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# PREPROTOTYPE NITROGEN SUPPLY SUBSYSTEM DEVELOPMENT

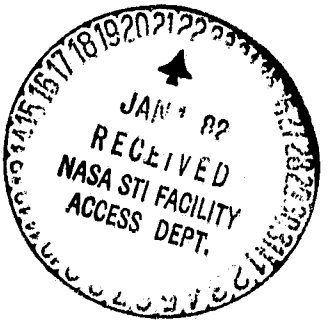


## INTERIM REPORT

by

D. B. Heppner, T. M. Hallick
and F. H. Schubert

June, 1981




Prepared Under Contract NAS2-10673

by

*Life Systems, Inc.*
Cleveland, OH 44122

for

AMES RESEARCH CENTER
National Aeronautics and Space Administration

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## FOREWORD

The development work described herein was conducted by Life Systems, Inc. during the period June, 1980 to May, 1981. The Program Manager was Dennis B. Heppner, Ph.D. Support was provided as follows:

| Personnel | Area(s) of Responsibility |
|---|---|
| Ken A. Burke | Nitrogen Generation Module (NGM) Test Stand Design and Checkout |
| Steve Czernec | Mechanical Hardware Assembly and Checkout |
| Tim M. Hallick | NGM Testing and Data Reduction |
| Don W. Johnson | NGM Test Stand Electrical Assembly and Checkout |
| Franz H. Schubert | System Design Support |
| Lowell Wolfe | Gas Chromatograph Setup, Checkout and Data Reduction |

The contract's Technical Monitor was P. D. Quattrone, Chief, Advanced Life Support Office, NASA Ames Research Center, Moffett Field, CA.

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## SUMMARY

Life Systems, working with the National Aeronautics and Space Administration, is developing a Nitrogen Supply Subsystem based on the dissociation of hydrazine into a mixture of hydrogen and nitrogen. The latter is separated to provide makeup nitrogen to control the composition of spacecraft atmospheres. Recent advances in specific hardware developments have resulted in the design and fabrication of a nominal 3.6 kg/d (8 lb/d) nitrogen generation module. The design integrates a hydrazine catalytic dissociator, three ammonia dissociation stages and four hydrogen separation stages into a 33 kg (73 lb), 14 $dm^3$ (0.5 $ft^3$) module. A technique has been devised to alternate the ammonia dissociation and hydrogen separation stages to give high nitrogen purity in the end product stream. Tests have shown the product stream to contain less than 0.5% hydrogen and 10 parts per million ammonia.

The program accomplishments to date are presented in this Interim Report. Specifically, the Report describes the design and development of a test stand for the nitrogen generation module and a series of tests which verified its operation and performance capability. Over 900 hours of parametric testing were achieved. The results from this testing are being used to design an advanced nitrogen generation module and a self-contained, preprototype nitrogen supply subsystem. Preliminary results of this activity are included.


## INTRODUCTION

Future long-term manned spacecraft missions will utilize an atmosphere of nitrogen ($N_2$) and oxygen ($O_2$). Space vehicle gas leakage and airlock repressurizations following extravehicular missions necessitate on-board storage of the primary cabin atmospheric constitutents: $N_2$ and $O_2$. The $N_2$ component of the air can be stored as liquid hydrazine ($N_2H_4$) and the $N_2H_4$ catalytically dissociated to an $N_2$ and hydrogen ($H_2$) mixture. The $N_2/H_2$ mixture can then separated to yield the makeup $N_2$. The byproduct $H_2$ can be used in the reduction of metabolically generated carbon dioxide ($CO_2$) in a regenerative Environmental Control/Life Support System (EC/LSS).

This $N_2$ Supply Subsystem (NSS) concept using liquid $N_2H_4$ as the stored form of $N_2$ reduces tankage and expendables weight compared to high pressure gaseous or cryogenic liquid $N_2$ storage. The advantage of supplying $N_2$ through $N_2H_4$ compared to other storage methods is shown in Figure 1. These trade curves are for the National Aeronautics and Space Administration's (NASA's) projected Space Operations Center (SOC), an eight-person mission with a 90-day resupply period. The estimated air leakage rate for the SOC is 5.5 kg/d (12 lb/d) corresponding to the 4.4 kg/d (9.6 lb/d) $N_2$ leakage rate indicated. At this value, an NSS saves 25 to 35% of equivalent weight compared to gaseous or cryogenic storage. If the $H_2$ is used for $CO_2$ reduction, an additional 300 kg (660 lb), or 30% is saved.

Incorporating the $N_2H_4$-based NSS into advanced missions like SOC will cause no problems and has certain advantages. Hydrazine will be available since it is used for other purposes (e.g., propulsion). Therefore, there are no added special transporting or handling considerations. The technology is simple and mature. The present concept and hardware development, sponsored by the NASA and Life Systems, Inc. (LSI), has progressed to a stage where NSS flight hardware can be available for the SOC or other missions.

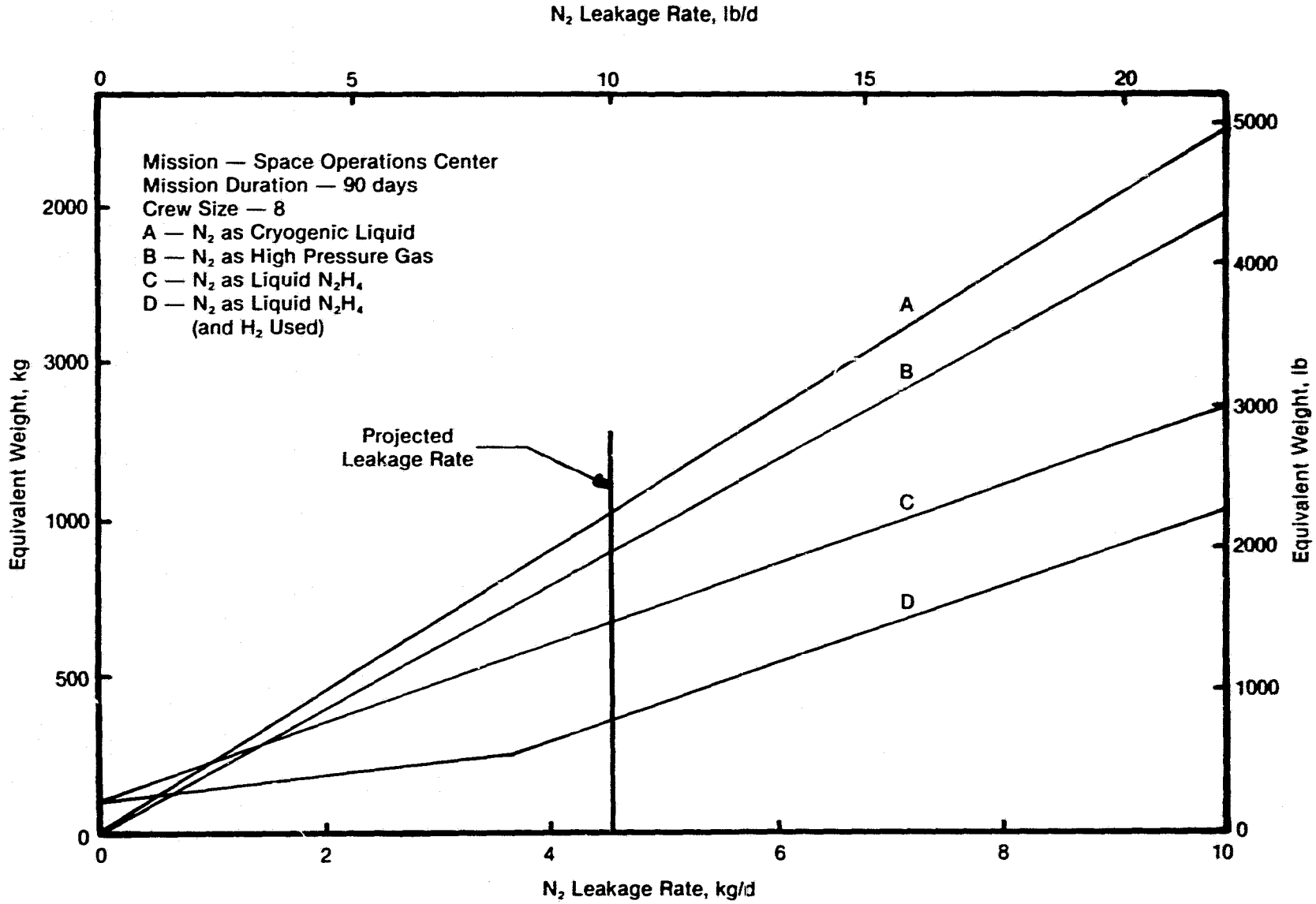



FIGURE 1 CANDIDATE NITROGEN SOURCE TRADE-OFF

## Background

The NSS utilizing $N_2H_4$ catalytic dissociation and $N_2/H_2$ separation has evolved through NASA sponsorship under Contracts NAS2-7057, NAS2-8732 and NAS2-10096. The concept has progressed from individual $N_2/H_2$ separator and $N_2H_4$ catalytic dissociator breadboards through the combination of the separator and dissociator hardware into an engineering breadboard NSS and finally to the operation of the breadboard NSS as part of an integrated, experimental Air Revitalization System. Included in these activities was the development of a staged NGM which integrates the dissociation and separation processes into a single unit. Staging is employed (i.e., alternate separation and dissociation stages) to eliminate ammonia ($NH_3$) contamination of the product $N_2$ stream.

During an earlier program[1] Life Systems, Inc. (LSI) identified two attractive $N_2$ generation systems based on the catalytic dissociation of $N_2H_4$. In the first system, liquid $N_2H_4$ was catalytically dissociated to yield an $N_2/H_2$ gas mixture. Separation of the gas mixture to yield $N_2$ and byproduct $H_2$ was accomplished using a Polymer-Electrochemical $N_2/H_2$ Separator.[2,3] In the second system, the $N_2/H_2$ product gas from the dissociator was separated in a palladium/ silver (Pd/Ag) $N_2/H_2$ Separator.

The program culminated in the successful design, fabrication and testing of an $N_2H_4$ catalytic two-stage Pd/Ag Separator. Based on the results of this program it was recommended that an $N_2$ generation system, and subsequently an NSS, be developed based on $N_2H_4$ catalytic dissociation and the Pd/Ag method of $N_2/H_2$ separation.

During a following program,[4-6] LSI developed and tested various components of the NSS including an NGM, $N_2H_4$ storage and advanced instrumentation. Tests were conducted to support the development of the NGM and to advance NSS technology. The current program continues the NSS development by designing a preprototype NSS using an advanced NGM and computer-based instrumentation. This development step is based on additional characterization and parametric testing of the prior NGM and incorporation of certain improvements in its design.

## Program Objectives

The objectives of the current program are to develop a preliminary design of a preprototype NSS including an advanced NGM with passive thermal control and optimized reactor/gas separation stages. Prior to beginning the preprototype hardware design, existing NGM hardware was tested to generate the technology data base required for an advanced NGM design. The advanced NGM is being designed for incorporation in the preprototype NSS.

## Program Organization

To meet the above objectives the program was divided into five tasks plus the documentation and program management functions. The five tasks were:

1. Design, fabricate and checkout an NGM test stand to support characterization and parametric testing of an existing NGM.

(1) References cited are at the end of this report.

2. Accumulate an NGM data base using the NGM developed under Contract NAS2-10096.

3. Design an advanced NGM based on the results of prior testing and having goals of passive thermal control and elimination of sealing surfaces.

4. Design a preprototype NSS including the advanced NGM, $N_2H_4$ storage and feed mechanism, ancillary components and advanced Control/Monitor Instrumentation (C/M I).

5. Perform a design of the NSS Test Support Accessories (TSA) needed to simulate NSS and spacecraft interfaces and resources.

Results of the first two tasks, completed to date, are covered in this Interim Report along with preliminary results of the other three tasks.

### Report Organization

This Interim Report covers the work performed during the period June, 1980 through May, 1981. The following four sections present the technical results grouped according to (1) NGM Development, (2) NGM Test Facility, (3) NGM Data Base Generation Testing and (4) Preprototype NSS Design. These sections are followed by Conclusions based on the work performed.

## NITROGEN GENERATION MODULE DEVELOPMENT

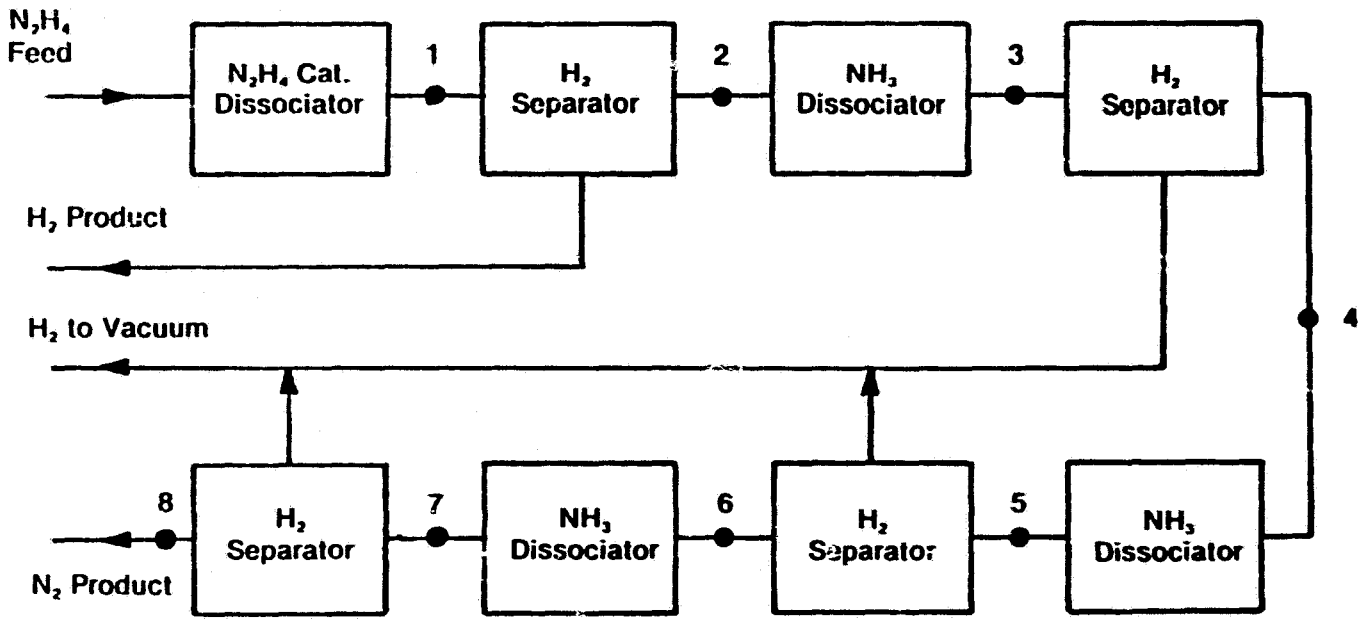
The function of the NGM is to generate $N_2$ and byproduct $H_2$ from liquid $N_2H_4$. The NGM consists of alternate catalytic dissociation and $H_2$ separation stages configured to give high purity $N_2$ and $H_2$. The dissociation and separator stages are packaged as a single unit to minimize heat rejection to ambient since both operate at elevated temperatures. The single package concept also allows the heat generated during the dissociation of $N_2H_4$ to reduce the heater power required to maintain the NGM at operating temperature.

