NOVEL CONCEPTS FOR THE COMPRESSION OF LARGE VOLUMES OF CARBON DIOXIDE – PHASE III

Final Report

Reporting Period Start Date: 01/01/11
Reporting Period End Date: 06/30/14

Prepared by:

J. Jeffrey Moore, Ph.D.
Timothy C. Allison, Ph.D.
Neal D. Evans
Brian S. Moreland
Augusto J. Garcia-Hernandez
Meera M. Day
Brandon L. Ridens

DOE Award No. DE-FC26-05NT42650
SwRI® Project No. 18.11919

Prepared for:

U.S. Department of Energy
National Energy Technology Laboratory
626 Cochrans Mills Road
P.O. Box 10940
Pittsburgh, PA 15236-0940

September 28, 2014

SOUTHWEST RESEARCH INSTITUTE®

SOUTHWEST RESEARCH INSTITUTE®
6220 Culebra Road
San Antonio, Texas 78238

NOVEL CONCEPTS FOR THE COMPRESSION OF LARGE VOLUMES OF CARBON DIOXIDE – PHASE III

Final Report

Reporting Period Start Date: 01/01/11
Reporting Period End Date: 06/30/14

Prepared by:

J. Jeffrey Moore, Ph.D.
Timothy C. Allison, Ph.D.
Neal D. Evans
Brian S. Moreland
Augusto J. Garcia-Hernandez
Meera M. Day
Brandon L. Ridens

DOE Award No. DE-FC26-05NT42650
SwRI® Project No. 18.11919

Prepared for:

U.S. Department of Energy
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236-0940

September 28, 2014

Approved:

Edgar B. Bowles, Jr.

Edgar B. Bowles, Jr., Director
Fluids & Machinery Engineering Department

SOUTHWEST RESEARCH INSTITUTE®

DISCLAIMER

ABSTRACT

In the effort to reduce the release of CO_2 greenhouse gases to the atmosphere, sequestration of CO_2 from Integrated Gasification Combined Cycle (IGCC) and Oxy-Fuel power plants is being pursued. This approach, however, requires significant compression power to boost the pressure to typical pipeline levels. The penalty can be as high as 8-12% on a typical IGCC plant. The goal of this research is to reduce this penalty through novel compression concepts and integration with existing IGCC processes. The primary objective of the study of novel CO_2 compression concepts is to reliably boost the pressure of CO_2 to pipeline pressures with the minimal amount of energy required. Fundamental thermodynamics were studied to explore pressure rise in both liquid and gaseous states. For gaseous compression, the project investigated novel methods to compress CO_2 while removing the heat of compression internal to the compressor. The high-pressure ratio, due to the delivery pressure of the CO_2 for enhanced oil recovery, results in significant heat of compression. Since less energy is required to boost the pressure of a cooler gas stream, both upstream and inter-stage cooling is desirable. While isothermal compression has been utilized in some services, it has not been optimized for the IGCC environment. Phase I of this project determined the optimum compressor configuration and developed technology concepts for internal heat removal. Other compression options using liquefied CO_2 and cryogenic pumping were explored as well. Preliminary analysis indicated up to a 35% reduction in power is possible with the new concepts being considered. In the Phase II program, two experimental test rigs were developed to investigate the two concepts further. A new pump loop facility was constructed to qualify a cryogenic turbopump for use on liquid CO_2. Also, an internally cooled compressor diaphragm was developed and tested in a closed loop compressor facility using CO_2. Both test programs successfully demonstrated good performance and mechanical behavior. In Phase III, a pilot compression plant consisting of a multi-stage centrifugal compressor with cooled diaphragm technology has been designed, constructed, and tested. Comparative testing of adiabatic and cooled tests at equivalent inlet conditions shows that the cooled diaphragms reduce power consumption by 3-8% when the compressor is operated as a back-to-back unit and by up to 9% when operated as a straight-though compressor with no intercooler. The power savings, heat exchanger effectiveness, and temperature drops for the cooled diaphragm were all slightly higher than predicted values but showed the same trends.

TABLE OF CONTENTS

List of Figures

List of Tables

Table | Page

1. EXECUTIVE SUMMARY

In the effort to reduce the release of CO_2 greenhouse gases into the atmosphere, sequestration of CO_2 from Integrated Gasification Combined Cycle (IGCC), Oxy-Fuel, and Pulverized Coal (PC) power plants have been investigated. Capture and sequestration of CO_2, however, requires significant compression power to boost the pressure to typical pipeline levels. The penalty can be as high as 8–12% on a typical IGCC plant and even higher on Oxy-Fuel and PC plants. The goal of the research described herein was is to reduce this penalty through novel compression concepts and integrating these concepts with existing IGCC processes.

The primary objective was to examine methods of boosting the pressure of CO_2 to pipeline pressures with minimal amount of energy required. First, fundamental thermodynamics were studied to explore whether pressure rise in liquid or gaseous states was preferred. Since the first phase of the project involved conceptual brainstorming, flexibility was built into the project to permit investigation of several concepts. Southwest Research Institute® (SwRI®) and Dresser-Rand (D-R) Company partnered in this project to advance the state-of-the-art in pressurization of CO_2.

For gaseous compression, the project investigated novel methods to compress CO_2 while removing the heat of compression internal to the compressor. The high-pressure ratio compression of CO_2 results in significant heat of compression. Since less energy is required to boost the pressure of a cool gas, both upstream and inter-stage cooling is desirable. While isothermal compression has been utilized in some services, it has not been optimized for the IGCC environment. Furthermore, external intercooling results in higher losses and more complicated piping systems. Phase I of the project determined the optimum compressor configuration and developed technology for internal heat removal. Other concepts that liquefy the CO_2 and boost pressure through cryogenic pumping were also explored in the research during Phase I.

Two of the concepts investigated have the potential to reduce the required compression power by double digits compared to a conventional compressor selection. One concept that was studied is a semi-isothermal compression process where the gas is continually cooled in the path through the compressor (after each stage). A simple cooling jacket insert, used in the diaphragm of each stage, could provide this type of continuous cooling. The savings in horsepower in the semi-isothermal process are significant (up to a 30% reduction in total power). The other concept that offered similar savings in required horsepower over a standard compression process is the concept of pumping liquefied CO_2. In this concept, the primary power requirements are the initial compression required to boost the CO_2 to approximately 250 psia and the refrigeration power required to liquefy the gas. Once the CO_2 is liquefied, the pumping power to boost the pressure to pipeline supply pressure is minimal.

Phase II included development of two experimental test rigs. The first was used to verify performance and integrity of a liquid CO_2 turbopump. A development pump was procured from a pump vendor and a dedicated liquid CO_2 loop was constructed. The second test rig tested an internally-cooled compressor concept by using an existing compressor test rig and replacing internal components, including the rotor. Both test programs successfully met all test objectives as described below.

The goal of Phase III was to develop and construct a pilot-scale demonstration compression plant to optimize CO_2 compression, as well as perform a balance of plant measurement for total power required and savings realized using the technology developed in Phase II. The compressor used a multi-stage version of the cooled diaphragm design. A new compressor, based on a D-R DATUM D12 frame size, consisted of a six-stage, back-to-back centrifugal compressor that incorporated the cooled diaphragms. A new test loop with required coolers, valves, and piping was constructed to test this new compressor. Year 1 activities included design of the multi-stage cooled diaphragms and design of the test loop.

An additional work task was added near the end of the project. That phase of work consisted of gas properties testing of CO_2 mixtures. This additional task is described in Section 4.1.4.

The compressor package and pipe loop were commissioned, including oil flush, pipe alignment, shaft alignment, and mechanical testing. All mechanical parameters of the compressor met manufacturer's specifications. A trim balancing on the high-speed coupling on the gearbox end was performed to reduce the vibration to acceptable levels. Some speed control issues with the electric motor variable frequency drive (VFD) were resolved and inaccurate readings from the torque meter were corrected. Some rework of the cooling water piping was required. Aerodynamics testing with dry (adiabatic) diaphragms was then performed, followed by cooled diaphragm testing. The project completed testing on time at the end of June 2014.

Several compressor operating configurations were tested in order to verify compressor performance and determine the effects of the cooled diaphragms. The adiabatic tests (with no cooling water) showed close correlation to the predicted aerodynamic performance maps. These tests established a baseline temperature distribution and power. The liquid cooling system was commissioned and tuned to provide the correct flow distribution to the diaphragms. The subsequent cooled diaphragm testing showed similar head-flow characteristic curves, but slightly higher head and pressure ratio for a given flow due to the increased volume reduction caused by lower stage discharge temperatures. Therefore, subsequent testing matched overall pressure ratio and flow for multiple adiabatic and cooled operating points by adjusting throttle valve position and compressor speed. This data showed that the cooled diaphragms reduce power consumption by 3-8% when the compressor is operated as a back-to-back unit, with the higher power savings at high flow operating points. At the design pressure ratio, the heat exchanger effectiveness and temperature drops for the cooled diaphragm were all slightly higher than predicted values but showed the same trends. A third test was performed with no intercooler in order to mimic a straight-through compressor. During this test, speed was reduced to approximately 80% design speed in order to keep adiabatic test temperatures below compressor limits. The test results showed 9% horsepower savings when operating at the low-flow side of the map%, nearly achieving the project's goal of double-digit power reduction for CO_2 compression. Based on trends from the back-to-back test, horsepower savings at the high-flow side of the map is expected to be higher than 10%.

2. SUMMARY OF PHASE II RESULTS

As a result of the conceptual design study performed in Phase I, two promising concepts were identified. The first concept was inter-stage cooling for the low pressure (LP) compressor attempting to achieve near isothermal compression. The LP compressor boosted the CO_2 streams to about 250 psia. The second concept proposed to liquefy the CO_2 and pump the liquid to the desired pressure of 2,200 psia. Both of these concepts were demonstrated through subscale rig testing in Phase II. The first rig consisted of a single-stage centrifugal compressor test installed in the existing Multi-Stage Test Rig (MSTR) facility at SwRI, as described in Section 3. An optimized flow path design was created, and new internals were manufactured, including a new shaft, impeller, seals, and diaphragms. The flow path was optimized for CO_2 and a novel vaned diffuser was developed that maximized heat transfer, yet had good pressure rise. The cooling liquid passed through the diffuser vanes, maximizing heat transfer. The return channel vanes were also cooled internally. Custom diaphragms were fabricated that contained the cooling jacket and flow passages. Figure 2-1 shows a photo of the cooled diaphragm developed in Phase II. Both ambient temperature and chilled water schemes were tested. The performance of the heat exchanger and the total pressure losses were quantified using internal instrumentation. Figure 2-1 also shows the internal components of the cooled diaphragm test rig developed under Phase II. The compressor was tested both adiabatically (without cooling) and diabatically (with cooling) for a range of flows, speeds, pressures, and cooling medium conditions. The compressor performed better than predicted, resulting in as much as 55% removal of the heat of compression. A patent application has been submitted for this technology.

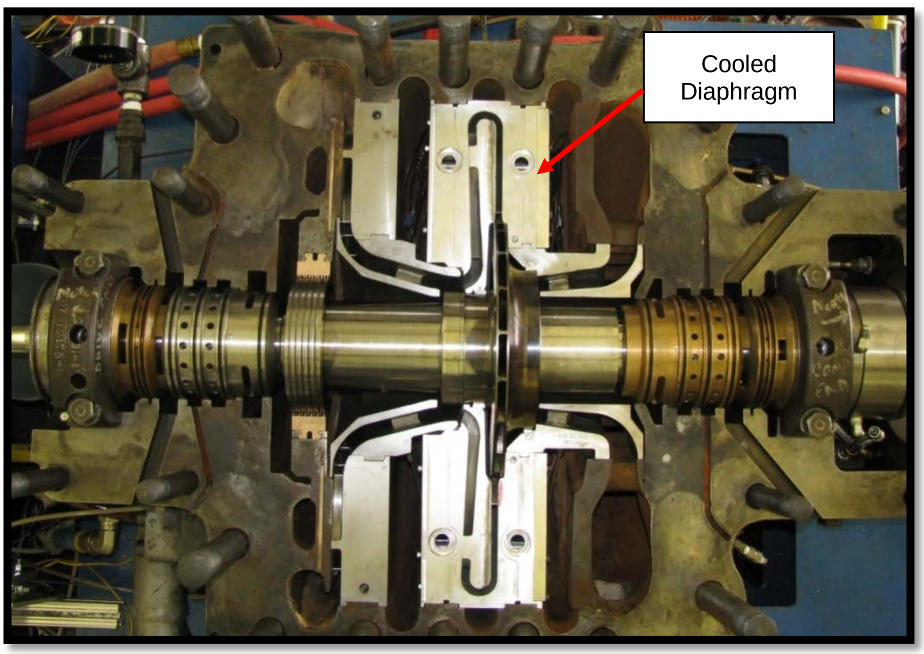


Figure 2-1. Photograph of Cooled Diaphragm Test Rig

The second test rig developed in Phase II consisted of a newly constructed liquid CO_2 test loop and a custom-developed, sub-scale multi-stage pump. This scale factor was selected to keep the cost of the facility to a minimum, yet still provide valid performance and mechanical data. A schematic of the loop is shown in Figure 2-2.

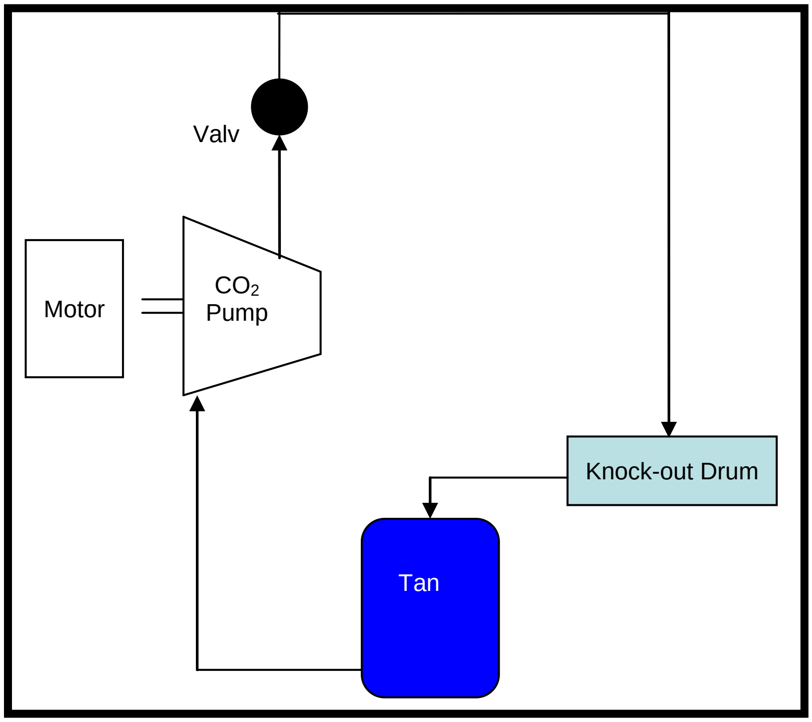


Figure 2-2. Schematic of Liquid CO_2 Pump Loop

The pump loop consisted of a 12-stage pump driven by a variable-speed electric motor through a speed increasing gearbox. The scaled pump parameters are shown in Table 2-1 and demonstrate the motivation for the subscale testing.

Table 2-1. Summary of Sub-Scale Pump Parameters

	Full Scale	1/3 Scale
Horsepower	1,355	150
Flow Rate (gpm)	968	107

The size of the loop components and the power requirements drove the subscale design. The pump was fed from a 1,000-gallon pressurized tank that maintained liquid CO_2 at its boiling temperature of -10°F and 250 psia. The discharge of the pump fed an orifice flow meter run followed by a control valve that dropped the pressure from 2,200 psia down to 250 psia. Some flashing of the gas back to the vapor phase occurred and was vented through a back pressure control valve. Figure 2-3 shows a photo of the pump loop after construction was completed. Performance and mechanical testing on the pump were performed and demonstrated good behavior, meeting targets for discharge pressure and flow range.

Figure 2-3. Existing Liquid CO_2 Pump Loop Constructed at SwRI

3. PHASE III APPROACH

3.1 Project Objectives

The goal of Phase III was to develop a new multi-stage centrifugal compressor that contained the cooled diaphragm technology. The pilot-scale test set-up was capable of measuring the overall power balance and determining the net savings, including all ancillary equipment. This testing was a critical next step before full-scale commercialization of the system.

3.2 Project Scope

Phase III included development and testing of a cooled diaphragm multi-stage centrifugal compressor operating on gaseous carbon dioxide. The compressor was selected based on the required inlet volume flow and had two sections in a back-to-back configuration. An intercooler was installed between the two compressor sections, and an after-cooler was installed following the discharge of the second section. This permitted the compressor to operate with and without internal cooling. After exiting the after-cooler, the stream was near 250 psia and near atmospheric temperature. Finally, the high-pressure discharge gas was throttled across control valves, dropping the pressure back to near atmospheric pressure and temperature, ready to be fed back to the compressor inlet.

3.3 Tasks to Be Performed

The following tasks were identified and divided by year. These tasks have been modified slightly from the original to reflect the delay in the project start date.

3.3.1 Year 1: Task 1.0 – Compressor and Test Loop Design

Subtask 1.1 Project Management and Reporting

Subtask 1.2 Conceptual Design of Flow Loop

Subtask 1.3 Conceptual Design of Multi-stage Internally Cooled Diaphragm and Manufacturing Procedure

Subtask 1.4 Kick-off Meeting

Subtask 1.5 Thermo-physical Properties Kickoff Meeting at DOE NETL Facilities

Subtask 1.6 Characterization of Representative Gas Mixtures: Determination of the Representative Carbon Dioxide Gas Mixtures

3.3.2 Year 2: Task 2.0 – Hardware Procurement and Site Preparation

Subtask 2.1 Detail Design Flow Loop

Subtask 2.2 Detail Design Multi-stage Internally Cooled Diaphragm and Manufacturing Procedure

Subtask 2.3 Project Management and Reporting

Subtask 2.4 Compressor Procurement

Subtask 2.5 Procure all Major Equipment (Piping, Valves, Coolers)

Subtask 2.6 Procure Instrumentation and Develop Data Acquisition and Control Program

Subtask 2.7 Prepare Site

2.7.1 Pour Concrete Pad

2.7.2 Install Electrical Supply and Transformer

2.7.3 Construct Control Room

Subtask 2.8 Meeting in Olean, NY and Morgantown, WV

Subtask 2.9 Design of Generation 3 Cooled Diaphragm

3.3.3 Year 3: Task 3.0 – Test Loop Assembly, Commissioning, and Testing

Subtask 3.1 Project Management and Reporting

Subtask 3.2 Compressor Procurement – Take Delivery and Final Payment

Subtask 3.3 Test Loop Assembly

3.3.1 Install Major Pieces of Equipment, Including Coolers, Heat Exchangers, Cooling Tower, and Compressor

3.3.2 Install Piping Completing Welding of Field Joints

3.3.3 Perform X-ray Inspection of the Welds and Hydro Test the Piping

3.3.4 Plumb Up Piping to the Compressor, Including Cooling Water and Lube Oil to the Coolers

3.3.5 Install Electrical Connections to all Equipment

3.3.6 Install Instrumentation on Compressor Skid

Subtask 3.4 Testing

3.4.1 Perform Commissioning Tests on Compressor and Motor Drive Including Performance and Mechanical Tests

3.4.2 Perform Tests

3.4.3 Measure Performance, Mechanical Data, and Overall Power Balance

Subtask 3.5 Final Review Meeting in Morgantown, WV

Subtask 3.6 Testing of Generation 3 Cooled Diaphragm

The following describes the major subtasks.

3.4 Year 1: Task 1.0 – Compressor and Test Loop Design

3.4.1 Subtask 1.1 – Project Management and Reporting

Project management was performed, as described in the SwRI Project Management Plan previously submitted, using a tollgate and task-management approach. Within this process, the project manager coordinated activities of individual task managers to assure that project tollgates, budgets, and external deadlines were met and that the overall project stayed on schedule. The project manager also coordinated activities with external stakeholders [DOE and D-R] through bi-monthly conference calls. Additional conference calls were held as necessary. DOE was informed of the project progress through quarterly and annual reports (per the Federal Reporting Requirements).

3.4.2 Subtask 1.2 – Conceptual Design of Flow Loop

First, a conceptual design of the flow loop was developed. A basic layout of the equipment was generated. Engineering calculations for flow rates determined the required pipe sizes and pressure ratings. Pipe lengths will be determined and pressure drops were calculated. Pipe and flange sizing was determined using ASME piping guidelines. All pressure vessels adhered to ASME pressure vessel code requirements.

3.4.3 Subtask 1.3 – Conceptual Design of Multi-stage Internally Cooled Diaphragm and Manufacturing Procedure

Working jointly with D-R, SwRI staff developed a multi-stage diaphragm concept. Case penetrations for the cooling flow were designed. Conjugate heat transfer (CHT) computational fluid dynamics (CFD) analysis was used to optimize the design.

3.4.4 Subtask 1.4 – Kick-off Meeting

Kick-off meetings were held prior to initiating project activities as follows:

1. Internal SwRI kick-off in San Antonio, TX
2. D-R kick-off in Olean, NY
3. DOE kick-off in Pittsburgh, PA

Additional kick-off meetings were scheduled, as necessary. Kick-off meetings were held at a place and date convenient for all involved parties but no later than three months from project initiation.

