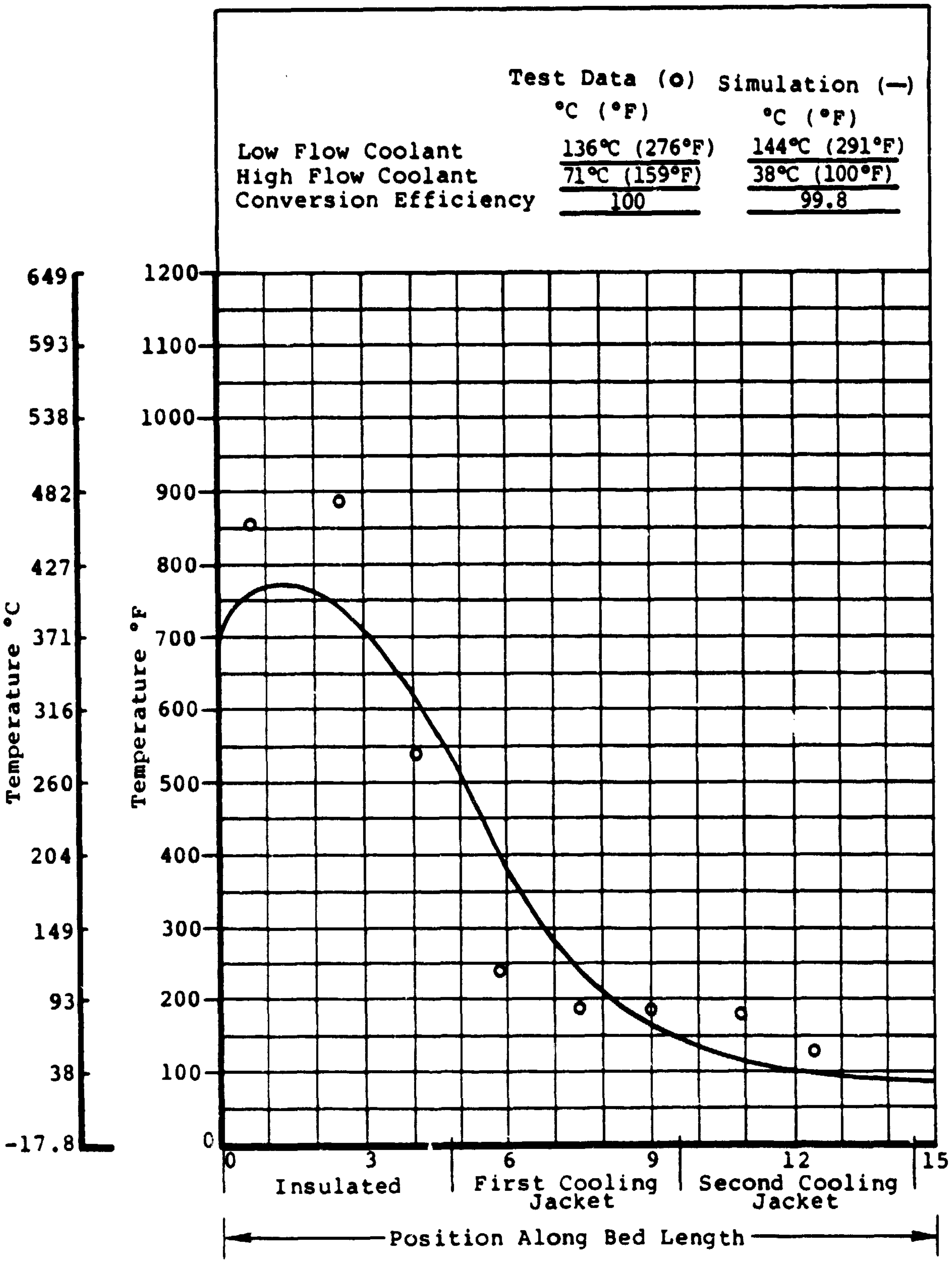
	Test Data (o) °C (°F)	Simulation (—) °C (°F)
Low Flow Coolant	118°C (245°F)	117°C (243°F)
High Flow Coolant	73°C (164°F)	34°C (93°F)
Conversion Efficiency	99.6	99.3

FIGURE 33
SABATIER STEADY STATE BED TEMPERATURES
1 MAN CONTINUOUS
MOLAR RATIO = 2.5



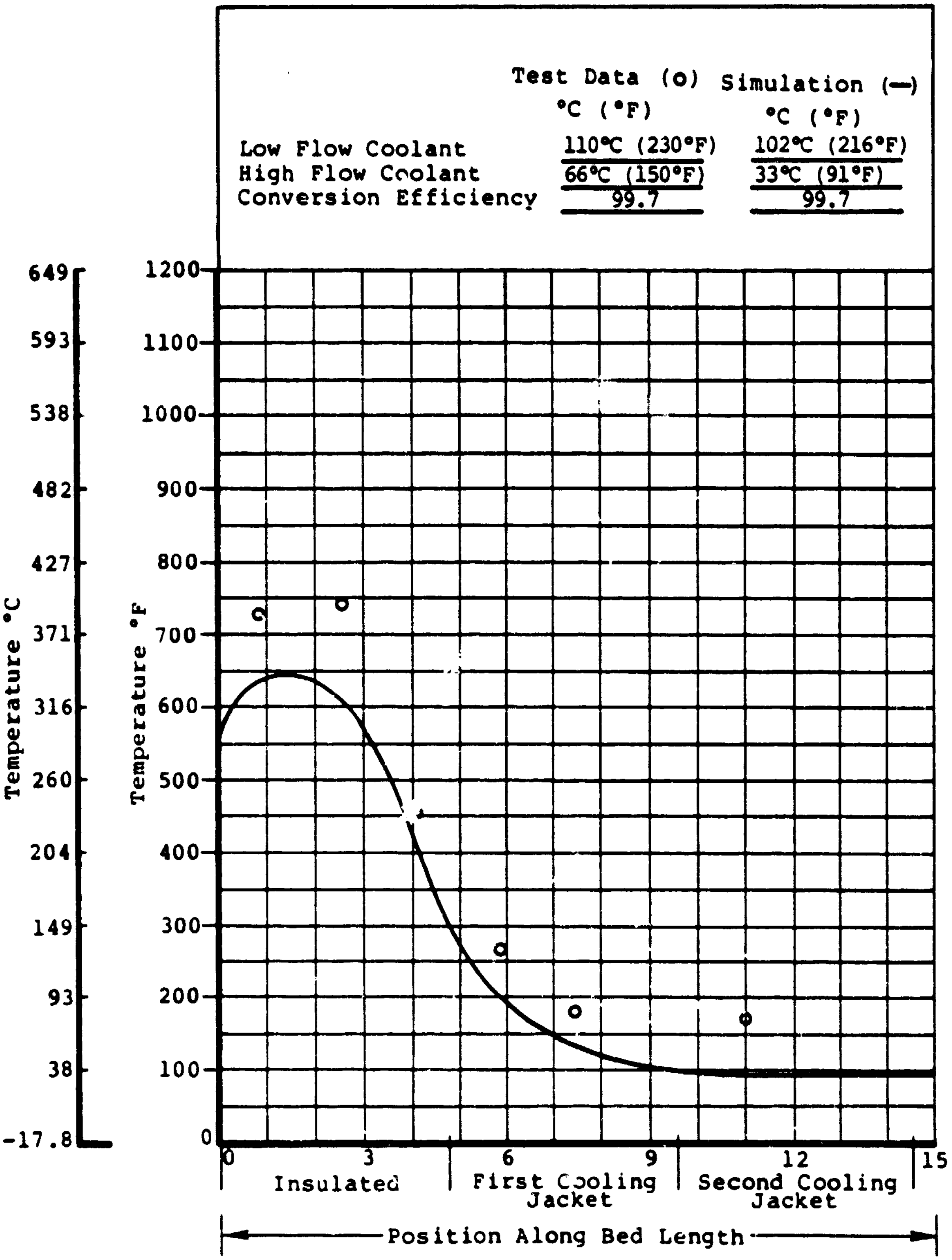
	Test Data (○) °C (°F)	Simulation (—) °C (°F)
Low Flow Coolant	157°C (314°F)	139°C (283°F)
High Flow Coolant	78°C (172°F)	36°C (97°F)
Conversion Efficiency	99.5	98.9

FIGURE 34
SABATIER STEADY STATE BED TEMPERATURES
1 MAN CONTINUOUS
MOLAR RATIO = 4.0



	Test Data (o) °C (°F)	Simulation (—) °C (°F)
Low Flow Coolant	136°C (276°F)	144°C (291°F)
High Flow Coolant	71°C (159°F)	38°C (100°F)
Conversion Efficiency	100	99.8

FIGURE 35
SABATIER STEADY STATE BED TEMPERATURES
1 MAN CONTINUOUS
MOLAR RATIO = 5.0



	Test Data (o) °C (°F)	Simulation (—) °C (°F)
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

FIGURE 36
SABATIER STEADY STATE BED TEMPERATURE
1 MAN CYCLIC
MOLAR RATIO = 1.8

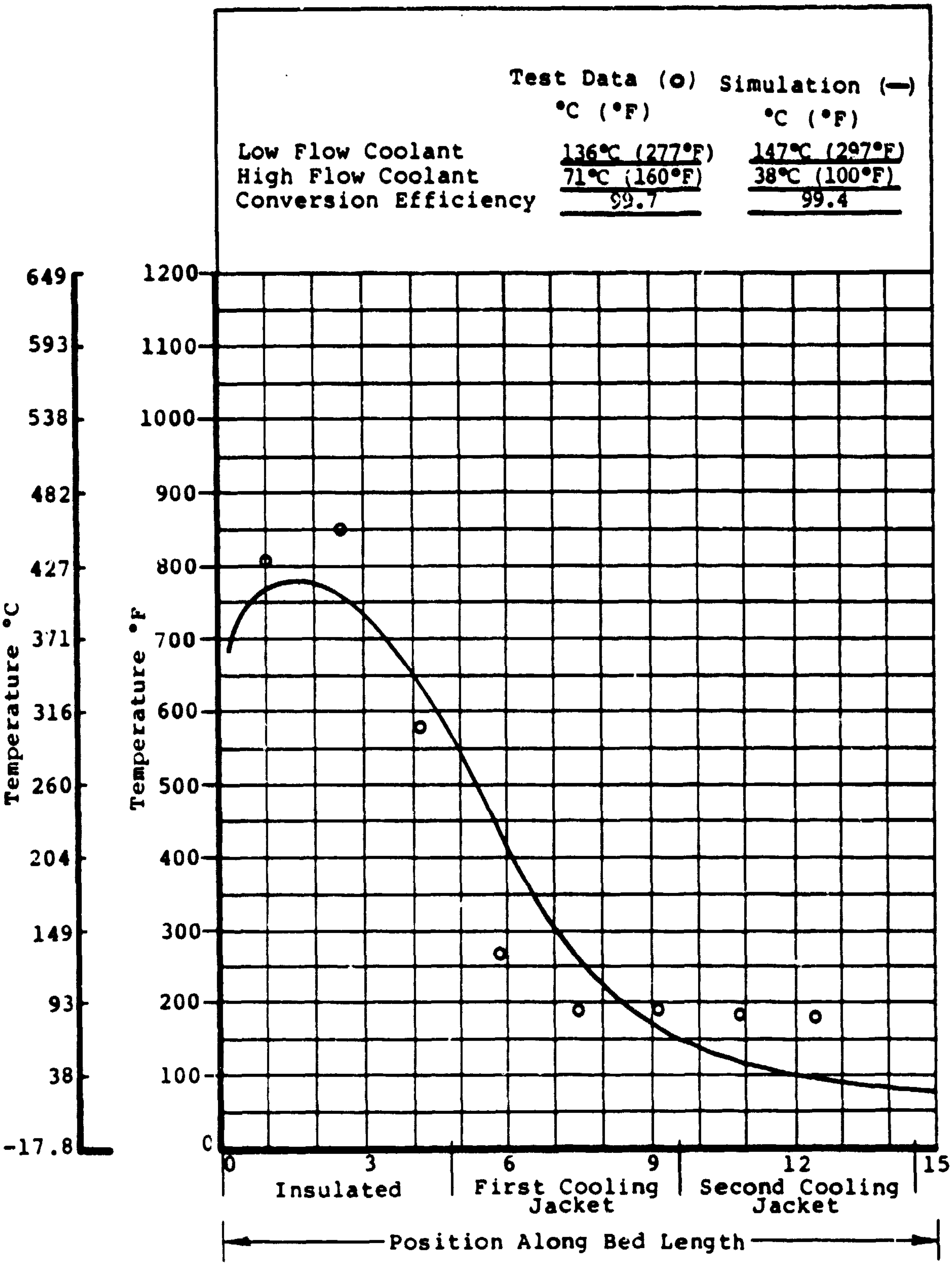
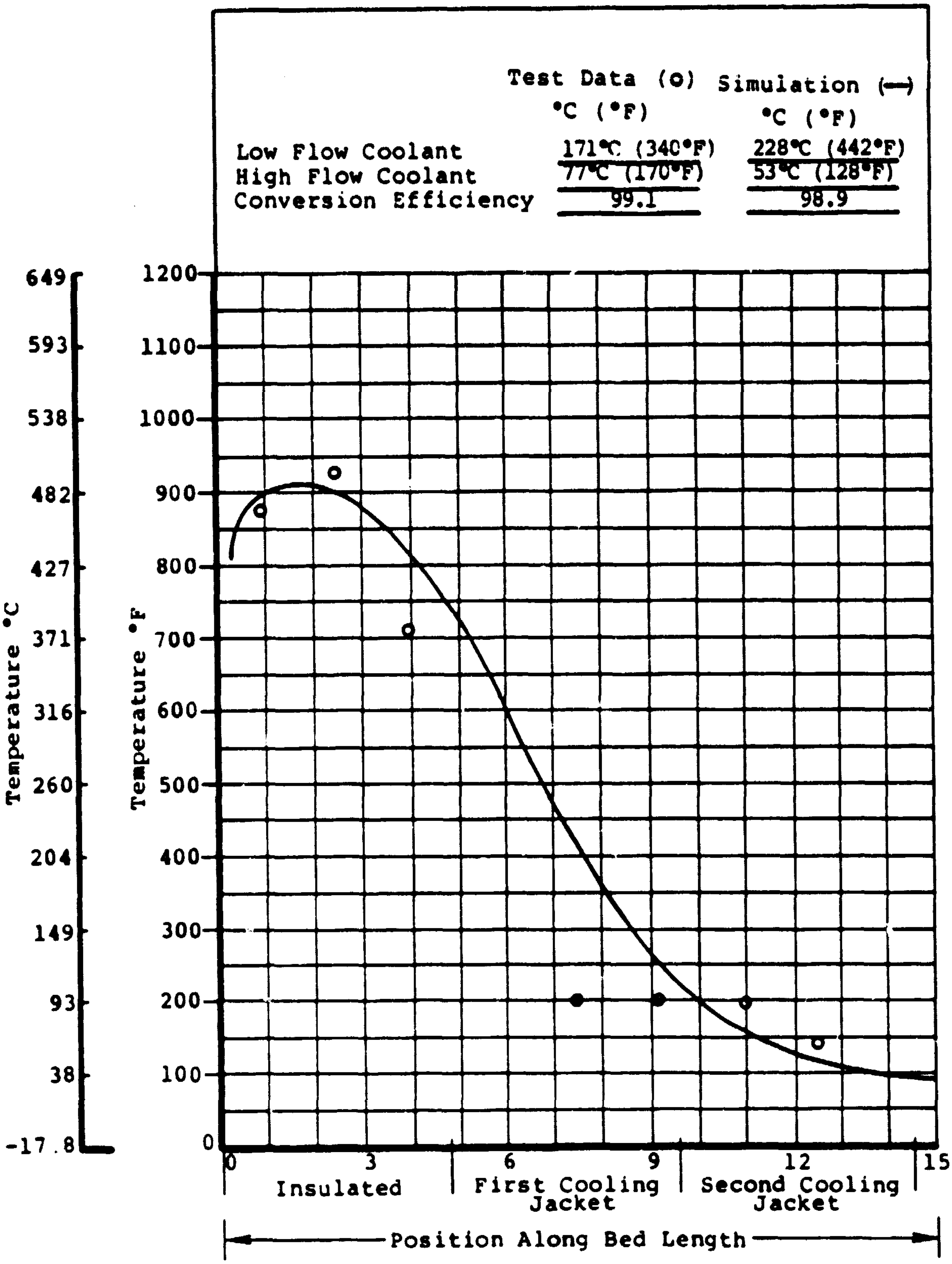
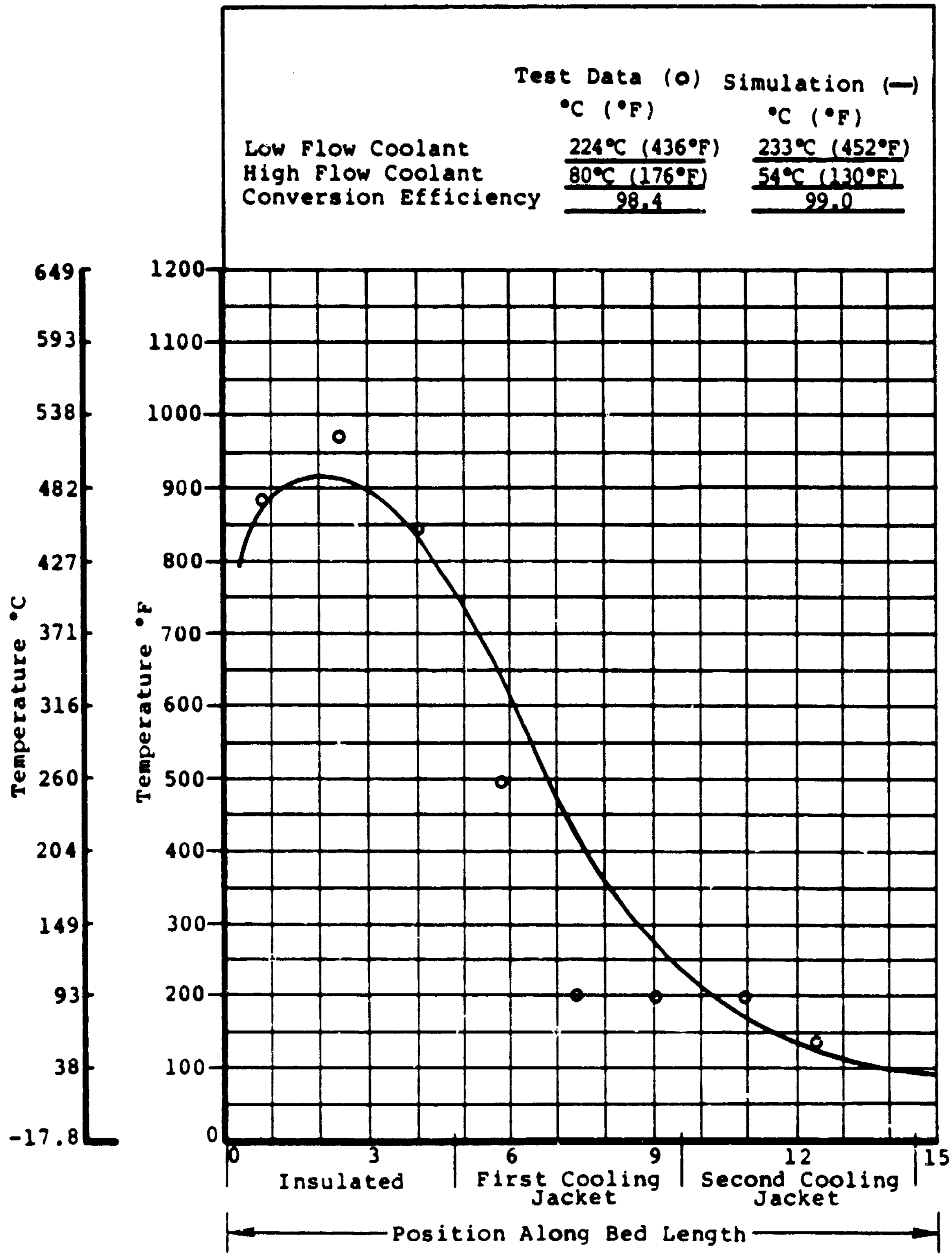


FIGURE 37
SABATIER STEADY STATE BED TEMPERATURES
1 MAN CYCLIC
MOLAR RATIO = 2.5



	Test Data (○) °C (°F)	Simulation (—) °C (°F)
Low Flow Coolant	171°C (340°F)	228°C (442°F)
High Flow Coolant	77°C (170°F)	53°C (128°F)
Conversion Efficiency	99.1	98.9

FIGURE 38
SABATIER STEADY STATE BED TEMPERATURES
1 MAN CYCLIC
MOLAR RATIO = 3.5



	Test Data (○) °C (°F)	Simulation (—) °C (°F)
Low Flow Coolant	224°C (436°F)	233°C (452°F)
High Flow Coolant	80°C (176°F)	54°C (130°F)
Conversion Efficiency	98.4	99.0

FIGURE 39
SABATIER STEADY STATE BED TEMPERATURES
1 MAN CYCLIC
MOLAR RATIO = 4.0

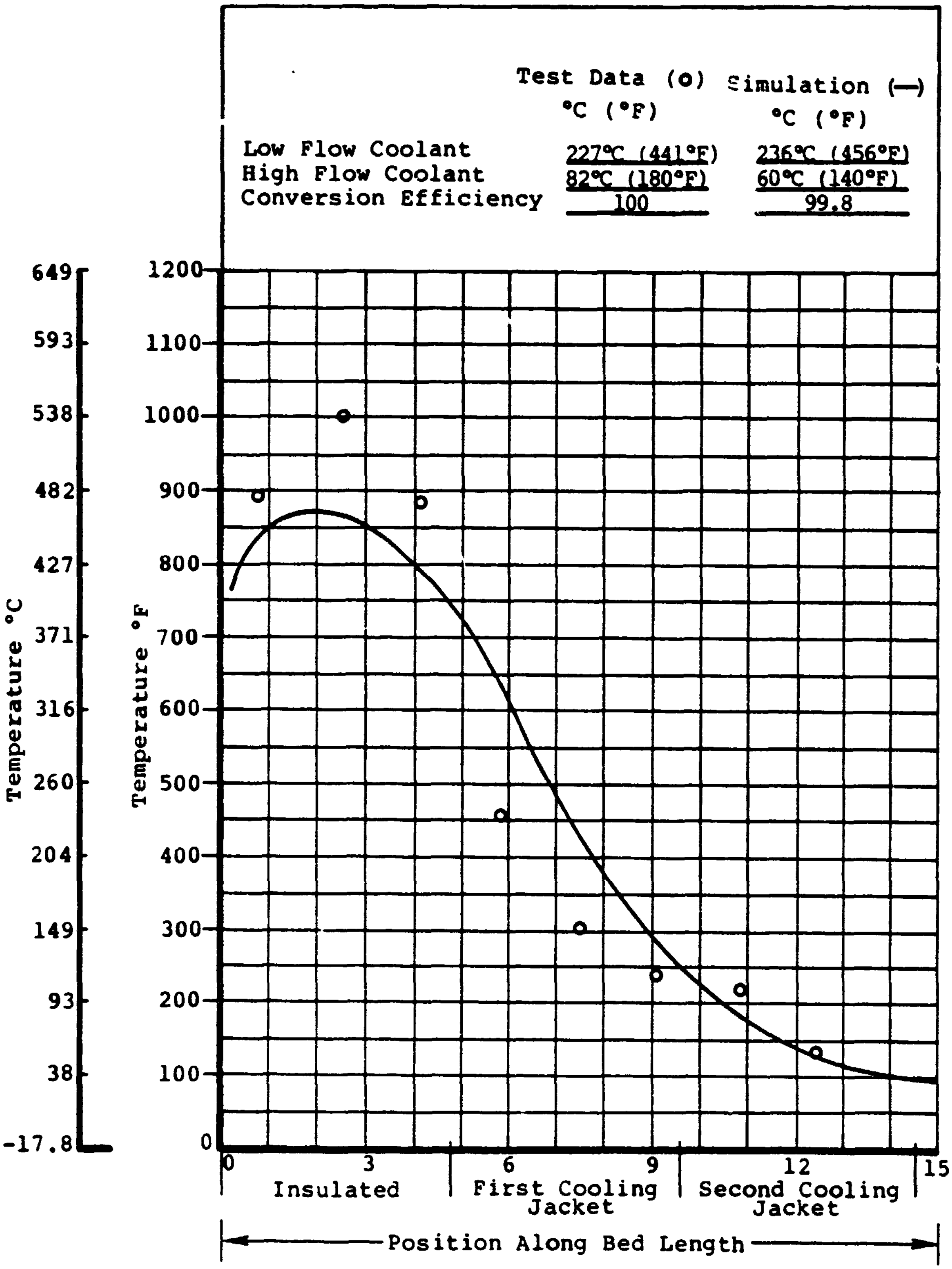
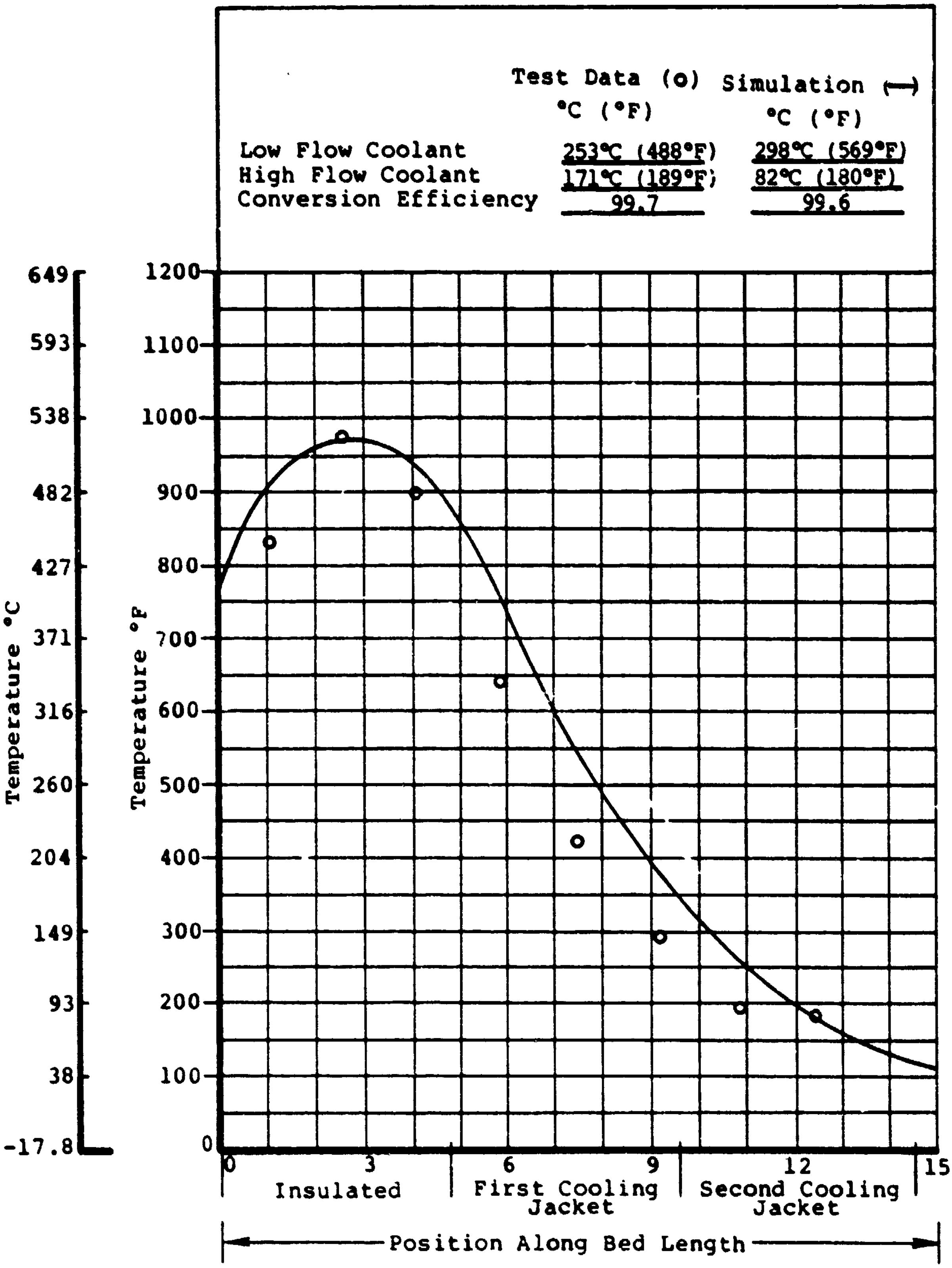