The objective of prior development activities was to develop the initial NGM hardware required to (a) demonstrate and verify the staging concept and the single unit NGM design, and (b) experimentally generate a technology base for use in optimizing subsequent advanced NGM designs. Emphasis in these development activities, therefore, was placed on developing an NGM that could be used as a test bed to generate necessary design data. Secondary emphasis was placed on optimizing NGM hardware design, such as weight and volume.

The following sections review the NGM design concept and its operation and present a summary of the hardware fabricated.

### Concept Description

A block diagram showing the staging concept is presented in Figure 2. The NGM consists of one $N_2H_4$ dissociation stage, three $NH_3$ dissociation stages and




| Stream | % $N_2$ | % $H_2$ | % $NH_3$ | Eff. % | Temp. K (F) |
|---|---|---|---|---|---|
| 1 | 32.8 | 64.0 | 3.2 | 93 | 1000 (1340) |
| 2 | 77.3 | 15.1 | 7.6 | 90 | 644 (700) |
| 3 | 75.8 | 22.8 | 1.4 | 80 | 811 (1000) |
| 4 | 96.7 | 1.5 | 1.8 | 95 | 644 (700) |
| 5 | 95.9 | 4.0 | 0.09 | 95 | 811 (1000) |
| 6 | 99.8 | 0.08 | 0.09 | 98 | 644 (700) |
| 7 | 99.78 | 0.2 | 19 ppm | 98 | 811 (1000) |
| 8 | 99.9 | 0.1 | 19 ppm | 50 | 644 (700) |

FIGURE 2 NGM STAGING CONCEPT BLOCK DIAGRAM

four $H_2$ separation stages. The $N_2H_4$ feed/$N_2$ product stream flows in series from stage to stage. The calculated gas concentrations following each dissociation and $H_2$ separation stage illustrate how the staging concept yields the low $NH_3$ and $H_2$ concentrations in the final product $N_2$.

Hydrazine is catalytically dissociated in the first stage via the following reactions:

$$N_2H_4 = 1/3\ N_2 + 4/3\ NH_3 \quad (1)$$

$$4/3\ NH_3 = 2/3\ N_2 + 2H_2 \quad (2)$$

$$N_2H_4 = N_2 + 2H_2 + 1.57\ MJ/kg\ (678\ BTU/lb) \quad (3)$$

All the $N_2H_4$ is dissociated in this initial stage. Not all of the $NH_3$ formed by equation 1, however, is dissociated in the $N_2H_4$ catalytic dissociator.

The $N_2$, $H_2$ and unreacted $NH_3$ gases from the first stage enter the first $H_2$ separation stage. Most (90%) of the $H_2$ entering this stage is removed and collected at 103 kPa (15 psia) for use in a $CO_2$ reduction subsystem. The product gas from the first separation state is then manifolded to the first $NH_3$ dissociation stage. The high $NH_3$ and $N_2$ concentrations entering the dissociator favor further $NH_3$ dissociation and the formation of more $N_2$ and $H_2$ (equation 2).

Alternate $H_2$ separation and $NH_3$ dissociation stages are used to attain the final $N_2$ product purity. The $H_2$ removed in the last three $H_2$ separation stages is vented to space vacuum and is therefore not available for further use. The $H_2$ separation to vacuum is required to attain the low $H_2$ concentration needed in the product $N_2$.

Figure 3 is a functional schematic of the NGM showing a representation of its three functions - $N_2H_4$ dissociation, $NH_3$ dissociation and $H_2$ separation. The addition of an $N_2H_4$ storage tank, sensors and controls are all that is needed to form a complete NSS.

## Hardware Description

Designed to operate at 1830 kPa (265 psia), the NGM consists of two major subassemblies - dissociator and separator - joined by an end plate. The end plate is manifolded to pass gases back and forth between the various dissociation and separator stages. Gaskets permit disassembly for inspection. Front and rear views of the assembled NGM are presented in Figures 4 and 5, respectively. Figure 6 shows the disassembled NGM hardware.

### Physical Characteristics

The temperatures of the dissociation stages and separation stages are maintained using three cartridge heaters located in the dissociator core and five band heaters located around the outside of the separator housing. Thermocouples within the NGM are used to provide closed-loop, feedback temperature control.

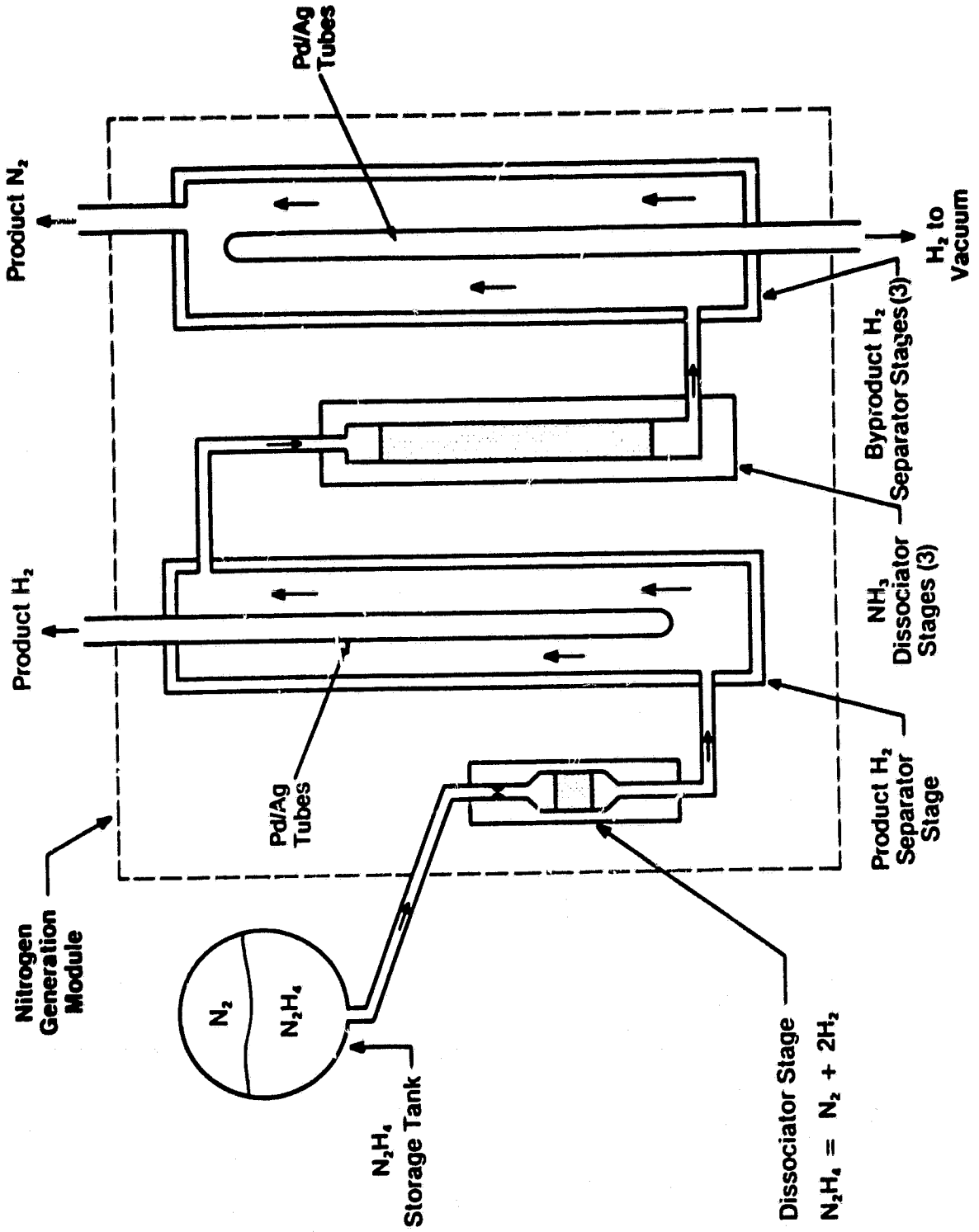



FIGURE 3 NGM FUNCTIONAL SCHEMATIC

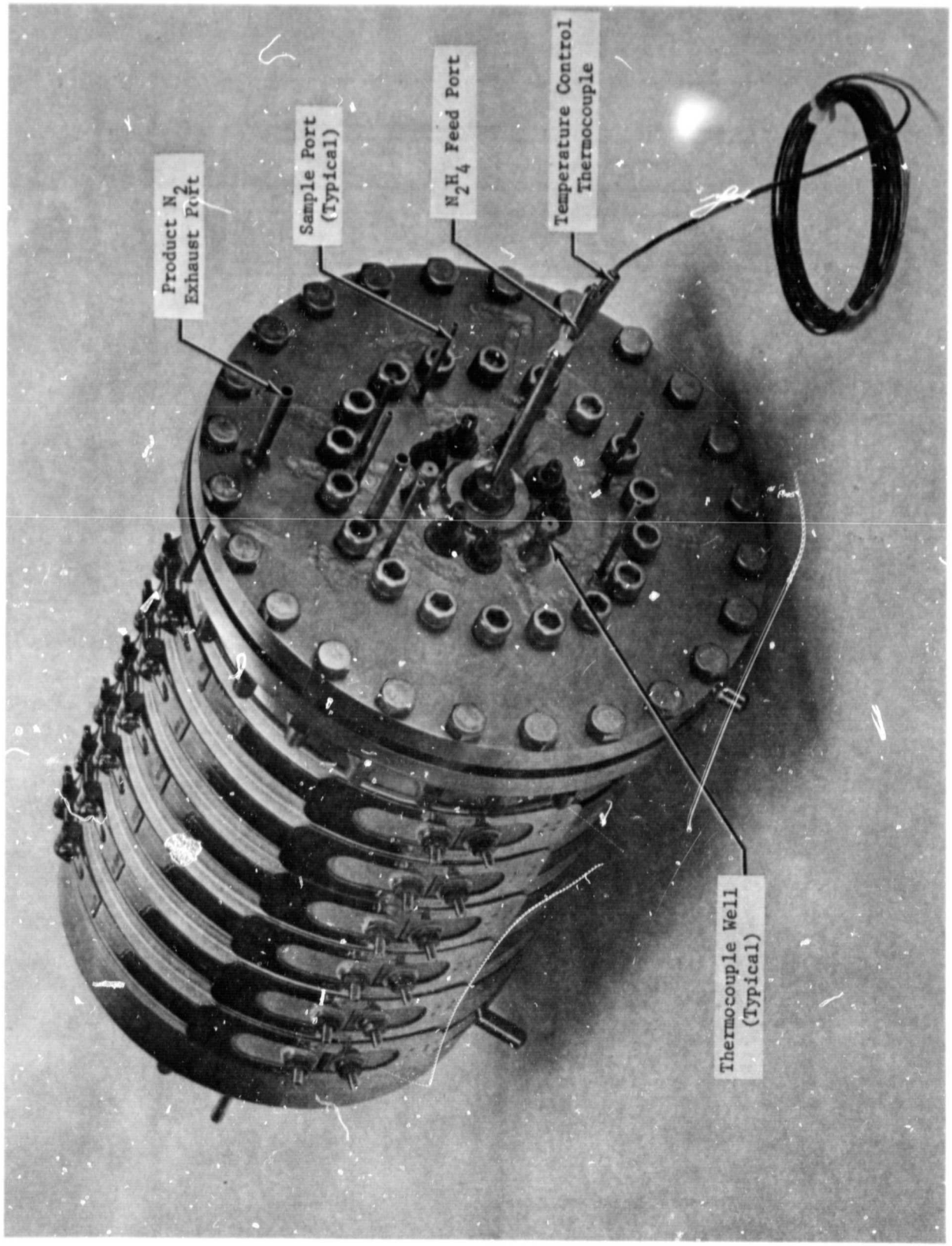



FIGURE 4 ASSEMBLED NGM (FRONT VIEW)

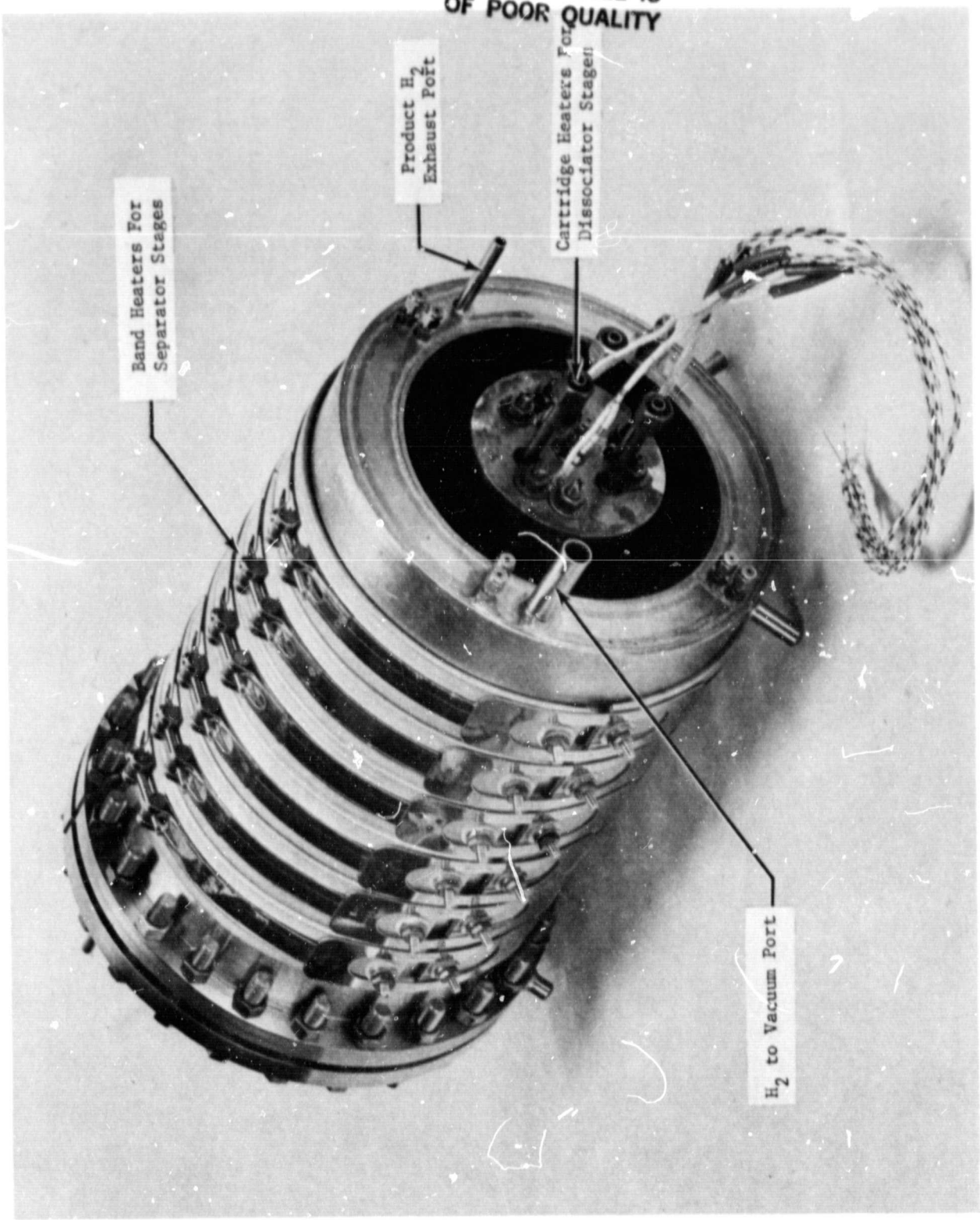



FIGURE 5 ASSEMBLED NGM (REAR VIEW)