3.4.5 Subtask 1.5 – Thermo-physical Properties Kickoff Meeting at DOE NETL Facilities

A kick-off meeting was held at the NETL facilities to discuss project background and strategy.

3.4.6 Subtask 1.6 – High Pressure Thermophysical Gas Property Testing, Uncertainty Analysis, and Equation-of-State Comparison for Supercritical CO_2 Compression Applications

Density, speed of sound (SOS), and specific heat at constant volume tests were conducted using carbon dioxide gas mixtures at a multitude of different temperature and pressure values. Initial determination of the representative CO_2 mixture was conducted. The gas mixtures represented three post-combustion separation mixtures, one oxy-fuel, and one super critical pipeline CO_2 mixture.

3.5 Year 2: Task 2.0 – Hardware Procurement and Site Preparation

3.5.1 Subtask 2.1 – Detailed Design of Flow Loop

First, a detailed design of the flow loop was developed and represented by a solid model. The pipe loop was modeled in Caesar II to assess weight loads and thermal stress. The Caesar II model facilitated the design of the pipe layout and the placement of supports. The proposed piping was also analyzed in Stoner Pipeline Simulator (SPS) to ensure that pressure drops throughout the system were acceptable. A Process and Instrumentation Diagram (P&ID) was generated detailing the final pipe design and supporting equipment.

3.5.2 Subtask 2.2 – Detailed Design of Multi-stage Internally Cooled Diaphragm and Manufacturing Procedure

Engineering drawings of the diaphragms were developed. A detailed manufacturing plan was generated. Final specifications of the compressor were made.

3.5.3 Subtask 2.3 – Project Management and Reporting

Additional to the previously described project management activities (Task 1.1), the project manager coordinated with a local site construction contractor and D-R to assure that the installation was completed safely, within budget, and on schedule. A project review meeting was held in Morgantown, WV, to evaluate status and schedule.

3.5.4 Subtask 2.4 – Compressor Procurement

An order was placed with D-R for the compressor. The target date for delivery was established. The compressor was sized to meet the operating conditions as outlined above and in Figure 2-1.

Approximate operating conditions were:

1. Suction Pressure: 15-25 psi
2. Discharge Pressure: 230-260 psi
3. Mass Flow: 60,000-70,000 lbm/hr
4. Power: 3,000 hp
5. Design: Multistage centrifugal compressor with back-to-back sections and intercooling and aftercooling

The compressor was mounted with a variable-speed electric motor and gearbox on a single skid. A dry gas seal system and the variable frequency drive (VFD) were also supplied.

3.5.5 Subtask 2.5 – Procure Major Equipment

All other major pieces of equipment including piping, valves, and coolers were specified and procured.

3.5.6 Subtask 2.6 – Procure Instrumentation and Develop Data Acquisition and Control Program

The data acquisition and control software developed in Phase II was modified for the new test loop. All instrumentation was specified. The required instrumentation was ordered.

3.5.7 Subtask 2.7 – Prepare Site

The site preparation for the new lab space including excavation and civil work was performed. All utilities including the electrical supply, natural gas, and compressed air, were supplied. Provisions were made to provide cooling water and compressed CO_2 and N_2 to the facility and associated testing areas; N_2 was made available at tank pressure and CO_2 will be available up to 3,000 psi was made available via a pumping station. The required transformer, along with the running of the high-voltage power lines, was installed. A control building was erected.

3.5.8 Subtask 2.9 – Design of Generation 3 Cooled Diaphragm

In lieu of building a liquefaction and pumping system, a third generation-cooled diaphragm was developed to substantially increase the heat transfer without increasing the size of the diaphragm and without additional pressure drop. Conjugate Heat Transfer (CHT) Computational Fluid Dynamics (CFD) was used to optimize the design and quantify the heat transfer and pressure drop. This optimized design was implemented using the existing Generation 1 cooled diaphragm and tested in Year 3 in the same D-R 1M compressor used in Phase II.

3.6 Year 3: Task 3.0 – Test Loop Assembly, Commissioning, and Testing

3.6.1 Subtask 3.1 – Project Management and Reporting

The project management task, as outlined above for Task 1.1, was performed. Additionally, weekly meetings were held to coordinate test activities and to review test data. At the end of this task, report-out meetings were held as follows:

1. At SwRI (San Antonio, TX)
2. At D-R (Olean, NY)
3. At DOE (Pittsburgh, PA)

Additional report-out meetings were held, as necessary. All report-out meetings were held at a time and location convenient for all parties but no later than three months after the completion of the project.

3.6.2 Subtask 3.2 – Compressor Procurement

The D-R compressor train was delivered and inspected by SwRI prior to installation on a suitable foundation at SwRI. A review of all build records, including rotor component and assembly balance records, impeller diffuser alignment, and internal seal clearances, was performed.

3.6.3 Subtask 3.3 – Test Loop Assembly

The test loop was assembled. All large equipment was mounted, including the compressor, coolers, and heat exchangers. All field-piping joints were completed after the trial installation. The piping was x-ray inspected and hydro tested. All instrumentation and electrical systems were installed. The assembled system was leak checked, followed by commissioning of the facility.

3.6.4 Subtask 3.4 – Testing

Mechanical and aerodynamic testing of the compressor occurred first, and the full-scale compression testing followed. Measurements of compressor performance, including all other ancillary equipment, were made to derive the total power budget. Twenty-five days of testing was budgeted. The results are detailed in this report.

3.6.5 Subtask 3.5 – Design of Generation 3 Cooled Diaphragm

A Generation 3 cooled diaphragm design was developed for improved heat transfer characteristics. The diaphragm design work involved computational fluid dynamics analysis of baseline and parameterized models in order to identify configurations with high effectiveness and minimal overall pressure drop increase when compared to an existing diaphragm flow path.

The design was completed and a significant increase in diaphragm effectiveness was expected based on analysis results.

3.7 Deliverables

In addition to the Federal Reporting Requirements specified on the Reporting Checklist, Attachment 3, the following deliverables were required:

- TOPICAL REPORT: Cooled Diaphragm Design. The cooled diaphragm concept was extended to a multi-stage design. Many design challenges to bring the flow into and out of the casing, as well as manufacturing processes, were developed, maturing the design for commercialization. Since the cooled diaphragm concept works by reducing the power required in the downstream stages, actual power reduction was measured.

- FINAL REPORT: The system dynamics were measured. An overall power balance, including the compressor as well as all coolers, was measured.

3.8 Briefings/Technical Presentations

Two briefings were planned at the NETL facilities in Morgantown, WV. First, a kick-off meeting was held to present the goals of the project and obtain feedback from NETL personnel. A progress meeting was scheduled in Year 2. A final meeting will be held at the conclusion of the project to present the final results. Furthermore, presentations will be made at the DOE/NETL Annual Contractor Review Meeting, as well as at least one technical conference.

4. RESULTS AND DISCUSSIONS

4.1 Year 1: Task 1.0 – Compressor and Test Loop Design

4.1.1 Subtask 1.1 – Project Management and Reporting

The SwRI team held multiple teleconferences with the D-R team to refine and review the cooled diaphragm design, including monthly teleconference calls to discuss the manufacturing progress.

4.1.2 Subtask 1.2 – Conceptual Design of Flow Loop

4.1.2.1 Process and Instrumentation Diagram

Figure 4-1 shows the process and instrumentation diagram (P&ID) for the compression part of the test flow loop. The two sections of the D-R back-to-back compressor were fed by two independent loops that could be placed in series or parallel operation, depending on the position of the hand valves. This design offered maximum flexibility for performance testing. The loop contained after-coolers following each section to permit both adiabatic and diabatic (with cooled diaphragms) testing. The flow in each section could be independently controlled in parallel mode or by a single valve in serial mode. The control valve (CV002) served as a recycle valve. A hot gas bypass was placed around each after-cooler to permit temperature control of the suction temperature in each loop using the two control valves (CV003 and CV004).

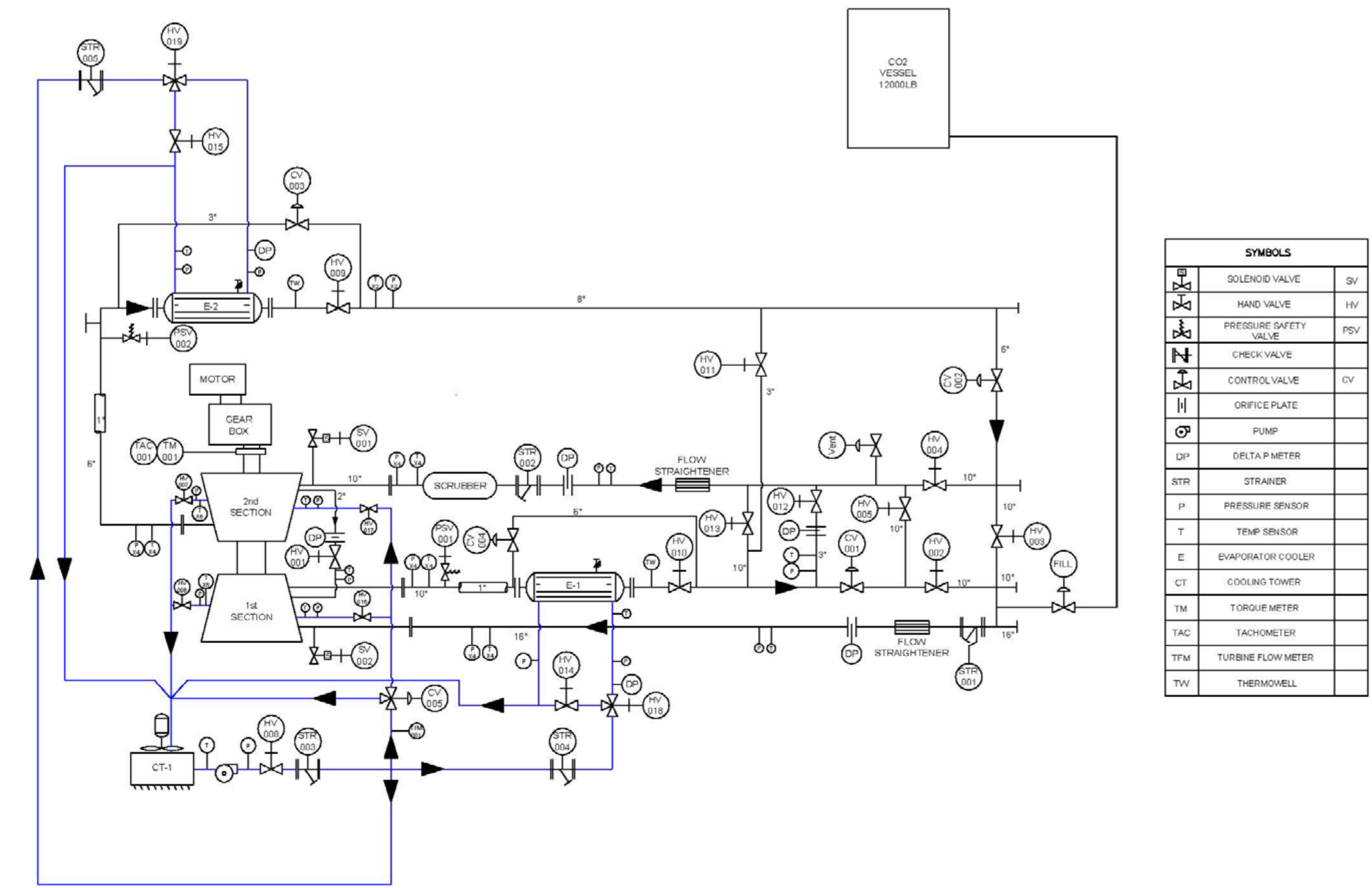


Figure 4-1. P&ID of Compressor Loop

The low-pressure (LP) compression process entailed increasing the pressure of the gaseous CO_2 stream from ambient pressure (14.8 psia) to either the liquefaction pressure or high-pressure compression suction pressure, typically near 250 psia. Similar results were presented in Phase II in order to investigate different cooled diaphragm concepts in a multistage design. However, these previous analyses considered only straight-through compressors with no intercoolers. Therefore, the current results consider both straight-through and back-to-back compressors with a single intercooler.

In addition to considering additional low-pressure compression technologies, the performance calculation methodology was updated in order to increase the accuracy of power savings estimates by utilizing real gas properties for compressor head calculations rather than assuming a constant specific heat, which improved the accuracy of the predictions. Calculations for required power included gas power only and neglected bearing and windage losses, and any heat transfer that may have occurred in uncooled diaphragms. The analysis also assumed that the cooled diaphragm heat transfer effectiveness was not limited by an insufficient flow of water.

First, the updated methodology was applied to the same straight-through concepts that were analyzed previously in the Phase II final report. The concept variations included basic adiabatic baseline cases and, also cooled-diaphragm cases with changes to the radius ratio, speed, and heat transfer enhancements in the diaphragm. The updated results are compared in Table 4-1 with previous power savings estimates. These results show that although previous power savings estimates were slightly high, significant power savings up to 15.3% are still predicted for straight-through compressors. However, a straight-through compressor results in excessive discharge temperature for this application, so the results should be viewed as a relative comparison rather than attainable power savings.

The updated analysis results indicate, as did the previous results, that power savings are optimized by increasing the radius ratio and decreasing compressor speed (adding stages). Heat transfer enhancements had a net decrease in power savings due to the increased pressure drop of the proposed enhancements.

Table 4-1. Previous and Updated LP Compression Power Savings Calculations

Geometry	RPM	Radius Ratio	# Stages	HX Effectiveness	Previous Estimate of Gas Power Savings	Updated Gas Power Savings
Adiabatic Reference	12,850	1.5	5	NA	0%	0%
Smooth Wall	12,850	1.5	5	0.15	9.5%	7.0%
Smooth Wall	12,850	1.8	5	0.197	12.3%	8.6%
Ribs and Dimples	12,850	1.5	5	0.25	4.3%	1.2%
Ribs, Dimples, and Grooves	12,850	1.5	5	0.31	2.4%	-0.93%
Adiabatic Reference	9,155	1.5	9	NA	0%	0%
Smooth Wall	9,155	1.5	9	0.15	16.6%	13.3%
Smooth Wall	9,155	1.8	9	0.197	>20%	15.3%

4.1.3 Overall (LP/HP) Compression Savings

In this section, various technologies are combined in order to analyze the entire compression process including both LP and HP regimes. The methods are applied to the following conditions as the power baseline for the DOE reference pulverized coal plant with carbon capture in [1]:

- Single stream inlet Pressure/Temperature = 14.8 psia / 115°F
- Discharge Pressure = 2,150 psia
- Intercooler/After-cooler Exit Temperature = 115°F

The following methods were analyzed for power comparisons:

1. DOE Baseline (efficiencies and refrigeration/liquefaction cycle performance calibrated to match data in [1]
2. Back-to-back LP and HP compressors with uncooled diaphragms
3. Back-to-back LP and HP compressors with cooled diaphragms, 15% effectiveness, 85°F cooling water
4. Back-to-back LP and HP compressors with cooled diaphragms, 20% effectiveness, 85°F cooling water
5. Back-to-back LP compression with cooled diaphragm (15% effectiveness, 85°F cooling water), liquefaction, and pumping
6. Back-to-back LP compression with cooled diaphragm (20% effectiveness, 85°F cooling water), liquefaction, and pumping
7. Back-to-back LP compression with cooled diaphragm (15% effectiveness, 85°F cooling water), liquefaction (ideal economizer), and pumping
8. Back-to-back LP compression with cooled diaphragm (15% effectiveness, 85°F cooling water) up to 425 psia, ideal economizer (removes all superheat), liquefaction, and pumping

The power calculations in this analysis include gas horsepower for compression, cooling horsepower required for liquefaction, pumping horsepower, and gearbox power losses of 2%. The estimates exclude bearing and windage losses and power required for the pumping and chilling of cooling water.

The overall compression system analysis results for the methods shown above are displayed in Table 4-2. A back-to-back compressor with a cooled diaphragm is expected to achieve 10.4-11.7% power savings (15-20% effectiveness). Savings due to the liquefaction/pumping approach with an ideal economizer is expected to produce a 7.4% savings over the DOE compression/pumping reference case. With more realistic economizer performance, this savings should be closer to 5.7%. Case 10, which increases the LP discharge pressure (and, thus, the liquefaction temperature) allows the economizer to remove all superheat, but produces 2.1% power savings using the same coefficient of performance (COP) as the previous case.

Based on the superior savings of the cooled diaphragm and the fact that a high-pressure diaphragm had been developed, the decision was made to focus on the compression only approach for the experimental test program. Further development of a cooled diaphragm using the existing single stage rig developed during Phase II of this program was employed to test these advanced concepts.

Table 4-2. Overall Compression Power Savings Analysis Results

Case Description	Predicted Gas Power [hp/(lbm/min)]	Power Savings	Discharge Temp (°F)	Gas Heat Removal (Btu/lbm)	Horsepower Breakdown
DOE Baseline	4.7634	0%	271 Comp -34 Condenser -7 Pump	117.3	4.7634 = 2.6603 Compressor + 1.7945 Condenser + 0.3086 Pump
D-R B2B LP and HP (Uncooled Diaphragm)	4.4489	6.6%	384 LP 296 HP 115 After-cooler	283.9	4.4489 = 2.8060 LP Compressor + 1.6429 HP Compressor
D-R B2B LP and HP (Cooled Diaphragm, 15% Effectiveness)	4.2672	10.4%	312 LP 229 HP 115 After-cooler	276.3	4.2672 = 2.7175 LP Compressor + 1.5497 HP Compressor
D-R B2B LP and HP (Cooled Diaphragm, 20% Effectiveness)	4.2083	11.7%	292 LP 210 HP 115 After-cooler	278.8	4.2083 = 2.6896 LP Compressor + 1.5187 HP Compressor
D-R B2B LP (Cooled Diaphragm, 15% Effectiveness), Liquefaction & Pumping	4.4092	7.4%	312 Comp 115 After-cooler 15 Economizer (gas)* -15 Condenser 8 Pump 57 Economizer (liquid)	121.3	4.4092 = 2.7175 Compressor + 1.4283 Condenser + 0.2634 Pump
D-R B2B LP (Cooled Diaphragm, 15% Effectiveness), Liquefaction & Pumping	4.4914	5.7%	312 Comp 115 After-cooler 46 Economizer (gas)* -15 Condenser 8 Pump 42 Economizer (liquid)	121.3	4.4914 = 2.7175 Compressor + 1.5105 Condenser + 0.2634 Pump
D-R B2B LP (Cooled Diaphragm, 20% Effectiveness), Liquefaction & Pumping	4.4635	6.3%	292 Comp 115 After-cooler 46 Economizer (gas) -15 Condenser 8 Pump 42 Economizer (liquid)	120.2	4.4635 = 2.6896 Compressor + 1.5105 Condenser + 0.2634 Pump
D-R B2B LP (Cooled Diaphragm, 20% Effectiveness) up to 425 psia, Economizer down to saturation T, Liquefaction & Pumping	4.8628	2.1%	400 Comp 115 After-cooler 20 Economizer (gas) 19 Condenser 45 Pump 95 Economizer (liquid)	283.0	4.8628 = 3.4551 Compressor + 1.1473 Condenser + 0.2605 Pump. Used DOE COP value for liquefaction, may be able to increase COP at higher T

4.1.4 Subtask 1.6 High Pressure Thermophysical Gas Property Testing, Uncertainty Analysis, and Equation of State Comparison for Supercritical CO_2 Compression Applications

SwRI developed high-accuracy test methods for density and speed of sound determination for the supercritical regimes for a variety of gas mixtures. Following is a discussion of the results from these high pressure gas property tests performed using specialized anti-corrosion, high pressure, institute-designed test fixtures. The analyzed gas mixtures included high CO_2, hydrocarbon, and natural gas mixtures. These results were used to compare experimental data of specified gas properties with varying equation of state (EOS) model predictions. Uncertainty limits and bounds for primary direct measurements and reference conditions were calculated based on data from each gas mixture, test condition, and equipment uncertainties. Recommendations are made for selected EOS models for the specific mixtures and conditions from model and test measurement comparisons.

Accurate gas property prediction is a necessary component for proper sizing and selection of equipment, improving overall efficiency, making accurate predictions, and reducing operating costs. High-accuracy test methods developed by SwRI for density, speed of sound (SOS), and specific heat at constant volume were implemented for five different CO_2 gas mixtures at supercritical regimes. The gas mixtures tested in this campaign included process impurities commonly seen in CO_2 separation such as methane, argon, oxygen, nitrogen, water and sulfur dioxide.

4.1.4.1 Characterization of Representative Gas Mixtures

In order to determine the representative carbon dioxide gas mixtures which are likely to be produced from the various commercially available separation processes for fossil-fuel based power plants (namely pulverized coal, NGCC, IGCC and oxy-fuel cycles), a technical literature review of measured and modeled CCS processes and interviews with DOE and industry personnel was conducted to determine adequate recommendations for the mixture compositions.

The mixture constituents for CO_2 gases are likely to be derived by processes that result in hydrocarbons and coal / natural gas impurities such as sulfur compounds, hydrogen sulfide, nitrogen, and argon. This task was accomplished by a thorough technical paper review of previous studies and modeling efforts, in addition to consultation with leading technical experts and separation equipment manufacturers. The task included the formulation of multiple mixtures to represent S-CO_2 power generation cycle with expected impurities.