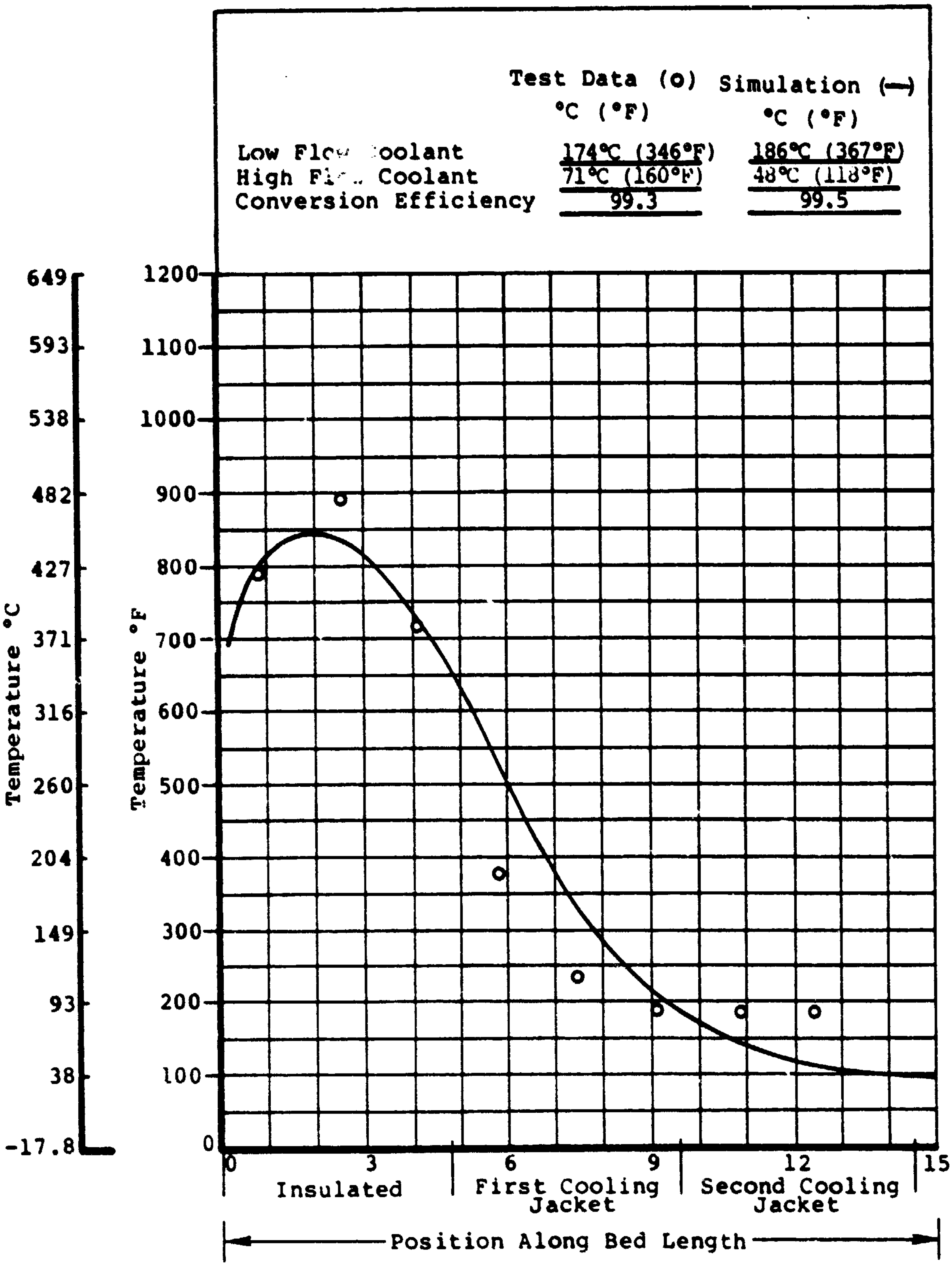
FIGURE 40
SABATIER STEADY STATE BED TEMPERATURES
1 MAN CYCLIC
MOLAR RATIO = 5.0

c-2



	Test Data (o) °C (°F)	Simulation (—) °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



	Test Data (o) °C (°F)	Simulation (—) °C (°F)
Low Flow Coolant	174°C (346°F)	186°C (367°F)
High Flow Coolant	71°C (160°F)	48°C (118°F)
Conversion Efficiency	99.3	99.5

FIGURE 42
SABATIER STEADY STATE BED TEMPERATURES
3 MAN CONTINUOUS
MOLAR RATIO = 1.8

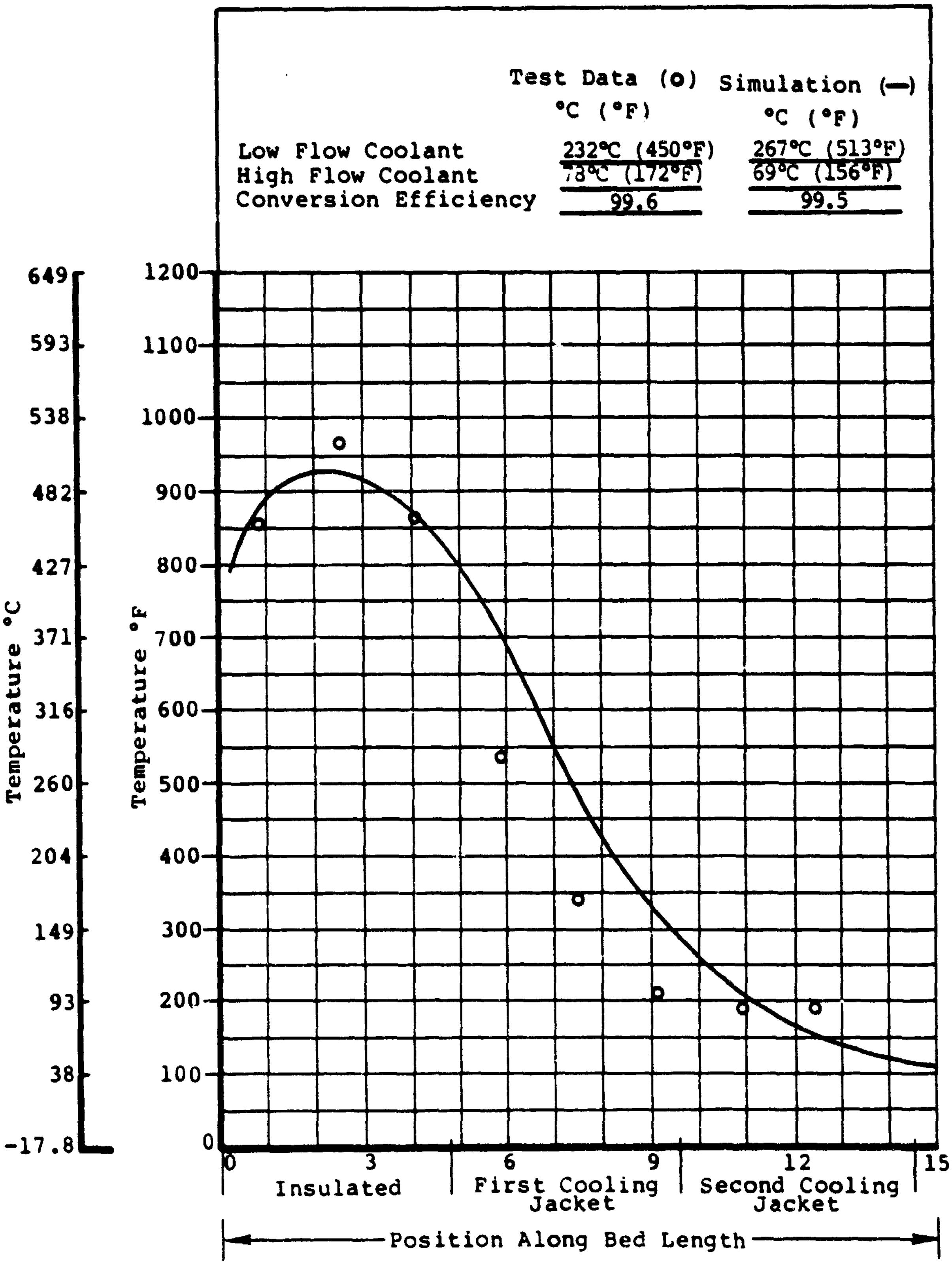
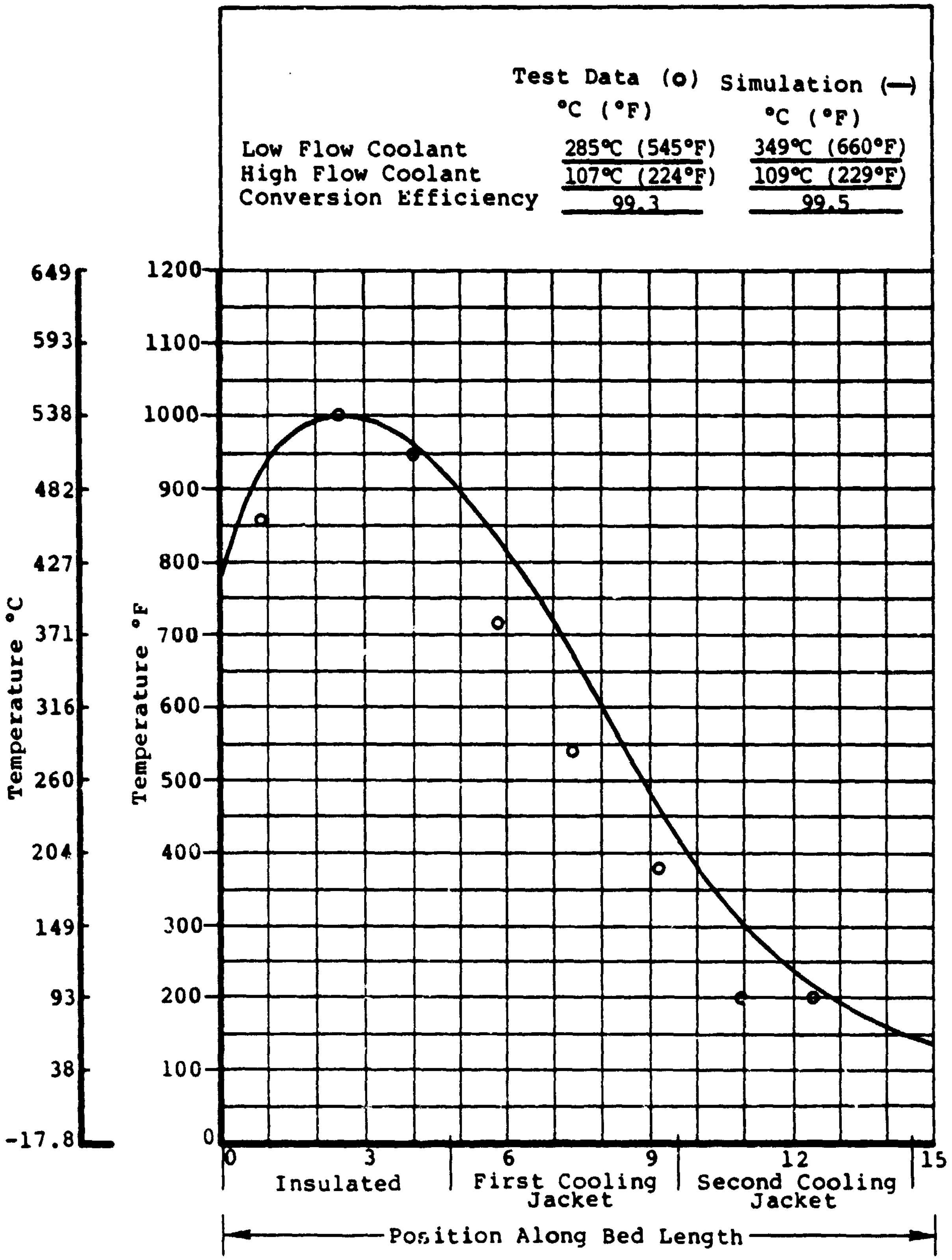


FIGURE 43
SABATIER STEADY STATE BED TEMPERATURES
3 MAN CONTINUOUS
MOLAR RATIO = 2.6



	Test Data (o) °C (°F)	Simulation (—) °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

	Test Data (o) °C (°F)	Simulation (—) °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

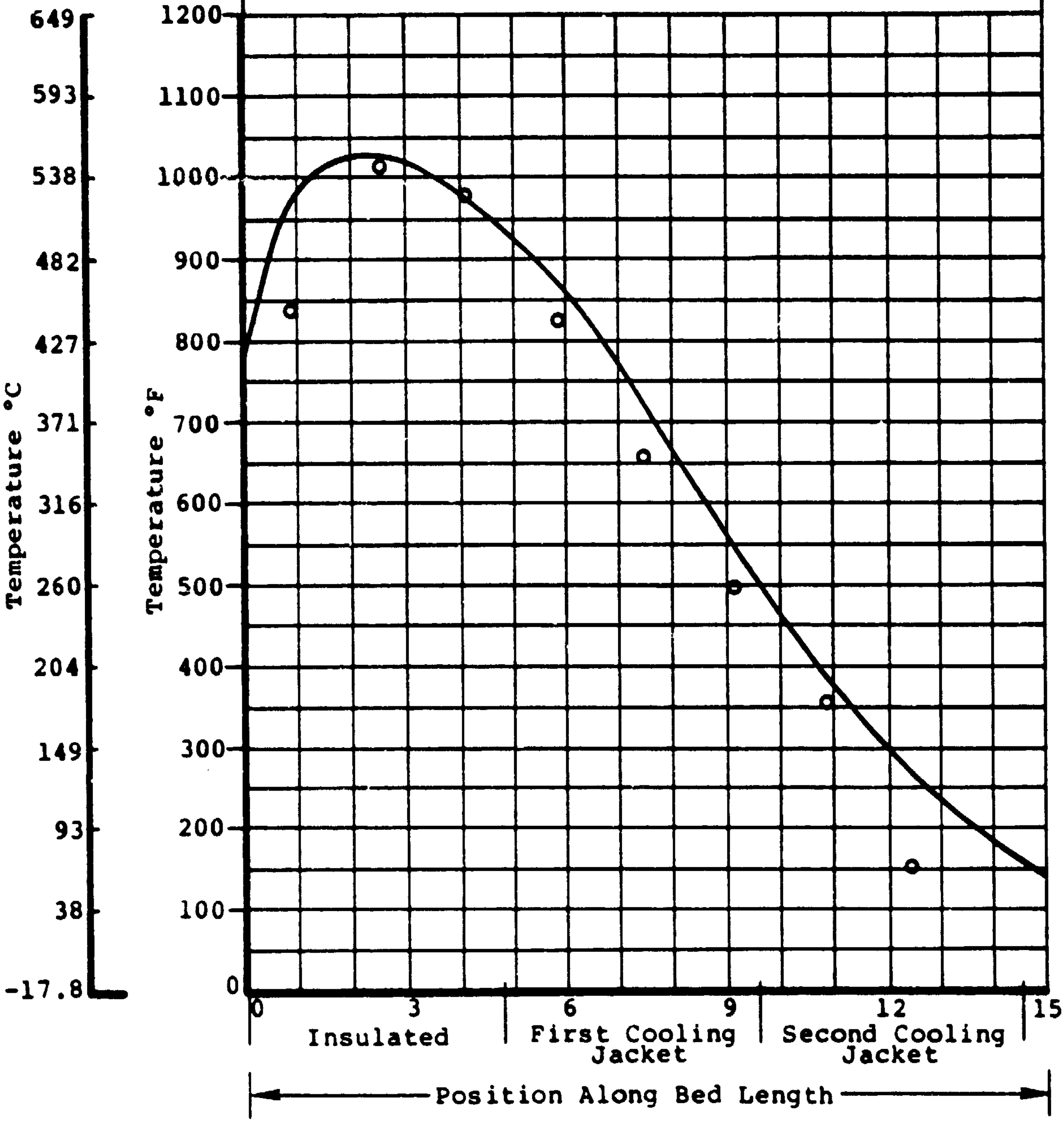


FIGURE 45
SABATIER STEADY STATE BED TEMPERATURES
3 MAN CONTINUOUS
MOLAR RATIO = 4.0

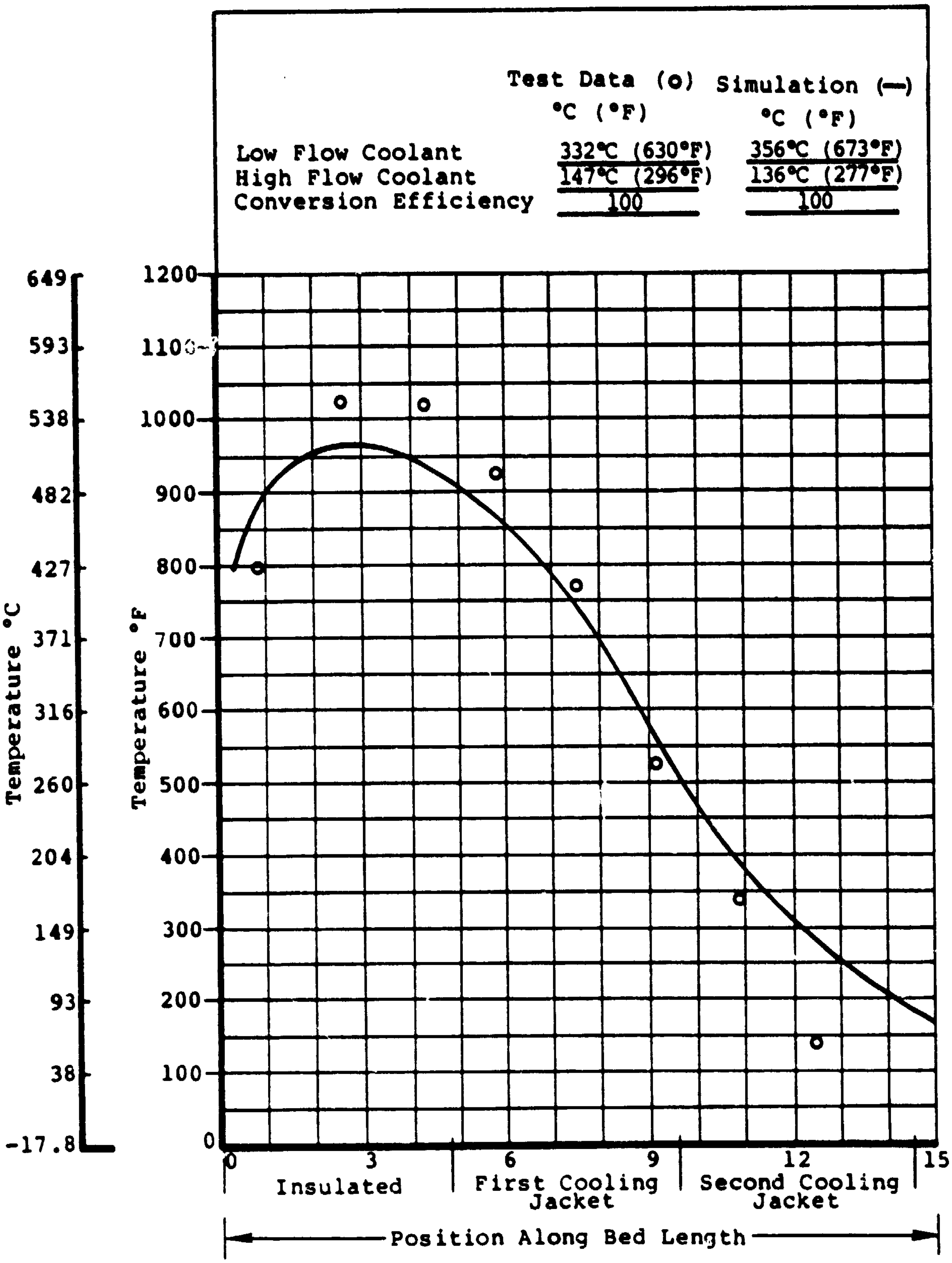
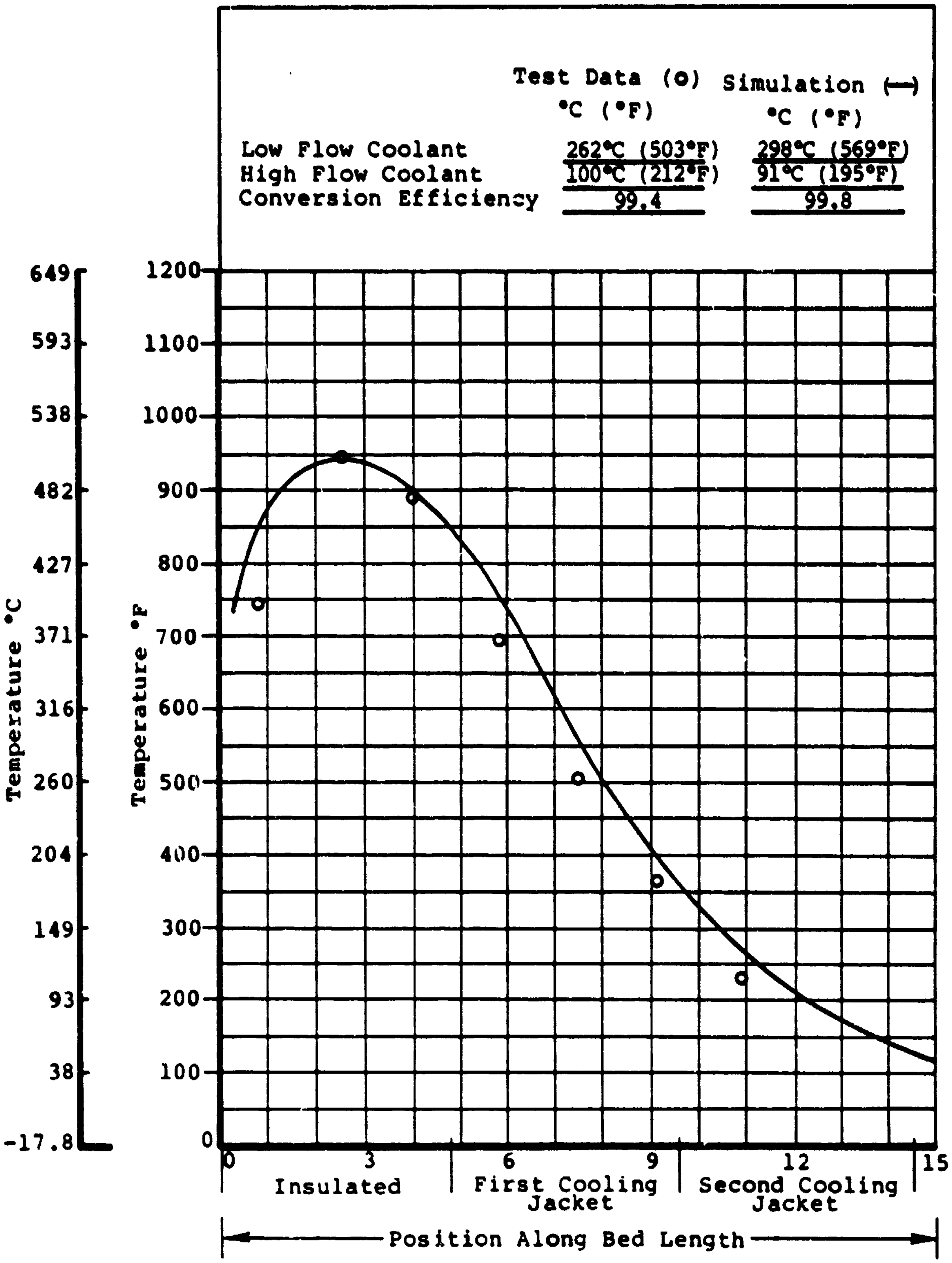


FIGURE 46
SABATIER STEADY STATE BED TEMPERATURES
3 MAN CONTINUOUS
MOLAR RATIO = 5.0



	Test Data (o) °C (°F)	Simulation (—) °C (°F)
Low Flow Coolant	262°C (503°F)	298°C (569°F)
High Flow Coolant	100°C (212°F)	91°C (195°F)
Conversion Efficiency	99.4	99.8

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

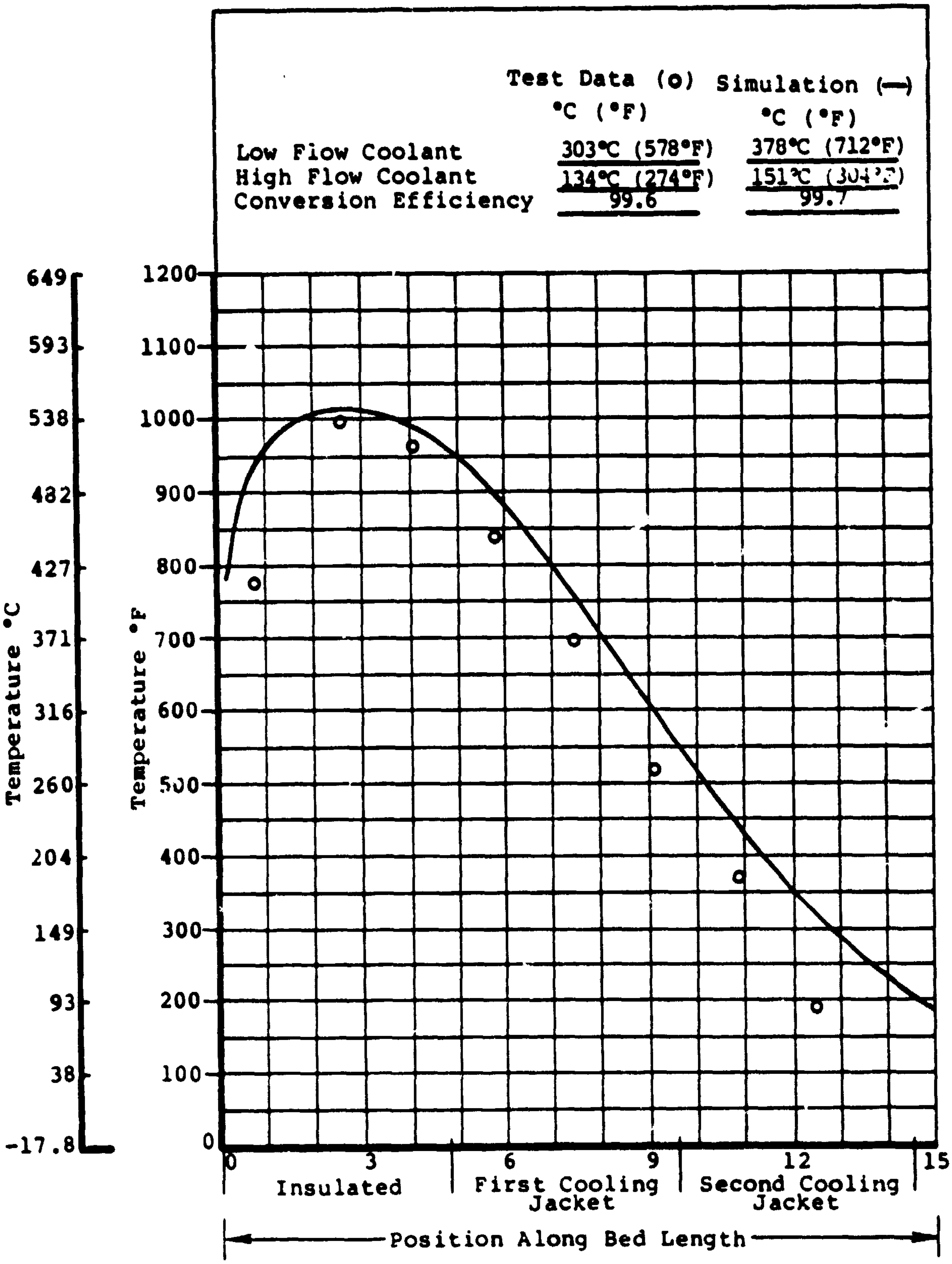
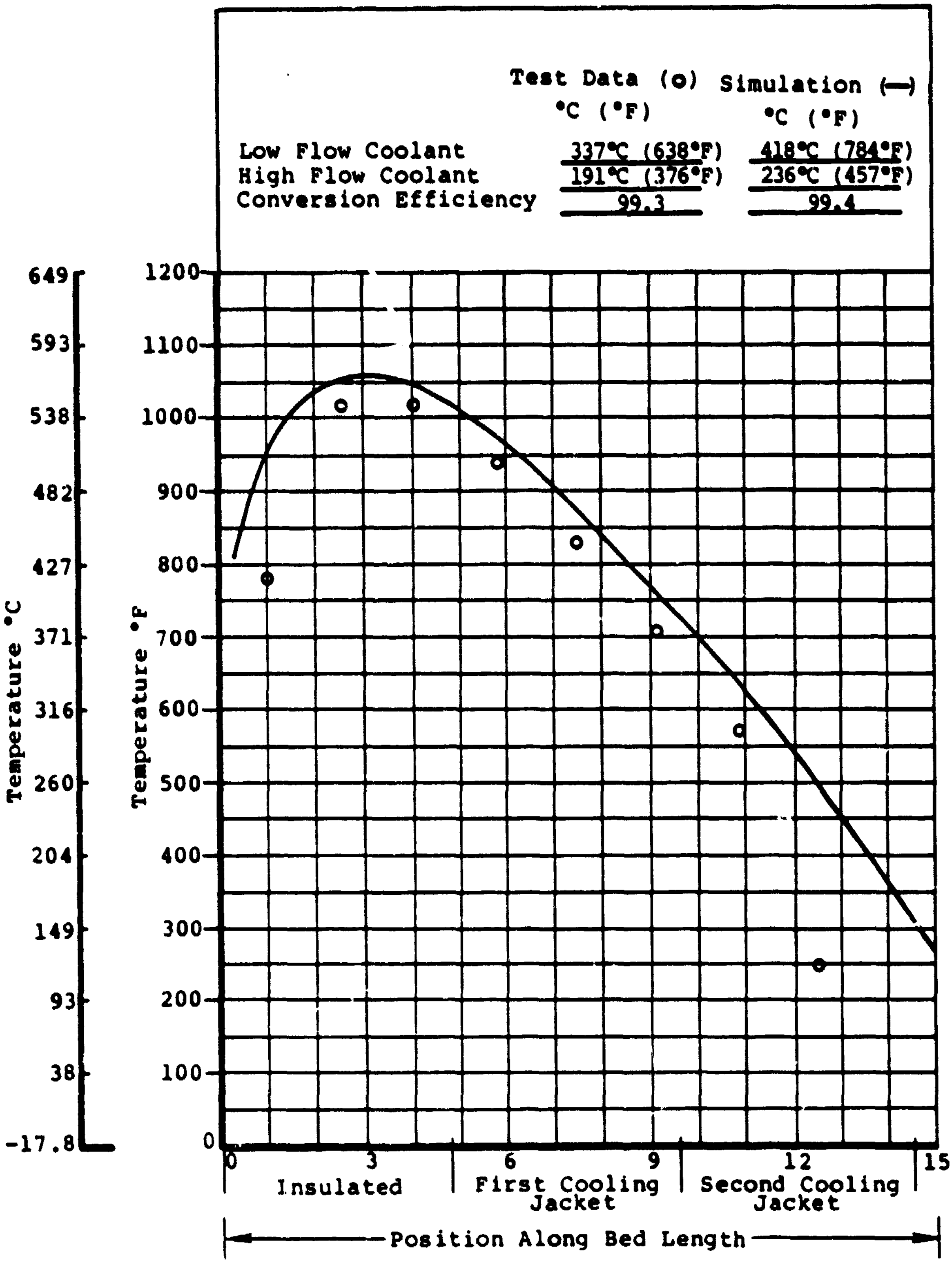