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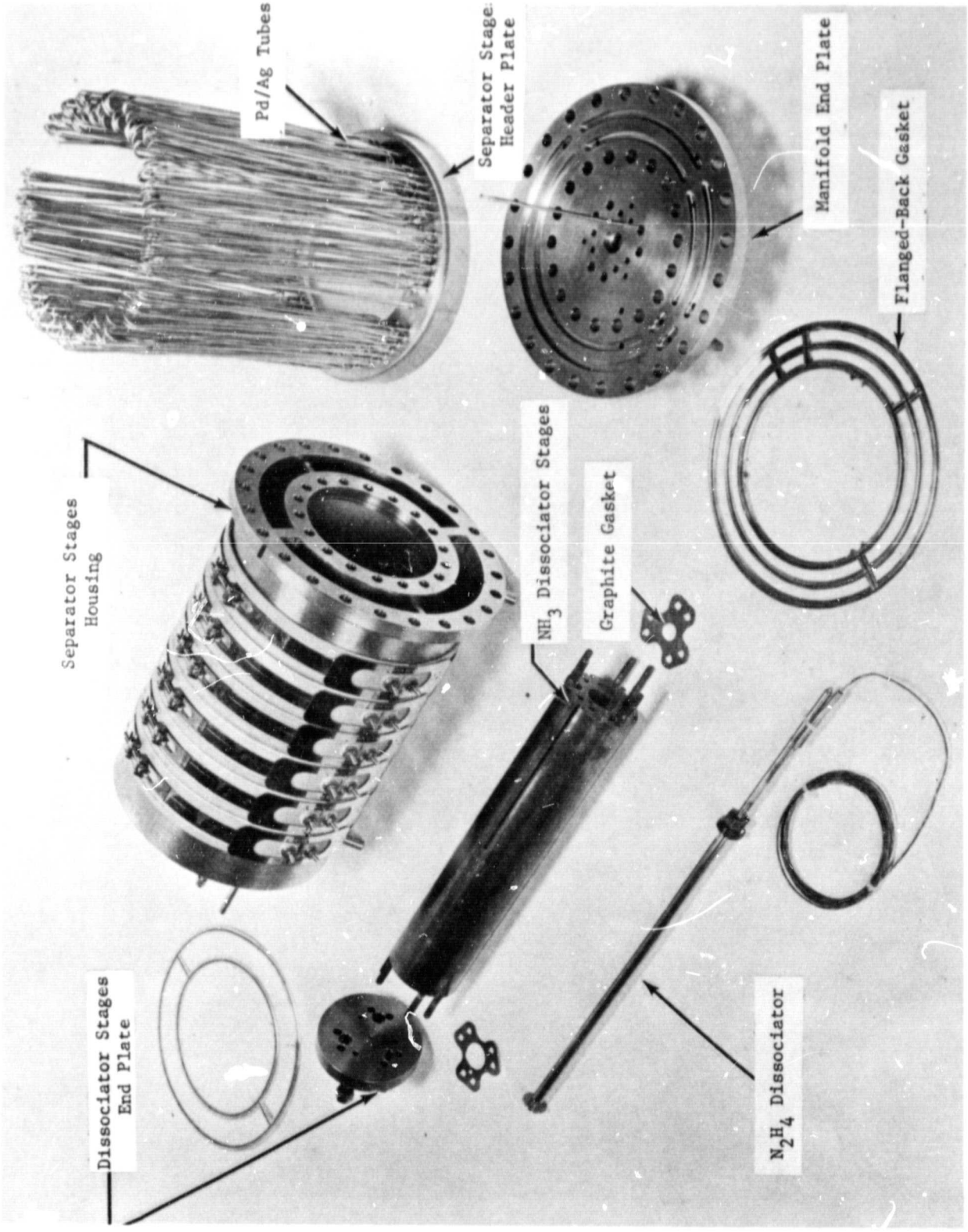


FIGURE 6 DISASSEMBLED NGM

The dissociator core is controlled at 1000 K (1340 F) and the Pd/Ag separator tubes are controlled at 644 K (700 F). Besides control thermocouples, several others have been added to monitor temperatures during development testing.

Physical characteristics of the NGM are summarized in Table 1. The NGM was designed to give a nominal $N_2$ generation rate of 3.6 kg/d (8.0 lb/d); however, testing has shown that the output can be controlled over a wide range, i.e., 1.8 to 6.8 kg/d ( 4 to 15 lb/d). Only five mechanical interfaces are needed: $N_2H_4$ feed, $N_2$ product, $N_2$ purge, $H_2$ product and $H_2$ to vacuum. Several other ports have been added for interstage sampling.

Operational Flexibility

Since the NGM was used to generate performance and design data for future NGM designs, maximum flexibility in the design and operation of the NGM was required. The capability to monitor performance of individual stages and temperature profiles, and to individually control separator and dissociator stage temperatures was incorporated into the design. Gas sample taps between each state were incorporated to allow quantifying individual stage performance during parametric testing. The NGM temperature distribution/profile monitoring capability was provided by 16 thermocouples. Both radial and axial temperature profile determinations were possible. Separate temperature control of the dissociation stages and separator stages was provided through the heaters connected to feedback temperature controllers.

Maintainability

Maintainability is not a design requirement of a flight version NGM. Maintainability, however, for the NGM fabricated for development testing under the present effort was required to add testing flexibility. Operation at elevated temperatures and pressures, and the dimensional tolerances required for adequate sealing make disassembly and maintainability difficult. Operation at elevated temperatures causes the metal surfaces to adhere to each other through oxidation and scaling. In addition operation at elevated pressures and the large surface area required for sealing result in high sealing forces.

As was shown in Figure 6 the NGM was divided into several subassemblies and components for ease in disassembly during maintainance. Sealing between the subassemblies is provided by graphite or flanged-backed gaskets. Bolts are used to hold these subassemblies together and provide the sealing forces required. However, this design approach was shown to be inadequate. Following prior testing, an inspection revealed a weakness in the separator housing design.(6) The bolt flanges of the housing (both inner and outer) showed signs of high temperature yield and structural deformation which led to a loss in sealing. New inner and outer flange spacers were designed, fabricated and installed for the present testing. This approach solved the flange leakage problems. Elimination of all seals, however, became a primary requirement for the advanced NGM.

TABLE 1 NGM CHARACTERISTICS

| | |
|---|---|
| Nominal $N_2$ Generation Rate, kg/d (lb/d) | 3.6 (8.0) |
| Weight, kg (lb) | 33 (73) |
| Volume, $dm^3$ ($ft^3$) | 11.6 (0.41) |
| Power, W | |
| Startup | 8200 |
| Operational | 300 |
| Time for Heatup, h | 0.4 |
| Mechanical Interfaces | 5 |

## Operation

The NGM operation has been described in detail previously.[6] The following is a summary of its operation. The NGM performs three functions: $N_2H_4$ dissociation, $NH_3$ dissociation and $H_2$ separation. The temperatures of the dissociation stages and separation stages are controlled separately using two sets of heaters. Heat is (a) generated in the $N_2H_4$ dissociation process, (b) required for the $NH_3$ dissociation process and (c) lost to ambient since the surface of the NGM (the $H_2$ separator stages) is at 644 K (700 F). The NGM has two distinct temperature zones. The $H_2$ separator stages must operate at 644 ±28 K (700 ±50 F). The separation process is favored by higher temperatures but temperatures above 700 K (800 F) decrease the structural integrity and life of the Pd/Ag tubes. The $NH_3$ dissociation stages require temperatures, greater than or equal to 811 K (1000 F). The center of the dissociator housing (i.e., the $N_2H_4$ dissociation stage) operates at approximately 1000 K (1340 F). The temperature decreases to 811 K (1000 F) at the surface of the dissociator core.

### Hydrazine Dissociation

Hydrazine dissociation takes place in the center cavity of the NGM. Liquid $N_2H_4$ at a pressure of approximately 1830 kPa (265 psia) is injected into the dissociator through a capillary orifice in the header assembly. The diameter of the capillary opening is smaller than the quenching diameter for $N_2H_4$ to prevent propagation of the dissociation reaction back to the supply. In the feed orifice, $N_2H_4$ is converted from a liquid at ambient temperature to a vapor slightly above the boiling point of $N_2H_4$ at the operating pressure. Hydrazine vapor enters the central dissociator tube at an elevated temperature and dissociates autocatalytically.

At the end of the central tube the direction of the product gases is reversed. The product gases then flow in the annular housing concentric with the central tube and exit at the hottest zone of the reactor. The decomposition of $NH_3$ into $N_2$ and $H_2$ (equation 2) is favored kinetically and thermodynamically at higher temperatures.[7] The product gas from the $N_2H_4$ dissociation stage is manifolded to the first $H_2$ separation stage.

### Hydrogen Separation

The four $H_2$ separation stages are located around the periphery of the NGM. The Pd/Ag tubes are connected to a donut-shaped header plate and are thermally isolated from the central NGM core where $N_2H_4$ and $NH_3$ dissociation takes place. The $H_2$ separation stages operate at 644 K (700 F) while the dissociator core is maintained at 1000 K (1340 F). The $N_2/H_2$ mixture from a dissociation stage enters the inside ends (i.e., closest to the center of the NGM) of the Pd/Ag tubes in the stage. The process gas passes through all of the Pd/Ag tubes in each individual stage in parallel. The $H_2$-depleted gas stream from a $H_2$ separation stage is then manifolded from the outlet of the tubes to the next $NH_3$ dissociation stage.

In the first $H_2$ separation stage $H_2$ is collected at less than or equal to 172 kPa (25 psia).[2] The $H_2$ removed in the second, third and fourth $H_2$ separation stages exhausts the NGM through a common manifold and is vented to vacuum.

### Ammonia Dissociation

The three $NH_3$ dissociation stages are located in the central NGM core around the outside of the $N_2H_4$ dissociation stage. The product $N_2$ gas stream, enriched in $N_2$ and $NH_3$ after passing through a $H_2$ separation stage, is fed into a $NH_3$ dissociation stage at the same end of the NGM as the $N_2H_4$ feed. The product gas passes through the packed catalyst bed traveling the length of the dissociation core. At the end of the first catalyst bed the gases are manifolded to the second portion of the catalyst bed in the dissociation stage. The product gas then travels back the length of the reactor core and exists at the same end of the reactor as the feed stream. Each $NH_3$ dissociation stage, therefore, consists of two side-by-side passages packed with catalyst.

### Operating Conditions

Table 2 gives the mominal operating conditions for the NGM. These values are for a 3.6 kg/d (8.0 lb/d) $N_2$ generation rate. The values shown in Table 2 for $H_2$ and $NH_3$ concentration in the $N_2$ product stream have been met or exceeded in the testing program.

## NGM TEST FACILITY

An NGM Test Facility was designed and assembled to support the data base generation testing of the NGM. This facility consists of an NGM test stand and support facilities including $N_2H_4$ supply, instrumentation, recorders and chemical analysis equipment. These are described in the following sections.

### NGM Test Stand

A test stand dedicated to NGM characterization and endurance testing was designed, fabricated and checked out (see Figure 7). This test stand, built according to Life Systems test stand development philosophy, permits continuous, automated operation with a minimum of operator or test engineer interface. It has self-protection features for unattended operation.

### Description

Figure 8 shows the mechanical schematic for the test stand. In many respects the test stand contains all components neeeded for a complete NSS without automated control for some of them. The automated features permit safe shutdowns and some control and monitor functions. Others are performed manually.

Considering the NGM (NM1) as the end item under test, the schematic consists of those components which supply inputs and those which measure or control outputs. Hydrazine is stored in a supply tank (HT1) and fed to the NGM under pressure through a manual shutoff valve (MV7), pneumatic shutoff valves (V1 and V27), manual flow control valve (MV8) and a flow control orifice (RX5). The pressure of the liquid $N_2H_4$ is controlled by a manual regulator (PR2) and sensed by a pressure gauge (P23). The source pressure is an external, high pressure $N_2$ tank. The pneumatic valves V1 and V27 are controlled by the electrical three way valve V2 which supplies a 520 kPa (75 psia) pressure through regulator PR3. The flow control office RX5 develops a pressure drop measured by pressure sensor P2. In this fashion a flow monitor (designated

## TABLE 2 NGM NOMINAL OPERATING CONDITIONS

| | |
|---|---|
| Catalytic Dissociator Temperature, K (F) | 1000 (1340) |
| Pd/Ag Separator Temperature, K (F) | 644 (700) |
| Hydrazine Feed | |
| Source | Liquid Hydrazine |
| Hydrazine Flow Rate, kg/d (lb/d) | 4.15 (9.14) |
| $dm^3$/min | 2.9 |
| Composition, Weight % | |
| Hydrazine | 99.5 to 100 |
| Water | 0 to 0.5 |
| Temperature, K (F) | 291 to 297 (65 to 75) |
| Pressure, kPa (psia) | 1794 (260) |
| Nitrogen Product | |
| Flow Rate, kg/d (lb/d) | 3.64 (8.0) |
| $dm^3$/min (cfm) | 2.2 (0.078) |
| Composition, Volume % | |
| Hydrogen | 0.5 |
| Ammonia | $1.9 \times 10^{-3}$ |
| Water | <0.1 |
| Temperature, K (F) | 644 (700) |
| Pressure, kPa (psia) | 1725 (250) |
| Hydrogen Byproduct | |
| Flow Rate, kg/d (lb/d) | 0.44 (0.96) |
| $dm^3$/min (cfm) | 3.6 (0.13) |
| Purity, Volume % | 99.9999 to 100 |
| Temperature, K (F) | 644 (700) |
| Pressure, kPa (psia) | 172 (25) |
| Hydrogen Vented | |
| Flow Rate, kg/d (lb/d) | 0.08 (0.18) |
| $dm^3$/min (cfm) | 0.68 (0.024) |
| Temperature, K (F) | 644 (700) |
| Pressure, Pa (mm Hg) | 0 to 1330 (0 to 10) |