The following is a result of a literature review from multiple sources including experimental reports, theses, technical papers, and journal articles from both the industry and academia. Power plants using coal, NGCC, IGCC, and oxy-fuel cycles were reviewed.

An analysis of a natural gas combined cycle power plant that was modeled for carbon capture and sequestration with various oxy-combustion characteristics was performed by the Department of Mechanical Engineering at the University of Alabama [7]. Models included air separation units, power plants, an amine scrubbing unit, and a carbon dioxide compression and drying unit. Combustion products were produced of primarily CO_2 and water from the hydrocarbon fuel in air. For density testing purposes, the mixture to represent the combustion product during the power plant cycle including amine separation was defined as being 96% mol CO_2 and 4% mol H_2O.

A paper by the Department of Energy (DOE) and Foster Wheeler [2] reviewed a conceptual novel process for CO_2 sequestration that utilized an oxygen-fired pulverized coal (PC) boiler with a Rankine steam cycle to form a high efficient, seemingly zero emission, stackless power station. An oxidizer consisting of a mixture of O_2 and flue gas, containing primarily CO_2 gas, was utilized with a coal fired boiler. The flame temperature was controlled with the recycled flue gas in the boiler furnace to maintain acceptable waterwall temperatures. With the use of combustion staging and reburning and char reduction, NOx emissions were minimized in the flue gas and effectively all of the flue gas heat energy was recovered. This left the plant with virtually pure CO_2 to compress, condense, and provide to a separate site for sequestration. Based upon membrane separation, the cold flue gas exiting the wet-end economizer contained primarily CO_2 (over 90% by mass) and small amounts of 0_2 and H_20. For testing purposes, the mixture to represent this flue gas was defined as being 94.74% mol CO_2 and 5.26% mol O_2.

A study by the University of Cincinnati and the U.S. Environmental Protection Agency in the Journal of the Air and Waste Management Association [6] estimated multiple potential flue gas impurities in CO2 streams separated from coal-fired power plants to examine the use of different air pollution control devices. The presence of sulfur dioxide (SO_2) within the glue gas was investigated due to its high concentration during the desulfurization and CO_2 separation processes involved with pulverized coal power plants. For testing purposes, the mixture to represent this flue gas before reducing the SO_2 constituents was defined as being 95% mol CO_2 and 5% mol SO_2.

An article by Dresden University of Technology [3] provided a technological and economic evaluation of an oxyfuel lignite-fired power plant with advanced supercritical steam parameters and CO_2 capture. This process was based on a design developed with the same boundary conditions and conventional power plant equipment of lignite-fired power plants with efficiencies close to 50%. The presented flue gas composition in the oxyfuel process before compression was 82.2% vol CO_2, 9.2% vol N_2, 4.4% vol O_2, 0.6% vol Ar, 3.7% vol H_2O, and 0.03% vol SO_2. For testing purposes, the mixture to represent this flue gas was defined as being 85.42% mol CO_2, 9.38% mol N_2, 5.21% mol O_2.

The "CO_2 Impurity Design Parameters – Quality Guidelines for Energy Systems Studies" [4] provides a guideline and recommended impurity limits for CO_2 stream components for use in studies of CO_2 carbon capture, utilization, and storage systems. This guideline, developed by the National Energy Technology Laboratory and the U.S. Department of Energy, is based on information collected from various studies and arranged by component and application. The recommended maximum of CO_2 impurities for enhanced oil recovery or saline reservoir carbon capture and sequestration applications is presented as 95% vol (min) CO_2, 4% vol N_2, 4% vol O_2, 4% vol Ar, 4% vol CH4, 4% vol H_2, and smaller to trace amounts (in ppmv) of other constituents. For testing purposes, the mixture to represent pipeline grade CO_2 is condensed down to 95.96% mol CO_2, 2.02% mol N_2, 1.01% mol Ar, and 1.01% mol CH4.

The list of gas mixture compositions with their respected labels for the following test campaign is presented in Table 4-3.

Table 4-3. Campaign Gas Mixture Compositions

Mixture	CO_2 %mol	N_2 %mol	H_20 %mol	O_2 %mol	SO_2 %mol	Ar %mol	CH_4 %mol	Description
1	96	0	4	0	0	0	0	Amine Separation
2	94.74	0	0	5.26	0	0	0	Membrane Separation
3	95	0	0	0	5	0	0	Pulverized Coal
4	85.42	9.38	0	5.21	0	0	0	Oxy-Comb Lignite-Fired
5	95.96	2.02	0	0	0	1.01	1.01	Pipeline CO_2

All thermophysical property datasets (for each mixture) utilized five pressure points and three temperatures spanning the range from 100-10,000 psi and from 100-300°F. A majority of the test points were within the supercritical regime, above the critical temperature and pressure of CO_2 of roughly 88°F and 1,057 psi, respectively. These pressure and temperature points covered the foreseeable range for carbon capture and sequestration activities (separation, compression, transport and re-injection) and turbomachinery designs for closed S-CO_2 loops for power generation.

4.1.4.2 Test Description and Methodology

The testing utilized the Mixed Gas Laboratory in the Turbomachinery Research Facility. All test procedures adhered to the Standard Operating Procedures for the lab and specialized test methods were developed for density, speed of sound, and specific heat property measurements. The testing utilized four certified gas mixtures, which were routinely, as needed, ordered from a gas supply company to complete the test runs, and a custom mixture of CO_2 and H_2O.

Based on the range of test pressures within this program campaign and for accuracy purposes, three test fixtures were required. A high pressure, concentrated volume autoclave designed for precision scale measurements was utilized for density calculations at elevated pressures. Figure 4-2 displays the closed cylinder used for the density measurements, rated for 10,000 psi operation, accompanied by two pressure taps for a Type K thermocouple, a pressure transducer, and a fill line. The autoclave was placed vertically on the high precision scale to take the mass measurements. A high pressure fixture, composed of high pressure tubing/piping was used for the speed of sound measurements, see Figure 4-3. By design, to determine the response frequency, there were multiple high-pressure fittings along the fixture's length for dynamic pressure (using an internal acoustic-to-electric transducer), static pressure, temperature, and fill line purposes using similar equipment as the test setup for the density measurements. A high pressure, concentrated volume autoclave similar to that used for the density measurements was used for the specific heat measurements. Figure 4-4 displays the closed cylinder utilized for these measurements that shares the same dimensions as the density autoclave with a larger high pressure tap to accommodate an electric heating element. The pressure transducer and Type K thermocouple were connected to the high pressure fill line.

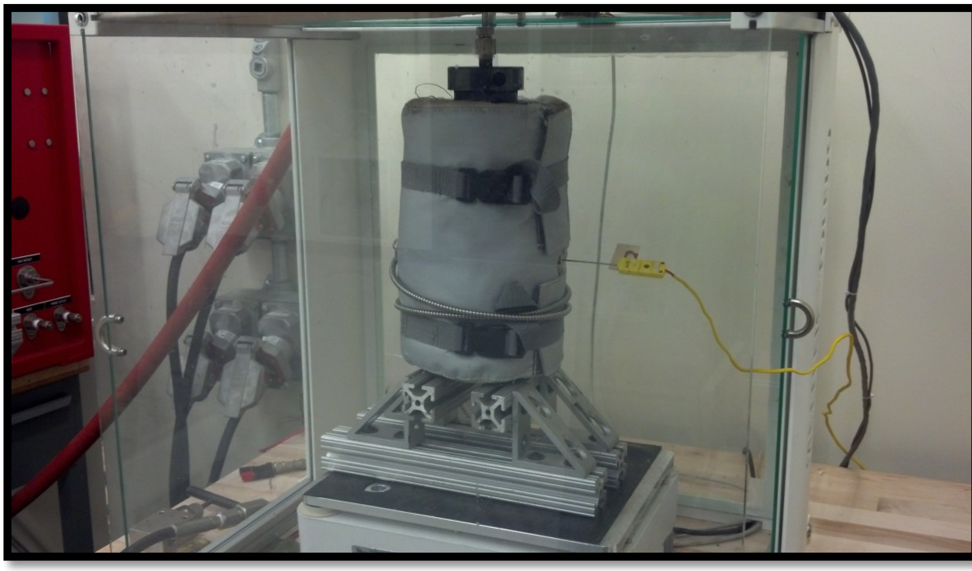


Figure 4-2. High Pressure Test Fixture for Density Measurements

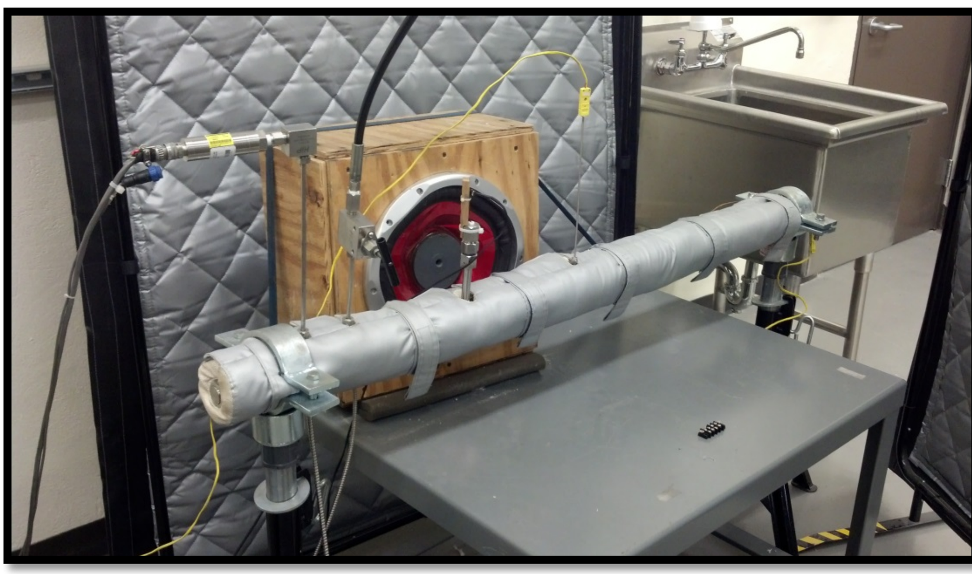


Figure 4-3. High Pressure Test Fixture for Speed of Sound Measurements

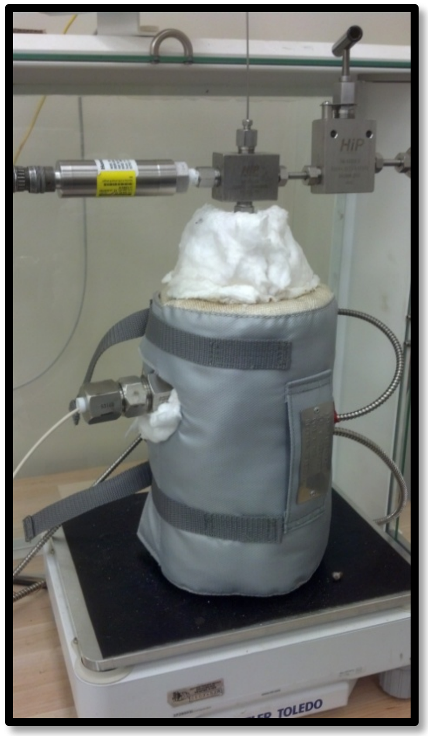


Figure 4-4. High Pressure Test Fixture for Specific Heat Measurements

The test program was performed in a pressure space equipped with gas detectors tied to a safety control system. The laboratory test space was humidity and temperature controlled for assurance of instrumentation calibration standards.

4.1.4.2.1 Measurement of Density

Gas density (specific volume) was measured using separate measurements of gas mass and internal volume of the test fixture. Water displacement was used to determine an accurate internal volume of the test fixture. The masses of the gas mixture and test fixture were measured using a precision industrial laboratory mass comparator scale with a precision of 0.001 gram and a total capacity of 26 kg.

The density was determined using a fixed-volume measurement of the test chamber and measurements of the variable mass of the gas mixture based on the pressure and temperature condition. Compensation for the material expansion due to temperature was considered in the final calculation of density and uncertainty calculations. The mass comparator scale was calibrated by a specialized technician in place at SwRI.

In order to ensure high precision measurements of the gas mass, the steady-state condition was established and a vacuum was pulled each time between test runs. The test gas was used as a purge gas between test runs utilizing different gas mixtures. When testing with Mix 3, nitrogen was used as a purge gas between test runs. The test fixture was disconnected fully from the gas filling line and the mass measurement was recorded once the steady condition had been reached. Before and after each run, the test fixture gas was released and then the vacuum pump was used to remove all remaining trace amounts of gas. Tare weight measurements were taken in the vacuum state.

4.1.4.2.2 Measurement of Speed of Sound

The natural acoustic resonance of a pipe with two closed ends can be used to determine speed of sound. Fundamental acoustic theory states that a pipe with two open or two closed ends will resonate at a frequency corresponding to the half-wave mode of the pipe which is equal to the speed of sound divided by two times the acoustic length of the test fixture. The effective acoustic length can be solved using a calibration test gas to yield a frequency-based determination of speed of sound.

A high power speaker was used to introduce a standing wave into the test fixture while a high frequency acoustic-to-electric transducer (microphone) was used to measure the frequency content of this standing wave. It was important to establish defined hard ends on both ends of the test fixture to generate the pure half-wave response at the single resonant frequency. The microphone was placed near the middle of the test fixture to obtain the largest amplification of the standing wave. Through a performed frequency sweep, a peak amplitude and associated frequency was recorded, see Figure 4-5, and used to calculate the speed of sound.

To accommodate elevated gas temperatures, the test fixture was heated to the specified temperature using higher power electrical heat wraps or heat jacket. A high pressure extension for the microphone was designed to be mounted to the fixture at the pressure tap. The extension permitted a 4″ piece of tubing to be used to hold the microphone and still register the pressure wave reflections in the primary test fixture. If needed, the extension piece was continuously cooled through its external walls to maintain lower temperature for the microphone. This adaptation of the speed of sound test method was tested first using pure CO2 gas to assure that the calibrated acoustic length of the primary test chamber was still valid.

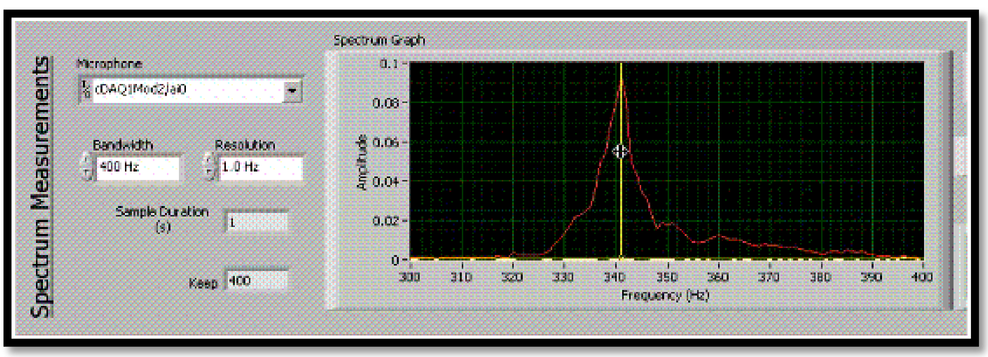


Figure 4-5. Example Peak Amplitude at Resonant Frequency

4.1.4.2.3 Measurement of Specific Heat at Constant Volume

Specific heat at constant volume was measured using separate measurements of gas mass, internal volume of the test fixture, and temperature and pressure rise over time. Water displacement was used to determine an accurate internal volume for the test fixture.

The specific heat was determined using a fixed-volume measurement of the test chamber and measurements of the temperature and pressure increase of the gas mixture as heat was added using a heating element. Compensation for the material expansion due to temperature was considered in the final calculations. A steady-state condition was established below each test point so that the temperature and pressure of the gas would reach the desired test point conditions during the test run as the temperature and pressure increased, which was caused by the activated heating element.

For each test iteration, the power supply to the heating element was activated which sent a voltage signal to the data acquisition system indicating that energy was being added to the system. The data acquisition recorded the rise in heat within the autoclave for approximately 25 seconds. A pure, instrument grade, gas was initially tested to calculate a calibration heat energy absorbed over a specific period of time. This gas, based from the primary component of the test mixture, was used to compare property values to the related test mixture established from the known specific heat of the pure gas using the GERG equation of state model in NIST REFPROP. The test gas mixture was run at the same conditions as the calibration gas test. The calibration heat energy absorbed from the calibration gas was used to calculate the specific heat for the test gas mixture of interest. An energy correction factor, based on the average ratio of the calculated calibration energy and predicted energy of the test gas for the same time period, was implemented.

4.1.4.3 Uncertainty Analysis

The test uncertainty was calculated for the primary direct measurements and reference condition (pressure, temperature, EOS model prediction, and gas mixture uncertainty) at each test condition. The test uncertainty is a function of the sensor measurement uncertainty and additional uncertainties in the test geometry (length and internal volume). The instrument uncertainty estimate is described for the pressure, temperature, density, and speed of sound measurements. Additional contributions to test uncertainty included the gas mixture variation based on a 1% or 2% uncertainty in each gas component per the certified mixture and the equation of state model uncertainty for the reference condition.

Prior to determining a test uncertainty, it was important to know whether the measured variables in the test were independent or dependent. This aided in determining which method of calculating uncertainty must be employed. If the measured variables in an experiment are truly found to be independent, then the method to determine total uncertainty is simply an addition of all individual measurement uncertainties, as seen in the equation below.

$$\Delta F = |\Delta x_1| + |\Delta x_2| + |\Delta x_3| + |\Delta x_4| + \cdots |\Delta x_n| = \sum_{i=1}^{n} |\Delta x_i| \tag{4.1}$$

$where$:
$\Delta F = Total\ Uncertainty$
$\Delta x = Individual\ Measurement\ Uncertainties$

The two gas property values involved independent measurements of at least two quantities and, therefore, required an analysis of contributing uncertainties. In the case of density, these direct measurements were gas volume and mass. In the case of speed of sound, these were the test fixture length and the resonant frequency. The most accurate analysis to determine total uncertainty of dependent variable measurement systems is the perturbation method, which is based on the actual function F and does not require any linearity assumptions, as seen in the equation below.

$$\begin{aligned}\Delta F &= \Delta F(\Delta x_1) + \Delta F(\Delta x_2) + \Delta F(\Delta x_3) + \ldots \Delta F(\Delta x_n) \\ &= \left|F(x_1) - F(x_1 + \Delta x_1)\right| + \left|F(x_2) - F(x_2 + \Delta x_2)\right| + \left|F(x_3) - F(x_3 + \Delta x_3)\right| + \ldots \left|F(x_n) - F(x_n + \Delta x_n)\right| \\ &= \sum_{i=1}^{n} \left|F(x_i) - F(x_i + \Delta x_i)\right| \end{aligned} \tag{4.2}$$

The perturbation method is implemented by sequentially perturbing (or altering) the input values, such as temperature and pressure, by their respective uncertainties and recording the effects on the calculated output quantity (density and speed of sound). Using the perturbation method, the influence of each test parameter uncertainty can be directly evaluated for the particular gas mixture at the pressure and temperature condition selected for the iteration. The NIST REFPROP [5] program was used for all EOS model predictions and to evaluate the gas mixture uncertainty, pressure uncertainty, and temperature measurement uncertainty on the measured properties (density and speed of sound). To find the final test uncertainty, the root sum square addition was used to represent a true superposition of all positive and negative uncertainties. The individual contributions were squared, added together, and then the total test uncertainty was determined by the square root of the sum, seen in the equation below.

$$\Delta V = \sqrt{\Delta x_1^2 + \Delta x_2^2 + \Delta x_3^2 + \Delta x_4^2 \ldots \Delta x_n^2} \tag{4.3}$$

$$\begin{aligned}&where: \\ &\Delta V = Total\ Uncertainty \\ &\Delta x = Uncertainty\ Contribution\ of\ Each\ Measurement\end{aligned}$$

Pressure and temperature variations due to the instrumentation precision uncertainties were modeled in NIST REFPROP to determine the effect on the gas property at the temperature and pressure condition for each run. The uncertainty in each gas component was reported to be either 1% or 2% based on the certification supplied by the gas supplier. This effect was modeled in the NIST REFPROP software by considering the analytical uncertainty effect on the primary constituent. This method allowed the uncertainty to be customized for the specific gas mixture and pressure/temperature condition of interest. The amount of additional uncertainty due to the gas components varied by mixture.

Measured uncertainties for specific heat were based from the highest density total uncertainty from the respective pressure and temperature conditions of the density tests proceeding. The density, used to determine the mass of the gas, was calculated in REFPROP; from which the uncertainties from the density tests could be extrapolated. Due to the combination of both the calibration and test uncertainties, the total uncertainty in specific heat varied from 1% to 12% depending on gas mixture and test point.

4.1.4.3.1 Pressure Measurement

Pressure measurement was performed using multiple Honeywell Sensotech pressure transducers with a specific accuracy of 0.25%. Multiple transducers (0-5000 psi range and 0-10,000 psi range) were required to cover the wide pressure range required for the testing. The appropriate range pressure transducer was installed based on the test condition. For uncertainty calculations, pressure uncertainty was estimated at 0.25% for all test conditions to provide a “worst case” high uncertainty for the low-end measurements of each transducer’s range. Pressure variations due to the instrumentation precision uncertainty were modeled in NIST REFPROP to determine the effects on the gas property at the temperature and pressure conditions for each run.

