NASA/CR—2001-210765/REV1

Low-Pressure Long-Term Xenon Storage for Electric Propulsion

Dwight D. Back, Charlie Ramos, and John A. Meyer
Mainstream Engineering Corporation, Rockledge, Florida

Document Availability Change Notice

This document was published in April 2001 with an SBIR restriction. It was changed October 2004 to Unclassified/Unlimited per DAA modified October 29, 2004.

SBIR Rights Notice

These Phase II SBIR data are furnished with SBIR rights under Contract NAS3–99077. For a period of 4 years after acceptance of all items to be delivered under this contract, the Government agrees to use these data for Government purposes only, and they shall not be disclosed outside the Government (including disclosure for procurement purposes) during such period without permission of the Contractor, except that subject to the foregoing use and disclosure prohibitions, such data may be disclosed for use by support contractors. After the aforesaid 4–year period, the Government has a royalty–free license to use, and to authorize others to use on its behalf, these data for Government purposes, but is relieved of all disclosure prohibitions and assumes no liability for unauthorized use of these data by third parties. This notice shall be affixed to any reproductions of these data, in whole or in part.
Date for public release: June 18, 2004.

INFORMATION CONTAINED HEREIN IS PROPRIETARY FOR 4 YEARS IN ACCORDANCE WITH FAR 52.227–20.

February 2005

The NASA STI Program Office . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program Office plays a key part in helping NASA maintain this important role.

The NASA STI Program Office is operated by Langley Research Center, the Lead Center for NASA's scientific and technical information. The NASA STI Program Office provides access to the NASA STI Database, the largest collection of aeronautical and space science STI in the world. The Program Office is also NASA's institutional mechanism for disseminating the results of its research and development activities. These results are published by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA's counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services that complement the STI Program Office's diverse offerings include creating custom thesauri, building customized data bases, organizing and publishing research results . . . even providing videos.

For more information about the NASA STI Program Office, see the following:

- Access the NASA STI Program Home Page at ***http://www.sti.nasa.gov***

- E-mail your question via the Internet to help@sti.nasa.gov

- Fax your question to the NASA Access Help Desk at 301–621–0134

- Telephone the NASA Access Help Desk at 301–621–0390

- Write to:
  NASA Access Help Desk
  NASA Center for AeroSpace Information
  7121 Standard Drive
  Hanover, MD 21076

NASA/CR—2001-210765/REV1

Low-Pressure Long-Term Xenon Storage for Electric Propulsion

Dwight D. Back, Charlie Ramos, and John A. Meyer
Mainstream Engineering Corporation, Rockledge, Florida

Document Availability Change Notice

This document was published in April 2001 with an SBIR restriction. It was changed October 2004 to Unclassified/Unlimited per DAA modified October 29, 2004.

SBIR Rights Notice

These Phase II SBIR data are furnished with SBIR rights under Contract NAS3–99077. For a period of 4 years after acceptance of all items to be delivered under this contract, the Government agrees to use these data for Government purposes only, and they shall not be disclosed outside the Government (including disclosure for procurement purposes) during such period without permission of the Contractor, except that subject to the foregoing use and disclosure prohibitions, such data may be disclosed for use by support contractors. After the aforesaid 4–year period, the Government has a royalty–free license to use, and to authorize others to use on its behalf, these data for Government purposes, but is relieved of all disclosure prohibitions and assumes no liability for unauthorized use of these data by third parties. This notice shall be affixed to any reproductions of these data, in whole or in part.
Date for public release: June 18, 2004.

INFORMATION CONTAINED HEREIN IS PROPRIETARY FOR 4 YEARS IN ACCORDANCE WITH FAR 52.227–20.

Prepared under Contract NAS3–99077

National Aeronautics and
Space Administration

Glenn Research Center

February 2005

Document Change History

This printing, numbered as NASA/CR—2001–210765/REV1, February 2005, replaces the previous version, NASA/CR—2001–210765, April 2001.

This document was published in April 2001 with an SBIR restriction. It was changed in October 2004 to Unclassified/Unlimited per DAA modified October 29, 2004.

Page 27: Appendix B has been added.

Report Document Page, block 11: Project Manager, Eric Pencil, Power and On-Board Propulsion Technology Division, NASA Glenn Research Center, organization code RPP, 216–977–7463, has been added as the contact person.

Trade names or manufacturers' names are used in this report for identification only. This usage does not constitute an official endorsement, either expressed or implied, by the National Aeronautics and Space Administration.

Available from

NASA Center for Aerospace Information
7121 Standard Drive
Hanover, MD 21076

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22100

Available electronically at http://gltrs.grc.nasa.gov

FOREWORD

This report summarizes the technical progress and details of the effort performed by Mainstream Engineering Corporation, 200 Yellow Place, Rockledge, FL 32955, on the Phase II SBIR Contract NAS3-99077, "Low-Pressure Long-Term Xenon Storage for Electric Propulsion," during the period, December 18, 1998 through June 18, 2000. The report constitutes the final quarterly report and the final report.

TABLE OF CONTENTS

Foreword iii

I. Project Summary 1

II. Project Objectives 2

III. Work Carried Out 2

IV. Research Findings or Results 3

V. Technical Details 14

VI. Technical Merit and Feasibility Assessment 16

VII. Potential Applications 17

Referenced Figures 18

Appendix A 23

Appendix B 27

Appendix C 57

Appendix D 65

References 94

LOW-PRESSURE LONG-TERM XENON STORAGE FOR ELECTRIC PROPULSION

Dwight D. Back, Charlie Ramos, and John A. Meyer
Mainstream Engineering Corporation
Rockledge, Florida 32955

I. PROJECT SUMMARY

The objectives of the Phase II research effort were to develop and test a Xenon (Xe) storage system comprised of an activated carbon (AC) storage bed. The ultimate purpose of this system is to provide an alternative means for Xe storage and delivery for ion propulsion thrusters which is less expensive, is lighter-weight, provides lower storage pressures, requires fewer mechanical parts, and provides potentially cleaner Xe than compressed gas (CG) storage.

The initial research carried out in this effort was an engineering and experimental analysis of Xe storage capacities on AC and a comparison of these capacities to existing CG storage. This effort then focussed on designing, developing and testing a demonstration breadboard system which utilizes AC to store and regulate Xe flow.

We conclude from this research that the primary storage of Xe on AC storage provides limited advantages with regard to weight relative to CG. There are some scenarios in which this AC storage can reduce the weight of the flow management system, but the most promising design would be to use the AC storage in combination with a compressed gas or two-phase storage system. The storage of Xe on activated carbon does, however, provide volumetric reductions and can potentially reduce space-borne pressures in a XIPS system.

Perhaps the best use of AC storage of Xe in XIPS is as a *temporary* storage media which decouples the primary CG storage vessel from the thruster and allows for multiple, independent thruster operations at various flow rates. The decoupled regulator also isolates the thruster from the compressed gas storage tank. It is also possible that the activated carbon with or without a catalysts such as Ni on silica could further purify the Xe *in situ* prior to thruster flow. This activated carbon storage and flow regulator (ACSFR) also seems to have advantages with regard to weight relative to currently used regulators. The system also only uses electrical resistance heating for flow control and no mechanical or moving parts other than the usual solenoid or latch valves used in the XIPS system.

We performed over 12,000 minutes of flow tests with ACSFR systems, with flow rates ranging between 2 and 45 sccm and controlled pressures ranging between about 25 and 300 psia. For these various Xe flow scenarios, the net average power consumption was 5 W, the average flow rate variance was ±1.2%, and the average pressure variance was ±0.48%. The variances could be reduced by changing the PID control settings for pressure and optimizing the bed size for a specific Xe application and flow rate.

II. PROJECT OBJECTIVES

The objectives of the Phase II research effort was to develop and test a Xenon (Xe) storage system comprised of an activated carbon (AC) storage bed. The ultimate purpose of this project was explore and demonstrate alternative means for Xe storage and delivery for ion propulsion thrusters which is less expensive, is lighter-weight, provides lower storage pressures, requires fewer mechanical parts, is lower cost, and provides potentially cleaner Xe than compressed gas (CG) storage.

Initially this project focussed on AC as a primary storage media for Xe. Engineering estimates and laboratory capacity studies led us to conclude that primary activated carbon storage has some advantages over CG storage, but the weight for the system is not appreciably improved if at all. There are, however, other potential advantages of primary AC storage. These are lower storage pressures in space, smaller volumes, and *in situ* Xe gas clean up prior to use in the thruster. Owing to the limited advantages of primary AC storage with regard to weight savings, we explored a related innovative use of activated carbon storage --- as a *secondary* storage device which also serves as the flow regulator. This system was coined an "Activated Carbon Storage and Flow Regulator", or ACSFR. Current flow regulation occurs by dual "bang-bang" valves, pneumatic valves or other electrically activated valves. These regulators are generally expensive and mechanical.

The objective of this project was then to demonstrated and test the ACSFR device under several flow scenarios. Flows from about 2 sccm up to 45 sccm were evaluated with the device for durations and cycles of 15 minutes to 7 hours.

III. WORK CARRIED OUT

The work carried out in this Phase II SBIR can be summarized by the following bullets:

(A.) <u>Activated carbon characterization:</u> Several activated carbons were selected and characterized for this adsorption capacity with Xe. A range of surface areas, physical form, and silver impregnated carbons were considered. The SorboNorit 3 carbon was eventually selected for the ACSFR demonstration system due to its pelletized form and Xe capacity. The ultimate capacity of a carbon is not as critical in a secondary Xe storage device as it is in a primary Xe storage device.

(B.) <u>Compare AC Xe storage properties to compressed gas:</u> We evaluated the use of activated carbon for the primary storage of Xe and compared this to compressed gas storage. There are limited advantages to using activated carbon as the primary storage media. In particular, the gravimetric density and hence the overall system weight of an activated carbon system offers little if any advantage over compressed gas systems, but activated carbon can provide more compact volumetric storage. There may also be scenarios involving two-phase or long-term and large quantity storage for which AC would be beneficial. Activated carbon can also reduce storage pressures in space which may reduce explosion risks. Activated carbon and other solid media such as Ni on silica can also clean the Xe *in situ* prior to use in the thruster.

(C.) Develop dialog with industry regarding XIPS systems: Mainstream contact companies which manufacture satellites using Xe ion propulsion. Hughes offered the most input with regard to system requirements and potential improvements to existing XIPS technologies.

(D.) Design and fabricate a demonstration system: A demonstration system was designed and fabricated for testing. This system was comprised of an activated carbon storage and flow regulator (ACSFR) which served as a secondary Xe storage device and a flow regulator. The system also included a composite tank compressed gas storage vessel, solenoid valves, a sintered metal flow restrictor, and a mass flow meter. This use of activated carbon storage provides steady, reliable flow control without any mechanical parts, and the device is inexpensive relative to current regulators which can exceed $90,000 each.

(E.) Perform breadboard tests: The ACSFR system was tested under various protocols. These protocols were compiled from conversations with Hughes and NASA-Glenn to represent current ion propulsion systems. The breadboard demonstration system was fully automated and data-logged using LabView.

Each of the above items are discussed in more detail in the following section.

IV. RESEARCH FINDINGS OR RESULTS

This project researched an alternative to compressed gas Xe storage and flow regulation for ion propulsion. The conclusions reached from this research effort are summarized below:

- Activated carbon used for primary Xe storage does not offer any appreciable weight savings over compressed gas.
- Activated carbon used for primary Xe storage can reduce the volume of a Xe storage system.
- Activated carbon storage could provide slight benefits with regard to weight if used in partial fill with compressed gas.
- Activated carbon could be used in a CG combination system to suppress two-phase flow to a thruster.
- An activated carbon bed containing Xe and a heater can control Xe flow rates to within about 1.2% of a setpoint over a broad range of pressures (25-300 psia) and flow rates (2-45 sccm). The variance can be reduced by optimizing the PID control setting for pressure.
- Power requirements are strongly affected by the bed size. Average power requirements for a properly designed ACSFR would be about 0.5-18 watts, depending on the design flow rate.
- An ACSFR system comprised of an activated carbon bed can reduce mechanical complexity cost, and weight compared to current Xe flow regulators. These systems also isolate the thruster from the compressed gas storage vessel, can potentially clean the Xe further in situ prior to thruster use, and can provide a simple means to supply multiple, independent thrusters at variable flow rates.

- The flow from the ACSFR can be throttled by applying heat to the activated carbon bed and/or by heating the flow restrictor.
- Pressure feedback control of a heater is an effective means to regulate Xe flow from a carbon bed through a flow restrictor.

The specific areas of work listed in the previous section are now discussed in more detail with results.

Activated Carbon Characterization

Five activated carbons were characterized by adsorption isotherm measurements. These carbons were Norit SUPRA A, SorboNorit 3, Hygene Mark I, Norit 2030, and DARCO KB. The isotherms for these materials are shown in Appendix A. Polynomial curvefits are also shown. The variable γ^* is the total or net gravimetric storage density of Xe on in the activated carbon storage vessel: this includes interstitial and adsorbed Xe and has the units of weight Xe per weight carbon. For comparison, a figure is also show in the Appendix A which compares Ar, Kr, and Xe storage on SUPRA A carbon: In general, the capacity of the carbon increases with molecular weight (and boiling point) in the noble gas group. Note also the shape of the Xe-AC adsorption curve. This type of curve is generally referred to as a Type IV or V, which is indicative of adsorption with a finite multilayer formation corresponding to complete filling of the capillaries in the activated carbon material.

We chose to use the SorboNorit 3 activated carbon for the ACSFR system due to its pelletized form and capacity. The SUPRA A carbon had the highest capacity overall and could potentially be compacted to higher apparent densities. This material was not used in the ACSFR system since capacity was not as critical for this type of system and the SUPRA A powder was difficult to handle and could potentially cause problems in a thruster system if not properly filtered.

Figure 1 is a composite of *isostere* (constant γ^* or mass) curves for SorboNorit 3 compiled from a series of adsorption isotherm measurements. Since the charging pressure (P_{CG}), bed temperature (T_{bed}), and loading (γ^*) are related uniquely for each carbon, these isosteres can be used to design the ACSFR system. In particular, given 1) a prescribed loading γ^* (i.e., the quantity of Xe needed for one or more thruster cycles) for the storage and flow control unit and 2) the pressure of the CG storage tank P_{CG} (which decreases with life), there is one corresponding temperature, $T_{bed}=f(\gamma^*, P_{CG})$. For a satellite, this relationship could be imbedded in a control element.

Compare AC Xe Storage Properties to Compressed Gas

Early in this project we undertook a detailed engineering estimate of the weights and volumes for activated carbon systems relative to compressed gas storage. Mr. James Sovey of NASA Glenn provided us with some critical weight data for current systems so that a proper comparing of the systems could be made. This comparison was made under the assumption that the activated carbon would be used for the primary storage of Xe. Figure 2 summarizes our calculations using measured AC capacities for SUPRA A which presented us the best case scenario for activated carbon. As shown, the total system weight W* is compared as a function of pressure. This total weight is computed using best estimates for existing hardware for a compressed gas storage system, and then varying weights for hardware in a AC storage system.

To put the comparison on a common denominator, we assumed the storage vessel was aluminum with a pressure vessel design using 2.5 for a safety factor. In summary, the AC storage of Xe produces total system weights which exceed those for CG with 4 kg additional hardware (i.e., 1 filter, 2 latch valves, 1 solenoid valve, 2 pressure transducers, 1 plenum, 1 service valve, 4 temperature transducers, 3 flow restrictors, and misc. plumbing hardware) for pressures exceeding around 1000 psia. The AC storage scenario which would produce lighter weight systems would be a reduction of about 3 kg in additional hardware and/or partial fills of activated carbon. That is, the primary storage vessel would be filled partially with activated carbon.

A reduction in hardware is possible since the AC bed would be the flow regulator which can weigh 1-2 kg. Lower pressure storage of Xe (less than about 100 psia) also makes AC storage more advantageous. Using a lighter composite vessel in the design calculations would not appreciably alter the relative positions of the curves or these conclusions. Actual values of W* for the NSTAR and other NASA systems range about 1.25 to 1.40 based on currently available data. The commercial systems for Hughes typically have W* values of around 1.22-1.25 (telephone conversation, 2/25/99) which includes 1 regulator, 2 latch valves, 1 pressure sensor, and pyro valves.

The penalties in weight for an AC system might be acceptable if a reduction in space-borne pressures is critically important, or if a volume reduction outweighs or balances the increases in weight. Figure 3 compares the net density of the AC stored Xe (SUPRA A) to CG. The ultimate balance between weight penalties and these other positive factors must be evaluated on a case by case system and mission.

We return briefly to the concept of partial fills of activated carbon since this led in part to our final design. The benefits of a partial AC fill with a CG vessel are two-fold: First, activated carbon will lower the pressure of the vessel as the temperature drops relative to CG alone, and second, the activated carbon could be used in a block or cartridge form at the mouth of the CG vessel outlet to "filter" and adsorb any liquid Xe condensed at the cooler space storage temperatures. The later benefit could become more important for higher pressure and density storage of Xe for longer missions.

The limited benefits of AC as a primary Xe storage vehicle led us to consider other uses and advantages of activated carbon in Xe flow control system. Activated carbon storage is attractive since heat or electrical power can be used to generate a pressure which in turn can control a flow rate across a flow restriction. This process involves no mechanical devices. After speaking with Hughes regarding the high cost (approx. $90,000) of current pneumatic regulators used on their XIPS satellites, and then developing the concept of a partial fill Xe storage vessel, a design a design evolved which used AC storage in conjunction with a CG storage vessel. This concept could also potentially reduce the cost of the Xe flow regulator by one or two orders of magnitude and provide other benefits. We coined this the Activated Carbon Storage and Flow Regulation (ACSFR) system.

Develop Dialog with Industry Regarding XIPS Systems

We contacted Loral and Hughes to develop an understanding of their needs and requirements in a XIPS flow and regulation system. The most useful input was gained from Hughes (Mr. Jerry Hermel and Dr. Ray Kushida, 2/25/99). Per Hughes, potential areas of improvement would be:

i. cost,
ii. hardware simplicity,
iii. Xe purity, and
iv. heat rejection.

Specific system requirements for Hughes XIPS satellites (Dr. Ray Kushida, 6/8/99) are:

(1a.) HS 601 HP XIPS system: 18 mN thrust (T) and 2568 seconds ISP at 5 hours per day. This equates to F_m=0.72 mg/s or 7.4 sccm Xe for 5 hours per day or about 13 grams Xe per day (F_m=T/ISP/g).
(1b.) 165 mN thrust and 3800 seconds ISP for 30 minutes per day. This equates to 4.4 mg/s Xe or 45 sccm for 30 minutes, or about 8 grams Xe per day.

NASA's requirements for NSTAR and related systems (Mr. James Sovey, 4/18/00) are:

(2a.) flow range of 6-24 sccm for plenum and 2 sccm Xe for the cathodes,
(2b.) flow rate tolerance of ± 3% but could tolerate ± 5% on plenum,
(2c.) throttling over the plenum range is also important.

We also contacted Space Systems/Loral and received little feedback about their requirements. An article was also published in the *BMDO Update* [Back, Summer 1999], and we received several requests for additional information. We have also spoken briefly with JPL regarding our BMDO article and activated carbon storage concepts.

Design and Fabricate a Prototype Demonstration System

To demonstrate the ACSFR concept, we designed and fabricated a breadboard Prototype system. A photograph and schematic of the system is shown in Figures 4a and 4b. There are components in the system of Figure 4b which would not be necessary in an actual system. Many of these components were included in the breadboard prototype to provide additional design and performance data. For example, only one pressure transducer would be needed, and only 2 latch valves would be needed. The pressure transducer located between the CG vessel and solenoid 1 is not needed, and the solenoid 3 is not needed.

For the prototype system a spherical Al-lined ***composite tank*** (Lincoln Composites) having a volume of 67 in^3 (1100 cm^3) was used for Xe compressed gas storage. This CG vessel weighs 486 grams. A smaller ***ACSFR vessel*** was fabricated from 304 stainless steel spherical vessel having a nominal internal diameter of 2.15" (volume of about 85 cm^3). A series of photographs of the ACSFR is shown in Figure 5. The weight of this SS sphere is about 90 grams. This sphere has a wall thickness of 0.045" which could be reduced, and the sphere could also be made of Al or Ti. Using pressure vessel design formulas, the weight of an Al sphere rated to 1200 psia with a safety factor of 2.5 would weigh 30 g. We originally went through several iterations fabricating this vessel from Al to reduce weight but were unable to qualify the vessel for the pressures needed in the application. We believe these difficulties were caused by thermal stresses induced from cooling the vessel after welding the two hemispherical pieces.

The 2" SS sphere is fitted with a thermal well, a port for a cartridge FireRod® heater, and inlet and outlet ports for Xe flow. The design uses an Al extended fin surface attached to the ***internal***

heater. The FireRod® heater is rated at 50 W/24 VDC which should be well oversized for this system. The Firerod® heater to be used in the 2" SS ACSFR sphere weighs 36 grams (includes NPT fitting and leads). The additional extended surface area fin (1/16" Al) attached to the Firerod® heater weighs 16 grams. The fins could be reduced in weight by using thinner Al. The ***K-type thermocouple*** used in the ACSFR sphere weighs 15 g.

The ***solenoid valves*** used in the test system are 120 VAC ASCO RedHat II valves (1500 psia), weighing 616 g each. We originally planned to use VACCO latch valves which weigh about 340 grams. However, due uncertainties in contract extensions at the time, the long lead time, and cost of these valves we decided to use a more readily available 120 VAC valve. The latch valves used on NSTAR weigh 0.23 kg/2 or about 115 grams, and the solenoid valves weigh 430 grams each. The control logic for the system will not be affected by using these surrogate solenoid valves, but the weights will obviously not be representative.

The ***pressure transducers*** which will be used are MSI Model MSP400. These weigh about 105 g each including leads.

A total of 4 ***flow restrictors*** were procured from Mott for flow testing. These restrictors are characterized by

- 300 psia to 35 psia; nominal 12 sccm air
- 150 psia to 35 psia; nominal 12 sccm air
- 65 psia to 35 psia; nominal 12 sccm air
- 45 psia to 35 psia; nominal 12 sccm air

The weight of these restrictors including the M-M Cajon VCR fitting is 39 grams each with actual sintered metal restrictor weighing less than 1 gram of this total (i.e., most of the weight is the fitting).

Filters (0.5 μm and 10 μm) were also present in the system. Each weighs 0.75 g and we used a total of 3, or 2.25 grams.

We also added ***insulation*** to the 2" ACSFR sphere. The sphere was wrapped with 1/8" ceramic wrap having an Al oxide base which in turn was wrapped with a 3 mil thickness high temperature fiberglass tape reinforced with Al. This wrap had a weight of about 70 g. We also added a 4"x4"x4" fiberglass block machined out for sphere for most of the breadboard tests, but this would not be necessary for an actual system, nor was the weight, and size of the insulation optimized. The weight of the 4"x4"x4" fiberglass block was about 273 grams.

A 24 VDC power supply, simulating power available on a satellite, was used to excite and power the 24 VDC devices. Other amplifiers, power supplies, and I/O modules were needed to provide power to the 120 VAC solenoids and flow meter and to communicate with the computer. The weights for these devices are only to simulate and support the primary components and hence are not important in overall weight comparisons.

LabView was used to develop the PID control strategy for the system, and to monitor the system power, pressures, temperatures, and flow rates. The program and GUI written for this project is given in Appendix B. In a production system, this controller would be replaced by a microprocessor or PLC. A PID controller which could be used on the Prototype system is a

Watlow Model 93BB-1DA1. This controller has additional readouts and packaging which would not be necessary for a production unit. The actual board in the unit weighs about 105 grams.

The plan was to test a system comprising about 1-2 kg Xe. For example, the 1100 cm^3 composite vessel loaded to 1000 psia at 25 C (Z=0.327) would provide about 1.2 kg Xe for testing. Since our compressed gas supplier could only supply Xe gas at 550, 650 and 850 psia, and composite cylinders were only available off-the-shelf in specific sizes, the maximum quantity of Xe contained in the CG vessel was about 0.63 kg during testing.

TABLE 1 – Component Weights

Component	*Weight (grams)*
(1) Composite vessel for CG, 1100 cm^3	486
(1) Pressure transducer	105
(1) Thermocouple	15
(1) ACSFR System: 85 cm^3 SS spherical vessel@90g, heater including fins@52g, activated carbon@27g, flow restrictor@39g, insulation@70g	278
(3) Sintered metal filter gasket	2
(1) tubing and fittings, wires (assumes NSTAR weights-estimate)	640
(1) service valve (assumes NSTAR weight)	120
(2) latch valves (assumes NSTAR weights)	230
TOTAL	1,876

Table 1 summarizes the component weights listed above. In the NSTAR system, a dual solenoid "bang-bang" regulator is used. One Moog model weighs about 200 grams. The NSTAR system also includes 2 additional pressure transducers (230 g each), 3 additional temperature transducers (10 g each), and 1 plenum (1,500 g), which totals about 1990 grams. To make a comparison of an equivalent NSTAR-like system to that of Table 1, eliminate the 278 grams for the ACSFR System and add in 200 grams for a "bang-bang" regulator and another 1,990 grams for the additional hardware. The total weight would be about 3,788 grams, or twice as heavy as the ACSFR regulated system. The ACSFR system also eliminates the mechanical "bang-bang" regulators. Note also that if an Al ACSFR vessel were used, an additional 60 grams would be cut from the ACSFR System.

A pneumatic pressure regulator built by Moog (and assumed to be similar to that used by Hughes) weighs about 450 grams and a series redundant model would weigh 900 grams. This weight can be compared to the 278 grams for the ACSFR system. Assuming a system similar to that of Table 1 and a single pneumatic regulator, the total weight would be about 2,053 grams, slightly more than the ACSFR regulated system. The cost of the ACSFR system has also been estimated to be one to two orders of magnitude lower than the $90,000 pneumatic regulators.

Perform Breadboard Tests

A series of flow tests were performed on the breadboard Prototype system. A total of more than 12,000 minutes of flow tests were made with this final breadboard system over flow rates ranging from about 2 sccm to 45 sccm. We also undertook a series of preliminary tests for several hundred minutes using Ar, Kr, and Xe.

Protocol guidelines were first established to cover the various requirements and flow protocols of NASA and Hughes. These were compiled from bullets (1a.), (1b.), and (2a.)-(2c.) earlier in this sections. They are:

Protocol "A" 7.4 sccm for 5 hours (Hughes HS 601 HP)

Protocol "B" 45 sccm for 30 minutes (Hughes HS 702)

Protocol "C" 2 sccm (approx.) for long duration (NASA, simulated cathode flows)

Protocol "D" 6-24 sccm for varying duration's and throttling (NASA, plenum flows)

Protocol "E" Repeated ACSFR fill and flow cycling, various flow rates

The ACSFR functions in the following procedure: (1) The propulsion system signals the Xe flow control system to prepare; (2) The heater in the ACSFR system activates and pre-heats the carbon bed. Typical pre-heat times are 15 min to 1 hour (depends on PID controller settings); (3) At the end of pre-heat, the downstream latch valve opens and the Xe flows from the ACSFR to the thruster. Electrical power is supplied to the heater in the ACSFR to control the pressure upstream of a flow restrictor which in turn controls the flow rate; (4) After completion of a thruster duty cycle, the downstream latch valve is closed, and the regulator is incrementally heated to temperature T_{fill} (Note that the regulator will have already been heated from the previous thruster cycle so only incremental heat is needed at this point); (5) The upstream latch valve is opened between the tank and ACSFR regulator and the Xe charge is established in the regulator prescribed by the pressure-capacity relationship of the carbon at T_{fill}; (6) The upstream latch valve is then closed, and the regulator cools until the next thruster duty cycle begins.

A table summarizing the results of the final breadboard Prototype tests using Xe is given in Appendix C. This table shows the average flow rates and %variation (1 standard deviation) for the pressure and flow rate. The duration of the flow is given as well as the average power usage, temperature range for the carbon bed during the flow cycle, the temperature range of the Xe flow exiting the ACSFR, and the controller settings (PB=proportional band, I=integral time constant, D=derivative time constant). The "test protocol" column refers to the objective of the particular experiment as listed above. Graphs of flow rate and bed pressure or temperature with time for each of these experiments is given in Appendix D.

Referring to the graphs in Appendix D, a spike in flow rate is observed at the start of each flow cycle. Note the absence of any corresponding pressure spike which would have to be present to drive any large spike in true flow. We determined that this effect was a result of solenoid magnet interference and other electrical noise on the Aalborg flow meter. We contacted Aalborg and were unable to resolve the problem. This spike is not attributable to any flow disturbance in the system since the magnitude of the spike would require pressures several times larger than those present anywhere in the system and we were also able to reproduce the spike at will by opening and closing valves or power cycling the flow meter. Experiment ***test1a-6-13-00*** illustrates the false spikes which can be generated in the Aalborg flow meter—these spikes were intentionally induced to illustrate the magnitude and nature of the false flow reading. The spikes were filtered out of the averaging process for flow rates reported in the table of Appendix C.

The earlier experiments with the breadboard system also experienced some electrical noise and interference, some related to our external power processing boards. We later resolved this

problem and also replaced computer memory which was also causing some control problems with the LabView program.

We will now walk through most of the experiments shown in the table of Appendix C and the graphs of Appendix D. In these plots, the Xe flow rate is always shown, and the carbon bed temperature or pressure is then shown on the other Y-axis.

Test2a-3-30-00 is an experiment showing how the ACSFR can be used to throttle different flow rates separated by 30-45 minutes all from a single Xe change on the ACSFR (i.e., no refill from the CG tank in between flows). As mentioned above, the spike on the first curve is "false" due to electrical/magnetic interference between the flow meter and solenoid valves. The PID controller settings are not optimal as can be seen by the slow ramp up an overshoot near the start of the individual flow cycles. We were also experiencing electrical noise in the I/O modules which was later corrected.

Test1a-4-03-00 is an experiment similar to the previous. The flow ranged from about 35 sccm to 5 sccm from a single charge on the ACSFR bed. The temperature of the bed varied from about 80 C to 130 C during the last 2 hour flow cycle.

Test1a-4-05-00 is an experiment illustrating a full cycling of the ACSFR bed with complete "flow and refill" cycles. The flow rate varied within ±1% for four 30 minute cycles where the bed temperature ranged from about 50 to 140 C each time. The power requirement for these cycles was about 14 watts. The PID control parameters were varied throughout the run and were not optimized.

Experiment ***test1a-4-06-00*** was a long duration flow test of 300 minutes and 7.41 sccm Xe. The flow varied by 1.1% over this 5 hour period. The carbon bed was heated from 39 to 174 C during the 5 hours, and the average power consumption was 5.3 watts. We were still experiencing some anomalous pressure spikes which resulted in flow perturbations: these were later resolved to be related to the controller settings and connections in the I/O module.

Test1a-4-10-00 shows another series of complete fill and flow cycles at about 35 sccm. At the end of the third cycle the setpoint was lowered to throttle down the flow.

Experiment ***test1a-4-11-00*** is another example of complete fill and flow cycling with the Xe flow varying in magnitude and duration. There are still some notable fluctuations in pressure die to the controller settings which were being varied. These resulted in some flow rate perturbations.

Test1a-4-13-00 shows another series of complete fill and flow cycles at about 35 sccm. The temperature ranged from about 30 C to 200 C during the Xe flow cycles. The power usage was about 18 watts during the 40 minute cycle which is directly related to the low γ^* and high temperatures that the bed was driven to (i.e., the enthalpy of desorption increases with γ^* so more energy is required to maintain the flow rate as the bed depletes so the bed gets hotter and then there are more heat losses). Note also that the temperature of the gas flowing through the flow meter only varied by a few degrees (see the Table in Appendix C) even though the bed temperature approached 200 C. This suggests that the slow flow, expansion through the restrictor, and flow through the tubing was enough to cool the gas stream back to around ambient.

Test1a-4-14-00 is an experiment with 3 separate fill and flow cycles, each with a 60 minute flow period. This might simulate 3 days in a thruster cycle using 32.5 sccm Xe for 1 hour each day. For this experiment, the 60 minute cycle required about 11 watts. Different PID settings were used for the pressure control. The differences in the flow and pressure oscillations can be noted in the graph.

Experiment ***test1a-4-17-00*** is another full cycling fill and flow example. PID control is being varied between the two 60 minute flow cycles, and the power usage was about 10-11 watts.

Test1a-4-18-00 is a throttling example with flow rates ranging from 20 sccm to 7 sccm. The PID controller is not optimized but this plot gives a general idea as to the time scales involved with switching from one flow rate to another without closing off the latch valve to the thruster.

An example of a throttling down from 7 sccm to about 2 sccm followed by a long 2.2 sccm flow is shown by experiment ***test1a-4-19-00***. The PID control parameters were being changed throughout the experiment which caused oscillations in pressure and flow.

Test1a-4-20-00 is a long duration low flow rate experiment with an expanded Y-axis from 0-3 sccm. Aside from the initial overshoot and oscillation caused by the PID controller settings used in the experiment the flow is very steady at 2.22 sccm ±1.62% for 7 hours. The power usage is minimal at these low flow rates, averaging about 2.1 watts with a range of 0.9 to 3.3 watts. Note that the power usage dos increase with time because the bed is getting hotter (see Appendix C and the power usage for each hour segment of the run).

Test1a-4-25-00 is just another example of repeated flow cycles using different PID control parameters. The initial overshoot in the pressure curve is during the preheat cycle which settles before the downstream valve opens and allows flow.

Experiment ***test1a-4-26-00*** is another series of repeated flow cycles at 12.5 sccm. The flow variance for these runs were about 1.5%, and the average flow rates for each 30 minute series varied by only 0.15%. Since all of these 30 minute flow cycles were from a single ACSFR loading, the temperature increased during the run and so did the power consumption (due to the depleting bed and smaller γ^*). For the first and last 30 minute flow, 2.2 and 3.8 watts, respectively, were required.

Test1a-4-27-00 is yet another series of repeated flow cycles at 12.5 sccm. The PID control parameters were being varied during this run which caused some of the oscillations.

In ***test1a-5-01-00***, the flow throttled down from about 25 sccm (100 psia setpoint) to 13 sccm (60 psia setpoint) in 17 minutes, and then throttled back up from 13 sccm to a stabilized 20 sccm in about 10 minutes.

Test1a-5-02-00 is an example of throttling flow rates with the pressure being dropped while the downstream latch valve is closed. That is, the varying flow rates are separated by now flow at which time the bed is cooling and the pressure dropping toward the next lower pressure setpoint. During the last segment of this experiment, the pressure setpoint was increased in increments of 5 psia every 5 minutes—at each step there is some overshoot and the net throttling change is not smooth. We conclude that throttling would be best accomplished by optimizing the controller settings and increment the setpoint in a single step.

Test1a-5-03-00 shows a series of fill and flow cycles. The CG tank was at a pressure of about 425 psia during the fills, and the carbon bed was heated to 125 C. The PID control setting were again varied somewhat during this run. The first two flow cycles had an activated carbon bed pressure set point of 140 psia, and the last flow cycle had a setpoint of 150 psia.

The experiment of ***test1a-5-04-00*** shows yet another series of fill and flow cycles. The CG tank was at a pressure of about 400 psia during the fills, and the carbon bed was heated to 125 C. The PID control settings were constant during these 45 minute flows at 32 sccm. The temperature varied between about 40 and 120 C during each flow period.

Test1a-5-05-00 and ***test1a-5-08-00*** are good example of pressure setpoint variation between fills from a CG tank at 300-350 psia. Xe flow rates are varied between 12 and 32 sccm with a variance of 1-2% separated by 1-2 hours with the downstream latch valve closed. Again, note the "false" spike in flow for the first flow cycle of test1a-5-05-00. This spike is not always caught by the data-logger since the logging increment was every 10 seconds.

In ***test1a-5-10-00*** at the end of the run the flow rate was throttled from 25 sccm to 10 sccm in about 7 minutes. The beginning of this throttling run is obscured by the false spike.

Test1a-5-15-00 is a long duration, low-flow experiment. The flow rate was 2.0 sccm ±2.1%, and the average power usage was 1.4 watts for 6 hours. There was a false flow spike at the start of the experiment. The activate carbon bed temperature varied from 28 to 57 C during this 6 hour run.

The remaining tests were performed at the Cohen-Coon PID controller settings for pressure. ***Test1a-5-18-00*** is a series of flows from a single ACSFR loading. The false spike is present on each curve with no corresponding pressure spike.

Experiment ***test1a-5-19-00*** is a 5 hour and a 1.5 hour flow cycle at a nominal flow rate of 7.4 sccm. These two flow periods were separated by a fill from a CG vessel at 220 psia. The variance in flow is improved using the Cohen-Coon PID settings for both pressure (±0.08%) and flow (±0.6%). The temperature ranged from about 30 to 105 C for the 5 hour test, and 75 to 105 C for the 1.5 hour test.

Test1a-5-22-00, ***test1a-5-23-00***, and ***test1a-5-24-00*** are very good examples of the tight pressure and flow control with the Cohen-Coon PID settings. The flow was controlled to within about 0.5% for a period of 5 hours and a temperature range of 40-150 C. The ACSFR was filled from a CG vessel at 400-450 psia for these experiments.

Test1a-5-25-00 is a series of repeated flow cycles from a single ACSFR loading at about 450 psia. Again, the pressure and subsequent flow control were very tight for this experiment, even though the temperature of the bed varied from 45 c to about 130 C during the 5 cycles.

Experiment ***test1a-5-25-00*** shows two major flow cycles, for 2 hours at about 5 sccm, and another for about 90 minutes at 3 sccm. The false electrical spike is very obvious in this graph.

Test1a-5-30-00 and ***test1a-5-31-00*** show repeated 30 minute flow segments from a single ACSFR loading, each separated by 15 minutes of "OFF" flow. The flow rates were typically 2.4 sccm ±1.2%. The flow was throttled from 2.4 sccm (110 psia) to 25 sccm (500 psia) in about

11 minutes at the end of the test1a-5-30-00 run. Power usage was generally 0.5-2 watts during these cycles.

Numerous 2.4 sccm flow segments are depicted in ***test1a-6-01-00***. The flow and pressure properties for this experiment were very similar to the previous.

Test1a-6-02-00 is a series of 4.5 sccm flow segments from a single ACSFR loading. Very tight flow variances, typically less than 1%, were measured for the 15 and 30 minute segments. The temperature varied from about 38-100 C during the run, and the power consumption also increased from about 1.6 watts to 5.5 watts between the first and last flow segment.

Test1a-6-05-00 is a series of 7.4 sccm flow segments from a single ACSFR loading. Very tight flow variances, typically less than 0.5%, were measured for the 15 minute segments. The temperature varied from about 50-120 C during the run, and the power consumption also increased from about 2.4 watts to 6.9 watts between the first and last flow segment.

Test1a-6-06-00 is a series of 10.5 sccm flow segments from a single ACSFR loading. Very tight flow variances, typically less than 0.7%, were measured for the twelve 15 minute segments.

Experiment ***test1a-6-09-00*** is a series of three flow segments using a CG vessel fill at about 400 psia. The first two segments are 10.5 sccm, and the last is at 13.7 sccm. Flow variances again were less than 1% and the power usage was 2-4.4 watts.

Test1a-6-15-00 is a high flow rate example. At this flow rate, the bed depletes very quickly and the temperature rise is rather rapid. This is due to the size of the carbon bed relative to the loading and required flow rate. Optimally, a larger bed would be used for this flow rate since the power usage would be much reduced (i.e., it is a function of temperature, and with a larger bed the temperature would not rise as quickly as in this example). The flow rates were about 43.7 sccm ± 0.7% for 13-15 minutes.

Test1a-6-16-00 is a final example of a high flow rate. The first flow segment of this experiment was run to bed completion to illustrate what happened to an undersized bed. For the first 12 minutes of this run the flow was fairly steady at 44.9 sccm ±0.64%. The bed temperature ramped from 27 to 129 c during this period and then continued to heat to 200 C. The oscillation of temperature at the end of this first segment was due to a temperature limit we placed on the system. During the segment flow segment after a 600 psia refill from a CG vessel, the flow rate was 44.8 sccm ±0.64% for 10 minutes.

The power requirements for the pre-heat cycle are always less than that for the flow cycle roughly by the heat of desorption of the activated carbon. In general, the power requirement during pre-heat ranged between about 25 and 75% of the power requirement for the flow cycle. The power for pre-heat is highest when the bed us the hottest and when the flow rates are small since in these cases the heat losses by convection are much larger than the heat input needed for Xe description from the activate carbon.

In summary, these breadboard tests demonstrated the versatility and accuracy of Xe flow control which can be achieved using an ACSFR system. The ACSFR device for a specific XIPS system would be optimized by carbon weight, heater size, restrictor, and PID control settings for the pressure range of interest.

V. TECHNICAL DETAILS

The flow rates for these test-out runs were generally controlled within 1.2% and the pressures were controlled to within about 0.48%. Some of this variation is due to the rise in temperature of the bed during the run, and some is due simply to the controller settings which were varied through the runs. The temperature inversely affects the flow rate which can be seen mathematically by an equation describing flow through porous media:

$$\dot{V}_s = \frac{1}{2}\frac{\alpha\mu}{\gamma}\frac{ART_s}{P_s M}\left[\sqrt{1+\frac{2M\gamma\left(p_1^2-p_2^2\right)}{RTL\alpha^2\mu^2}}-1\right] \tag{1}$$

Where V_s is the standard-condition volumetric flow rate (e.g., sccm), μ is the viscosity, A is the flow cross sectional area, T_s and P_s are the standard T and P (constants), M is the molecular weight of the gas, R is the ideal gas constant, p_1 and p_2 are the upstream and downstream pressures, and α and γ are constants for a the porous media. As T increases, the second term in the square root radical decreases and in the limit approaches 1 so that the entire bracketed term decreases and approaches 0. So, as the temperature of the bed and thus the flowing gas increases during the flow cycle and the pressure is being controlled, the flow rate can decrease. We corrected the flow for temperature in the LabView program and found that the variation of the exiting gas stream was generally very small (See the table in Appendix C).

We found that the PID pressure control settings had a significant effect on the pressure and flow variations and also the required pre-heat time. These settings can of course be optimized for a specific system. With the breadboard system we found the best control with Cohen-Coon (C-C) settings—these were used in all of the later experiments after 5/18/00. These recommended settings can be found in any Process Control text book and are determined by performing step changes in heater power and measuring the pressure or temperature change. The C-C settings for controller heater power to the carbon bed during flow were PB=16.4, I=3.5, and D=0.53. We also used 3 different controller settings: 1 set for flow control, 1 set for static pre-heat control, and another set for temperature control when filling the bed from the CG tank.

The temperature of the ACSFR bed during fill from the CG would be controlled using an equation generated from adsorption measurements. This temperature as mentioned earlier is a function of the desired bed loading of Xe and the pressure of the CG tank which varied during its mission as Xe is depleted. We can illustrate one such equation for the SorboNorit 3 activated carbon. Using a multivariate linear curve fit with 11 variables and 97 data points the following equation was found to represent the data well.

$$T_{fill} = a_0 + \frac{a_{20}}{\gamma *} + \frac{a_{23}}{(\gamma *)^2} + \frac{a_{26}}{(\gamma *)^3} + P\left(a_{13} + \frac{a_{21}}{\gamma *} + \frac{a_{24}}{(\gamma *)^2} + \frac{a_{27}}{(\gamma *)^3}\right) + P^2\left(a_{15} + \frac{a_{22}}{\gamma *} + \frac{a_{25}}{(\gamma *)^2} + \frac{a_{28}}{(\gamma *)^3}\right) \tag{2}$$

where

a_0= -8.087	a_{13}= 0.6696	a_{15}= -0.000265
a_{20}= 670.3	a_{21}= -2.589	a_{22}= 0.000845
a_{23}= -632.3	a_{24}= 3.614	a_{25}= 0.000127
a_{26}= 199.6	a_{27}= -1.043	a_{28}= -0.00105

The R^2 is 0.99498, the standard deviation is 5.134 K, and F statistic for the model is 1531.4, which illustrates that excellent models of $T_{fill}=f(P,\gamma^*)$ can be developed from activated carbon adsorption data.

The manner in which this equation or something similar would be used is as follows: (1) The CG tank pressure P is read by pressure transducer; (2) the capacity γ^* corresponding to a particular Xe loading is inputted or kept constant for a mission in which case the equation 1 above is just a function of P, and (3) the required temperature T_{fill} is determined. The carbon bed is then heated to this temperature with the latch valve connecting the CG tank and ACSFR bed opened.

To evaluate the concept of adding a catalyst or other Xe purifying adsorbent to the activated carbon bed we performed a series of gas chromatograph (GC) tests. Our results with Ni on silica were inconclusive, mainly because the resolution of our instrumentation was too large for the purity of interest. The purity of our supplied Xe is quoted as 99.995%. A much high quality GC coupled with mass spectrometry would be needed for the high purities of Xe used in propulsion systems.

The Aalborg flow meter used to measure the flow rates of Xe in this research required a temperature correction. This was implemented in the LabView program, and the equation given to us by Aalborg was:

$$F_m(\text{actual}) = F_m\,[1 - (T_{gas} - 20)*0.0015] \tag{3}$$

Where F_m is the flow rate, and T_{gas} is the gas temperature in C for gas flowing through the flow meter. As the temperature increases, the flow rate of the gas is corrected downward.

Were unable to get 45 sccm for 30 minutes per protocol B. We do however have data for 10-15 minute cycles. We could not achieve 30 minute segments because of the combination of flow restrictors, ACSFR bed size, and heater. A larger bed would have allowed for a larger loading and hence a longer flow time of 30 minutes. A different flow restrictor with this same ACSFR would have allowed for a higher activated carbon loading and flow pressure. A larger heater (i.e., > 50 W) would have kept the bed at proper temperature corresponding to the desired pressure setpoint up to about 200 C. This points out some of the critical design parameters for the ACSFR. For this particular high flow rate case, the optimal design would be a larger bed whereby the temperature of the bed would remain lower throughout the flow cycle, and the γ^* of the bed is rapidly decreasing. From the Phase I effort, we were able to show that the enthalpy of desorption approximately decreases with γ^* by:

$$\Delta H_{des} = a(T) - b(T)\ln(\gamma^*) \tag{4}$$

where a(T) and b(T) are greater than 0. Since the power requirement to the heater can be represented by:

$$P = F_m \Delta H_{des} + Q_{loss} \quad (5)$$

Where F_m is the Xe mass flow rate, and Q_{loss} are heat losses from the ACSFR (e.g., radiation, convection). As γ^* decreases, ΔH_{des} increases and the power requirement increases. The increased heat requirement increases the bed temperature rapidly and then there are more resulting heat losses. For γ^* to remain higher during the flow cycle, thereby keeping ΔH_{des} smaller, the bed must be sized larger so that any depletion of the bed, flow time* F_m, does not ever reach the total mass loading of the bed. For this particular case, of a high flow rate ACSFR, we would probably resize the bed by doubling its volume (and mass of carbon)—the 2" sphere would become a 2.5" sphere with about 55 grams of carbon.