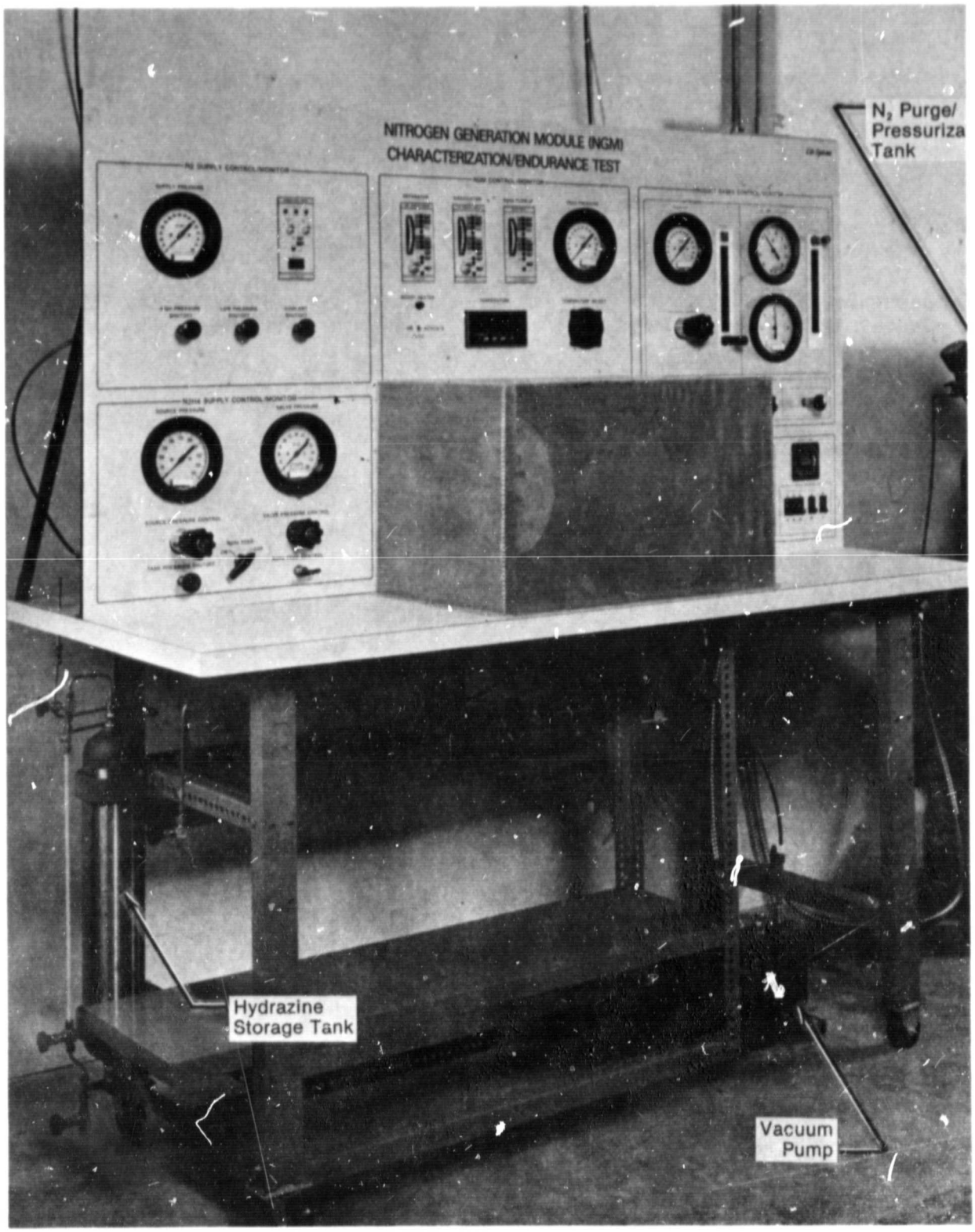


FIGURE 7 NGM TEST STAND

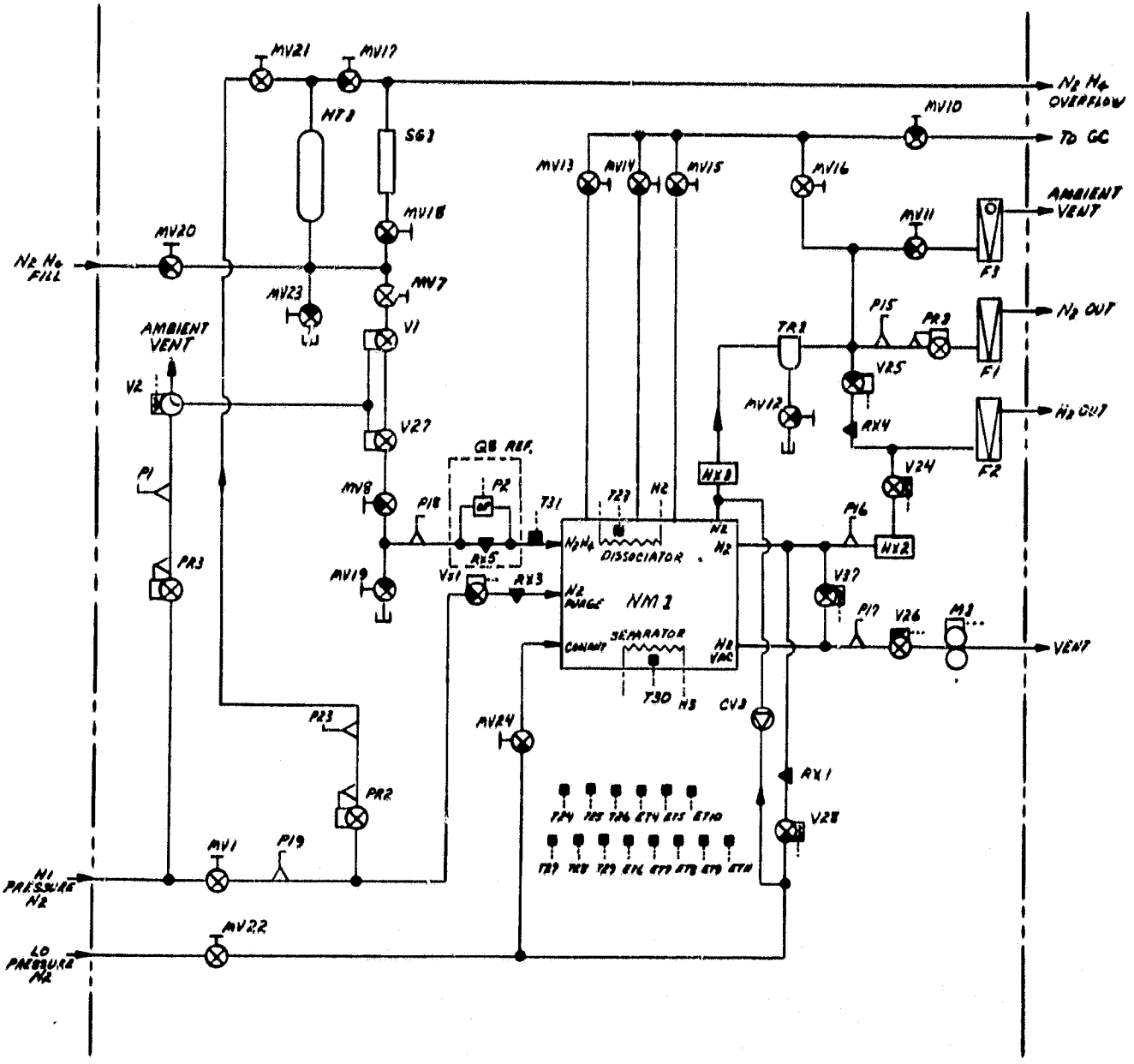


FIGURE 8 NGM TEST STAND MECHANICAL SCHEMATIC

Q8) records the flow as a function of the upstream pressure (monitored by P18) and the downstream pressure developed in the module.

The high pressure source is also used for purging the system through valve V31 and flow control office RX3. This was used to purge the $N_2$ gas chambers of the NGM. A laboratory source of low pressure $N_2$ provides purge of the $H_2$ chambers through V28 and RX1 and also coolant through MV24 when required.

At the outlet of the NGM, three flow streams are considered. Nitrogen exits the module and passes through a moisture trap (TR1), a back pressure regulator (PR1) and flowmeter (F1). A portion of the stream can be diverted through MV16 and MV10 to the gas chromatograph (GC) for analysis. As indicated, other sample streams can be diverted to the GC using valves MV13 through 15. The $H_2$ product gas stream passes through V24 and flowmeter F2.

The $H_2$-to-vacuum stream passes through a shutoff valve (V26) and vacuum pump (M1). Pressure sensor P17 monitors the vacuum level on the test stand. Valve V37 is used to evacuate both $H_2$ outlet chambers prior to startup. Pressure gauge P15 monitors the operating pressure of the system. Designed into the test stand is a method to induce a controlled leak of the system using MV11 and F3. The capability is for checkout purposes only and is seldom used.

Control and Monitor Instrumentation

The NGM test stand control and monitor instrumentation is a combination of automated controllers and mechanical gauges. It is grouped into six logical functions as shown in the front panel layout of Figure 9. In the upper left hand corner is the $N_2$ supply control and monitoring function. It contains the supply pressure gauge (P19) and the high pressure (MV1), low pressure (MV22) and coolant (MV24) shutoff valves. The $N_2$ purge controller (NPC) permits automated purging of the system (energizes V31) upon startup and shutdown. The purge time is selectable on the front panel of the NPC.

The lower left hand corner contains those components which establish hydrazine pressure and flow control. They include the source pressure regulator (PR2), source pressure guage (P23) and the tank shutoff valve MV21. Also the pneumatic valve pressure control (PR3) and the pneumatic pressure gauge (P1) are shown. The $N_2H_4$ feed shutoff (MV7) and flow control (MV8) are located here.

The top central portion of the test stand panel is dedicated to control and monitor the NGM itself. Two electronic controllers maintain the temperatures of the dissociator and separator. These are further defined in Table 3. A pressure monitor senses and displays the WP across RX5 which establishes the $N_2H_4$ flow. The feed pressure is monitored with a pressure gauge (P18). Below is a temperature sensor selector switch and display from which any of the NGM thermocouples can be monitored.

The upper right section of the front panel is dedicated to $N_2$ and $H_2$ product gas monitoring. The $N_2$ control/monitoring consists of the back pressure regulator PR1, pressure gauge P15 and flow meter F1. Hydrogen product gas is monitored by pressure gauge P16 and flow meter F2. The vacuum is monitored with pressure gauge P17. Below the product gas monitoring section of the

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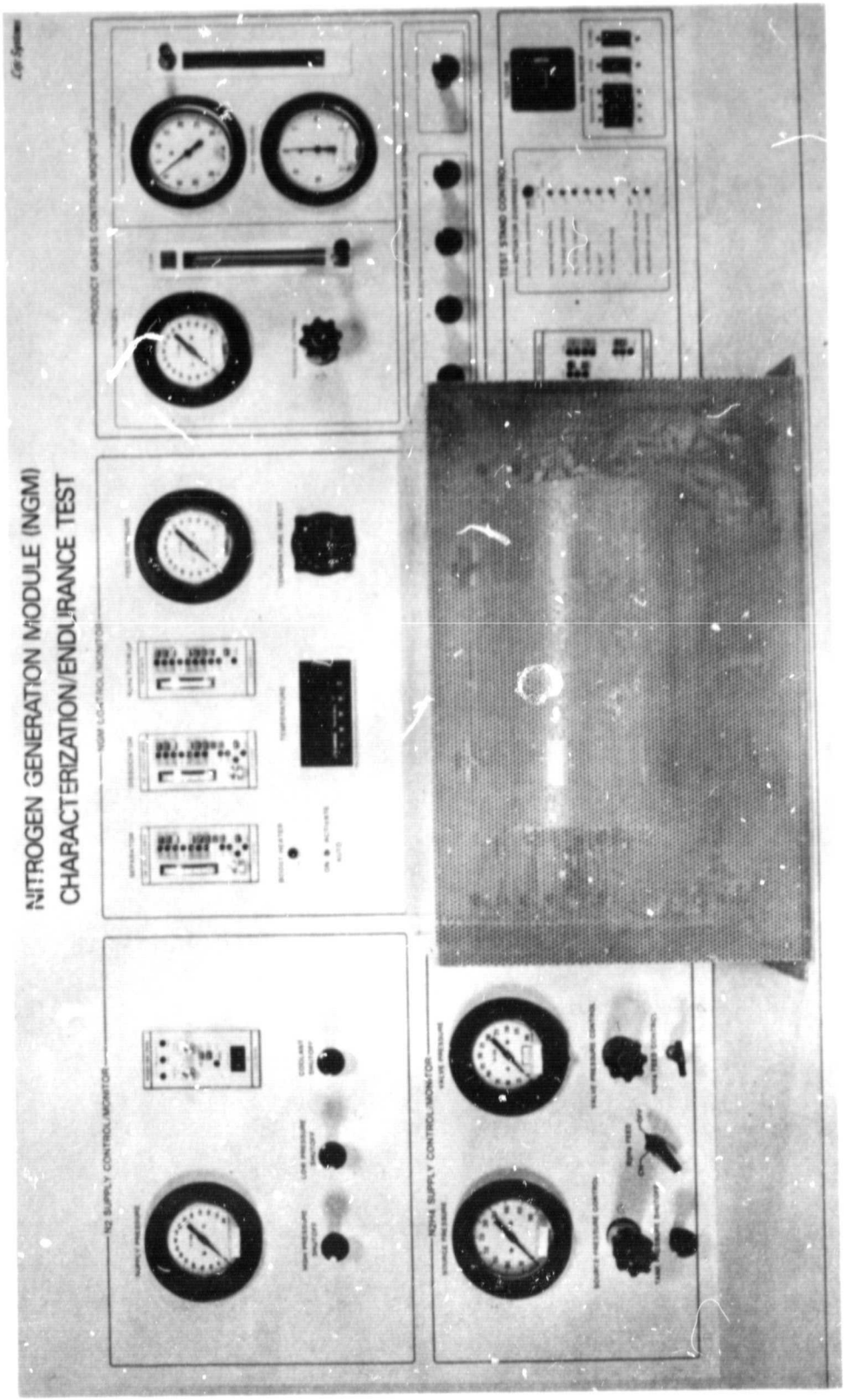


FIGURE 9 NGM TEST STAND FRONT PANEL

TABLE 3 NGM TEST STAND CONTROLLERS

| No. | Name | Description | Actuator | Sensor | Control Range, K (F) | Setpoint Range, K (F) | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | Caution | Warning | Alarm |
| 1 | TeCM1 | Dissociator Temperature Control/Monitor | H2 | T23 | 983-1019 (1300-1375) | 922-1033 (1200-1400) | 894-1047 (1150-1425) | 866-1061 (1000-1450) |
| 2 | TeCM2 | Separator Temperature Control/Monitor | H3 | T30 | 630-644 (765-700) | 602-650 (625-710) | 575-658 (575-725) | 533-672 (500-750) |
| 3 | PM | $N_2H_4$ Feed Flow $\Delta P$ Monitor, kPa (psid) | -- | Q8 | -- | 27-130 (4-19) | 14-140 (2-20) | 7-150 (1-22) |
| 4 | NPC | $N_2$ Purge Controller | V31 | -- | -- | -- | -- | -- |
| 5 | OpC | Test Stand Operations Controller | Other Controllers, Valves | -- | -- | -- | -- | -- |

panel are five manual valves (MV10, 13 to 16) for controlling interstage sample streams to the GC.

Located in the lower right hand corner of the test stand are functions for controlling the test stand itself. An electronic operations controller (OpC) permits the operator to select the shutdown, standby and normal operating modes. Each actuator (valves and heaters) can be overriden or placed under automatic control. A timer is provided for accumulating the time that the test stand is in an operating mode and not just when power is applied. Finally circuit breakers are provided for input power to the test stand and to the NGM heaters.

Operation

The operation of the NGM and its test stand is straightforward. After the NGM is installed as shown in Figure 10, all cavities are pressurized with $N_2$ and pressure gauges monitored to detect plumbing leaks. Then the module is purged to eliminate all air from the module and lines. This can be done either manually or automatically using the NPC. The NGM is then pressurized by opening valve V31 and manually closing regulator PR3 until the desired operating pressure is obtained. Regulator PR2 is adjusted until a fixed delta above the P15 reading is obtained, usually 70 kPa (10 psid). Then MV21 is opened and the $N_2H_4$ tank pressurized. After the NGM has achieved operating temperature, $N_2H_4$ flow to it is controlled manually and then automatically by valves MV8 and V21/27. At the same time the operations controller (OpC) is put to the "normal" operating mode which controls the position of the remaining solenoid valves. Once operational, removing all override switches from the controllers and the actuators will permit the test stand to operate fully automatically. If any of the key sensors (Q8, T23 or T30) as identified in Table 3 go out of tolerance the test stand goes to shutdown. Also, if it is desired during normal operation to go to a standby mode, the OpC allows pushing the standby button which automatically closes the $N_2H_4$ valves (V1/V27).