4.1.4.3.2 Temperature Measurement

Gas temperature was measured using a thermocouple probe inserted through a high pressure fitting. Additional thermocouples were instrumented along the surface of the test fixture as a secondary measurement. Type K thermocouples were used, which are rated for a specified accuracy of 0.2°C. This accuracy level resulted in varying uncertainty percentages, from 0.5% to 2%, depending on the temperature value, and was utilized in the uncertainty analysis shown below. Temperature variations due to the temperature measurement precision uncertainty were modeled in the NIST REFPROP to determine the effect on the gas property at the temperature and pressure condition for each run.

4.1.4.3.3 Density Measurement

Gas mass varied based on the pressure condition required for the test. At low pressures, the lower mass amounts resulted in slightly higher test uncertainties. The precision scale (mass comparator type) manufactured by Mettler Toledo was designed for a total capacity of 26 kg and a resolution of 0.001 grams. Mass balancing on the scale was performed for each test run to assure that imbalance errors did not occur. Also, auxiliary cables and tubing were disconnected during the mass measurement of the test fixture in the pressurized condition. Internal volume for each test fixture was determined using water displacement tests, with an uncertainty of 2.54 mm^3 or 0.1 in^3. Total uncertainty in gas density varied from 0.95% to 9.5%.

4.1.4.3.4 Speed of Sound Measurement

The speed of sound measurement relied on high sensitivity acoustic microphones for detection of the standing pressure wave within the test chamber. To determine resonant frequency and the corresponding speed of sound, the SwRI Field-Das data acquisition system was utilized. The frequency of the pressure wave resonant condition was measured to within 0.01 Hz. The length of the chamber provided the half-wave acoustic length for the half wave mode. This length was based on calibration runs to determine the closed end-to-end acoustic length of the chamber and resulted in a very low-length uncertainty of less than 0.003 ft. The total speed of sound uncertainty varied from 0.3% to 15.4% based on the test condition.

4.1.4.3.5 Specific Heat Measurement

Specific heat at constant volume was determined using the internal volume measurement of the test fixture and the measurement of the pressure and temperature rise caused by the heating element. The same volume was maintained for all tests with a single test fixture using the high pressure autoclave.

The GERG EOS model was used to calculate the energy absorption of the gas from the heating element given the pressure and temperature rise of the calibration gas. The rate of temperature and pressure increase varied based on the pressure conditions required for the tests. Measured uncertainties were based on the highest density total uncertainty from the respective pressure and temperature conditions of the density tests preceding. The density, used to determine the mass of the gas, was calculated in REFPROP; from which the uncertainties from the density tests could be extrapolated. The total uncertainty of specific heat varied from 1.0% to 11.7%.

4.1.4.3.6 Summary of Test Uncertainties

The test uncertainty was calculated for each test run based on the specified instrumentation uncertainties and the reference measurement for the gas properties, speed of sound, density, and specific heat. In addition to the directly measured gas property uncertainties, the reference property was determined based on the contributing test condition uncertainties. Specifically, these uncertainties included temperature and pressure measurement, gas mixture effects, and the equation of state model being used to predict the reference gas property. This analysis was performed within REFPROP using the GERG equation of state model.

In some cases, the contribution of each test variable towards the total uncertainty varied significantly. The temperature and pressure uncertainties in combination with gas mixture uncertainties had larger effects on the gas property near the critical point. This can be seen in Figure 4-6 through Figure 4-18, with the non-linear "spikes" in the uncertainty curves. For Mix 1, density uncertainties could not be calculated at the pressure and temperature combination of 1800 psi and 200°F due to an error reported in REFPROP where the "liquid density iteration did not converge." For Mix 2, the density and speed of sound uncertainties could not be calculated at the pressure and temperature combination of 1,250 psi and 100°F due to the same error reported in REFPROP and 1,800 psi and 100°F for specific heat. Uncertainties for Mix 3 could not be calculated at the pressure and temperature test points of 1250 psi and 100°F, 1250 psi and 200°F, and 1800 psi and 200°F. Similarly, the density, speed of sound and specific heat uncertainties due to the gas composition for Mix 4 could not be calculated at 1,800 psi and 100°F due to the same error. For these points, the average of all of the uncertainties due to gas composition variations for the gas mixture was used for that uncertainty point. Such deviations may explain why there was considerably more difference in the measured density, speed of sound, and specific heat compared to the model predictions. The test conditions near the critical point for carbon dioxide are shown on the Pressure-Enthalpy diagram to highlight proximity to the critical point of pure CO_2, as shown in Appendix D.

Overall, the largest component towards the total uncertainty of the test (of both reference conditions and direct measurement quantities) was the gas mixture component uncertainty. The standard gas mixture certification provided a 1% or 2% variation in each component, which was largest for the majority component. Depending on the test pressure and temperature, this component uncertainty can lead to fairly large differences in the predicted density and speed of sound. In field applications, consistency of gas mixtures and presence of impurities can be represented by these component variations and mixture component uncertainties.