VI. TECHNICAL MERIT AND FEASIBILITY ASSESSMENT

We have demonstrated an alternative Xe storage and regulation system using activated carbon as a secondary storage media. The following bullets summarize the measured performance of the system:

- Flow rate variance at an approx. 2.4 sccm setpoint typically ranged between about ±1 and ±1.5% for periods ranging from 15 minutes to 7 hours. The PID controller settings have a moderate influence on these variances.
- It is important to optimize PID controller settings for pressure.
- Flow rate variances for an approx. 7.4 sccm setpoint for 5 hrs. were between about ±0.5 and ±1% depending on the PID controller settings.
- Flow variances for the highest flow rates of 32-45 sccm were generally less than about ±1%, but these again were a function of the PID controller settings.
- The flow rates of Xe were very repeatable to within about ±0.4% in multiple cycling at 2 to 45 sccm.
- Throttling between flow rates (e.g., 2.5-25 sccm) can be very rapid and on the order of minutes using a 50 watt (max.) heater.
- Power requirements range from about 0.6 to 50 W for flow rates of 2 to 45 sccm, respectively. A properly sized ACSFR should require about 0.5-18 watts of power. This power is only needed during the flow cycle and the pre-heat cycle before flow. The power requirements for a given flow can be reduced by increasing the size of the bed.

Other features of this type of storage and regulator system are:

- The weight of the ACSFR System is less than the flow regulation systems used on government and commercial systems.
- Potentially can further purify carbon *in situ* since adsorbents can remove impurities from the Xe vapor introduced by system contaminants or present as gas contaminants. Other adsorbents such as Ni on silica or silica [Zanevskii and Peshekhonov, 1990] can also be added in small amounts to the AC bed for this purpose.
- The quantity of Xe supplied to the thruster is metered and isolated from prime source during thruster operation – this can allow for the operation of 2 or more multiple thrusters at virtually any combination of Xe flow rates regardless of the prime source pressure or state (2-phase or compressed gas). (See Figure 6.)
- The AC Storage Flow Regulator provides a disconnect between the prime Xe source and thruster. Since it operates at temperatures above the Xe critical T there should never be any 2-phase Xe complications (i.e., the primary storage tank could be supercritical or 2-phase).
- AC could be used in conjunction with CG primary storage to prevent two-phase fluid from entering the thruster (See Figure 7.)
- The materials are vastly less expensive than current commercial pneumatic regulators (priced at about $90,000). We estimate the cost of the ACSFR to be about 2 orders of magnitude less.
- The operation of the AC Storage Flow Regulator is simple and non-mechanical.
- Zero power is needed by the AC Storage Flow Regulator when not in use, and only minimal power is required during Xe thruster duty cycles.
- The presence of the AC bed in the overall storage system provides for a backup Xe sink in case of high pressure/temperature excursions or pre-launch. Similarly, the presence of the AC may be designed to reduce overall system pressure during pre-launch.
- The system could be designed to use waste heat from PPU to heat the AC storage bed rather than an autonomous heater.

In summary, we believe this technology could provide reliable and versatile Xe flow control for XIPS at a lower cost, weight and complexity compared to current flow regulators. This device also offers fully independent operation amenable to multiple thruster and flow setpoint systems. The activated carbon may also prove to be a means to purify the Xe *in situ* prior to use in the thruster.

VII. POTENTIAL APPLICATIONS

The commercial and NASA application for this technology is Xe ion propulsion. This technology could be applied to earth-orbit satellites and also for longer term planetary or lunar missions whereby larger quantities of Xe are required.

Activated carbon storage could also be used with a primary compressed gas storage to eliminate complications related to two phase fluids. Activated carbon could also be used in combination with two-phase storage in long-term, large-quantity storage of Xe as a boil-off capture and reuse system.

Mainstream has a patent pending for the technology.

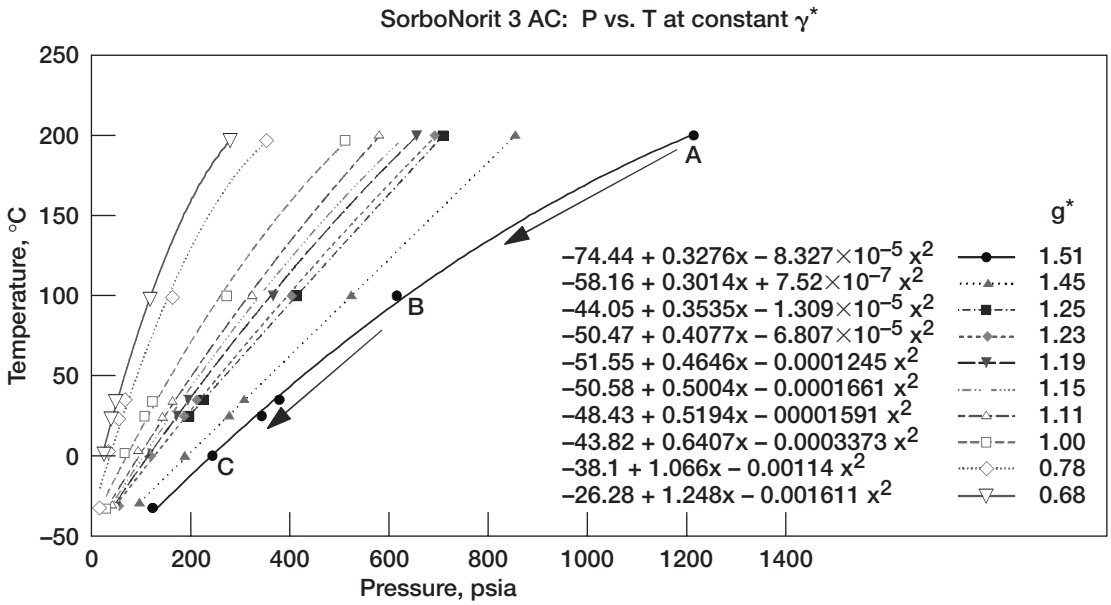


Figure 1.—Pressure-temperature relationship for SorboNorit 3 activated carbon for a range of constant γ^*.

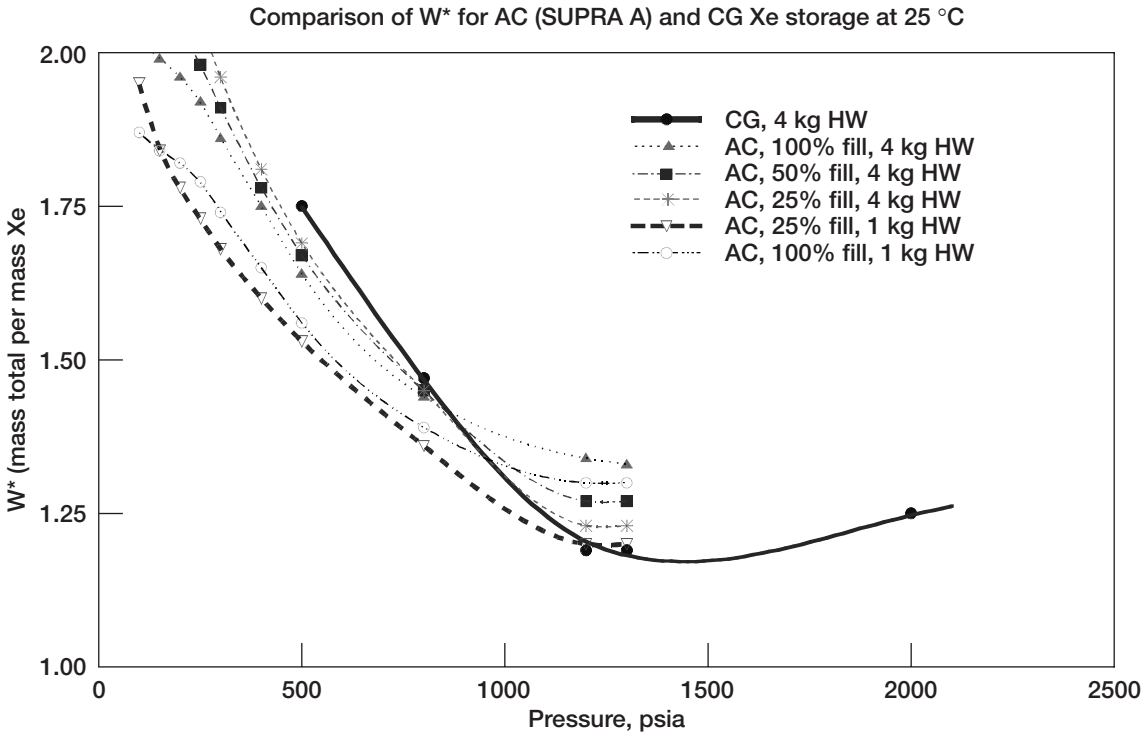


Figure 2.—Comparison of XIPS system weights for AC and CG.

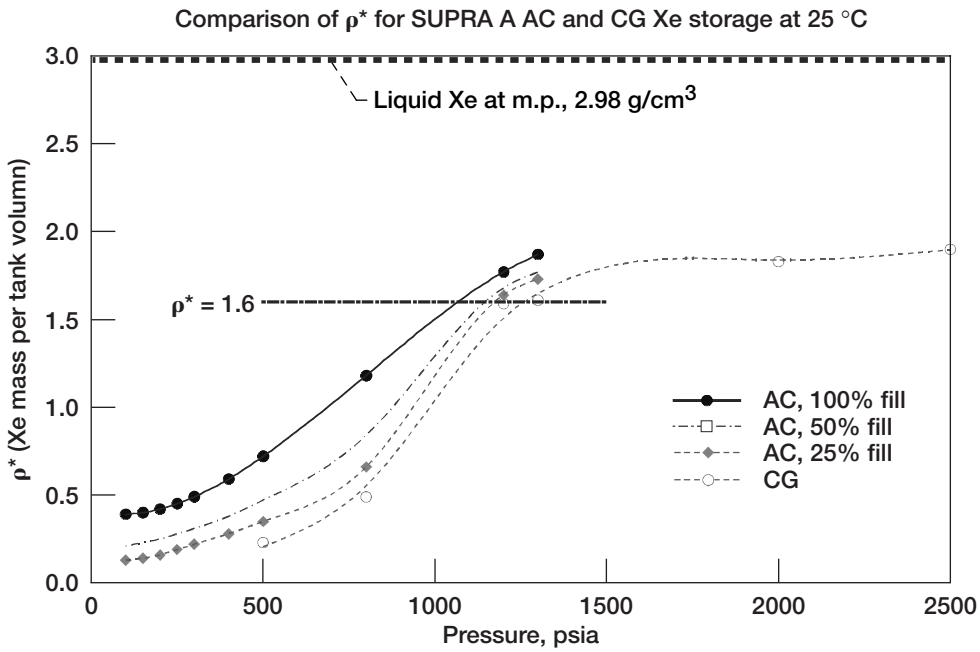
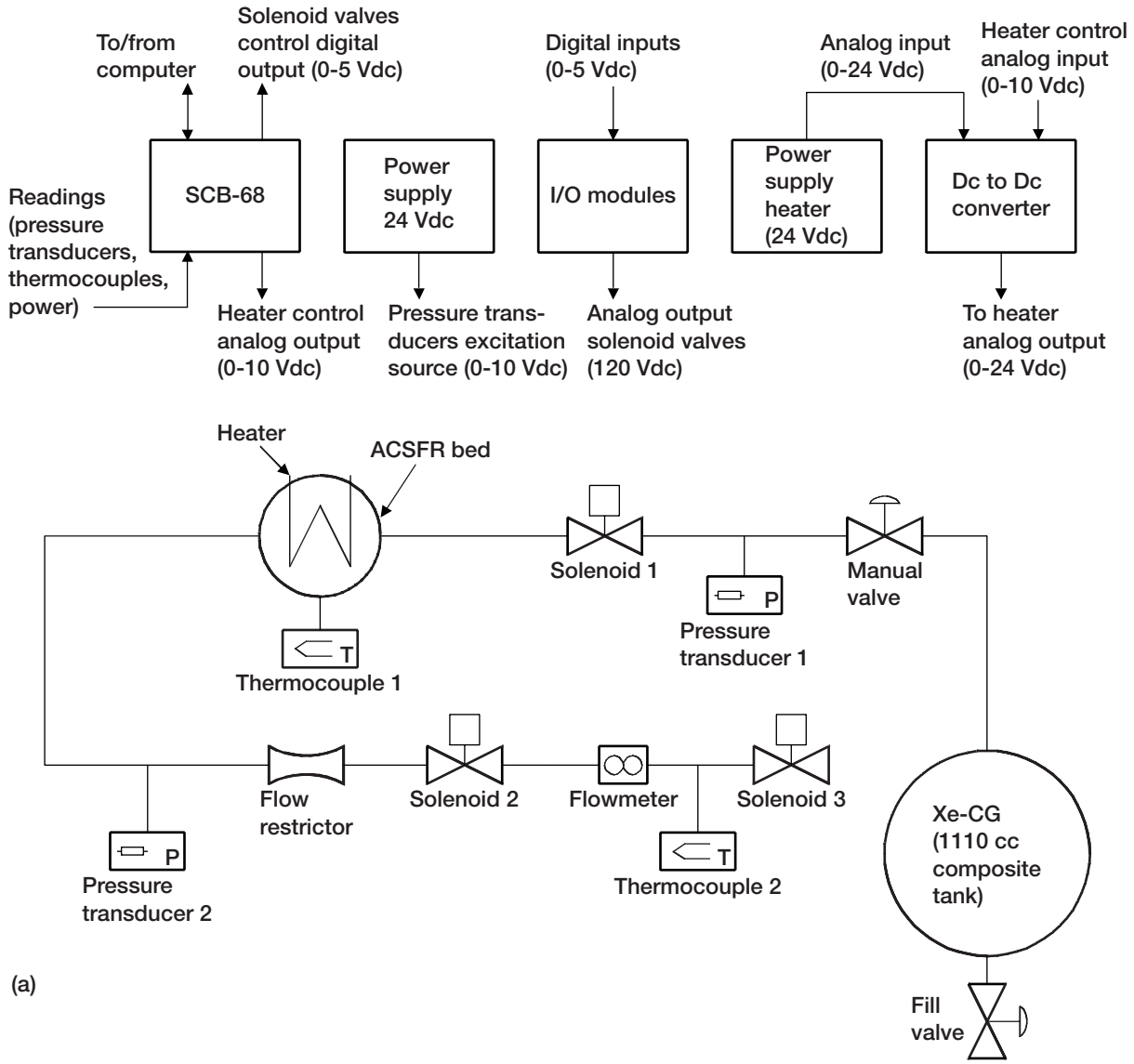


Figure 3.—Comparison of XIPS system densities for AC and CG.



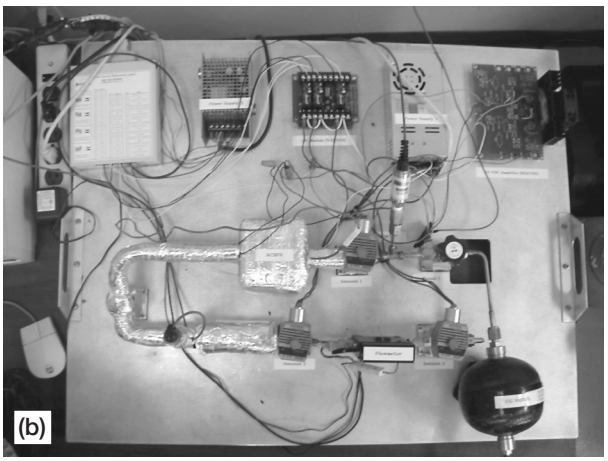


Figure 4a, b.—Breadboard system with schematic of components.

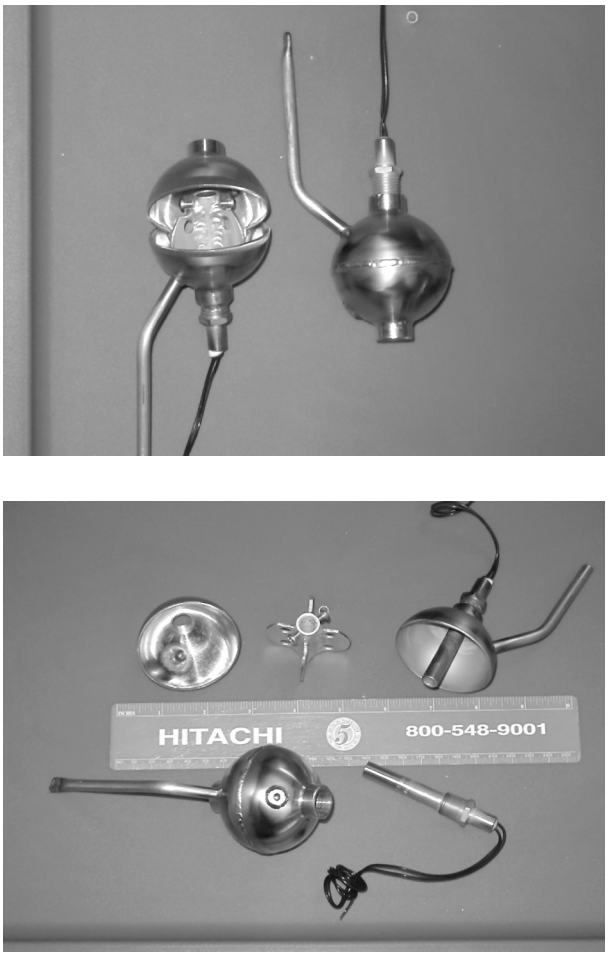


Figure 5.—Photographs of ACSFR prototype.
(For reference, ruler length is 10 inches).

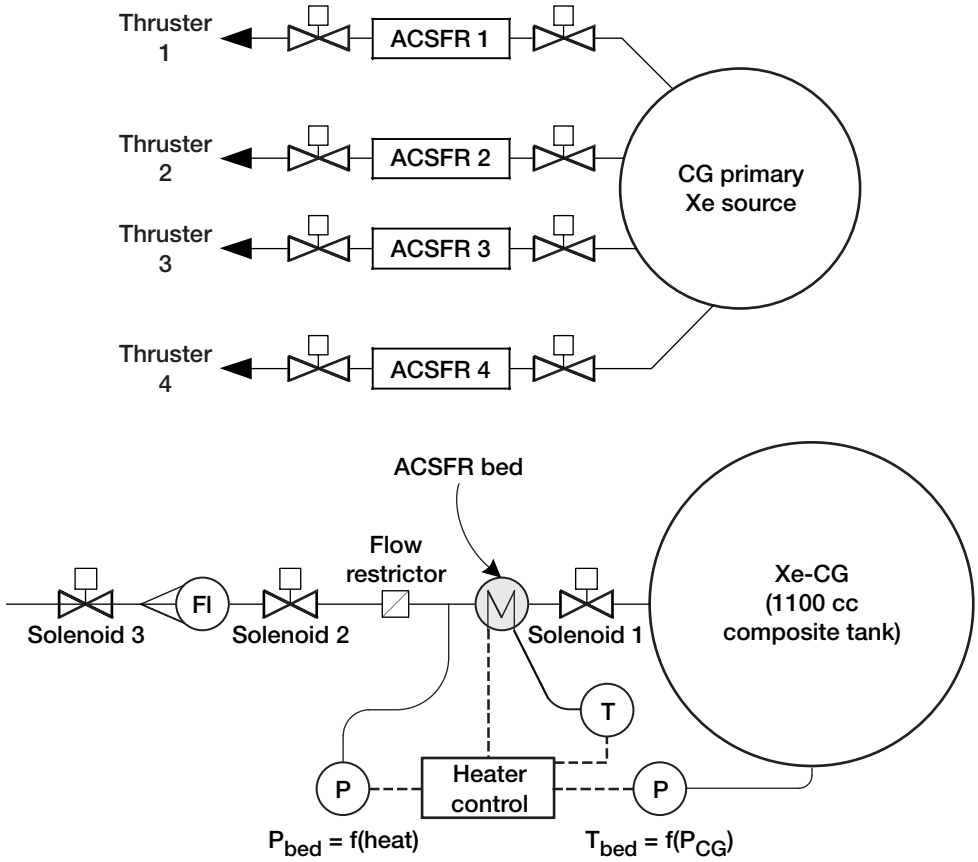


Figure 6.—Multiple ACSFR's providing feed to multiple thrusters independent of primary CG source and other thrusters.

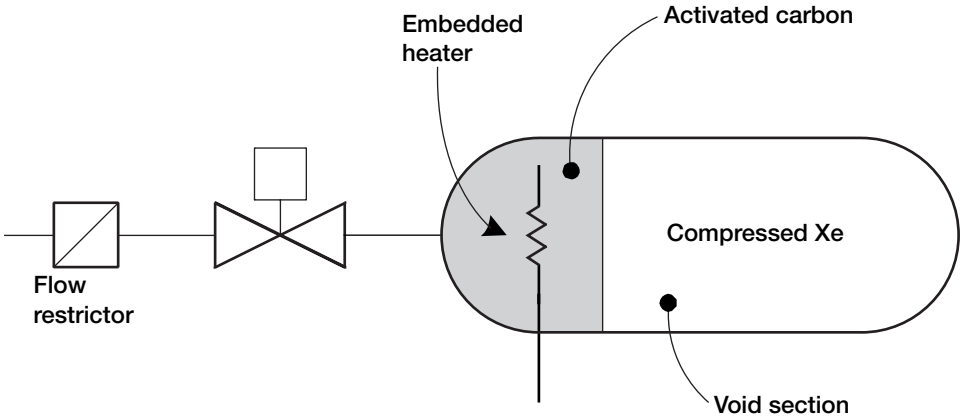


Figure 7.—The use of activated carbon to eliminate two-phase flow complications in compressed gas storage.

APPENDIX A

ADSORPTION ISOTHERMS FOR ACTIVATED CARBONS

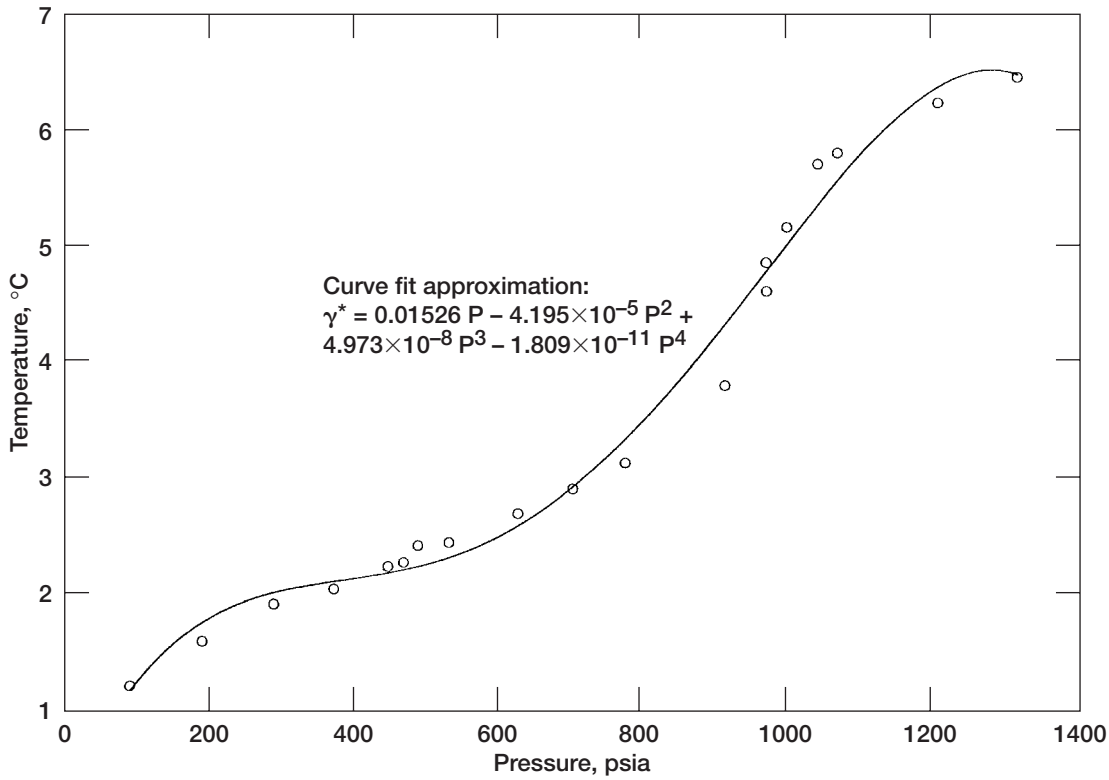


Figure A-1.—Norit supra A capacity γ^* with pressure.

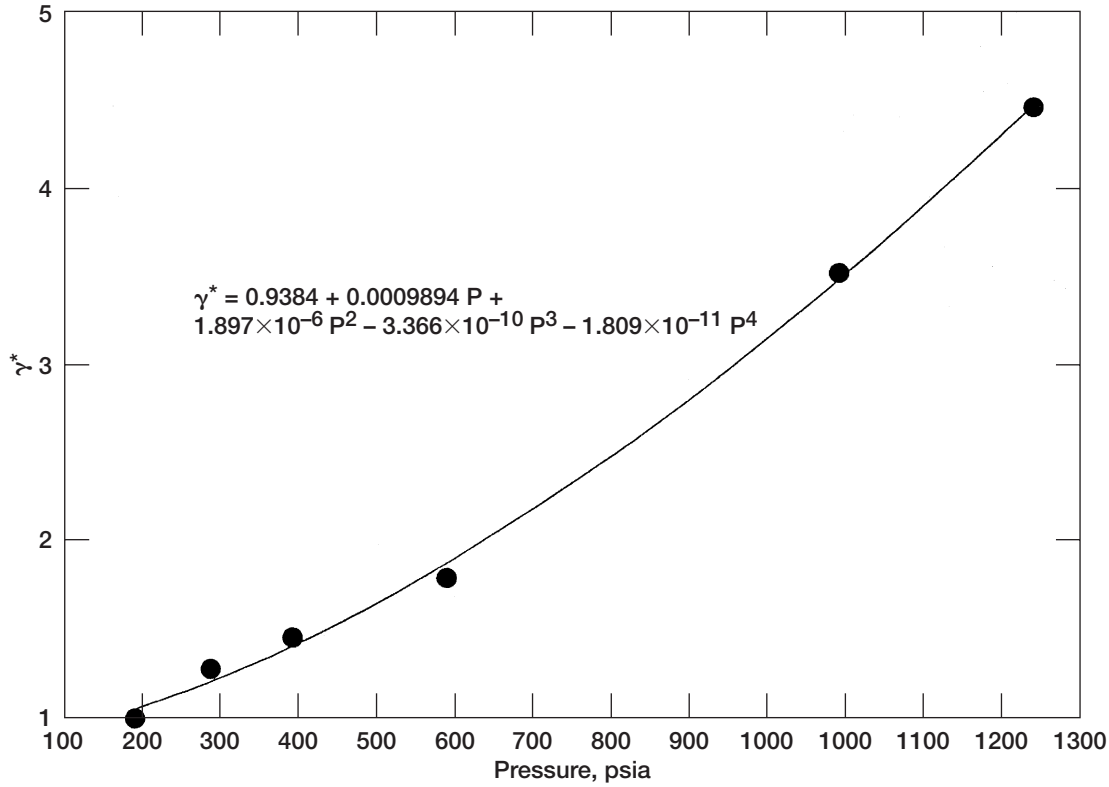


Figure A-2.—SorboNorit 3 capacity γ^* with pressure.

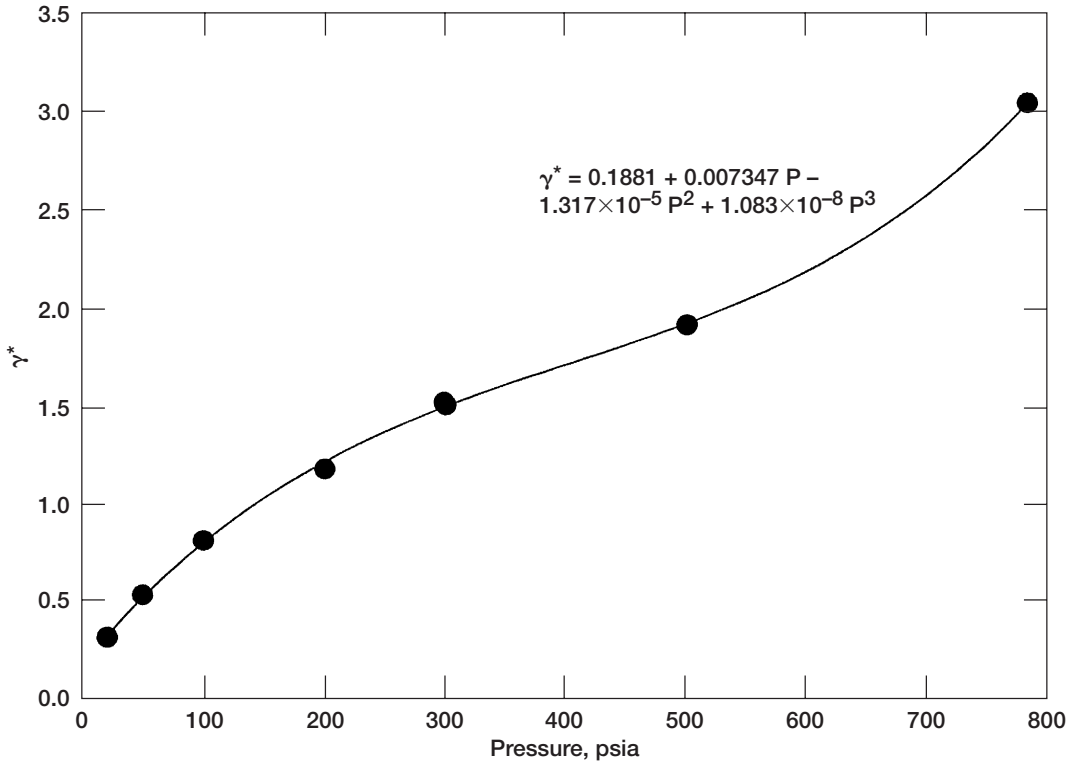


Figure A-3.—DARCO KB capacity γ^* with pressure.

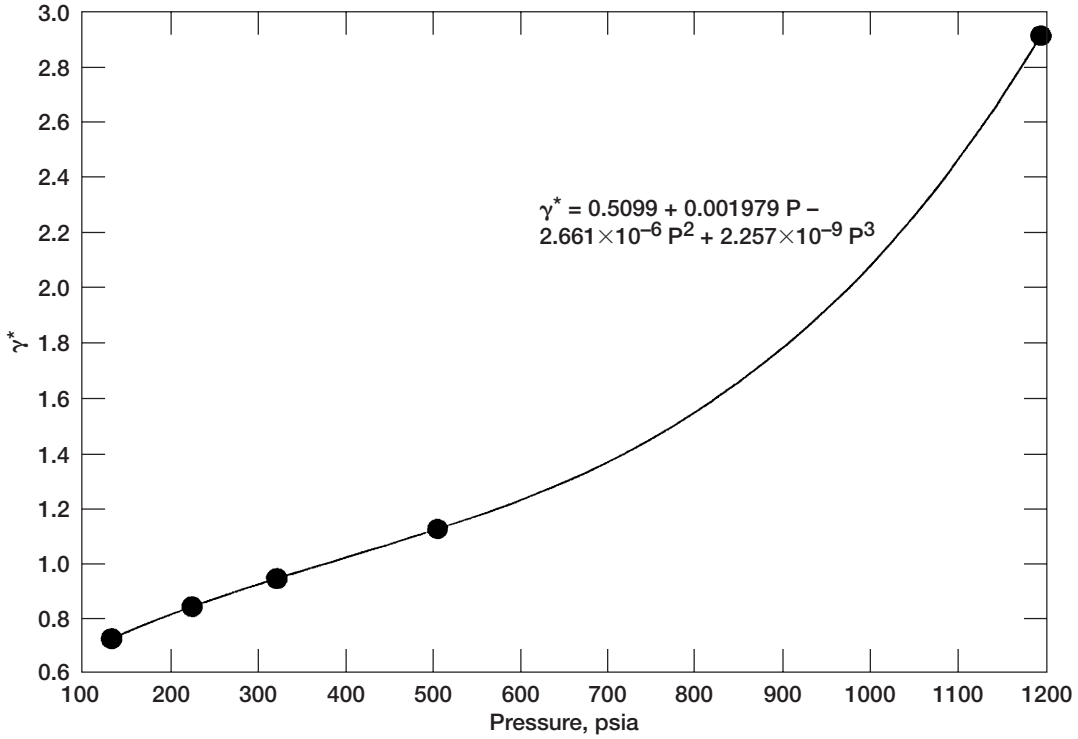


Figure A-4.—Hygene mark I capacity γ^* with pressure.

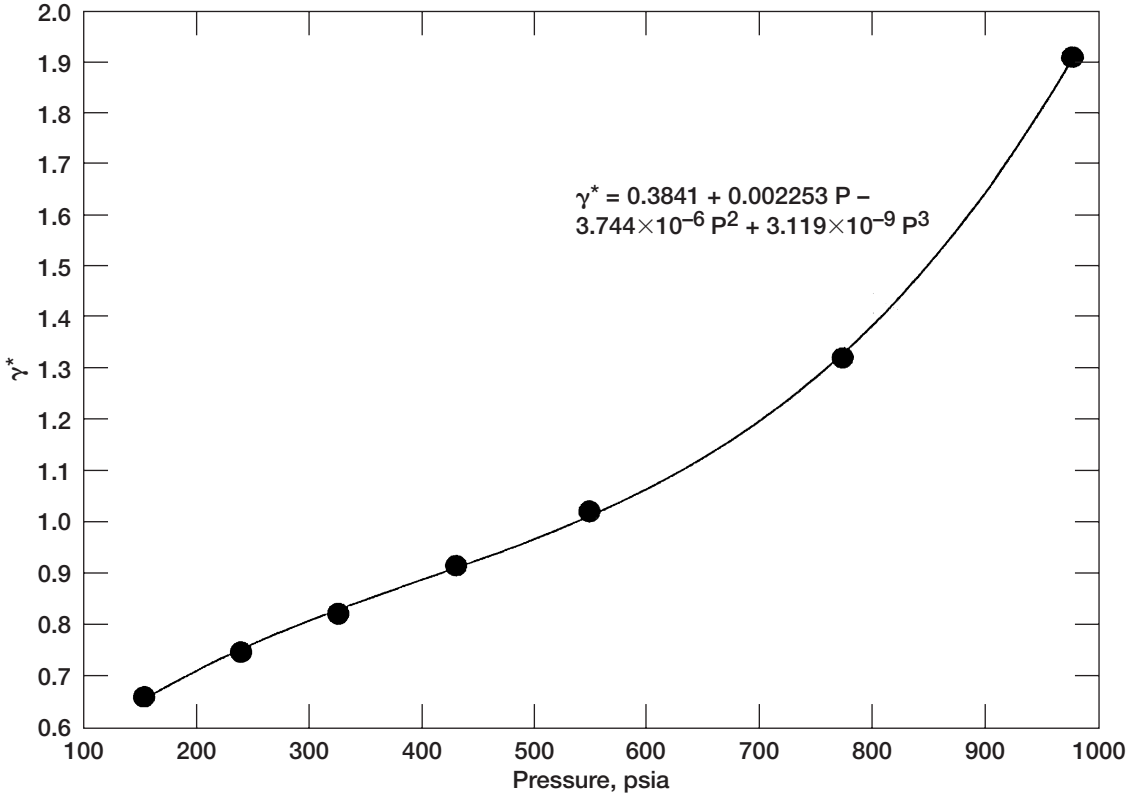


Figure A-5.—Norit 2030 capacity γ^* with pressure.

APPENDIX B

LABVIEW PROGRAM

Current PID

Tuning Parameters for Pressure FLOW

PB 2

I 2

D 2

Tuning Parameters for Pressure NG Flow

PB 1

I 1

D 1

Tuning Parameters for Temperature

PB

I

D

LOGGING

file path (for Power)

file path

Xenon Flowrate Vs. Time

C-Bed Fill Tset (C)

C-Bed NO HEAT time after fill (sec)

C-Bed Flow Pset (psia)

Max. C-bed T (C)

Pre-heat time (sec) before V2 opens

Flow ON duration (sec)

Flow OFF duration (sec)

Log increment (sec)

Cycles

Subcycles

Loop Delay (ms.)

Solenoid # 3

Xenon (sccm)

Solenoid # 2

Carbon Bed P (psia)

Carbon Bed T (C)

Heater

Power (watts)

Solenoid # 1

Composite Tank (psia)

Ambient T (C)

Carbon Bed Pressure Vs. Time

Carbon Bed Temp. Vs. Time

Composite Tank Pressure Vs. Time

Ambient T vs. Time

Time V1 open to equilibrate with tank

Old Power

Time to allow carbon bed to equilibrate before calculating Tset (sec.)

No PID V#2 closed

C-Bed Tset (C) calculated for Xe

output (EGU)

Capacity (Kg Xe/Kg carbon)

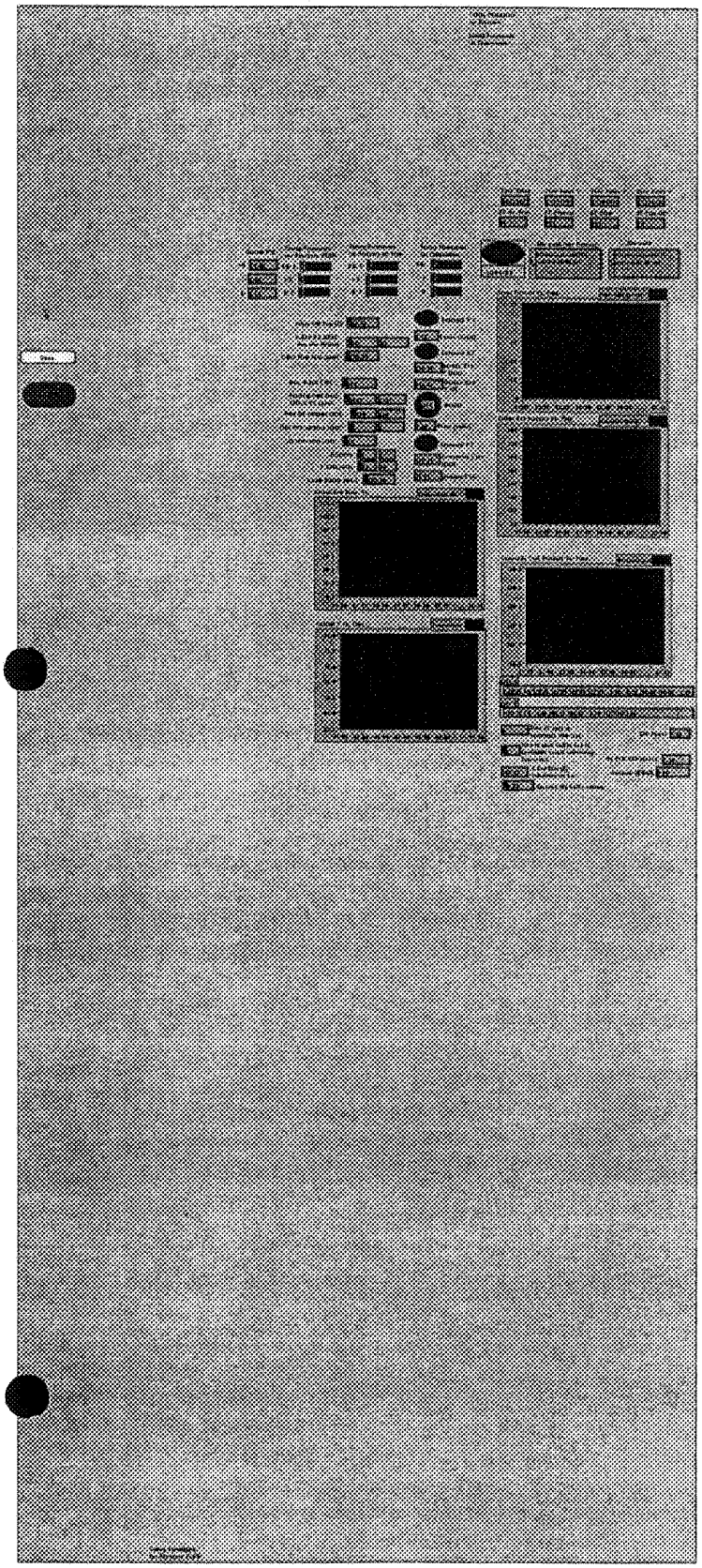
Xenon Breadboard Test 3.vi
A:\Xenon Breadboard Test 3.vi
Last modified on 6/13/2000 at 9:34 AM
Printed on 6/15/2000 at 11:19 AM

Connector Pane

Xenon Breadboard Test 3.vi

Xenon Breadboard Test 3.vi
A:\Xenon Breadboard Test 3.vi
Last modified on 6/13/2000 at 9:34 AM
Printed on 6/15/2000 at 11:19 AM

Fr[illegible]anel



Xenon Breadboard Test 3.vi
A:\Xenon Breadboard Test 3.vi
Last modified on 6/13/2000 at 9:34 AM
Printed on 6/15/2000 at 11:19 AM

Controls and Indicators

I32 # Cycles

TF LOGGING

DBL C-Bed Flow Pset (psia)

U32 Time to allow carbon bed to equilibrate before calculating Tset (sec.)

TF Done

TF STOP
(TF) STOP: Stop acquiring data and clear the board resources for this operation.

Tuning Parameters for Temperature

DBL PB
(DBL) P: The Proportional component. This is the amount by which the error gets multiplied. The error is the Set Point minus the Process Variable.

DBL I
(DBL) I: The Integral component. This is how much the PID will depend on what has happened in the past.

DBL D
(DBL) D: The derivative component. This is how much we want the PID to speculate what will happen in the future.

DBL Loop Delay (ms.)
[DBL] Loop Delay (ms): determines the loop timing for your PID system.

I32 Flow ON duration (sec)

Tuning Parameters for Pressure NO Flow

DBL PB 1
(DBL) P: The Proportional component. This is the amount by which the error gets multiplied. The error is the Set Point minus the Process Variable.

DBL I 1
(DBL) I: The Integral component. This is how much the PID will depend on what has happened in the past.

DBL D 1
(DBL) D: The derivative component. This is how much we want the PID to speculate what will happen in the future.

DBL Max. C-bed T (C)

I32 Log increment (sec)

I32 # Subcycles

I32 Flow OFF duration (sec)

DBL Capacity (Kg Xe/Kg carbon)

Xenon Breadboard Test 3.vi
A:\Xenon Breadboard Test 3.vi
Last modified on 6/13/2000 at 9:34 AM
Printed on 6/15/2000 at 11:19 AM

file path
file path is the path name of the file. If file path is empty (default value) or is Not A Path, the VI displays a File dialog box from which you can select a file. Error 43 occurs if the user cancels the dialog.

file path (for Power)
file path is the path name of the file. If file path is empty (default value) or is Not A Path, the VI displays a File dialog box from which you can select a file. Error 43 occurs if the user cancels the dialog.

I32 Pre-heat time (sec)
before V2 opens

DBL C-Bed Fill Tset (C)

I32 C-Bed NO HEAT
time after fill (sec)

Tuning Parameters
for Pressure FLOW

DBL PB 2
(DBL) P: The Proportional component. This is the amount by which the error gets multiplied. The error is the Set Point minus the Process Variable.

DBL I 2
(DBL) I: The Integral component. This is how much the PID will depend on what has happened in the past.

DBL D 2
(DBL) D: The derivative component. This is how much we want the PID to speculate what will happen in the future.