## Support Facilities

Besides the NGM test stand, the NGM test facility consists of a source of $N_2H_4$, recorders, gas chromatograph and chemical analysis equipment. Figure 11 shows these support facilities located in the vicinity of the test stand.

Hydrazine Supply

Figure 12 shows the schematic of the $N_2H_4$ supply from the storage area to the NGM test stand. Hydrazine is stored in a 0.21 $m^3$ (55 gallon) drum which can be pressurized up to 138 kPa (20 psia). In order to transfer the $N_2H_4$ from the drum located into the storage area to the tank located on the test stand, pressures greater than 138 kPa (20 psia) are required. An intermediate, higher pressure transfer tank is used for this purpose.

Recorders

Two recorders are used in the NGM test facility. The temperature trend recorder monitored eight experimental thermocouples located on the NGM. This information

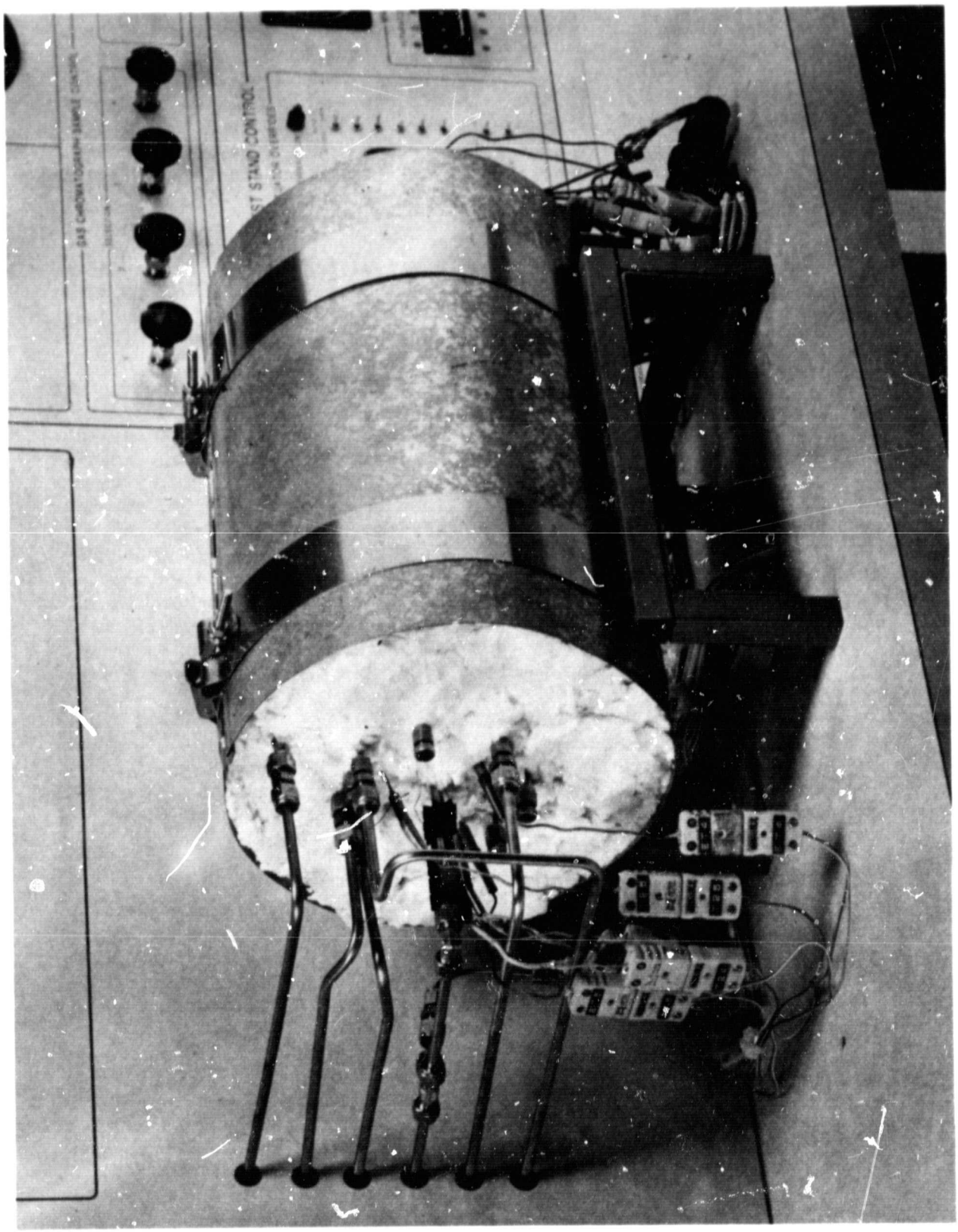

FIGURE 10 NGM MOUNTED ON TEST STAND

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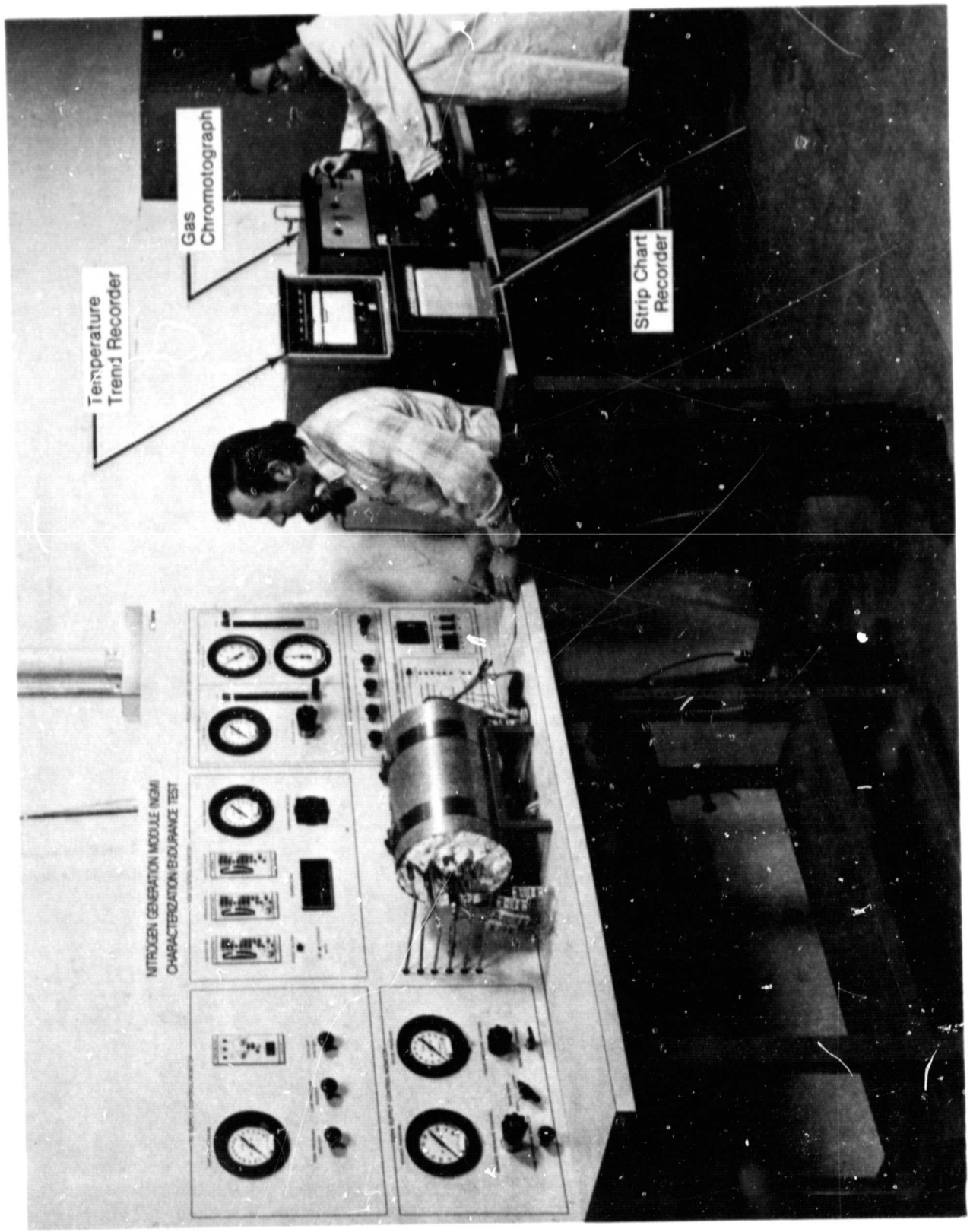


FIGURE 11 NGM TEST FACILITIES

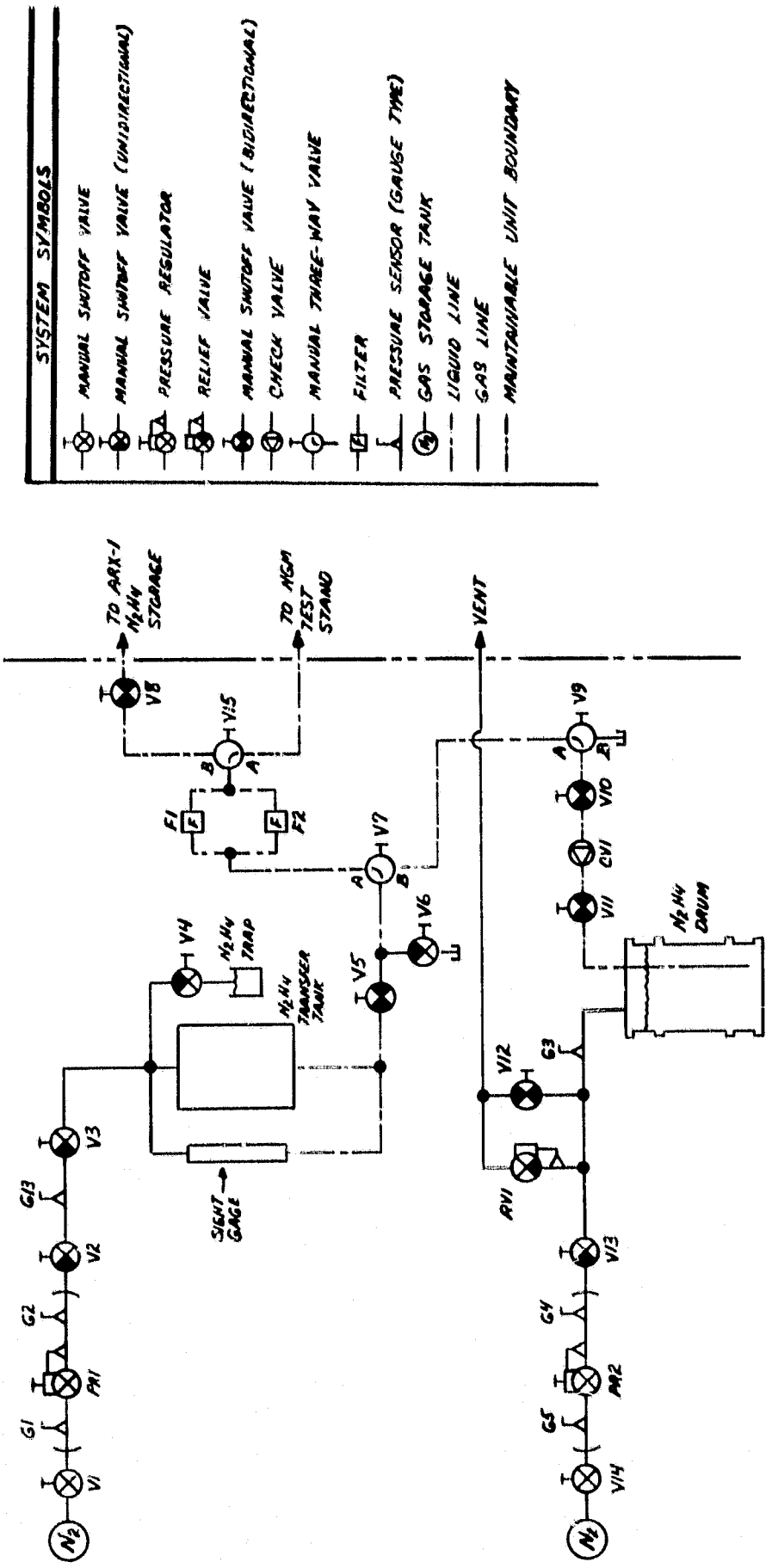


FIGURE 12 $N_2H_4$ SUPPLY SCHEMATIC

gave temperature distribution data in various portions of the dissociator and the separator. A strip chart recorder monitored two key temperatures and the $N_2H_4$ flow. These recorders were used primarily for observing long term data taken during periods of unattended operation (e.g., overnight).

Gas Chromatograph

A gas chromatograph was used to periodically sample the product $N_2$ stream from the NGM and measure the $N_2H_2$ and $NH_3$ concentrations. After testing was initiated a problem occured whereby the $NH_3$ concentration peak was obscured by a low moisture level in the $N_2$ product stream. This produced unreliable $NH_3$ concentration data. A chemical analysis technique was substituted.

Ammonia Concentration Analysis

Ammonia concentration of the $N_2$ product stream is a major measure of performance of the NGM. A wet chemistry technique was adopted for analysis as opposed to the gas chromatograph as discussed above. In this technique, the sample is bubbled through a gas washing bottle containing a hydrochloric acid (HCL) solution and a colorimetric indicator. The $NH_3$ concentration is given by the equation:

$$\text{Conc. } NH_3, \% = \frac{2205\ (C)(V)}{(T)(F)} \qquad (4)$$

Where C = Conc. HCl, M
V = Vol. HCl soln, liter
T = Time to color change, min
F = Flow rate, liter/min

This technique, independently verified with known samples, gave very reliable data.

## NGM DATA BASE GENERATION TESTING

The test program was designed to measure the response in performance of the NGM as a function of changes in five operating parameters: operating pressure, $N_2H_4$ feed rate, dissociator temperature, separator temperature and catalyst weight. Performance was defined as concentration of $H_2$ and $NH_3$ in the product $N_2$ outlet and % $H_2$ recovered in the product $H_2$ stream (versus total $H_2$ produced). A total of 900 hours of operating time and almost 100 data points were achieved during all phases of testing. The test durations and the number of data points taken met or exceeded test program goals.

### Test Procedures

The overall approach of the test program was to vary one parameter at a time while maintaining the other parameters at nominal values. The nominal values

were based on (a) prior operating experience (b) design analysis or (c) physical constraints. An example of the latter is the maximum amount of $NH_3$ catalyst as determined by the $NH_3$ dissociator stage size. Table 4 shows the nominal valves and ranges of the operating parameters for which data was recorded.

In a fairly complex chemical reaction, as occurs in the NGM, changing several parameters at one time could influence the optimization of other parameters in terms of overall NGM performance. Ideally, a rigorous testing program would evaluate the effect of all possible combinations of the selected parameters, with several replications to rule out measurement error. The approach taken instead was to vary one parameter while holding the others constant. Also, it was recognized early that operating pressure influences $H_2$ outlet concentration the most, while dissociator temperature impacts $NH_3$ concentration and $N_2H_4$ feed rate impacts both. Therefore, these three parameters were investigated extensively.