FIGURE 48
SABATIER STEADY STATE BED TEMPERATURES
3 MAN CYCLIC
MOLAR RATIO = 2.6



	Test Data (o) °C (°F)	Simulation (—) °C (°F)
Low Flow Coolant	337°C (638°F)	418°C (784°F)
High Flow Coolant	191°C (376°F)	236°C (457°F)
Conversion Efficiency	99.3	99.4

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

	Test Data (○) °C (°F)	Simulation (—) °C (°F)
Low Flow Coolant	349°C (660°F)	434°C (813°F)
High Flow Coolant	226°C (438°F)	271°C (520°F)
Conversion Efficiency	98.6	98.5

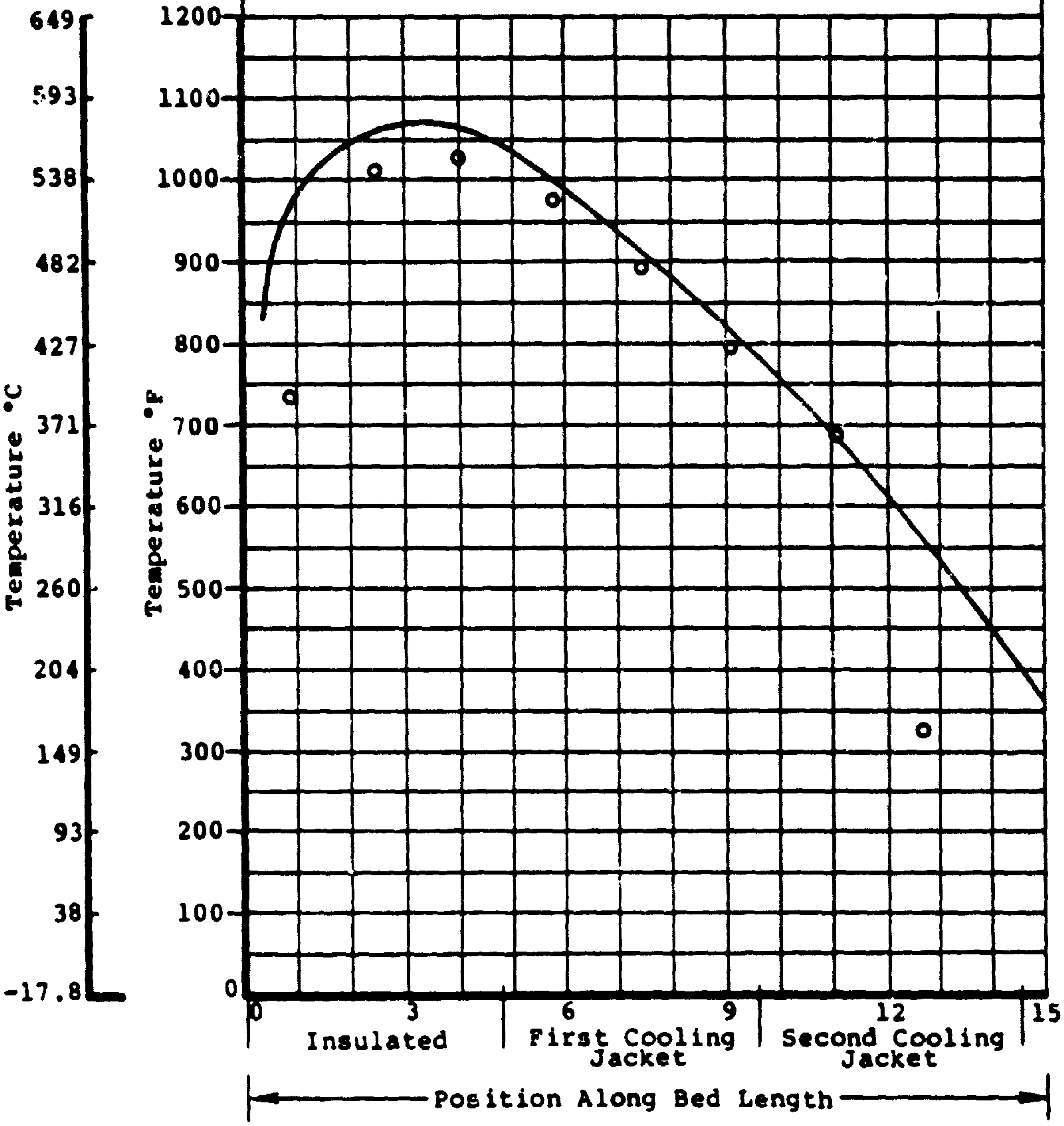
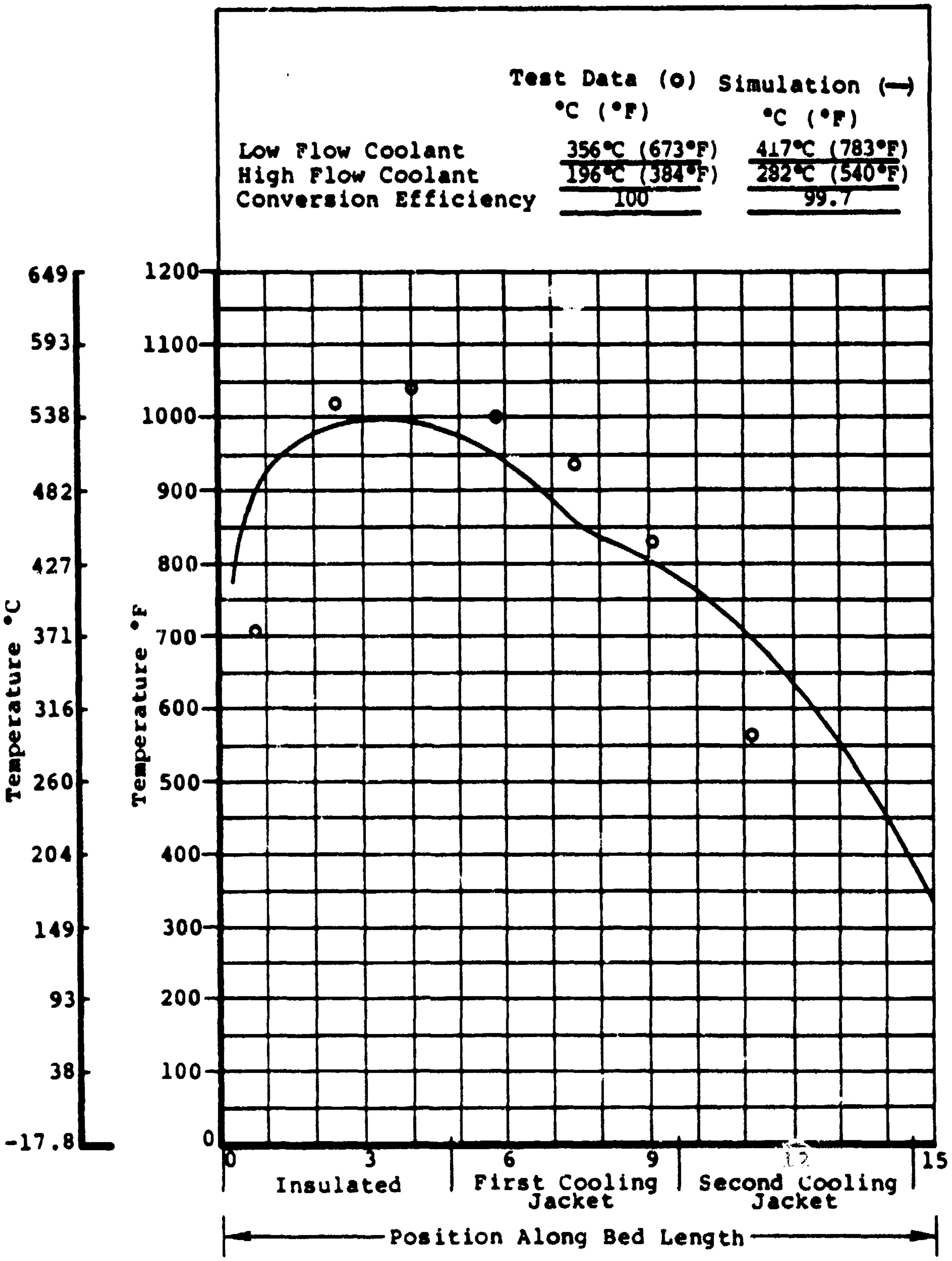


FIGURE 50
SABATIER STEADY STATE BED TEMPERATURES
3 MAN CYCLIC
MOLAR RATIO = 4.0



	Test Data (o) °C (°F)	Simulation (—) °C (°F)
Low Flow Coolant	356°C (673°F)	417°C (783°F)
High Flow Coolant	196°C (384°F)	282°C (540°F)
Conversion Efficiency	100	99.7

FIGURE 51
SABATIER STEADY STATE BED TEMPERATURES
3 MAN CYCLIC
MOLAR RATIO = 5.0

TABLE 19

AVERAGE CONVERSION EFFICIENCY FOR CYCLIC TESTS
(55 MIN. ON, 39 MIN. OFF)

Molar Ratio / CO_2 Flow	% H_2 Conversion				% CO_2 Conversion
	1.8	2.6	3.5	4.0	5.0
1 Man Continuous 2.2 lbm/day	99.6 99.5	99.6 99.5	99.4 99.2	98.6 99.0	100.0 100.8
2 Man Cyclic 7.48 lbm/day	99.6 99.5				
3 Man Continuous 6.6 lbm/day	99.6 99.6	98.8 *(99.4) 99.5	98.1 99.1	97.4 *(98.8) 98.8	100.0 100.0

*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 steadystate profile over the profile at 25minutes 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 steadystate, 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.