I32 Current Cycle

TF Solenoid # 1

TF Solenoid # 2

TF Heater

DBL Composite Tank
(psia)

DBL Carbon Bed
T (C)

DBL C-Bed Tset (C)
calculated for Xe

DBL Carbon Bed Temp. Vs. Time

DBL Carbon Bed Pressure Vs. Time

DBL Carbon Bed
P (psia)

DBL Xenon Flowrate Vs. Time

DBL Xenon (sccm)

DBL Power (watts)

abc data 1

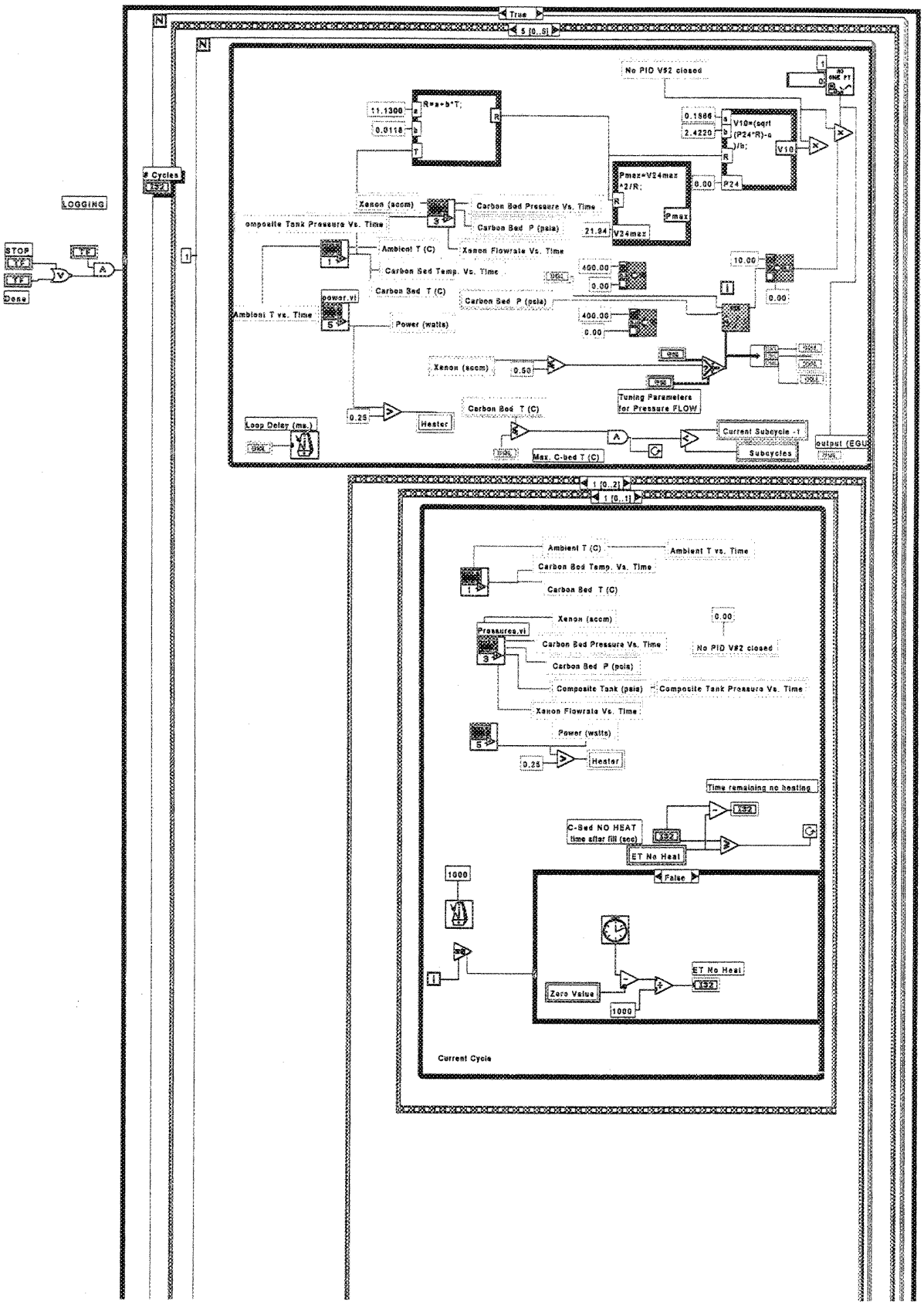
I32 Current Subcycle -1

Xenon Breadboard Test 3.vi
A:\Xenon Breadboard Test 3.vi
Last modified on 6/13/2000 at 9:34 AM
Printed on 6/15/2000 at 11:19 AM

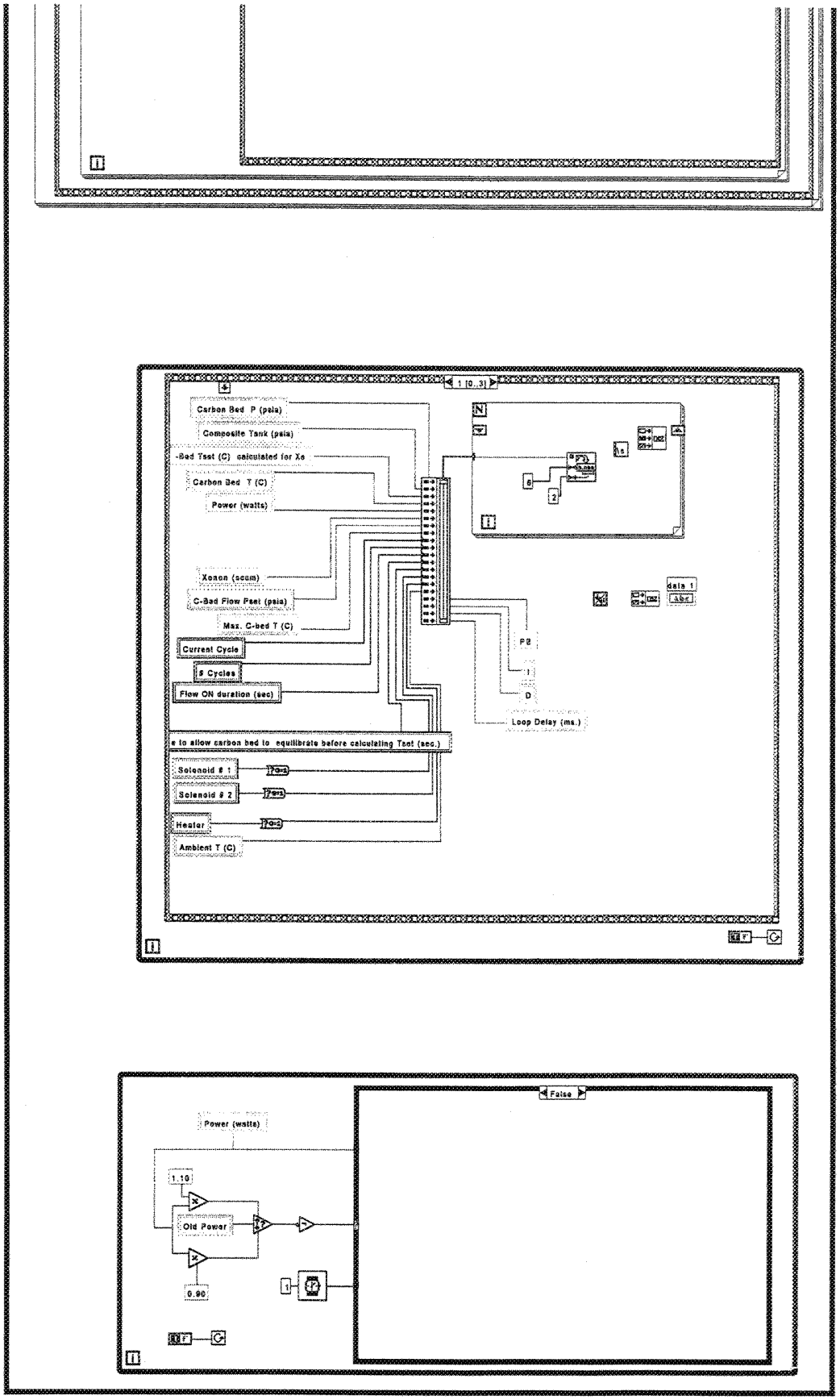
I32	Time V1 open to equilibrate with tank
I32	Xe flow time (sec)
I32	Xe no-flow time (sec)
DBL	Old Power
abc	data 2
I32	Time remaining before V2 opens
DBL	No PID V#2 closed
I32	Time remaining no heating
DBL	Ambient T (C)
DBL	output (EGU)
DBL	Composite Tank Pressure Vs. Time
DBL	Ambient T vs. Time
TF	Solenoid # 3
I32	ET No Heat
I32	Zero Value
I32	ET Preheat
I32	Zero Value 2
I32	ET Flow
I32	Zero Value 3
I32	ET Flow Off
I32	Zero Value 4
DBL	PB
DBL	I
DBL	D

Xenon Breadboard Test 3.vi
A:\Xenon Breadboard Test 3.vi
Last modified on 6/13/2000 at 9:34 AM
Printed on 6/15/2000 at 11:19 AM

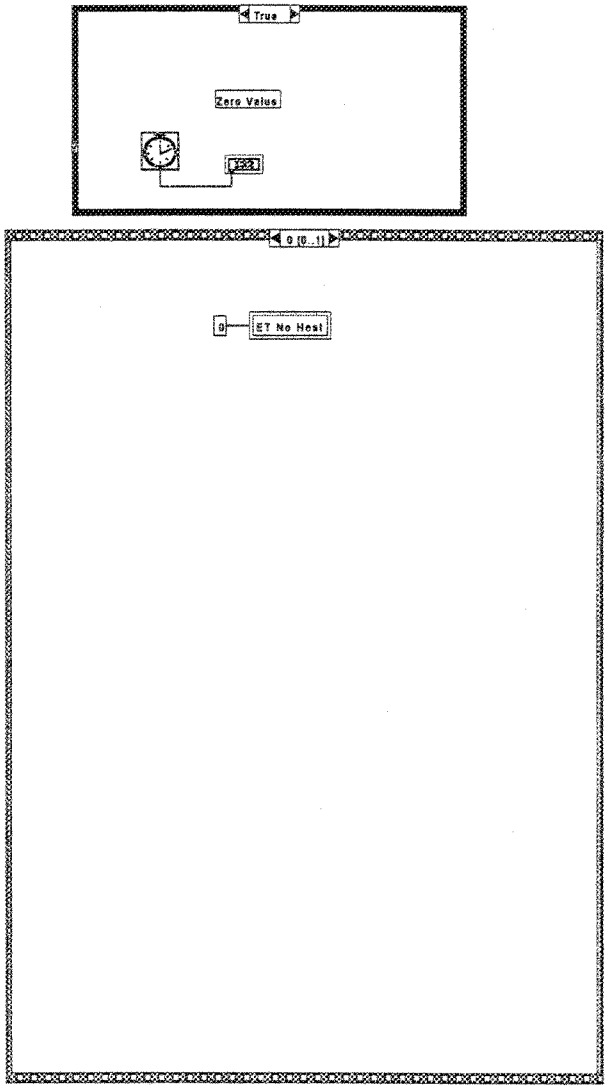
Bl[redacted]Diagram

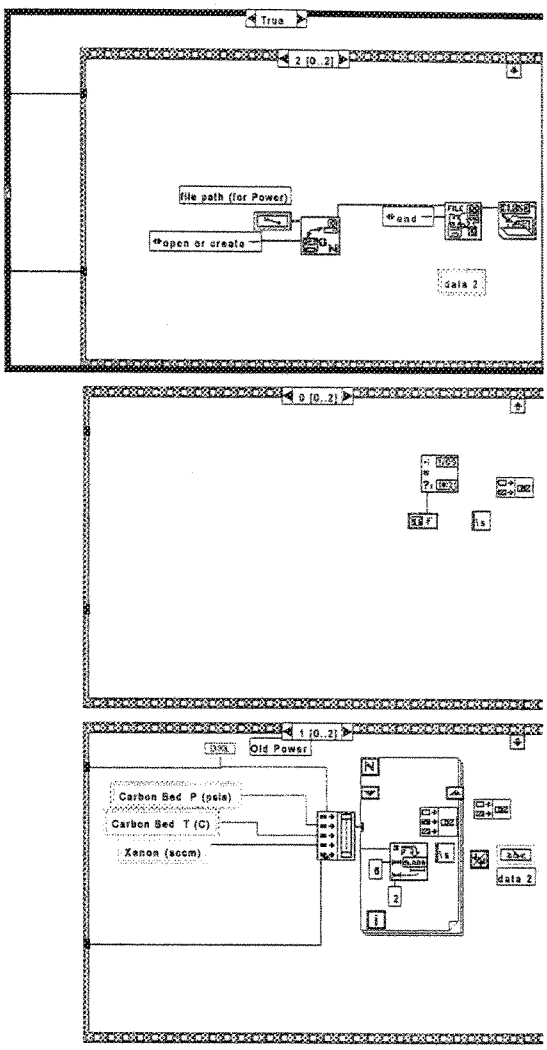


Xenon Breadboard Test 3.vi
A:\Xenon Breadboard Test 3.vi
Last modified on 6/13/2000 at 9:34 AM
Printed on 6/15/2000 at 11:19 AM

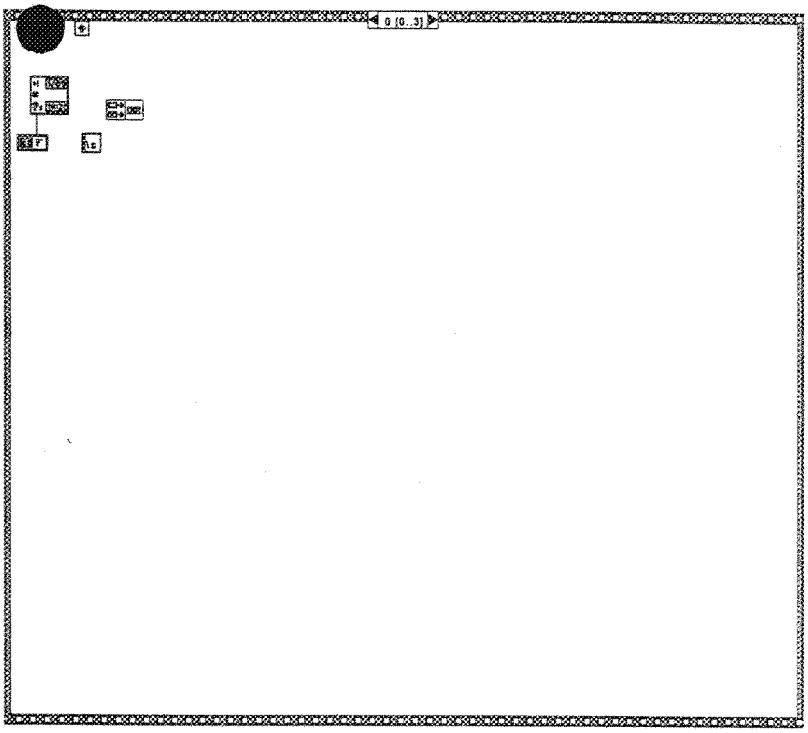


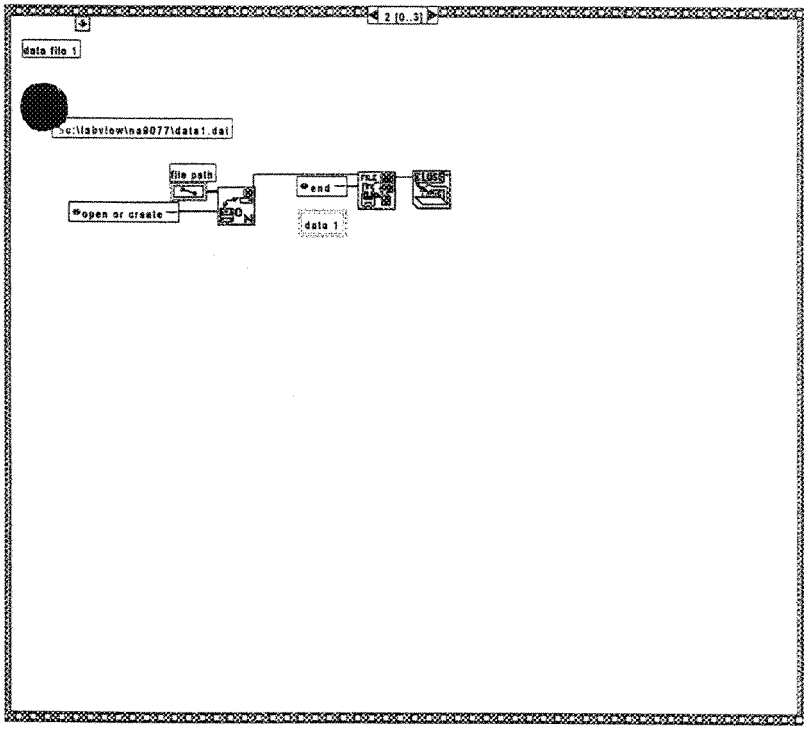
Xenon Breadboard Test 3.vi
A:\Xenon Breadboard Test 3.vi
Last modified on 6/13/2000 at 9:34 AM
Printed on 6/15/2000 at 11:19 AM



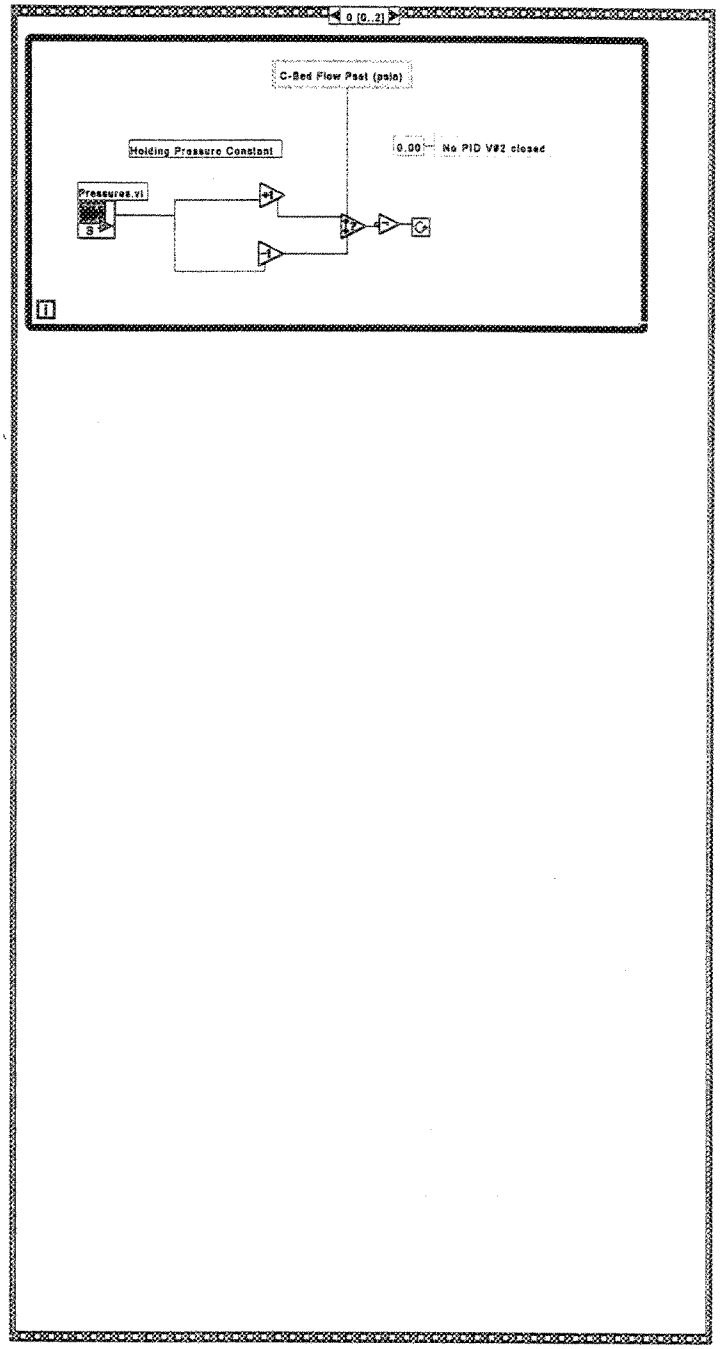


Xenon Breadboard Test 3.vi
A:\Xenon Breadboard Test 3.vi
Last modified on 6/13/2000 at 9:34 AM
Printed on 6/15/2000 at 11:19 AM

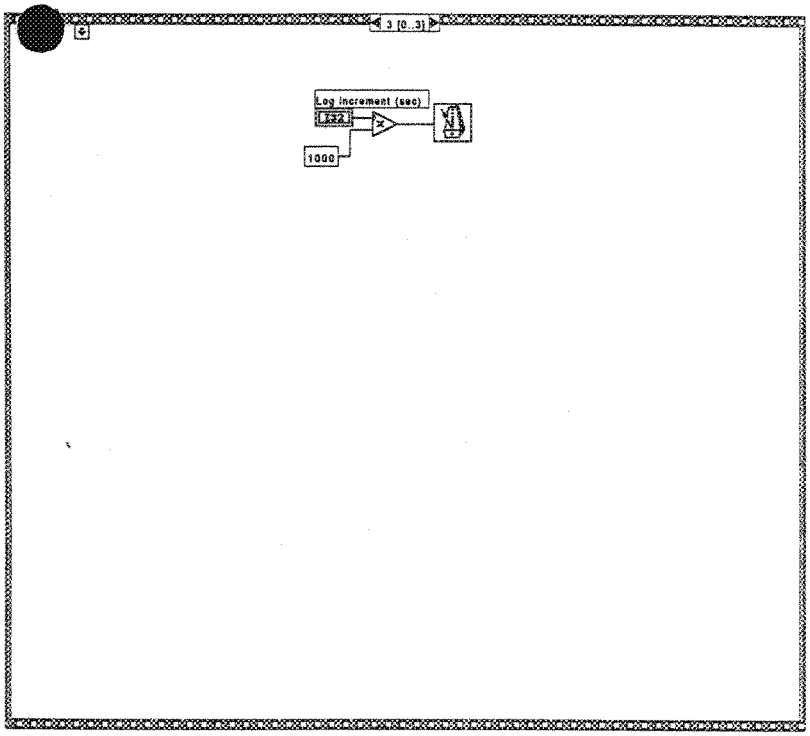




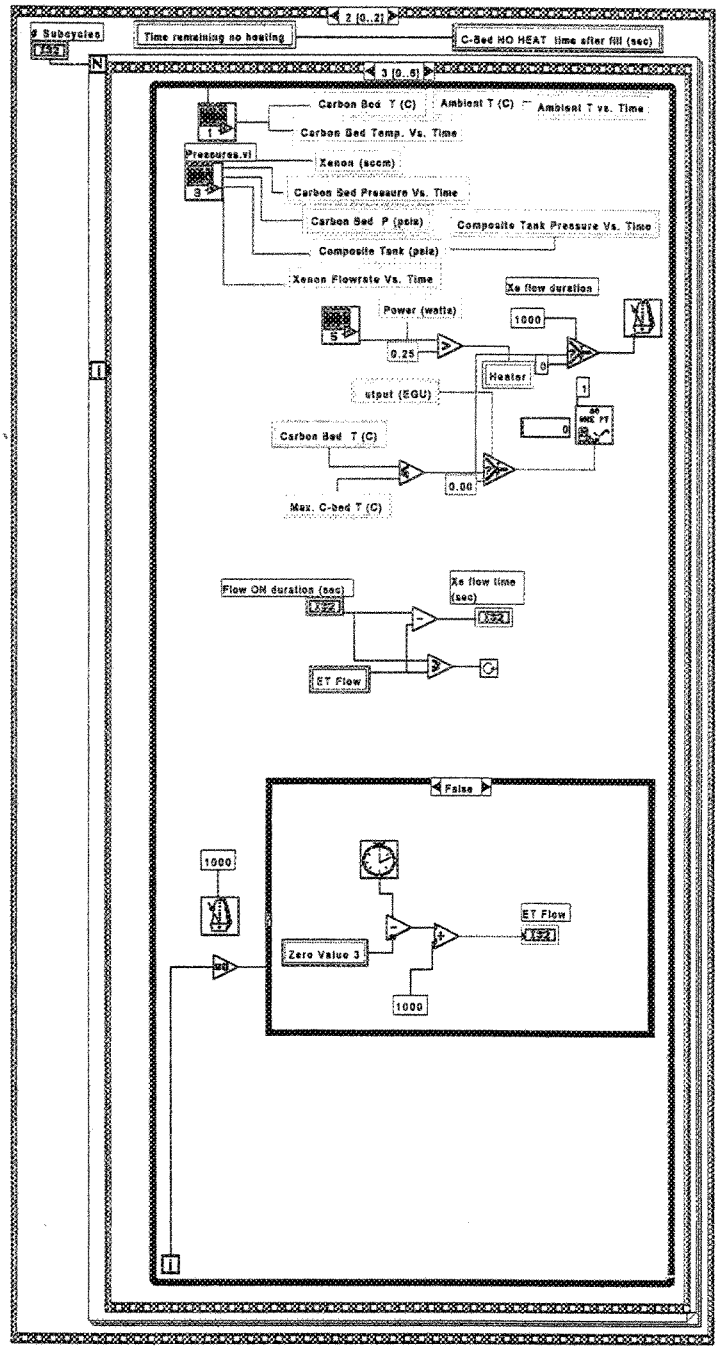
Xenon Breadboard Test 3.vi
A:\Xenon Breadboard Test 3.vi
Last modified on 6/13/2000 at 9:34 AM
Printed on 6/15/2000 at 11:19 AM

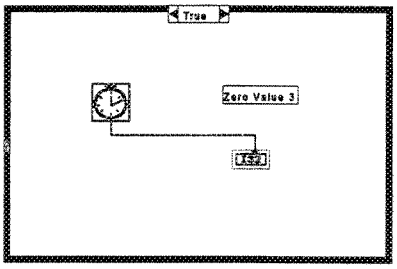


Xenon Breadboard Test 3.vi
A:\Xenon Breadboard Test 3.vi
Last modified on 6/13/2000 at 9:34 AM
Printed on 6/15/2000 at 11:19 AM

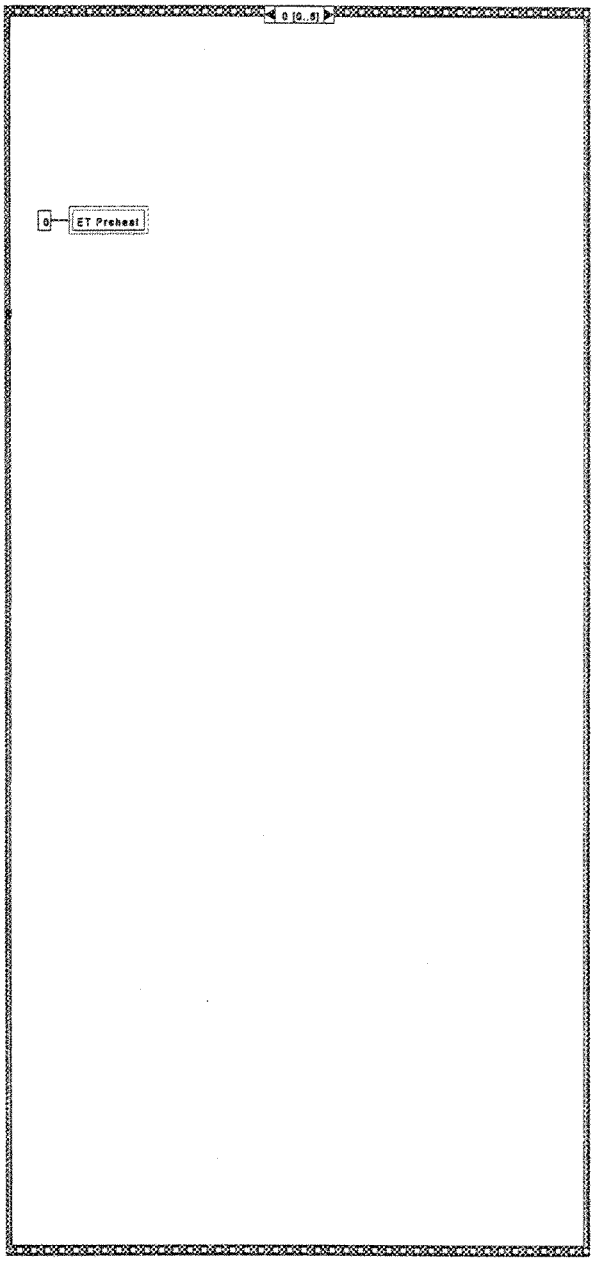


Xenon Breadboard Test 3.vi
A:\Xenon Breadboard Test 3.vi
Last modified on 6/13/2000 at 9:34 AM
Printed on 6/15/2000 at 11:19 AM

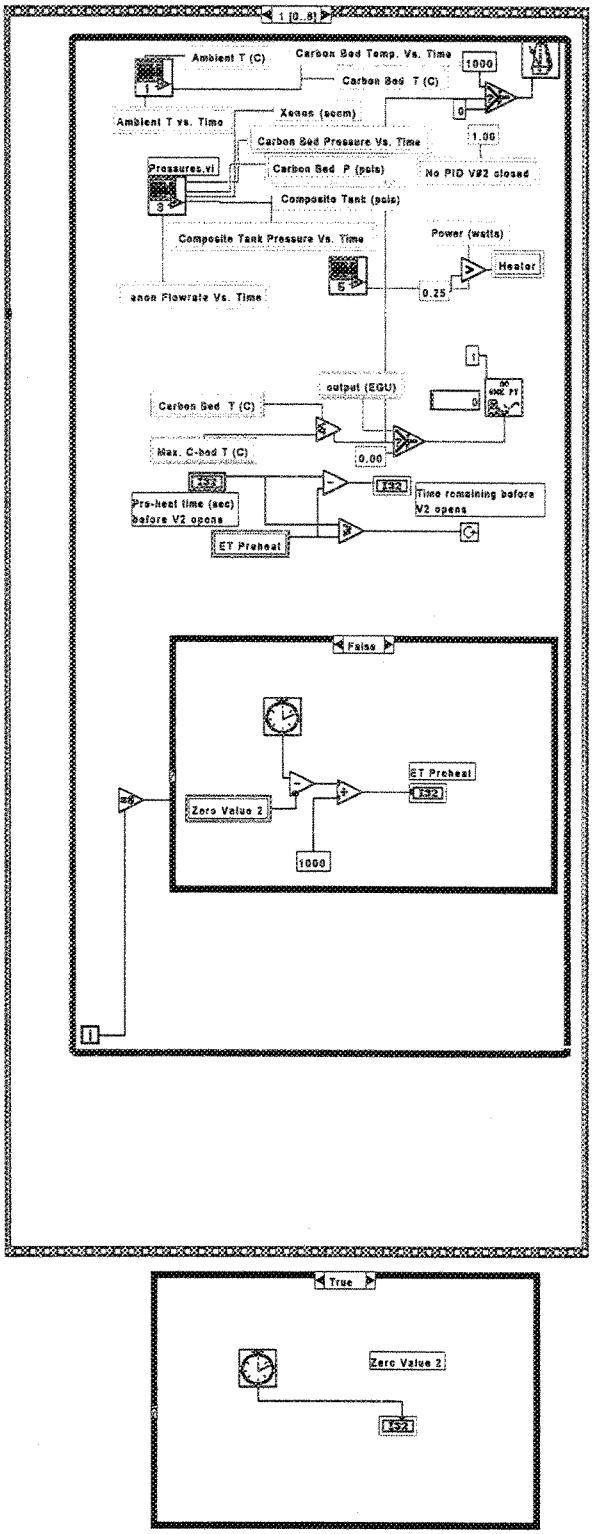




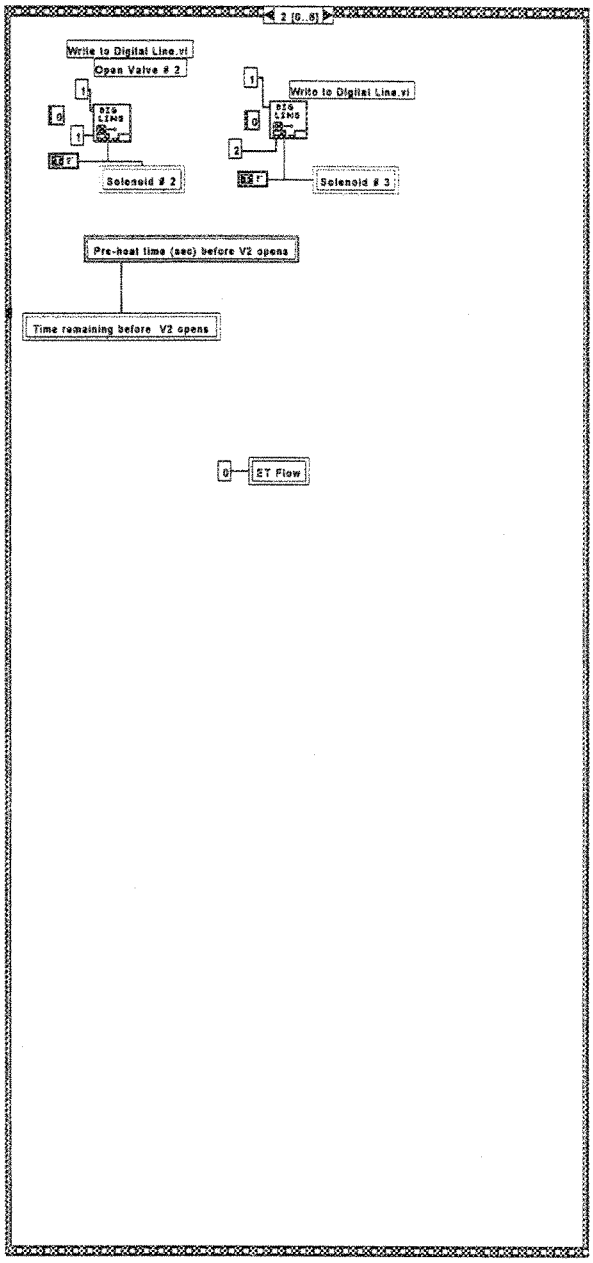
Xenon Breadboard Test 3.vi
A:\Xenon Breadboard Test 3.vi
Last modified on 6/13/2000 at 9:34 AM
Printed on 6/15/2000 at 11:19 AM



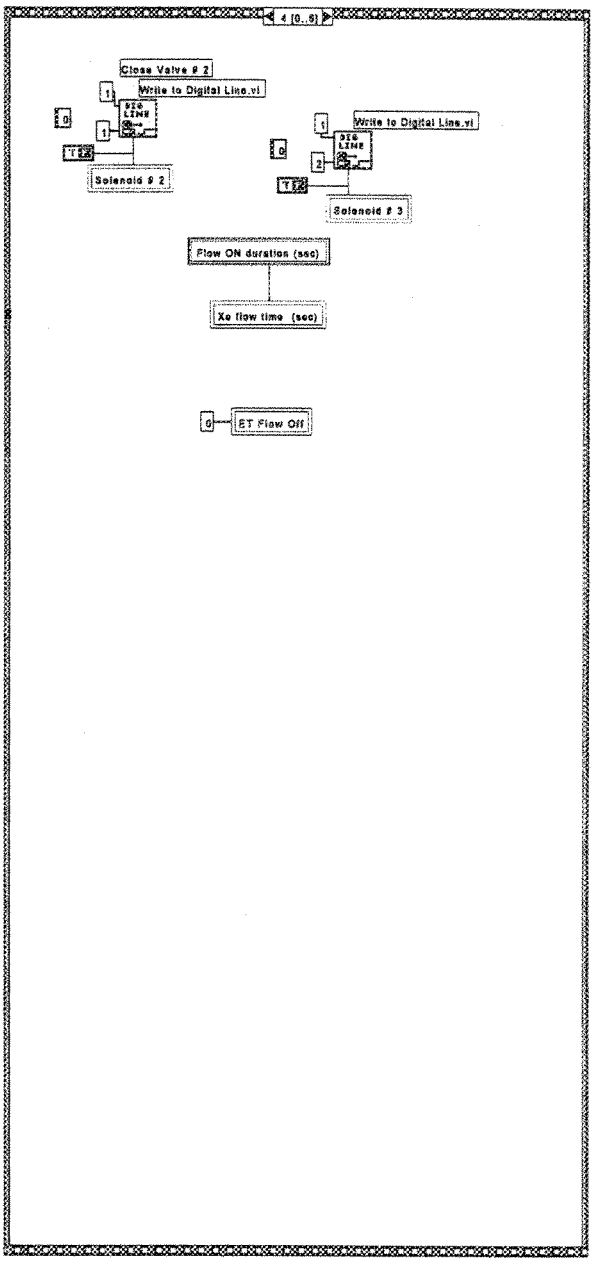
Xenon Breadboard Test 3.vi
A:\Xenon Breadboard Test 3.vi
Last modified on 6/13/2000 at 9:34 AM
Printed on 6/15/2000 at 11:19 AM



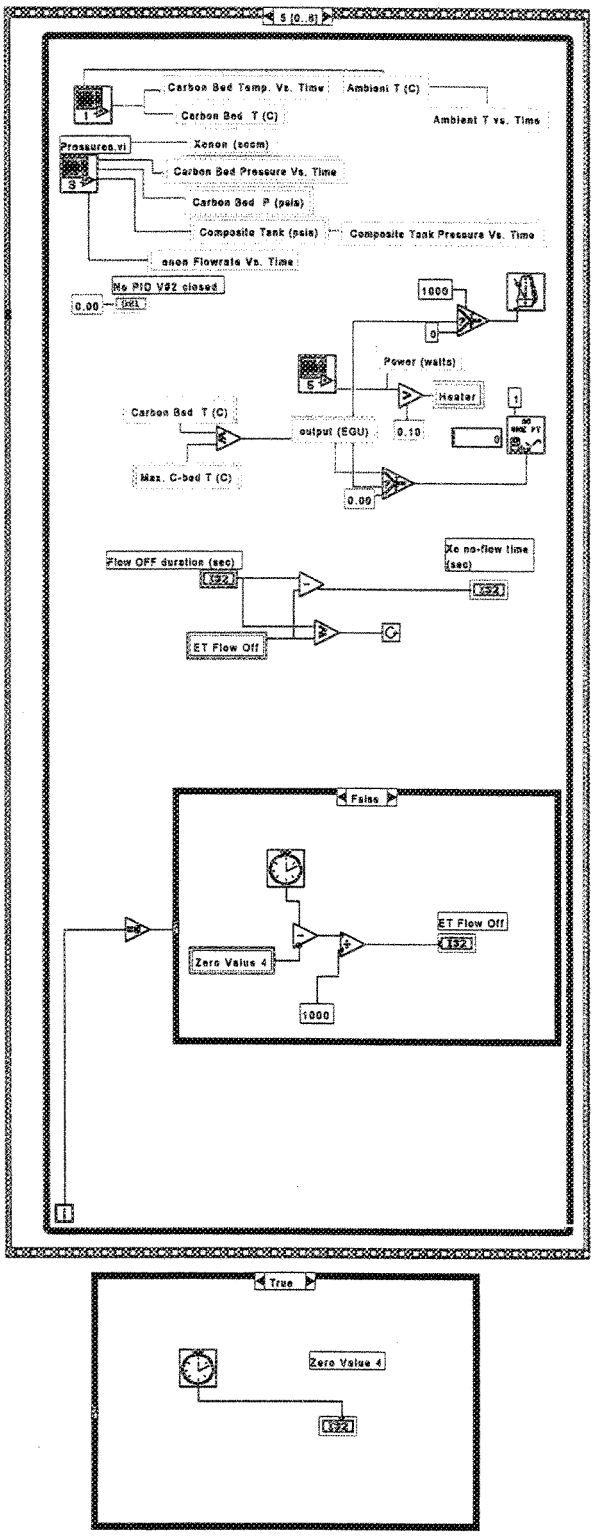
Xenon Breadboard Test 3.vi
A:\Xenon Breadboard Test 3.vi
Last modified on 6/13/2000 at 9:34 AM
Printed on 6/15/2000 at 11:19 AM



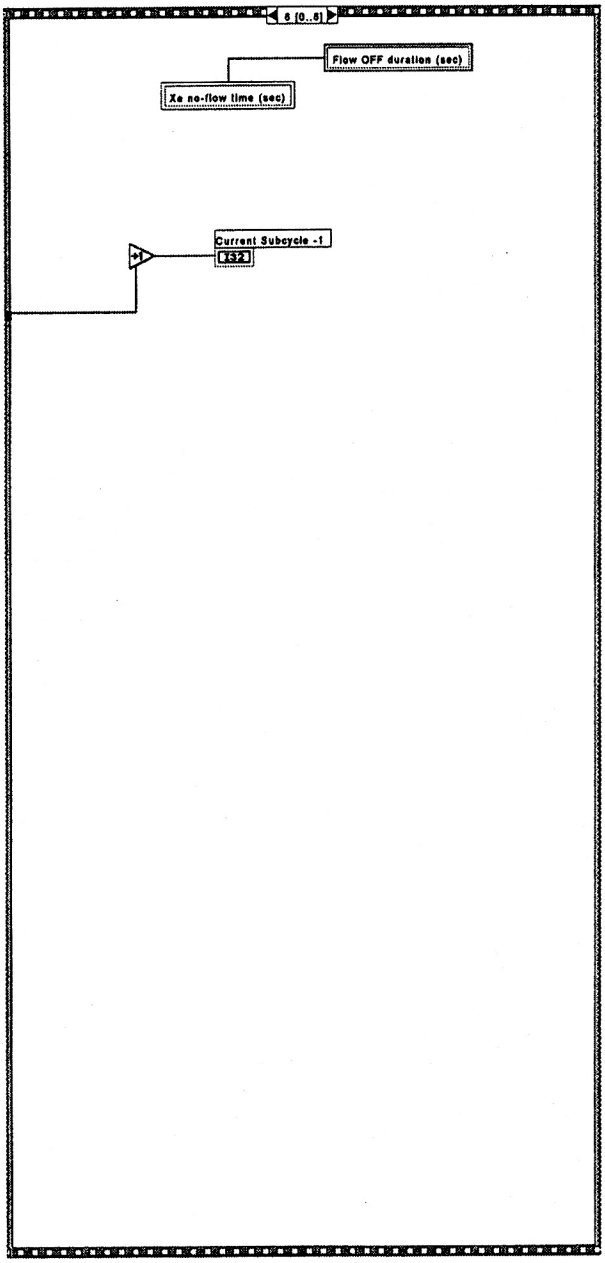
Xenon Breadboard Test 3.vi
A:\Xenon Breadboard Test 3.vi
Last modified on 6/13/2000 at 9:34 AM
Printed on 6/15/2000 at 11:19 AM



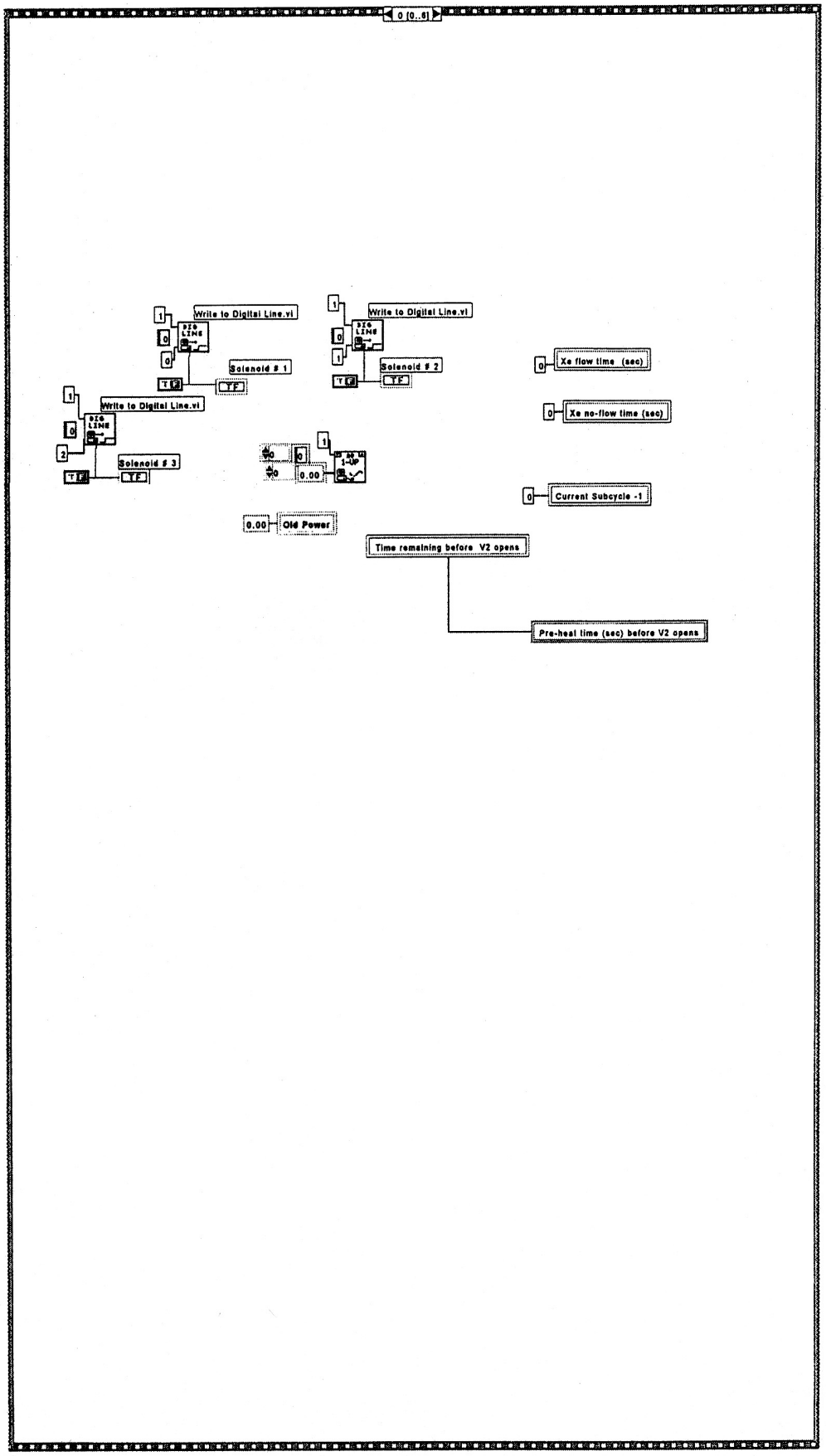
Xenon Breadboard Test 3.vi
A:\Xenon Breadboard Test 3.vi
Last modified on 6/13/2000 at 9:34 AM
Printed on 6/15/2000 at 11:19 AM