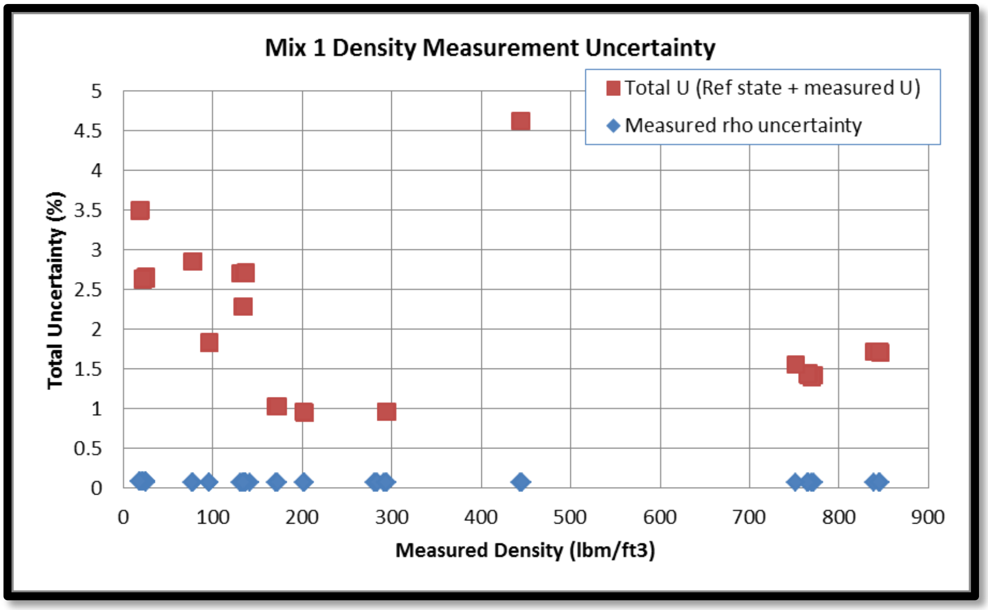


Figure 4-6. Density Measurement Uncertainty (U): Mix 1

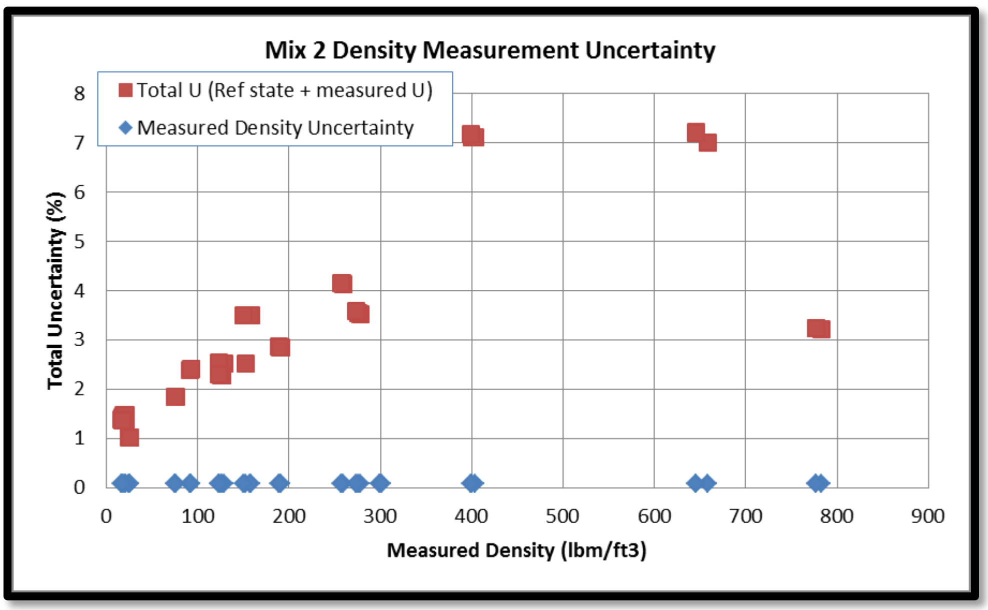


Figure 4-7. Density Measurement Uncertainty (U): Mix 2

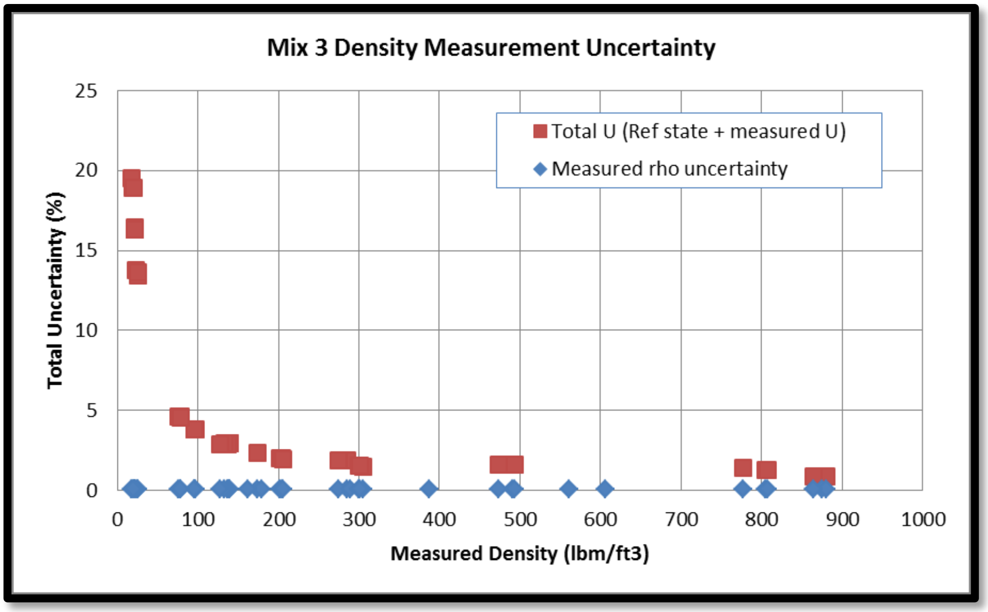


Figure 4-8. Density Measurement Uncertainty (U): Mix 3

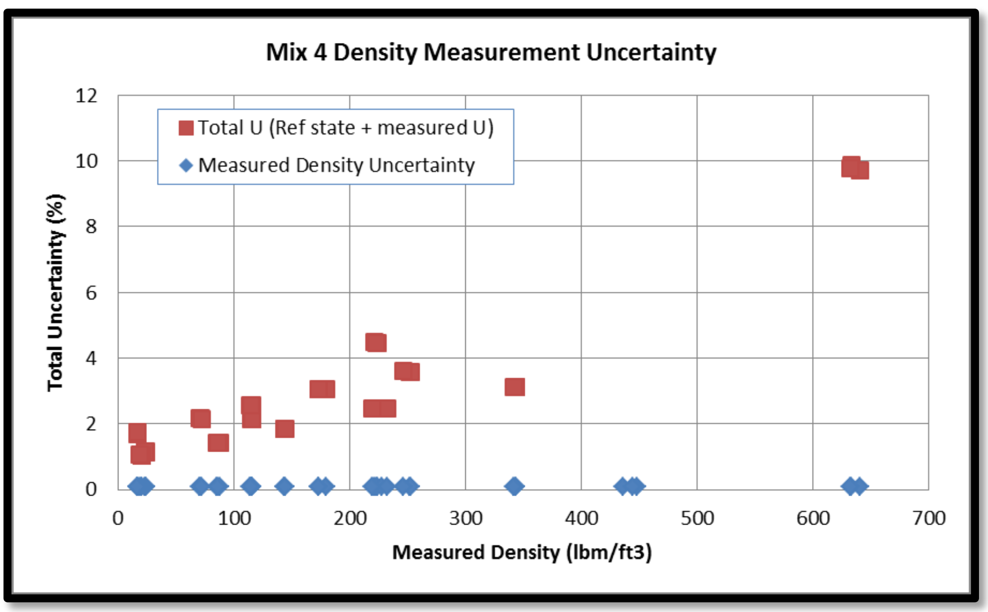


Figure 4-9. Density Measurement Uncertainty (U): Mix 4

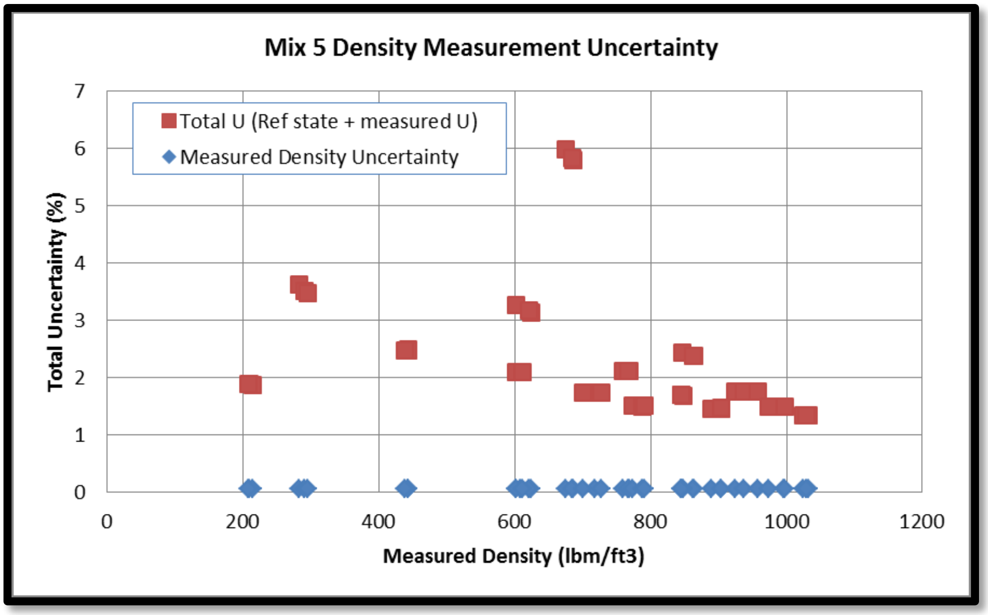


Figure 4-10. Density Measurement Uncertainty (U): Mix 5

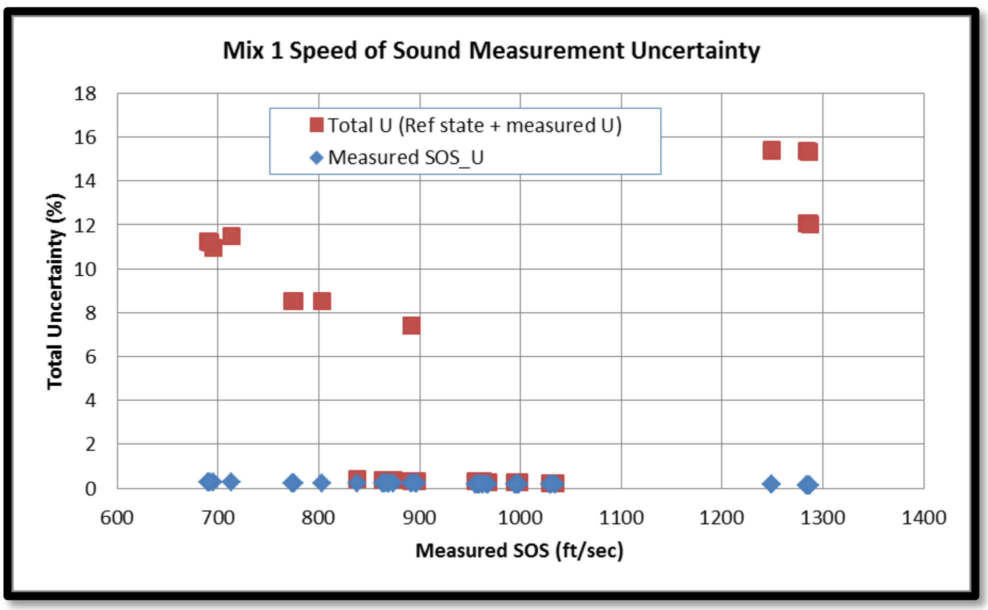


Figure 4-11. Speed of Sound Measurement Uncertainty (U): Mix 1

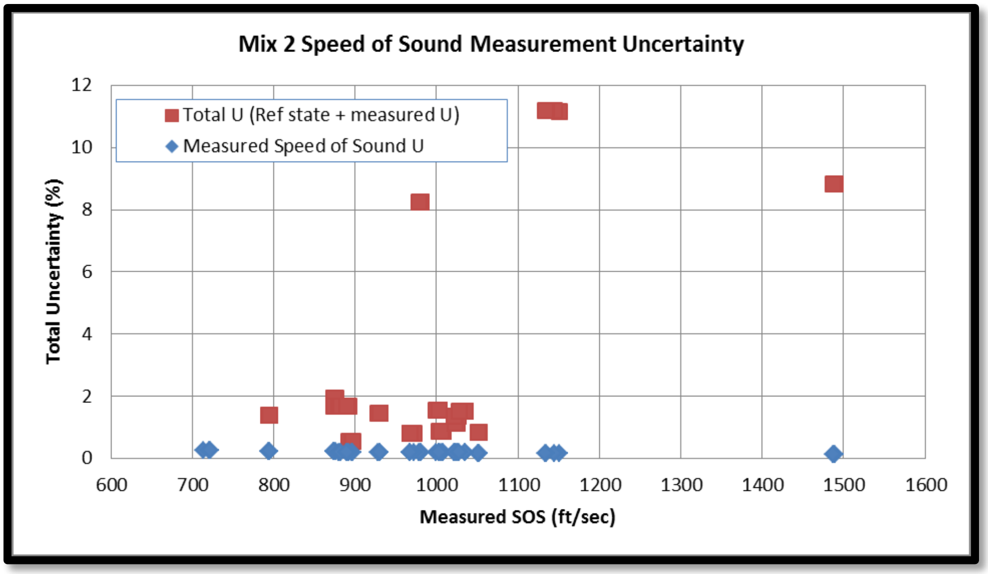


Figure 4-12. Speed of Sound Measurement Uncertainty (U): Mix 2

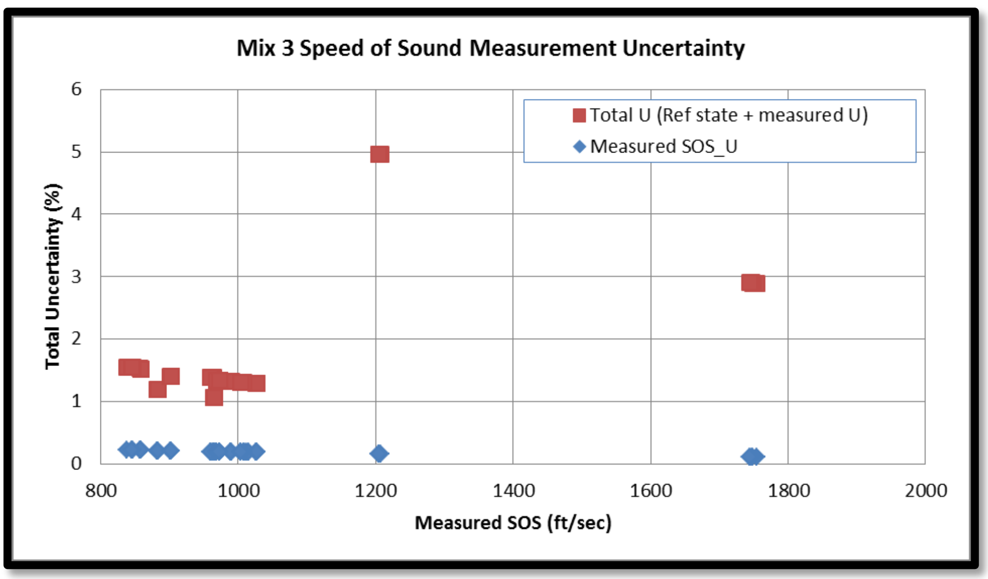


Figure 4-13. Speed of Sound Measurement Uncertainty (U): Mix 3

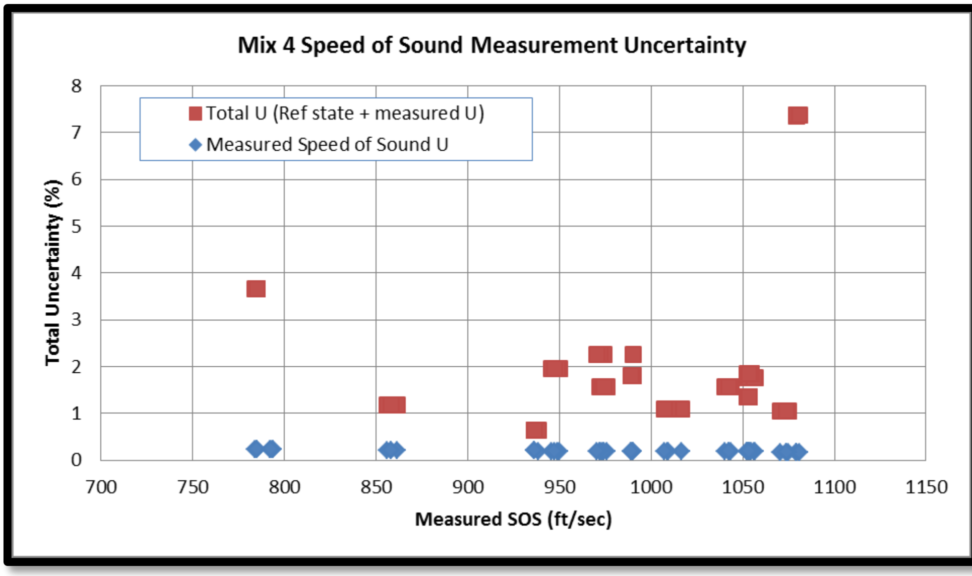


Figure 4-14. Speed of Sound Measurement Uncertainty (U): Mix 4

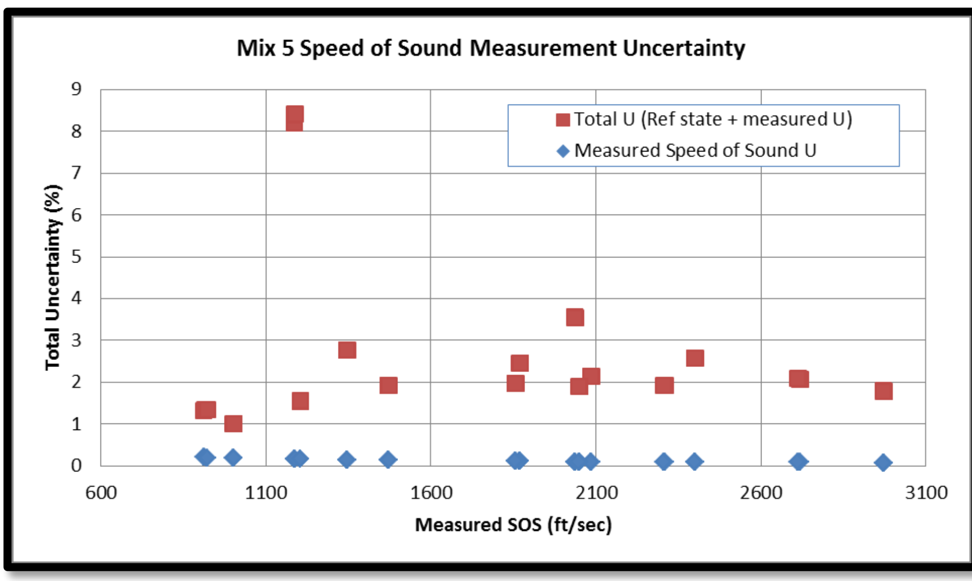


Figure 4-15. Speed of Sound Measurement Uncertainty (U): Mix 5

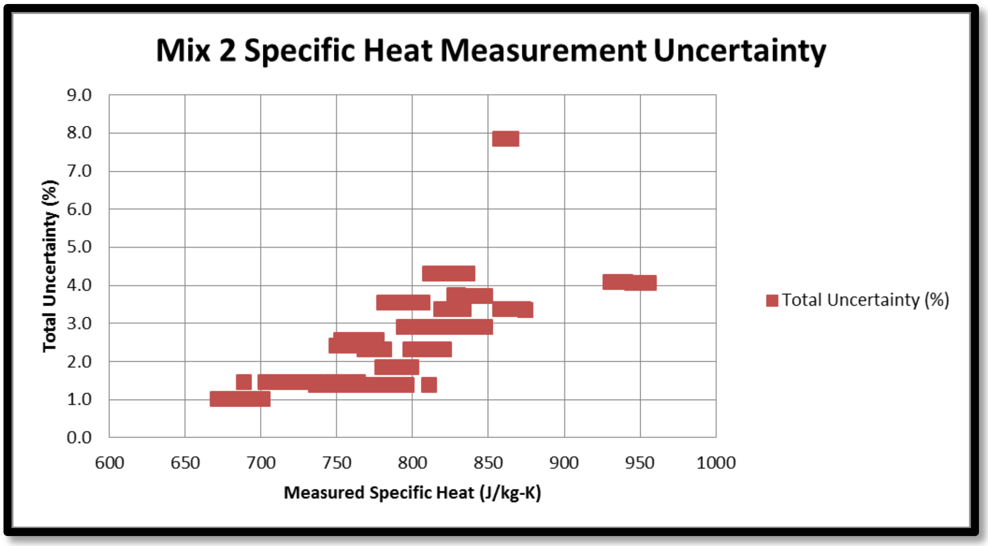


Figure 4-16. Specific Heat Measurement Uncertainty (U): Mix 2

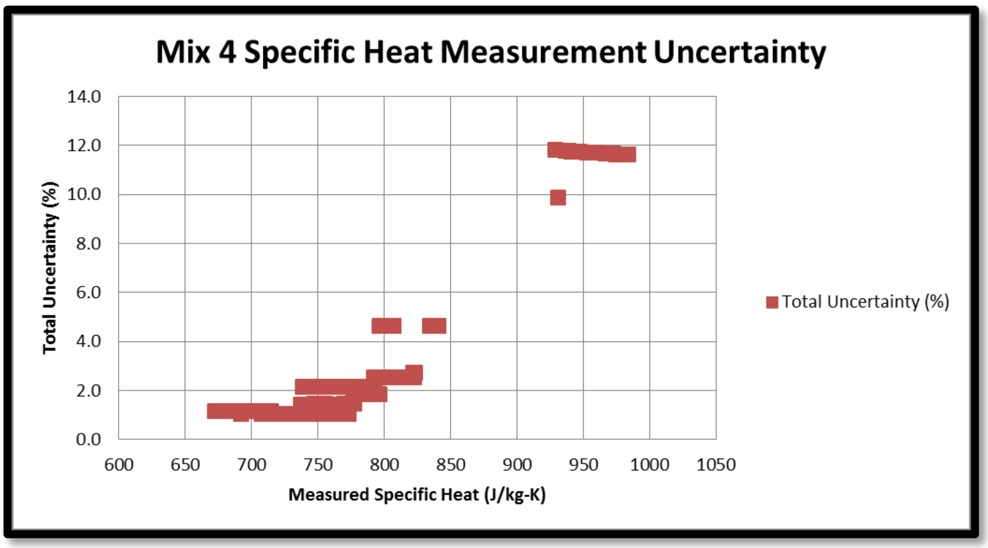


Figure 4-17. Specific Heat Measurement Uncertainty (U): Mix 4

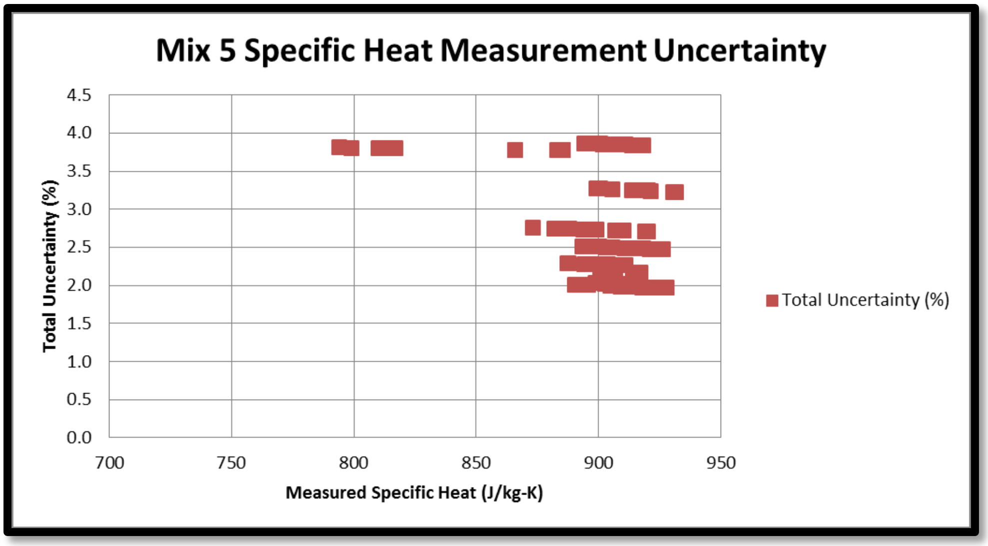


Figure 4-18. Specific Heat Measurement Uncertainty (U): Mix 5

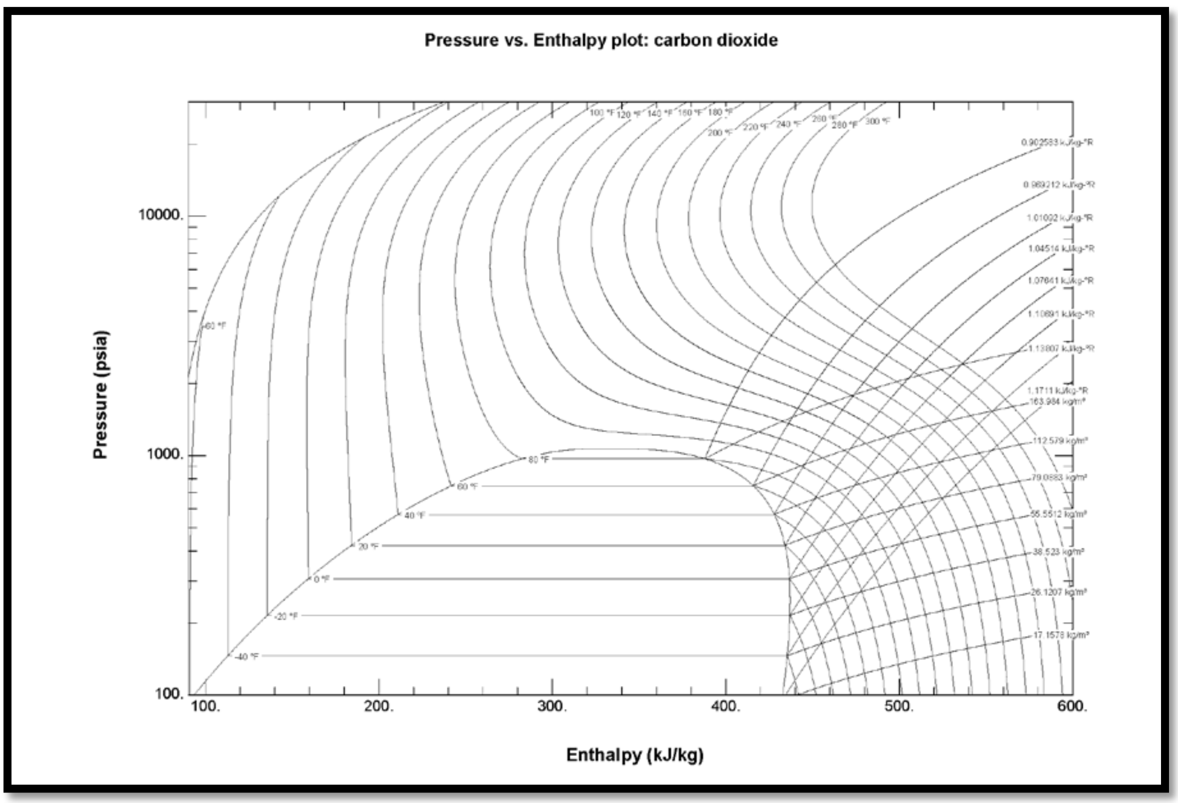


Figure 4-19. Pressure-Enthalpy Diagram for CO2

4.1.4.4 Test Campaign Results

To reduce test uncertainties and verify repeatability, a minimum of three iterations were performed for the density measurements, while a minimum of four iterations were performed for the speed of sound and specific heat measurements.

Test results are presented in Appendix C. The data shows the measured gas property, measured temperature and pressure, and the calculated, measured, and reference state uncertainty. The graphs in Figure 4-20 through Figure 4-32 display the measured gas property and measured pressure for the three different temperature points.

The reference state uncertainty varied from 0.9-11.2%, depending on the test condition and gas mixture. Total uncertainties, therefore, varied from 1.0% to 11.7% considering all contributions, including the gas mixture uncertainty. The driving factor in the reference state uncertainty was the gas mixture component uncertainty of upwards of 2% on each component per the certification from the gas supplier. All density, speed of sound, and specific heat measured uncertainties were below 1% for all test runs.

Also included in these data tables in Appendix C is the comparison with the European Gas Research Group (GERG) and default NIST equation-of-state. The comparison of the GERG and default NIST equation-of-state model predictions and experimental results is discussed further in the following section. In general, the GERG and NIST model predictions matched the experimental data within +/- 4% for most mixtures and test conditions. Higher deviations were notable for Mixes 1, 2, and 3 for the density measurements, Mix 4 for the specific heat measurements, and most mixtures at lower temperatures for the speed of sound measurements.

For Mixes 1, 2, 3, and 4, lower temperatures had a greater effect on density as pressure increased. In general, at lower pressures, density differed relatively little throughout the temperature range. As pressure increased, the influence of temperature was more prevalent as density increases at a faster rate at 100°F than at 200°F and 300°F. There was less of an influence of density due to pressure change at elevated pressures, above 4,000 psi, regardless of temperature, as seen in Figure 4-24. The largest increase between temperature and pressure points was between 1,250 psi and 1,800 psi at 100°F for Mixes 1, 2 and 4 and between 800 psi and 1,250 psi at 100°F for Mix 3. These trends can be seen in Figure 4-20 through Figure 4-24.

A notable trend with the speed of sound measurement was present in all of the mixtures at lower temperatures. At elevated temperatures, those at 300°F, change in pressure had relatively little effect on the speed of sound for the gas mixtures below 4,000 psi. As temperature decreased to 200°F, a slightly downward trend was noticed with the increase of pressure, resulting in lower speed of sound values. This slope changed around 1,500 psi where the speed of sound began to increase as the pressure rose. At the 100°F temperature range, lower speed of sound values were present, following a similar trend as for the 200°F and 300°F temperature ranges. A sharp increase in the speed of sound was measured as the pressure surpassed 1,500 psi at 100°F, displaying a distinctly greater slope than those of the higher temperatures, seen in Figure 4-25 and Figure 4-26. This trend, as well as the density trends, could be a result of the gas mixture approaching the critical point of CO_2, the point at which CO_2 begins to display characteristics of both a gas and a liquid. This phenomenon could explain why there was a relatively large and sharp increase of density and speed of sound as the gas mixture crosses into the critical and supercritical regions. When the gas was heated to 200°F and 300°F, the mixture was no longer near the critical point throughout the pressure range, resulting in a less extreme trend for density and speed of sound. Due to complications with reading the standing wave, the water content of Mix 1 was removed for the 200°F and 300°F measurements.

Similar to density and speed of sound, there were larger differences in specific gravity due to pressure at lower temperatures. As seen in Figure 4-30 and Figure 4-32, the range of specific heat between 165 psi and 1965 psi at 300°F was between roughly 750 J/kg-K and 850 J/kg-K, a difference of around 100 J/kg-K. This difference increases as temperature increases to roughly 300 J/kg-K at 100°F. At elevated pressures, above 3000 psi, the increase of both temperature and pressure has a notably smaller effect on specific heat as seen in Figure 4-31. Overall, specific heat changed relatively little at pressures above 4000 psi based on this test campaign. Due to the process of measuring and calculating specific heat, only results for Mix 2, 4 and 5 are available.