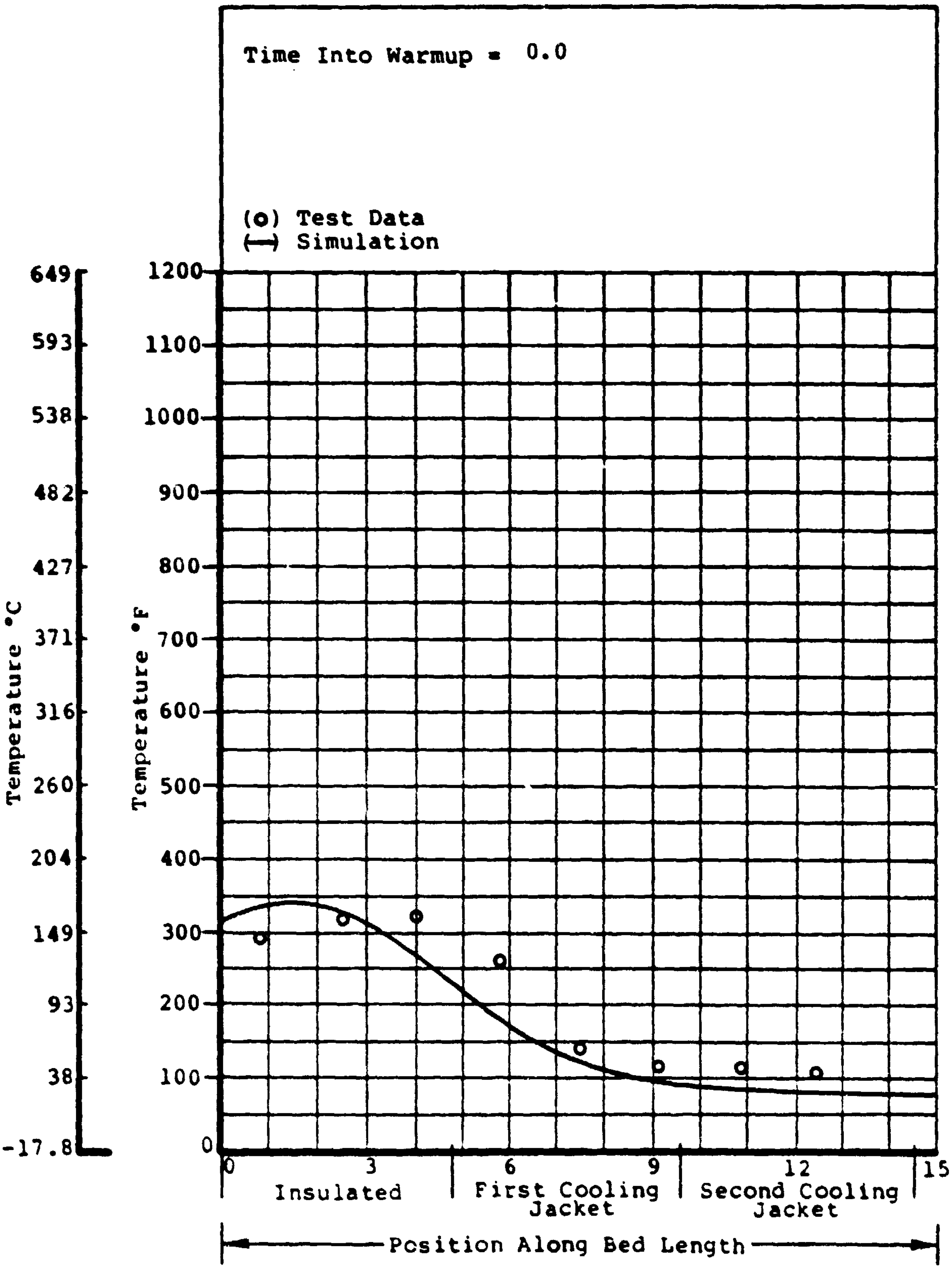


FIGURE 52
SABATIER TRANSIENT BED TEMPERATURES
1 MAN CYCLIC
MOLAR RATIO = 1.8

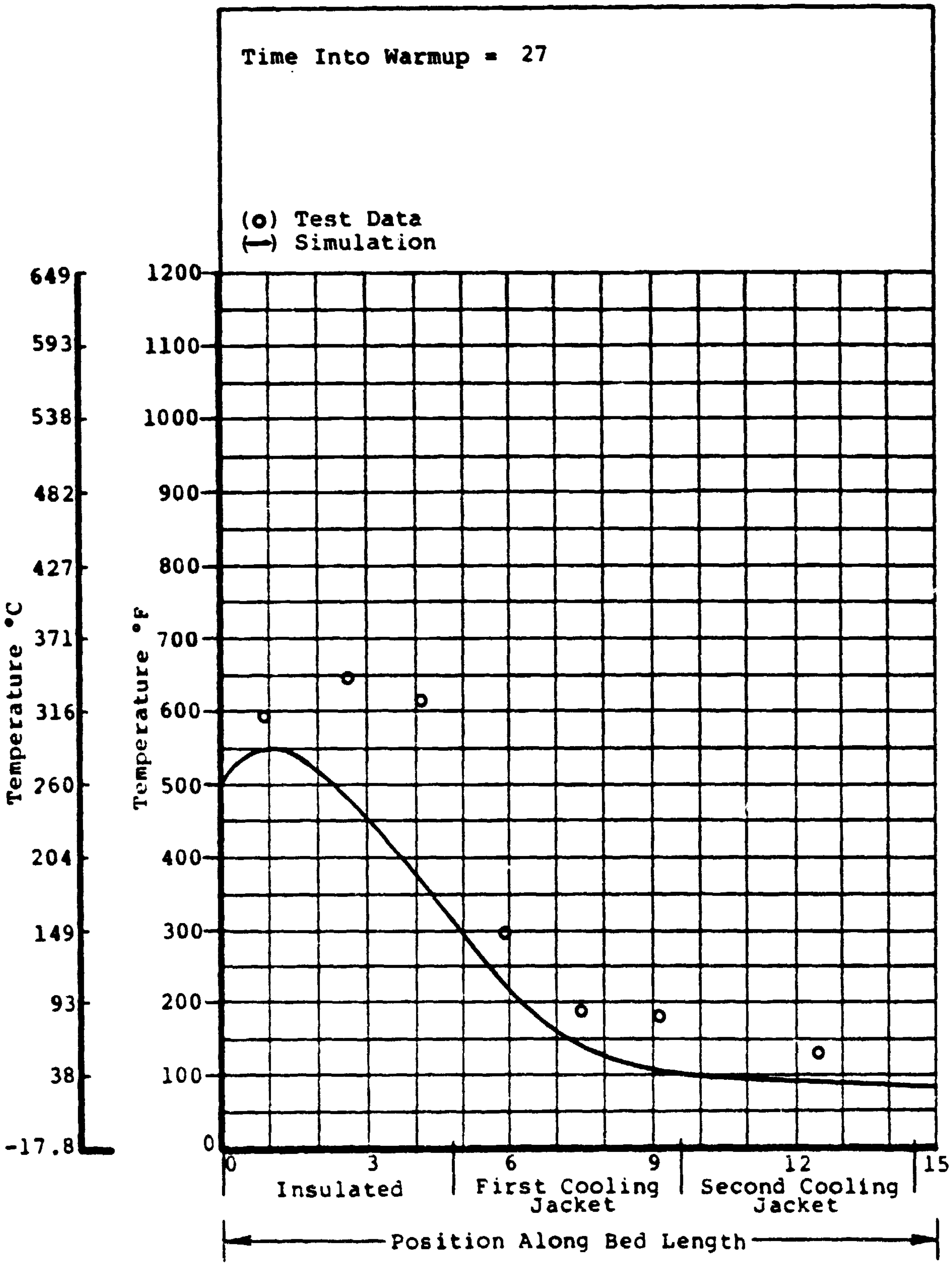


FIGURE 53
SABATIER TRANSIENT BED TEMPERATURES
1 MAN CYCLIC
MOLAR RATIO = 1.8

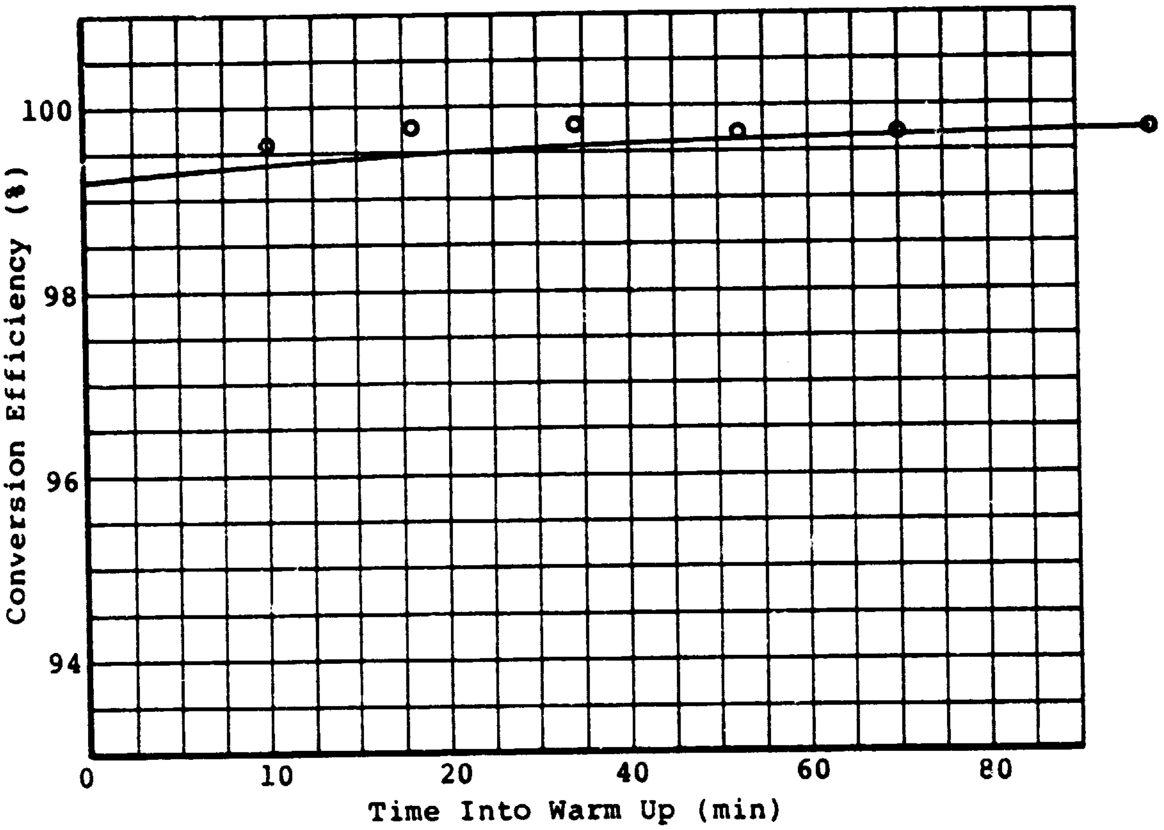


FIGURE 54
SABATIER WARM UP CONVERSION EFFICIENCY HISTORY
1 MAN CYCLIC
MOLAR RATIO = 1.8

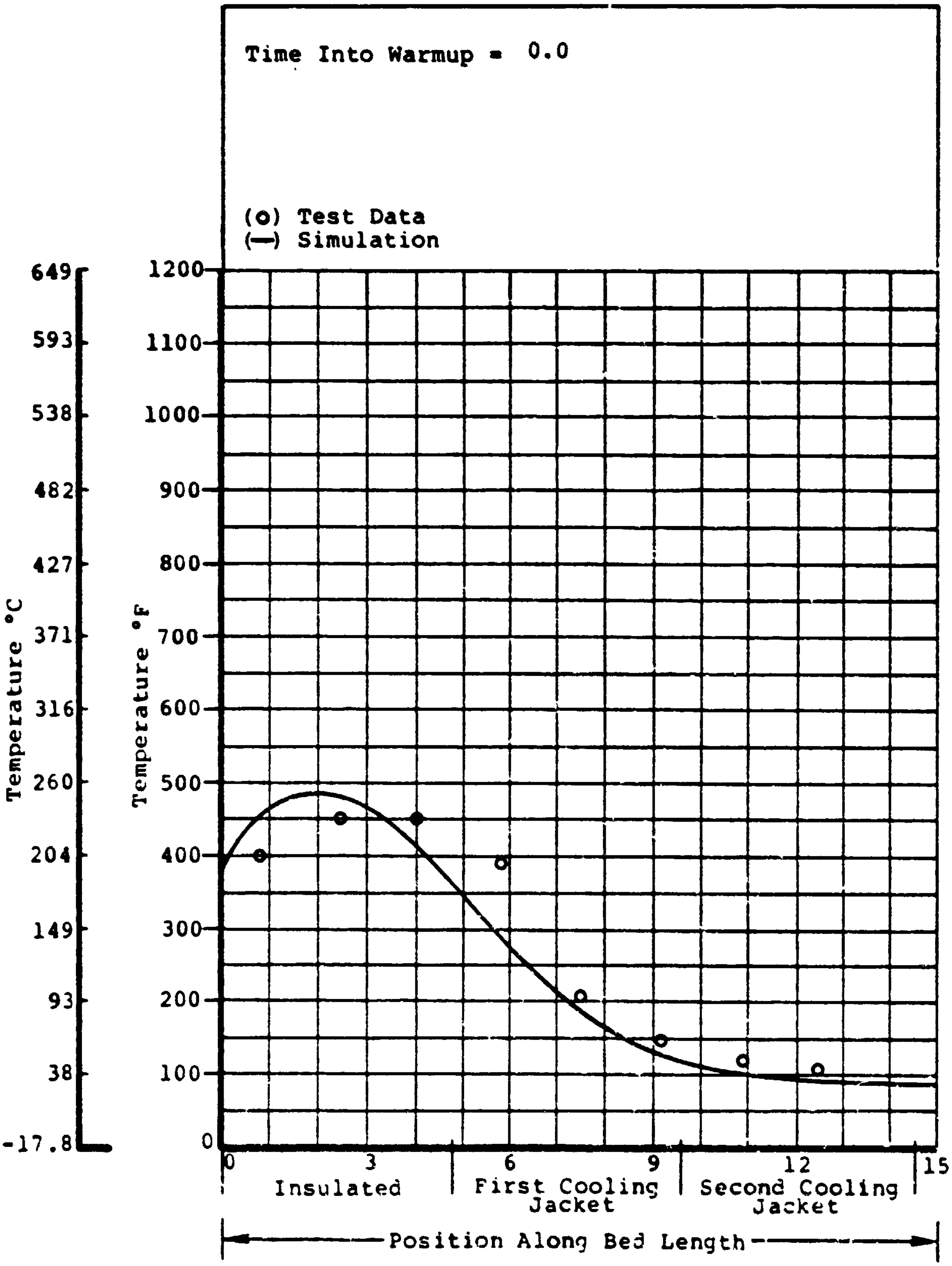


FIGURE 55
SABATIER TRANSIENT BED TEMPERATURES
2 MAN CYCLIC
MOLAR RATIO = 2.6

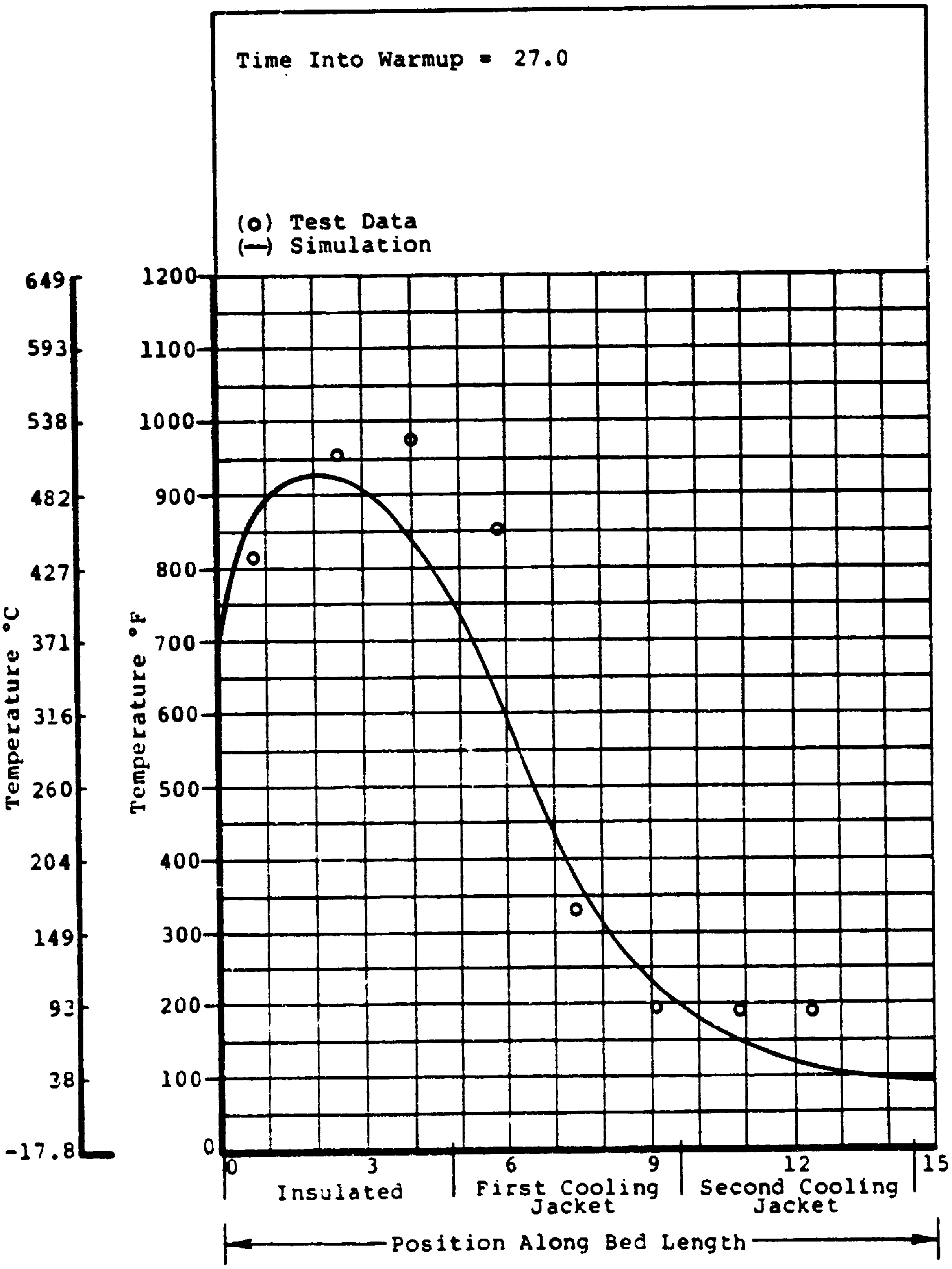


FIGURE 56
SABATIER TRANSIENT BED TEMPERATURES
2 MAN CYCLIC
MOLAR RATIO = 2.6

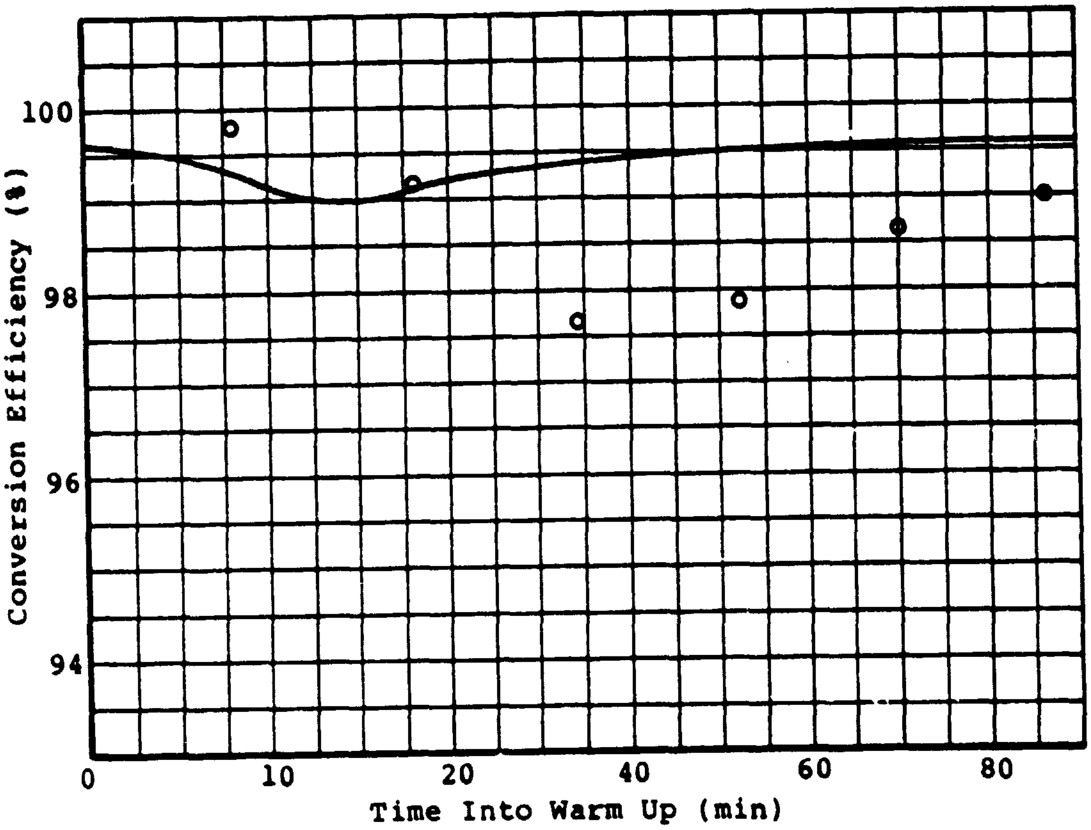


FIGURE 57
SABATIER WARM UP CONVERSION EFFICIENCY HISTORY
2 MAN CYCLIC
MOLAR RATIO = 2.6

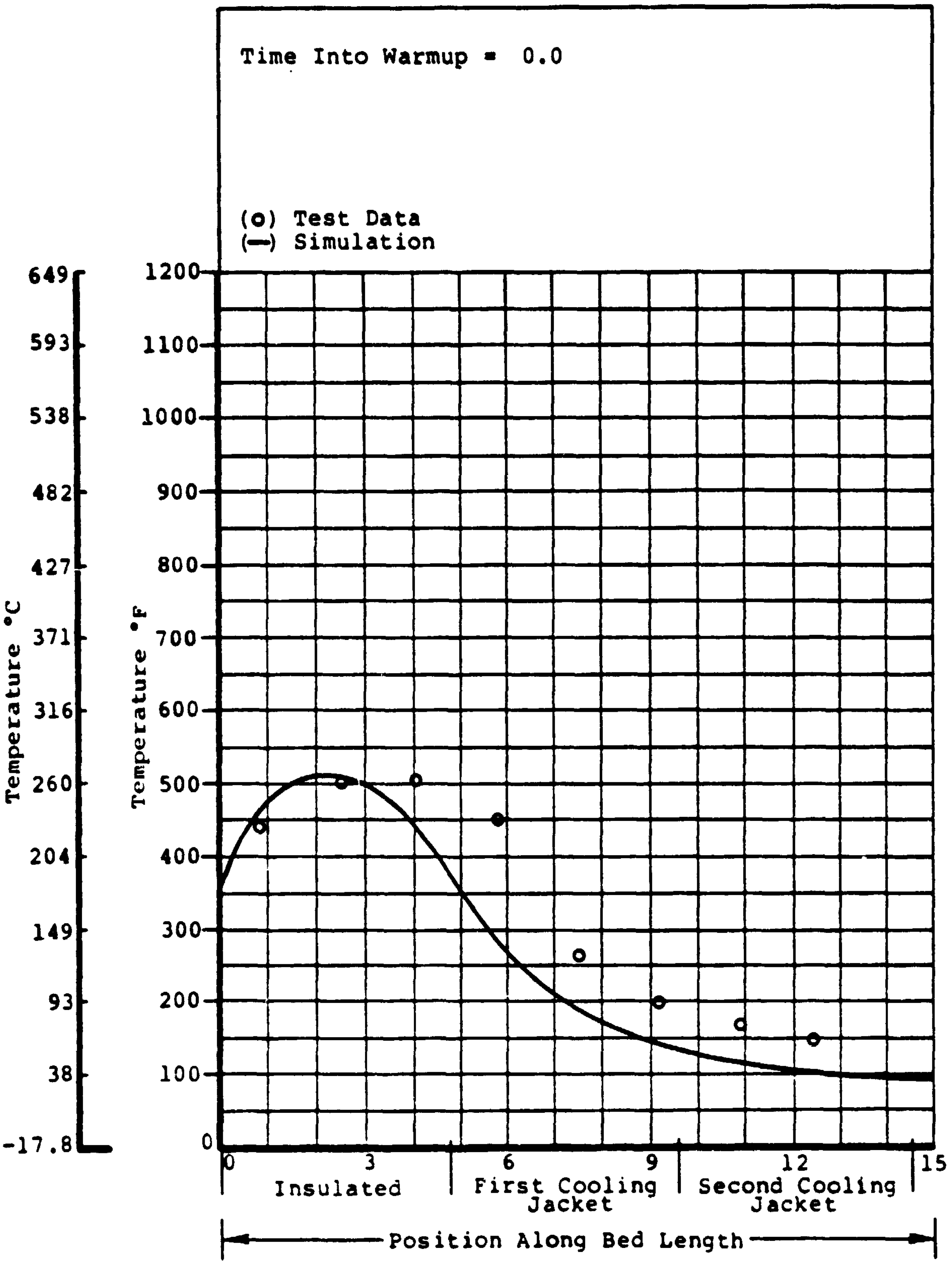


FIGURE 58
SABATIER TRANSIENT BED TEMPERATURES
3 MAN CYCLIC
MOLAR RATIO = 2.6

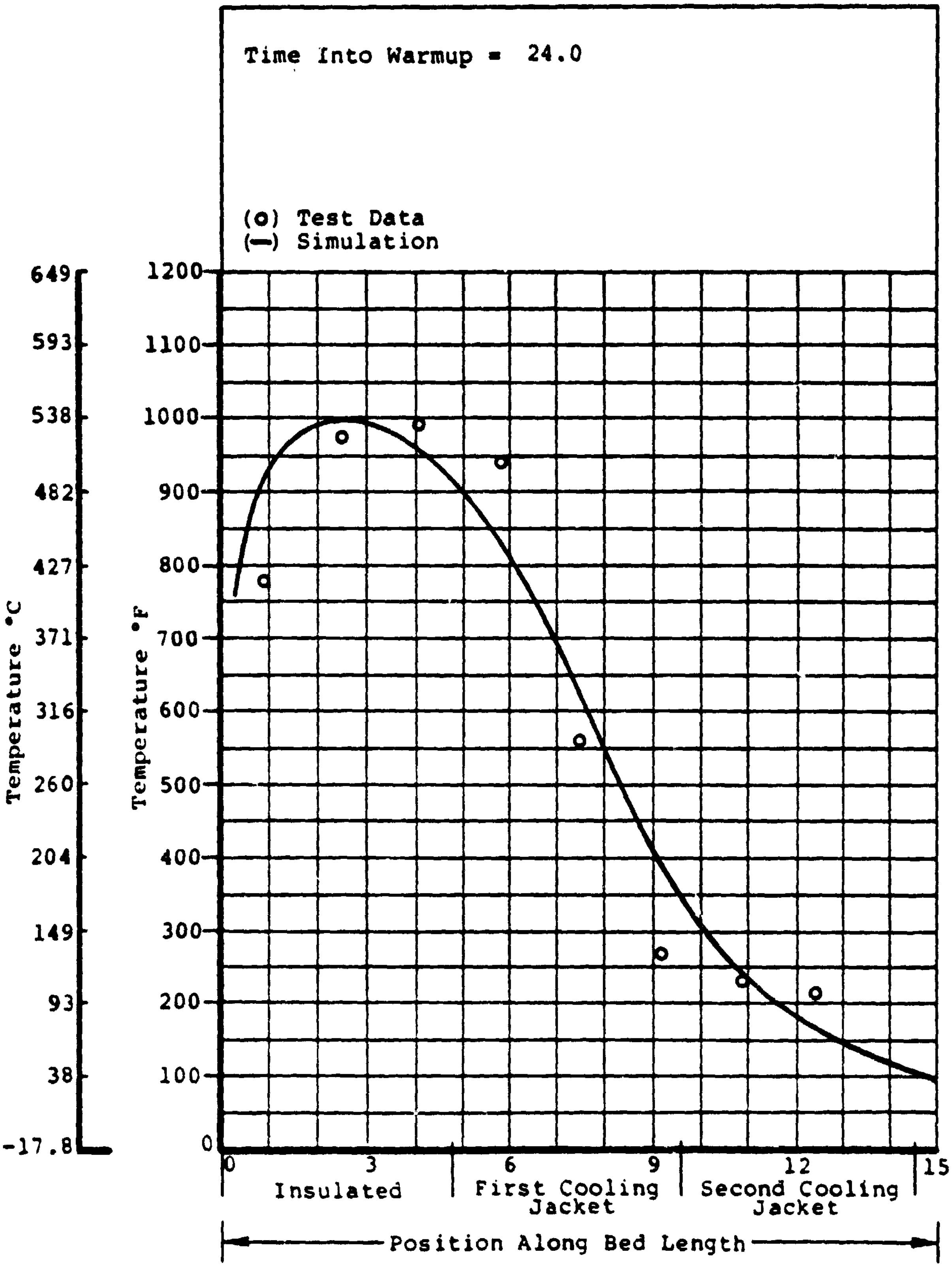


FIGURE 59
SABATIER TRANSIENT BED TEMPERATURES
3 MAN CYCLIC
MOLAR RATIO = 2.6

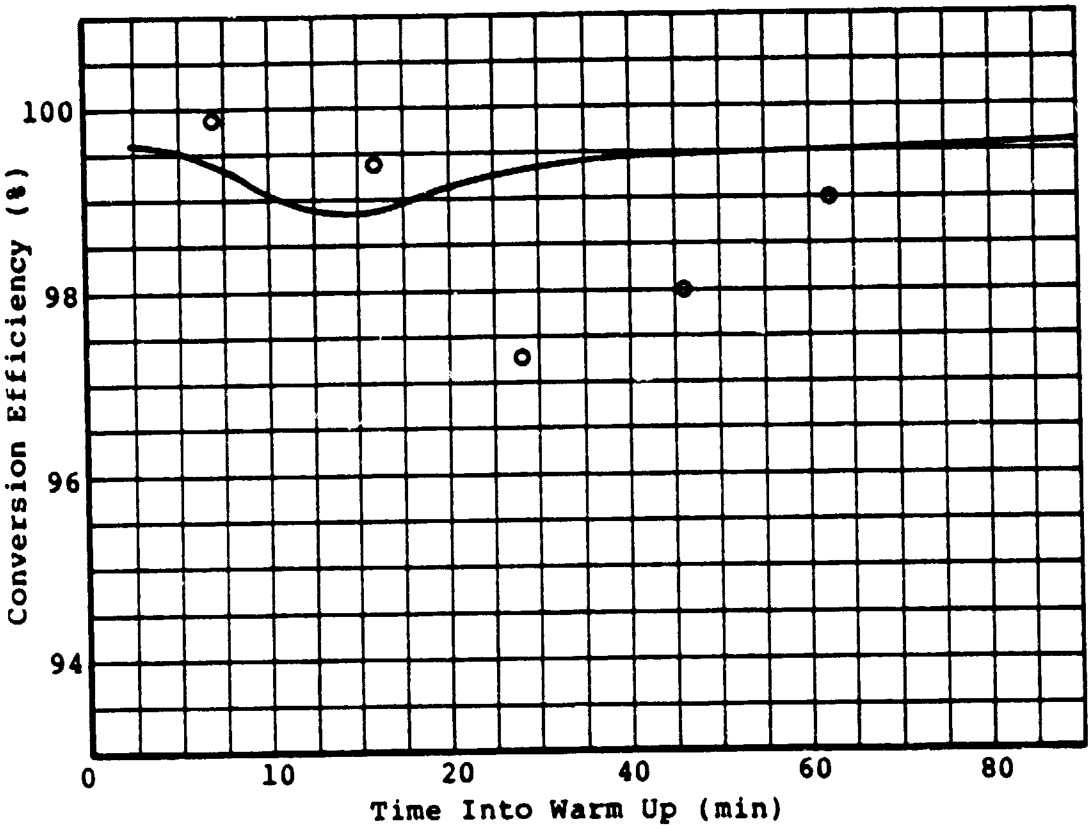


FIGURE 60
SABATIER WARM UP CONVERSION EFFICIENCY HISTORY
3 MAN CYCLIC
MOLAR RATIO = 2.6

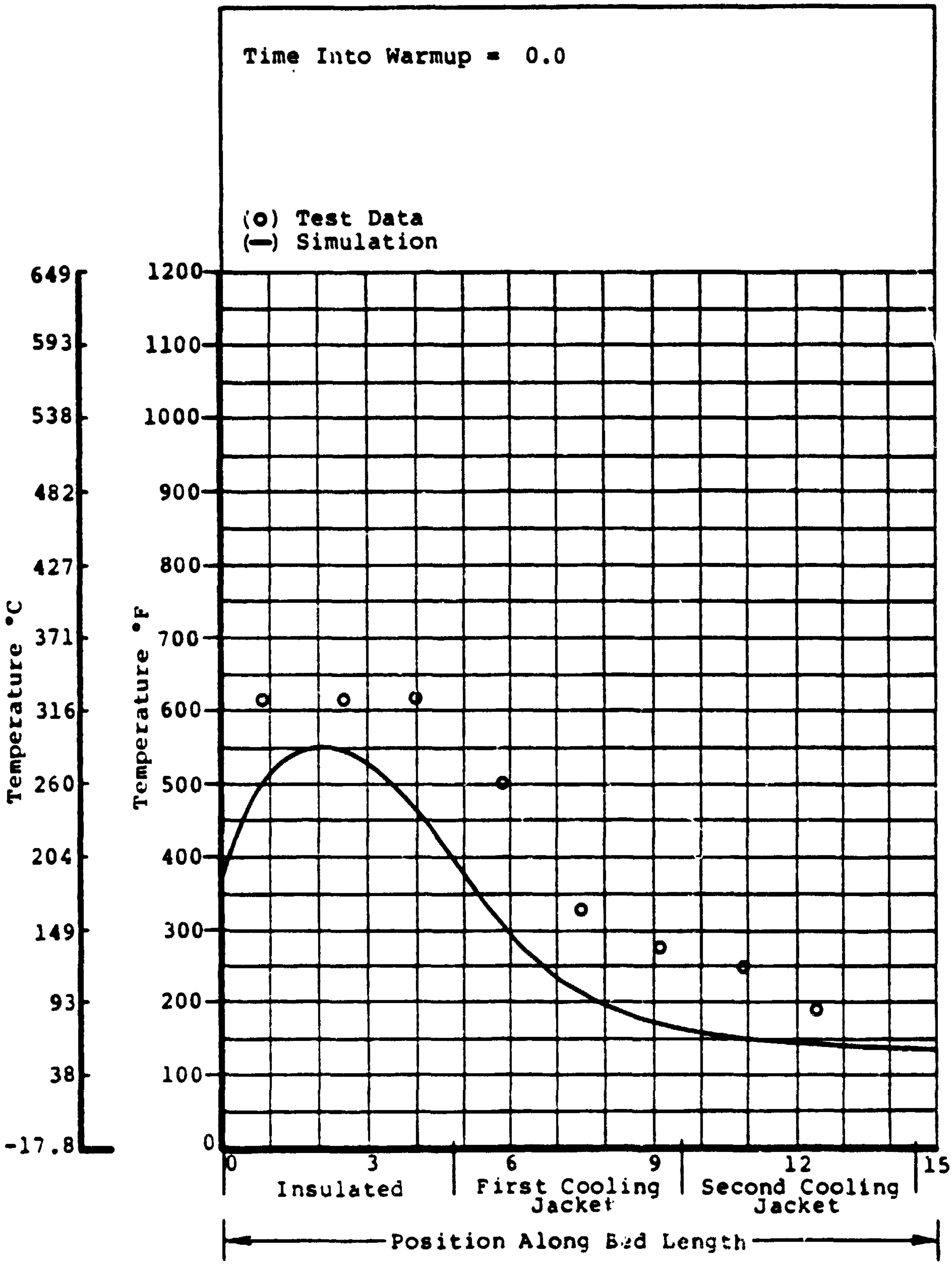


FIGURE 61
SABATIER TRANSIENT BED TEMPERATURES
3 MAN CYCLIC
MOLAR RATIO = 4.0

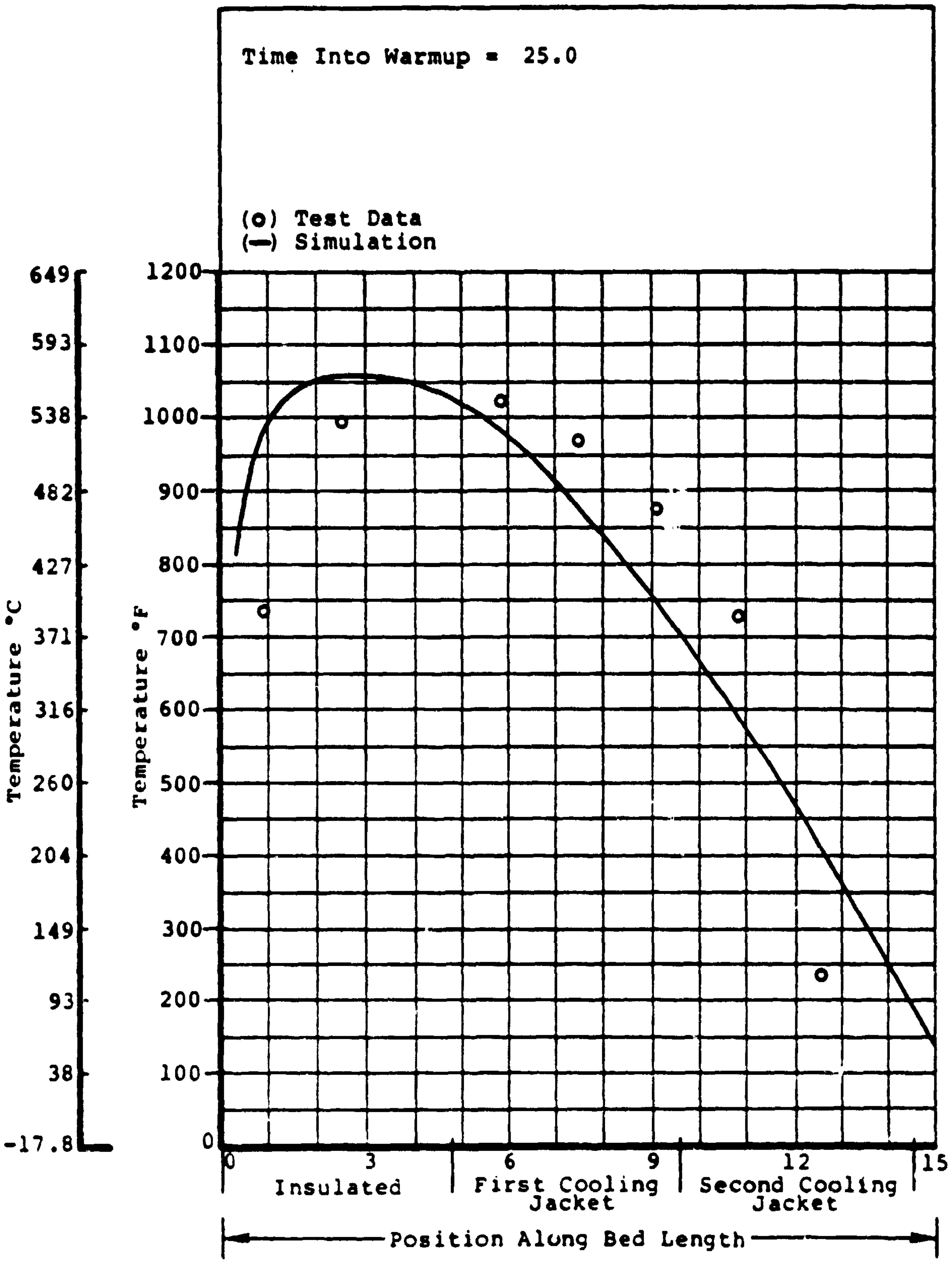


FIGURE 62
SABATIER TRANSIENT BED TEMPERATURES
3 MAN CYCLIC
MOLAR RATIO = 4.0

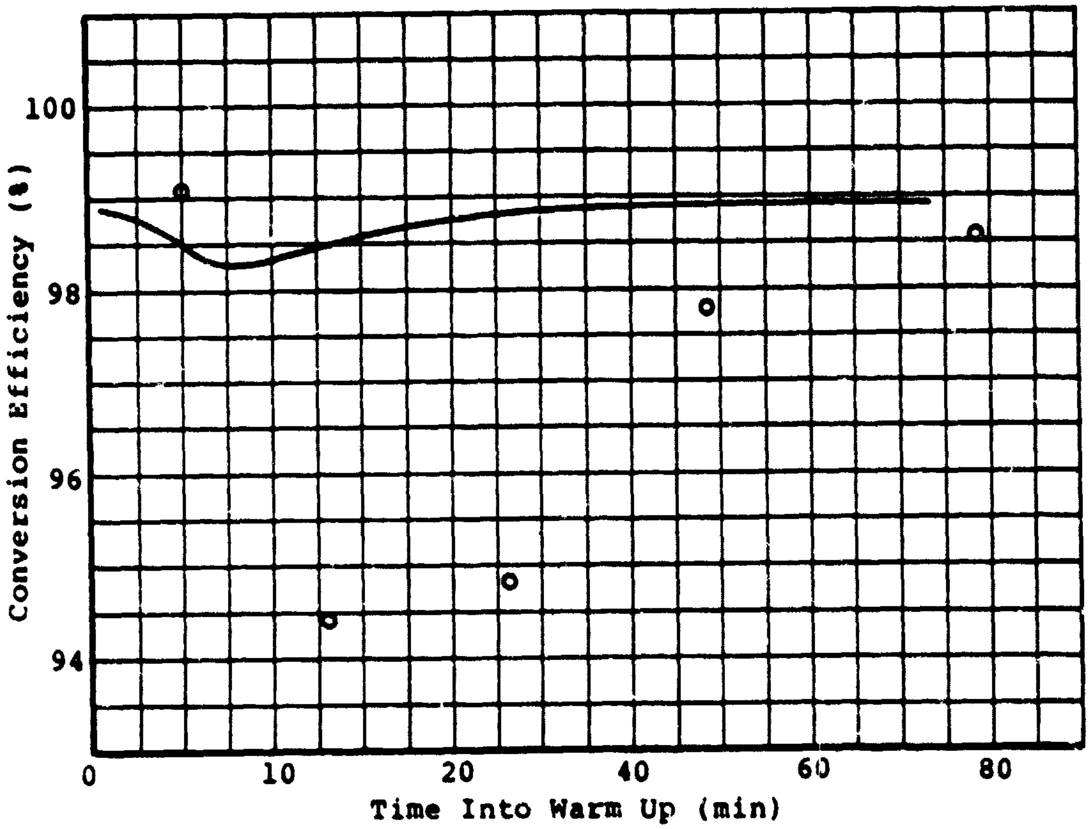


FIGURE 63
SABATIER WARM UP CONVERSION EFFICIENCY HISTORY
3 MAN CYCLIC
MOLAR RATIO = 4.0

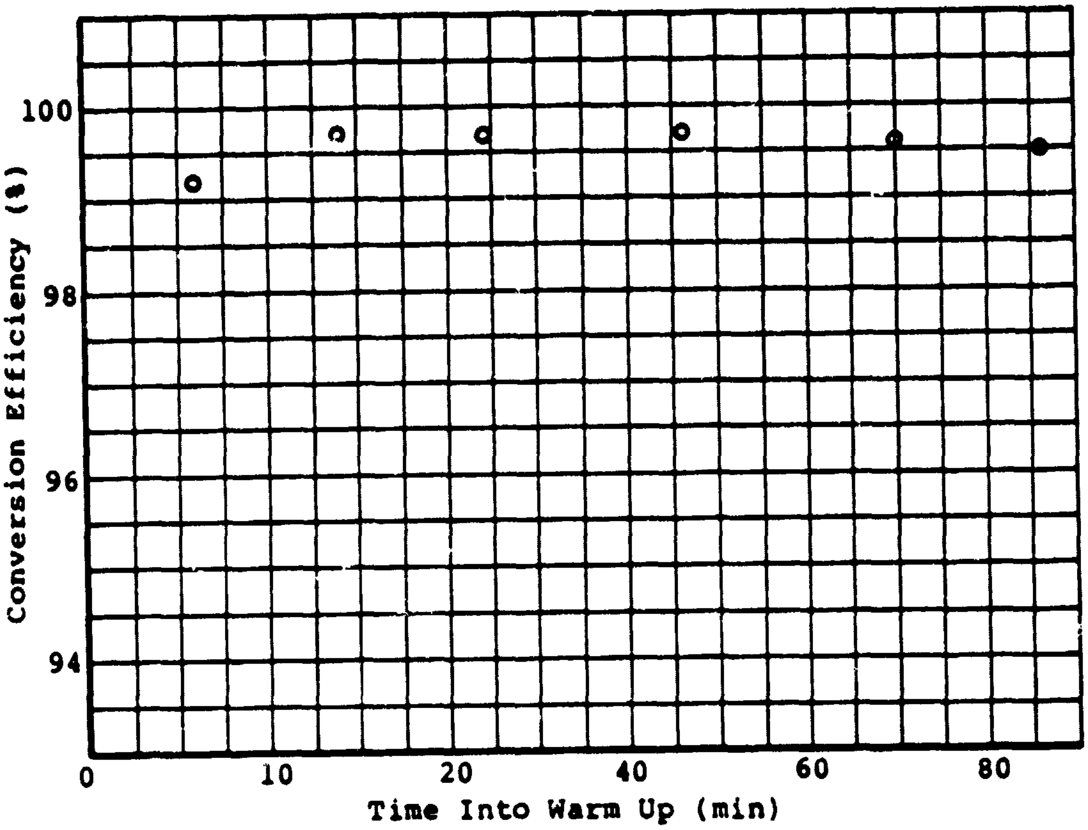


FIGURE 64
SABATIER WARM UP CONVERSION EFFICIENCY HISTORY
1 MAN CYCLIC
MOLAR RATIO = 2.6

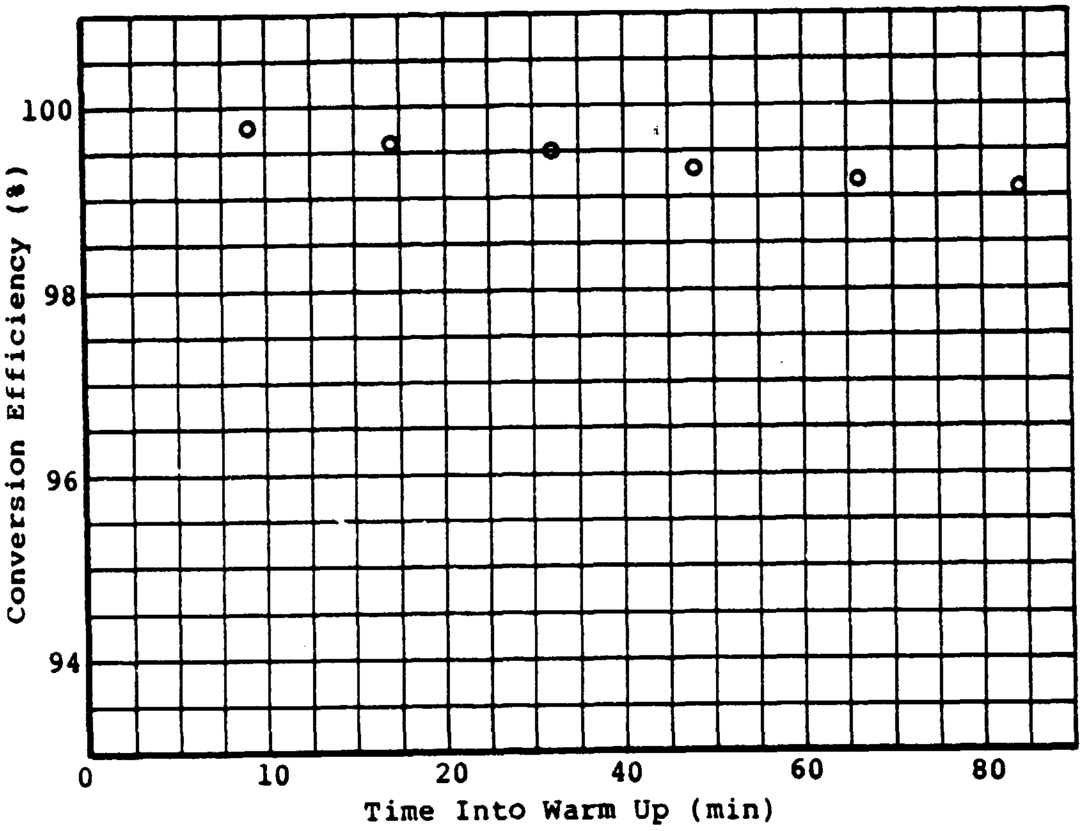


FIGURE 65
SABATIER WARM UP CONVERSION EFFICIENCY HISTORY
1 MAN CYCLIC
MOLAR RATIO = 3.5

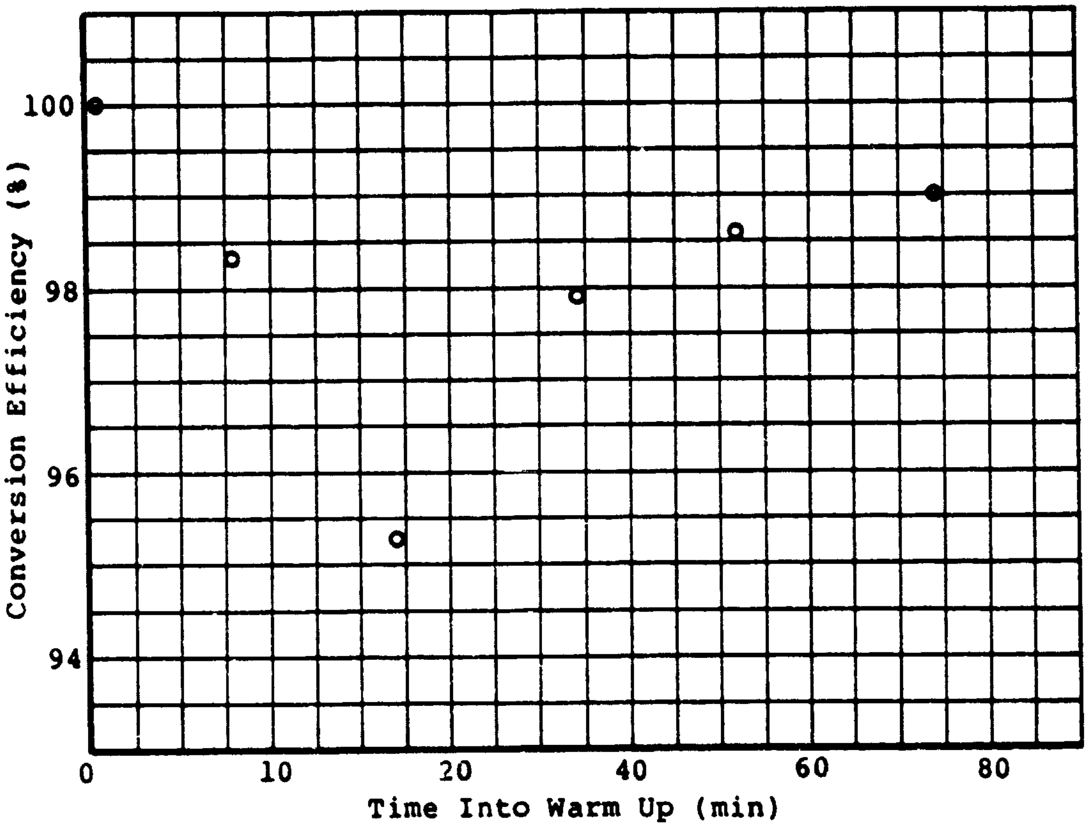


FIGURE 66
SABATIER WARM UP CONVERSION EFFICIENCY HISTORY
3 MAN CYCLIC
MOLAR RATIO = 3.5

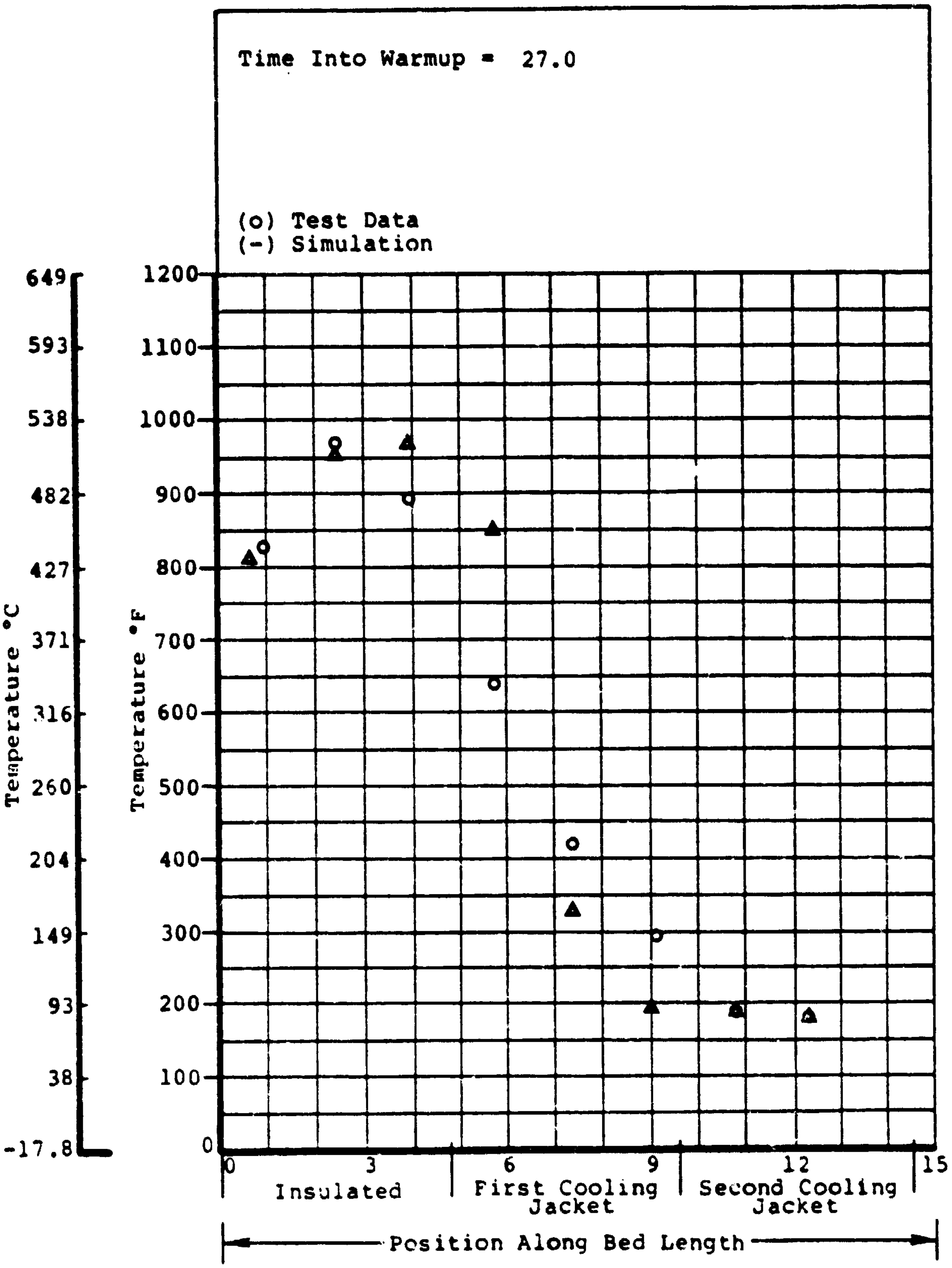


FIGURE 67

SABATIER COMPARISON OF STEADY STATE AND TRANSIENT BED TEMPERATURES
2 MAN CYCLIC
MOLAR RATIO = 2.6

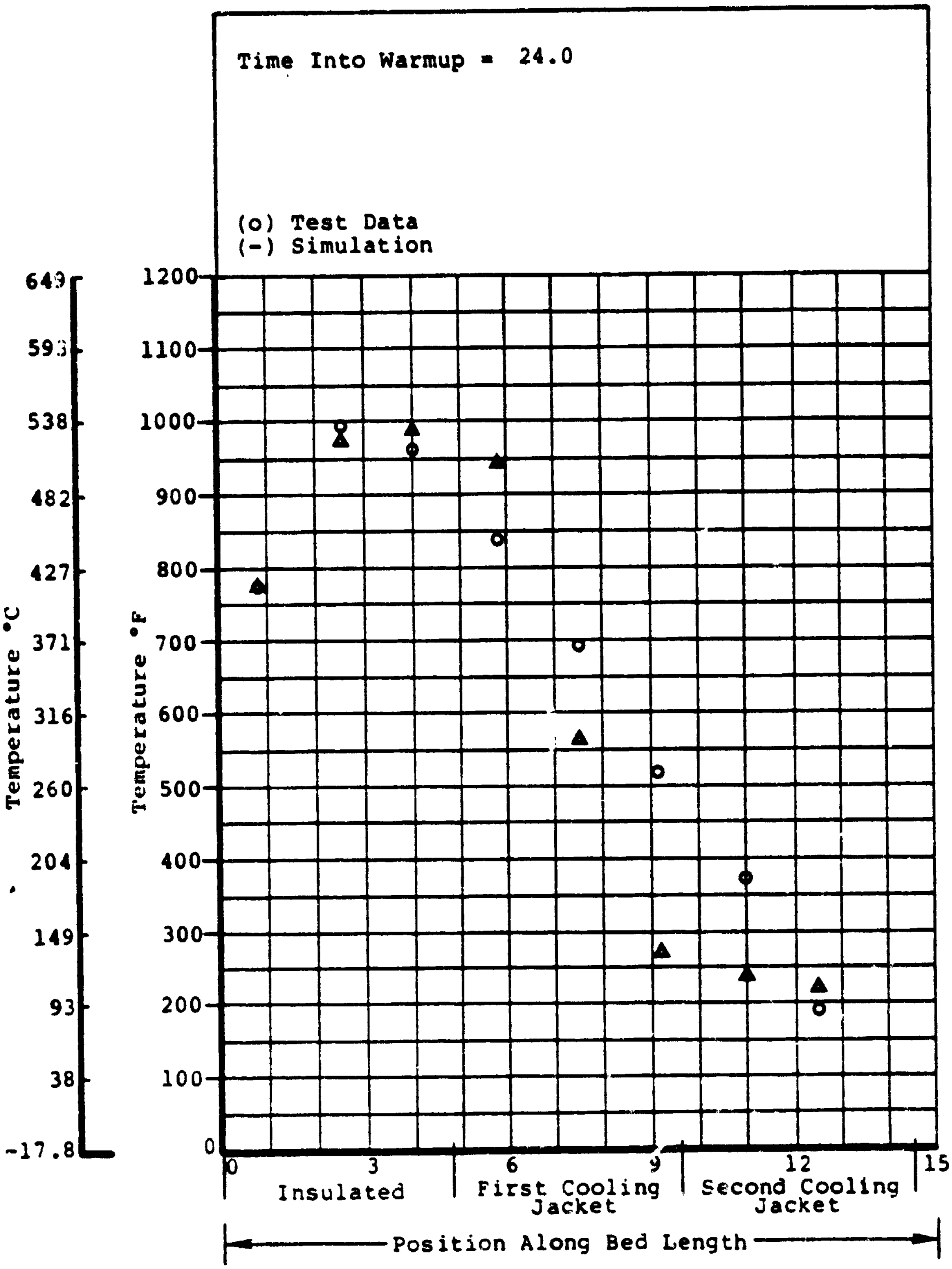


FIGURE 68
SABATIER COMPARISON OF STEADY STATE AND TRANSIENT BED TEMPERATURES
3 MAN CYCLIC
MOLAR RATIO = 2.6

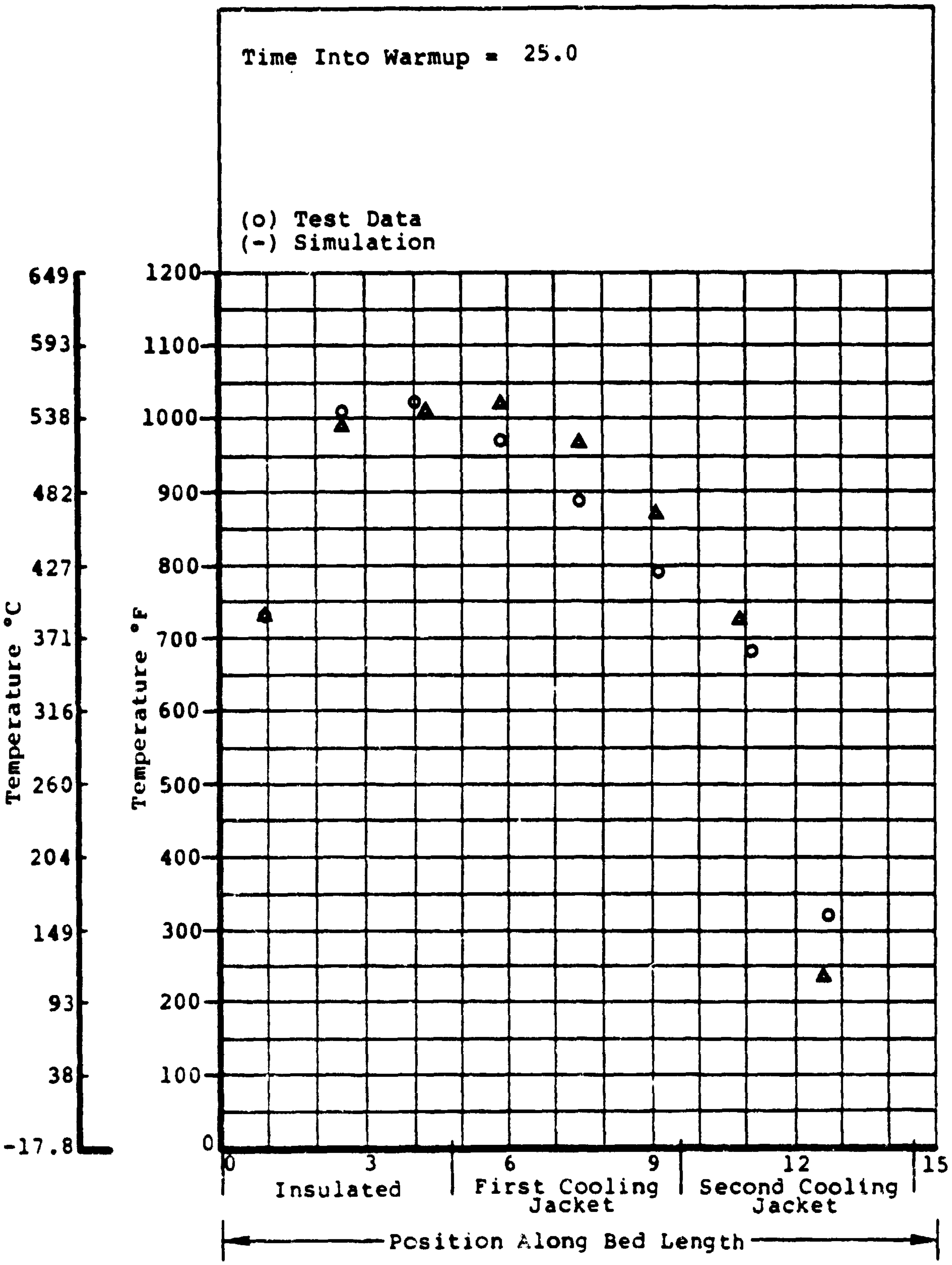


FIGURE 69
SABATIER COMPARISON OF STEADY STATE AND TRANSIENT BED TEMPERATURES
3 MAN CYCLIC
MOLAR RATIO = 4.0

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 CO_2 Reduction Subsystem schematic is shown in Figure 1. The subsystem closely matches the RLSE program Sabatier CO_2 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. CO_2 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.

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 20

DATA SUBMITTALS

DRL Item No.	Name	Document
1	Report, Monthly Progress	Submitted Monthly
2	Program Plan	Sabatier-04 dated June 13, 1978 Sabatier-10 dated August 18, 1978
3	Plan, Master Test	Sabatier-EM-13 dated January 12, 1979 SVHSER 7196
4	Report Final	Sabatier-EM-21 dated August 1980 SVHSER 7221
5	Technical Information Release	Submitted Quarterly - (No items were reported)
6	Report Financial Management	Submitted Monthly
7	Drawings, Engineering and Associated Lists	Sabatier-72 dated July 17, 1980
8	Manual, Familiarization and Operation	Sabatier- SVHSER 7222
9	FMEA	Sabatier-EM-19 dated June 22, 1980
10	Manual, Maintenance and Repair	Combined with DRL Item No. 8