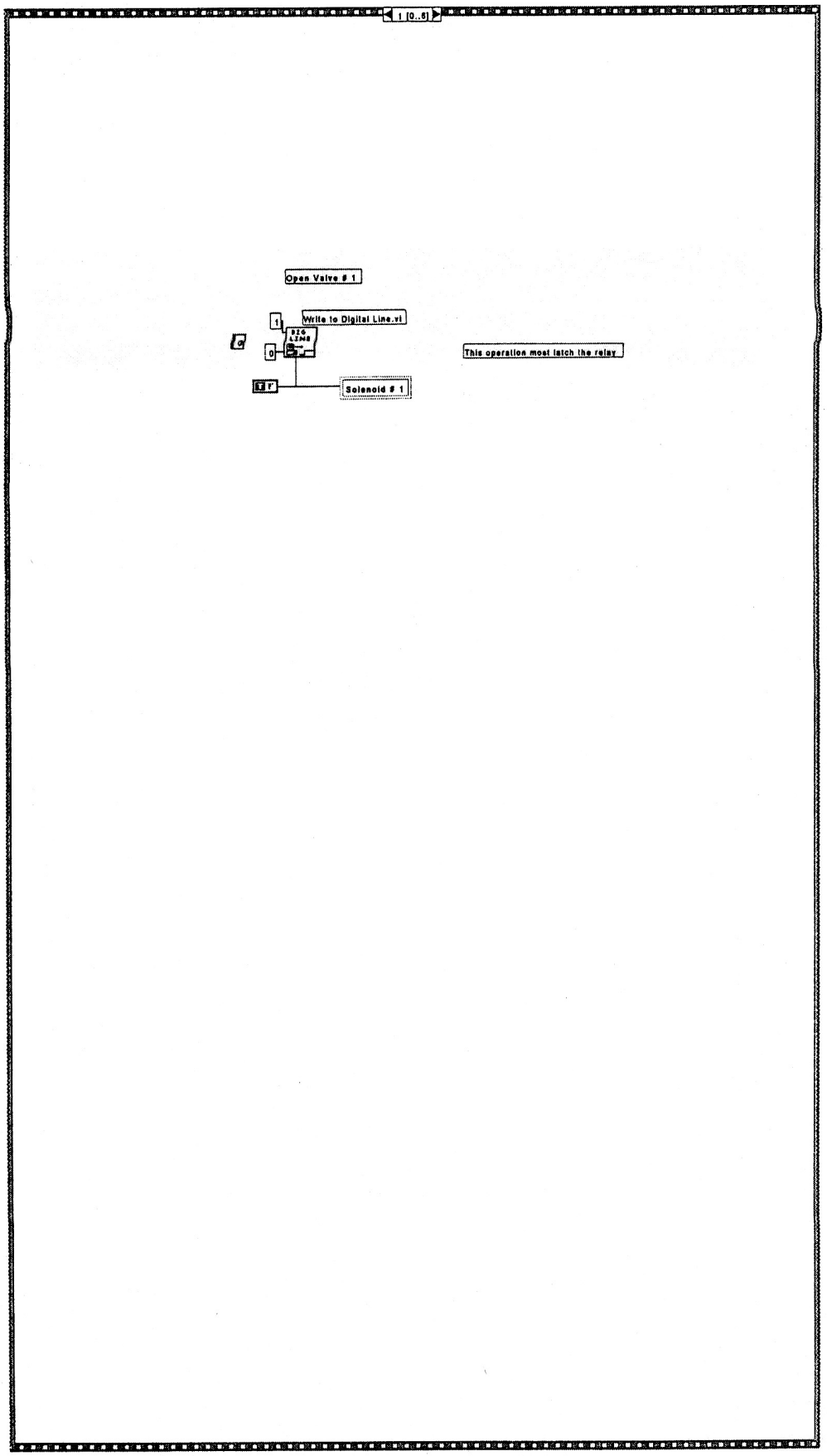
Xenon Breadboard Test 3.vi
A:\Xenon Breadboard Test 3.vi
Last modified on 6/13/2000 at 9:34 AM
Printed on 6/15/2000 at 11:19 AM



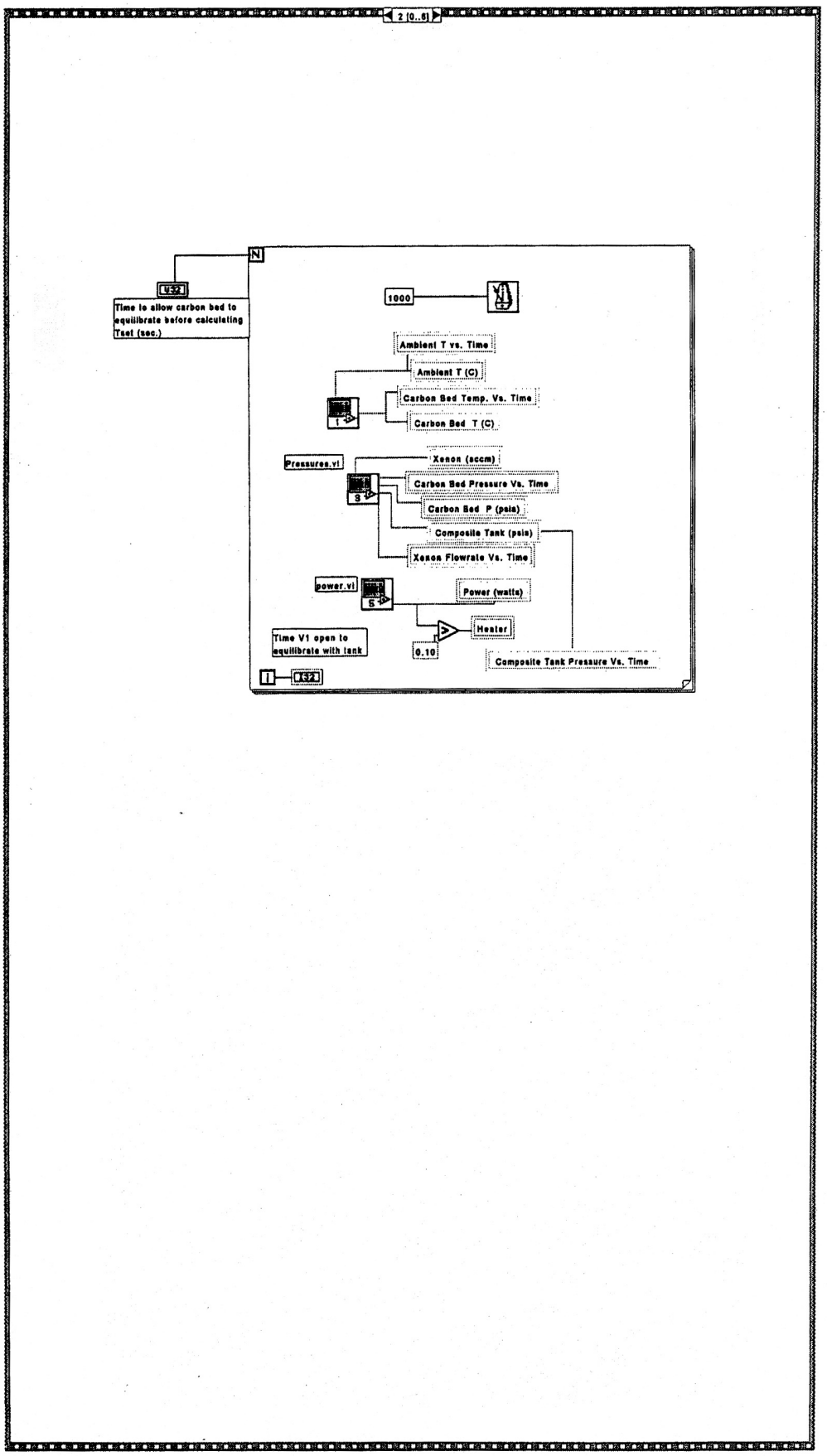
Xenon Breadboard Test 3.vi
A:\Xenon Breadboard Test 3.vi
Last modified on 6/13/2000 at 9:34 AM
Printed on 6/15/2000 at 11:19 AM



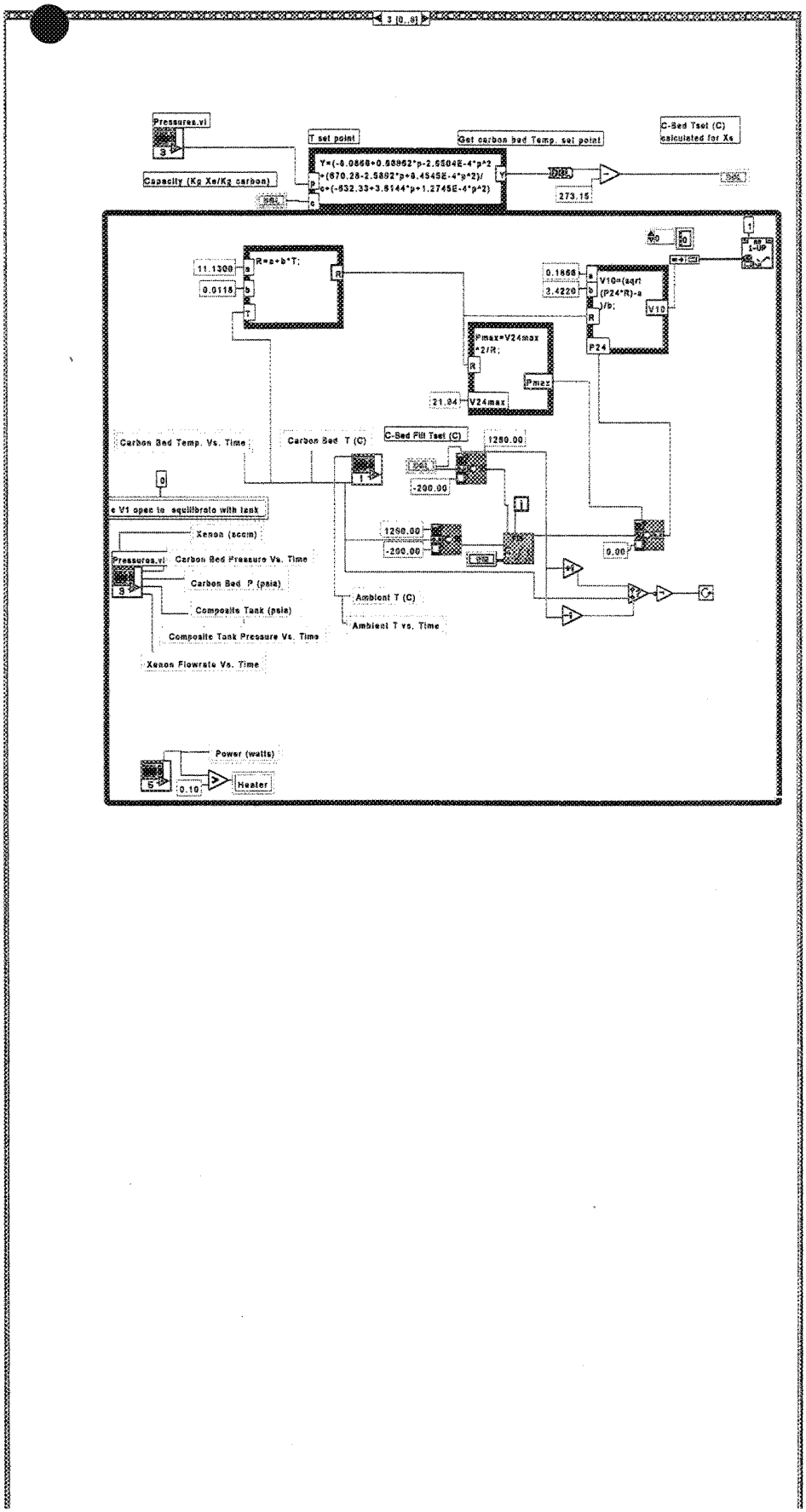
Xenon Breadboard Test 3.vi
A:\Xenon Breadboard Test 3.vi
Last modified on 6/13/2000 at 9:34 AM
Printed on 6/15/2000 at 11:19 AM



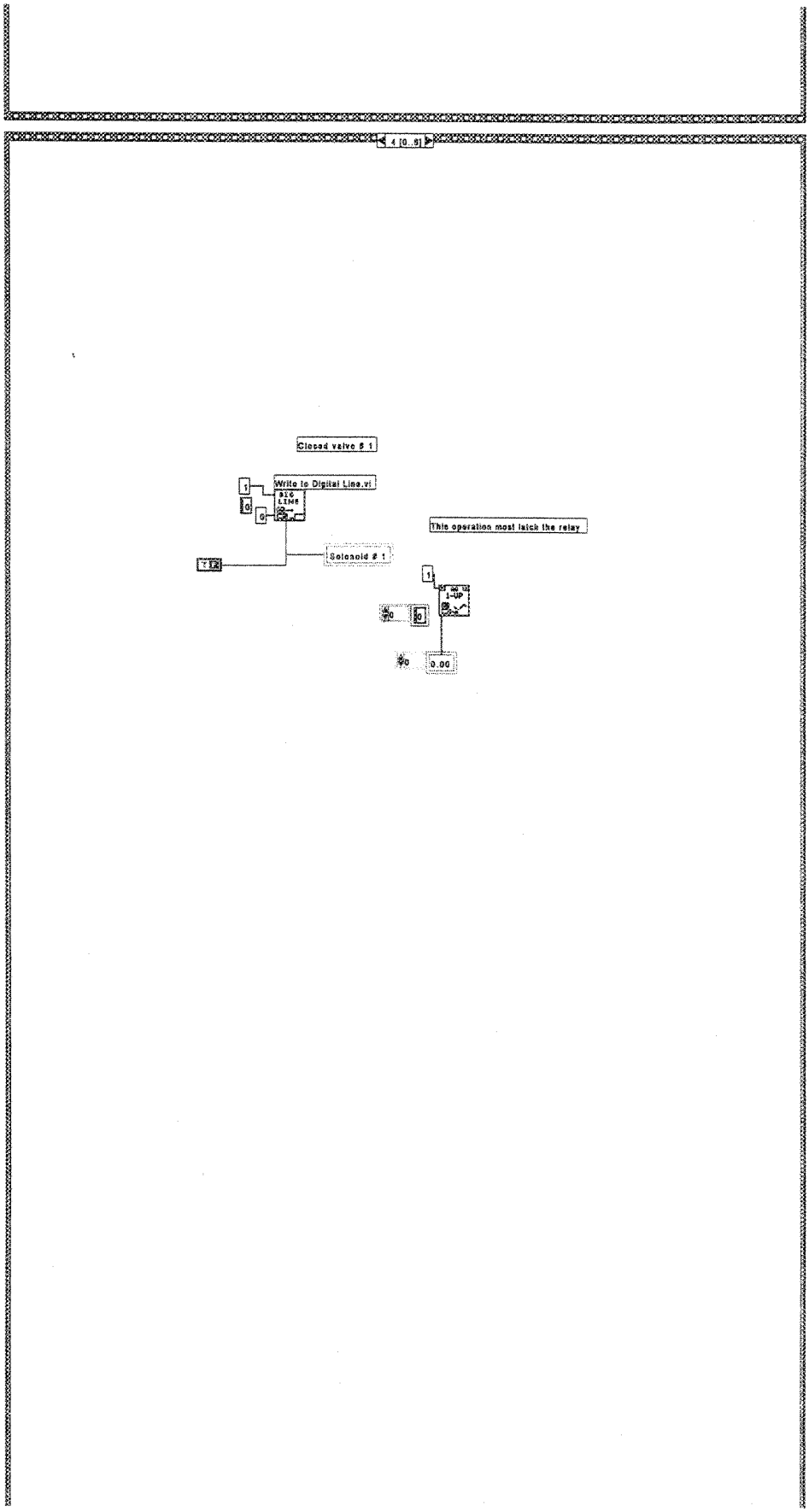
Xenon Breadboard Test 3.vi
A:\Xenon Breadboard Test 3.vi
Last modified on 6/13/2000 at 9:34 AM
Printed on 6/15/2000 at 11:19 AM



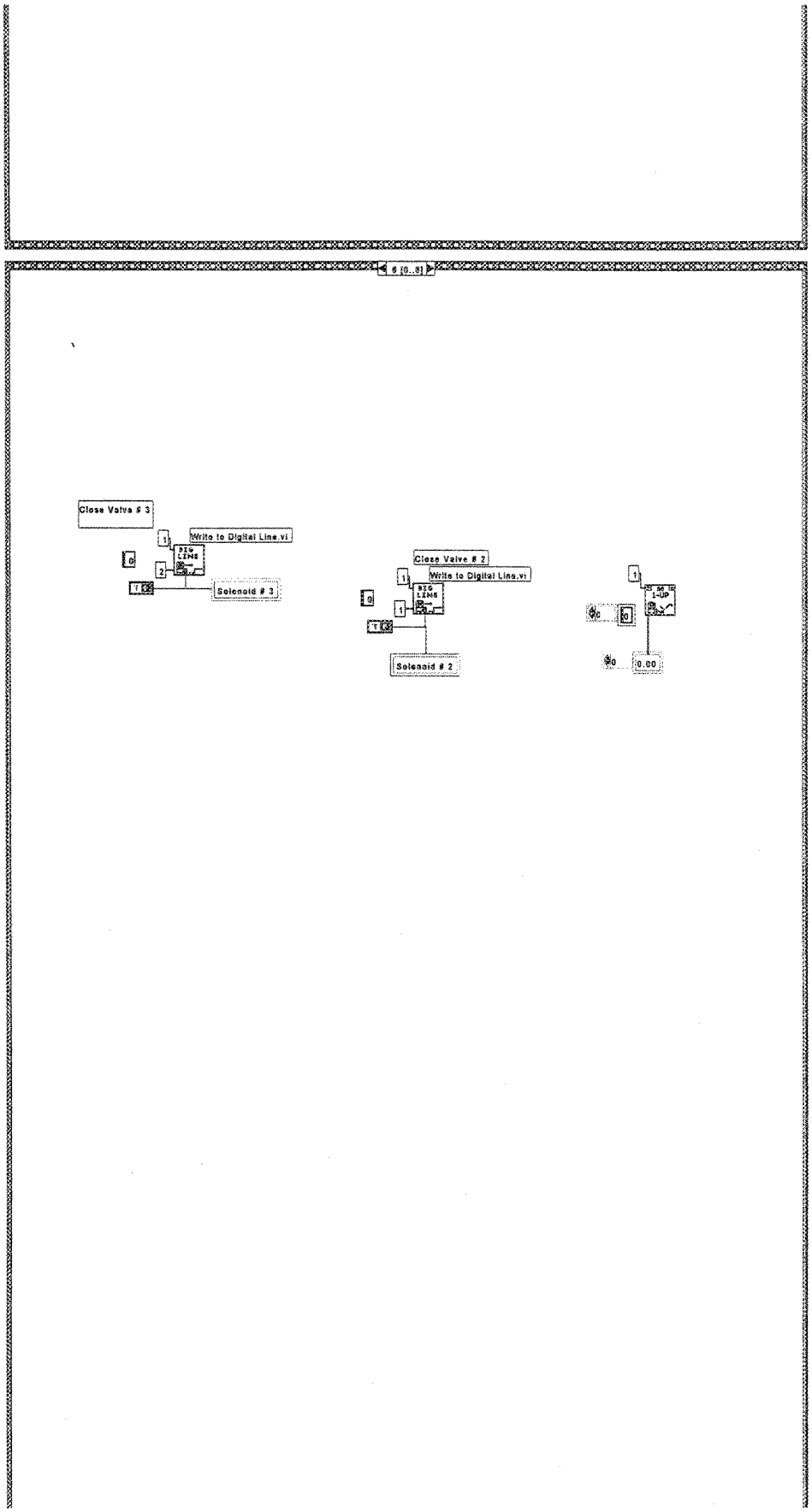
Xenon Breadboard Test 3.vi
A:\Xenon Breadboard Test 3.vi
Last modified on 6/13/2000 at 9:34 AM
Printed on 6/15/2000 at 11:19 AM



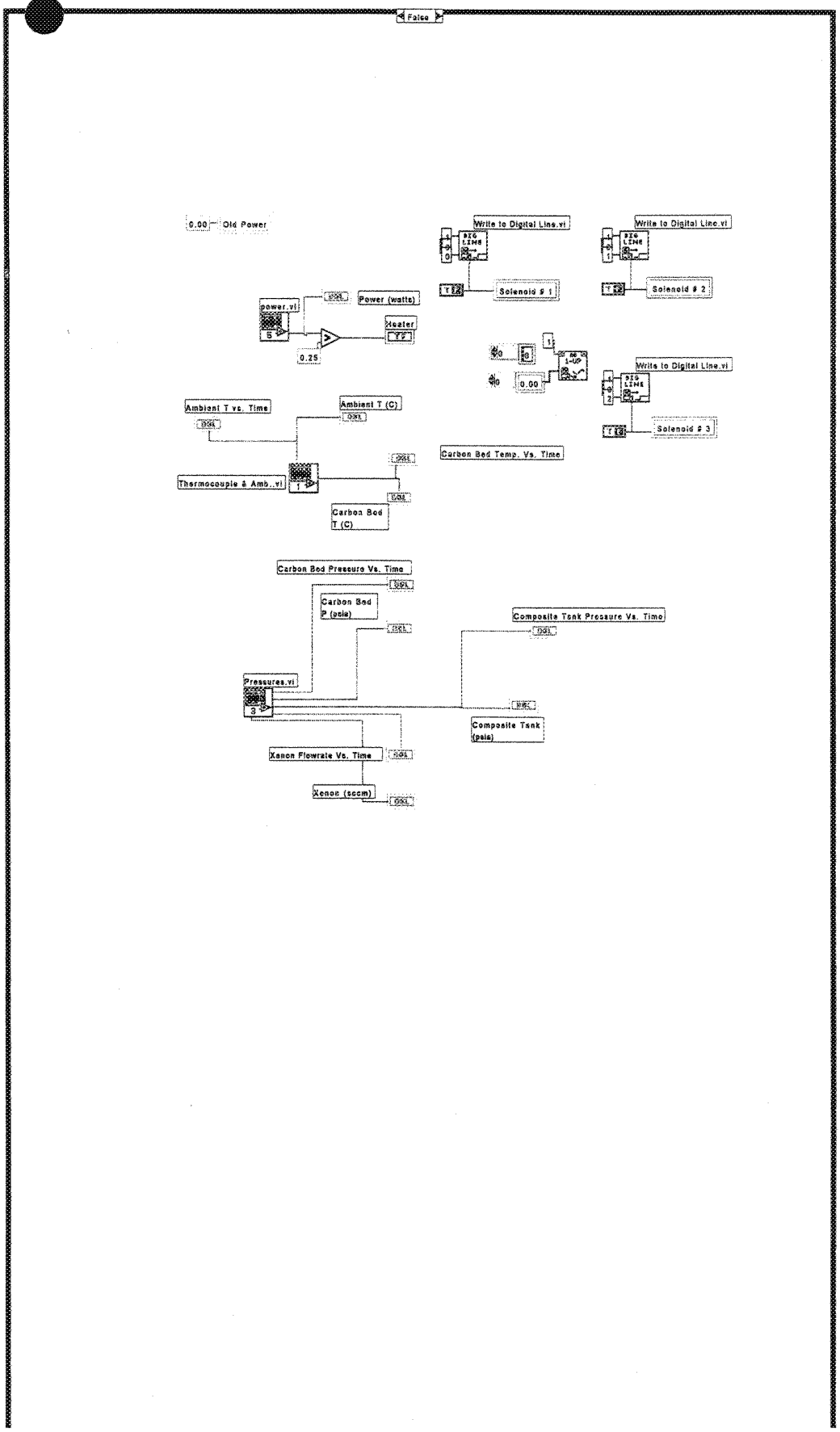
Xenon Breadboard Test 3.vi
A:\Xenon Breadboard Test 3.vi
Last modified on 6/13/2000 at 9:34 AM
Printed on 6/15/2000 at 11:19 AM



Xenon Breadboard Test 3.vi
A:\Xenon Breadboard Test 3.vi
Last modified on 6/13/2000 at 9:34 AM
Printed on 6/15/2000 at 11:19 AM

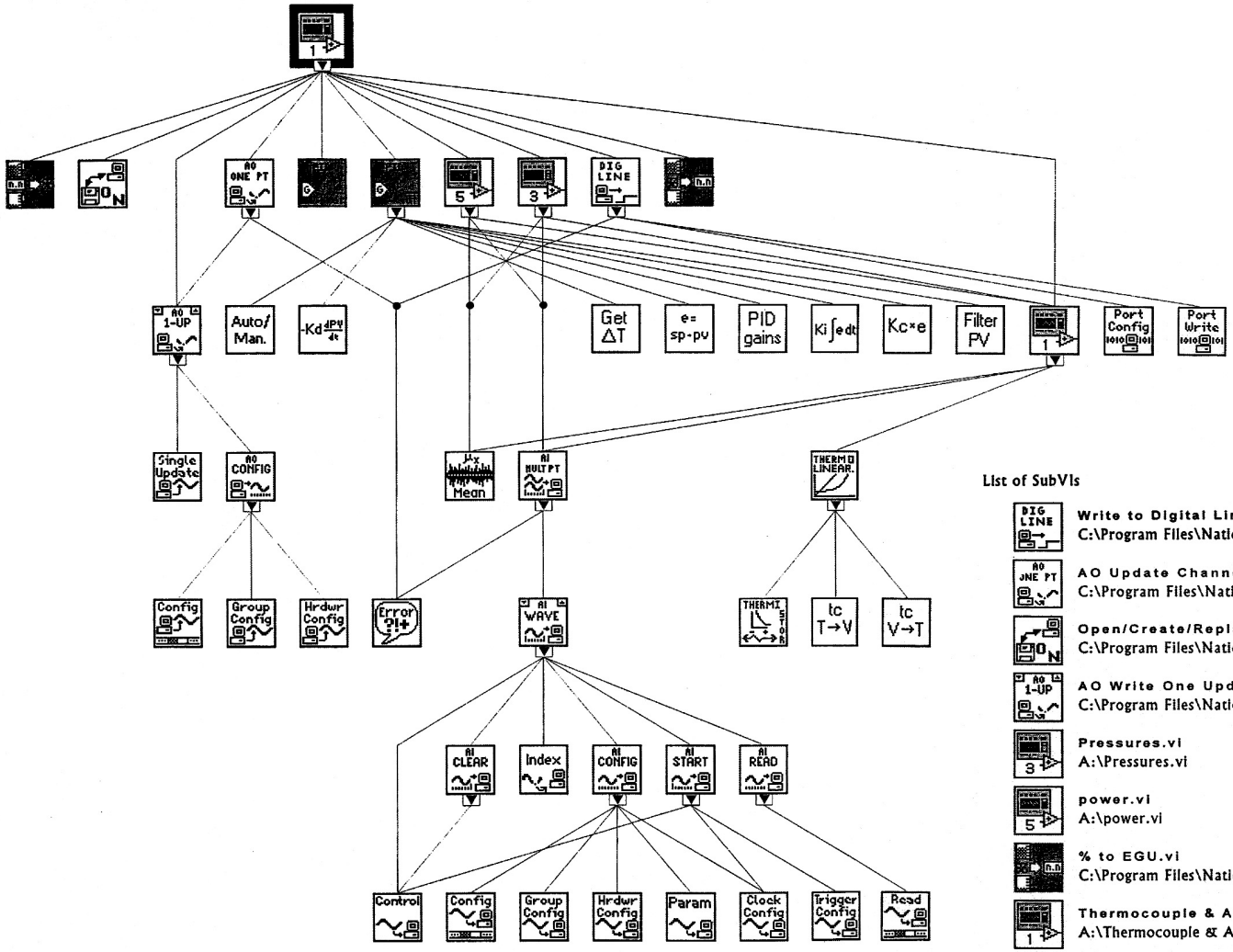


Xenon Breadboard Test 3.vi
A:\Xenon Breadboard Test 3.vi
Last modified on 6/13/2000 at 9:34 AM
Printed on 6/15/2000 at 11:19 AM



Position in Hierarchy

Xenon Breadboard Test 3.vi
A:\Xenon Breadboard Test 3.vi
Last modified on 6/13/2000 at 9:34 AM
Printed on 6/15/2000 at 11:19 AM



List of SubVIs

Write to Digital Line.vi
C:\Program Files\National Instruments\LabVIEW\vi.lib\DAQ\1EASYIO.LLB\Write to Digital Line.vi

AO Update Channel.vi
C:\Program Files\National Instruments\LabVIEW\vi.lib\DAQ\1EASYIO.LLB\AO Update Channel.vi

Open/Create/Replace File.vi
C:\Program Files\National Instruments\LabVIEW\vi.lib\Utility\file.llb\Open/Create/Replace File.vi

AO Write One Update.vi
C:\Program Files\National Instruments\LabVIEW\vi.lib\DAQ\AO.LLB\AO Write One Update.vi

Pressures.vi
A:\Pressures.vi

power.vi
A:\power.vi

% to EGU.vi
C:\Program Files\National Instruments\LabVIEW\vi.lib\Prcrntl.llb\% to EGU.vi

Thermocouple & Amb..vi
A:\Thermocouple & Amb..vi

EGU to %.vi
C:\Program Files\National Instruments\LabVIEW\vi.lib\Prcrntl.llb\EGU to %.vi

PID (Compatibility).vi
D:\CharlieTransfer\Projects\Na9077\PID (Compatibility).llb\PID (Compatibility).vi

PID.vi
C:\Program Files\National Instruments\LabVIEW\vi.lib\Prcrntl.llb\PID.vi

History

Xenon Breadboard Test 3.vi
A:\Xenon Breadboard Test 3.vi
Last modified on 6/13/2000 at 9:34 AM
Printed on 6/15/2000 at 11:19 AM

AO Update Channel.vi
C:\Program Files\National Instruments\LabVIEW\vi.lib\DAQ\1EASYIO.LLB\AO Update Channel.vi

Open/Create/Replace File.vi
C:\Program Files\National Instruments\LabVIEW\vi.lib\Utility\file.llb\Open/Create/Replace File.vi

AO Write One Update.vi
C:\Program Files\National Instruments\LabVIEW\vi.lib\DAQ\AO.LLB\AO Write One Update.vi

Pressures.vi
A:\Pressures.vi

power.vi
A:\power.vi

% to EGU.vi
C:\Program Files\National Instruments\LabVIEW\vi.lib\Prcrntl.llb\% to EGU.vi

Thermocouple & Amb..vi
A:\Thermocouple & Amb..vi

EGU to %.vi
C:\Program Files\National Instruments\LabVIEW\vi.lib\Prcrntl.llb\EGU to %.vi

PID (Compatibility).vi
D:\CharlieTransfer\Projects\Na9077\PID (Compatibility).llb\PID (Compatibility).vi

PID.vi
C:\Program Files\National Instruments\LabVIEW\vi.lib\Prcrntl.llb\PID.vi

---

History

"Xenon Breadboard Test 3.vi History"
Current Revision: 215

APPENDIX C

SUMMARY OF BREADBOARD EXPERIMENTS

SUMMARY OF BREADBOARD EXPERIMENTS

				MIN	24.9		1.6			0.61			
				MAX	300.8		44.9			50.5			
					129.6	0.48%		1.19%	8296	5.5	521		
FILE	DATE	Restrictor	TEST PROTOCOL	Flow P (psia)	Pressure variation %	Flow rate (sccm)	Flow variation %	Duration (min.)	Avg. power usage (W)	Total g Xe	T_{out} range	T_{bed} range	PB-I-D
test2a-3-30-00.xls	3/30/00	60	D	124.9	0.89%	29.47	1.91%	15	4.6	2.6	26-27	41-50	2-3-0.5
"	"	"	"	125.1	0.87%	29.46	1.94%	15	6.3	2.6	26-27	57-72	"
"	"	"	"	100.0	0.79%	24.70	1.69%	30	6.6	4.3	26-27	66-95	"
"	"	"	"	59.9	0.26%	12.40	1.58%	30	5.4	2.2	26-27	75-89	2-6-0.5
"	"	"	"	39.8	0.54%	5.69	1.90%	28	4.2	0.9	26-28	76-81	"
test1a-4-03-00.XLS	4/3/00	60	D	159.7	0.50%	33.10	1.01%	30	13.0	5.8	26-28	68-127	"
"	"	"	"	39.9	0.58%	5.71	1.36%	60	3.7	2.0	26-28	66-79	"
"	"	"	"	40.0	0.44%	5.71	1.15%	120	6.3	4.0	26-29	80-132	"
test1a-4-04-00.XLS	4/4/00	60	D	139.7	0.43%	31.39	1.08%	30	12.0	5.5	26-29	79-137	"
"	"	"	"	69.6	0.58%	15.58	0.85%	30	11.2	2.8	28-29	123-156	"
"	"	"	C	24.9	1.42%	1.61	4.97%	119	8.4	1.1	27-28	118-150	"
test1a-4-05-00.xls	4/5/00	60	B & E	199.6	0.59%	35.08	0.94%	30	14.1	6.2	24-27	52-134	2-8-0.5
"	"	"	"	199.8	0.68%	35.17	1.00%	30	13.3	6.1	25-27	51-130	2-6-0.5
"	"	"	"	199.5	0.56%	35.15	1.00%	30	13.5	6.1	25-27	53-131	2-10-0.5
"	"	"	"	199.8	0.57%	35.14	1.03%	30	13.6	6.1	24-26	52-131	2-12-1.0
test1a-4-06-00.xls	4/6/00	60	A	45.0	0.53%	7.41	1.10%	300	5.3	13.0	26-31	39-174	2-8-0.25
"	"	"	"	44.9	0.86%	7.42	1.94%	1st 60	2.1		26-29	39-52	"
"	"	"	"	45.0	0.39%	7.38	0.67%	2nd 60	3.2		28-30	52-68	"
"	"	"	"	45.0	0.32%	7.41	0.59%	3rd 60	4.6		30-31	68-89	"
"	"	"	"	45.0	0.54%	7.43	0.95%	4th 60	5.9		30-31	89-119	"
"	"	"	"	44.9	0.34%	7.41	0.60%	5th 60	9.0		30-31	120-173	"
test1a-4-07-00.xls	4/7/00	60	D	44.8	0.97%	7.41	1.89%	60	2.6	2.6	25-28	32-44	2-8-0.5
"	"	"	"	59.8	0.61%	12.54	1.61%	45	5.1	3.3	25-27	51-68	6-7-1
test1a-4-10-00.xls	4/10/00	60	B & E	199.5	0.58%	35.13	0.92%	30	14.2	6.2	26-28	55-139	3-10-0.5
"	"	"	"	199.5	0.52%	35.11	0.98%	30	14.7	6.1	26-27	57-141	3-8-1
"	"	"	"	150.1	0.70%	32.42	1.14%	32	11.2	6.1	25-27	64-124	2-7-1
test1a-4-11-00.xls	4/11/00	60	D & E	100.1	0.90%	24.91	1.46%	45	6.3	6.6	25-28	50-91	2-8-1
"	"	"	"	79.9	0.61%	19.08	1.16%	78	4.7	8.8	25-27	38-88	2-8-x
"	"	"	"	59.9	0.38%	12.56	0.67%	90	4.8	6.7	25-27	55-96	2-8-x
test1a-4-13-00.xls	4/13/00	"	B & E	249.7	0.67%	36.59	0.72%	43	18.4	9.1	25-27	24-190	2-x-y

FILE	DATE	Restrictor	TEST PROTOCOL	Flow P (psia)	Pressure variation %	Flow rate (sccm)	Flow variation %	Duration (min.)	Avg. power usage (W)	Total g Xe	T_{out} range	T_{bed} range	PB-I-D
"	"	"	"	249.7	0.73%	36.60	0.79%	40	18.2	8.5	25-27	31-191	2-4-0.5
test1a-4-14-00.xls	4/14/00	60	D & E	150.0	0.75%	32.46	0.87%	60	10.7	11.4	26-28	35-154	2-4-0.5
"	"	"	"	150.3	1.28%	32.48	0.94%	60	11.2	11.4	25-28	38-163	2-4-0.25
"	"	"	"	150.1	0.80%	32.46	0.96%	60	11.4	11.4	25-27	40-167	2-4-0.75
test1a-4-17-00.xls	4/17/00	60	D & E	149.7	0.29%	32.49	0.75%	60	9.7	11.4	26-29	31-139	4-4-0.5
"	"	"	"	149.9	0.61%	32.43	0.84%	60	11.0	11.4	25-28	37-159	4-3-0.5
test1a-4-18-00.xls	4/18/00	60	A & D	84.6	0.75%	20.50	1.93%	32	2.8	3.8	25-27	26-42	4-4-0.5
"	"	"	"	64.7	1.05%	14.13	1.58%	66	3.7	5.5	26-27	41-68	4-4-0.5
"	"	"	"	44.9	1.02%	7.36	1.95%	169	6.6	7.3	26-27	62-138	4-4-0.5
"	"	"	"	65.1	1.28%	14.23	1.71%	11	15.7	0.9	26-27	153-190	4-4-0.5
test1a-4-19-00.xls	4/19/00	60	C	27.2	0.42%	2.21	1.49%	294	1.9	3.8	25-27	32-61	x-y-z
test1a-4-20-00.xls	4/20/00	60	C	27.2	0.56%	2.22	1.62%	425	2.1	5.5	24-28	30-73	8-5-0.1
"	"	"	"	27.1	1.17%	2.19	3.21%	1st 60	0.9		24-26	30-34	"
"	"	"	"	27.2	0.36%	2.19	0.91%	2nd 60	1.2		26-27	34-39	"
"	"	"	"	27.2	0.47%	2.22	1.24%	3rd 60	1.3		26-27	39-44	"
"	"	"	"	27.2	0.28%	2.23	0.83%	4th 60	1.9		27-27	44-50	"
"	"	"	"	27.2	0.35%	2.23	0.90%	5th 60	2.3		26-27	50-56	"
"	"	"	"	27.2	0.28%	2.23	0.79%	6th 60	2.8		27-28	56-64	"
"	"	"	"	27.2	0.26%	2.22	0.84%	7th 60	3.3		26-27	64-72	"
test1a-4-25-00.xls	4/25/00	60	E	59.9	0.37%	12.59	1.13%	30	3.3	2.2	24-25	47-57	3-5-0.5
"	"	"	"	60.0	0.48%	12.58	1.52%	30	4.4	2.2	25-26	60-72	1-5-0.3
"	"	"	"	60.0	0.49%	12.55	1.58%	30	5.7	2.2	25-26	75-90	1-7-0.3
"	"	"	"	59.9	0.68%	12.55	1.92%	30	2.6	2.2	25-26	38-47	3-4-0.3
"	"	"	"	59.8	1.28%	12.52	2.47%	30	3.3	2.2	25-26	50-59	3-5-0.15
"	"	"	"	59.8	0.48%	12.53	1.76%	30	4.5	2.2	25-26	62-74	3-5-0.6
test1a-4-26-00.xls	4/26/00	60	E	59.9	0.39%	12.57	1.54%	30	2.2	2.2	25-27	33-42	2-5-0.4
"	"	"	"	59.9	0.33%	12.55	1.49%	30	3.0	2.2	26-27	45-54	"
"	"		"	59.9	0.42%	12.54	1.48%	30	3.9	2.2	26-28	57-68	"
"	"	"	"	59.9	0.48%	12.56	1.73%	30	5.1	2.2	26-27	71-84	"
"	"	"	"	59.9	0.46%	12.58	1.84%	30	3.8	2.2	26-26	54-65	"
"	"	"	"	59.9	0.43%	12.59	1.36%	30	4.8	2.2	26-27	68-81	"
test1a-4-27-00.xls	4/27/00	60	E	60.0	0.52%	12.65	1.38%	30	2.7	2.2	25-26	41-51	1.5-7-0.5
"	"	"	"	60.1	1.13%	12.62	2.27%	30	3.6	2.2	26-27	53-64	"
"	"	"	"	60.0	0.88%	12.59	0.74%	30	4.8	2.2	26-27	68-80	1.5-3-0.5
"	"	"	"	60.0	0.46%	12.58	1.43%	30	6.2	2.2	26-27	84-100	"
"	"	"	"	60.1	1.04%	12.67	2.10%	30	4.3	2.2	26-27	61-72	"
"	"	"	"	60.0	0.97%	12.61	1.88%	30	5.3	2.2	26-27	75-89	1.5-3-0.3
"	"	"	"	59.9	0.96%	12.55	2.76%	10	6.1	0.7	26-26	93-97	"

FILE	DATE	Restrictor	TEST PROTOCOL	Flow P (psia)	Pressure variation %	Flow rate (sccm)	Flow variation %	Duration (min.)	Avg. power usage (W)	Total g Xe	T_{out} range	T_{bed} range	PB-I-D
test1a-4-28-00.xls	4/28/00	60	E	200.8	1.02%	35.27	0.86%	30	10.2	6.2	25-26	27-89	1.5-3-0.3
"	"	"	"	199.8	0.68%	35.23	0.96%	30	15.0	6.2	25-26	60-144	1.5-8-0.3
"	"	"	"	79.8	0.62%	19.16	0.79%	30	4.3	3.4	26-27	53-70	"
test1a-5-01-00.xls	5/1/00	60	D	27-100 psia throttling		2.5-25 sccm throttling							x-8-0.3
test1a-5-02-00.xls	5/2/00	60	D	80.4	1.45%	19.40	2.30%	60	3.2	6.8	24-27	25-57	1.5-3-0.3
"	"	"	"	35.0	0.86%	4.39	2.15%	60	1.3	1.5	25-27	33-40	"
"	"	"	"	27.3	0.61%	2.30	2.23%	60	1.2	0.8	24-26	34-38	"
"	"	"	D	27-57 psia throttling, 5 psi incr		2.2-12 sccm throttling							x-y-0.3
test1a-5-03-00.xls	5/3/00	60	E	139.8	1.11%	31.64	1.34%	30	6.8	5.5	24-26	33-69	4-4-0.3
"	"	"	"	140.7	1.68%	31.78	1.56%	30	6.9	5.6	26-27	37-75	2-4-0.3
"	"	"	"	149.3	0.52%	29.41	1.39%	27	7.8	4.6	25-26	45-80	3-5-0.4
test1a-5-04-00.xls	5/4/00	60	E	139.8	0.63%	31.61	0.97%	45	8.8	8.3	24-26	41-110	3-5-0.4
"	"	"	"	139.8	0.62%	31.65	1.14%	45	9.3	8.3	25-27	45-117	"
"	"	"	"	139.7	0.34%	31.67	1.01%	45	9.7	8.3	26-26	48-122	"
test1a-5-05-00.xls	5/5/00	60	E	124.8	0.31%	29.77	0.98%	45	8.2	7.8	24-26	48-109	3-5-0.4
"	"	"	"	99.9	0.39%	25.07	1.20%	60	6.6	8.8	24-26	43-101	"
"	"	"	"	149.6	0.34%	32.54	1.01%	45	14.4	8.6	24-26	66-179	"
test1a-5-08-00.xls	5/8/00	60	E	99.7	0.49%	24.91	1.47%	30	5.3	4.4	26-27	46-69	3-5-0.4
"	"	"	"	79.8	0.64%	19.13	1.94%	30	3.7	3.3	26-28	42-57	"
"	"	"	"	59.7	0.78%	12.60	2.22%	30	2.9	2.2	25-26	43-52	4-4-0.5
test1a-5-09-00.xls	5/9/00	60	E	59.8	0.77%	12.65	1.68%	30	2.4	2.2	25-26	37-45	2-4-0.4
"	"	"	"	59.9	0.51%	12.67	1.60%	30	3.1	2.2	25-26	45-54	1.5-4-0.4
test1a-5-10-00.xls	5/10/00	60	D	49.9	0.72%	9.18	1.80%	30	1.8	1.6	25-26	35-41	1.5-4-0.4
"	"	"	"	64.9	0.49%	14.29	1.28%	45	3.5	3.8	25-27	45-62	1.5-6-0.3
"	"	"	"	79.9	0.63%	19.11	1.55%	30	6.2	3.3	26-27	70-90	"
"	"	"	D	80-50 psia throttling		25-10 sccm throttling							
test1a-5-11-00.xls	5/11/00	60	E	100.0	0.66%	24.98	1.54%	30	4.1	4.4	24-26	31-51	1.5-5-0.35
"	"	"	"	79.9	0.57%	19.16	1.35%	60	3.9	6.7	26-28	36-70	"
test1a-5-15-00.xls	5/15/00	300	C	103.0	0.29%	2.03	2.10%	360	1.4	4.3	27-29	28-57	8-5-0.1
test1a-5-17-00.xls	5/17/00	300	C	109.1	1.20%	2.31	4.08%	71	0.8	1.0	24-26	28-33	6-12-0.5
"	"	"	"	110.0	0.75%	2.38	3.00%	298	1.9	4.1	25-28	35-62	x-y-z
test1a-5-18-00.xls	5/18/00	300	C	110.0	0.18%	2.43	1.29%	44	0.9	0.6	26-27	30-34	16.4-3.5-0.53
"	"	"	"	110.0	0.92%	2.44	2.77%	104	1.1	1.5	26-28	32-39	"
"	"	"	"	109.9	0.14%	2.46	4.76%	30	1.2	0.4	26-27	36-38	"
"	"	"	"	109.9	0.12%	2.45	2.44%	30	1.4	0.4	26-27	40-42	"
test1a-5-19-00.xls	5/19/00	300	C & E	199.9	0.07%	7.40	0.62%	300	3.5	13.0	27-29	30-106	16.4-3.5-0.53
"	"	"	"	199.9	0.09%	7.42	0.62%	90	5.2	3.9	26-27	77-104	"
test1a-5-22-00.xls	5/22/00	300	C	199.9	0.08%	7.34	0.54%	300	5.6	12.9	26-29	54-152	16.4-3.5-0.53