The general procedure for data taking was as follows. After establishing an assumed steady-state, a data point was taken. This consisted of manual recording of all measurements (pressures, flows, temperatures, etc.), a wet chemical sample for $NH_3$ and a GC sampling. The GC was used primarily to measure $H_2$ concentration in the $N_2$ product stream. For several of the test points, additional measurements (wet chemistry and GC) were made at intermediate stages within the NGM. In this manner, the effect of $NH_3$ catalyst was determined.

The testing protocol maintained during one period illustrated the potential versatility of the NGM as part of an operational NSS. During this period of testing, a total of 439 hours of continuous operation were accumulated. Generally, the $N_2H_4$ flow was adjusted to the level required during the working day but kept at a low value during the night to conserve $N_2H_4$. Changes in flow, while manual, could be automated to provide an "on-demand" $N_2$ subsystem. This mode of operation worked extremely well.

## Parametric Tests

The test results of the effects of the five operating parameters on NGM performance are presented below. The order of presentation was selected in terms of decreasing order of parameter importance on overall NGM operation.

### Operating Pressure

Five levels of operating pressure were investigated: 450, 790, 1140, 1480 and 1830 kPa (65, 115, 165, 215 and 265 psia). Figure 13 shows the NGM performance as a function of pressure at nominal $N_2H_4$ feed rate and dissociator temperature. Unless otherwise stated, all performance curves will note the test conditions for the results shown. Parameters not stated explicitly were at nominal values (see Table 4). For example, separator temperature would be 644 K (700 F) and catalyst amount would be 160 g (0.352 lb).

Figure 13 shows the general trend seen in all pressure-related tests. Ammonia concentration in the product $N_2$ is a weak function of pressure while $H_2$ concen-

TABLE 4 OPERATING PARAMETER RANGES

| Parameter | Nominal | Range |
|---|---|---|
| Operating Pressure, kPa (psia) | 1270 (265) | 430-1270 (65-265) |
| Dissociator Temperature, K (F) | 1000 (1340) | 866-1061 (1100-1450) |
| $N_2H_4$ Feed Rate, kg/d (lb/d) | 4.15 (9.14) | 1.4-9.1 (3-20) |
| Separator Temperature, K (F) | 644 (700) | 589-672 (600-750) |
| Catalyst Weight, g (lb) | 160 (0.352) | 54-160 (0.119-0.352) |

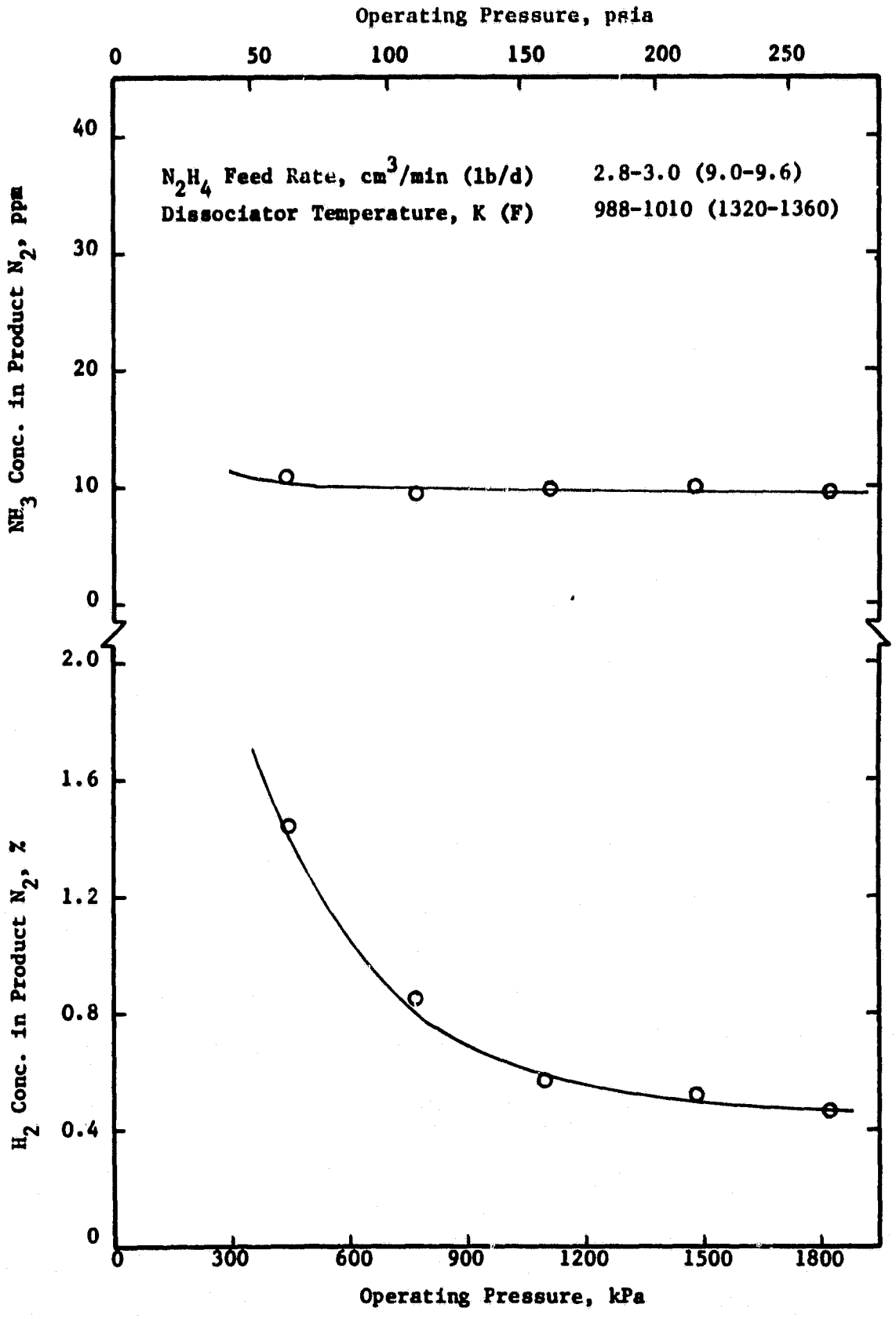


FIGURE 13 NGM PERFORMANCE AS A FUNCTION OF OPERATING PRESSURE

tration is strongly dependent on pressure. This is because $H_2$ diffusion through the Pd/Ag tubes is strictly a function of the partial $H_2$ pressure difference across the tube wall. The reason the $H_2$ concentration does not decrease linearly at higher pressures is probably caused by a mass transfer effect since tube surface area is fixed. At lower $N_2H_4$ feed rates (not shown) a sharp falloff with increasing pressure was noted.

Another important NGM performance parameter is the amount of $H_2$ actually recovered in the product $H_2$ stream compared to the available $H_2$ in the $N_2H_4$ feed. Figure 14 shows the results of a typical test. Two sets of curves are shown for both percent $H_2$ recovered and $H_2$ concentration in the product $N_2$ stream. In one case, the vacuum pump was on as in normal operation. In the other, the vacuum pump was turned off and the last three separator stages were exhausting to ambient pressure. It is seen that while more $H_2$ is recovered for use, the $H_2$ concentration in the $N_2$ stream is quite high, almost 9%. As expected, the vacuum stages, although causing a loss of available $H_2$, are definitely needed to provide low concentrations of $H_2$ in the product $N_2$.

Dissociator Temperature

Figure 15 shows $NH_3$ concentration in the product $N_2$ stream and a sample stream as a function of dissociator temperature. The sample stream is at the outlet of the second separator stage, downstream of the first $NH_3$ dissociator stage.

The endothermic reaction of $NH_3$ dissociation (equation 2) is a strong function of temperature and a catalyst temperature of around 1000 K (1340 F) is desired. The $NH_3$ concentration measurements, determined by a wet chemistry technique, actually indicated values less than 10 ppm, but, due to measurement uncertainty, were recorded as 10 ppm. At temperatures below about 940 K (1230 F) $NH_3$ concentration rises considerably and can increase two orders of magnitude for a lowering of only 28 K (50 F) in dissociator temperature.

Initially, it was planned to explore the effect of dissociator temperature up to 1088 K (1500 F). However, there was some difficulty in maintaining the separator temperature at or below 644 K (700 F) without cooling if the dissociator temperature rose above 950 K (1250 F). This is due to radiative heat transfer from the high temperature zone to the separator. This problem only occurred with low (or no) $N_2H_4$ flow since during normal operation heat required for $NH_3$ stage dissociation tends to keep the external surface of the dissociator core 56 to 83 K (100 to 150 F) cooler. Therefore, under these conditions, separator temperatures can go higher than the desired 644 K (700 F). Because of this, an insulating sheath was wrapped around the dissociator to reduce the radiative heat transfer. The advanced NGM will have provisions to account for this effect.

$N_2H_4$ Feed Rate

Figure 16 shows the percent of $H_2$ in the $N_2$ product stream as a function of $N_2H_4$ feed rate and system operating pressure. Obviously, this performance parameter improves with increasing pressure as this assists in the removal of $H_2$ from the $N_2$ stream. The increased $H_2$ concentrations at lower feed rates

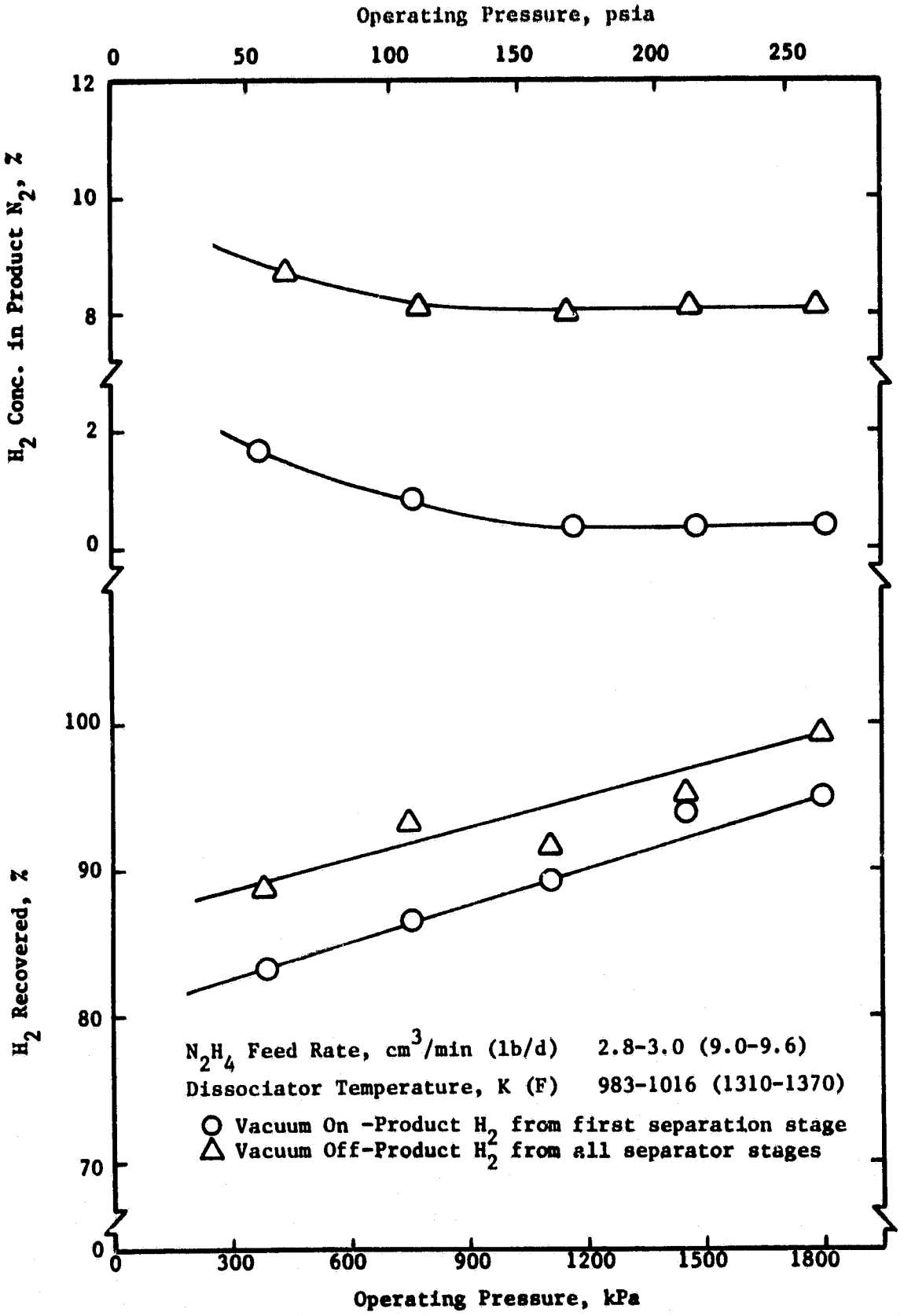


FIGURE 14 $H_2$ RECOVERY AS A FUNCTION OF OPERATING PRESSURE

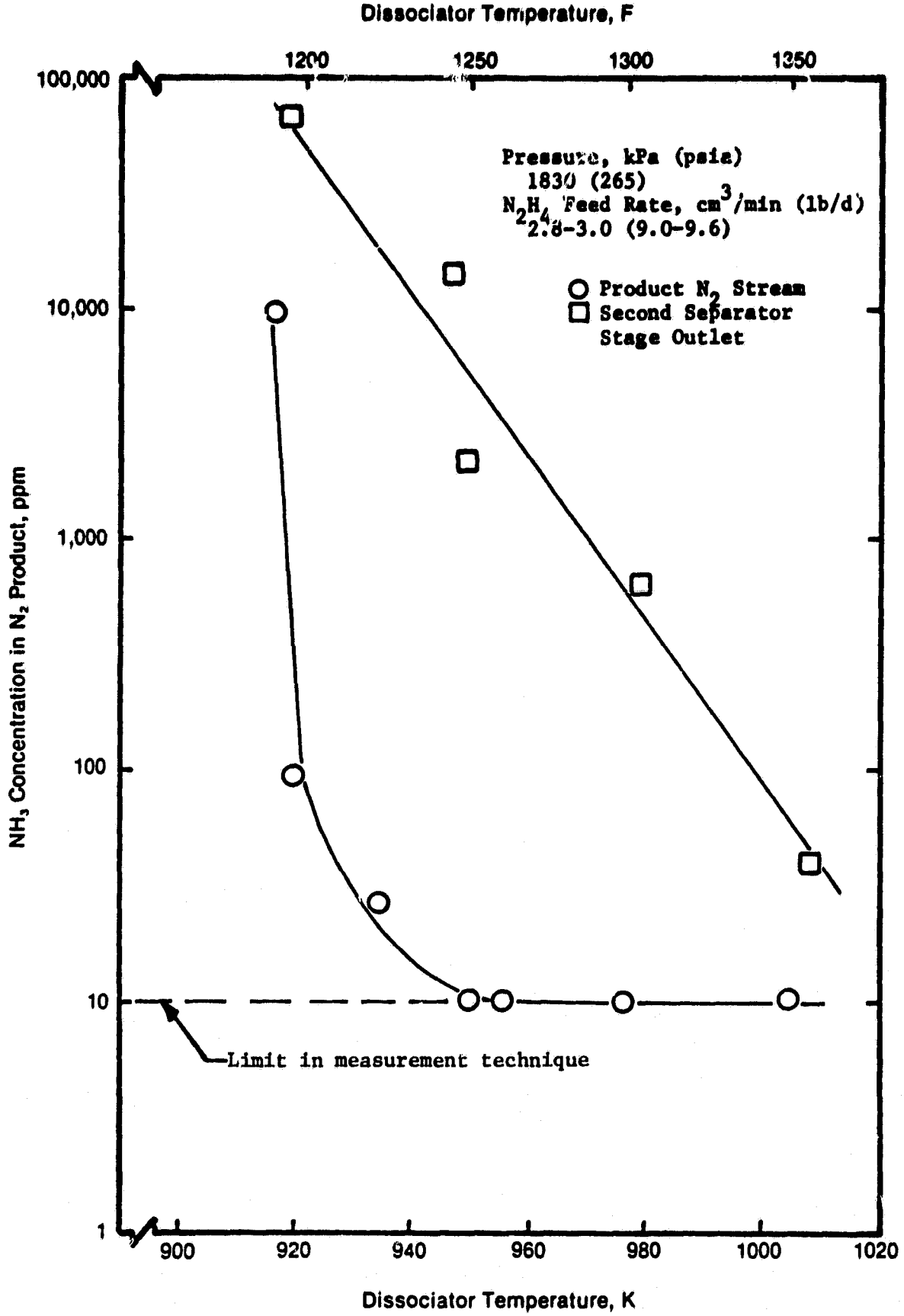


FIGURE 15 NGM PERFORMANCE ($NH_3$ CONCENTRATION IN PRODUCT $N_2$)