11	Lists, Nonmetallic Materials	Sabatier-EM-03 dated October 20, 1978

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.

Quantity Supplied	Delivered With Subsystem	Description
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* (less spares)	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 CO_2 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. Prir 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_2 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 cylic 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 H_2 or CH_4 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 CO_2 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 sucessive 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

HAMILTON STANDARD Division of United Technologies

SVHSER 7196
Revision A

HAMILTON STANDARD

DIVISION OF UNITED TECHNOLOGIES CORPORATION

JANUARY, 1979*.

MASTER TEST PLAN

FOR

PREPROTOTYPE SABATIER SUBSYSTEM

CONTRACT NAS 9-15470

PREPARED BY: Vincent A. Celino
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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 I TEST SUMMARY

ITEM NO.	DESCRIPTION	P/N	EOP	BASE POINT CAL	PROOF PRESS	LEAKAGE	PERFORM [1]
26	SILENCER	SVSK96471-1	X				
31	CHARCOAL CANISTER	SVSK96470-1	X		X	X	
41	CHECK VALVE	SVSK96466-1	X			X	OP
42	CHECK VALVE	SVSK101124	X			X	
46	FAN	SVSK96462-1	X				OP
51	CONDENSER/SEP	SVSK96349-1	X	X	X	X	
61	ACCUMULATOR	SVSK96490-1	X				CAL
71	DRIVER BOX	SVSK97813	X				OP
81	TEMP SENSOR	SVSK96465-1	X				CAL
82	TEMP SENSOR	SVSK96499-1	X				CAL
83	HEATER	SVSK96486-1	X	X			
85	TEMP SENSOR	SVSK96465-2	X				CAL
91	REACTOR	SVSK96482-1	X	X	X	X	
178	COMB GAS DETECTOR	SVSK84456-100 -200	X	X			CAL
306	ELEC S.O. VALVE	SVSK84424-100	X			X	OP
310	BACK PRESS. REG	SVSK84412-1	X	X	X	X	
507	MAN S.O. VALVE	SVSK84530-1	X		X	X	
545	PUMP	SVSK86329-2	X	X	X	X	
876	QUANT SENSOR	SV764179-1	X				OP
902	PRESSURE TRANSDUCER	SVSK101128	X		X	X	CAL
907	LIQUID WATER DETECTOR	SVSK101129	X	X	X	X	
259	ACCUMULATOR	SVSK96492	X		X	X	
	SUBSYSTEM	SVSK96498*	X	X	X	X	MAP ACCEPT

[1] CODE: OP - OPERATIONAL CHECK
MAP - PERFORM MAP
CAL - CALIBRATION OVER RANGE
ACCEPT - ACCEPTANCE TEST

*REFERENCE SABATIER PACK

FOLDOUT FRAME

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T SUMMARY

LEAKAGE	PERFORM ◁1	POWER CONSUMPT	CONTINUITY	ENDUR	FAIL MODE CHECKOUT
X					
X	OP				
X					
	OP	X			
X					
	CAL				
	OP		X		
	CAL				
	CAL				
		X	X		
	CAL				
X					
	CAL				
X	OP				
X					
X					
X		X	X		
	OP				
X	CAL				
X					
X					
X	MAP ACCEPT			X	X

NCE SABATIER PACKAGE ASSEMBLY SVSK96500

-3

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 H_2 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 H_2/CO_2 molar ratios, reactant flow rates, reactant operating pressures and gas cooling flow rates on H_2/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 mixtures at the flowmeter pressure to be used during test runs. 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

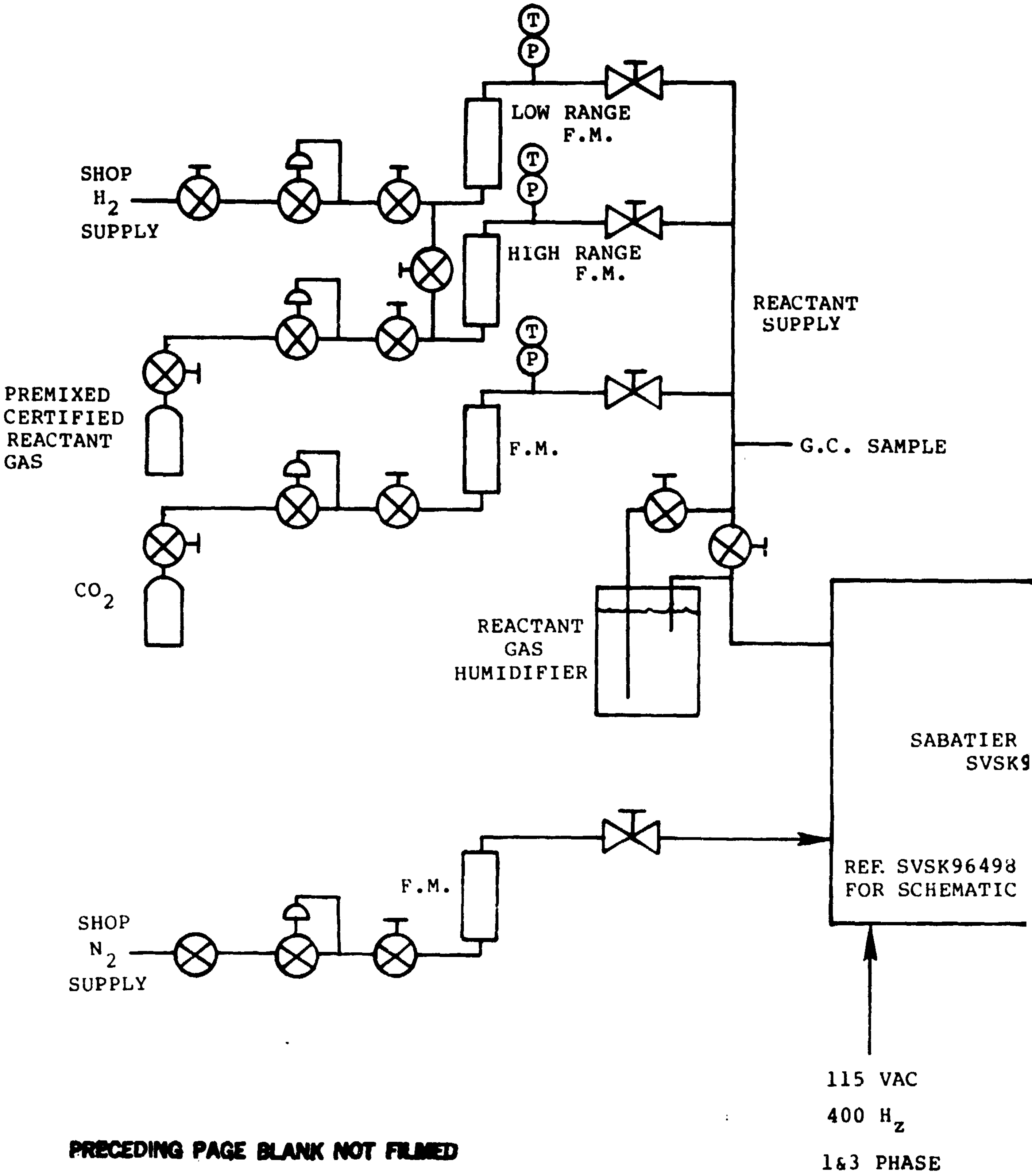
COMPONENT TESTS

H_2/CO_2 MOLAR RATIO	1.8		NOMINAL FLOW 2.6		5.0	
	TEST #	FLOW ON (HRS)	TEST #	FLOW ON (HRS)	TEST #	FLOW ON (HRS)
CO_2 MAN FLOW						
1	7	2			9	2
3			(2) 1	2		
			(2) 2	2		
			(2) 3	2		
(1) 3 CYCLIC	8	2	(3) 4	2	10	2
			(3) 5	2		
			(3) 6	2		
TOTAL HOURS		4	+	12	+	4 = 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 determines effect of reactor pressure on H_2 conversion efficiency.