FILE	DATE	Restrictor	TEST PROTOCOL	Flow P (psia)	Pressure variation %	Flow rate (sccm)	Flow variation %	Duration (min.)	Avg. power usage (W)	Total g Xe	T_{out} range	T_{bed} range	PB-I-D
test1a-5-23-00.xls	5/23/00	300	C	199.9	0.06%	7.36	0.52%	300	5.0	12.9	26-29	48-139	16.4-3.5-0.53
test1a-5-24-00.xls	5/24/00	300	C	199.9	0.08%	7.37	0.58%	299	4.7	12.9	26-29	44-131	16.4-3.5-0.53
test1a-5-25-00.xls	5/25/00	300	E	199.9	0.10%	7.39	0.77%	60	2.6	2.6	26-27	45-59	16.4-3.5-0.53
"	"	"	"	200.0	0.09%	7.32	0.36%	60	3.7	2.6	26-27	60-75	"
"	"	"	"	199.9	0.06%	7.33	0.36%	60	4.9	2.6	26-27	78-95	"
"	"	"	"	199.9	0.15%	7.33	0.41%	30	6.0	1.3	26-27	97-107	"
"	"	"	"	200.0	0.32%	7.34	0.58%	30	6.9	1.3	26-27	110-120	"
test1a-5-26-00.xls	5/26/00	300	C & D	160.0	0.17%	5.00	0.73%	119	1.5	3.5	25-28	29-47	16.4-3.5-0.53
"	"	"	"	119.4	1.46%	2.87	2.52%	83	1.4	1.4	26-28	34-43	"
test1a-5-30-00.xls	5/30/00	300	C & E	109.9	0.16%	2.41	1.70%	30	0.6	0.4	27-28	29-31	16.4-3.5-0.53
"	"	"	"	110.0	0.15%	2.38	0.89%	30	0.8	0.4	28-29	31-33	"
"	"	"	"	110.0	0.12%	2.39	1.19%	30	1.0	0.4	28-29	34-37	"
"	"	"	"	110.0	0.12%	2.39	1.20%	30	1.3	0.4	28-29	37-40	"
"	"	"	"	110.0	0.12%	2.40	1.15%	30	1.5	0.4	28-29	40-43	"
"	"	"	D	110-500 psia throttling		2.4-25 sccm throttling in 10 min							
test1a-5-31-00.xls	5/31/00	300	C & E	109.9	0.17%	2.41	1.43%	30	0.6	0.4	26-27	27-29	16.4-3.5-0.53
"	"	"	"	109.9	0.14%	2.39	1.04%	30	0.8	0.4	27-27	30-32	"
"	"	"	"	110.0	0.24%	2.40	1.02%	30	1.0	0.4	27-28	33-36	"
"	"	"	"	110.0	0.13%	2.39	1.21%	30	1.2	0.4	27-28	36-39	"
"	"	"	"	109.9	0.11%	2.39	1.27%	30	1.4	0.4	27-28	40-42	"
"	"	"	"	110.0	0.12%	2.38	1.23%	30	1.7	0.4	27-28	43-45	"
"	"	"	"	110.0	0.11%	2.38	1.15%	30	1.9	0.4	27-28	46-49	"
"	"	"	"	110.0	0.12%	2.40	1.12%	30	2.1	0.4	27-28	50-52	"
test1a-6-01-00.xls	6/1/00	300	C & E	112.9	0.19%	2.44	1.07%	15	0.6	0.2	24-25	25-27	16.4-3.5-0.53
"	"	"	"	112.9	0.17%	2.44	1.08%	15	0.7	0.2	25-26	27-28	"
"	"	"	"	112.9	0.15%	2.45	1.12%	15	0.9	0.2	26-26	29-30	"
"	"	"	"	112.9	0.16%	2.45	1.47%	15	1.0	0.2	25-26	31-32	"
"	"	"	"	113.0	0.08%	2.44	1.02%	15	1.1	0.2	26-26	33-34	"
"	"	"	"	113.3	0.60%	2.44	1.49%	15	1.1	0.2	26-27	34-36	"
"	"	"	"	112.8	0.25%	2.42	0.80%	15	1.4	0.2	26-27	36-37	"
"	"	"	"	113.1	1.07%	2.44	2.44%	15	1.4	0.2	26-26	38-39	"
"	"	"	"	112.9	0.09%	2.43	0.67%	15	1.6	0.2	26-27	40-41	"
"	"	"	"	113.0	0.07%	2.44	0.68%	15	1.7	0.2	26-27	41-43	"
"	"	"	"	113.0	0.07%	2.43	0.69%	15	1.8	0.2	26-27	43-45	"
"	"	"	"	113.0	0.54%	2.43	1.49%	15	1.9	0.2	26-27	45-46	"
"	"	"	"	112.9	0.09%	2.43	0.78%	15	2.1	0.2	26-27	47-48	"
"	"	"	"	113.0	0.17%	2.42	1.00%	15	2.2	0.2	26-27	49-51	"
"	"	"	"	113.0	0.57%	2.44	1.45%	15	2.4	0.2	26-27	51-52	"

FILE	DATE	Restrictor	TEST PROTOCOL	Flow P (psia)	Pressure variation %	Flow rate (sccm)	Flow variation %	Duration (min.)	Avg. power usage (W)	Total g Xe	T_{out} range	T_{bed} range	PB-I-D
test1a-6-02-00.xls	6/2/00	300	C & E	149.9	0.11%	4.46	1.17%	30	1.6	0.8	24-27	38-42	16.4-3.5-0.53
"	"	"	"	149.9	0.10%	4.44	0.68%	30	2.0	0.8	26-28	43-48	"
"	"	"	"	149.9	0.12%	4.43	0.60%	30	2.3	0.8	27-29	49-53	"
"	"	"	"	149.9	0.09%	4.45	0.78%	30	2.7	0.8	27-29	55-59	"
"	"	"	"	150.0	0.19%	4.44	0.54%	15	3.0	0.4	28-29	60-62	"
"	"	"	"	150.0	0.06%	4.43	0.42%	15	3.2	0.4	28-29	63-65	"
"	"	"	"	150.0	0.07%	4.43	0.73%	15	3.4	0.4	28-29	66-69	"
"	"	"	"	150.0	0.07%	4.43	0.68%	15	3.7	0.4	28-28	70-72	"
"	"	"	"	150.0	0.15%	4.43	0.68%	15	3.9	0.4	28-29	73-76	"
"	"	"	"	150.0	0.07%	4.44	0.44%	15	4.1	0.4	28-28	77-79	"
"	"	"	"	150.0	0.08%	4.43	0.50%	15	4.4	0.4	28-28	80-83	"
"	"	"	"	150.0	0.06%	4.44	0.47%	15	4.7	0.4	28-28	84-87	"
"	"	"	"	150.0	0.07%	4.44	0.48%	15	4.9	0.4	28-28	88-91	"
"	"	"	"	150.0	0.07%	4.44	0.44%	15	5.2	0.4	28-28	92-95	"
"	"	"	"	150.0	0.07%	4.43	0.48%	15	5.5	0.4	28-28	96-100	"
test1a-6-05-00.xls	6/5/00	300	C & E	199.9	0.13%	7.44	0.55%	15	2.4	0.6	26-27	47-50	16.4-3.5-0.53
"	"	"	"	199.9	0.13%	7.38	0.39%	15	2.7	0.6	27-28	52-54	"
"	"	"	"	199.9	0.10%	7.37	0.44%	15	3.0	0.6	27-28	57-60	"
"	"	"	"	199.9	0.11%	7.37	0.40%	15	3.4	0.6	27-28	62-65	"
"	"	"	"	199.9	0.12%	7.36	0.41%	15	3.8	0.6	27-28	67-71	"
"	"	"	"	199.9	0.12%	7.36	0.38%	15	4.1	0.6	27-28	73-76	"
"	"	"	"	199.9	0.11%	7.35	0.43%	15	4.6	0.6	27-28	79-82	"
"	"	"	"	199.9	0.11%	7.36	0.45%	15	5.0	0.6	27-28	85-89	"
"	"	"	"	199.9	0.11%	7.37	0.46%	15	5.5	0.6	27-28	91-95	"
"	"	"	"	199.9	0.11%	7.37	0.47%	15	5.9	0.6	27-28	98-102	"
"	"	"	"	199.9	0.11%	7.37	0.38%	15	6.4	0.6	27-28	105-109	"
"	"	"	"	199.9	0.10%	7.36	0.41%	15	6.9	0.6	27-28	112-117	"
test1a-6-06-00.xls	6/6/00	300	C & E	249.8	0.19%	10.58	0.42%	15	2.0	0.9	26-27	37-40	16.4-3.5-0.53
"	"	"	"	249.8	0.15%	10.50	0.64%	15	2.4	0.9	27-28	42-46	"
"	"	"	"	249.8	0.13%	10.46	0.63%	15	2.8	0.9	27-28	49-53	"
"	"	"	"	249.8	0.13%	10.46	0.65%	15	3.3	0.9	27-28	55-59	"
"	"	"	"	249.8	0.12%	10.45	0.65%	15	3.7	0.9	28-29	62-67	"
"	"	"	"	249.8	0.11%	10.46	0.64%	15	4.3	0.9	27-28	70-74	"
"	"	"	"	249.8	0.13%	10.46	0.67%	15	4.8	0.9	27-28	77-82	"
"	"	"	"	249.8	0.11%	10.46	0.62%	15	5.4	0.9	27-28	85-91	"
"	"	"	"	249.8	0.13%	10.46	0.65%	15	6.0	0.9	27-28	94-99	"
"	"	"	"	249.8	0.11%	10.45	0.64%	15	6.7	0.9	27-28	103-109	"
"	"	"	"	249.8	0.11%	10.46	0.66%	15	7.4	0.9	27-28	113-119	"

FILE	DATE	Restrictor	TEST PROTOCOL	Flow P (psia)	Pressure variation %	Flow rate (sccm)	Flow variation %	Duration (min.)	Avg. power usage (W)	Total g Xe	T_{out} range	T_{bed} range	PB-I-D
"	"	"	"	249.8	0.11%	10.47	0.62%	15	8.1	0.9	27-28	123-130	"
test1a-6-09-00.xls	6/9/00	300	E	249.8	0.13%	10.54	0.54%	30	2.0	1.8	25-28	35-43	16.4-3.5-0.53
"	"	"	"	249.8	0.13%	10.54	0.45%	30	2.1	1.8	25-28	36-44	"
"	"	"	"	299.7	0.13%	13.67	0.71%	19	4.4	1.5	26-27	66-73	"
test1a-6-15-00.xls	6/15/00	45	B	264.6	2.83%	43.63	0.73%	15	50.5	3.8	26-28	29-145	16.4-3.5-0.53
"	"	"	"	269.4	2.29%	43.84	0.62%	13	39.0	3.3	26-27	27-119	"
test1a-6-16-00.xls	6/16/00	45	B	300.8	2.81%	44.90	0.64%	12	35.6	3.2	26-27	27-129	16.4-3.5-0.53
"	"	"	"	299.1	3.19%	44.77	0.64%	10	38.0	2.6	25-26	41-125	"

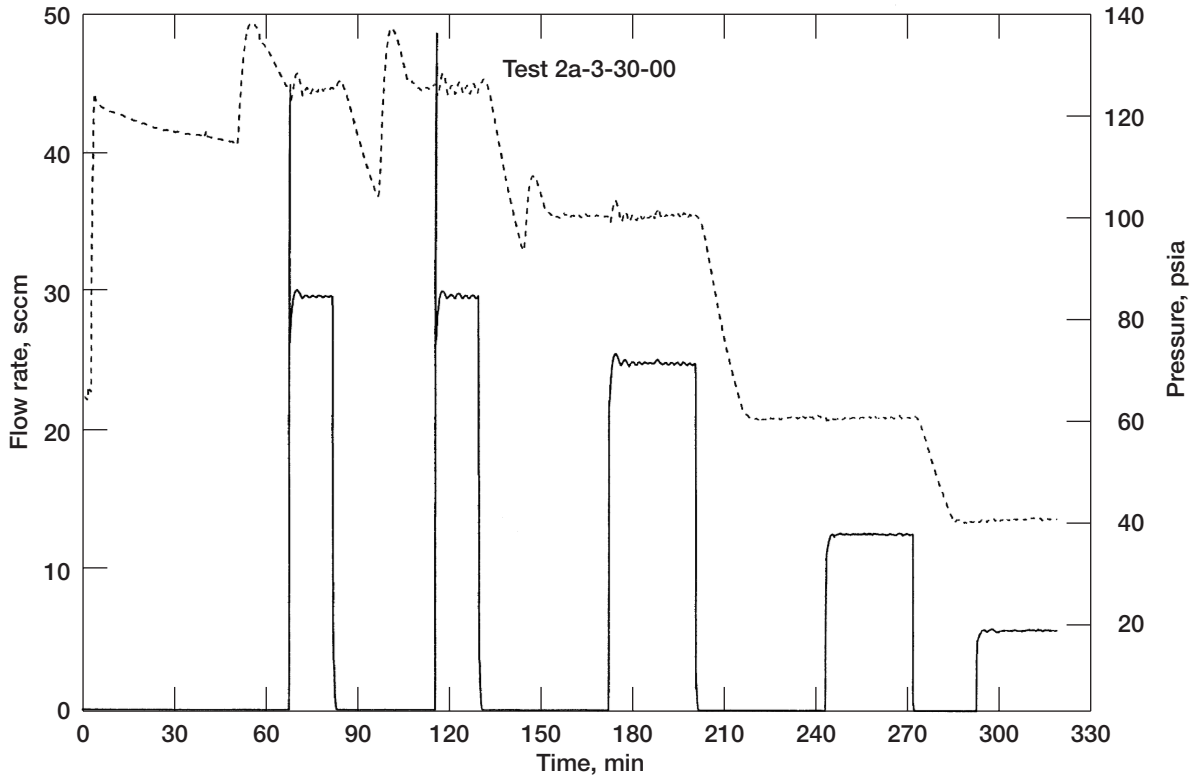
APPENDIX D

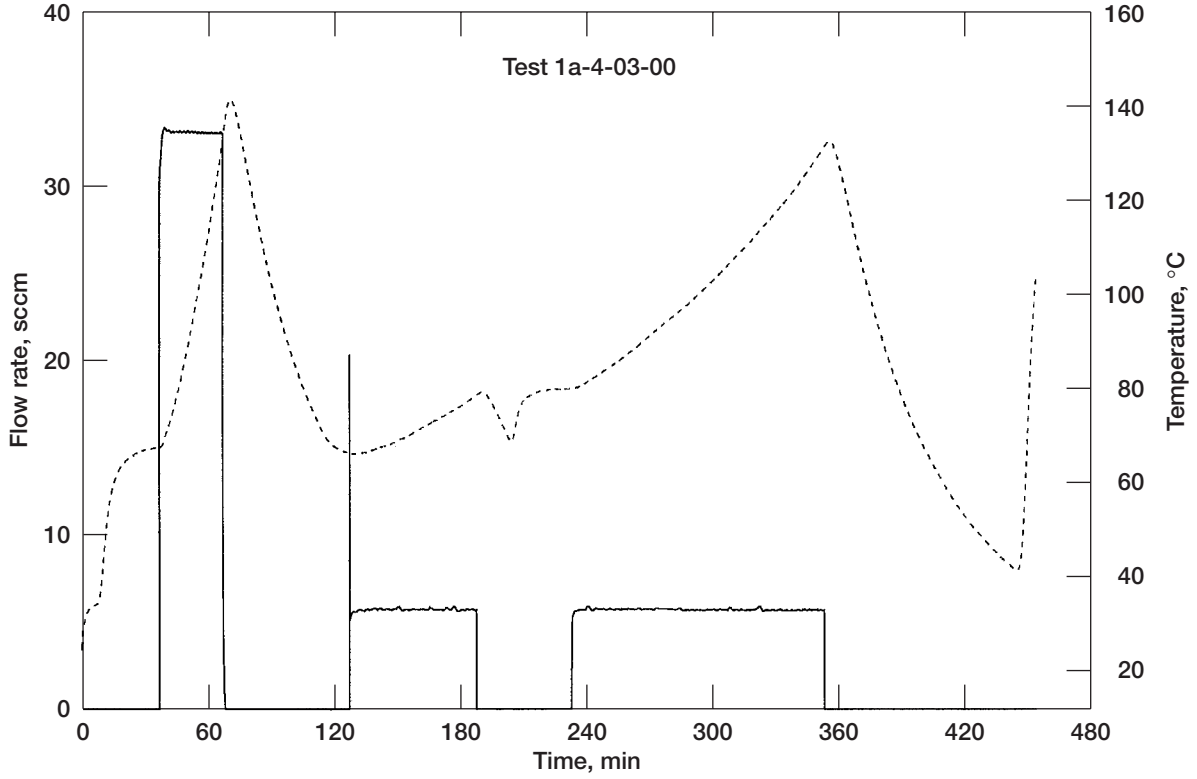
GRAPHICAL RESULTS OF BREADBOARD EXPERIMENTS

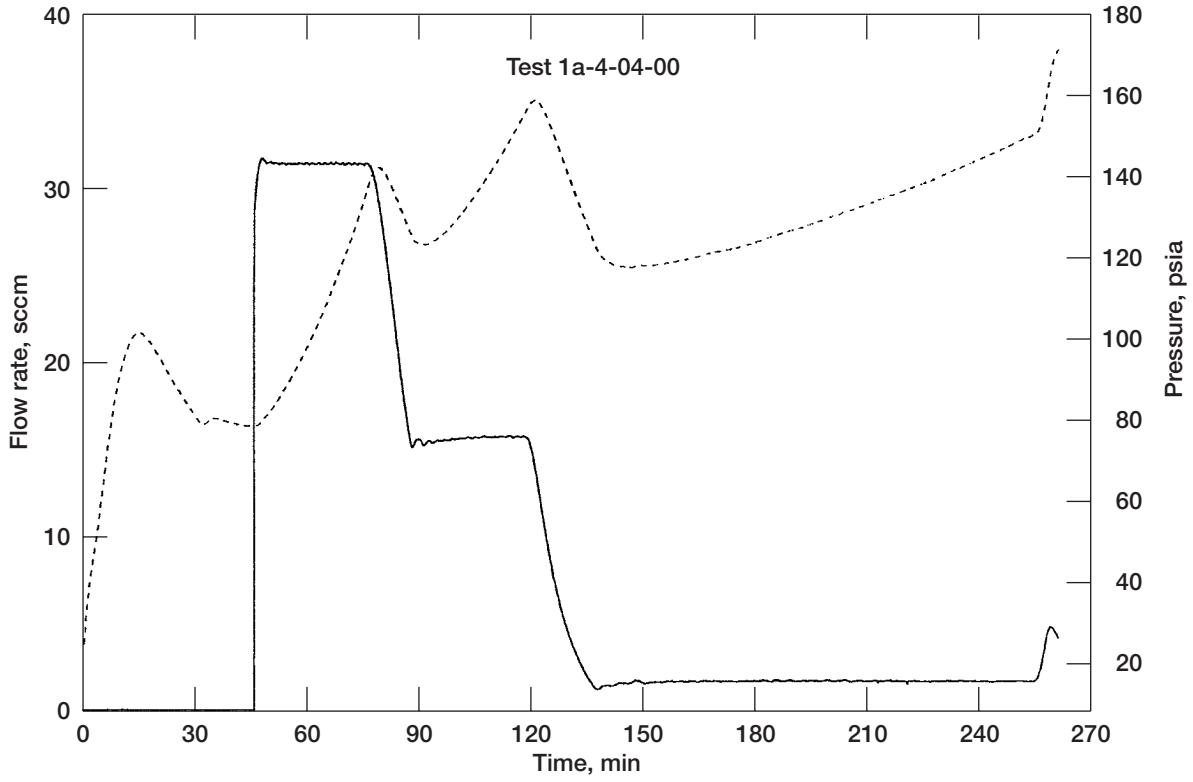
For all of the following graphs:

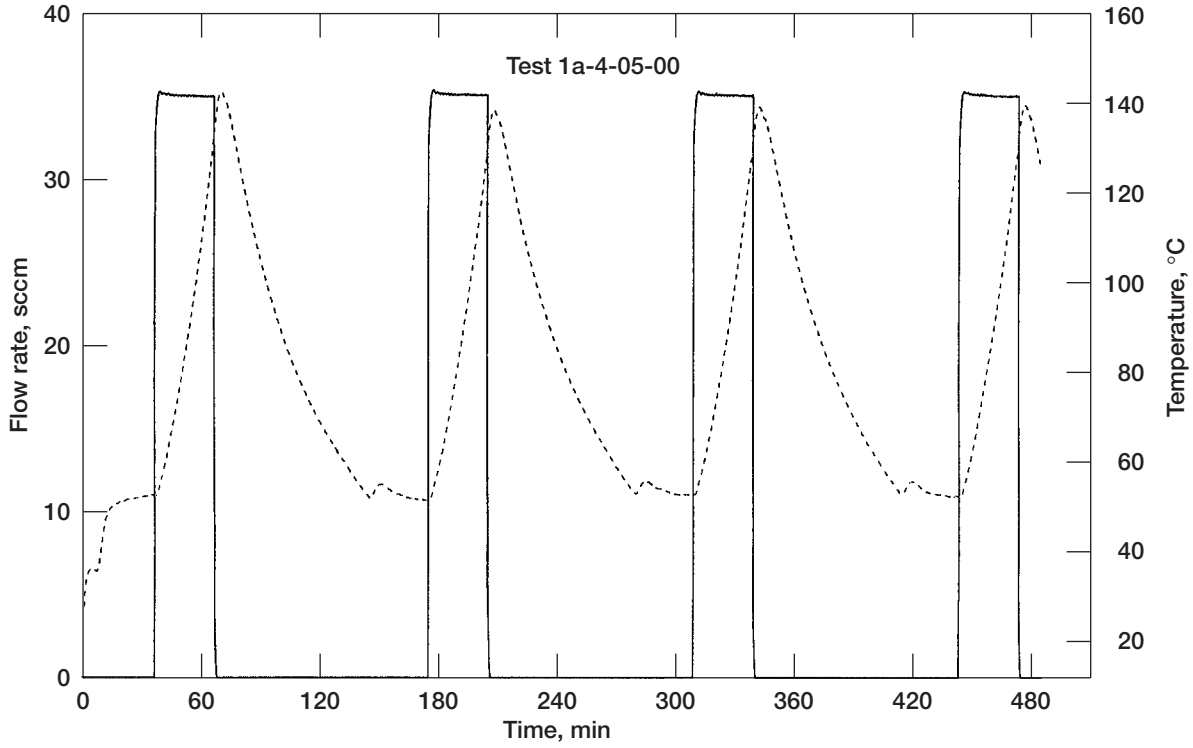
Xe Flow Rate in sccm – SOLID LINES

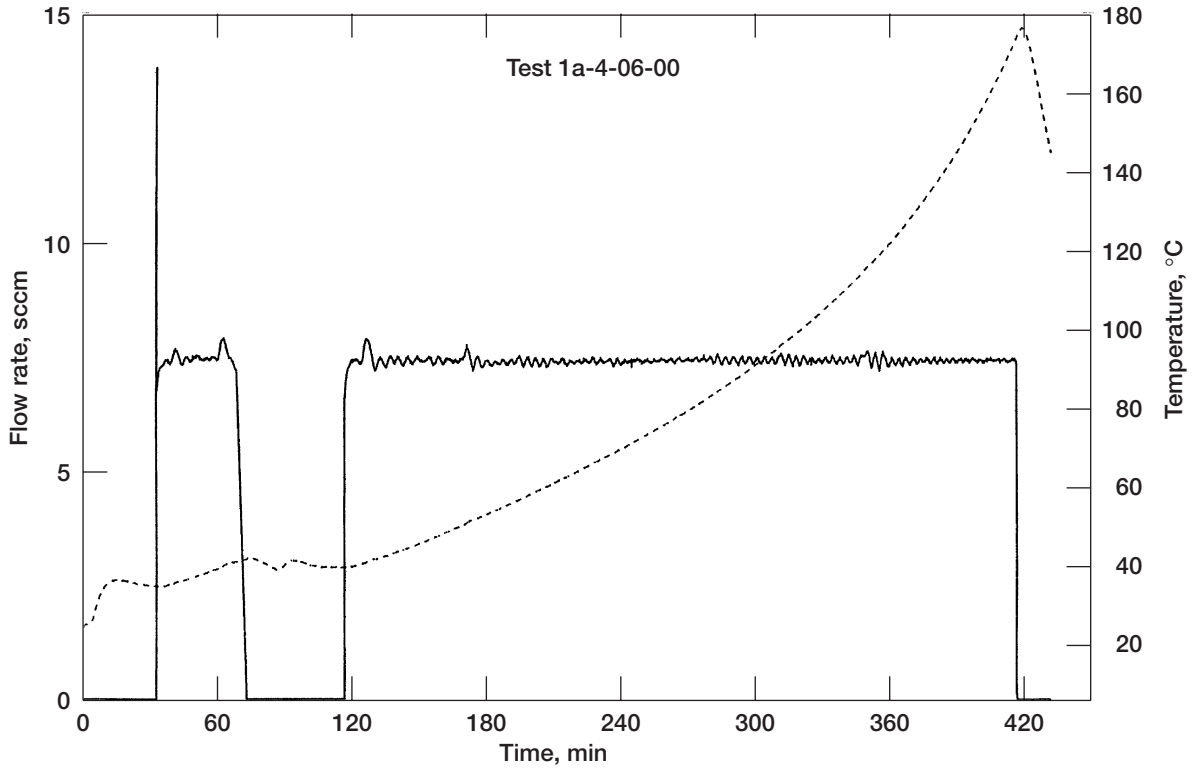
Carbon Bed Temperature or Pressure – DASHED LINES

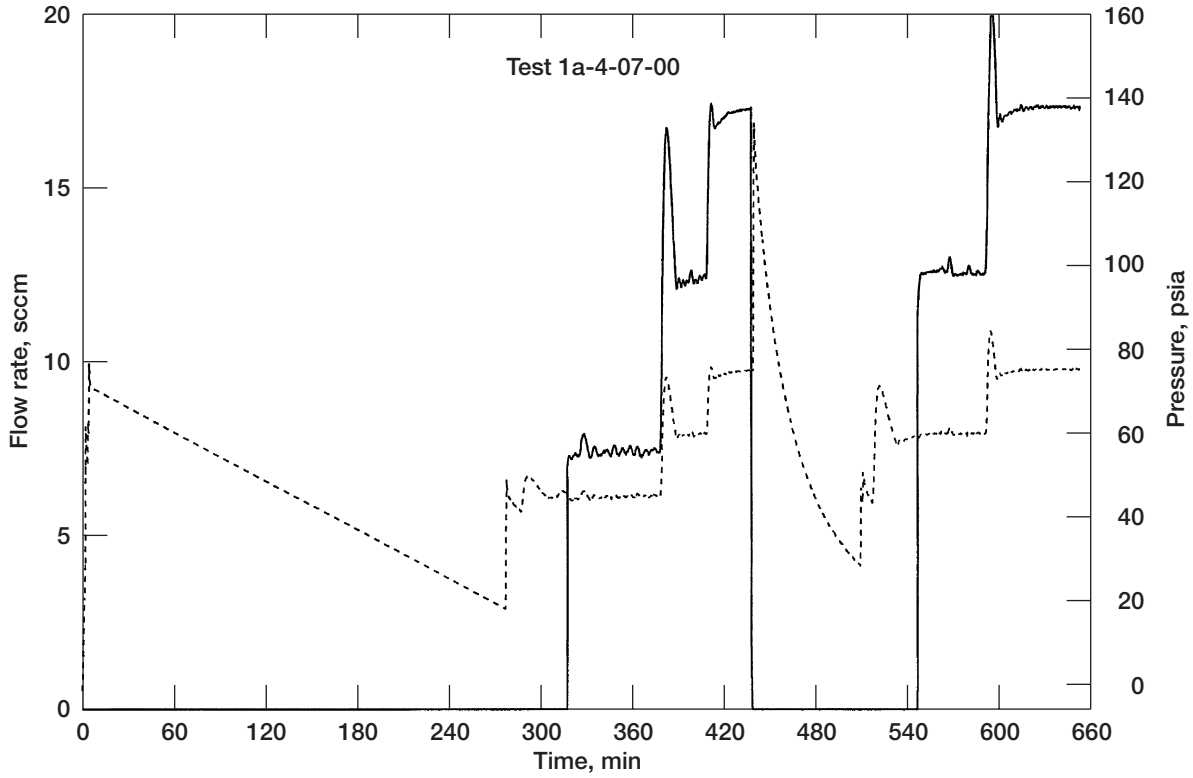

Test 2a-3-30-00
Flow rate, sccm
Pressure, psia
Time, min
0
10
20
30
40
50
20
40
60
80
100
120
140
0
30
60
90
120
150
180
210
240
270
300
330

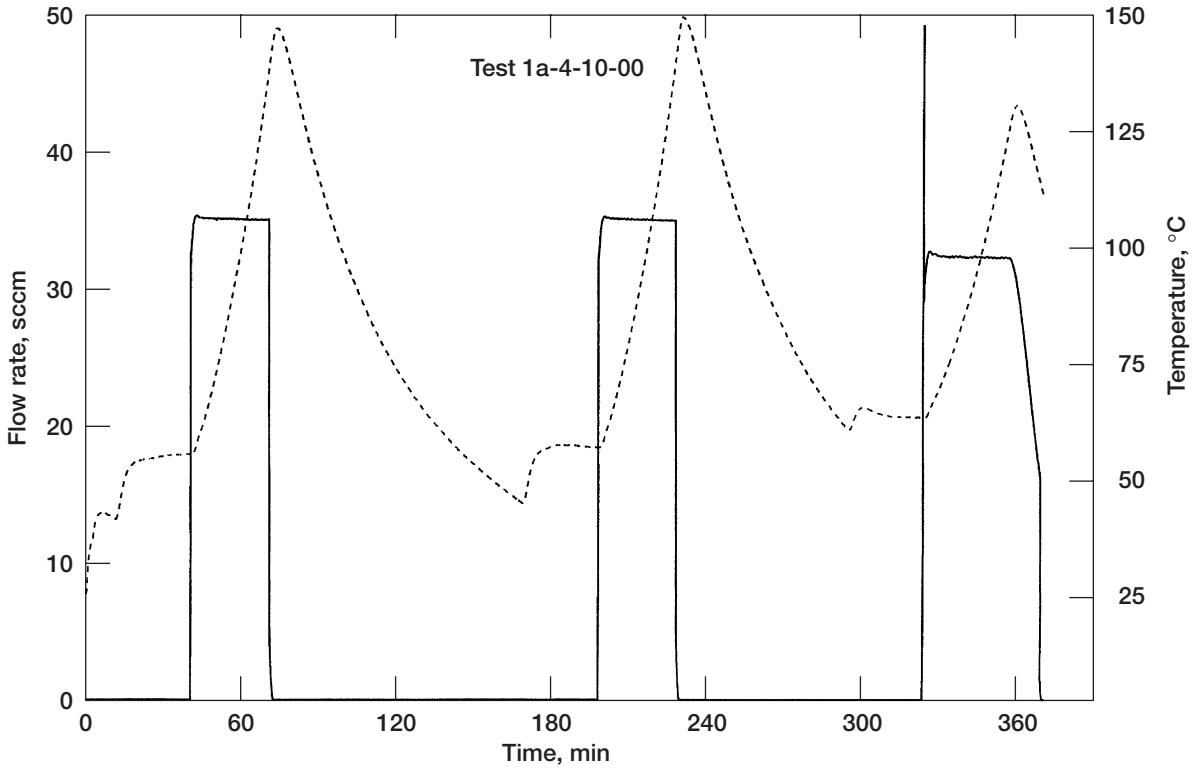

Test 1a-4-03-00
Flow rate, sccm
Temperature, °C
Time, min
0
10
20
30
40
20
40
60
80
100
120
140
160
0
60
120
180
240
300
360
420
480

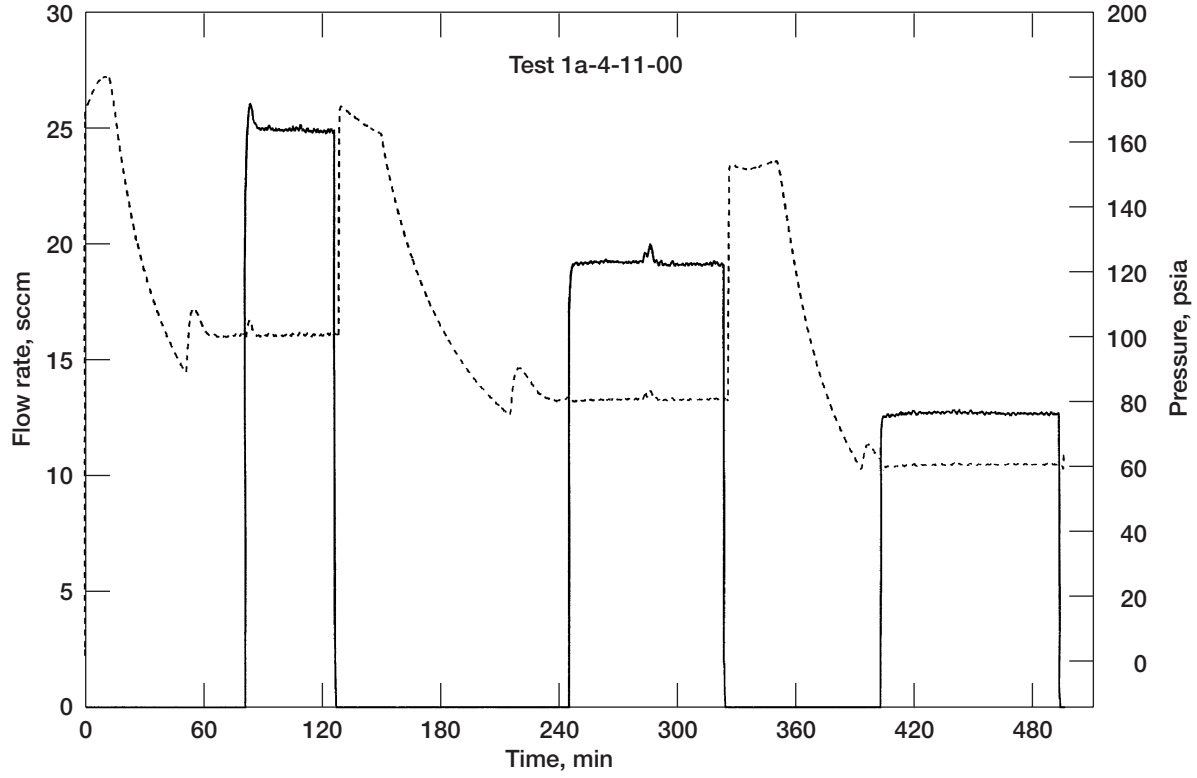

Test 1a-4-04-00
Flow rate, sccm
Pressure, psia
Time, min
0
10
20
30
40
20
40
60
80
100
120
140
160
180
0
30
60
90
120
150
180
210
240
270

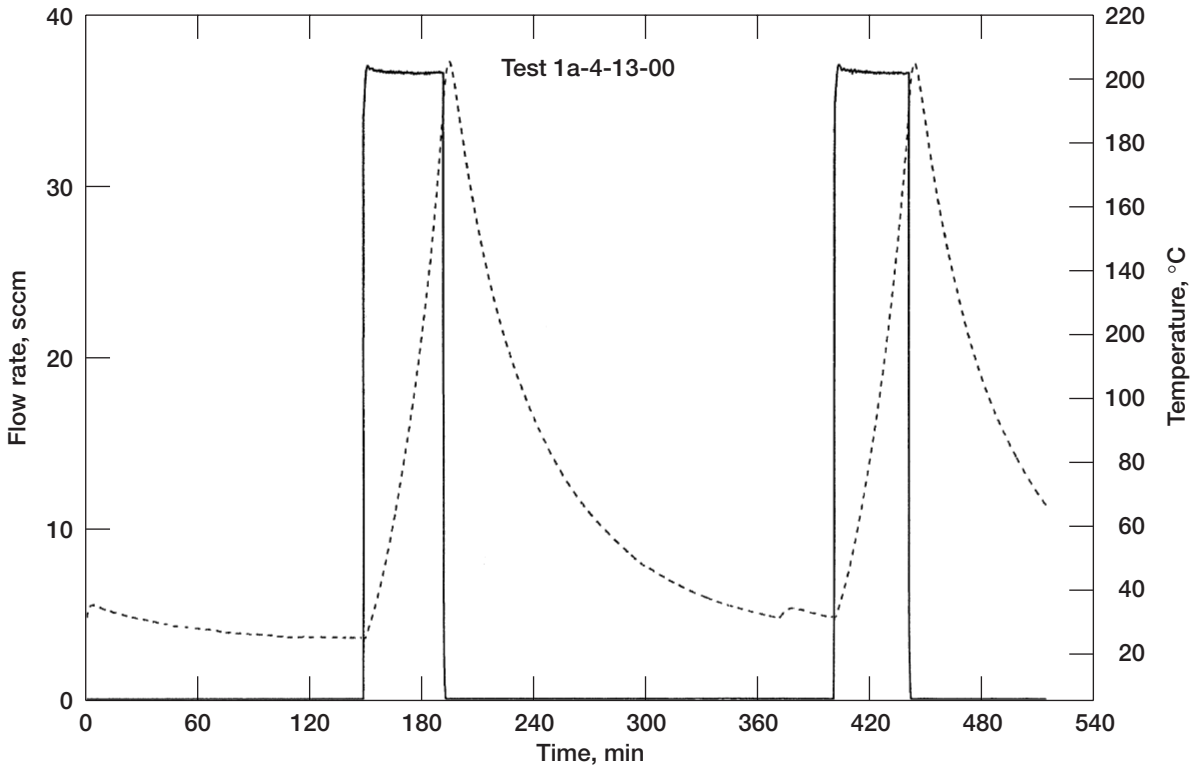

Test 1a-4-05-00
Flow rate, sccm
Temperature, °C
Time, min
0
10
20
30
40
20
40
60
80
100
120
140
160
0
60
120
180
240
300
360
420
480

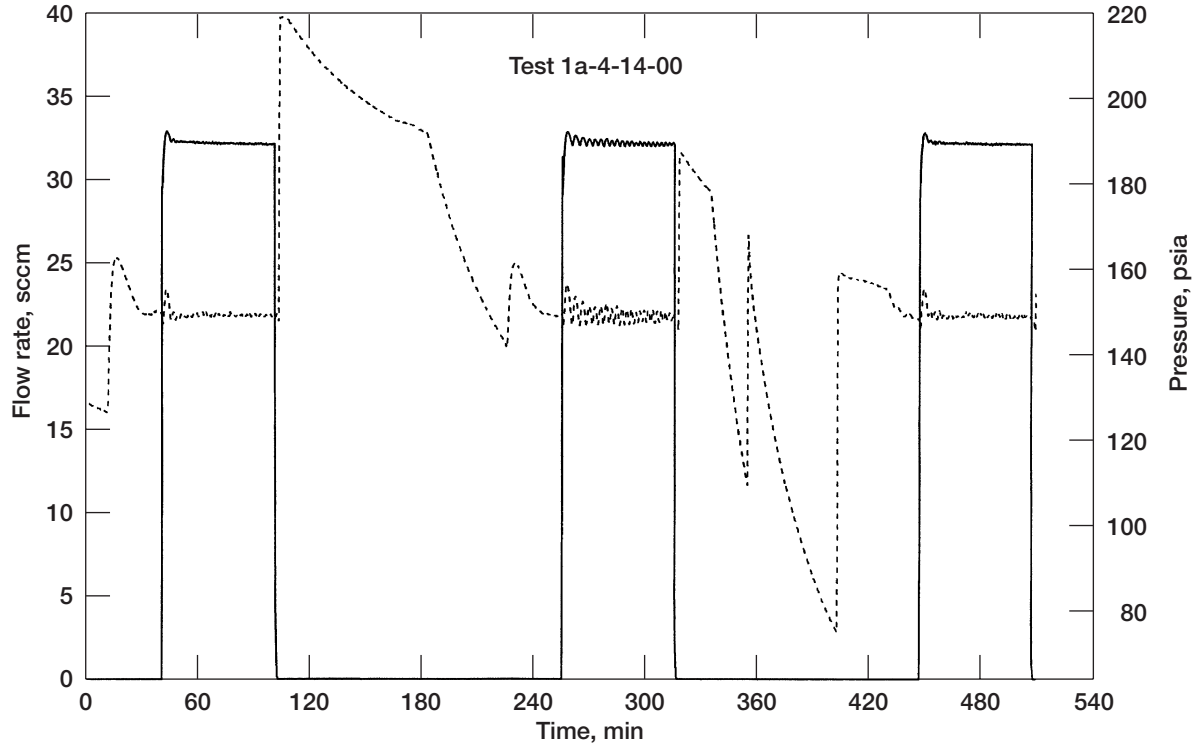

Test 1a-4-06-00
Flow rate, sccm
Temperature, °C
Time, min
0
5
10
15
20
40
60
80
100
120
140
160
180
0
60
120
180
240
300
360
420

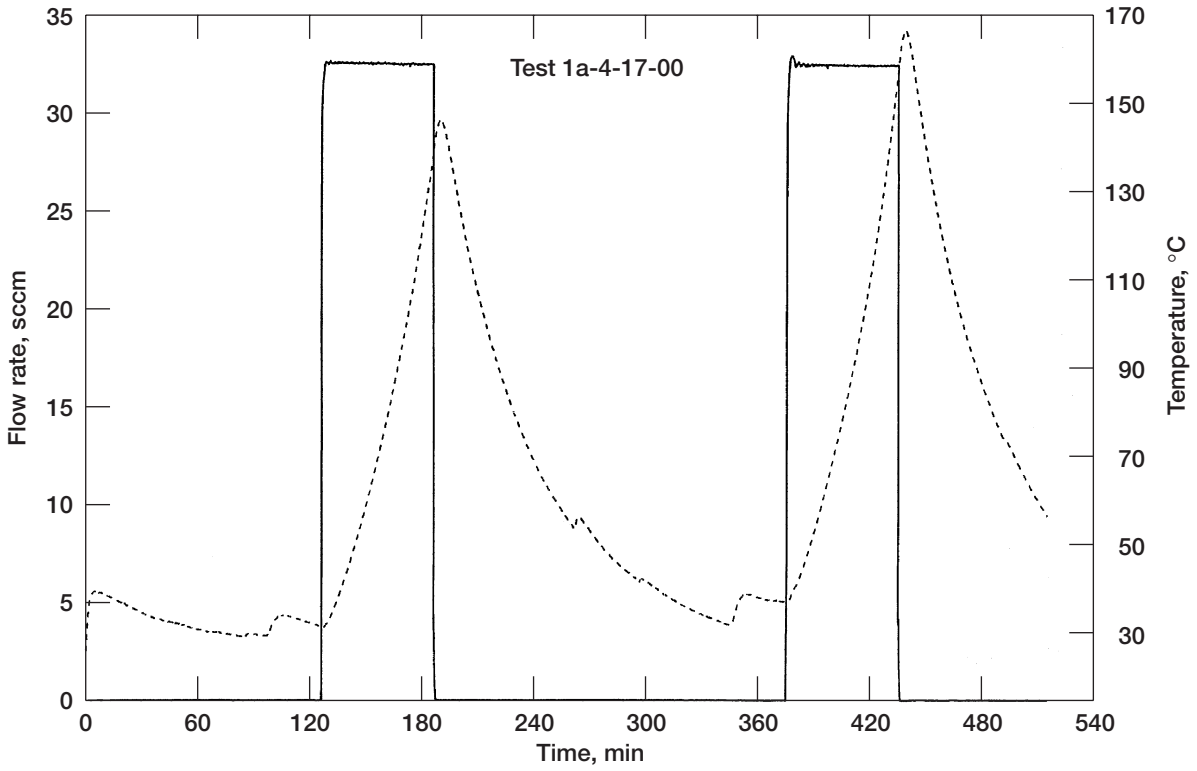

Test 1a-4-07-00
Flow rate, sccm
Pressure, psia
Time, min
0
5
10
15
20
0
20
40
60
80
100
120
140
160
0
60
120
180
240
300
360
420
480
540
600
660

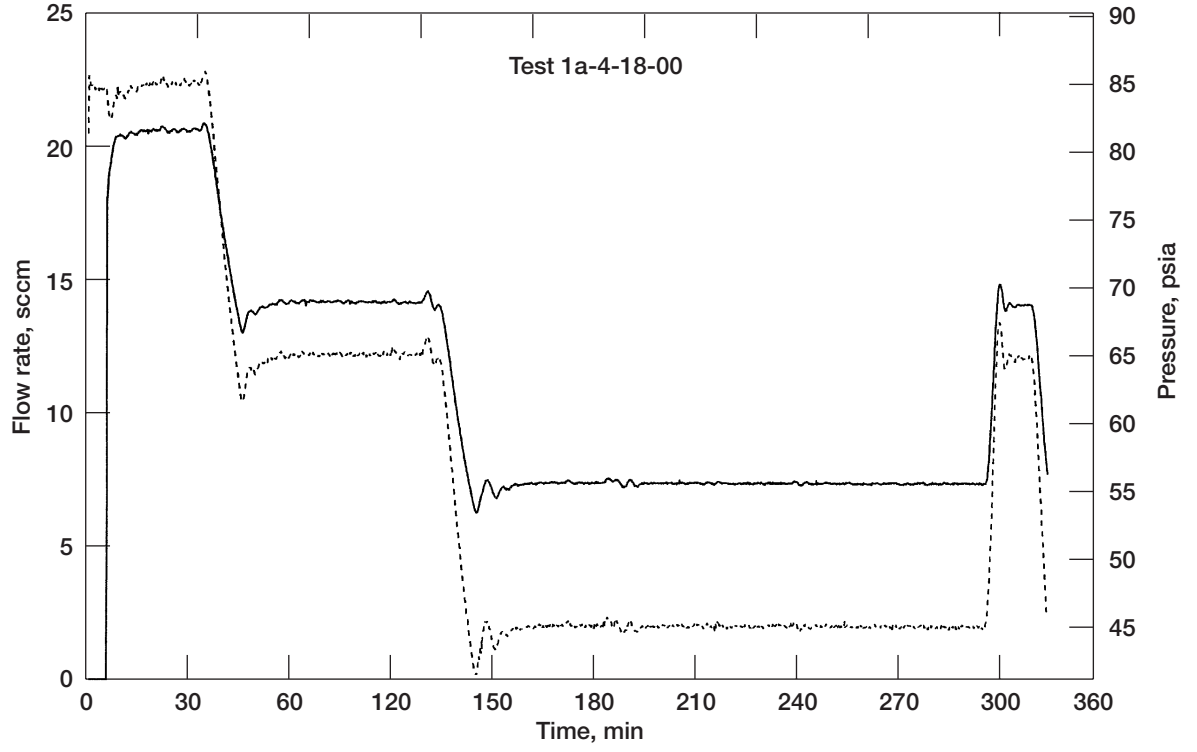

Test 1a-4-10-00
Flow rate, sccm
Temperature, °C
Time, min
0
10
20
30
40
50
25
50
75
100
125
150
0
60
120
180
240
300
360