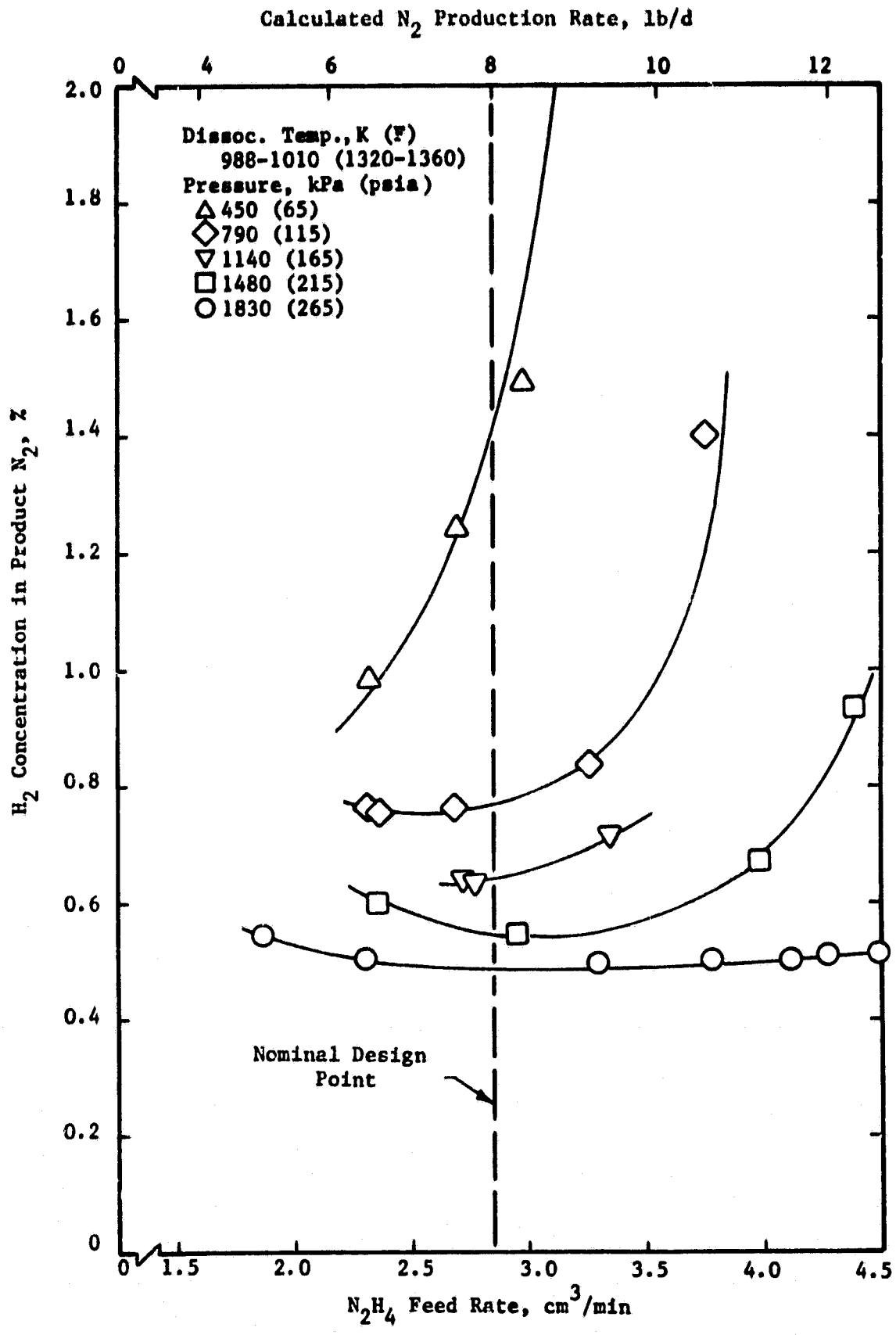


FIGURE 16 NGM PERFORMANCE ($H_2$ CONCENTRATION IN PRODUCT $N_2$)

(reversal of slope) were consistently observed and are probably due to a lower partial pressure of $H_2$. The $NH_3$ concentration shows a much larger dependence on $N_2H_4$ feed rate (see Figure 17). This is probably due to reaction rate and residence time limitations of the fixed-sized $NH_3$ dissociation stages.

Generally, these results supported the conclusion that the NGM, as presently configured, will provide $N_2$ generation rates at up to twice design values without much impact on $H_2$ impurity in the $N_2$ product stream at design pressure but $NH_3$ concentration will increase. Therefore, the advanced NGM will incorporate additional $NH_3$ catalyst and will do so without changing the size of the dissociator housing due to more efficient packaging.

Separator Temperature

No appreciable changes in $H_2$ or $NH_3$ concentration in the product $N_2$ stream were detected as a function of separator temperature variations. Due to the difficulty in achieving low separator temperatures because of dissociator radiative heating, only limited data was obtained in the range 589 to 672 K (600 to 750 F). No change in $NH_3$ concentration was observed with increasing temperature. Maintaining the NGM separator at 644 ±28 K (700 ±50 F) is the desired operating level.

Catalyst Weight

The effect of catalyst weight was achieved indirectly by analyzing samples at various $NH_3$ dissociation stages. Figure 15 showed the results of one such test. These data indicated that $NH_3$ dissociation performance is a function of residence time of the gas in the dissociation catalyst bed and not amount of catalyst directly. Bed length is more important than cross-sectional area although larger area will reduce space velocity for a given flow. For the current and projected advanced NGM, pressure drops in the catalyst beds are negligible.

## PREPROTOTYPE NSS DESIGN

The primary function of the NSS is to generate $N_2$ for cabin leakage makeup thereby controlling total cabin pressure. Development of an NSS has progressed to a point where a preprototype, self-contained NSS should be designed and built to demonstrate its readiness for manned habitability applications. This program is providing the design for such a subsystem.

A 4.4 kg/d (9.6 lb/d) capacity NSS is being designed based on further improvements in NGM performance and to characterize the NSS concept in general. The 4.4 kg/d (9.6 lb/d) capacity level allowed using the guidelines, philosophy and the specifications established for the Space Operations Center (SOC) currently being considered by NASA.[8] This selection simplifies direct comparison of the NSS concept with onboard storage in the form of cryogenic or gaseous $N_2$ as indicated previously in Figure 1.

### Design Specifications

Overall design specifications for the SOC NSS were established and are presented in Table 5. The requirements for the $N_2$ generation rate and product composition

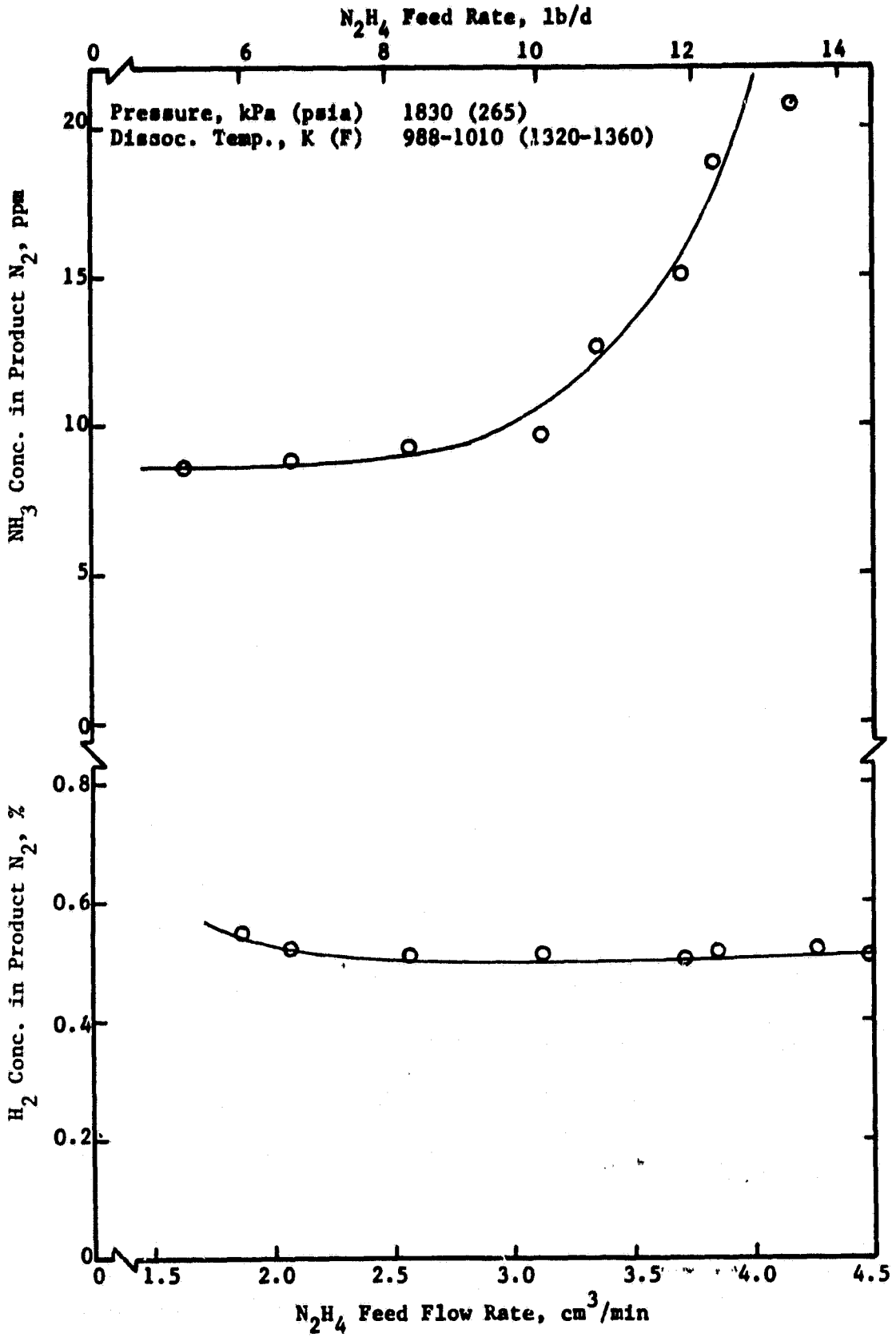


FIGURE 17 NGM PERFORMANCE AS A FUNCTION OF $N_2H_4$ FEED RATE

TABLE 5 NSS DESIGN SPECIFICATIONS

| | |
|---|---|
| Hydrazine Feed Rate, kg/d (lb/d) | 5.0 (11.0) |
| Nitrogen Generation Rate, kg/d (lb/d) | 4.4 (9.6) |
| Product Hydrogen Generation Rate, kg/d (lb/d) | 0.56 (1.23) |
| Pressure, kPa (psia) | 1830 (265) |
| Nitrogen Product Composition, Volume % | |
| Hydrogen | 0.2 |
| Ammonia | $1 \times 10^{-3}$ |
| Water | 0.1 |
| Hydrogen Byproduct Purity, Volume % | 99.9 |
| Product Hydrogen Removal Efficiency, % | 90 |
| Surface Temperature Guidelines, K (F) | 322 (120) |

were based on anticipated SOC requirements. Recent test experience and projected improvements in NGM performance confirm that they can be met at competitive equivalent weights.

The overall goal of the design effort is to design an NSS as a spacecraft utility. The design features were selected based on both subsystem and design requirements. The following is a list of the major design features incorporated.

1. The subsystem will be designed for location in an unpressurized area external to habitable confines.

2. A separate spacecraft $N_2H_4$ storage facility is assumed which will supply $N_2H_4$ to the NGM and other subsystems using $N_2H_4$ (e.g., reaction control units).

3. The byproduct $H_2$ generated can be used by a Sabatier reactor for $CO_2$ reduction.

4. Control and monitoring functions are provided by computer-based instrumentation utilizing software programming techniques.

5. Four steady-state operating modes are incorporated: Shutdown, Normal, Standby and Purge.

6. Manual overrides and controls have been included for off-design testing.

7. All materials of construction used are compatible with their environment.

Subsystem Schematic and Operation

A schematic of the NSS is shown in Figure 18. The design is based on the concept shown previously for hydrazine dissociation. There are two principal components of the NSS. Naturally, the NGM is the heart of the system. An $N_2$ pressure controller permits startup, attainment of subsystem pressure and maintenance of the source pressure for feeding the $N_2H_4$. These are discussed in detail below.

Advanced NGM

The preprototype NSS will incorporate the advanced NGM design, presently underway. The two principal design improvements are: (1) eliminate all sealing surfaces, and (2) minimize heater power required to maintain steady-state operating temperatures.