T
P
LOW RANGE F.M.
SHOP H_2 SUPPLY
HIGH RANGE F.M.
REACTANT SUPPLY
PREMIXED CERTIFIED REACTANT GAS
F.M.
G.C. SAMPLE
CO_2
REACTANT GAS HUMIDIFIER
SABATIER
SVSK9
REF. SVSK96498 FOR SCHEMATIC
F.M.
SHOP N_2 SUPPLY
115 VAC
400 H_z
1&3 PHASE

PRECEDING PAGE BLANK NOT FILMED

FOLDOUT FRAME

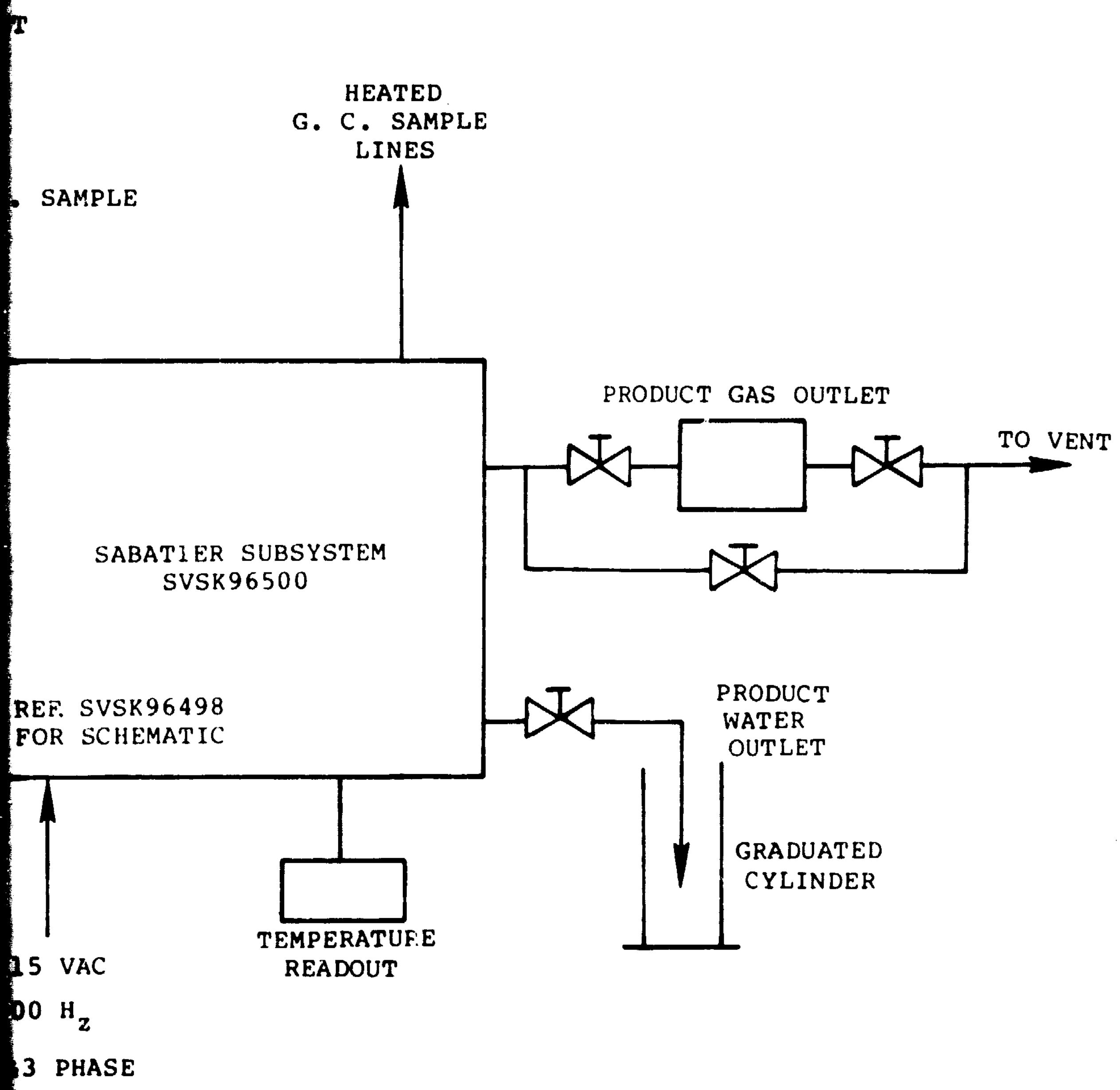

T
HEATED
G. C. SAMPLE
LINES
SAMPLE
PRODUCT GAS OUTLET
TO VENT
SABATIER SUBSYSTEM
SVSK96500
REF. SVSK96498
FOR SCHEMATIC
PRODUCT
WATER
OUTLET
GRADUATED
CYLINDER
TEMPERATURE
READOUT
15 VAC
00 H_z
3 PHASE

FIGURE 2

FOLDOUT FRAME 2

3.2 Laboratory Gas Analysis - Product gas mixture analysis shall be determined by gas chromatographic tests. Accuracies shall be as follow:

	Concentration Range	Accuracy
H_2	0 - 5%	± 0.1%
CO_2	0 - 5%	± 0.1%
CH_4	0 - 25%	± 0.5%

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.

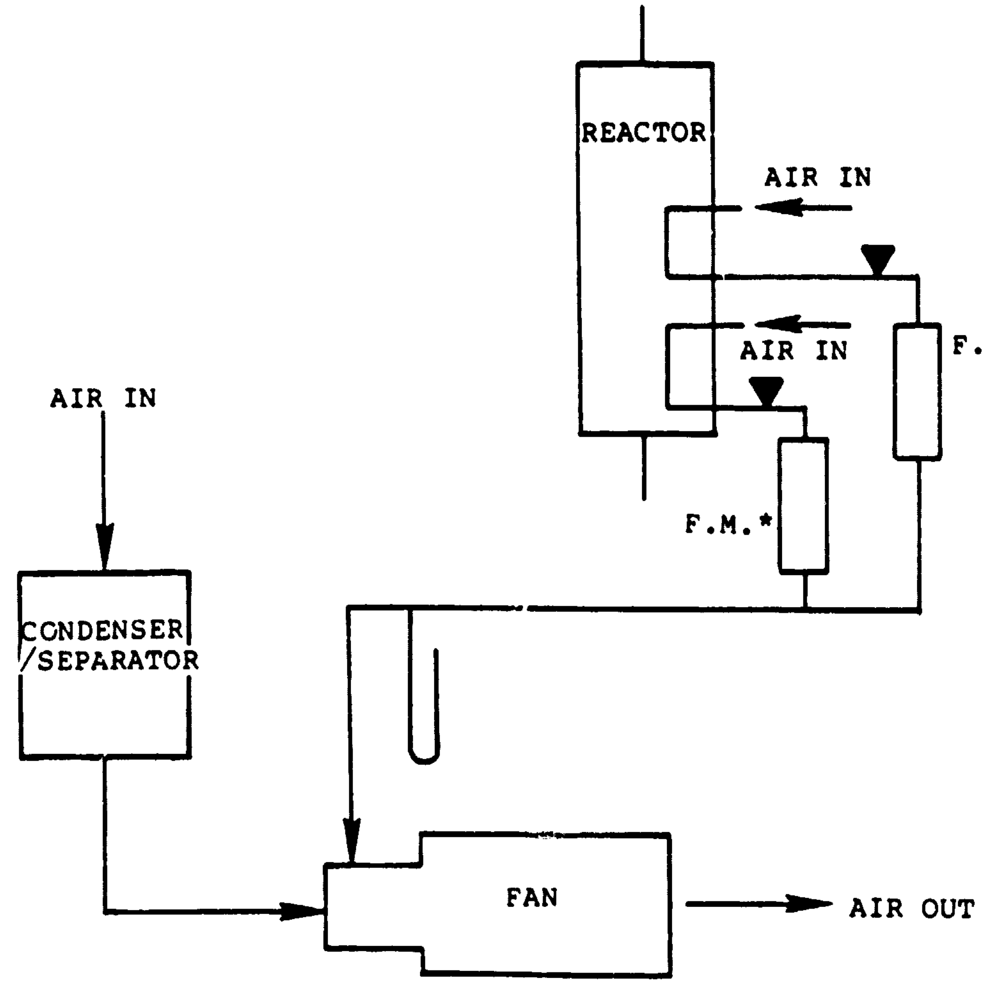
5.0 SUBSYSTEM TESTING

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 H_2/CO_2 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 H_2 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.


REACTOR
AIR IN
AIR IN
F.M.*
F.M.*
AIR IN
CONDENSER /SEPARATOR
FAN
AIR OUT

*TEST ONE LEG AT A TIME

FIGURE 2
REACTOR COOLING AIR FLOW TEST SETUP

TABLE III

(1) SABATIER SUBSYSTEM STEADY STATE RUNS

H_2/CO_2 MOLAR RATIO	1.8		NOMINAL FLOW 2.6		3.5		4.0		5.0	
	TEST NO.	FLOW ON (HRS)	TEST NO.	FLOW ON (HRS)	TEST NO.	FLOW ON (HRS)	TEST NO.	FLOW ON (HRS)	TEST NO.	FLOW ON (HRS)
CO_2 MAN FLOW										
1	11	2 (P)	14	50 (E)	20	2 (P)	23	2 (P)	26	2 (P)
3	12	2 (P)	(4) 15	8 (A)	21	2 (P)	24	2 (P)	27	2 (P)
			16	120 (E)						
			(4) 17	8 (A)						
(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	+	6	+	6 = 230 Hrs Total

(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% H_2 conversion efficiency requirement

(4) - Acceptance (Baseline) Test

A = Acceptance Testing

E = Endurance Testing

P = Parametric Testing

TABLE IV

[1] SABATIER SUBSYSTEM CYCLICAL RUNS

H_2/CO_2 MOLAR RATIO	1.8		NOMINAL FLOW 2.6		3.5		4.0		5.0	
	TEST NO.	FLOW ON (HRS)	TEST NO.	FLOW ON (HRS)	TEST NO.	FLOW ON (HRS)	TEST NO.	FLOW ON (HRS)	TEST NO.	FLOW ON (HRS)
[2] CYCLIC CO_2 MAN FLOW										
1	29	4 (P)	31	20 (E)	34	2 (P)	36	2 (P)	38	4 (P)
2			32	10 (E)						
3	30	4 (P)	33	20 (E)	35	2 (P)	37	2 (P)	39	4 (P)
TOTAL HOURS		8	+	50	+	4	+	4	+	8 = 74 Hrs Total

(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

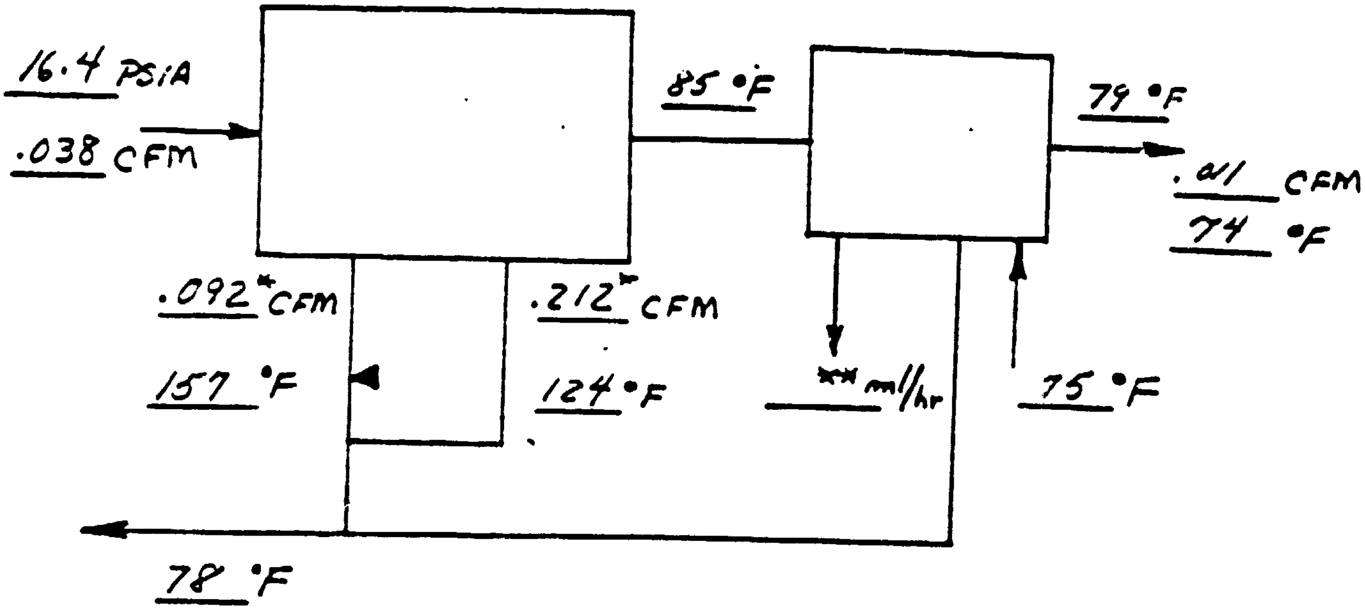
APPENDIX B

DATE: 3-7-10
RUN No. 9
TEST No. 7

SABATIER

1 MAN CONT.

M.R. 1.8


16.4 PSIA
.038 CFM
85 °F
79 °F
.01 CFM
74 °F
.092* CFM
157 °F
.212* CFM
124 °F
** ml/hr
75 °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
H_2 .32
CH_4 44.77
CO_2 53.72

$\mathcal{E} = 99.8$

* AT ROOM TEMP

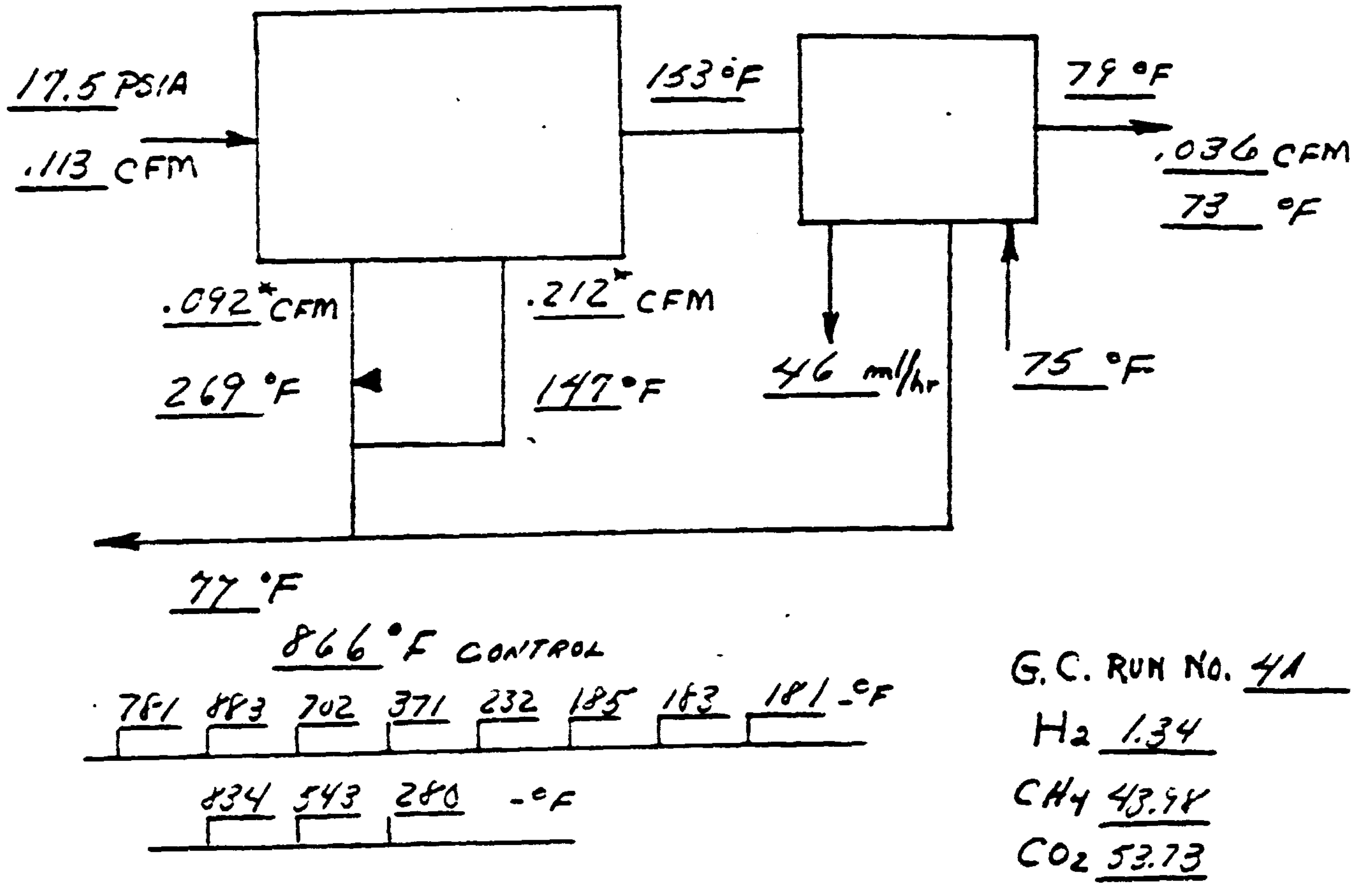
** RAN ONLY 2.5 HOURS
ACCUMULATOR DID NOT
DUMP

DATE: 3-7-80
RUN No. 4
TEST No. 12

SABATIER

3 MAN CONT.

M.R. 1.8


17.5 PSIA
.113 CFM
153°F
79 °F
.036 CFM
73 °F
.092* CFM
269 °F
.212* CFM
147°F
46 ml/hr
75 °F
77°F

866°F CONTROL

781 883 702 371 232 185 163 181 -°F

834 543 280 -°F

____ °F OVERTEMP

G.C. RUN No. 41
H_2 1.34
CH_4 43.98
CO_2 53.73

$\varepsilon = 99.3$

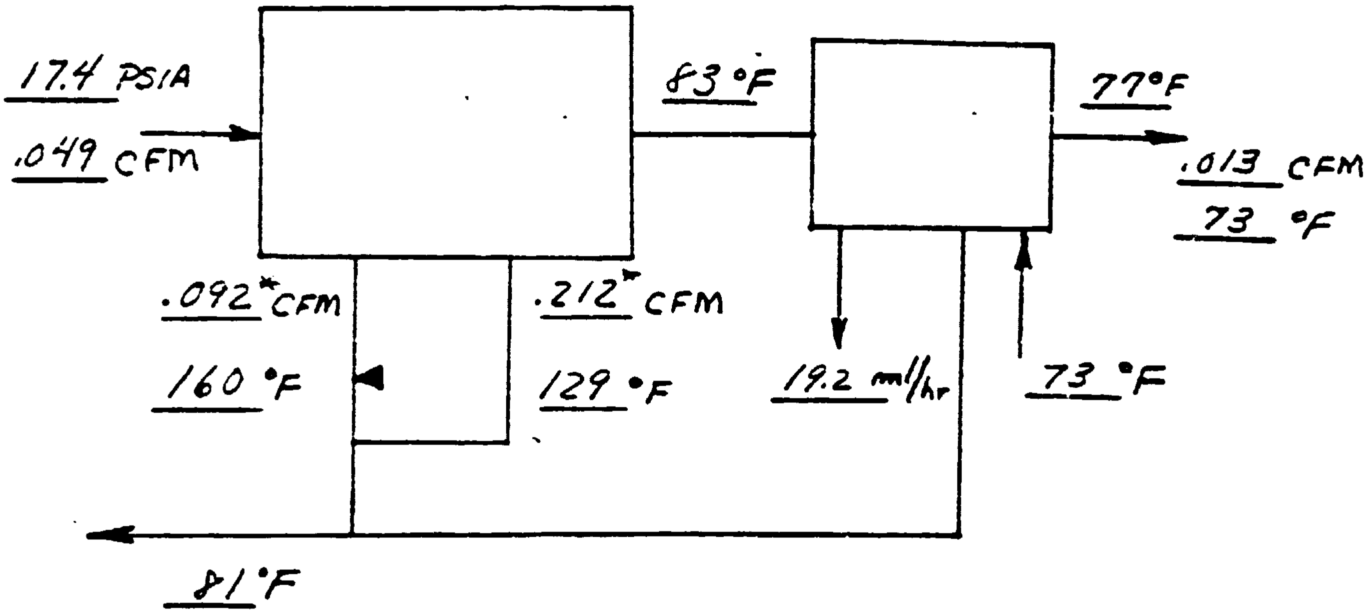
* AT ROOM TEMP

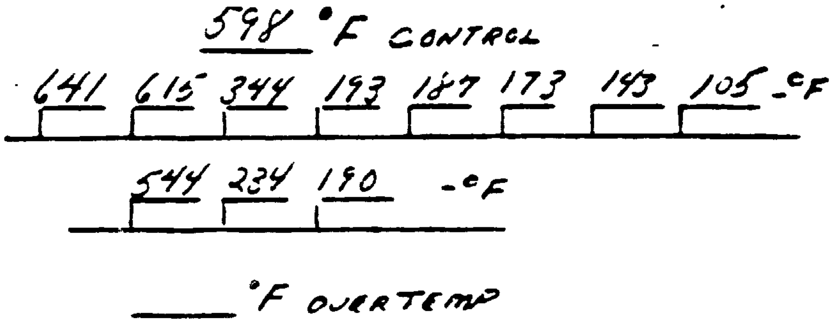
DATE: 2-22-80
RUN No. 41
TEST No. 14

SABATIER

1 MAN CONT.

M.R. 2.6


17.4 PSIA
.049 CFM
83 °F
77°F
.013 CFM
73 °F
.092* CFM
160 °F
.212* CFM
129 °F
19.2 ml/hr
73 °F
81°F


598 °F CONTROL
641 615 344 193 187 173 143 105 °F
544 234 190 °F
°F OVERTEMP

G.C. RUN NO. 8
H_2 .44
CH_4 62.75
CO_2 36.63

$\mathcal{E} = 99.8$

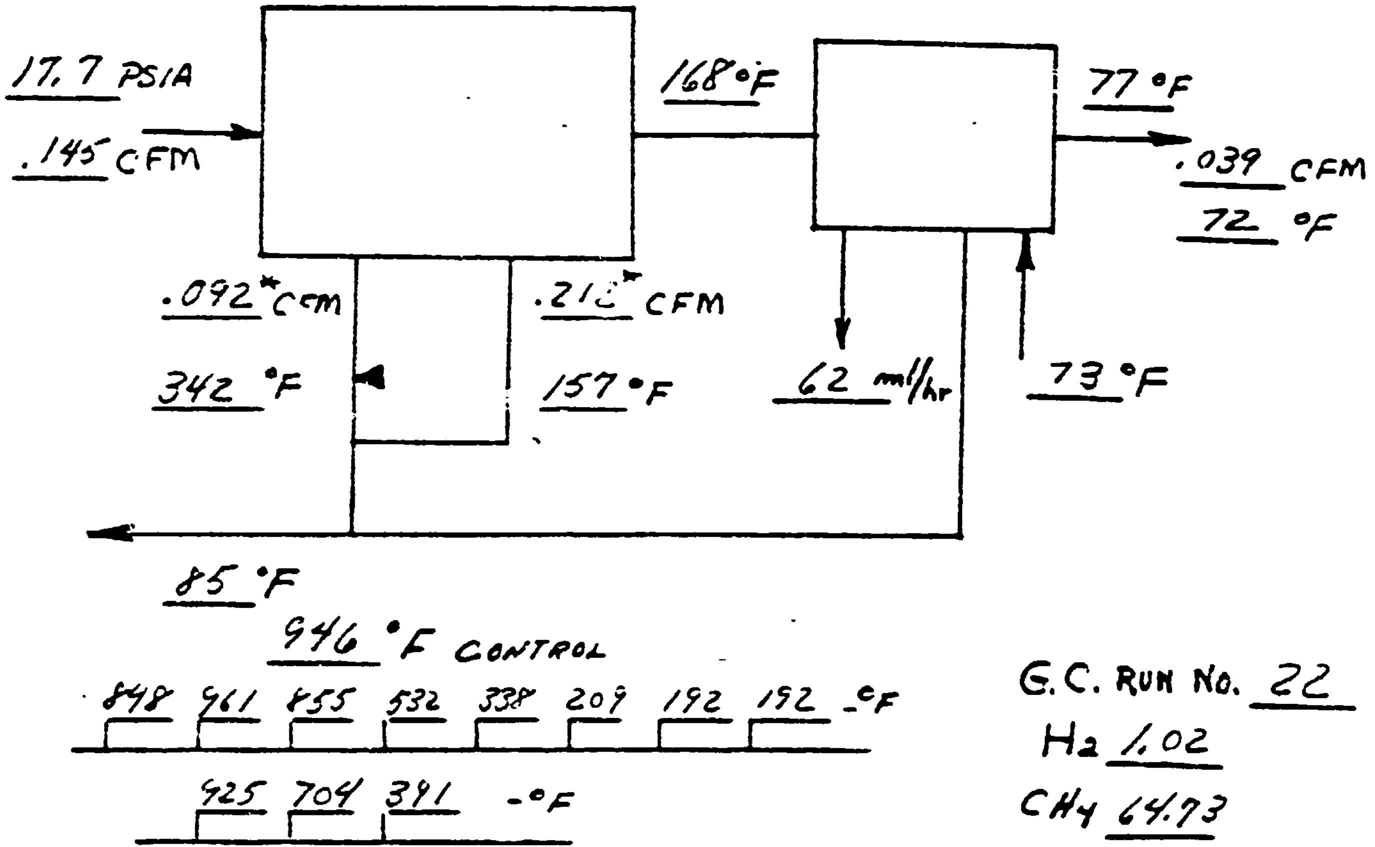
* AT ROOM TEMP.

DATE: 2-19-80
RUN No. 53
TEST No. 17

SABATIER

3 MAN CONT.

M.R. 2.60


17.7 PSIA
.145 CFM
168 °F
77 °F
.039 CFM
72 °F
.092* CFM
342 °F
.212* CFM
157 °F
62 ml/hr
73 °F
85 °F
946 °F CONTROL
848 961 855 532 338 209 192 192 °F
925 704 391 °F

G.C. RUN No. 22
H_2 1.02
CH_4 64.73
CO_2 34.02

____ °F OVERTEMP

E = 99.6

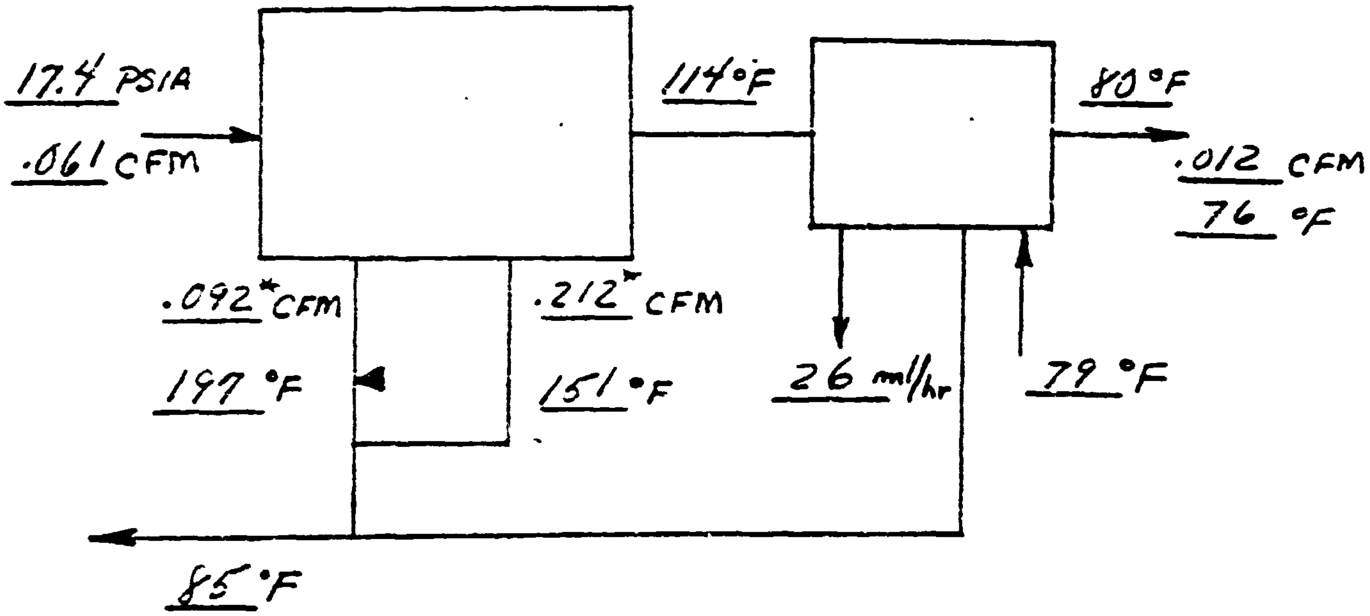
* AT ROOM TEMP.

DATE: 3-25-80
RUN No. 9
TEST No. 20

SABATIER

1 MAN CONT.

M.R. 3.5


17.4 PSIA
.061 CFM
114°F
80°F
.012 CFM
76 °F
.092* CFM
197 °F
.212* CFM
151 °F
26 ml/hr
79 °F
85 °F

763 °F CONTROL

786 781 476 199 197 193 187 134 °F

713 358 198 °F

— °F OVERTEMP

G.C. RUN No. 8
H_2 1.54
CH_4 86.42
CO_2 12.07

$E = 99.6$

* AT ROOM TEMP.