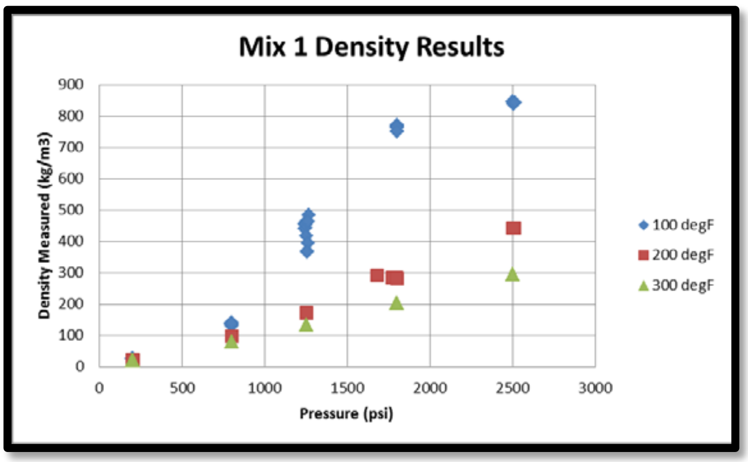


Figure 4-20. Density Measurement Results: Mix 1

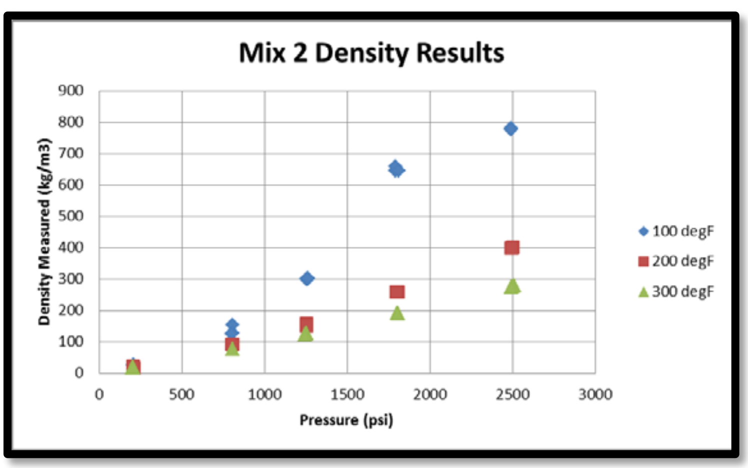


Figure 4-21. Density Measurement Results: Mix 2

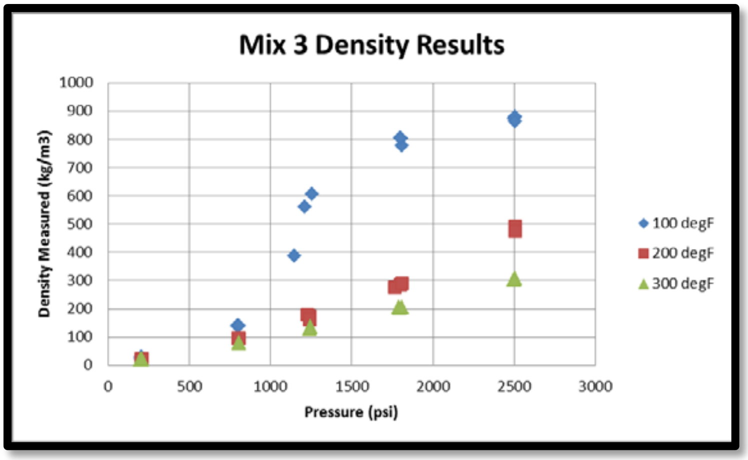


Figure 4-22. Density Measurement Results: Mix 3

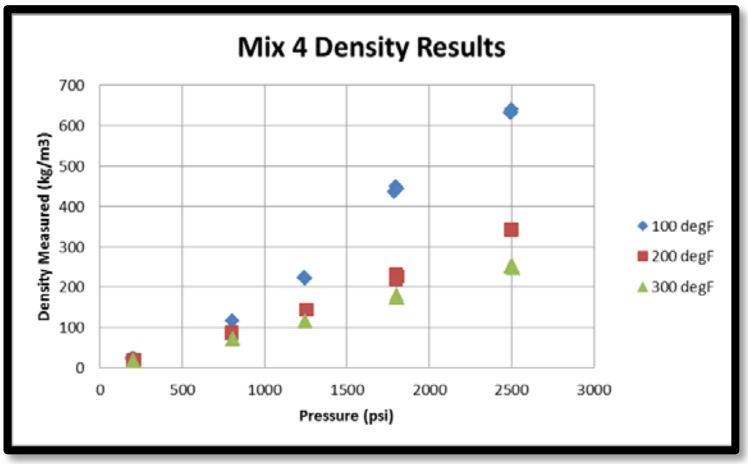


Figure 4-23. Density Measurement Results: Mix 4

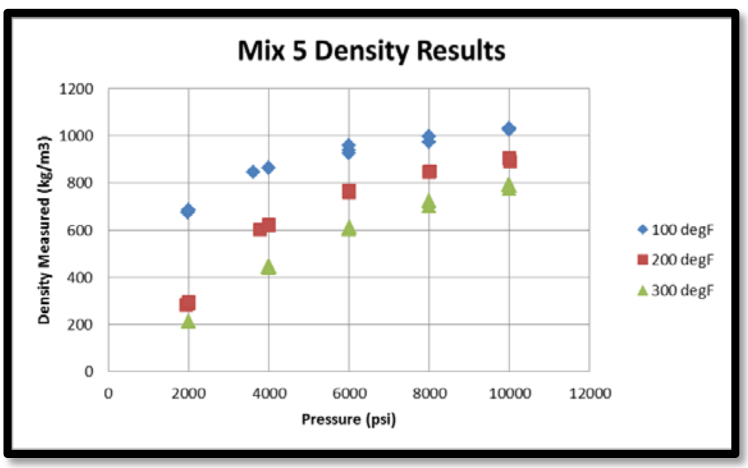


Figure 4-24. Density Measurement Results: Mix 5

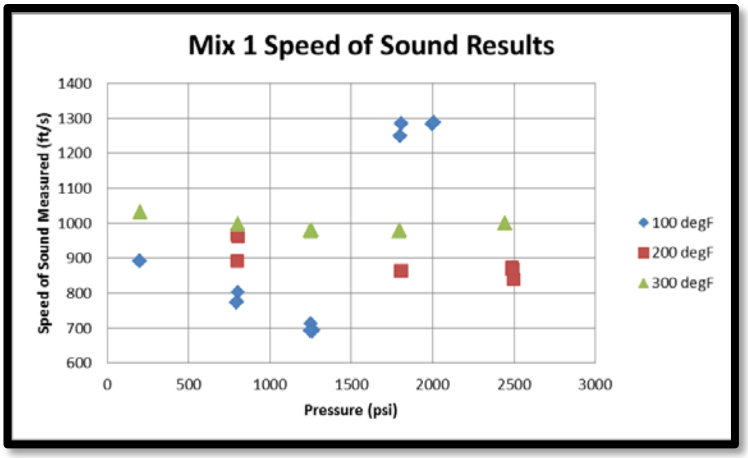


Figure 4-25. Speed of Sound Measurement Results: Mix 1

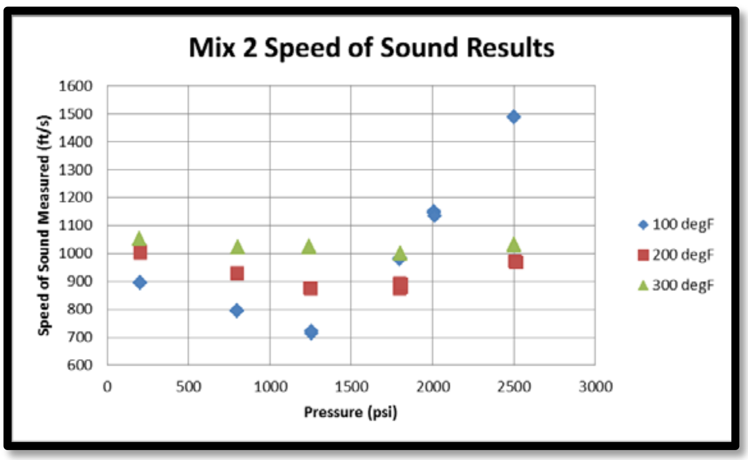


Figure 4-26. Speed of Sound Measurement Results: Mix 2

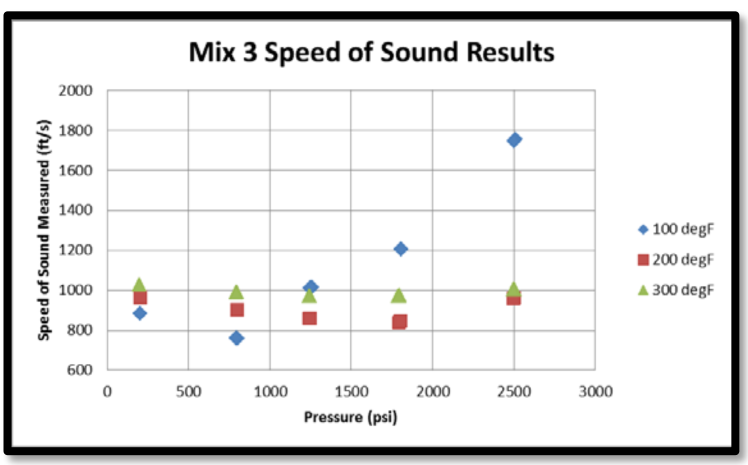


Figure 4-27. Speed of Sound Measurement Results: Mix 3

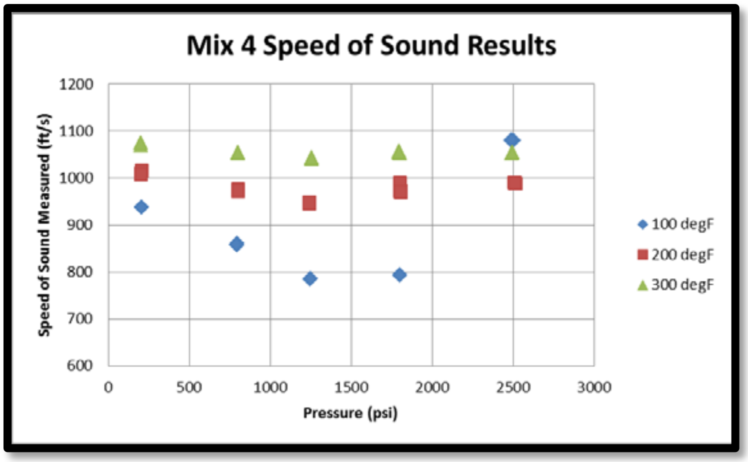


Figure 4-28. Speed of Sound Measurement Results: Mix 4

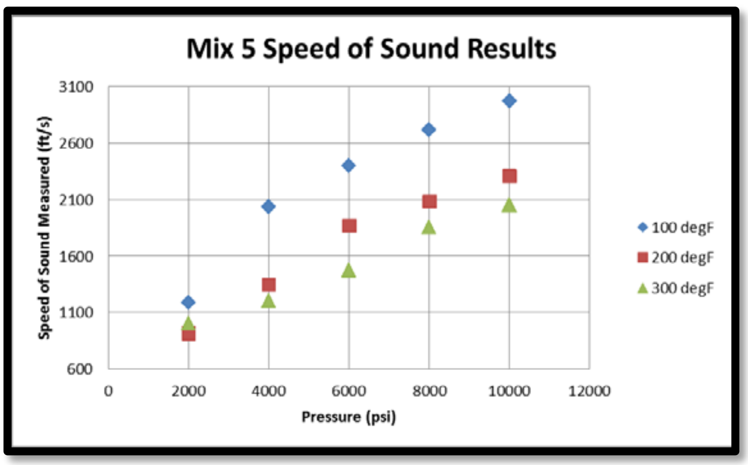


Figure 4-29. Speed of Sound Measurement Results: Mix 5

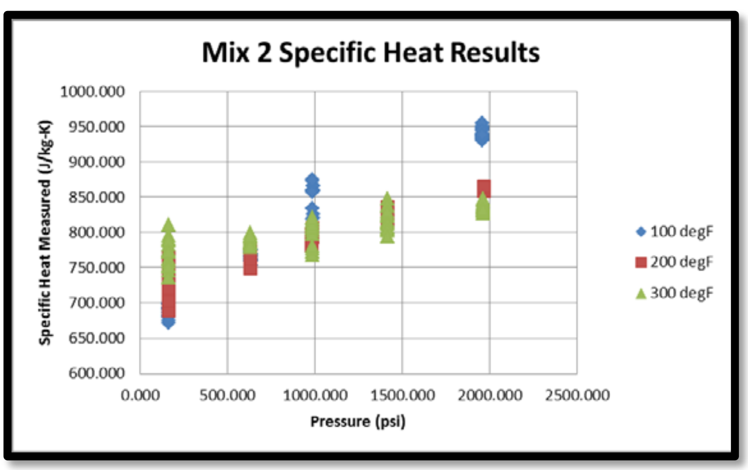


Figure 4-30. Specific Heat at Constant Volume Measurement Results: Mix 2

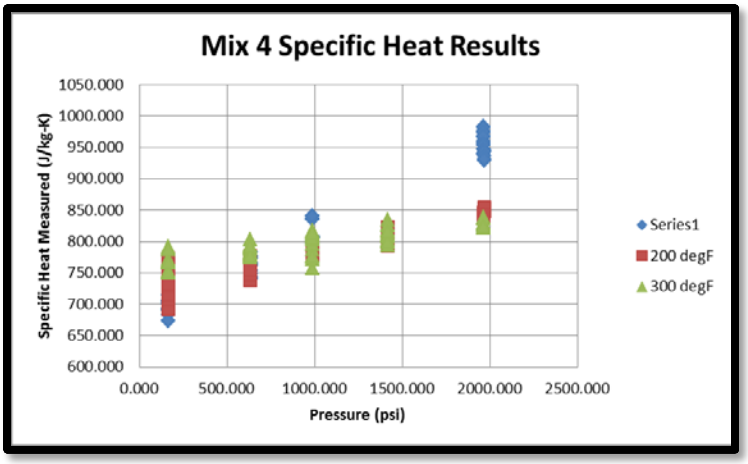


Figure 4-31. Specific Heat at Constant Volume Measurement Results: Mix 4

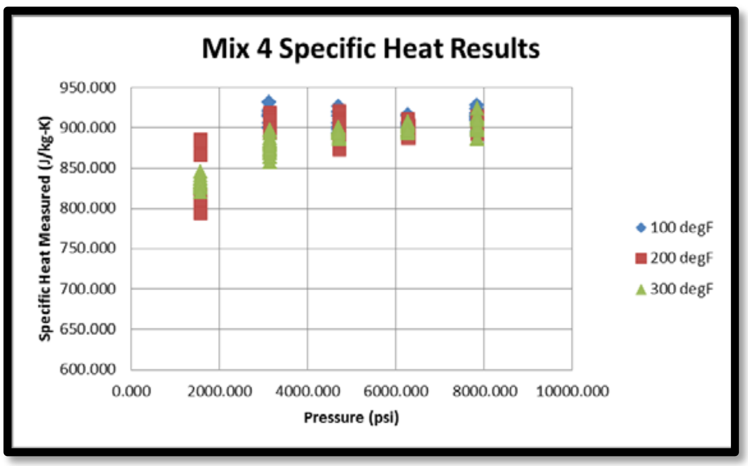


Figure 4-32. Specific Heat at Constant Volume Measurement Results: Mix 5

4.1.4.5 Equation of State Comparison and Conclusions

To compare the experimental test data with EOS model predictions, the measured temperature and pressure conditions were used to predict the density and speed of sound values according to the GERG and default NIST equation-of-state. All modeling was performed using NIST REFPROP software, which provided both EOS model outputs.

Although some variation in test results was noted due to the test uncertainty, there were specific trends which were notable for the mixtures and particular test conditions. The following observations are made regarding the use of the GERG or default NIST EOS model for mixtures similar to those in this test campaign.

The GERG and default NIST EOS models predicted similar density and speed of sound values for all of the mixtures for most test points. The largest deviation for density predictions between the two EOS models is 1.27 kg/m^3 for Mix 1, 0.54 kg/m^3 for Mix 2, 1.06 kg/m3 for Mix 3, 1.72 kg/m^3 for Mix 4, and 0.24 kg/m^3 for Mix 5. Generally, the GERG EOS model predicted slightly lower density values for most pressure points of 1250 psi through 2,500 psi among all temperatures for Mixes 1 through 4 when compared to the NIST EOS model. For Mix 5, the GERG EOS model predicted slightly higher density values for the majority of test points when compared to the NIST EOS Model. The largest deviation for speed of sound predictions between the two EOS models was 0.88 ft/s for Mix 1, 2.95 ft/s for Mix 2, 0.81 ft/s for Mix 3, 0.35 ft/s for Mix 4, and 3.98 ft/s for Mix 5. Overall, the GERG EOS model predicted both slightly lower and higher speed of sound values equally across all of the mixtures and pressure and temperature points. The largest deviation for specific heat predictions between the two EOS models was 2.71 J/kg-K for Mix 2, 8.26 J/kg-K for Mix 4, and 2.35 J/kg-K for Mix 5. Predominantly, the GERG EOS model predicted both slightly lower and higher specific heat values across all of the mixtures and pressure and temperature points.

The GERG and default NIST EOS models matched the experimental data for density within +/- 4% for the majority of test runs. Higher deviations were noticed in Mix 1 at elevated temperatures with a maximum of roughly 10.4%. Associated with the deviations, the EOS models predicted relatively lower values of density than what were experimentally calculated at temperatures of 200°F and 300°F. For Mix 2 at lower pressures (200 psi) in the test runs, the EOS models exceeded the measurements close to 7% at the maximum for temperatures at 200°F and 300°F. For Mix 3 at higher pressures in the test run, the EOS models exceeded the measurements close to 8% at 100°F and upwards to over 6% at 200°F and 300°F. At higher pressures, those within the supercritical regime, the EOS models predicted relatively lower values of density than what were experimentally calculated for Mixes 1 through 4. For Mix 5, measured values of density matched those of the EOS model predictions within the total uncertainty for all pressures at 100°F and 200°F. For the 300°F test runs, the EOS models predicted notably lower values of density than what were measured for all of the tested pressures of Mix 5. In general, the deviation between EOS model predictions and test measurements increased with pressure; with the EOS models predicting lower values of density as the pressure increased across all tested temperatures with Mix 1 through 4.

The GERG and default NIST EOS models matched the experimental data for speed of sound within +/- 4% for Mix 2 with the greatest deviations present in 100°F of 8% due to the water content. The two EOS models matched experimental data within +/- 5% for Mix 2, with the greatest deviations presented in the 100°F and 200°F ranges. For the 200°F and 300°F test points of Mix 3, the EOS models matched the experimental data for speed of sound within +/- 2% with larger deviations at 100°F with a maximum of roughly 8%. Results similar to Mix 2 were seen for Mix 4, with the greater deviations of the EOS models from the measured values present in the 100°F and 200°F ranges, with a greatest difference of roughly 5%. For Mix 5, the GERG and default EOS models matched the experimental data for speed of sound within +/- 8% with the greatest deviations present in the 100°F and 200°F ranges, similar to the other mixtures tested. Based upon the test performed, the EOS models predicted notably lower values of speed of sound than the experimental value for the majority of test points for all three mixtures. Similar to the density measurements, the speed of sound measurements deviated the least from the EOS models for the 300°F test points for all three mixtures, within the total uncertainties of the measurements.

The GERG and default NIST EOS models matched the experimental data for specific heat at constant volume within +/- 5% for Mix 2 for all temperature and pressure ranges. For Mix 4, the two EOS models matched the experimental data within 4% for all temperature and pressure ranges. For Mix 5, the two EOS models matched the experimental data within 3% for all temperature and pressure ranges with the exception of lower pressure points at 200°F. Due to the nature of the tests performed for specific heat, it was difficult to deduce trends and outlying data over a large range. Some inference could be made if viewing the data through clustering analysis, interpreting the results by their relative density (concentration). It could be inferred that both EOS models predict lower values for specific heat at the majority of pressure points at 100°F for Mix 2, 1400 psi at 200°F and 1000 psi at 300°F for Mix 4, and the majority of pressure points at 100°F for Mix 5. It is noted that the GERG EOS model was used in the calibration test measurements.

Overall, based on the test campaign, the GERG and default NIST EOS models predicted relatively the same values for speed of sound, density, and specific heat for the majority of test mixtures and ranges.

4.2 Year 2: Task 2.0 – Detail Design, Hardware Procurement, and Site Preparation

4.2.1 Subtask 2.1 – Detailed Design of Flow Loop

A detailed design of the flow loop including heat exchanger location was developed, as represented by the solid model in Figure 4-33. The compressor used up-connections and required upstream lengths were maintained per ASME PTC-10. The piping exited the lab building as shown in Figure 4-34. Updated outline drawings were received from D-R which required minor changes to the positioning of the package inside the building. The skid was designed to accommodate sub-sole plates. These were machined pads that were leveled and grouted onto the concrete slab. This permitted the compressor package to be set down onto the pads and bolted down without the need for additional grouting. This approach reduced the time required during commissioning of the package.

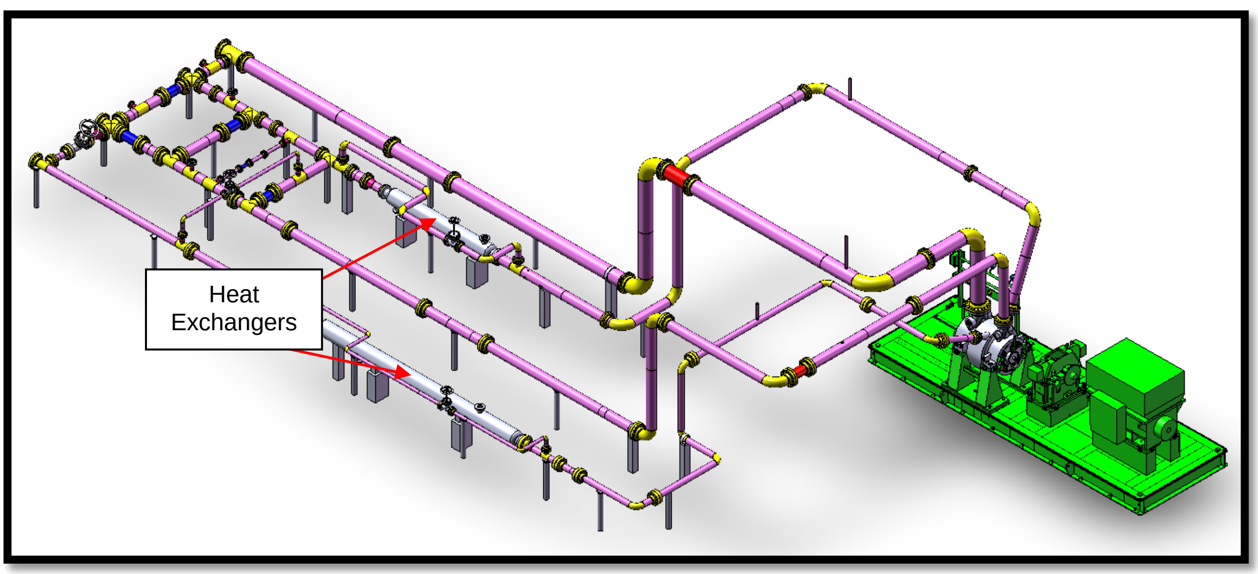


Figure 4-33. 3-D Solid Model of Compressor Test Loop

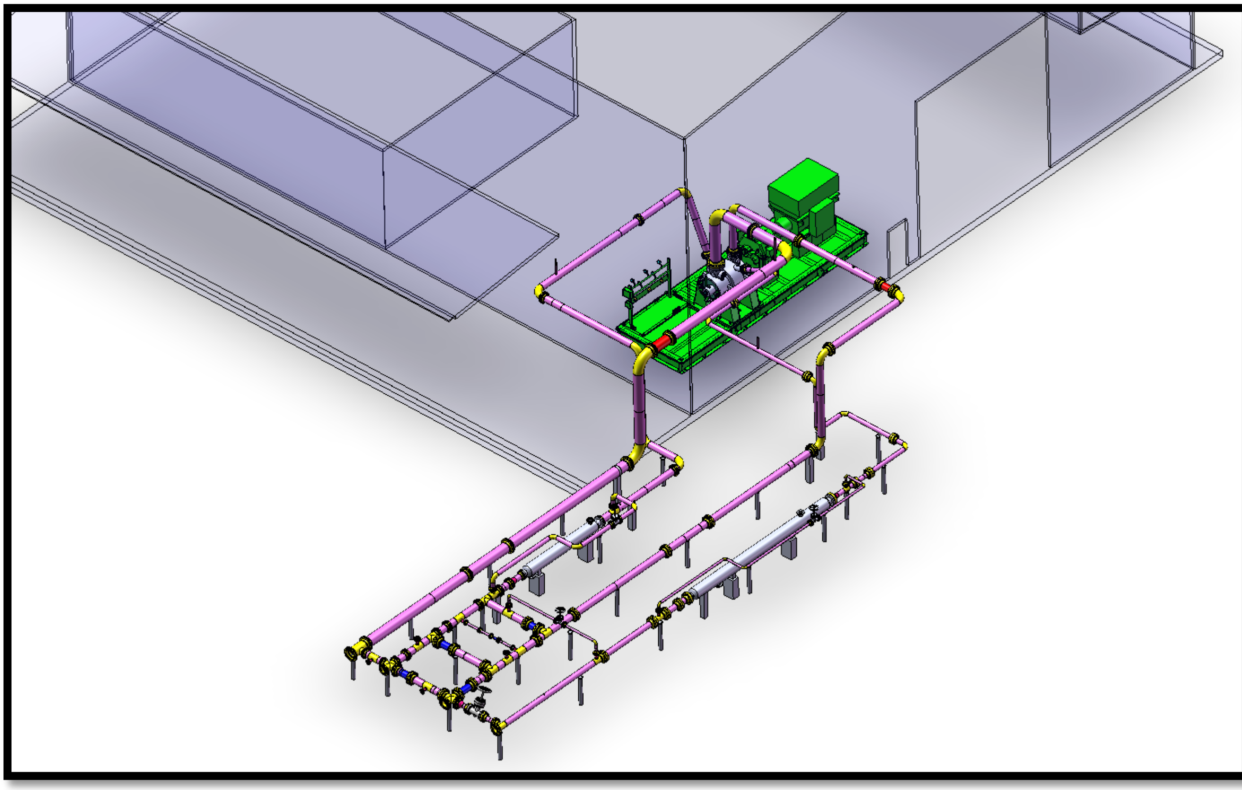


Figure 4-34. Test Loop and New Building

4.2.1.1 Loop Design Overview

4.2.1.1.1 Operating Conditions and Model Overview

The piping loop and associated components were installed at SwRI located in San Antonio, TX, including the piping, the associated components, and a two-section D-R Datum centrifugal compressor. Described here is the loop piping layout and required components including pipe dimensions, supports, restraints, spring hangers, and vessel support slabs.