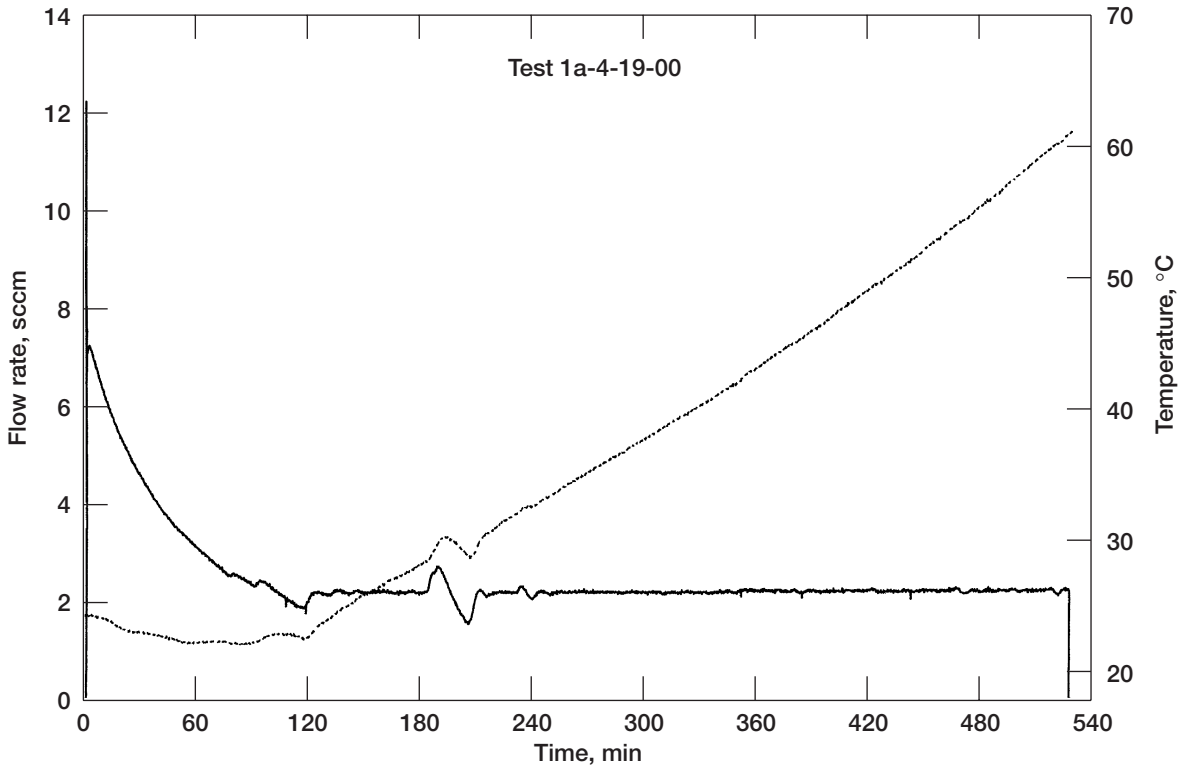

Test 1a-4-11-00
Flow rate, sccm
Pressure, psia
Time, min
0
5
10
15
20
25
30
0
20
40
60
80
100
120
140
160
180
200
0
60
120
180
240
300
360
420
480

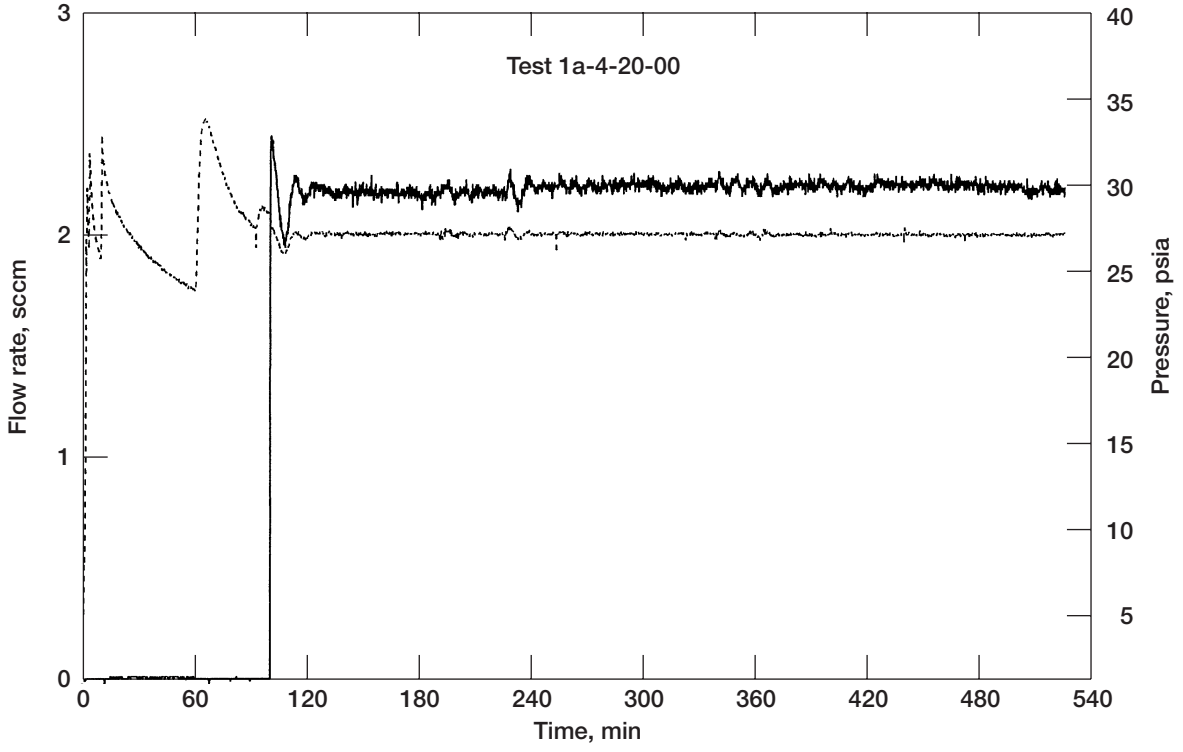

Test 1a-4-13-00
Flow rate, sccm
Temperature, °C
Time, min
0
10
20
30
40
20
40
60
80
100
200
140
160
180
200
220
0
60
120
180
240
300
360
420
480
540

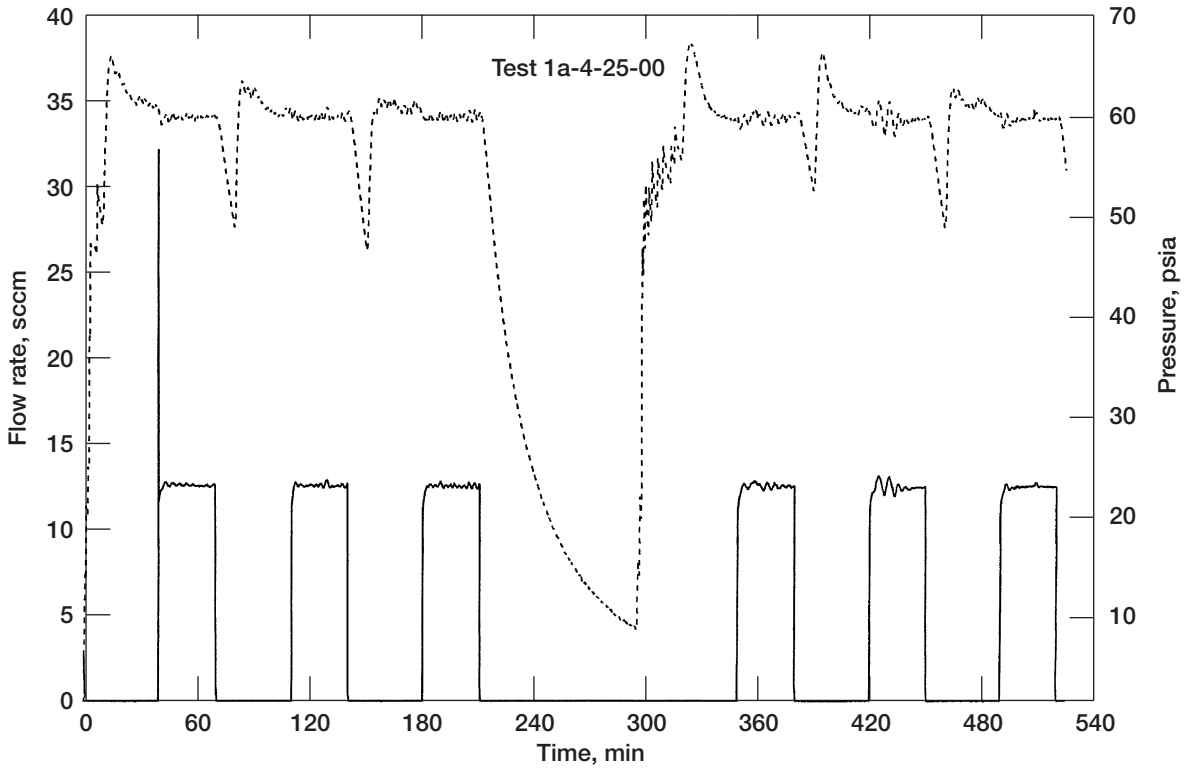

Test 1a-4-14-00
Flow rate, sccm
Pressure, psia
Time, min
0
5
10
15
20
25
30
35
40
80
100
120
140
160
180
200
220
0
60
120
180
240
300
360
420
480
540

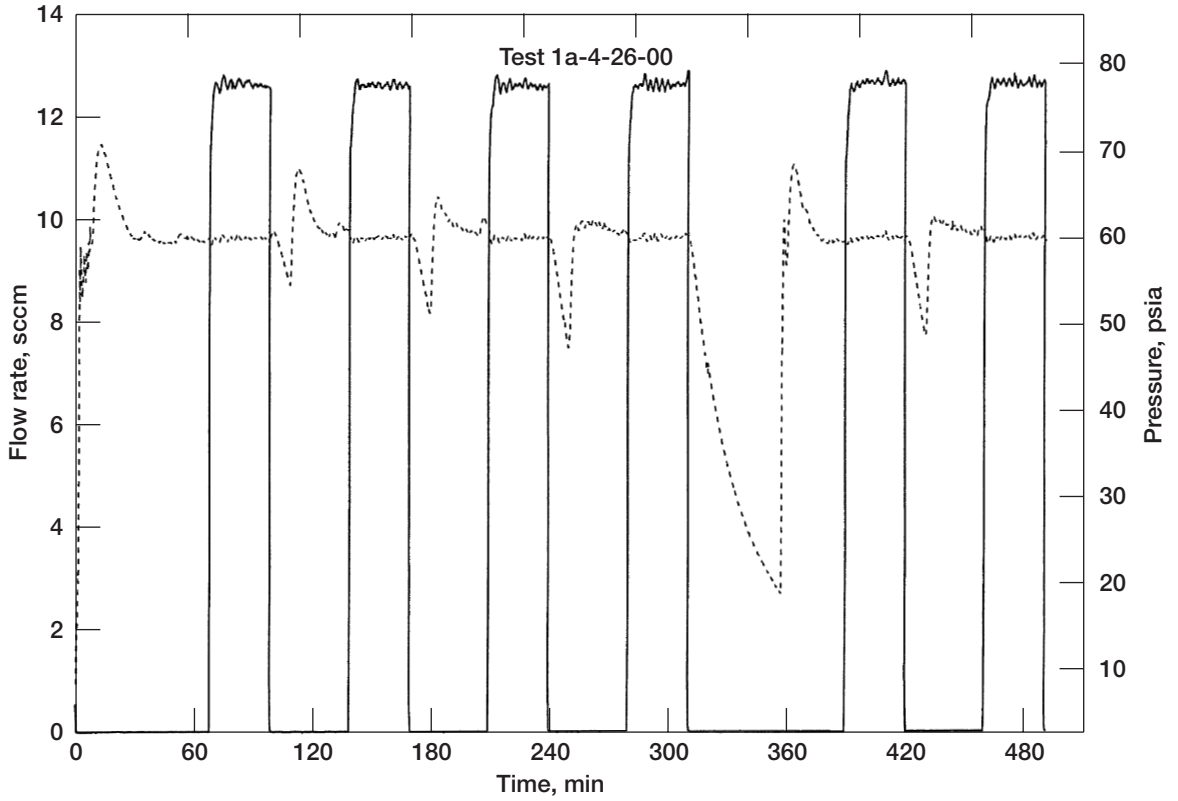

Test 1a-4-17-00
Flow rate, sccm
Temperature, °C
Time, min
0
5
10
15
20
25
30
35
30
50
70
90
110
130
150
170
0
60
120
180
240
300
360
420
480
540

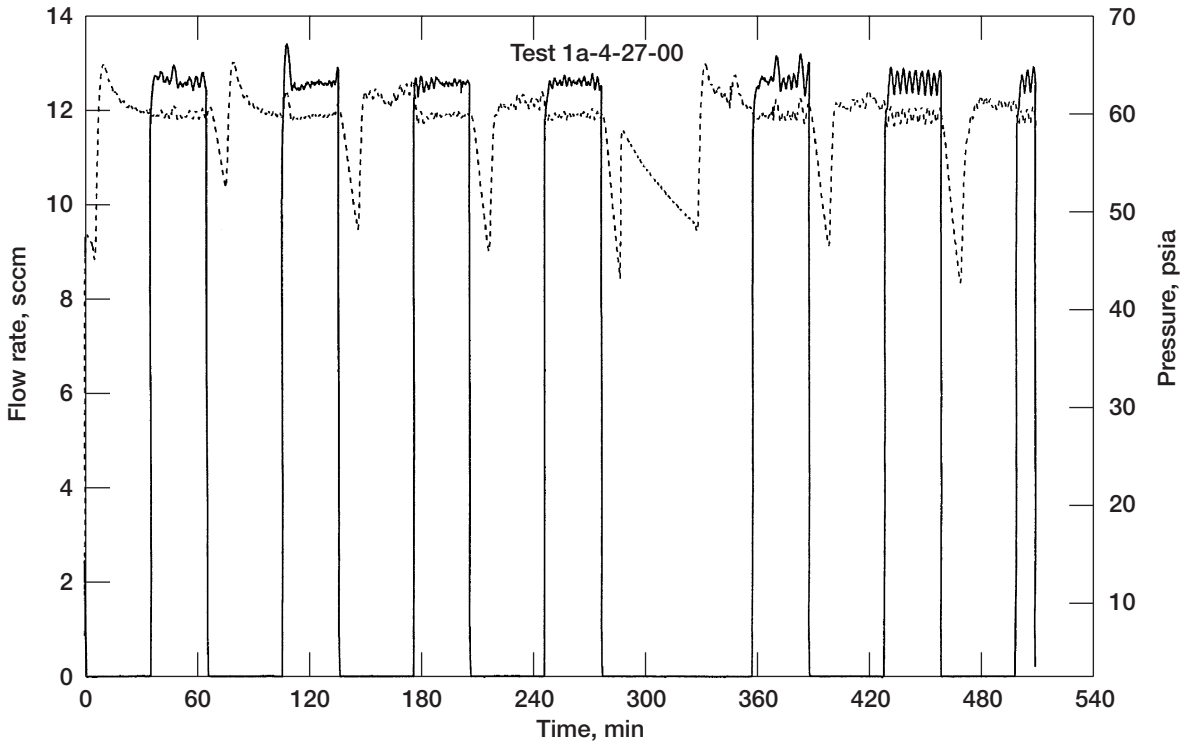

Test 1a-4-18-00
Flow rate, sccm
Pressure, psia
Time, min
0
5
10
15
20
25
45
50
55
60
65
70
75
80
85
90
0
30
60
120
150
180
210
240
270
300
360

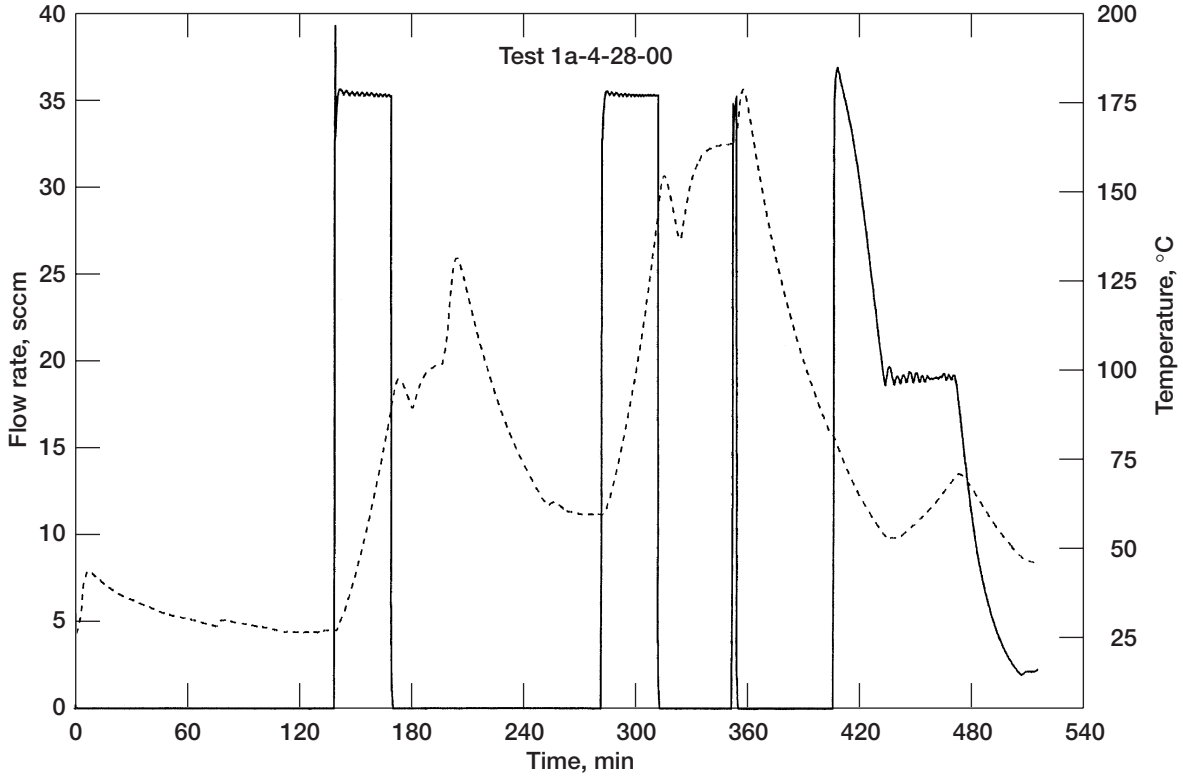

Test 1a-4-19-00
Flow rate, sccm
Temperature, °C
Time, min
0
2
4
6
8
10
12
14
20
30
40
50
60
70
0
60
120
180
240
300
360
420
480
540

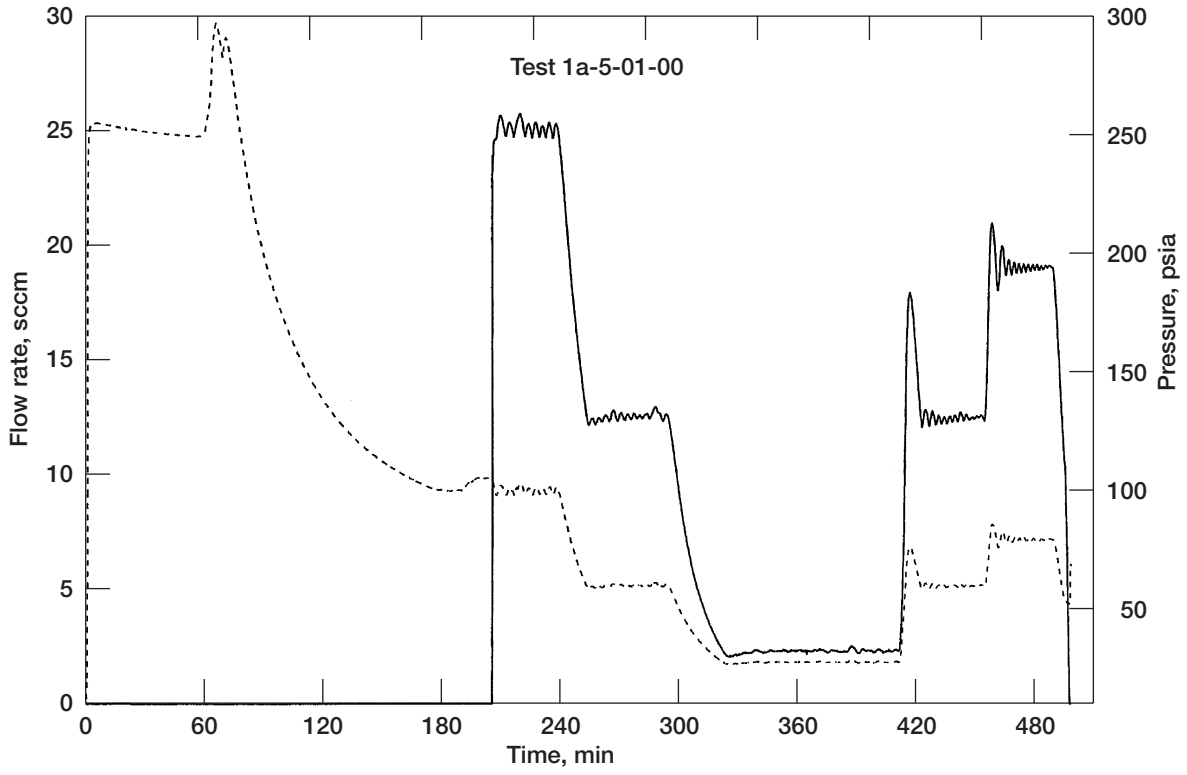

Test 1a-4-20-00
Flow rate, sccm
Pressure, psia
Time, min
0
1
2
3
5
10
15
20
25
30
35
40
0
60
120
180
240
300
360
420
480
540

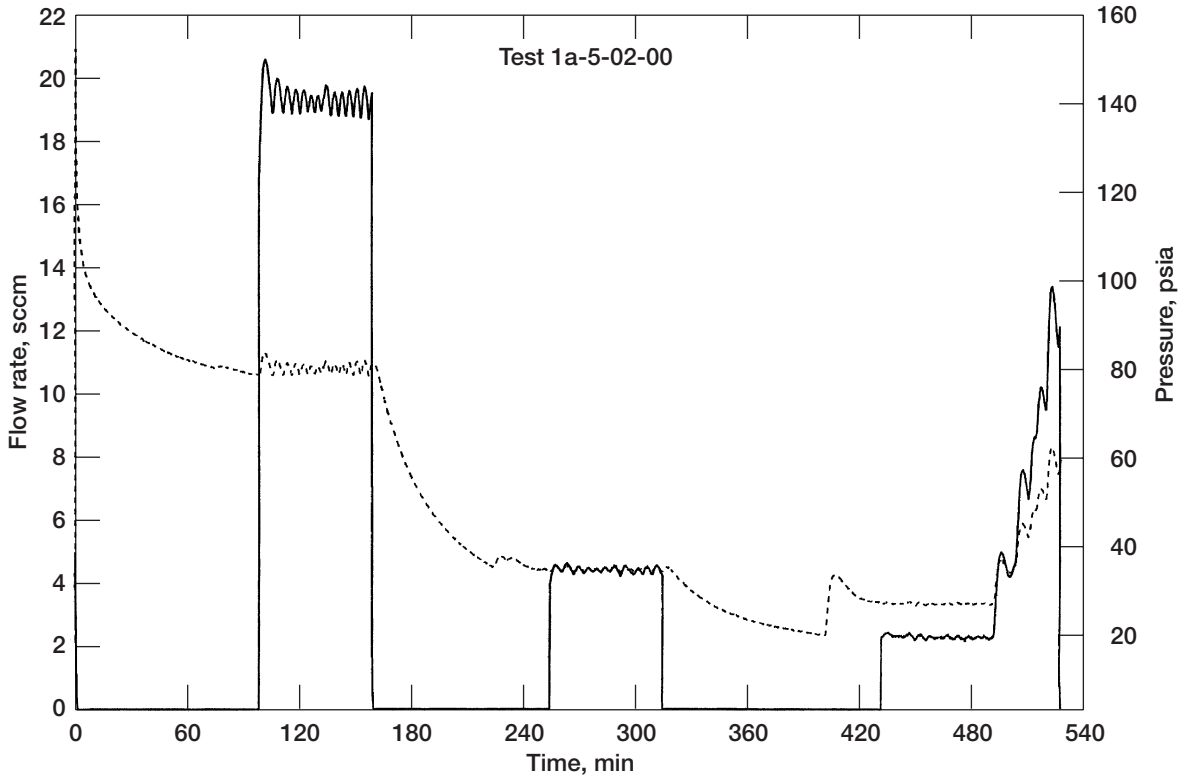

Test 1a-4-25-00
Flow rate, sccm
Pressure, psia
Time, min
0
5
10
15
20
25
30
35
40
10
20
30
40
50
60
70
0
60
120
180
240
300
360
420
480
540

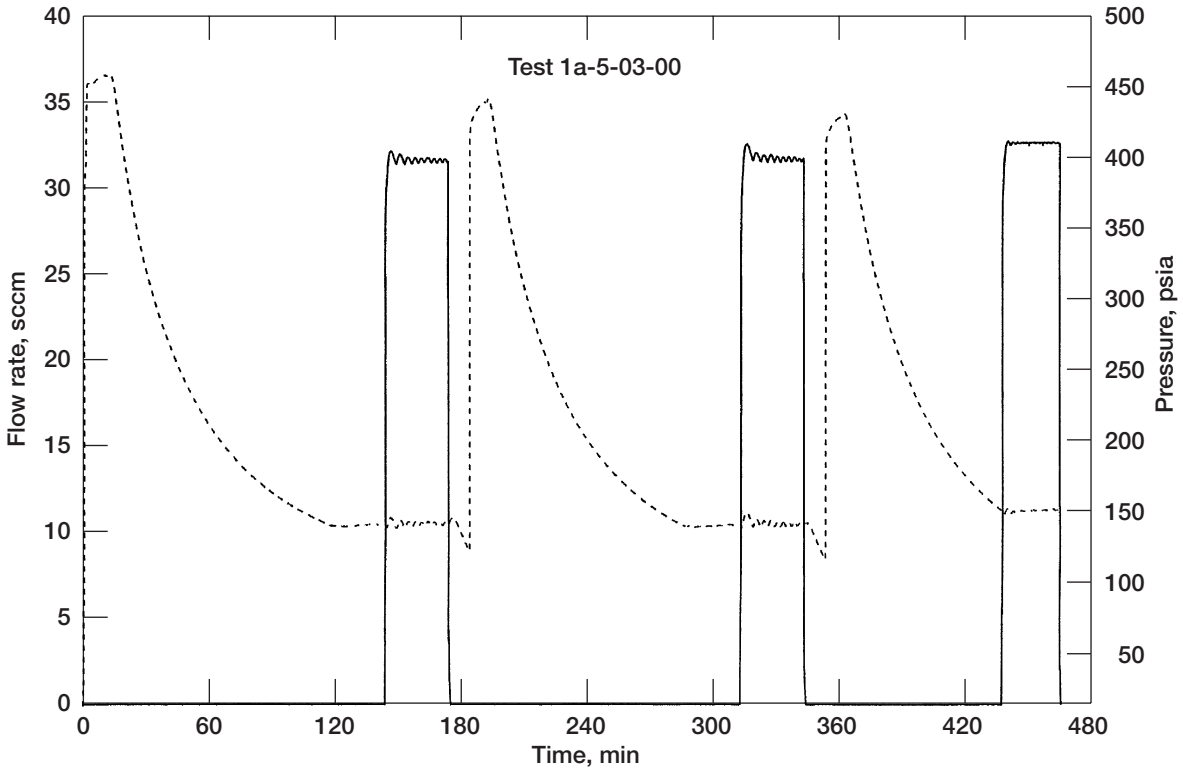

Test 1a-4-26-00
Flow rate, sccm
Pressure, psia
Time, min
0
2
4
6
8
10
12
14
10
20
30
40
50
60
70
80
0
60
120
180
240
300
360
420
480

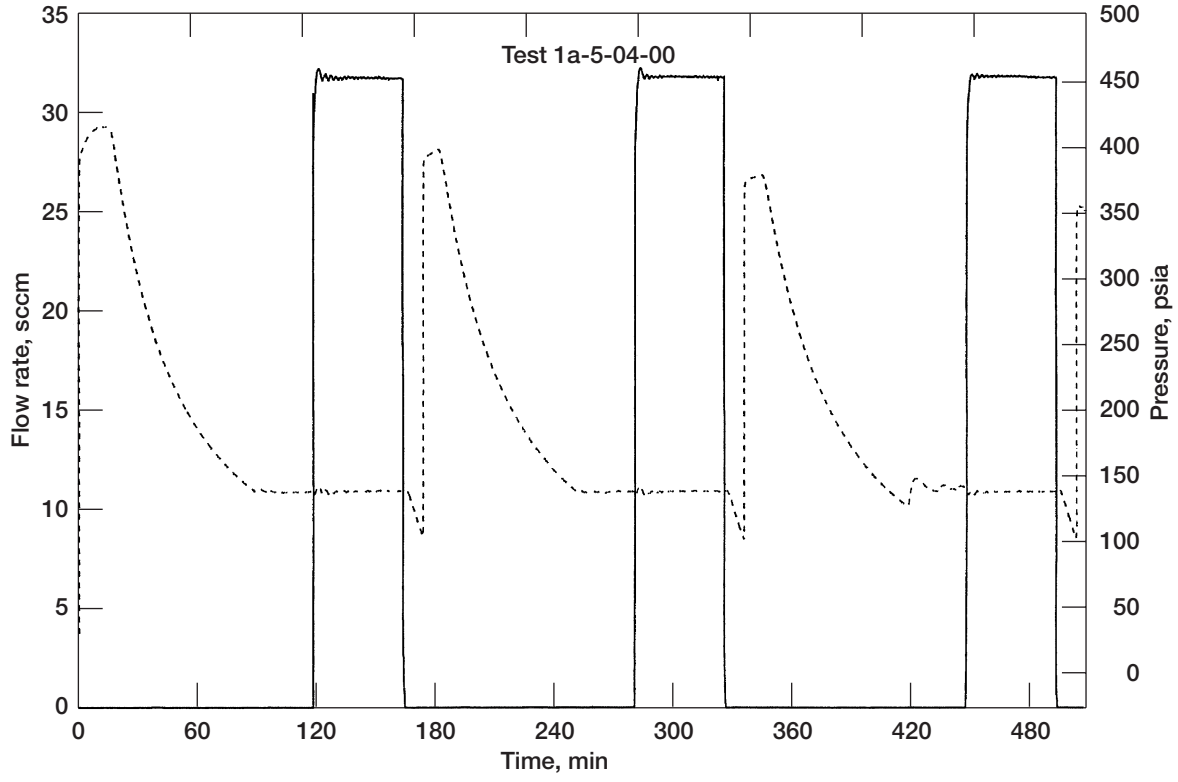

Test 1a-4-27-00
Flow rate, sccm
Pressure, psia
Time, min
0
2
4
6
8
10
12
14
10
20
30
40
50
60
70
0
60
120
180
240
300
360
420
480
540

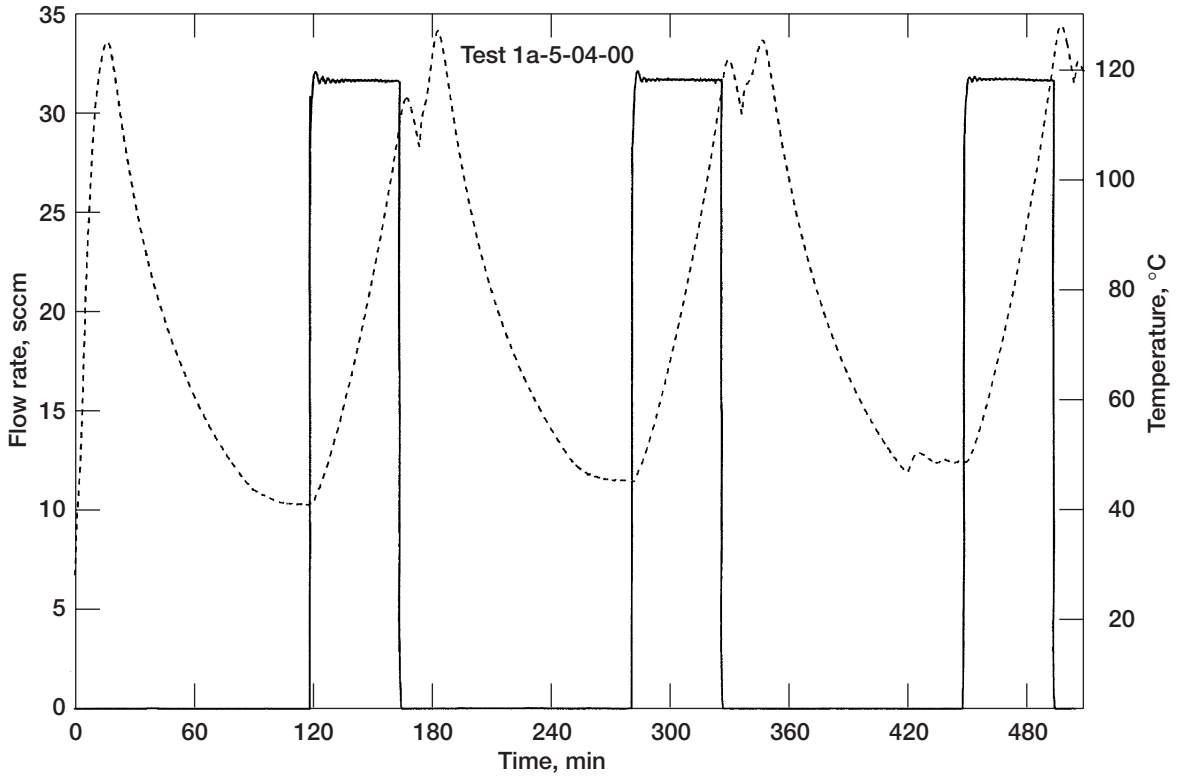

Test 1a-4-28-00
Flow rate, sccm
Temperature, °C
Time, min
0
5
10
15
20
25
30
35
40
25
50
75
100
125
150
175
200
0
60
120
180
240
300
360
420
480
540

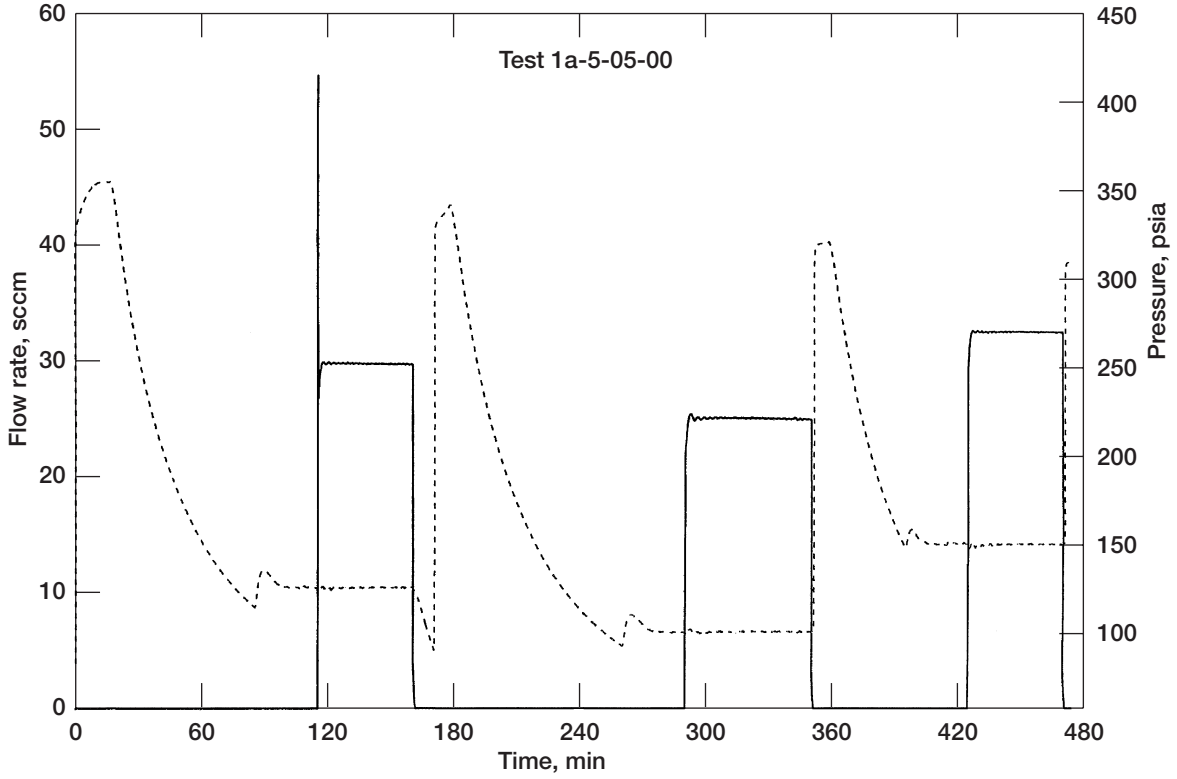

Test 1a-5-01-00
Flow rate, sccm
Pressure, psia
Time, min
0
5
10
15
20
25
30
50
100
150
200
250
300
0
60
120
180
240
300
360
420
480

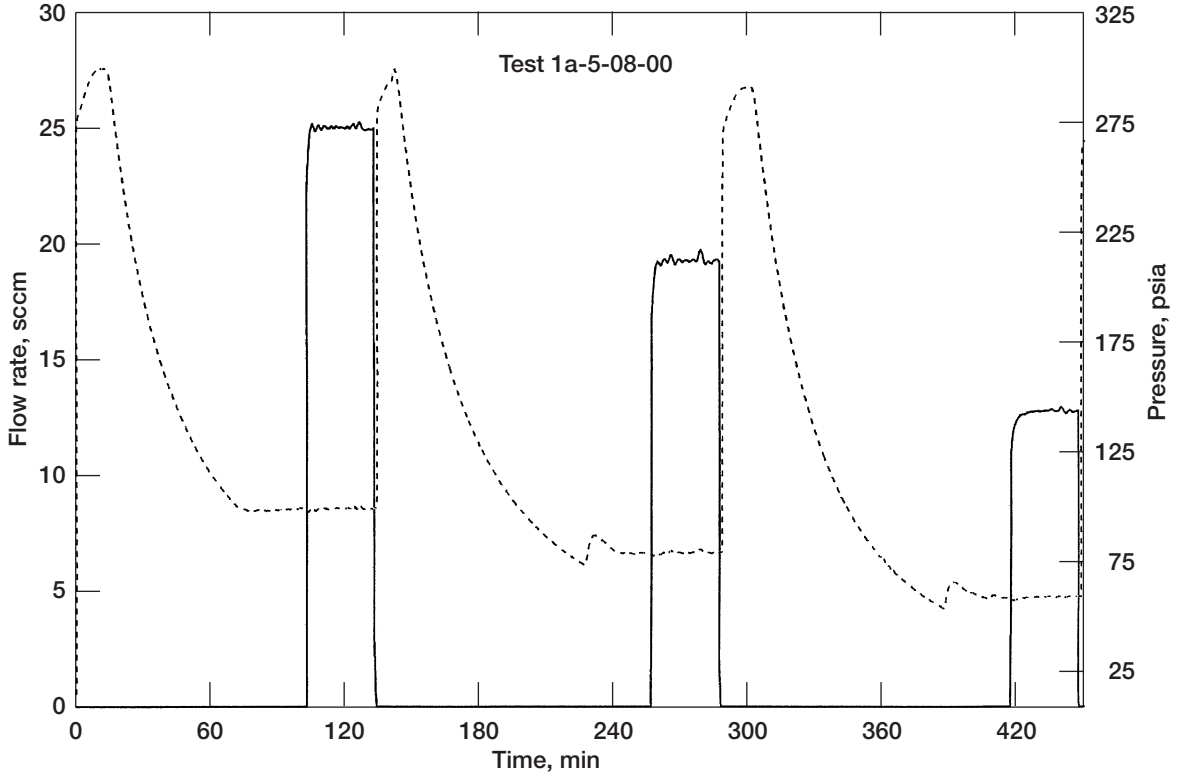

Test 1a-5-02-00
Flow rate, sccm
Pressure, psia
Time, min
0
2
4
6
8
10
12
14
16
18
20
22
20
40
60
80
100
120
140
160
0
60
120
180
240
300
360
420
480
540

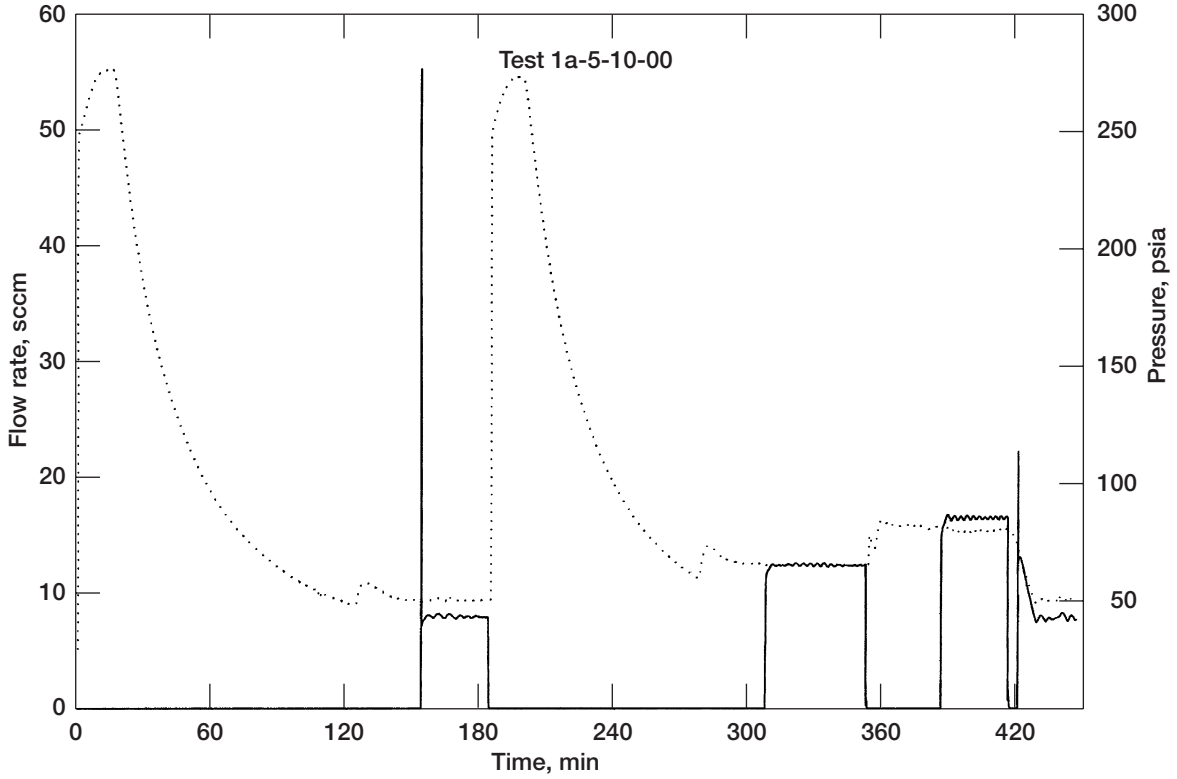

Test 1a-5-03-00
Flow rate, sccm
Pressure, psia
Time, min
0
5
10
15
20
25
30
35
40
50
100
150
200
250
300
350
400
450
500
0
60
120
180
240
300
360
420
480

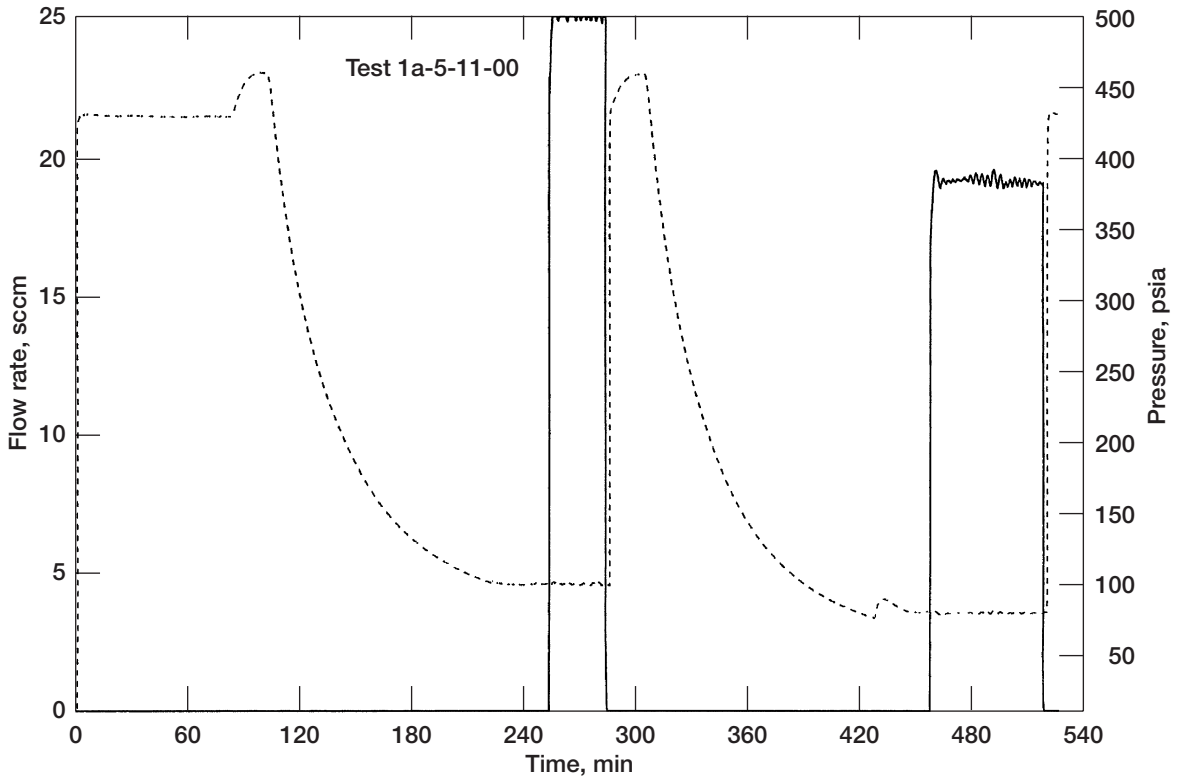

Test 1a-5-04-00
Flow rate, sccm
Pressure, psia
Time, min
0
5
10
15
20
25
30
35
0
50
100
150
200
250
300
350
400
450
500
0
60
120
180
240
300
360
420
480