The test results to date have confirmed that the current NGM configuration, size and staging concept will work even at an increased design $N_2$ production rate of 4.4 kg/d (9.6 lb/d). A requirement for the advanced NGM design was to maintain the current configuration but eliminate the sealing surfaces. A sketch of the current configuration and proposed changes are shown in Figure 19. All mechanical fasteners (bolts, studs, etc.) and gaskets will be eliminated

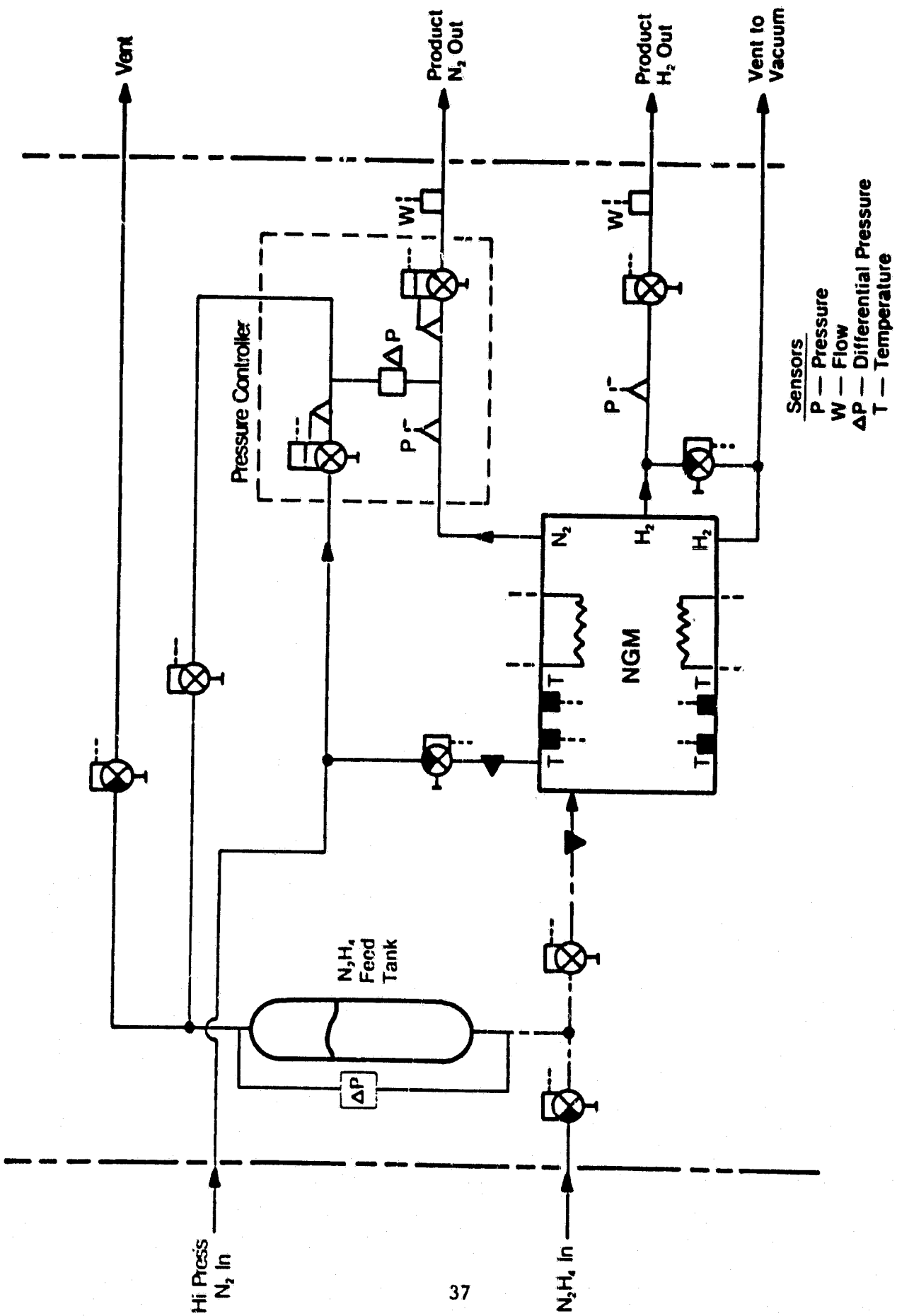


FIGURE 18 NSS SCHEMATIC

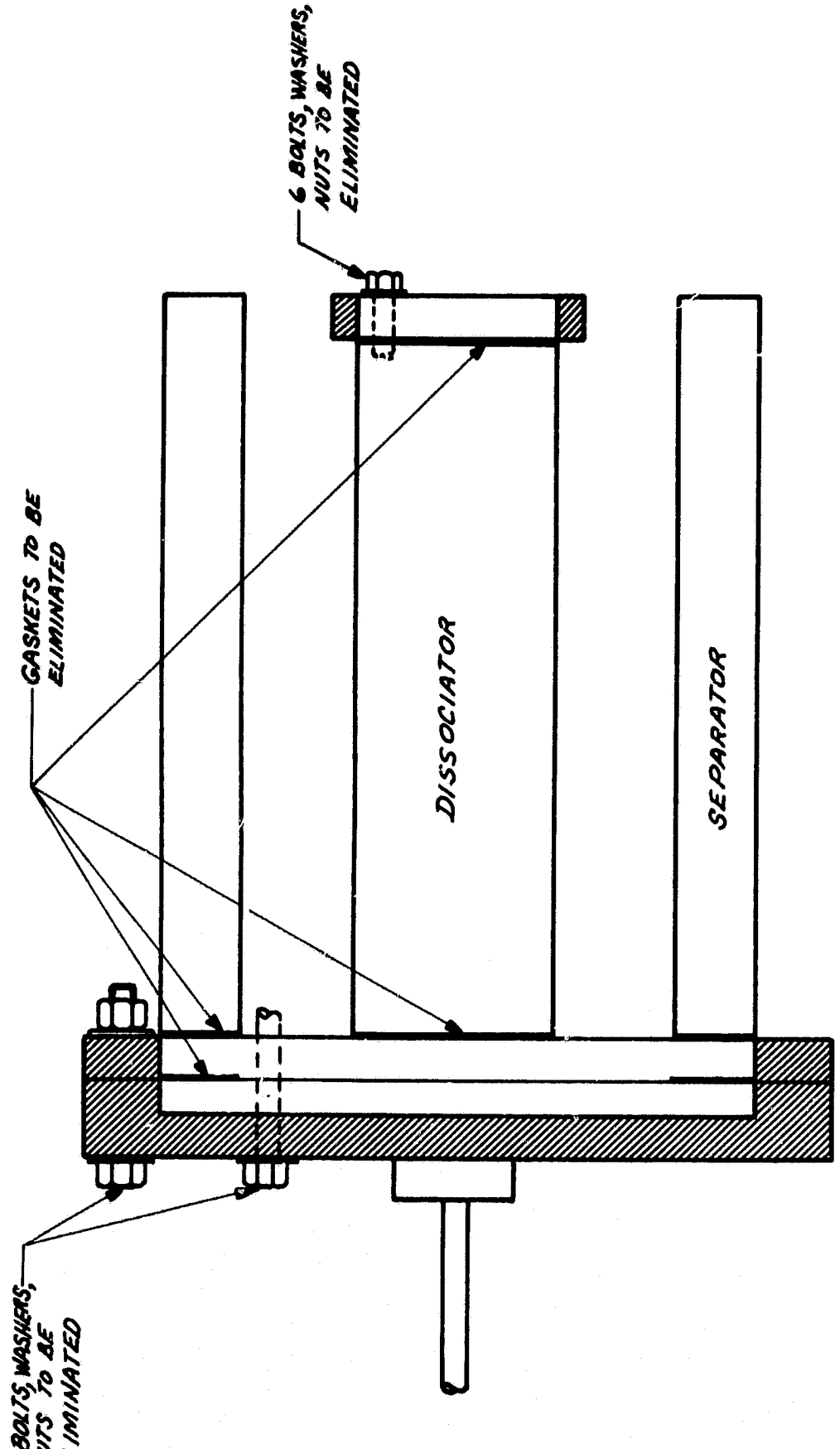


FIGURE 19 NGM DESIGN MODIFICATIONS HIGHLIGHTS

as the unit will be welded and brazed. This will permit elimination of the flanges and spacers of the present unit, as indicated. A projected 20-25% weight savings will result.

An additional 20% (from 50 to 60) Pd/Ag tubes will be added to the separator without increasing the diameter or length of the unit. This results from more effective utilization of dead space in the present header plate. The additional tubes will increase the $H_2$ removal capability and permit a larger $N_2$ generation capacity without increasing overall size.

The second design driver is to minimize heater power. It is recognized that input power can never be zero, or there would be no passive zone temperature control. On the other hand, the design must accommodate variations in $N_2$ generation rate which means that internally generated heat will vary. The addition of more insulation with provisions for some heat loss in the aft end will permit a reduction in net heater power. A goal of 150 W steady-state input power has been established.

Minor design changes include (a) use of welded thermocouple wells instead of compression fitted thermocouples to eliminate sources of leakage, and (b) elimination of interstage sample ports. Only those mechanical interfaces absolutely needed for the control or connection with other NSS components will be included. Past performance of the NGM has given confidence in the unit to perform its $N_2$ generation function without additional provisions for monitoring interstage performance. Therefore, those provisions have been eliminated.

Pressure Controller

The $N_2$ pressure controller permits subsystem startup from ambient pressure by using an external $N_2$ source. This $N_2$ source also provides the initial pressurization of the $N_2H_4$ to produce flow to the NGM. Over a SOC mission, this amount of $N_2$ is less than 2% of the total $N_2$ generated at baseline conditions. This gas can be returned to the cabin. Use of the high pressure $N_2$ source (and treated as a consumable) trades off favorably with a low reliability, power consuming $N_2H_4$ pump to provide $N_2H_4$ at the needed pressure.

The $N_2$ pressure controller is similar to others built by LSI for controlling absolute pressure and pressure differentials between two or more fluids. Its functional operation is shown in Figure 20. It combines in a single assembly the sensors and actuators necessary to control and monitor fluid pressure levels and differentials during all phases of operation including steady-state, startup, shutdown, etc. This is done with two motor-driven regulators, one total pressure level sensor, a differential pressure sensor and two feedback position indicators. The controller has four fluidic interfaces as shown in Figure 20 and a standard connector for the electrical interface with the subsystem instrumentation.

Ancillary Components

The major components are supported by valves, flow restriction orifices, a $N_2H_4$ storage tank, temperature and pressure transducers, instrumentation and

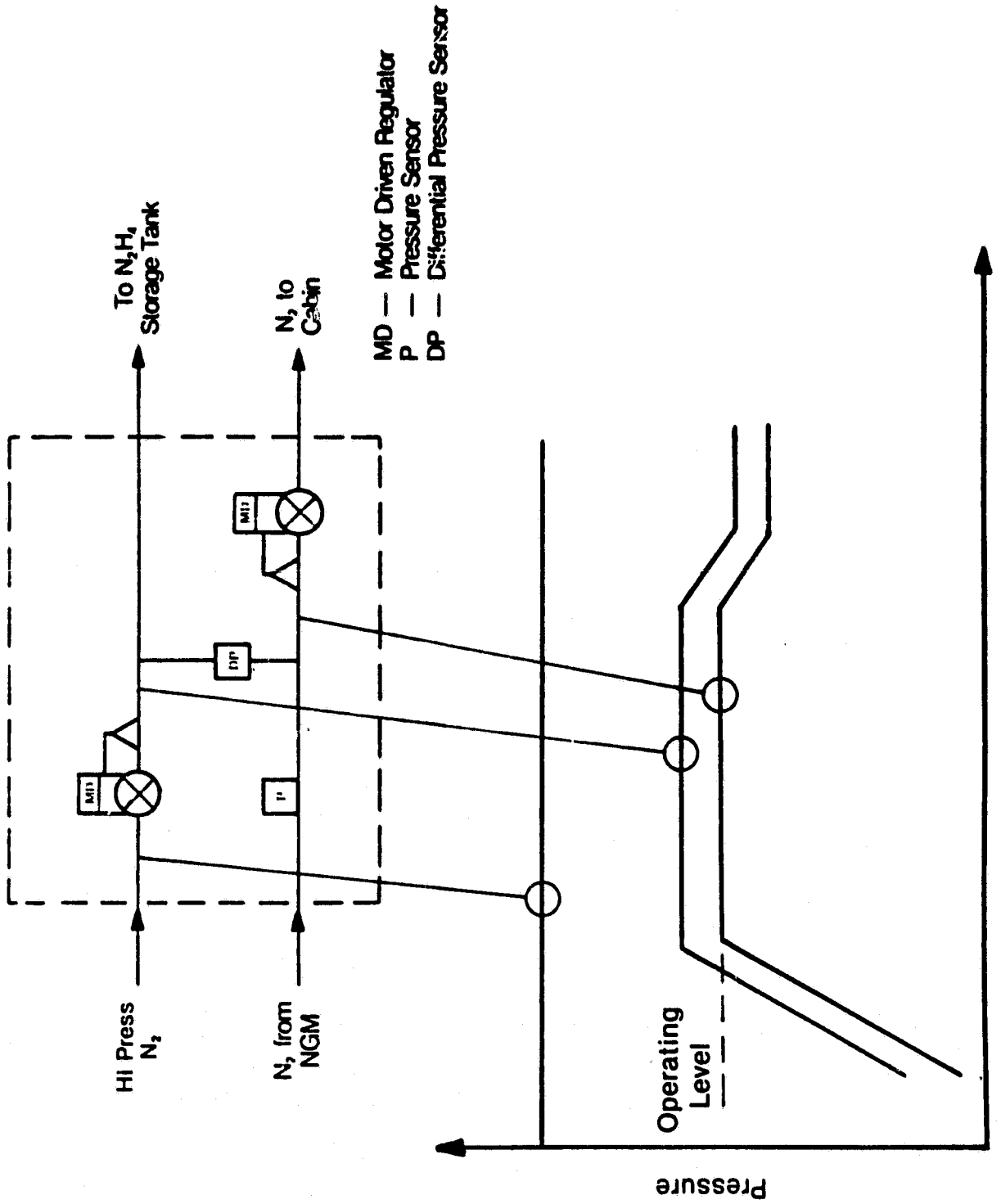


FIGURE 20 NSS PRESSURE CONTROLLER FUNCTIONAL DESCRIPTION

packaging. The instrumentation is only that necessary to permit the NSS to perform its functions. Testing to this point has indicated that no additional sensors would be required.

### Subsystem Characteristics

Preliminary definition of the preprototype NSS included characterizing the weight, power and heat rejection of the major components. Table 6 summarizes the results. The subsystem total fixed hardware weight including packaging is 59 kg (130 lb). Steady-state power requirements are 168 W of DC power. The heat rejection requirements on the spacecraft are assumed to be negligible since the NSS is to be located in an unpressurized area. The use of passive cold plates or radiation to space will permit passive thermal control. Since the NSS will be located external near an infinite vacuum source and near the spacecraft $N_2H_4$ storage, only one bulkhead feed-through (for $N_2$) will be required. An additional feed-through for $H_2$ is necessary if the $H_2$ is used.

## CONCLUSIONS

The testing conducted with the NGM to date has given the confidence that the $N_2H_4$-based NSS will be a success. Low amounts of $H_2$ (less than 0.5%) and $NH_3$ (less than 10 ppm) were measured in the $N_2$ product stream. Except for some hardware deficiencies, that will be addressed in the advanced NGM design, there are no major questions regarding the technology readiness of the NSS concept.

Nitrogen storage will be required for future manned space efforts to replace gases which leak from inhabited volumes. A $N_2H_4$-based NSS has been shown to be the most viable candidate for supplying the $N_2$. An NSS employing the inherently simple dissociation of $N_2H_4$ and subsequent separation of $N_2$ and $H_2$ is an exceptionally attractive subsystem. The NSS design will incorporate all the operational concepts projected for a flight unit. The design of a preprototype NSS will be the next step in developing prototype/flight hardware. Such a development effort will provide system planners and designers with details on operational characteristics. Maturation of this system will then provide maximum flexibility in meeting flight mission needs.

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TABLE 6 SUBSYSTEM COMPONENT SUMMARY

| Component | Weight, kg (lb) | Power, W | Heat Rejection, W |
|---|---|---|---|
| NGM | 28.2 ( 62) | 75[a] | 75 |
| Pressure Control | 2.7 ( 6) | (b) | -- |
| $N_2H_4$ Feed Tank | 2.3 ( 5) | -- | -- |
| Valves | 1.8 ( 4) | 63 | 63 |
| Instrumentation | 14.1 ( 31) | 30 | 30 |
| Ancillary Components and Packaging | 10.0 ( 22) | -- | -- |
| | 59.1 (130) | 168 | 168 |

(a) Steady-state operation only
(b) Power required only on a momentary basis

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