A thermal stress analysis and load study was performed for the CO_2 sequestration and compressor test loop using Intergraph Caesar II. Caesar II allows the user to input a series of pipes or structural steel members, modeled as beam elements, and define specific operating conditions for the system. The software computes displacements, loads, and stresses based on the user-defined inputs and compares these results to a database of codes and standards.

Piping was modeled using ASTM A106B steel pipe according to ASME pipe code B31.3 for process piping. Compressor nozzle allowable loads were computed in accordance with API 617. The heat exchangers were TEMA-type and load limits were not specified; the loop piping was designed to minimize heat exchanger nozzle loads. Pipe flanges, hand valves, and control valves were input as rigid elements with the appropriate weight and length. Caesar II calculated spring hanger properties given a chosen manufacturer and hanger location.

Three operational cases were defined: (1) normal operation, (2) maximum horsepower (max HP) operation, and (3) bypassing the first section intercooler (LP bypass). The temperature and pressure limits imposed for the three conditions are shown in Table 4-4. The forces and moments exerted on the compressor and heat exchanger nozzles were computed for these three operational load cases, where operational loads consist of pipe, flange and valve weights, temperature effects, and pressure effects. Results are provided for the normal, max HP and LP bypass cases. A schematic of the piping layout is shown in Figure 4-35, where the colors indicate temperature, and detailed pipe drawings are provided in Section 8, showing the length and schedule of each component.

Table 4-4. Operating Conditions – Gas Loop

	Normal	Max HP	LP Bypass
Mass Flow (lbm/hr)	54,300	208,000	54,300
Section 1 Discharge T (°F)	376.6	375	200
Section 1 Discharge P (psia)	67.6	238	67.6
Section 2 Suction T (°F)	115	115	200
Section 2 Suction P (psia)	62.6	232.7	62.6
Section 2 Discharge T (°F)	385.2	405.4	405
Section 2 Discharge P (psia)	250	1,005	250
Section 1 Suction T (°F)	115	115	115
Section 1 Suction P (psia)	15	55.5	15

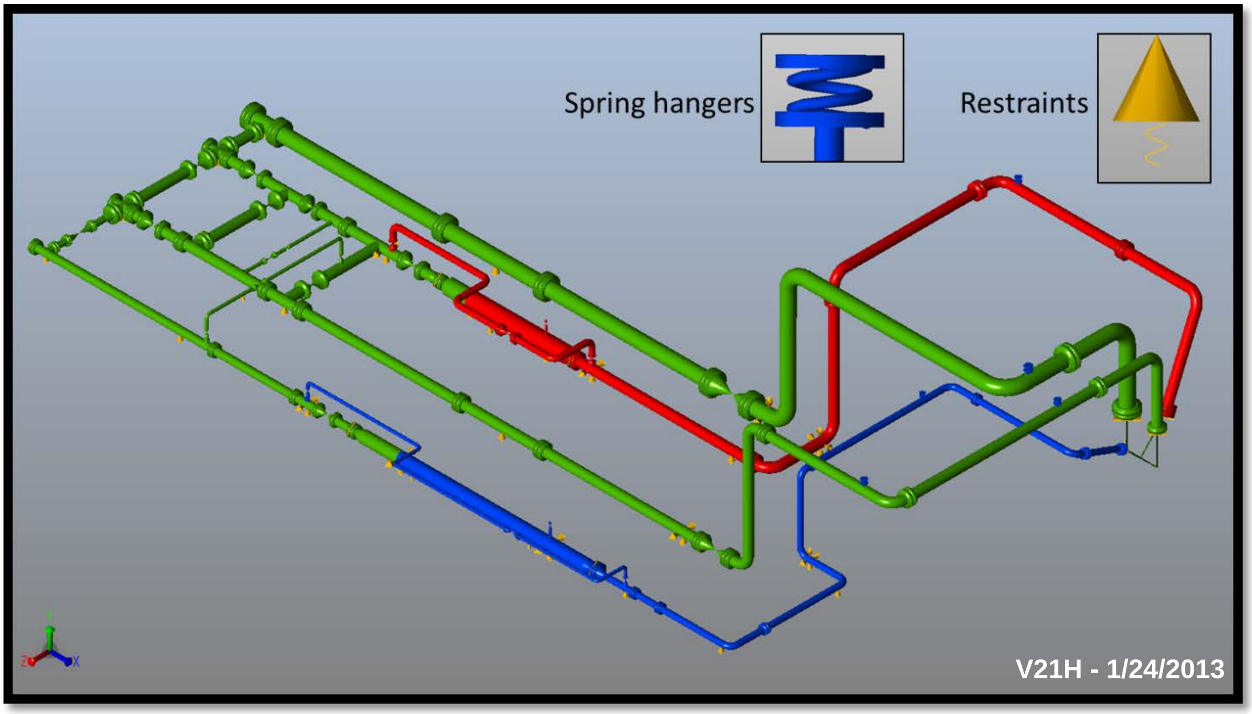


Figure 4-35. Caesar Piping Model Layout

Normal Temperatures: Green = 115°F, Red = 377°F, Blue = 385°F

4.2.1.1.2 Pipe Restraints and Supports

Pipe supports were used to support weight loads, constrain motion due to thermal expansion, and to control low frequency vibration. Pipe supports and restraints were of a pedestal, saddle, clamp, or lateral type, where pedestal-type restraints provided only vertical support; saddle restraints provided vertical and radial support but did allow axial and rotational movement; pipe clamps restrained vertical, radial, axial, and axial rotational motion; and lateral restraints restricted motion in one coordinate direction. Supports were given a stiffness of $1x10^6$ lbs. /in. in the appropriate direction. Rigid anchors were applied to the compressor case (stiffness $1x10^{12}$ lbs. /in.). Each pipe support was mounted atop a deep pier which constrained motion of the support in the event of groundswell. This helped to prevent differential movement of the piping, which could have led to high loads or failures at connections. Lighter loads, such as the heat exchanger hot gas bypass lines, were supported by pipe stands.

The piping and restraints were designed as a unit to accommodate thermal expansion, so it was important that the specified restraints were used at each location. Supports that appeared to have low loads were installed for modal vibration control rather than to support sustained or operational piping loads. Support and restraint types, locations, and loads are shown in Table 4-6.

Pedestal-type restraints were added underneath concentrated weight loads, such as control valves and hand valves, long pipe runs, intersection points, and U-bends, except where some vertical motion was required to reduce nozzle flange loads. Spring hangers were applied on the elevated portion of each line where it entered or exited the building housing the compressor. The required spring hanger values computed by Caesar II are shown in Table 4-5, where a single hanger was specified at each location. The hangers were designed “hot load centered” so that the spring had its maximum range of motion during system operation.

Table 4-5. Spring Hangers

Line	Spring Rate (lbs/in)	Installed Load (lbs)
1st suction (16")	900	2,597
2nd discharge (6")	1,200	2,602
2nd suction (10"), outer	300	698
2nd suction (10"), inner	900	2,348
1st discharge (10")	1,200	2,650

Table 4-6. Supports and Restraints

Node	Type	Fx (lbs)	Fy (lbs)	Fz (lbs)
126	Clamp	-9,593	-2,579	330
168	Pedestal	-565	-2,137	341
202	Pedestal	-365	-1,222	-39
345	Saddle	-2,607	-6,713	-2,376
440	Pedestal	-1,404	-4,691	235
570	Pedestal	-596	-1,989	193
715	Pedestal	-581	-1,941	135
780	Saddle	-662	-1,742	530
930	Saddle	423	-1,413	-626
987	Saddle	1,894	-1,512	5,333
990	Pedestal	325	-1,111	238
996	Clamp	1,482	-1,015	-4,136
3320	Clamp	4,135	-2,377	-782
3360	Clamp	10,697	-224	4,241
5345	Pedestal	-1,281	-4,301	340
5383	Pedestal	*	-1,026	*
5915	Clamp	-9,235	-2,266	345
13355	Pedestal	536	-1,987	261
13160	Saddle	*	-5,722	-1,471
13365	Clamp	6,260	-959	-2,368

Note: the y-axis is oriented vertically where a negative value indicates a downward force.
**Lateral forces will be created due to friction at pedestal and saddle type supports.*

4.2.1.1.3 Vessel Mounts and Support Slabs

Support slabs were required for the shell-and-tube heat exchangers and D-R Datum compressor. In the following specifications, the y-axis is oriented vertically; the low-pressure and high-pressure coolers are oriented axially along the x-axis (coordinate axes for this system are shown in (Figure 4-35). The shell-and-tube coolers were TEMA-type BEP class C heat exchangers with a floating tube sheet which was free to grow axially in the presence of external loads or thermal expansion. This allowance for expansion was expected to negate any externally applied axial loads.

The low-pressure intercooler (LP cooler) was approximately 14’2” from flange face to flange face, 18” in diameter, and weighs 4,060 lbs. when full of water, including the tube bundle. The cradles for the heat exchangers extended down 6” from the outer wall of the cooler. The LP cooler was not fixed to the support slab, but was free to move axially and laterally; only vertical and rotational motion was constrained.

The high-pressure after-cooler (HP cooler) was approximately 25’5” long and 16” in diameter with 6” cradles, and weighed 4,060 lbs. full. The HP cooler was mounted to allow axial growth at both ends, but was constrained laterally. The maximum expected operating loads on the heat exchanger supports are shown in Table 4-7.

Each heat exchanger required two support slabs, one under each of the cradle mounts. The mainline piping was 55” above the ground, so the LP cooler slabs rose 40” above ground level, and the HP cooler and heater slabs rose 42” above the ground to meet the cooler support cradle.

A 137-gallon lube oil tank was required to feed the D12 package during rundown in the event of a pump failure. The tank was mounted inside the building housing the package and the bottom of the tank was elevated 17’ from the centerline of the compressor (23’ from ground level). The tank included a catch pan in the event of a leak. The tank was 7’8” long and 24” in diameter and the empty tank weight was approximately 300 lbs. The lube oil weighed approximately 1,000 lbs., for a total weight of approximately 1,300 lbs.

The D-R Datum D12 package weight was approximately 111,000 lbs. and the baseplate dimensions were 34’ by 11’. The loads on the compressor during operation are shown in Table 4-7, excluding the weight of the compressor. The slab supporting the compressor was 4’ thick to provide sufficient mass (dynamic stiffness) for the compressor package. The anchor bolt lengths were 19 ¾” with a 6” projection. This was a change from the original dimensions and was based on conversation with a company that performs compressor installations.

The package baseplate was mounted on a series of twenty sub-soleplates and grouted to a 48” thick 4,000 psi concrete slab (see Figures 4-36 through 4-38). Anchor bolts were installed in the slab during the slab pour based on the baseplate dimensions and soleplate locations. The bolts were grouted to the top of the first pour (26” thick) and the remaining 22” were poured over the placed and grouted anchor bolts after the grout forms had been removed. Once the slab cured, 1” of the top layer was chipped away, exposing clean, coarse aggregate. The sub-sole plates were positioned and leveled to within 0.002” using laser leveling equipment and jacking screws. An epoxy grout was used to bind the soleplates to the slab. This installation was completed in accordance with API 686. Once the grout cured, the leveling screws were removed from the sub-sole plates. The baseplate was placed on top of the soleplates and secured via the anchor bolts to the proper torque (1" anchor bolts were torqued to 245 ft-lbs. per Annex B of API 686).

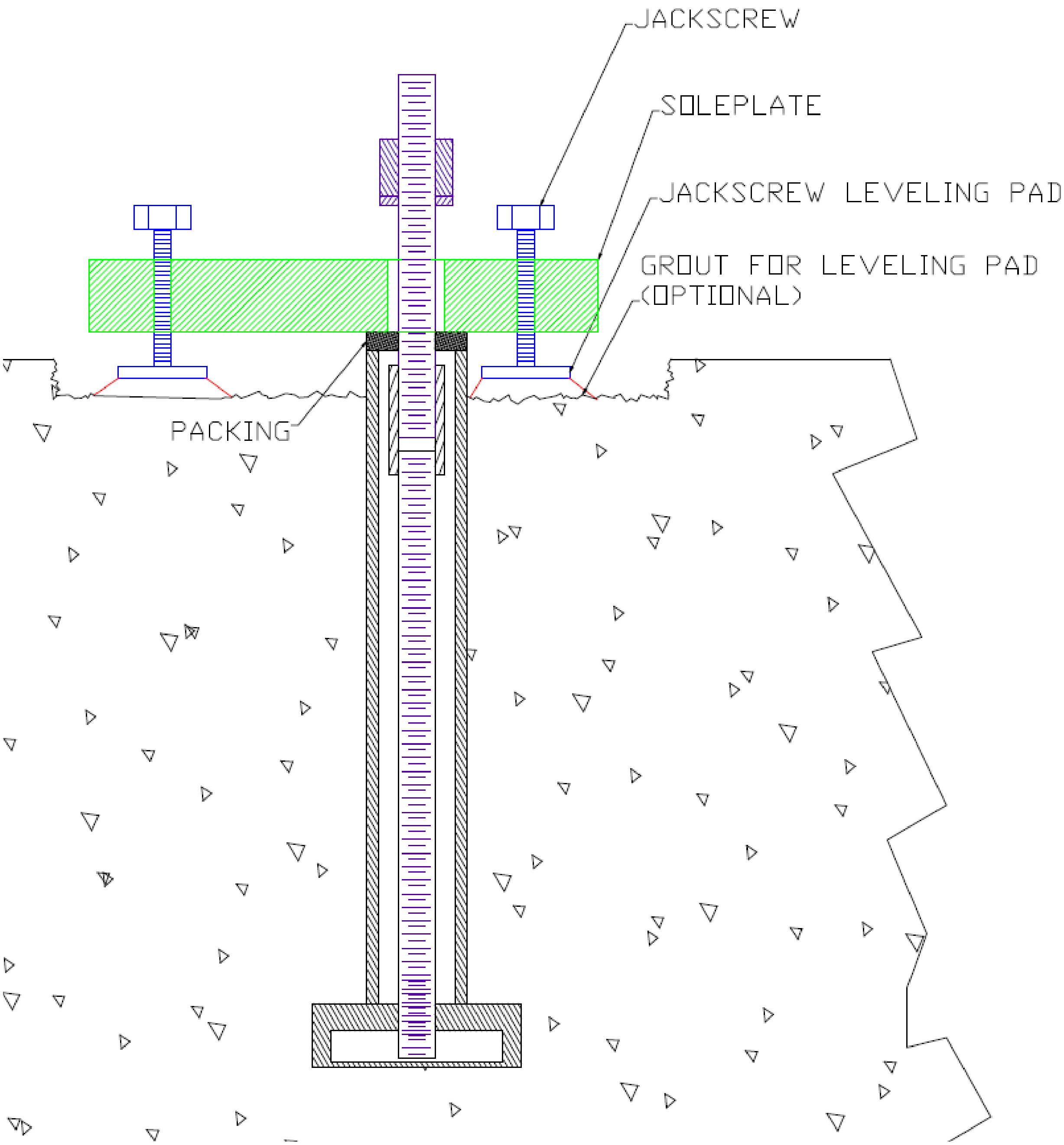


Figure 4-36. Baseplate Mounting Using Sub-soleplates

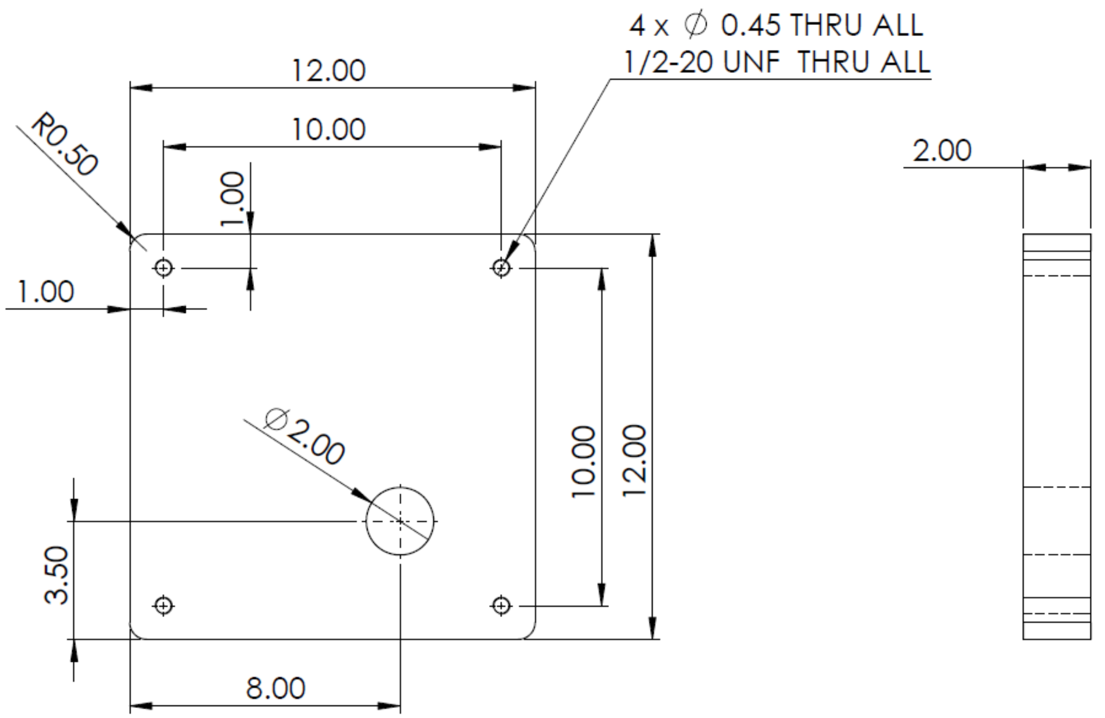


Figure 4-37. Baseplate Mounting Using Sub-soleplates

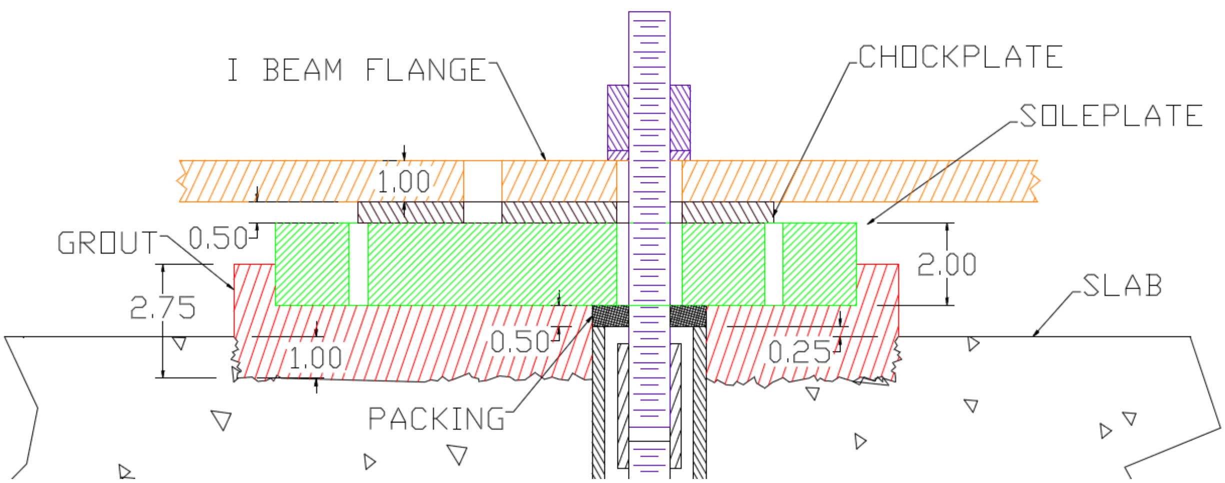


Figure 4-38. Baseplate Mounting Using Sub-soleplates

Table 4-7. Maximum Predicted Vessel Support Loads – Gas Loop

Vessel	Fx (lbs)	Fy (lbs)	Fz (lbs)	Mx (ft-lbs)	My (ft-lbs)	Mz (ft-lbs)
Compressor	167	-637+	-599	2,862	-2,740	-4,847
LP Cooler Upstream	*	-3,971	-548	177	0	0
LP Downstream	*	-5,108	-1,128	170	0	0
HP Cooler Upstream	*	-6,074	-817	209	0	0
HP Downstream	*	-6,386	-178	223	0	0

*Cooler axial loads are minimized by the floating tube sheet.

+This value does not include the weight of the compressor.

4.2.1.2 Thermal Stress Analysis and Predicted Nozzle Flange Loads Using Caesar II

The heat exchangers were installed, as described above, to allow for movement induced by thermal expansion. Initial analysis revealed excessive forces on the compressor 1st-stage suction and discharge nozzles and excessive moments on the compressor about all three coordinate axes. High axial stresses were observed on both the high-pressure and low-pressure heat exchangers with the initial mounting technique (one end fixed). Greater than allowable bending stress was observed at the 3” cooler bypass line connection point on the 6” line downstream of the high-pressure cooler.