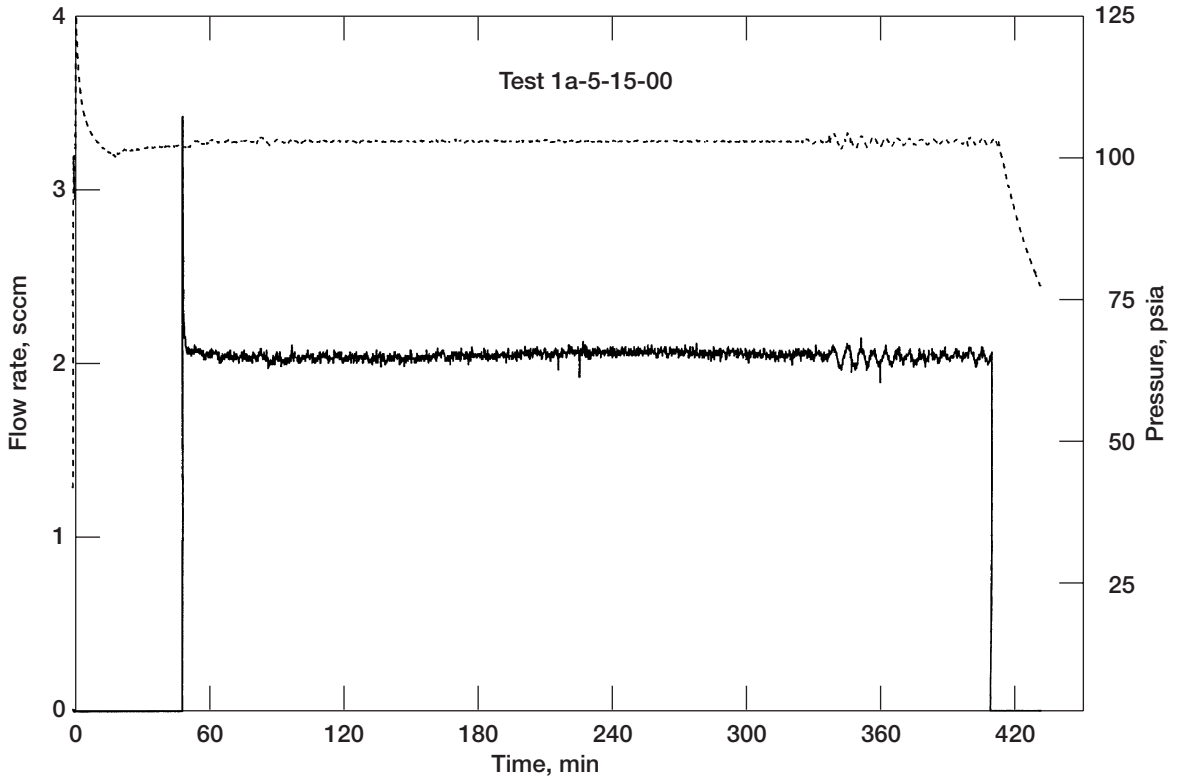

Test 1a-5-04-00
Flow rate, sccm
Temperature, °C
Time, min
0
5
10
15
20
25
30
35
20
40
60
80
100
120
0
60
120
180
240
300
360
420
480

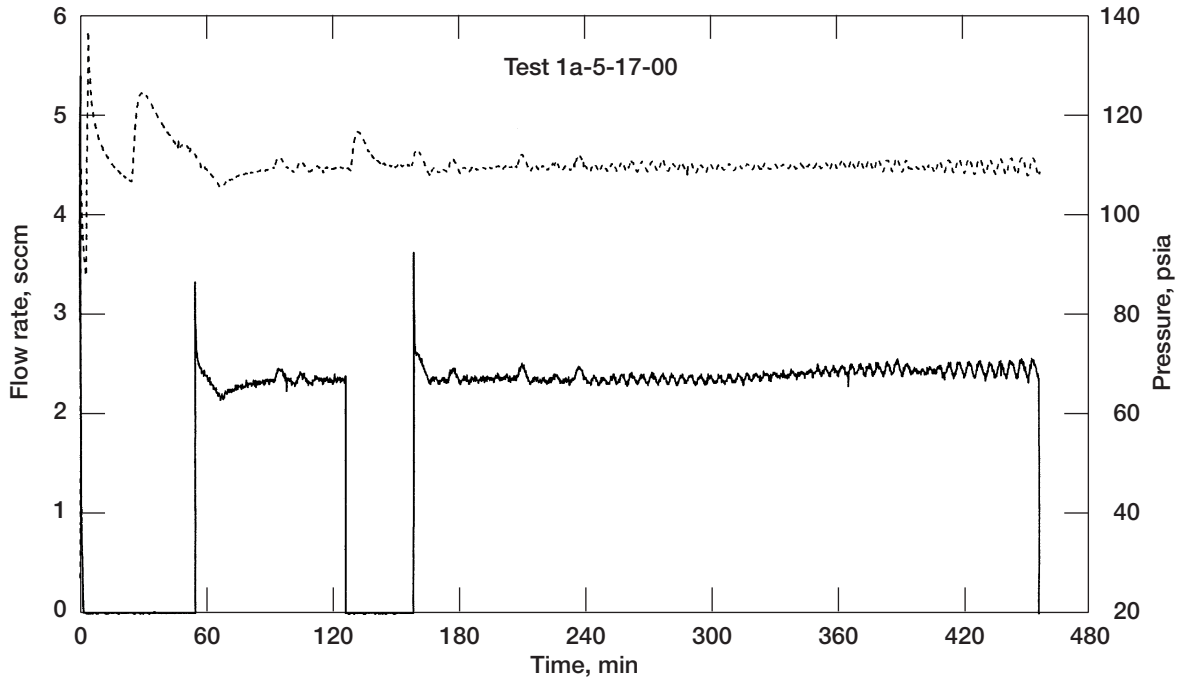

Test 1a-5-05-00
Flow rate, sccm
Pressure, psia
Time, min
0
10
20
30
40
50
60
100
150
200
250
300
350
400
450
0
60
120
180
240
300
360
420
480

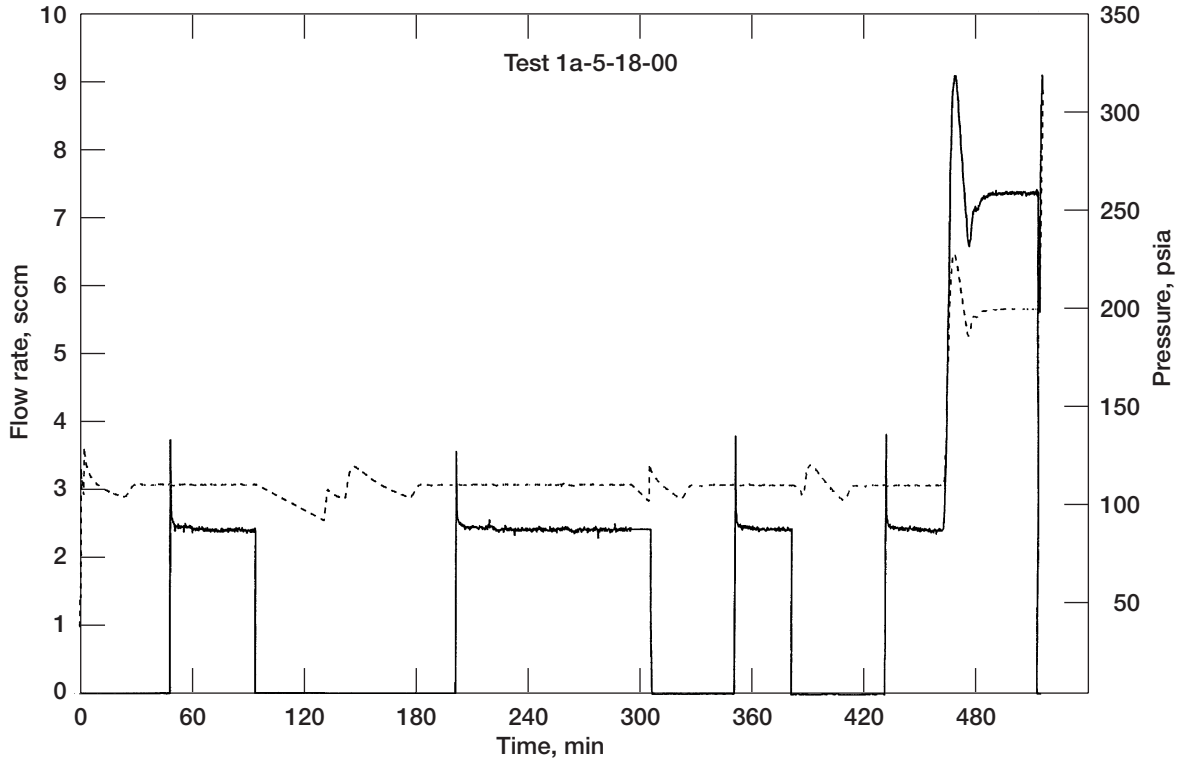

Test 1a-5-08-00
Flow rate, sccm
Pressure, psia
Time, min
0
5
10
15
20
25
30
25
75
125
175
225
275
325
0
60
120
180
240
300
360
420

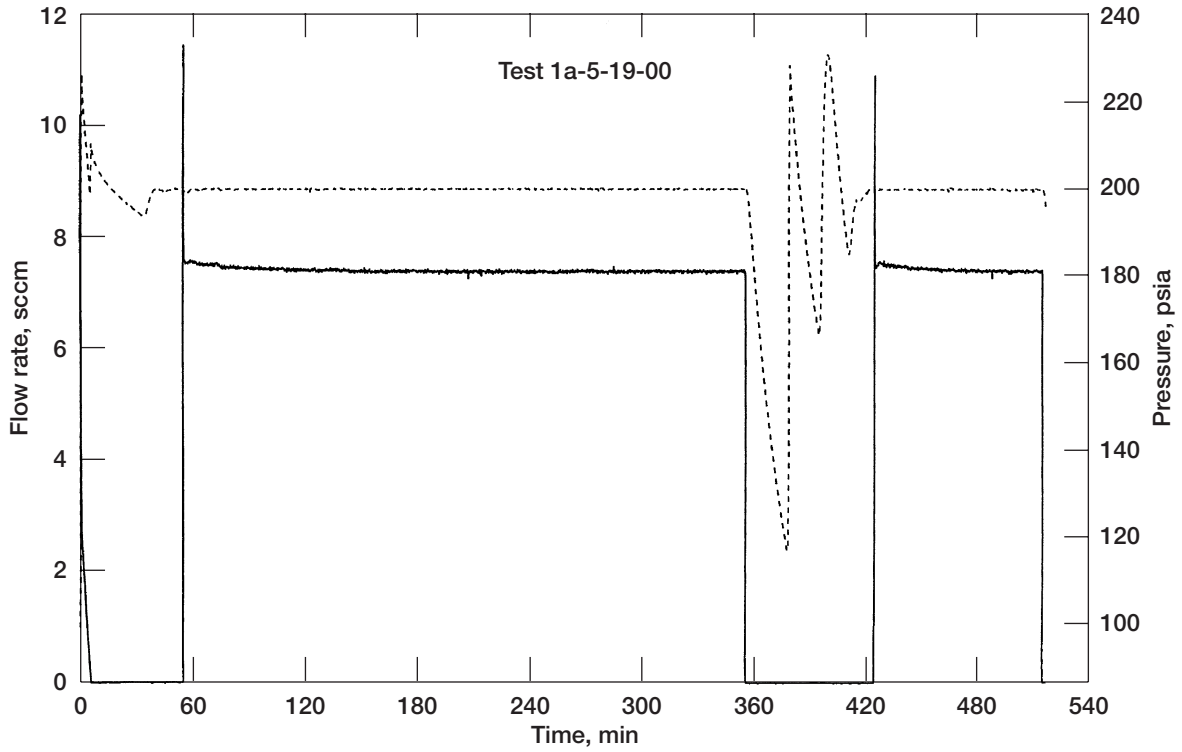

Test 1a-5-10-00
Flow rate, sccm
Pressure, psia
Time, min
0
10
20
30
40
50
60
50
100
150
200
250
300
0
60
120
180
240
300
360
420

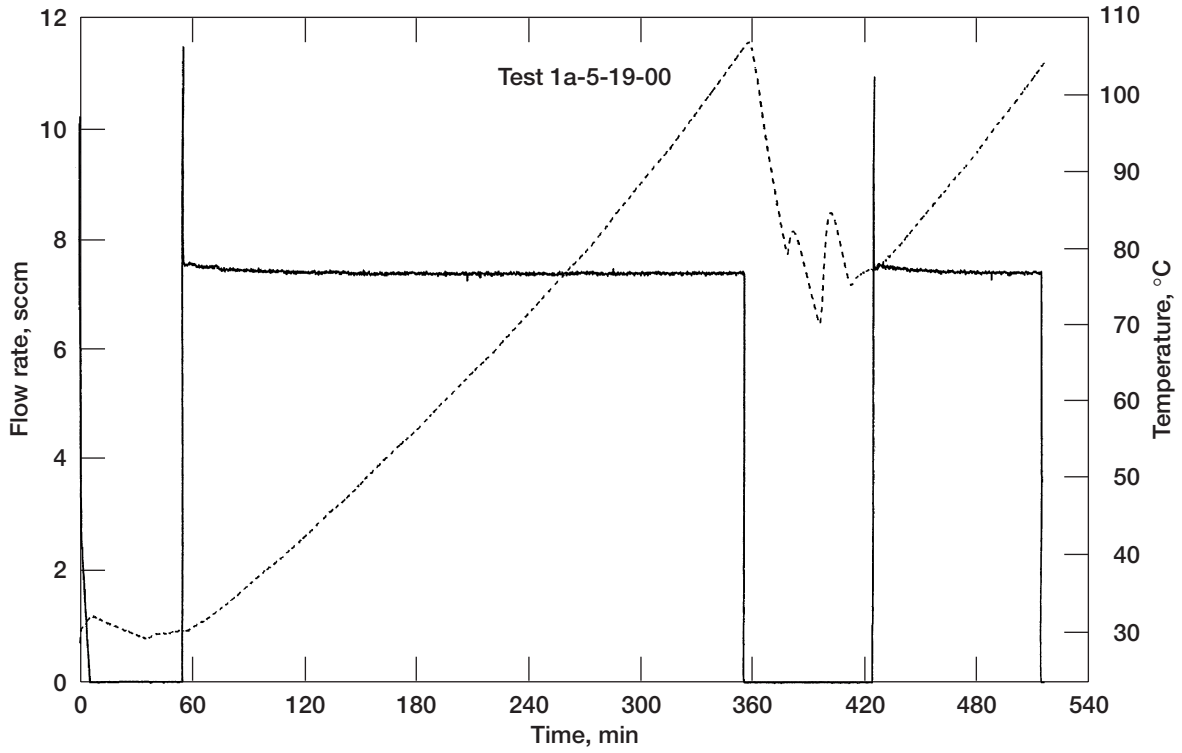

Test 1a-5-11-00
Flow rate, sccm
Pressure, psia
Time, min
0
5
10
15
20
25
50
100
150
200
250
300
350
400
450
500
0
60
120
180
240
300
360
420
480
540

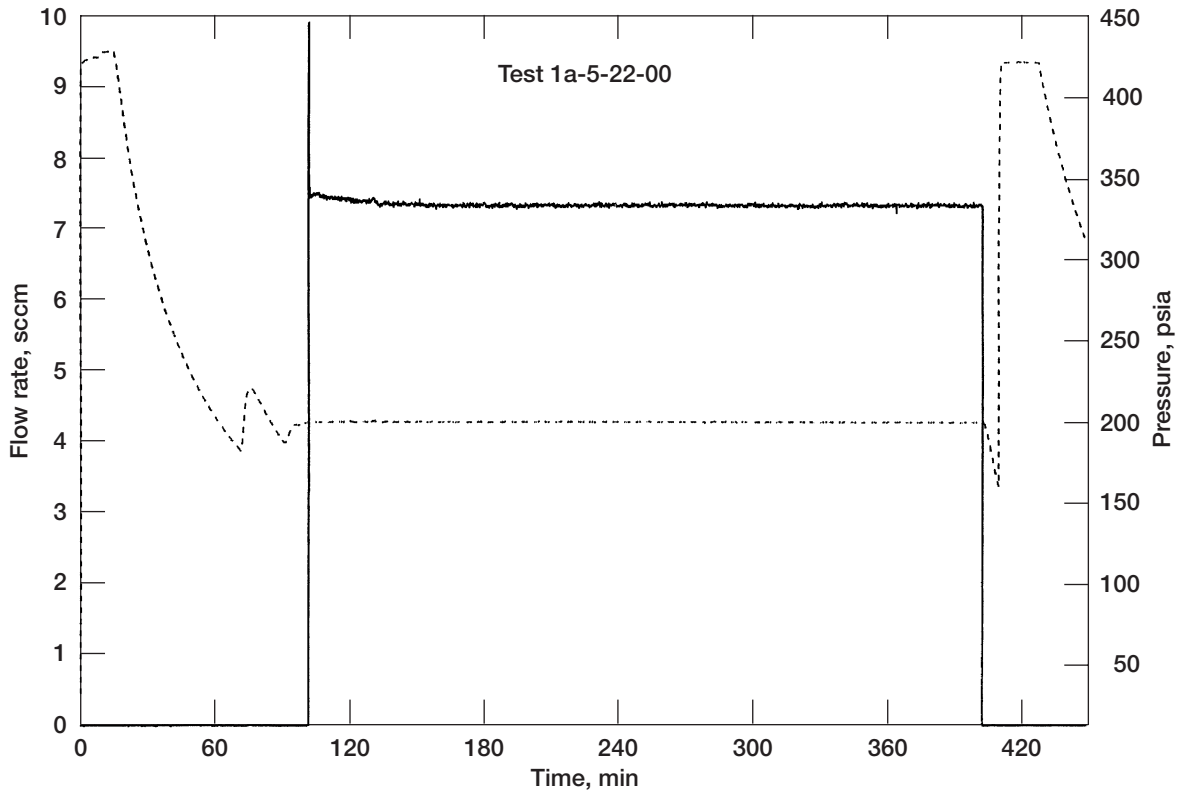

Test 1a-5-15-00
Flow rate, sccm
Pressure, psia
Time, min
0
1
2
3
4
25
50
75
100
125
0
60
120
180
240
300
360
420

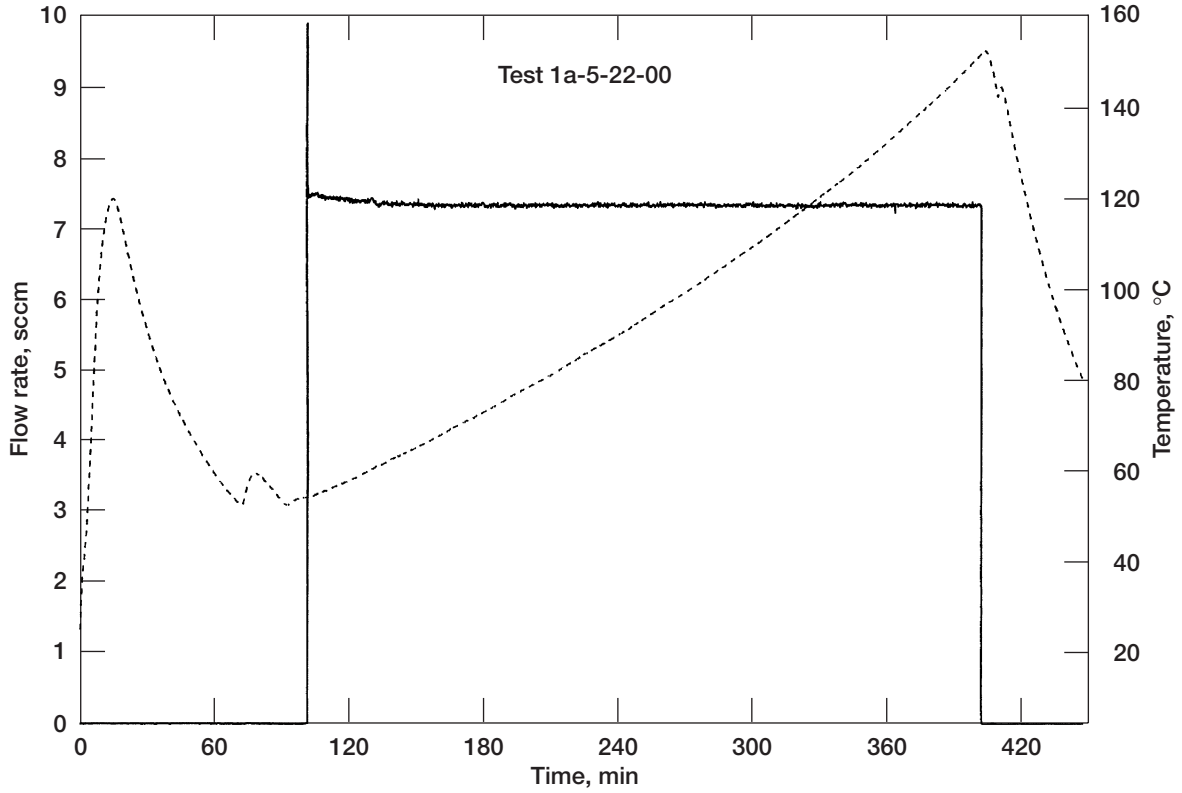

Test 1a-5-17-00
Flow rate, sccm
Pressure, psia
Time, min
0
1
2
3
4
5
6
20
40
60
80
100
120
140
0
60
120
180
240
300
360
420
480

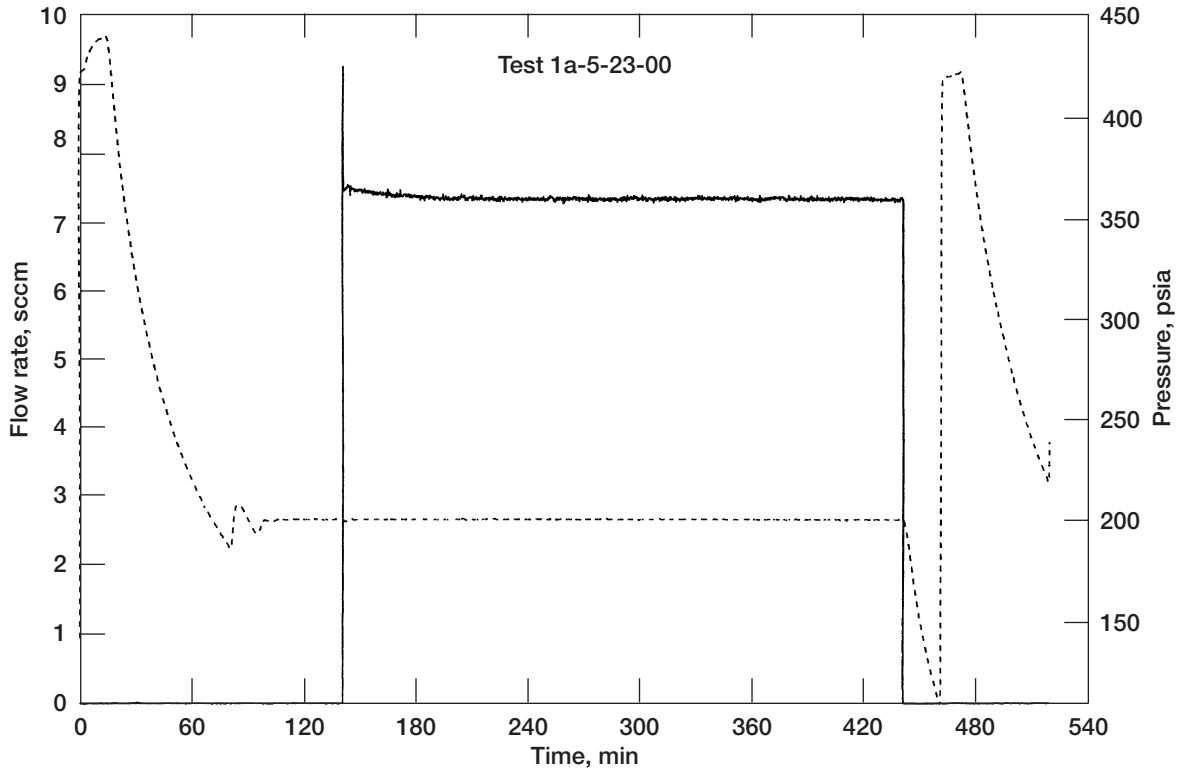

Test 1a-5-18-00
Flow rate, sccm
Pressure, psia
Time, min
0
1
2
3
4
5
6
7
8
9
10
50
100
150
200
250
300
350
0
60
120
180
240
300
360
420
480

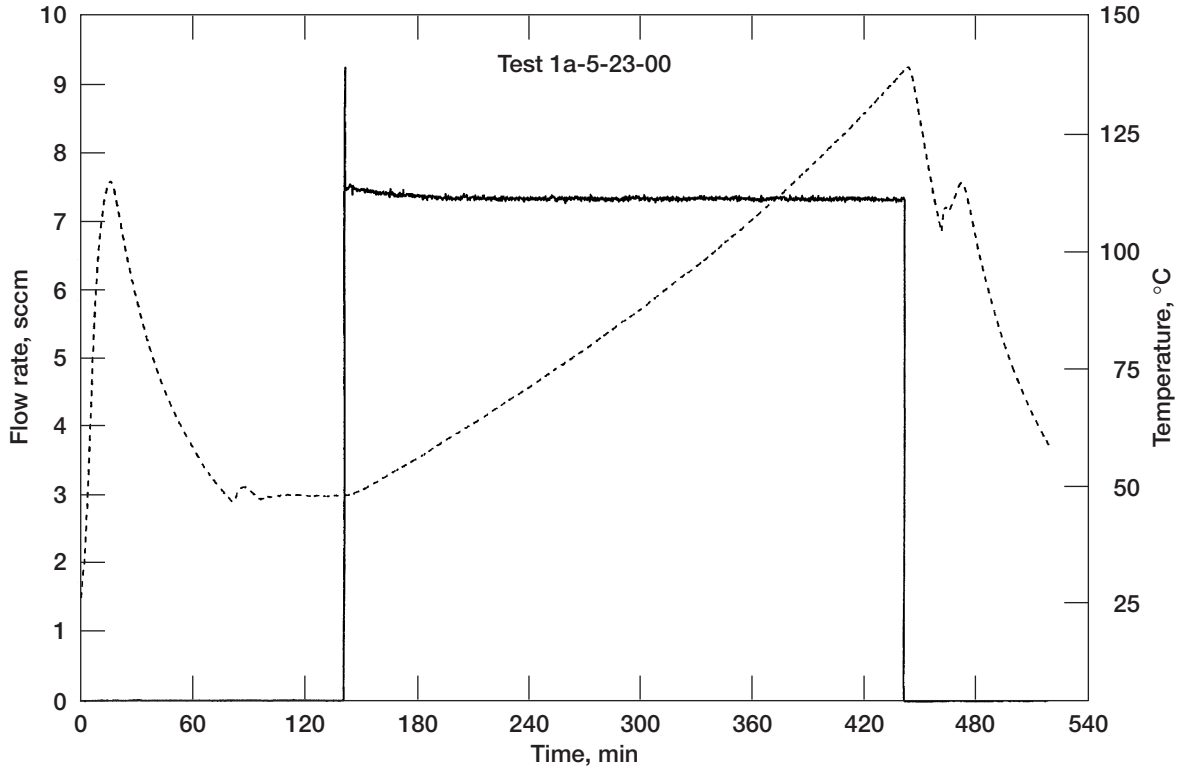

Test 1a-5-19-00
Flow rate, sccm
Pressure, psia
Time, min
0
2
4
6
8
10
12
100
120
140
160
180
200
220
240
0
60
120
180
240
300
360
420
480
540

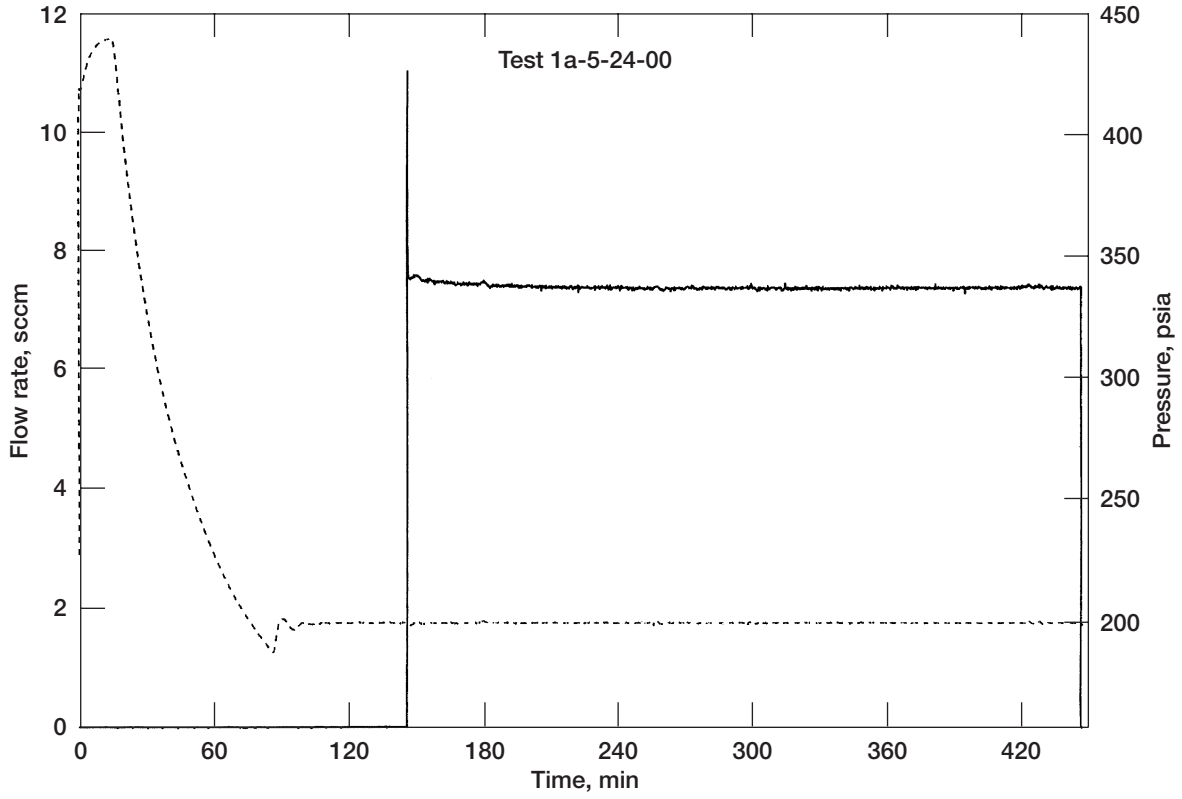

Test 1a-5-19-00
Flow rate, sccm
Temperature, °C
Time, min
0
2
4
6
8
10
12
30
40
50
60
70
80
90
100
110
0
60
120
180
240
300
360
420
480
540

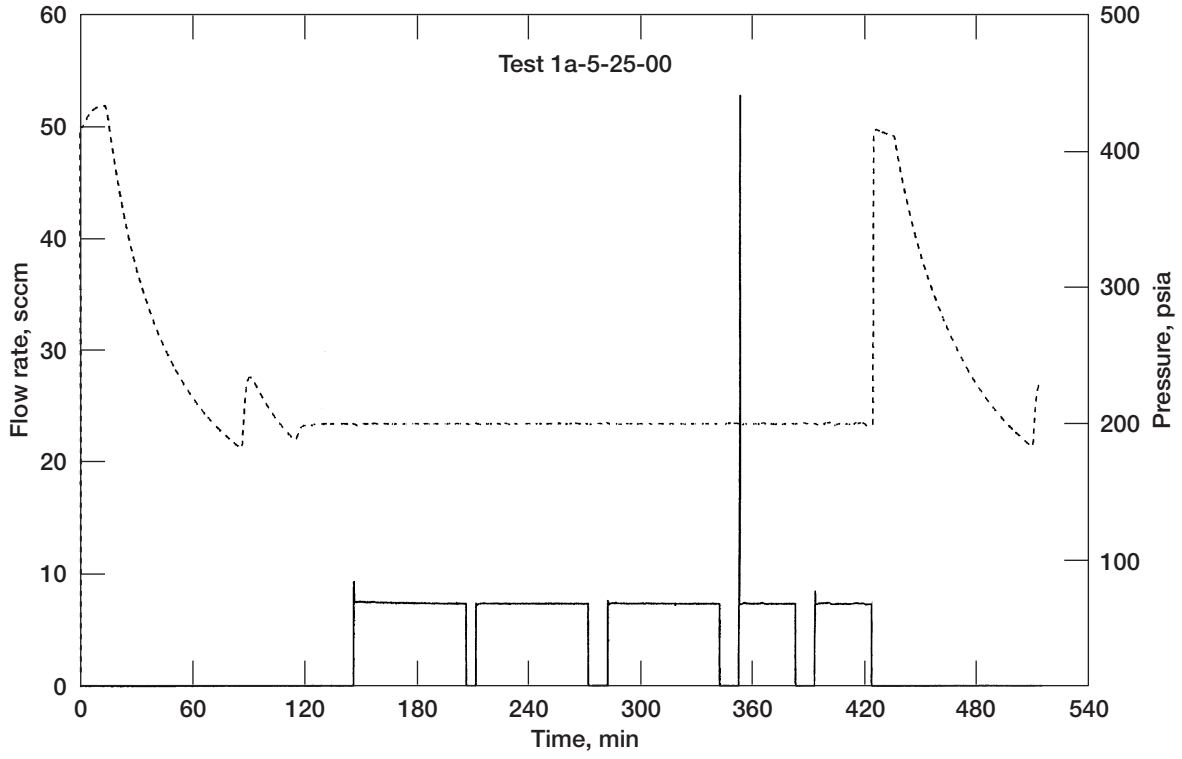

Test 1a-5-22-00
Flow rate, sccm
Pressure, psia
Time, min
0
1
2
3
4
5
6
7
8
9
10
50
100
150
200
250
300
350
400
450
0
60
120
180
240
300
360
420

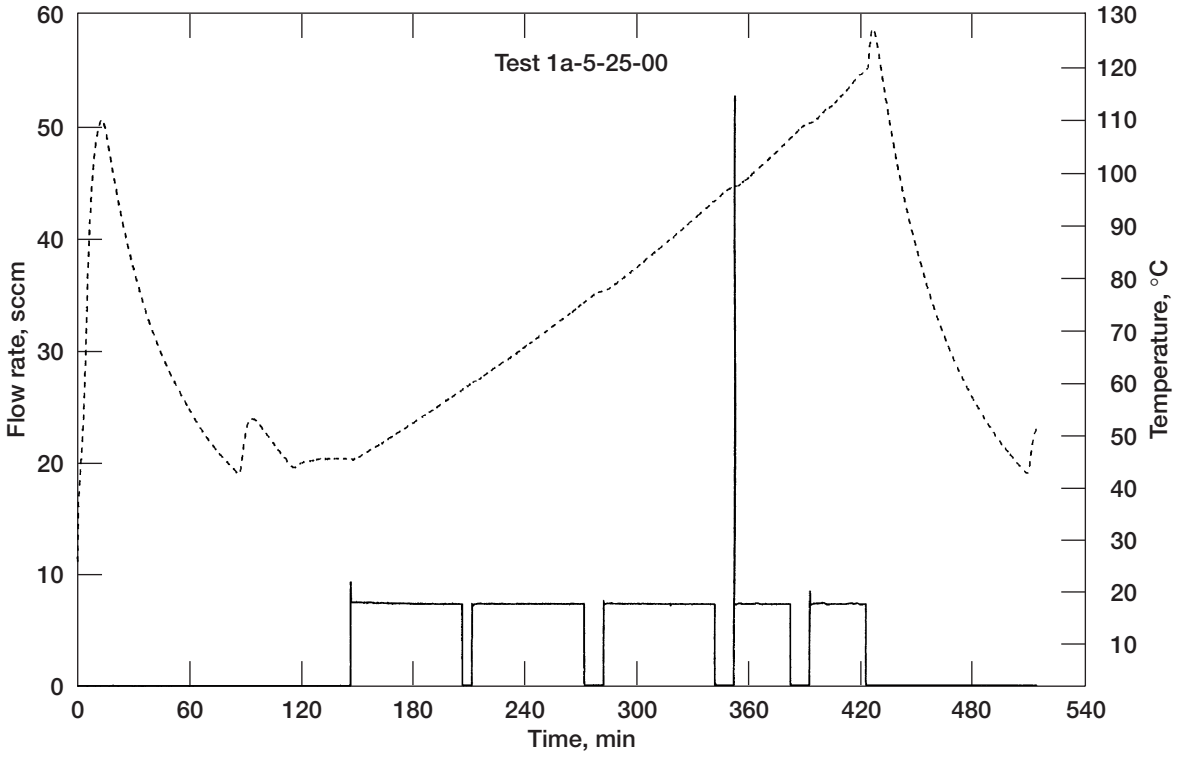

Test 1a-5-22-00
Flow rate, sccm
Temperature, °C
Time, min
0
1
2
3
4
5
6
7
8
9
10
20
40
60
80
100
120
140
160
0
60
120
180
240
300
360
420

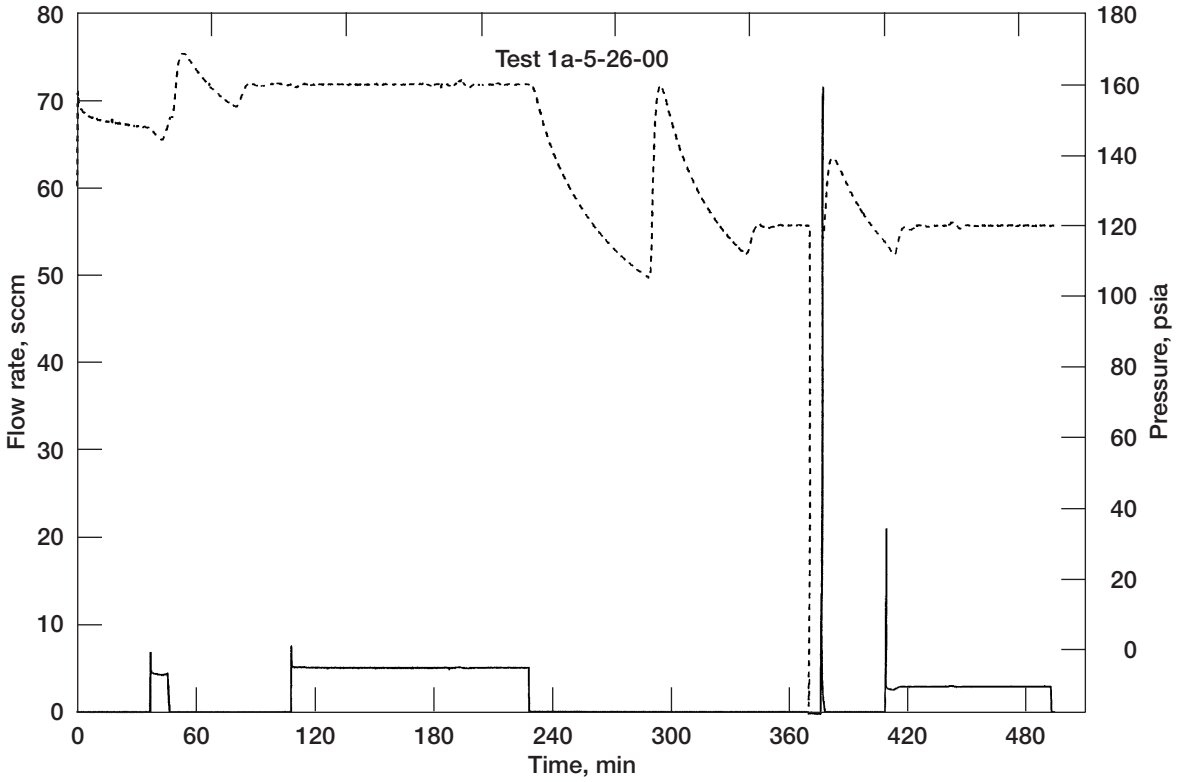

Test 1a-5-23-00
Flow rate, sccm
Pressure, psia
Time, min
0
1
2
3
4
5
6
7
8
9
10
150
200
250
300
350
400
450
0
60
120
180
240
300
360
420
480
540

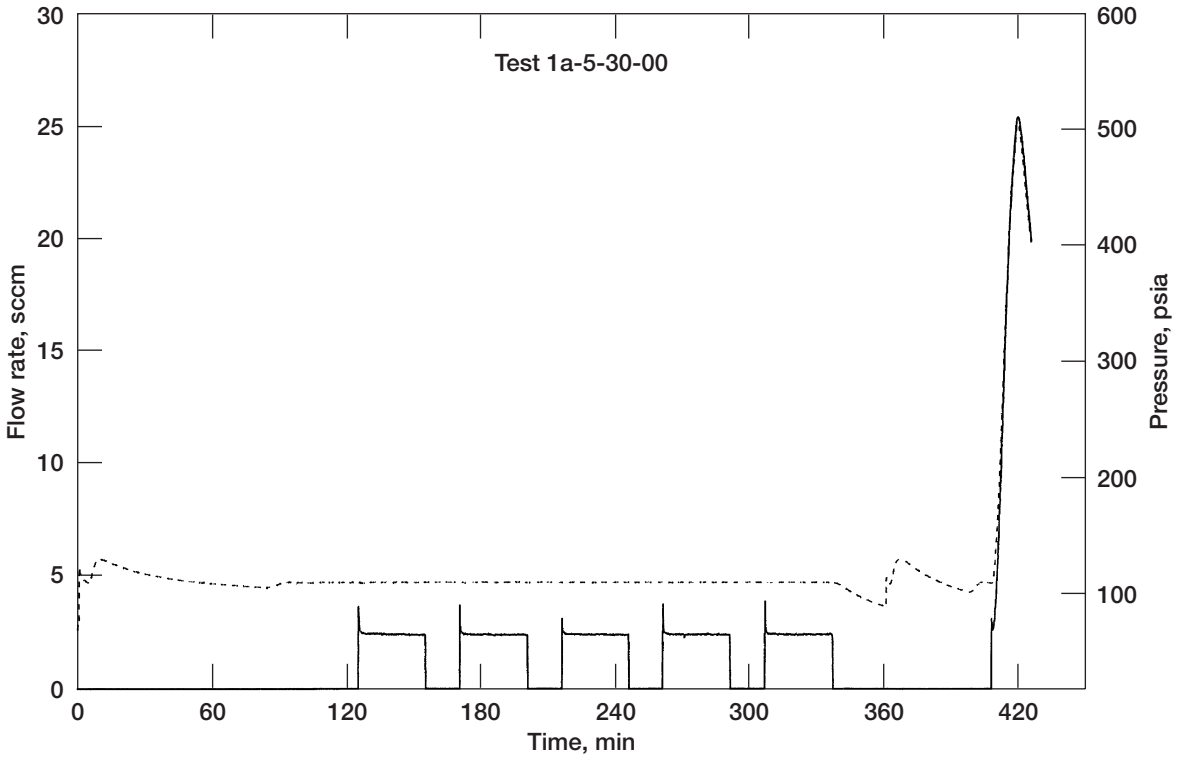

Test 1a-5-23-00
Flow rate, sccm
Temperature, °C
Time, min
0
1
2
3
4
5
6
7
8
9
10
25
50
75
100
125
150
0
60
120
180
240
300
360
420
480
540

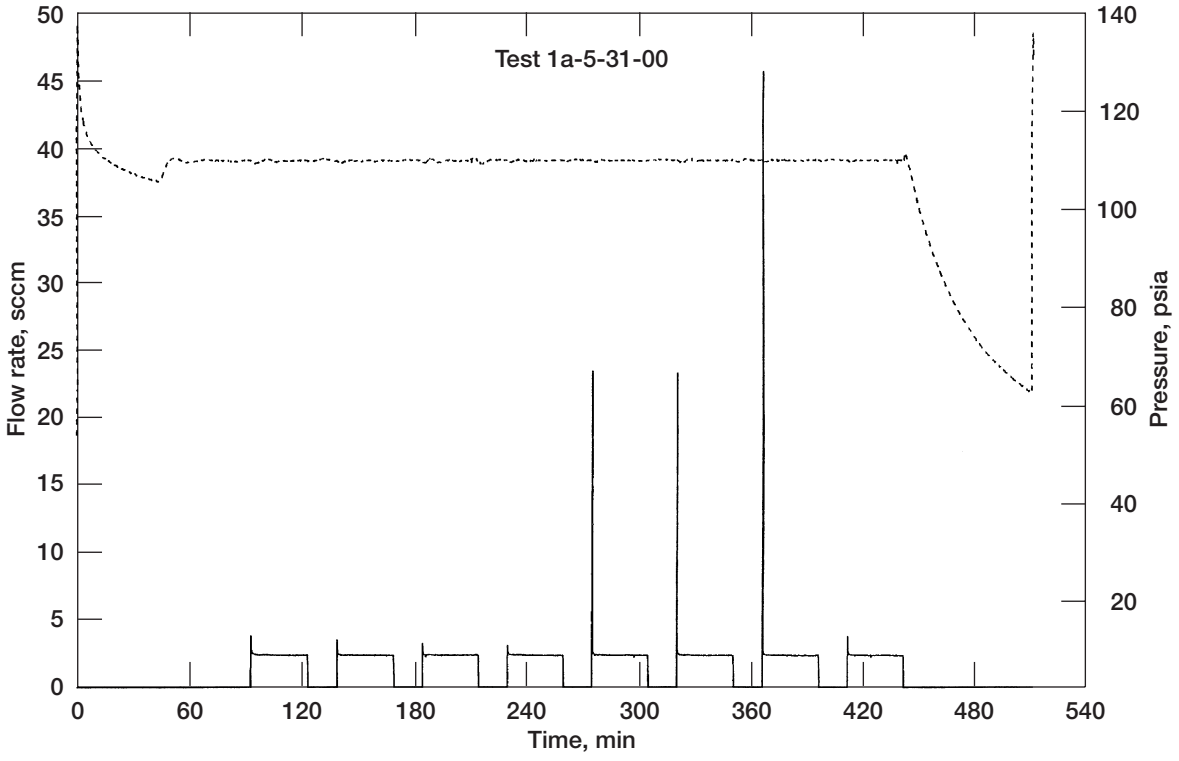

Test 1a-5-24-00
Flow rate, sccm
Pressure, psia
Time, min
0
2
4
6
8
10
12
200
250
300
350
400
450
0
60
120
180
240
300
360
420