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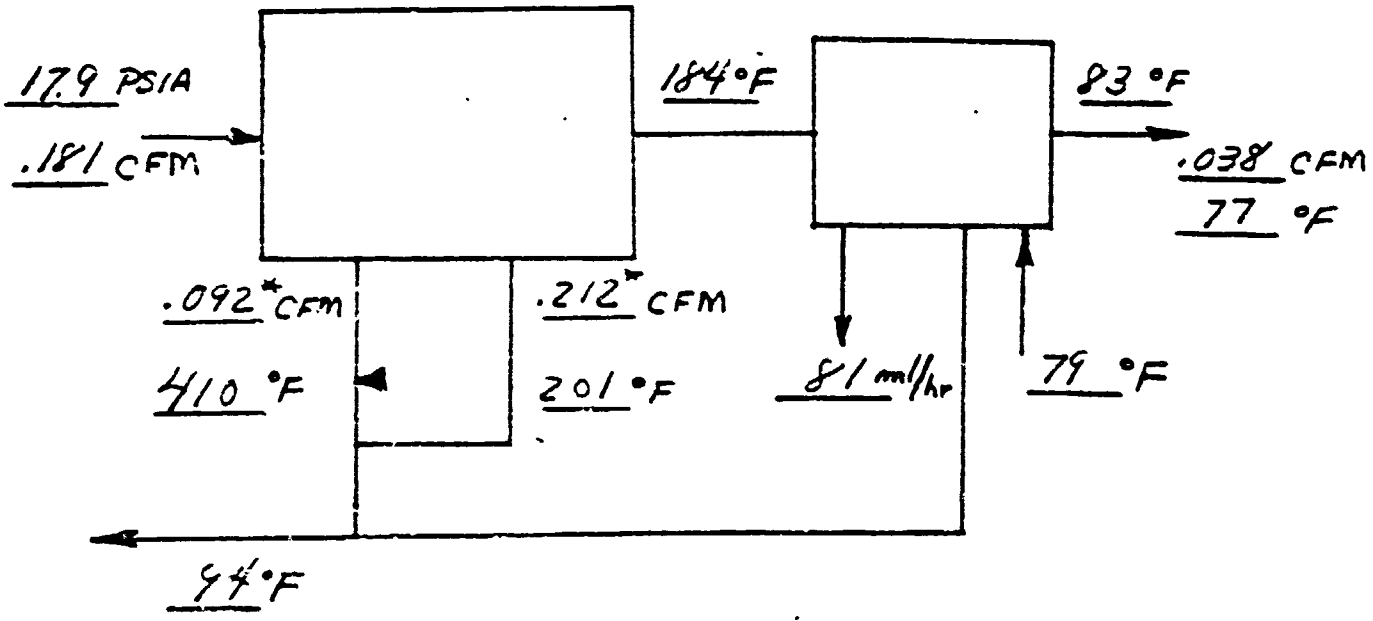
DATE: 3-24-80
RUN No. 11
TEST No. 21

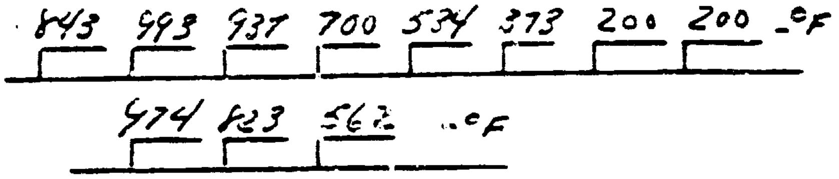
SABATIER

3 MAN CONT.

M.R. 3.5


17.9 PSIA
.181 CFM
184°F
83°F
.038 CFM
77 °F
.092* CFM
410 °F
.212* CFM
201 °F
81 ml/hr
79 °F
94°F

979°F CONTROL


843
993
937
700
534
373
200
200
°F
474
823
562
°F

__ °F OVERTEMP

G.C. RUN No. 15
H_2 2.58
CH_4 83.87
CO_2 12.63

$E = 99.3$

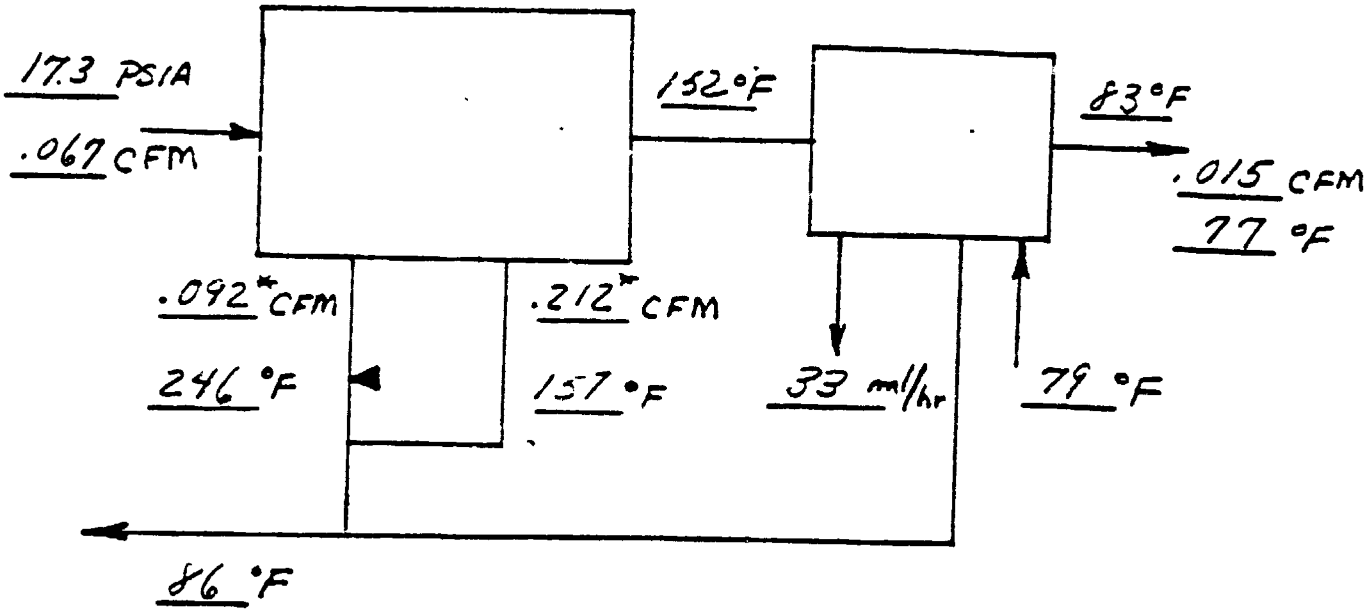
* AT ROOM TEMP

DATE: 3-28-80
RUN No. 6
TEST No. 23

SABATIER

1 MAN CONT.

M.R. 4.0


17.3 PSIA
.067 CFM
152 °F
83 °F
.015 CFM
77 °F
.092* CFM
246 °F
.212* CFM
157 °F
33 ml/hr
79 °F
86 °F

860 °F CONTROL

844 897 631 294 200 200 197 144 °F

824 480 234 °F

— °F OVERTEMP

G.C. RUN No. 9
H_2 3.53
CH_4 95.26
CO_2 .42

$\mathcal{E} = 99.1$

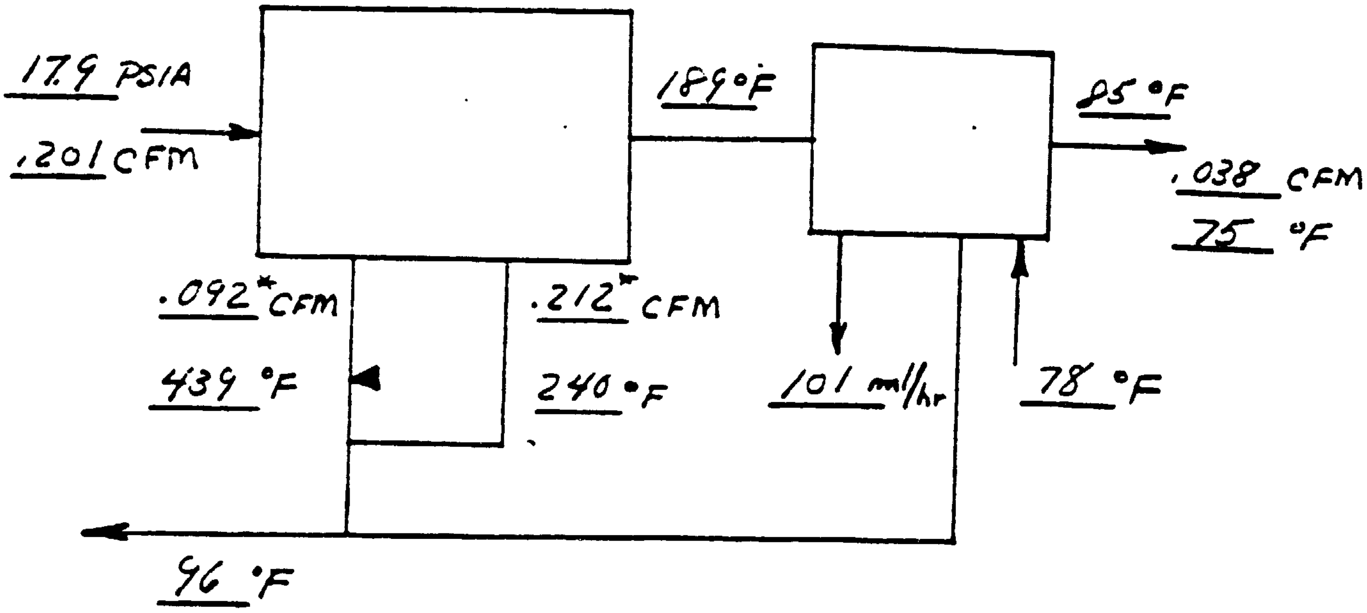
* AT ROOM TEMP.

DATE: 3-27-80
RUN No. 11
TEST No. 24

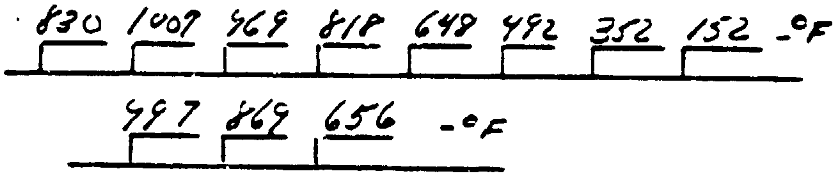
SABATIER

3 MAN CONT.

M.R. 4.0


17.9 PSIA
.201 CFM
189°F
85 °F
.038 CFM
75 °F
.092* CFM
439 °F
.212* CFM
240 °F
101 ml/hr
78 °F
96 °F

993 °F CONTROL


830
1009
969
818
648
492
352
152
-°F
997
869
656
-°F

— °F OVERTEMP

G.C. RUN NO. 16
H_2 5.34
CH_4 9309
CO_2 1.34

E = 99.0

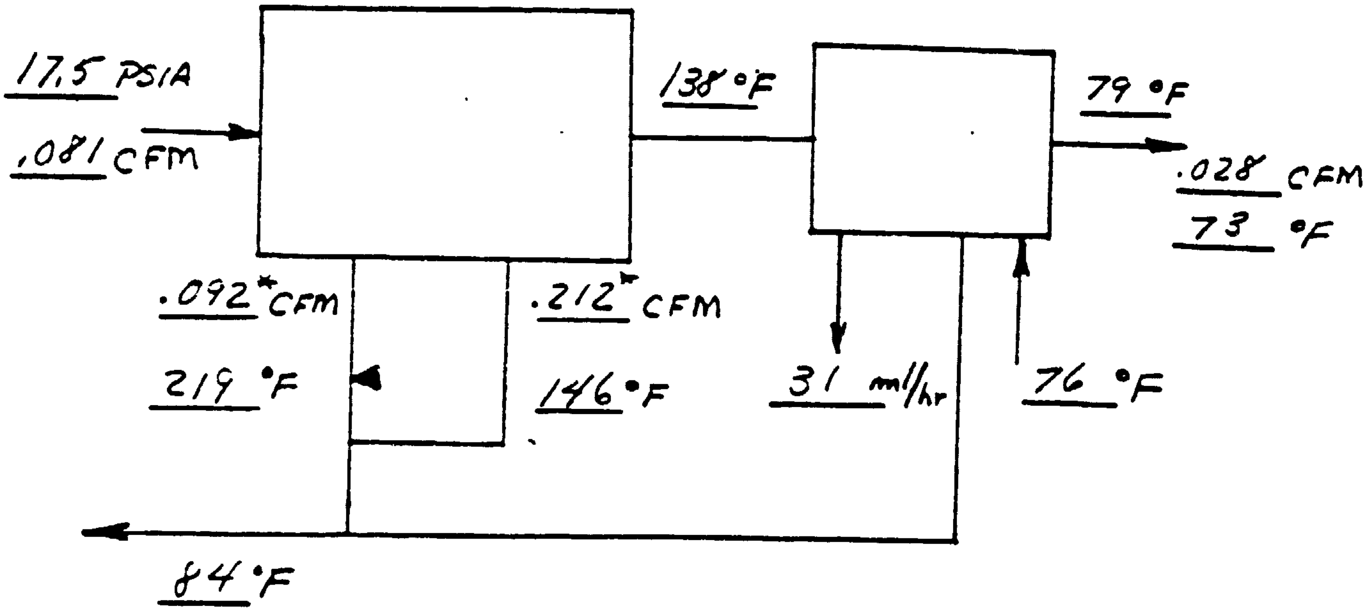
* AT ROOM TEMP

DATE: 4-2-80
RUN No. 6
TEST No. 9,26

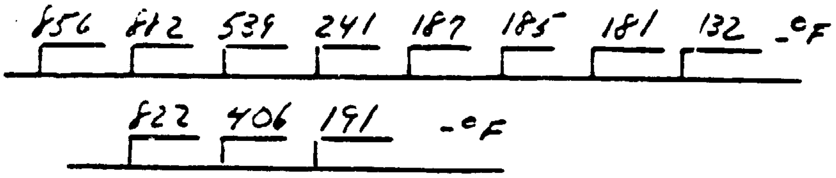
SABATIER

1 MAN CONT.

M.R. 5.0


17.5 PSIA
.081 CFM
138 °F
79 °F
.028 CFM
73 °F
.092* CFM
219 °F
.212* CFM
146 °F
31 ml/hr
76 °F
84 °F

864 °F CONTROL


856
812
539
241
187
185
181
132
°F
822
406
191
°F

— °F OVERTEMP

G.C. RUN No. 9
H_2 49.3
CH_4 50.49
CO_2 0

$$\varepsilon_{CO_2} = 100.0$$

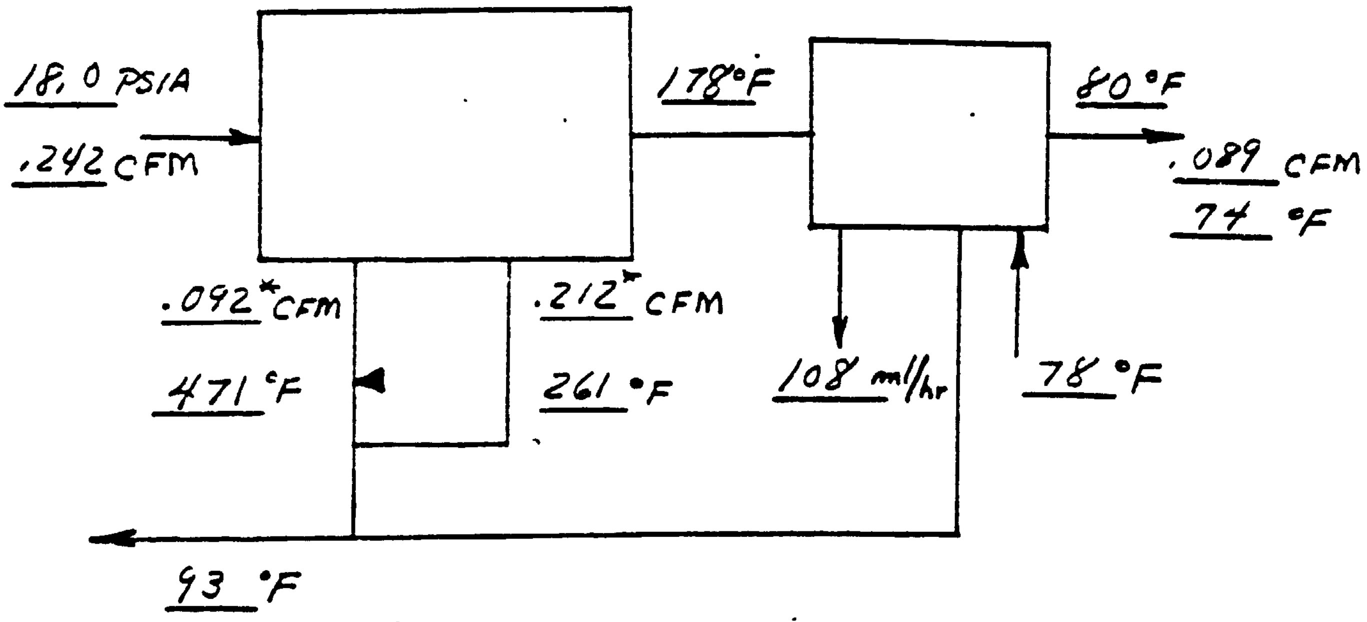
* AT ROOM TEMP.

DATE: 4-1-80
RUN No. 9
TEST No. 27

SABATIER

3 MAN CONT.

M.R. 5.0



18.0 PSIA
.242 CFM
178°F
80°F
.089 CFM
74 °F
.092* CFM
471 °F
.212* CFM
261 °F
108 ml/hr
78 °F
93 °F

1004 °F CONTROL

787 1018 1015 919 763 520 373 140 °F

1035 933 743 °F

— °F OVERTEMP

G.C. RUN No. p106
H_2 48.7
CH_4 49.9
CO_2 0

$$\mathcal{E}_{CO_2} = 100.0$$

* AT ROOM TEMP.

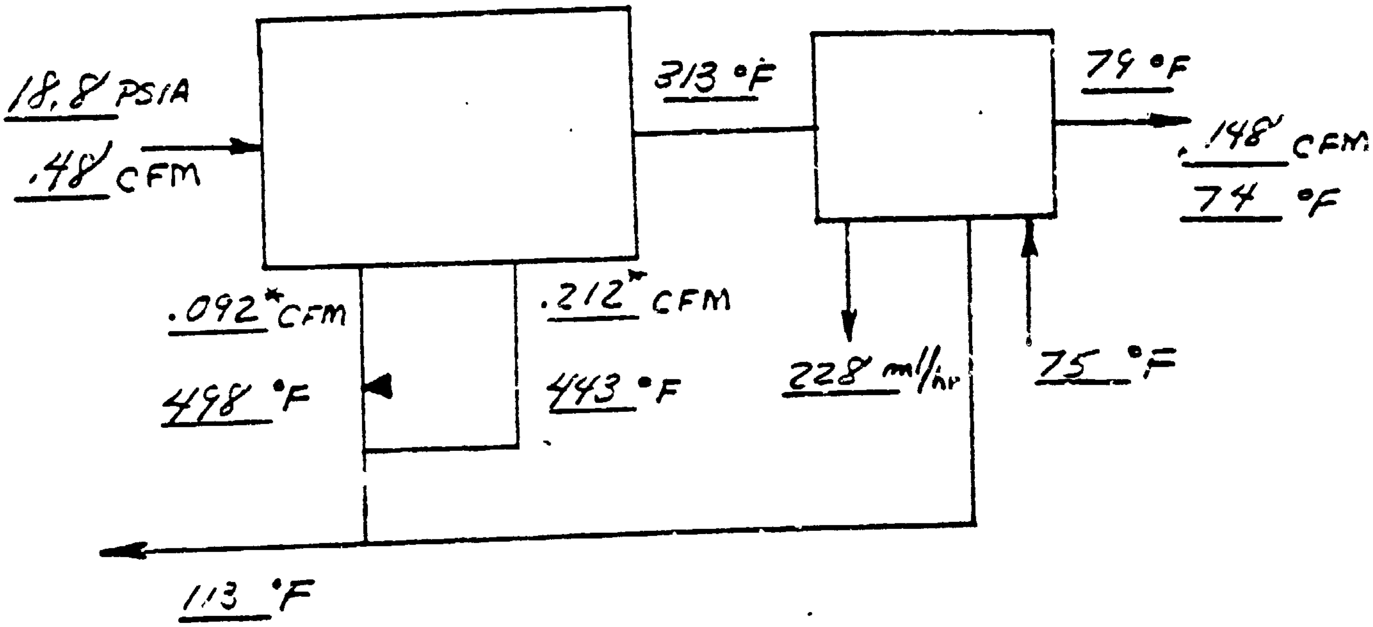
ORIGINAL PAGE IS
OF POOR QUALITY

DATE: 2-8-80
RUN No. 21
TEST No. 19

SABATIER

10 MAN CONT.

M.R. 2.6



18.8 PSIA
.48 CFM
313 °F
79 °F
.148 CFM
74 °F
.092* CFM
498 °F
.212* CFM
443 °F
228 ml/hr
75 °F
113 °F

974 °F CONTROL

644 990 1013 990 948 891 813 718 - °F

1020 966 887 - °F

— °F OVERTEMP

G.C. RUN NO. 6
H_2 7.18
CH_4 58.21
CO_2 34.61

$\mathcal{E} = 97.2$

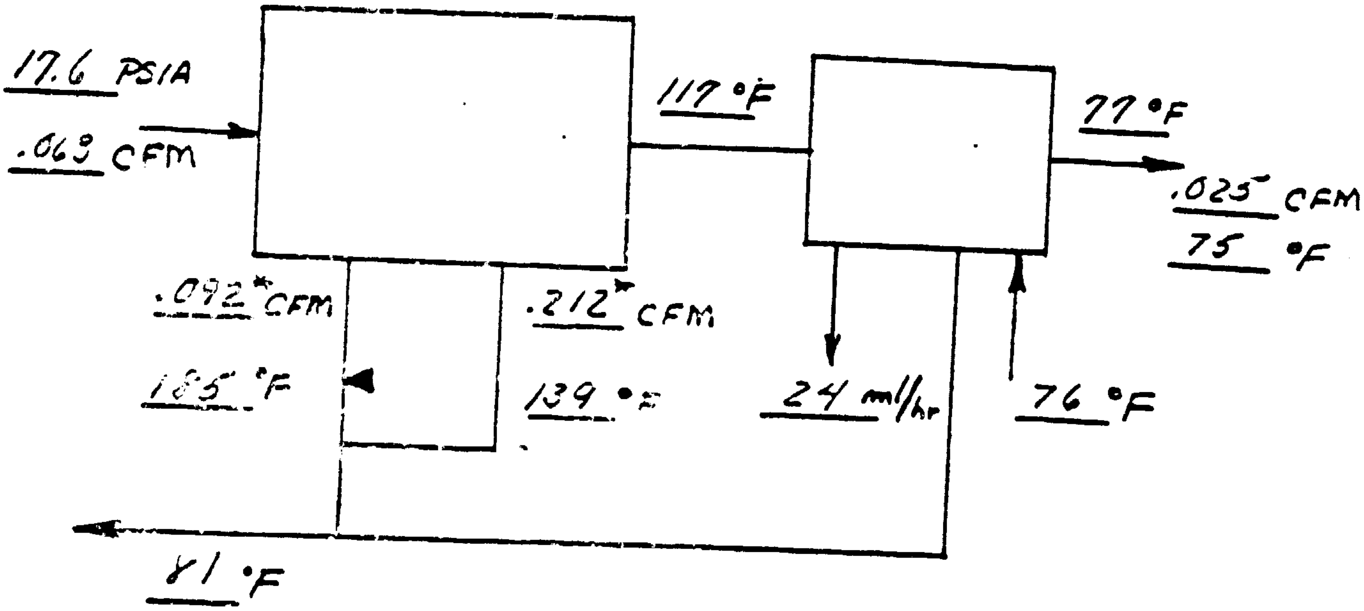
* AT ROOM TEMP

DATE: 3-16-60
RUN No. 5
TEST No. 29

SABATIER

1 MAN CYCLIC

M.R. 1.8


17.6 PSIA
.069 CFM
117 °F
77 °F
.025 CFM
75 °F
.092* CFM
185 °F
.212* CFM
139 °F
24 ml/hr
76 °F
81 °F

719 °F CONTROL

724 737 453 — 183 — 172 — -°F

967 667 341 -°F

— °F OVERTEMP

G.C. RUN NO. 5
H_2 .55
CH_4 44.95
CO_2 54.89

E = 99.7

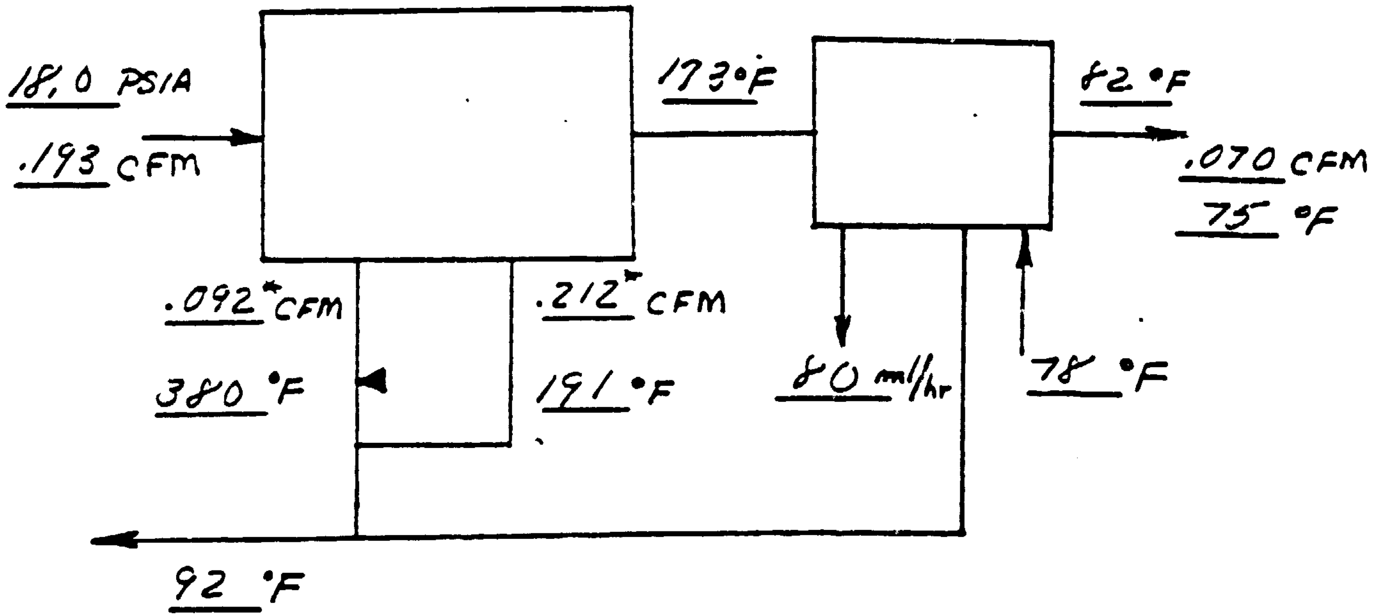
* AT ROOM TEMP

DATE: 3-13-80
RUN No. 5
TEST No. 8,13

SABATIER

3 MAN CYCLIC

M.R. 1.8


18.0 PSIA
.193 CFM
173 °F
82 °F
.070 CFM
75 °F
.092* CFM
380 °F
.212* CFM
191 °F
80 ml/hr
78 °F
92 °F

921 °F CONTROL

738 936 884 689 499 361 232 — °F

920 767 518 — °F

— °F OVERTEMP

G.C. RUN No. 6
H_2 1.11
CH_4 42.53
CO_2 57.07

$\mathcal{E} = 99.4$

* AT ROOM TEMP

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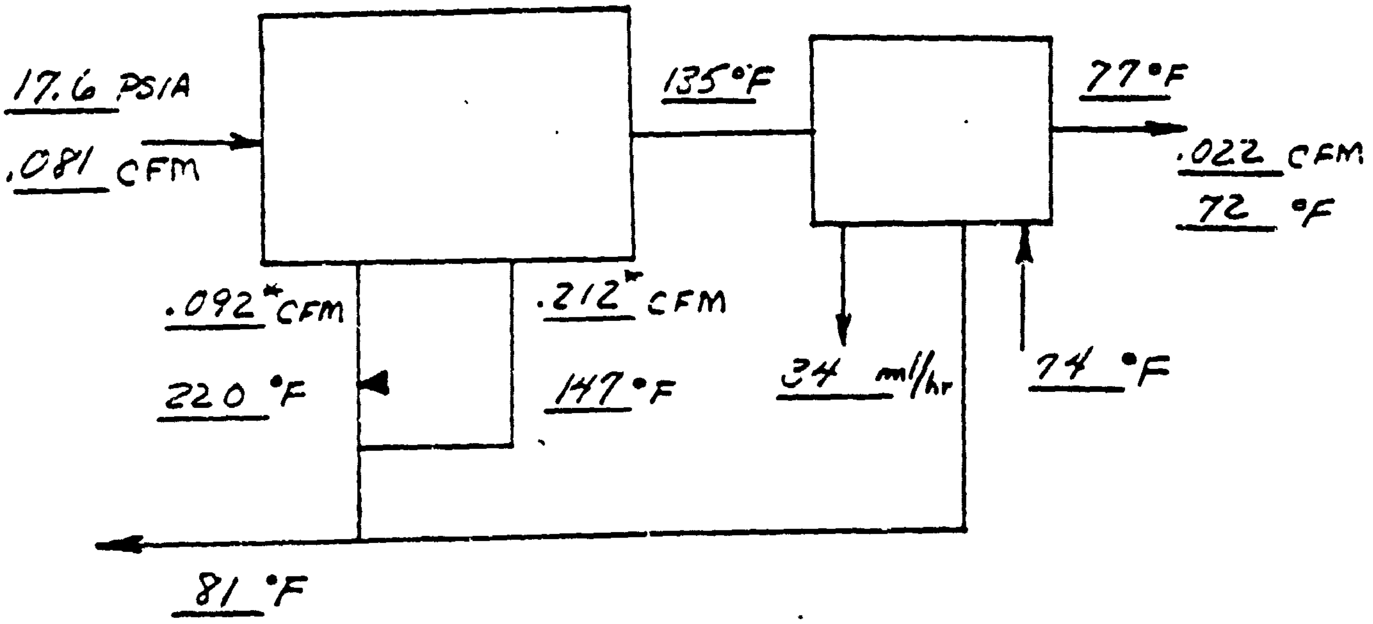
OF POOR QUALITY