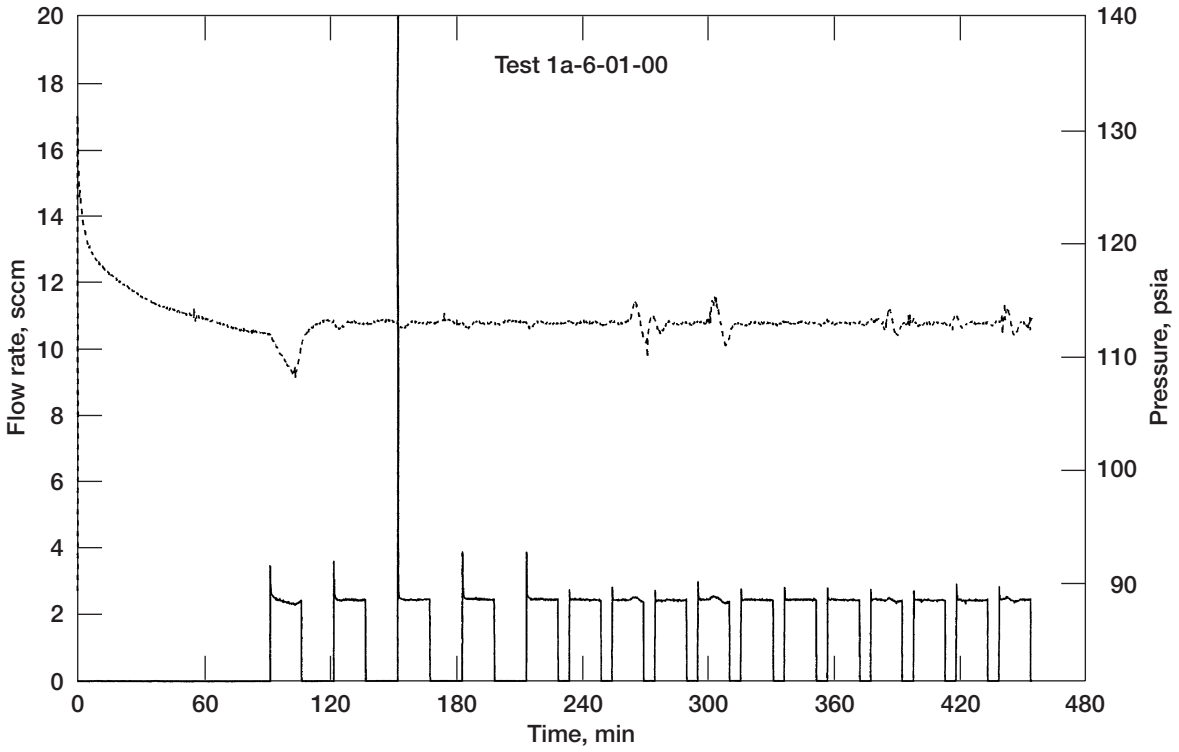

Test 1a-5-25-00
Flow rate, sccm
Pressure, psia
Time, min
0
10
20
30
40
50
60
100
200
300
400
500
0
60
120
180
240
300
360
420
480
540

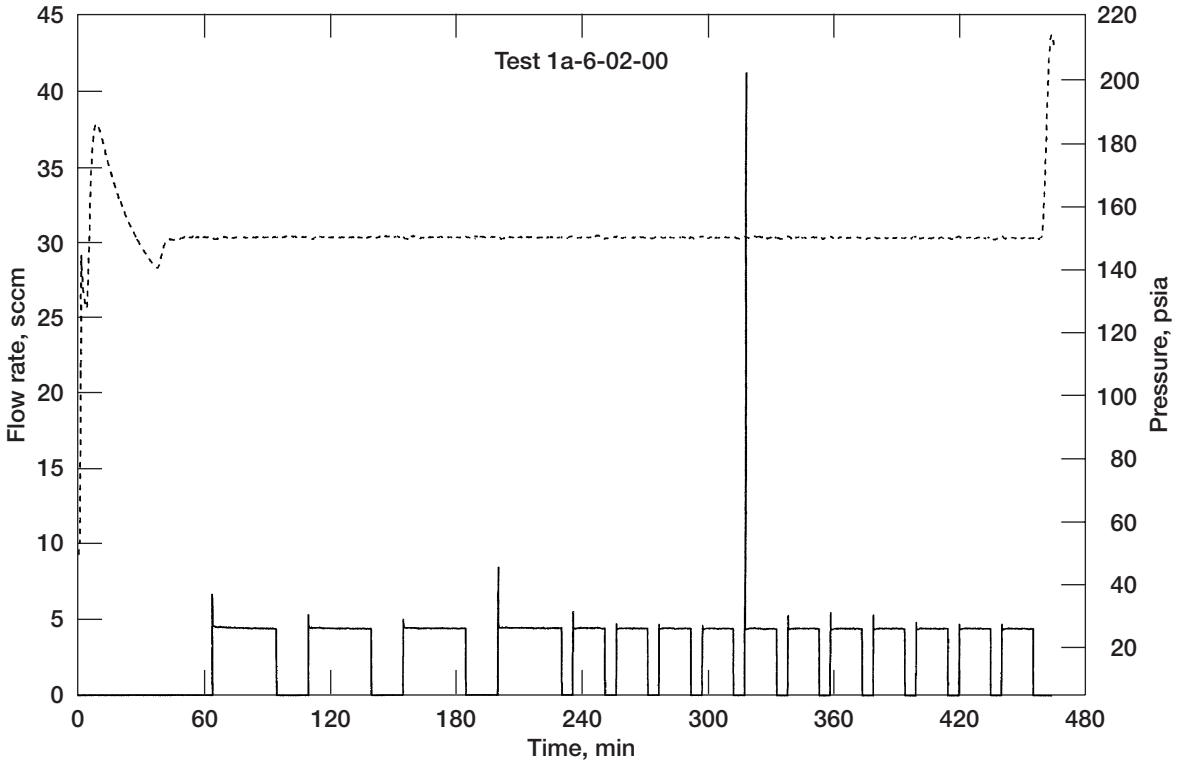

Test 1a-5-25-00
Flow rate, sccm
Temperature, °C
Time, min
0
10
20
30
40
50
60
0
60
120
180
240
300
360
420
480
540
10
20
30
40
50
60
70
80
90
100
110
120
130

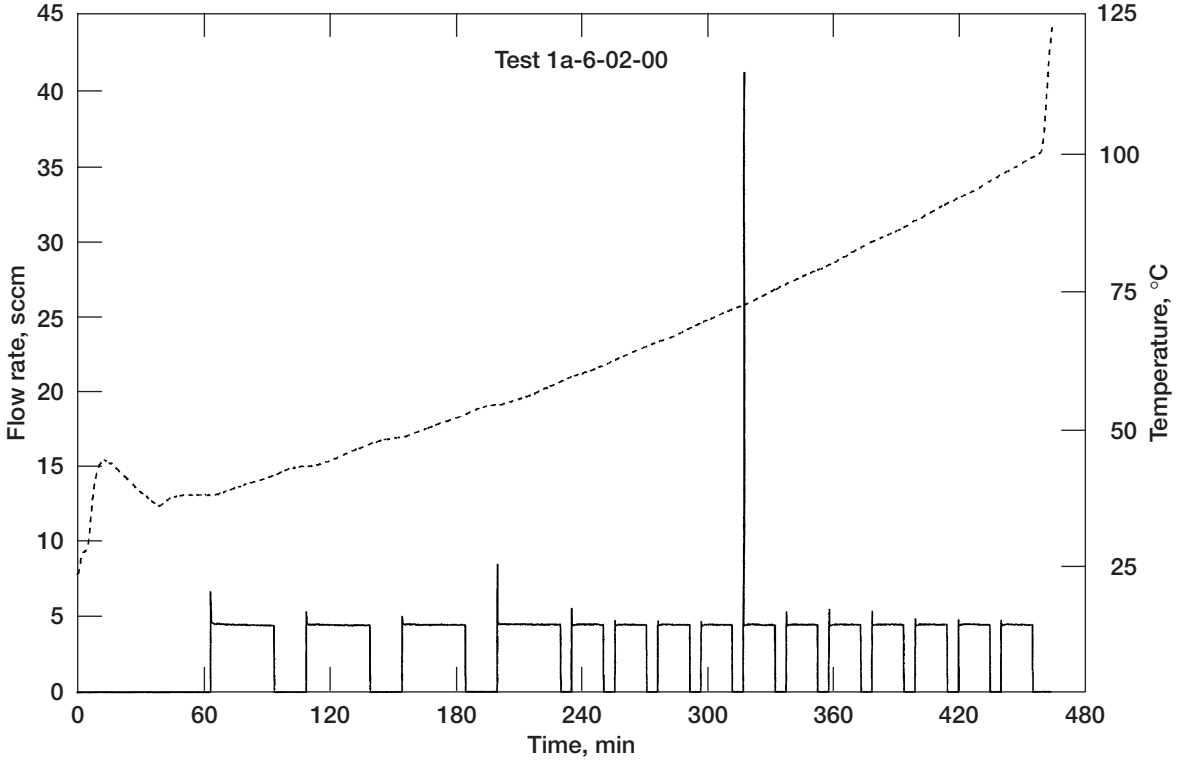

Test 1a-5-26-00
Flow rate, sccm
Pressure, psia
Time, min
0
10
20
30
40
50
60
70
80
0
60
120
180
240
300
360
420
480
0
20
40
60
80
100
120
140
160
180

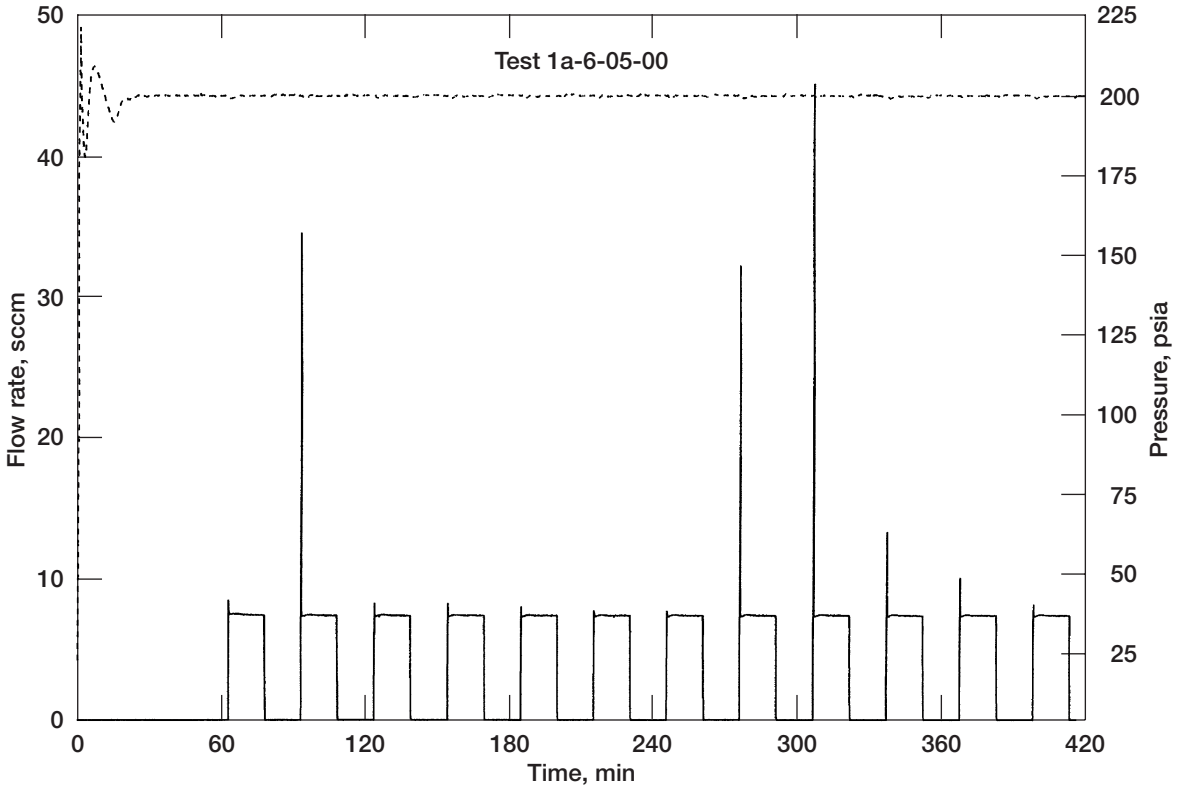

Test 1a-5-30-00
Flow rate, sccm
Pressure, psia
Time, min
0
5
10
15
20
25
30
100
200
300
400
500
600
0
60
120
180
240
300
360
420

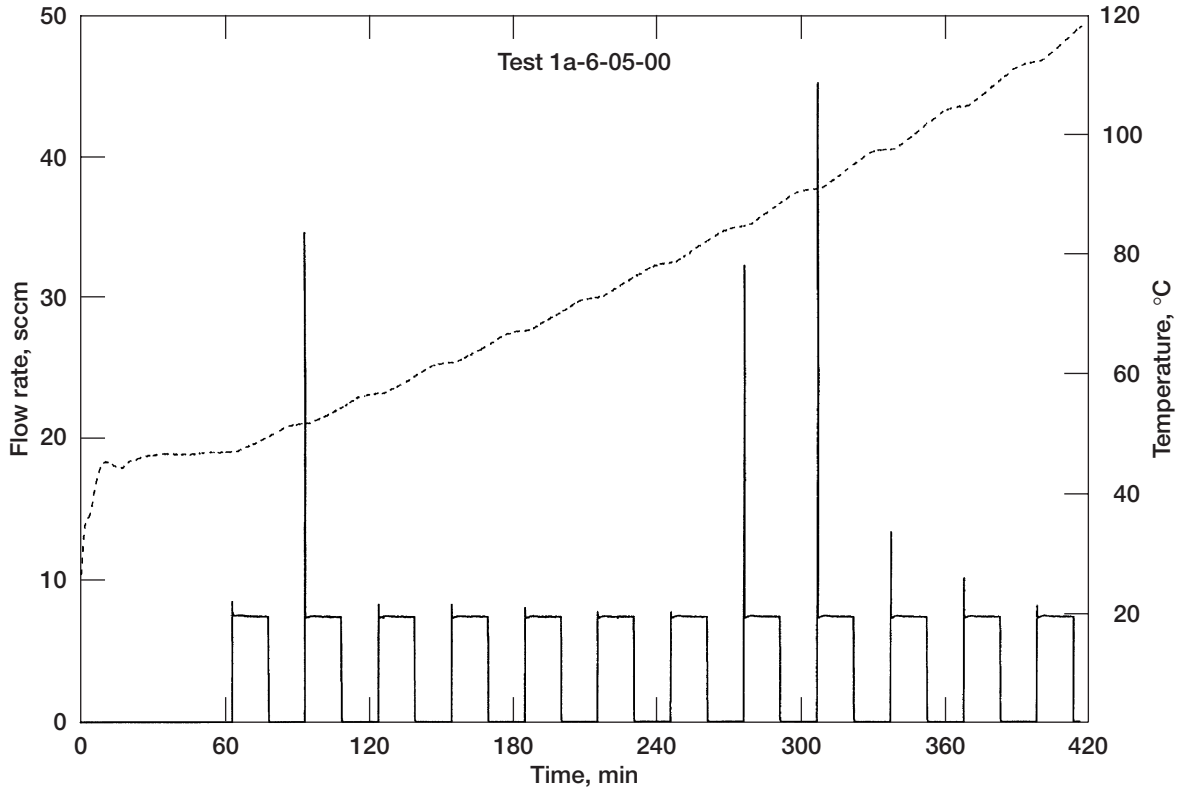

Test 1a-5-31-00
Flow rate, sccm
Pressure, psia
Time, min
0
5
10
15
20
25
30
35
40
45
50
20
40
60
80
100
120
140
0
60
120
180
240
300
360
420
480
540

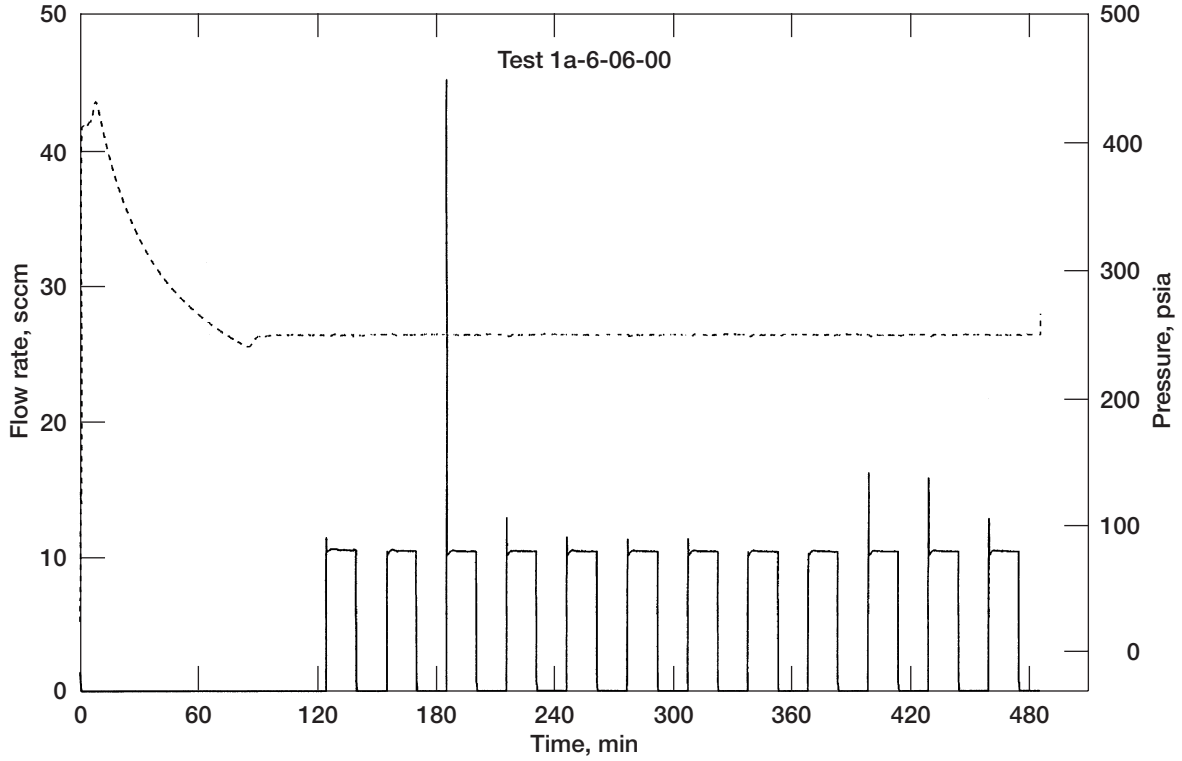

Test 1a-6-01-00
Flow rate, sccm
Pressure, psia
Time, min
0
2
4
6
8
10
12
14
16
18
20
90
100
110
120
130
140
0
60
120
180
240
300
360
420
480

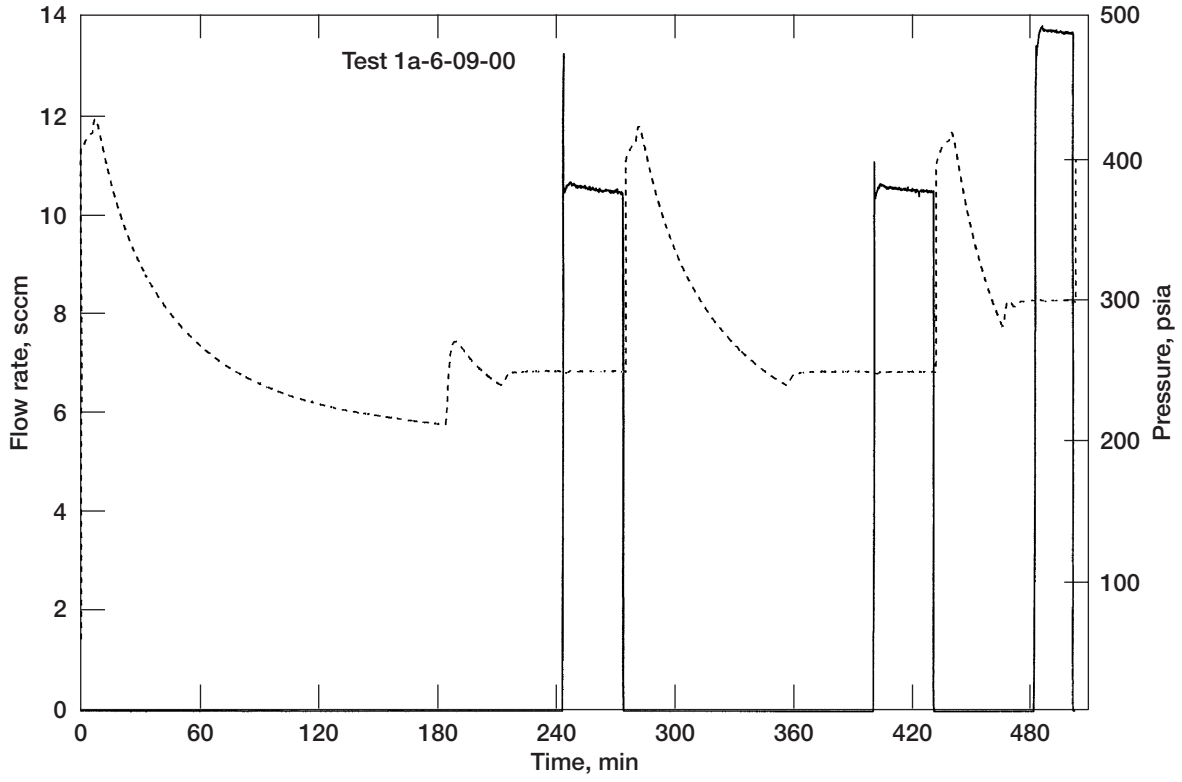

Test 1a-6-02-00
Flow rate, sccm
Pressure, psia
Time, min
0
5
10
15
20
25
30
35
40
45
20
40
60
80
100
120
140
160
180
200
220
0
60
120
180
240
300
360
420
480

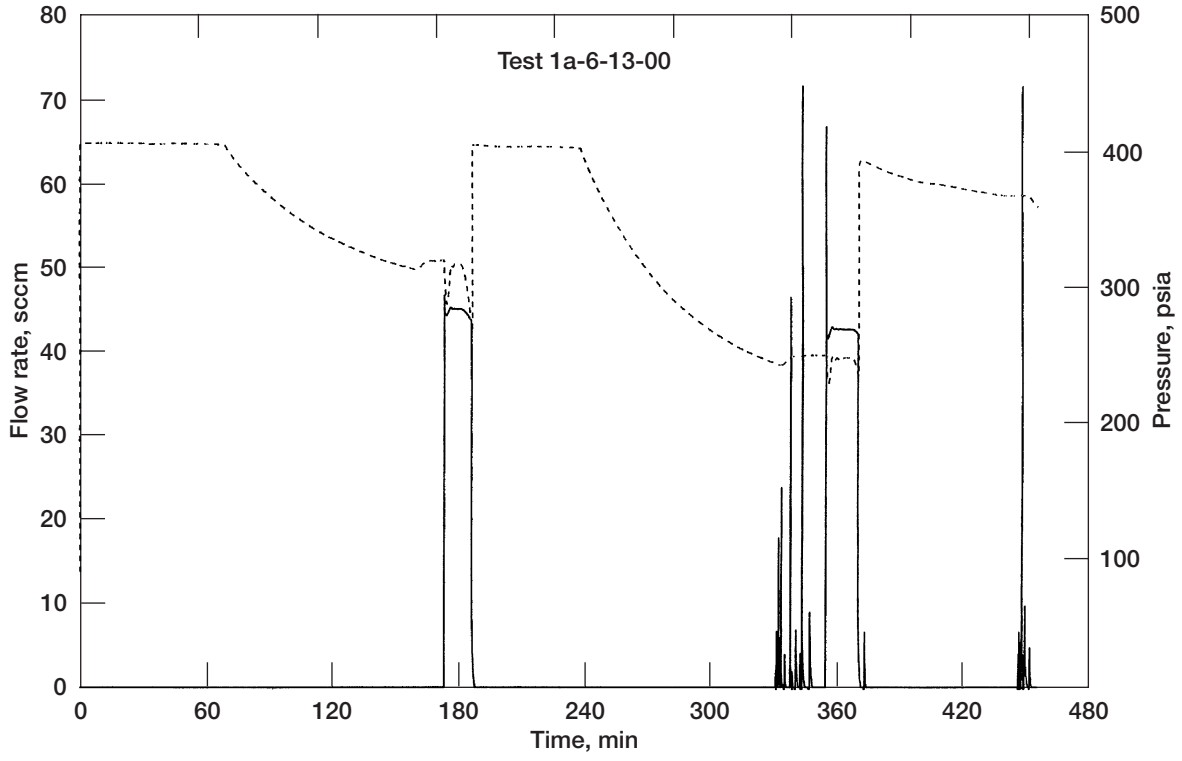

Test 1a-6-02-00
Flow rate, sccm
Temperature, °C
Time, min
0
5
10
15
20
25
30
35
40
45
25
50
75
100
125
0
60
120
180
240
300
360
420
480

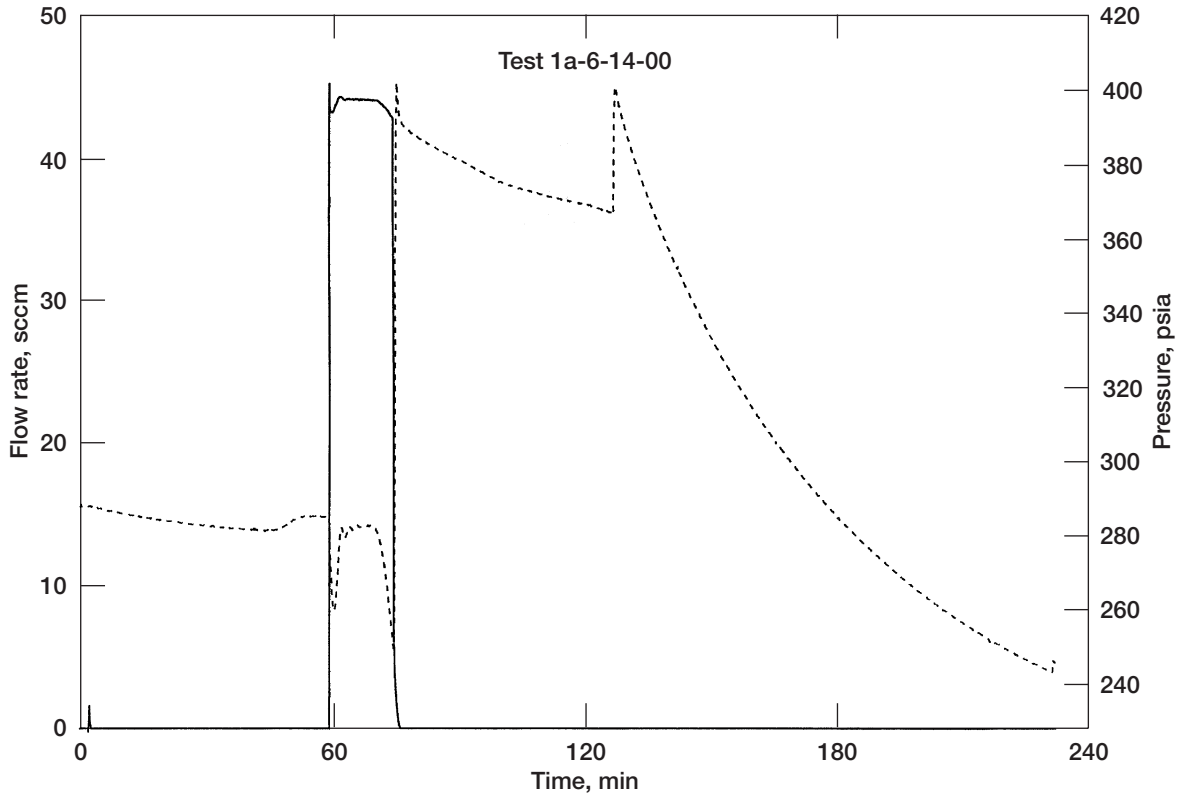

Test 1a-6-05-00
Flow rate, sccm
Pressure, psia
Time, min
0
10
20
30
40
50
25
50
75
100
125
150
175
200
225
0
60
120
180
240
300
360
420

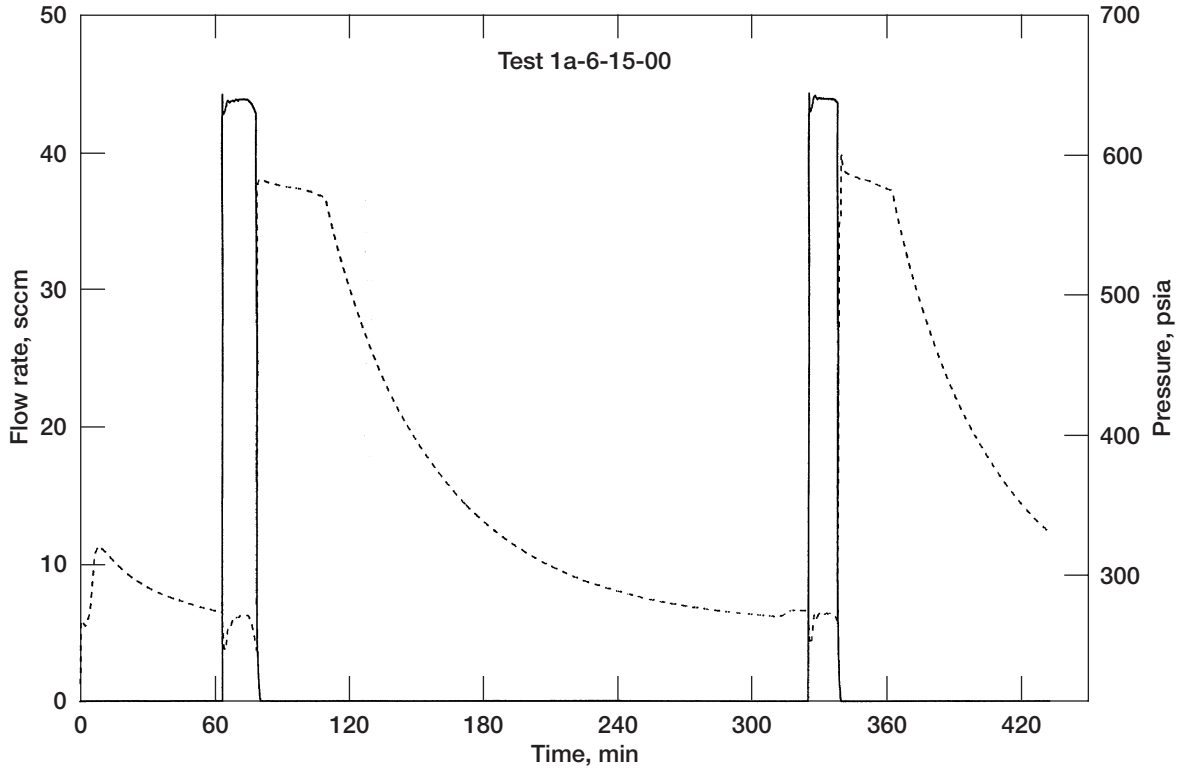

Test 1a-6-05-00
Flow rate, sccm
Temperature, °C
Time, min
0
10
20
30
40
50
20
40
60
80
100
120
0
60
120
180
240
300
360
420

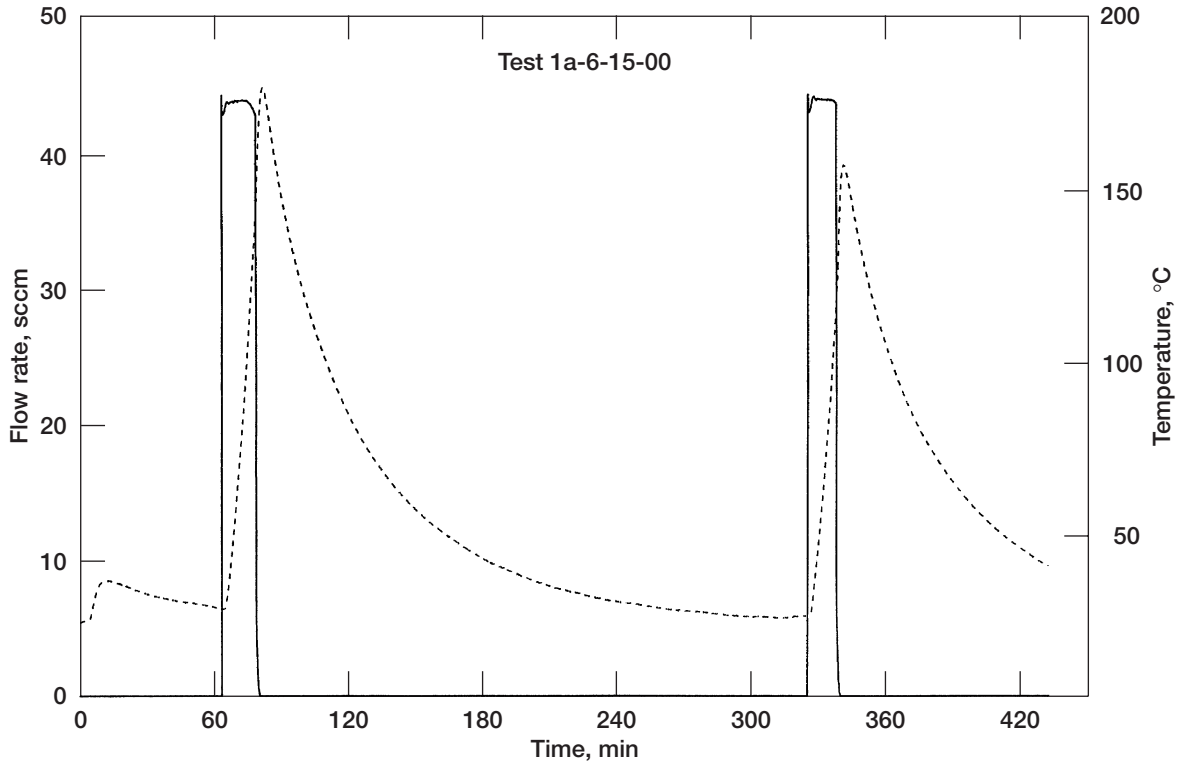

Test 1a-6-06-00
Flow rate, sccm
Pressure, psia
Time, min
0
10
20
30
40
50
0
100
200
300
400
500
0
60
120
180
240
300
360
420
480

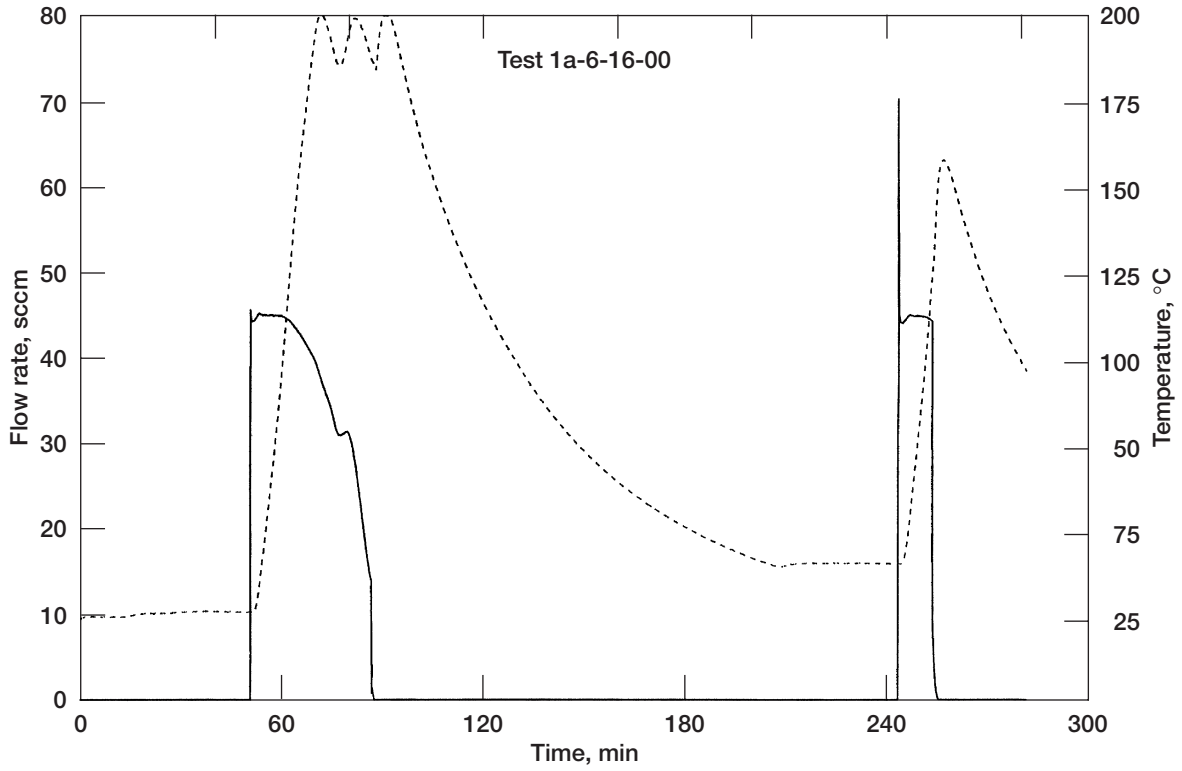

Test 1a-6-09-00
Flow rate, sccm
Pressure, psia
Time, min
0
2
4
6
8
10
12
14
100
200
300
400
500
0
60
120
180
240
300
360
420
480

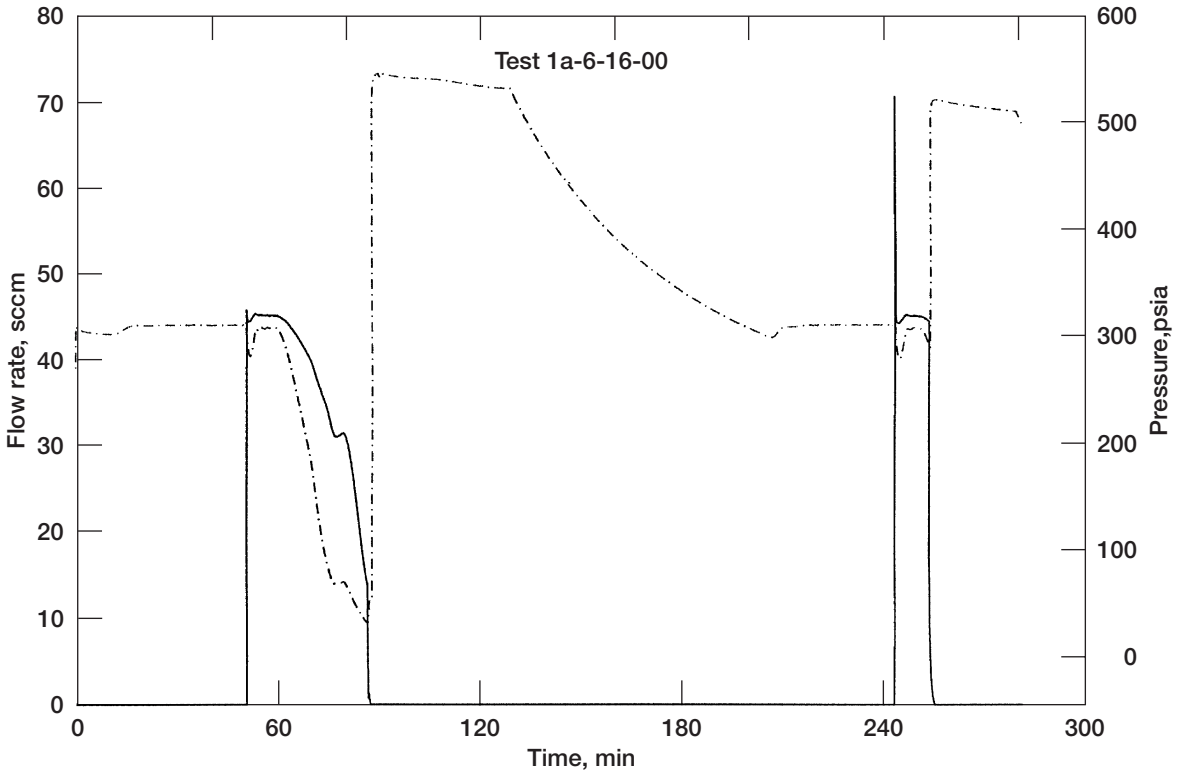

Test 1a-6-13-00
Flow rate, sccm
Pressure, psia
Time, min
0
10
20
30
40
50
60
70
80
100
200
300
400
500
0
60
120
180
240
300
360
420
480


Test 1a-6-14-00
Flow rate, sccm
Pressure, psia
Time, min
0
10
20
30
40
50
240
260
280
300
320
340
360
380
400
420
0
60
120
180
240


Test 1a-6-15-00
Flow rate, sccm
Pressure, psia
Time, min
0
10
20
30
40
50
300
400
500
600
700
0
60
120
180
240
300
360
420


Test 1a-6-15-00
Flow rate, sccm
Temperature, °C
Time, min
0
10
20
30
40
50
50
100
150
200
0
60
120
180
240
300
360
420


Test 1a-6-16-00
Flow rate, sccm
Temperature, °C
Time, min
0
10
20
30
40
50
60
70
80
25
75
100
125
150
175
200
0
60
120
180
240
300


Test 1a-6-16-00
Flow rate, sccm
Pressure,psia
Time, min
0
10
20
30
40
50
60
70
80
0
100
200
300
400
500
600
0
60
120
180
240
300

REFERENCES

Patents

1. Back, D.D., and Ramos, C., "Noble Gas Storage And Delivery System For Ion Propulsion," patent-pending.

Journals, Reports, Other

1. Telephone conversation with Mr. Jerry Hermel and Dr. Ray Kushida of Hughes, 2/25/99.
2. Telephone conversion with Mr. Erik Beiermeister of Marotta, 2/24/99.
3. E-mail correspondence with Dr. Ray Kushida of Hughes, 6/8/99.
4. Zanevskii, Y.V., and Peshekhonov, V.D., "Use of Ni/SiO2 as adsorbent for long term diffusion purification of gaseous xenon and xenon-methane mixtures," Instrum. Exp. Tech., 32, 4, pt. 1, pgs. 823–826, 1990.
5. Back, D.D., and Scaringe. R.P., "Low-Pressure Long-Term Storage of Xe for Electric Propulsion," Phase I SBIR Final Report, BMDO/NASA, Doc. No. MEC–NA7184–F, 1998.
6. Back, D.D., "Low-Pressure Long-Term Xe Storage for Electric Propulsion," Phase II SBIR, NASA Glenn/BMDO, Quarterly Reports 1–5.
7. Back, D.D., "Mainstream Fuels New Propulsion Technology," BMDO Update, issue 30, page 11, Summer 1999.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (*Leave blank*)

2. REPORT DATE
February 2005

3. REPORT TYPE AND DATES COVERED
Final Contractor Report

4. TITLE AND SUBTITLE
Low-Pressure Long-Term Xenon Storage for Electric Propulsion

5. FUNDING NUMBERS
WU–344–96–7A–00
NAS3–99077

6. AUTHOR(S)
Dwight D. Back, Charlie Ramos, and John A. Meyer

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Mainstream Engineering Corporation
200 Yellow Place
Rockledge, Florida 32955

8. PERFORMING ORGANIZATION REPORT NUMBER
E–12694–1

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546–0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA CR—2001-210765-REV1

11. SUPPLEMENTARY NOTES
Project Manager, Eric Pencil, Power and On-Board Propulsion Technology Division, NASA Glenn Research Center, organization code RPP, 216–977–7463.

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Document Availability Change Notice

This document was published in April 2001 with an SBIR restriction. It was changed October 2004 to Unclassified/Unlimited per DAA modified October 29, 2004.

SBIR Rights Notice

These Phase II SBIR data are furnished with SBIR rights under Contract NAS3–99077. For a period of 4 years after acceptance of all items to be delivered under this contract, the Government agrees to use these data for Government purposes only, and they shall not be disclosed outside the Government (including disclosure for procurement purposes) during such period without permission of the Contractor, except that subject to the foregoing use and disclosure prohibitions, such data may be disclosed for use by support contractors. After the aforesaid 4–year period, the Government has a royalty–free license to use, and to authorize others to use on its behalf, these data for Government purposes, but is relieved of all disclosure prohibitions and assumes no liability for unauthorized use of these data by third parties. This notice shall be affixed to any reproductions of these data, in whole or in part.
Date for public release: June 18, 2004.
INFORMATION CONTAINED HEREIN IS PROPRIETARY FOR 4 YEARS IN ACCORDANCE WITH FAR 52.227–20.

Unclassified - Unlimited
Subject Categories: 16 and 20 Distribution: Nonstandard
Available electronically at http://gltrs.grc.nasa.gov
This publication is available from the NASA Center for AeroSpace Information, 301–621–0390.

12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 words)***

This Phase 2 effort demonstrated an alternative Xe storage and regulation system using activated carbon (AC) as a secondary storage media (ACSFR). This regulator system is nonmechanical, simple, inexpensive, and lighter. The ACSFR system isolates the thruster from the compressed gas tank, and allows independent multiple setpoint thruster operation. The flow using an ACSFR can also be throttled by applying increments in electrical power. Primary storage of Xe by AC is not superior to compressed gas storage with regard to weight, but AC storage can provide volume reduction, lower pressures in space, and potentially in situ Xe purification. With partial fill designs, a primary AC storage vessel for Xe could also eliminate problems with two-phase storage and regulate pressure. AC could also be utilized in long-term large quantity storage of Xe serving as a compact capture site for boil-off. Several Xe delivery ACSFR protocols between 2 and 45 sccm, and 15 min to 7 hr, were tested with an average flow variance of ±1.2 percent, average power requirements of 5 W, and repeatability's of about ±0.4 percent. Power requirements are affected by ACSFR bed sizing and flow rate/duration design points, and these flow variances can be reduced by optimizing PID controller parameters.

14. SUBJECT TERMS
Propulsion; Electric propulsion; Xenon; Flow control;
Ion propulsion; Activated carbon; Flow regulation

15. NUMBER OF PAGES
100

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT
Unclassified

18. SECURITY CLASSIFICATION OF THIS PAGE
Unclassified

19. SECURITY CLASSIFICATION OF ABSTRACT
Unclassified

20. LIMITATION OF ABSTRACT