DATE: 2-28-80
RUN No. 31
TEST No. 6

SABATIER

1 MAN CYCLIC

M.R. 2.6


17.6 PSIA
.081 CFM
135°F
77°F
.022 CFM
72 °F
.092* CFM
220 °F
.212* CFM
147 °F
34 ml/hr
74 °F
81 °F

826 °F CONTROL

804 844 576 264 192 192 186 181 -°F

780 431 199 -°F

___ °F OVERTEMP

G.C. RUN No. 5
H_2 .91
CH_4 60.35
CO_2 38.09

$E = 99.7$

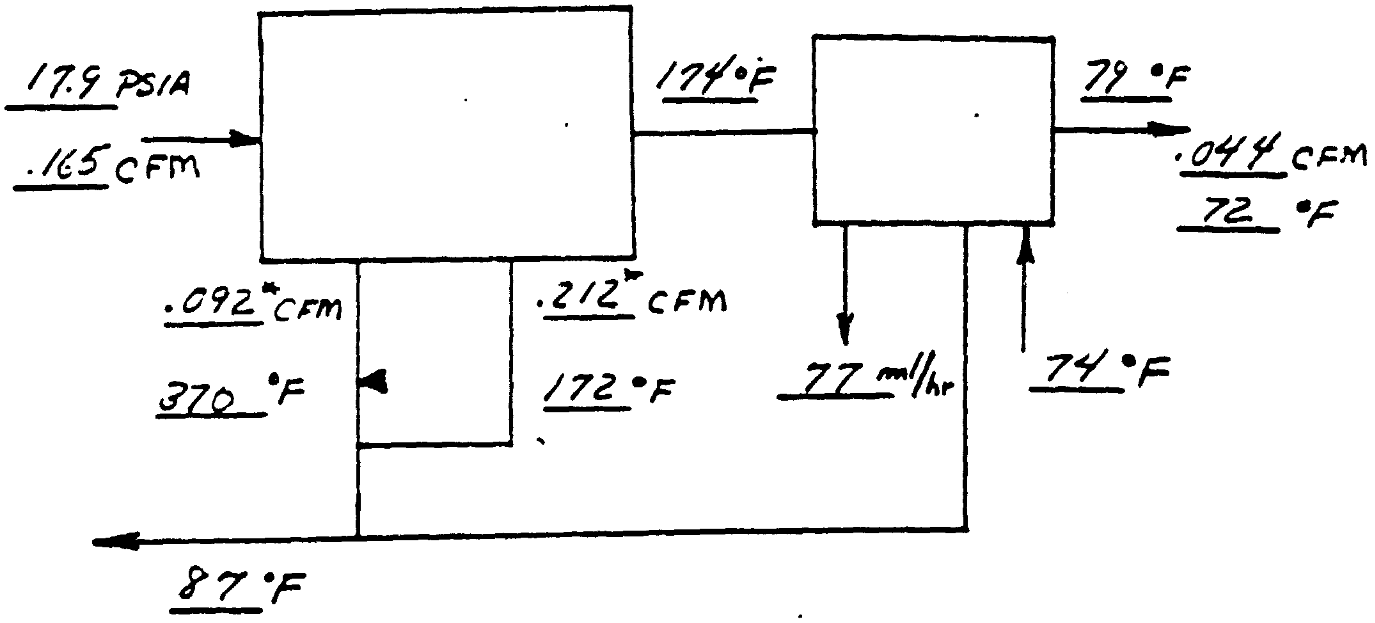
* AT ROOM TEMP

DATE: 3-4-80
RUN No. 6
TEST No. 32

SABATIER

2 MAN CYCLIC

M.R. 2.6



17.9 PSIA
.165 CFM
174°F
79 °F
.044 CFM
72 °F
.092* CFM
370 °F
.212* CFM
172 °F
77 ml/hr
74 °F
87 °F

953 °F CONTROL

823 968 894 635 419 289 194 195 -°F

940 765 469 -°F

— °F OVERTEMP

G.C. RUN No. 10
H_2 .86
CH_4 65.51
CO_2 33.47

E = 99.7

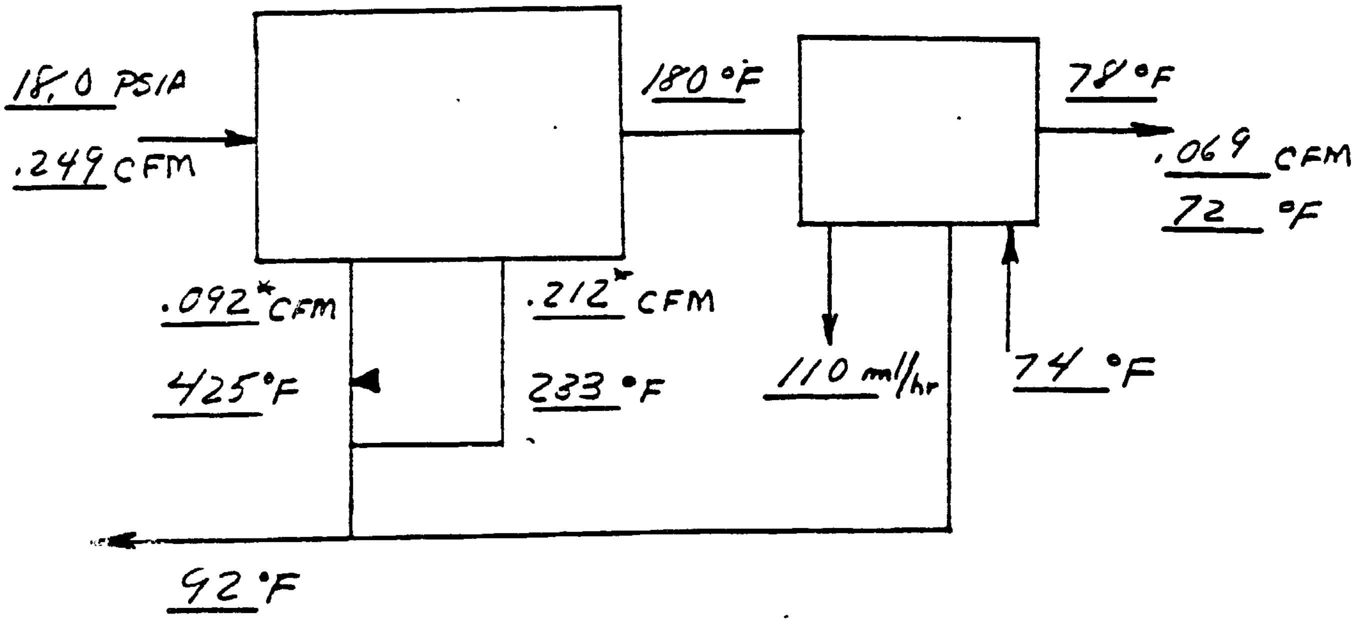
* AT ROOM TEMP

DATE: 2-20-80
RUN No. 18
TEST No. 18

SABATIER

3 MAN CYCLIC

M.R. 2.6


18.0 PSIA
.249 CFM
180 °F
78 °F
.069 CFM
72 °F
.092* CFM
425 °F
.212* CFM
233 °F
110 ml/hr
74 °F
92 °F

956 °F CONTROL

783 971 946 819 658 484 356 195 -°F

966 849 655 -°F

— °F OVERTEMP

G.C. RUN No. 4
H_2 1.08
CH_4 60.95
CO_2 37.73

$\mathcal{E} = 99.6$

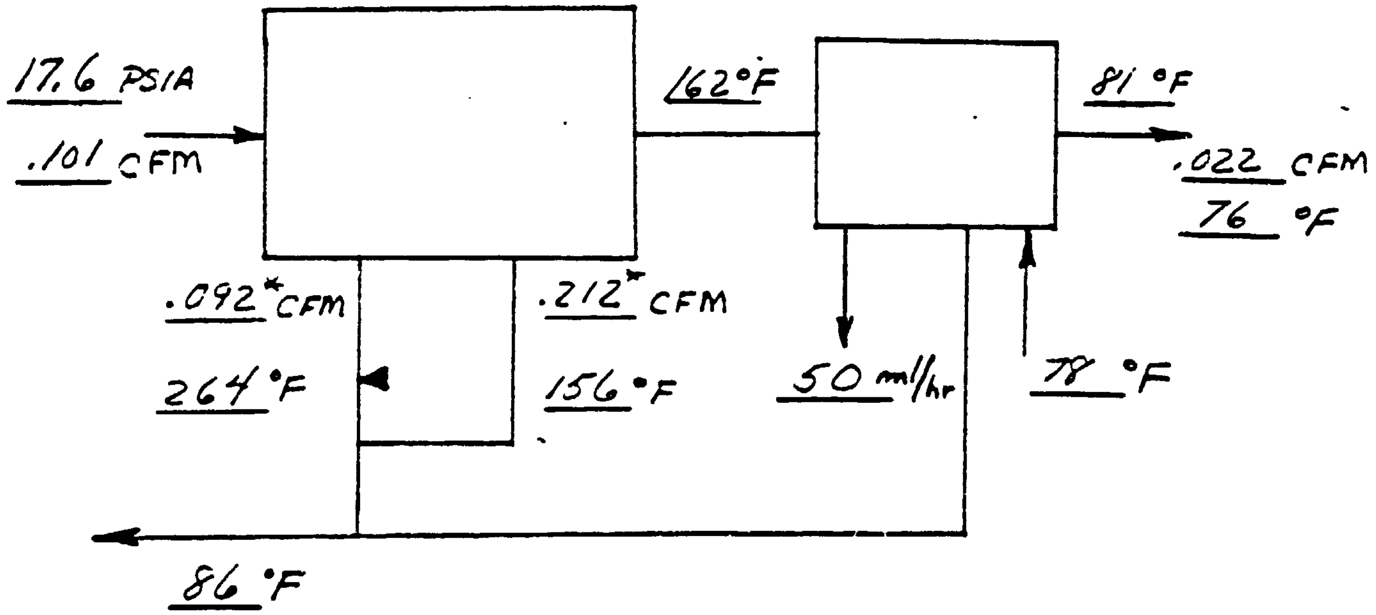
* AT ROOM TEMP.

DATE: 3-25-80
RUN No. 12
TEST No. 34

SABATIER

1 MAN CYCLIC

M.R. 3.5


17.6 PSIA
.101 CFM
162°F
81 °F
.022 CFM
76 °F
.092* CFM
264°F
.212* CFM
156°F
50 ml/hr
78 °F
86 °F

903 °F CONTROL

865 920 704 — 197 198 195 141 °F

870 540 198 °F

— °F OVERTEMP

G.C. RUN No. 12
H_2 3.10
CH_4 84.66
CO_2 12.00

$\mathcal{E} = 99.2$

* AT ROOM TEMP

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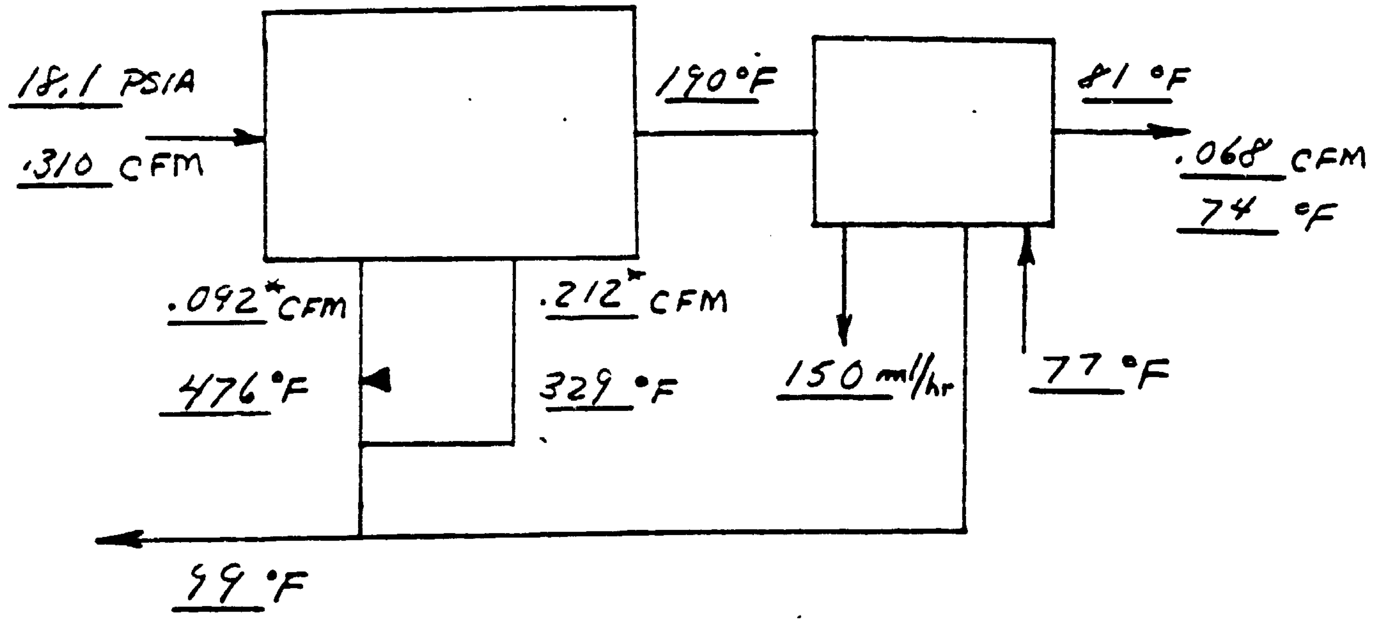
DATE: 3-26-80
RUN No. 7
TEST No. 22

SABATIER

3 MAN CYCLIC

M.R. 3.5


18.1 PSIA
.310 CFM
190°F
81 °F
.068 CFM
74 °F
.092* CFM
476 °F
.212* CFM
329 °F
150 ml/hr
77 °F
99 °F

496 °F CONTROL

777 1010 1006 928 820 697 558 240 °F

1021 933 786 °F

— °F OVERTEMP

G.C. RUN No. 7
H_2 2.33
CH_4 86.26
CO_2 10.41

$\mathcal{E} = 99.3$

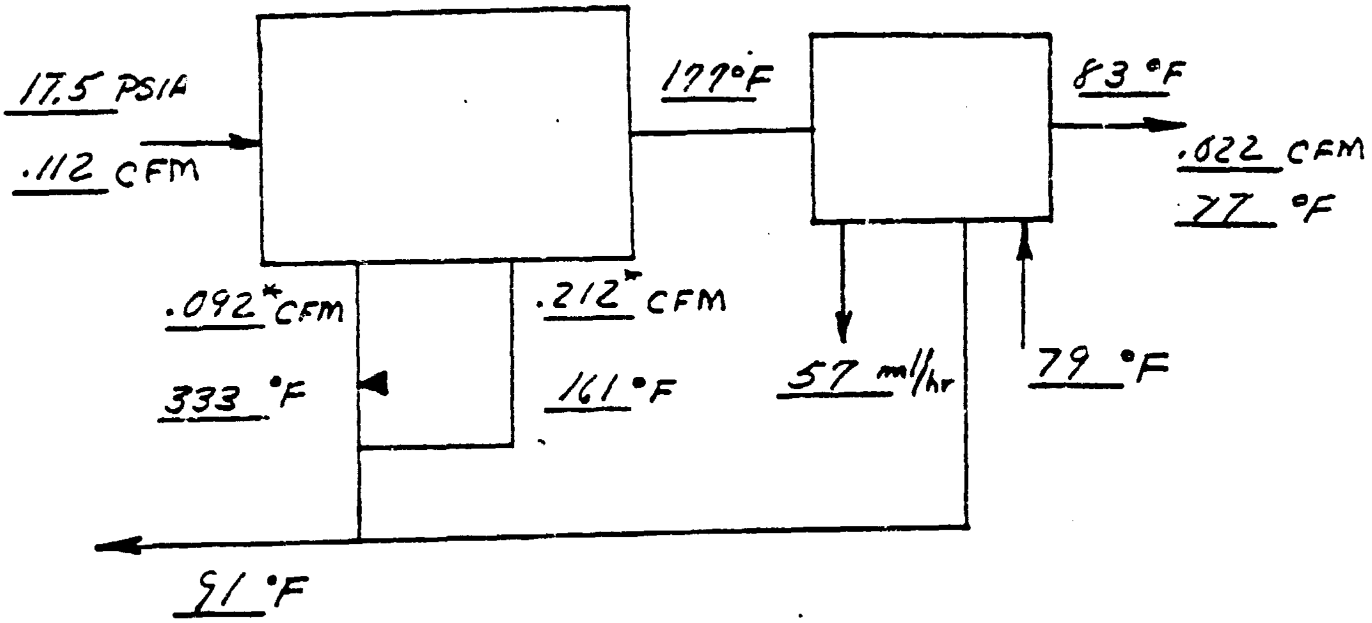
* AT ROOM TEMP

DATE: 3-28-80
RUN No. 9
TEST No. 36

SABATIER

1 MAN CYCLIC

M.R. 4.0



17.5 PSIA
.112 CFM
179°F
83 °F
.022 CFM
77 °F
.092* CFM
333 °F
.212* CFM
161 °F
57 ml/hr
79 °F
91 °F

949 °F CONTROL

870 964 638 482 201 200 200 133 -°F

929 688 347 -°F

— °F OVERTEMP

G.C. RUN No. 12
H_2 8.24
CH_4 89.25
CO_2 2.02

E = 98.2

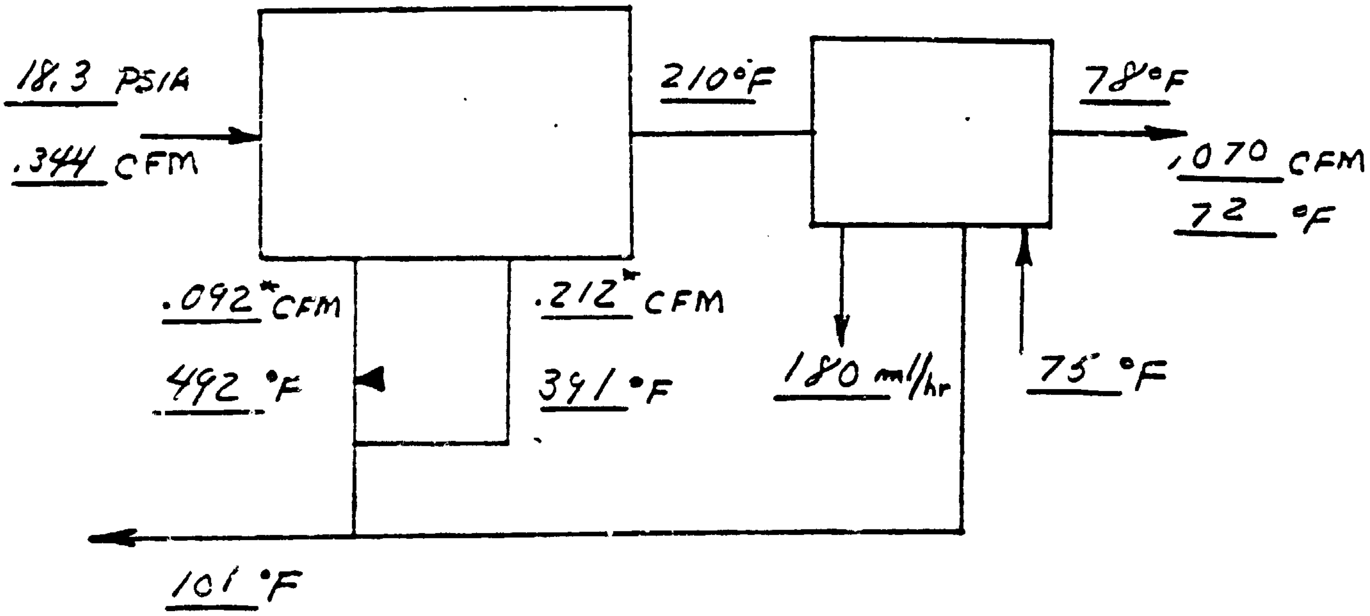
* AT ROOM TEMP

DATE: 3-31-80
RUN No. 9
TEST No. 2537

SABATIER

3 MAN CYCLIC

M.R. 4.0


18.3 PSIA
.344 CFM
.092* CFM
492 °F
.212* CFM
391 °F
210°F
78°F
.070 CFM
72 °F
180 ml/hr
75 °F
101 °F

497 °F CONTROL

745 1012 1024 473 893 798 694 343 -°F

1039 964 845 -°F

— °F OVERTEMP

G.C. RUN NO. 92
H_2 6.71
CH_4 89.22
CO_2 2.52

$\mathcal{E} = 98.4$

* AT ROOM TEMP.

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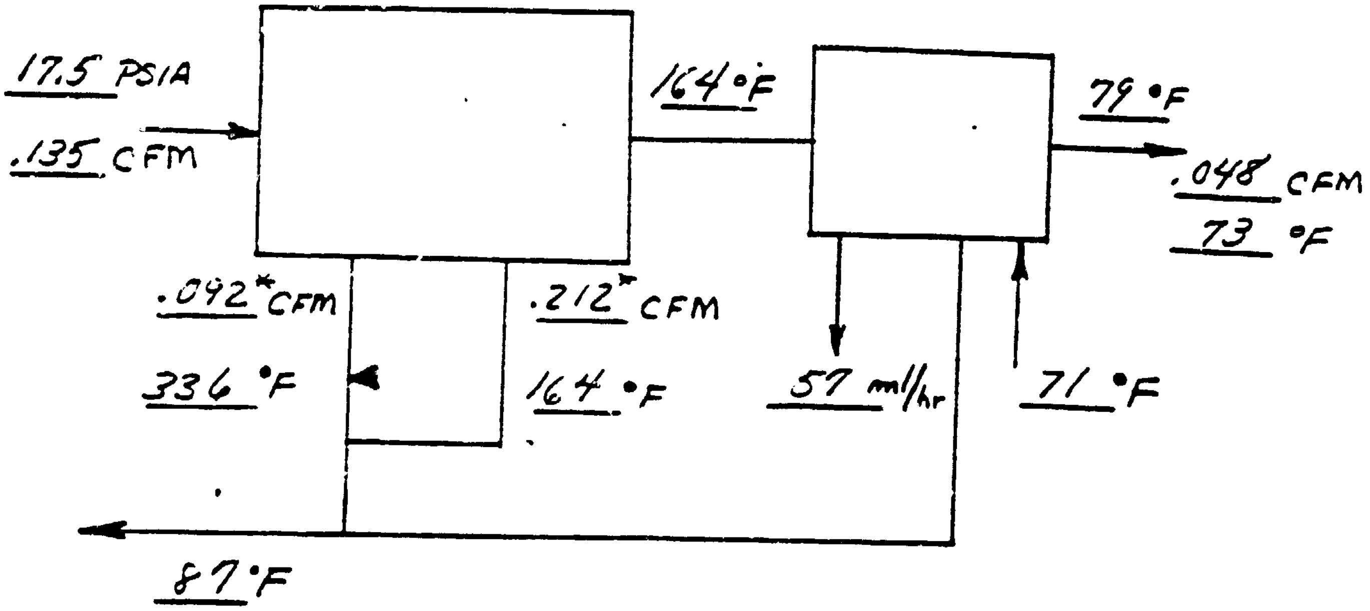
DATE: 4-3-80
RUN No. 4
TEST No. 38

SABATIER

1 MAN CYCLIC

M.R. 5.0


17.5 PSIA
.135 CFM
164 °F
79 °F
.048 CFM
73 °F
.092* CFM
336 °F
.212* CFM
164 °F
57 ml/hr
71 °F
87 °F

983 °F CONTROL

884 999 880 452 301 240 221 136 °F

964 698 346 °F

— °F OVERTEMP

G.C. RUN No. 136
H_2 49.52
CH_4 50.30
CO_2 0

$$E_{CO_2} = 100.0$$

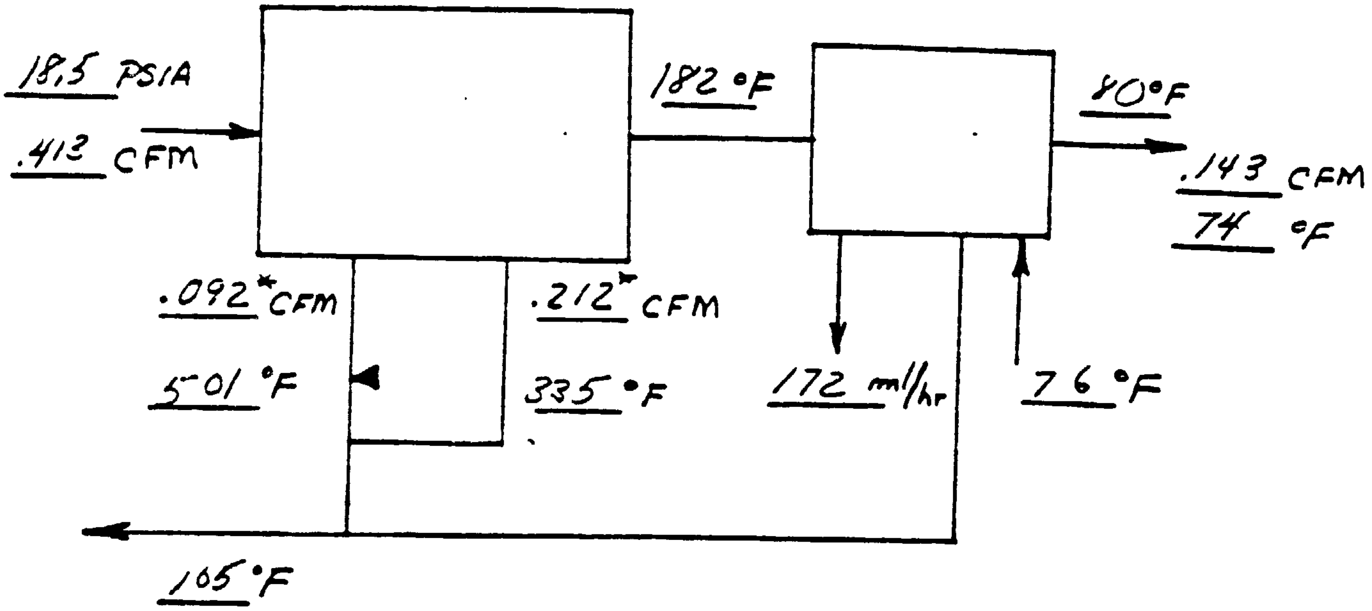
* AT ROOM TEMP

DATE: 4-2-80
RUN No. 14
TEST No. 10,28

SABATIER

3 MAN CYCLIC

M.R. 5.0


18.5 PSIA
.413 CFM
182 °F
80°F
.143 CFM
74 °F
.092* CFM
501 °F
.212* CFM
335 °F
172 ml/hr
76 °F
105 °F

1004 °F CONTROL

706 1019 1039 999 927 823 560 97 °F

1055 984 871 °F

– °F OVERTEMP

G.C. RUN No. 15
H_2 49.28
CH_4 50.42
CO_2 0

$$E_{CO_2} = 100.0$$

* AT ROOM TEMP.

APPENDIX C

End
Date
2/81