In some cases, restraints were not sufficient to reduce the compressor and heat exchanger nozzle flange loads. It was necessary to reroute some pipe sections to reduce the forces and moments observed on the nozzles. These reconfigurations provided additional room for the piping to flex and reduced the nozzle forces to acceptable levels. A U-bend was added on the second-stage discharge line leading into the HP cooler to reduce loads on the inlet nozzle, and bends were added to the HP and LP cooler bypass lines to reduce forces and moments on both nozzles as the line expands. These bends also provided access to the cooling water discharge nozzle flanges.

All heat exchanger nozzle forces and moments were minimized without adding unreasonable pipe lengths and bends, and all pipe stresses were found to be within ASME B31.3 limits for the normal, max HP, and low-pressure intercooler bypass operating scenarios. The individual compressor nozzle reaction forces were designed to be within 200% of the allowable loads defined by API 617. The maximum observed loads were 156% of the allowable defined by API 617 for the normal operating case (1st stage discharge nozzle), 156% for the max HP case (1st stage discharge nozzle), and 108% for the LP bypass case (2nd stage discharge nozzle). The force and moment values on the compressor nozzles predicted by Caesar II, and the allowable forces and moments, are shown in Tables 4-8 through 4-10.

In order to analyze the effect of groundswell on the compressor, the load simulation was run for ¼” and ½” displacements of the compressor nozzles in relation to the rest of the piping system. Results of this analysis are shown in Table 4-11, and indicate that the relative compressor motion should be kept to less than ¼” from its neutral position.

Table 4-8. Compressor Loads – Computed and Allowable, Normal Operating Condition

Nozzle	Load Component	Predicted Load (lb or ft-lb)	Resultant	3F+M	Allowable (927*D)	% of Allowable
1st suction (16") D_{eq} = 10.667	Fx	-82	345	7,265	9888	73.47%
	Fy	-332				
	Fz	-44				
	Mx	-5,519	6,231			
	My	-953				
	Mz	2,731				
2nd discharge (6") D_{eq} = 6	Fx	-144	648	6,932	5,562	124.63%
	Fy	-613				
	Fz	-155				
	Mx	1,797	4,987			
	My	-958				
	Mz	-4,552				
1st discharge (10") D_{eq} = 8.667	Fx	18	1,052	7,423	8,034	92.39%
	Fy	-993				
	Fz	-346				
	Mx	-1,477	4,268			
	My	-1,344				
	Mz	-3,772				
2nd suction (10") D_{eq} = 8.667	Fx	18	46	3,942	8,034	49.06%
	Fy	34				
	Fz	-25				
	Mx	-3,519	3,804			
	My	116				
	Mz	1440				

Table 4-9. Compressor Loads – Computed and Allowable, Max HP Operating Condition

Nozzle	Load Component	Predicted Load (lb or ft-lb)	Resultant	3F+M	Allowable (927*D)	% of Allowable
1st suction (16") D_{eq} = 10.667	Fx	-80	343	7,256	9,888	73.38%
	Fy	-331				
	Fz	-45				
	Mx	-5,524	6,226			
	My	-940				
	Mz	2,713				
2nd discharge (6") D_{eq} = 6	Fx	-147	654	6,971	5,562	125.34%
	Fy	-610				
	Fz	-186				
	Mx	1,704	5,008			
	My	-1,133				
	Mz	-4,571				
1st discharge (10") D_{eq} = 8.667	Fx	20	1,051	7,445	8,034	92.66%
	Fy	-992				
	Fz	-347				
	Mx	-1,491	4,292			
	My	-1,364				
	Mz	-3,786				
2nd suction (10") D_{eq} = 8.667	Fx	19	48	3,955	8,034	49.23%
	Fy	34				
	Fz	-28				
	Mx	-3,532	3,811			
	My	127				
	Mz	1,427				

Table 4-10. Compressor Loads – Computed and Allowable, LP Bypass Operating Condition

Nozzle	Load Component	Predicted Load (lb or ft-lb)	Resultant	3F+M	Allowable (927*D)	% of Allowable
1st suction (16") D_{eq} = 10.667	Fx	-32	327	7,150	9,888	72.31%
	Fy	-318				
	Fz	-71				
	Mx	-5,659	6,168			
	My	-540				
	Mz	2,393				
2nd discharge (6") D_{eq} = 6	Fx	91	681	7,223	5,562	129.87%
	Fy	-556				
	Fz	-382				
	Mx	1,163	5,181			
	My	-1,427				
	Mz	-4,843				
1st discharge (10") D_{eq} = 8.667	Fx	56	978	6,755	8,034	84.08%
	Fy	-972				
	Fz	-92				
	Mx	355	3,821			
	My	111				
	Mz	-3,803				
2nd suction (10") D_{eq} = 8.667	Fx	135	237	5,445	8,034	67.77%
	Fy	43				
	Fz	-190				
	Mx	-4,435	4,734			
	My	1,590				
	Mz	463				

Table 4-11. Compressor Loads – Effect of Compressor Slab Displacement

Normal Operation % Allowable Load			
Nozzle	**0 displacement**	**1/4" disp**	**1/2" disp**
1st discharge (10")	156%	148%	205%
2nd suction (10")	58%	62%	82%
2nd discharge (6")	109%	175%	283%
1st suction (16")	109%	128%	268%
Max HP Operation % Allowable Load			
Nozzle	**0 displacement**	**1/4" disp**	**1/2" disp**
1st discharge (10")	156%	149%	205%
2nd suction (10")	59%	62%	82%
2nd discharge (6")	111%	172%	278%
1st suction (16")	110%	128%	267%
LP Bypass Operation % Allowable Load			
Nozzle	**0 displacement**	**1/4" disp**	**1/2" disp**
1st discharge (10")	89%	127%	208%
2nd suction (10")	108%	110%	125%
2nd discharge (6")	108%	175%	285%
1st suction (16")	100%	131%	276%

4.2.1.3 Steady-state Flow Analysis and Predicted Pressure Drop

A steady-state flow analysis of the test loop was run using the Stoner Pipeline Simulator (SPS) to simulate flow velocities, pressure drop, compressor performance, and valve operations. Stoner Pipeline Simulator is a transient and steady-state hydraulic modeler that simulates dynamic flow of single-phase fluids. Pipe elements are used to handle transient flow, heat transfer, and pipe friction. The model for the application was set up in a series configuration, where the section one discharge of the back-to-back axial compressor led to the section-two suction, and the section-two discharge led to the section one suction. The primary purposes of this model were to verify the pressure drop between compressor sections and to ensure that flow velocities were not excessive.

Valves were modeled as “block” or “gas block” elements which depended on the flow coefficient Cv (gallons/min-√psi) or Cg (ft^3/hr-psi), respectively. SPS can model valves as either a block or gas block type, but only gas block valves are designed to accommodate sonic flow. The value of the valve coefficient was obtained for control valves from the manufacturer provided valve data sheets and was computed for hand valves based on valve dimensions and published empirical formulas. The inlet and outlet boundary conditions were imposed on the system as first-section discharge pressure, second-section suction flow rate, second-section discharge flow rate, and first-section suction pressure. The second-section discharge pressure was increased to match the desired value by throttling control valve CV002. The working fluid was carbon dioxide gas from 115°F to 405°F, depending on the operating condition and position along the loop. A schematic of the model is shown in Figure 4-39.

Each element was modeled as a run of straight pipe or as a valve. The pressure drop through each element was computed using the equivalent length or valve coefficient, determined from relationships between the friction factor, K, and the nominal pipe size [Flow of Fluids through Valves, Fittings, and Pipe. Technical Paper #410, Crane, 1988]. Typical K values for elbows and Tees are provided in the Crane handbook. For hand valves (gate, globe, and ball types), the valve coefficient is related to the friction factor by Equation 4.4, where d is the nominal pipe diameter and K is related to the Moody friction coefficient, f. A friction coefficient of 0.015 was used in this analysis. Orifice plates and flow conditioning devices were combined into a single valve element for each pair, and the valve coefficient of each was tuned to match the manufacturer-specified pressure drop.

$$C_v = \frac{29.9d^2}{\sqrt{K}} \quad (4.4)$$

The shell-and-tube coolers were modeled using a single equivalent pipe each, and were tuned to match the manufacturer-specified expected pressure drop at the normal operating condition. The low-pressure intercooler pressure drop was 1.607 psi and the high-pressure cooler pressure drop was 1.460 psi. All elbows, tees, flow straighteners, and reducers were modeled as equivalent pipe lengths based on their respective friction factor, K, and the nominal pipe size.

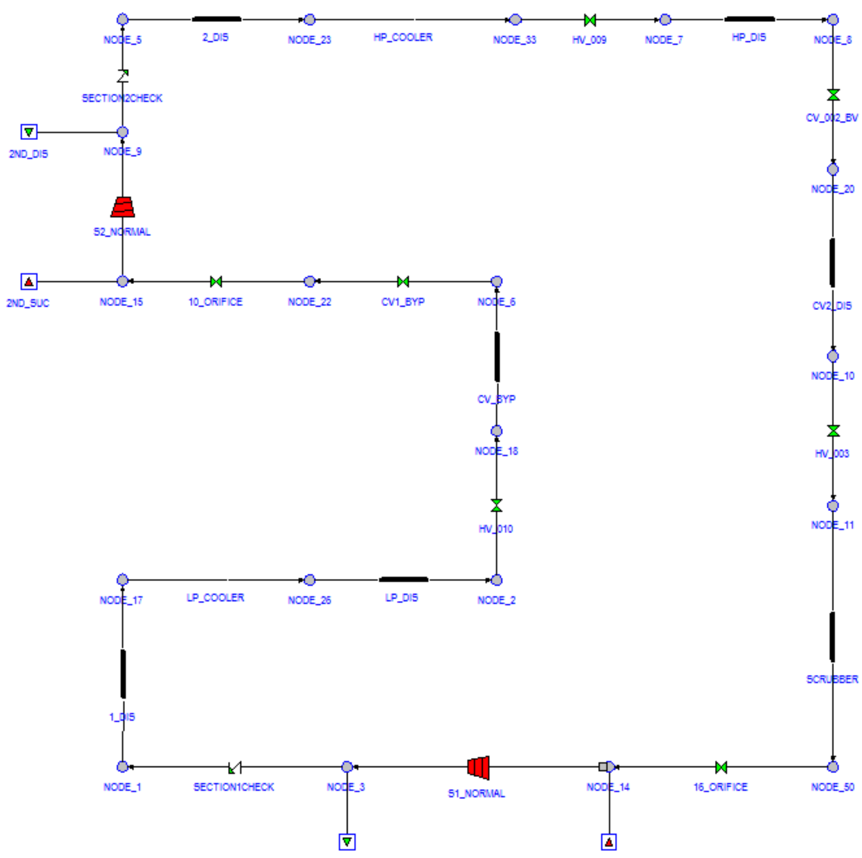


Figure 4-39. SPS Piping Schematic

The initial loop design contained a single line leading from the LP intercooler back to the second-section suction. This layout created an excessive pressure drop over the low-pressure loop due to control valve CV001, and the desired inlet pressure to the second-section suction could not be met. An additional 10” diameter line of piping was added, parallel to the 3” metering run, to bypass CV001 and reduce the total pressure drop. This line included a hand-operated gate valve should it need to be bypassed. This addition reduced the overall pressure drop from the first-section discharge to second-section suction to about 6.4 psia.

The compressor inlet pressures and temperatures and discharge flow rates were designed for three different operating scenarios: normal, alternate, and maximum horsepower. These boundary conditions are shown in Table 4-12. The observed pressure drop over each element, as well as the predicted flow velocity for the design condition, is shown in Table 4-13.

Table 4-12. Boundary Conditions

Quantity	Normal	Alternate	Max. HP	Units
Discharge P (Section 2)	250	295	1,005	psia
Discharge T (Section 2)	385.2	336.6	405.4	°F
Suction Q (Section 1)	7,757 (11.24)	10,286 (14.90)	29,722 (43.04)	SCFM (MMSCFD)
Discharge P (Section 1)	67.6	97.7	238	psia
Discharge T (Section 1)	376.6	341.8	375	°F
Suction Q (Section 2)	7,758 (11.24)	10,291 (14.90)	29,784 (43.04)	SCFM (MMSCFD)

Table 4-13. Predicted Flow Conditions, Normal Operating Condition (Flow = 11.24 MMSCFD)

Device	P_{up} (psia)	P_{down} (psia)	DP	V (ft/s)	T (°F)	% Open	Cg (ft^3/hr-psi)
1st Dis. Pipe	67.60	66.76	0.84	91.22	376.6		
LP Cooler	66.76	65.16	1.61				
HV010	65.16	65.05	0.10		115		400,000
LP Dis. Pipe	65.05	64.80	0.26	62.10	115		
CV001 Bypass	64.80	64.69	0.10		115	100	400,000
CV001 Byp. Pipe	64.69	64.01	0.68	62.88	115		
10" Orif. + Conditioner	64.01	61.19	2.82		115		
Section 1 DP			6.41				
Device	**P_{up} (psia)**	**P_{down} (psia)**	**DP**	**V (ft/s)**	**T (°F)**	**% Open**	**Cg (ft^3/hr-psi)**
2nd Dis. Pipe	250.14	248.52	1.63	67.67	385.2		
HP Cooler	248.52	247.03	1.49				
HV009	247.03	246.98	0.05		115	100	400,000
HP Dis. Pipe	246.98	246.70	0.28	25.28	115		
CV002	246.70	20.95	225.75		115	22.7	3,806
CV002 Dis. Pipe	20.95	20.34	0.61	200.58	115		
HV003	20.34	20.15	0.18		115	100	400,000
16" Orif. + Conditioner	18.15	16.01	2.14		115		
1st Suction Pipe	16.01	15.00	1.01	115.01	115		
Section 2 DP			235.14				

Line sizes were chosen such that the flow velocities would be acceptable. An area of concern was downstream of control valve CV002, where a large pressure drop occurred (~250-15 psia). The predicted velocity in the 10" pipe downstream of CV002 was 240 ft/s, and in the 10" pipe downstream of the control valve was 270 ft/s.

4.2.1.4 Loop Volume and Expected Required Fill Pressure

The test loop volume was approximately 500 ft^3, divided up by section as shown in Table 4-14. Based on the normal and max HP operating conditions in each section, the working density of CO_2 could be found and used to calculate the amount of CO_2 required for operating the loop. The normal operating condition required a mass of 175 lbs. (1,570 SCF) and the max HP condition required 788 lbs. (7,070 SCF). Assuming a tank density of 67 lbs/ft^3, this would correspond to approximately 19 and 88 gallons of liquid CO_2, respectively, and loop fill pressures of approximately 48 and 207 psia, respectively.

Similarly, for nitrogen, 108 lbs. (1,500 SCF) and 408 lbs. (5,710 SCF) were required to operate at normal and maximum HP conditions, respectively. Based on a tank density of 37 lbs/ft^3, this would correspond to 22 and 82 gallons of LN_2 and loop fill pressures of 47 and 179 psia, respectively. These figures were used to size the CO_2 and LN_2 tank and vaporizer components.

Table 4-14. Loop Volume by Section

Section	Volume (ft^3)
1st stage discharge to CV001	101
2nd stage suction from CV001 to compressor	66
2nd stage discharge to CV002	41
1st stage suction from CV002 to compressor	295
Total volume:	**503**

4.2.2 Subtask 2.2 – Detailed Design of Multi-stage Internally Cooled Diaphragm and Manufacturing Procedure

Due to the confidential nature of the cooled-diaphragm design, a presentation of this design effort on the new cooled-diaphragm concept, including thermodynamic and heat transfer calculations, was made to NETL personnel on March 29, 2012. A manufacturing plan and detailed layout were presented along with cooling supply and drain schemes. Several manufacturing first articles were produced to validate the proposed joining process. The diaphragm manufacturing was completed.

4.2.3 Subtask 2.3 – Project Management and Reporting

Additional to the previously described project management activities (Task 1.1), the project manager coordinated with a local site construction contractor and D-R to assure that the installation was completed safely, within budget, and on schedule. A project review meeting was held in Morgantown, WV, to evaluate status and schedule.

4.2.4 Subtask 2.4 – Compressor Procurement

The compressor package was delivered on September 3, 2013 and was then set, leveled, and bolted to the 20 sub-sole plates (Figure 4-40). The lube oil skid and rundown tank were moved into place and oil pipe connections were completed. The lube oil console was filled with ISO32 turbine oil and a lube oil flush was completed to ensure the cleanliness of the system before operation. All electrical connections between the variable frequency drive (VFD) and motor were completed, and the motor was successfully tested uncoupled from the gearbox and compressor. Final alignment and connection of the motor and gearbox and was then completed.

Figure 4-40. Installed Dresser-Rand Datum Compressor Package

4.2.5 Subtask 2.5 – Status of Hardware Acquisitions

The loop piping underwent a final design review and major components were purchased, received, and installed. Hand valves, control valves, orifice plates, flow conditioners, strainers, and the cooling tower were received and installed. The heat exchangers and piping were assembled and the cooling water supply was tested through the process heat exchangers. The completed pipe assembly is shown in Figure 4-41.

Figure 4-41. Pipe Loop Assembly Ariel View

Control valves CV001, CV002, CV003, and CV004, and all 3”, 8”, and 10” hand valves were provided by CVI (Dyna-Flo). Orifice plates and weld-neck flange unions for the 16” first stage suction, 10” second stage suction, and 3” balance line were provided by Daniel Measurement and Control, Inc. (Emerson Process Management). Pipe support saddles, pedestals, and clamps were custom designed and built; spring hangers were supplied by Piping Technology.

A crane was rented locally from Americrane to assist in moving the compressor skid from the delivery vehicle and lifting it into position on the slab. The installation was accomplished via a combination of a large truck crane, the facility bridge crane, and a set of skates used for rolling the package into its final position. DECO heavy-duty adjustable anchor bolts were used to hold the compressor package down to the slab. Each bolt had a tensile strength of at least 115,000 lbs. and yield strength of 100,000 lbs. and was mounted in a 2 ¾” diameter steel tube to separate the bolt shank from grout. Once set, the allowed lateral movement of the stud was ½” from center in any direction. These bolts were placed in the compressor slab ahead of delivery. The compressor soleplate leveling and grouting was performed by AllTech Engineering.

N_2 and CO_2 handling equipment was provided by Matheson. Liquid CO_2 was stored in a 6-ton tank at a pressure of approximately 300 psi. Gaseous CO_2 was sent to the facility via a heated vaporizer. A 1,500-gallon LN_2 tank and vaporizer provided gaseous N_2 to the facility at a pressure of approximately 200 psi. The CO_2 and N_2 systems were delivered, installed, and connected.

Cooling water was provided to the heat exchangers and compressor diaphragm via an 800 gpm Marley cooling tower, providing 225 gpm to each heat exchanger, 280 gpm to the compressor diaphragm, and 70 gpm to the lube oil cooler. The HP heat exchanger was sized to accommodate the full 800 gpm to provide greater cooling capacity for future applications.

4.2.6 Subtask 2.6 – Procure Instrumentation and Develop Data Acquisition and Control Program

The data acquisition system for the new loop was composed of three separate systems, as described in Table 4-15. The first system utilized National Instruments' hardware and a modified version of the data acquisition and control software developed in Phase II. This system allowed the user to control loop conditions, compressor speed, etc. and also calculate real-time compressor performance and heat exchanger effectiveness. A second system, provided by Woodward, provided health monitoring and protection of the compressor package. The third system was a Bently Nevada system for vibration monitoring and protection.

Table 4-15. Phase III Data Acquisition Systems

Manufacturer	**National Instruments**	**Woodward**	**Bently Nevada**
Model	CompactRIO 9082 System	MicroNet Plus Simplex Control System	3500 Monitoring System
Function	• Loop control • Loop monitoring • Performance calculations	• Monitoring of motor, gearbox, and compressor • Alarm and trip functionality for machinery protection	• Vibration monitoring of motor, gearbox, and compressor • Alarm and trip functionality for machinery protection
Channels	• 67 process & cooling water temperature measurements • 52 process & cooling water pressure measurements • 4 differential pressures for orifice flow meters • 1 torque meter for high speed shaft torque • 5 flow meters for cooling water flow • 2 level indicators for CO_2 and N_2 supply • 10 outputs for control/purge/drain valves	• 23 RTDs for bearings, windings, lube oil, and process • 3 pressure switches for motor cooling • 9 differential pressures for seal gas, lube oil filter, orifice runs • 2 level indicators for lube oil tanks • 7 pressure transducers for lube oil and process	• 17 proximity probes • 2 tachometers • 4 accelerometers
Cost	**$33,027.12**	**Est. $44,892**	**$28,174**

A comprehensive channel list was identified that encompassed all instrumentation for purposes of machinery health monitoring, performance measurement, and loop control. This list was divided into sections for loop measurements (Table 4-16), condition monitoring (Table 4-17), vibration monitoring (Table 4-18), and compressor diaphragm/cooling water measurements (Table 4-19).

Table 4-16. CO2 Loop Instrumentation

Location	Tag	Type	Description
Ambient	BP	Barometric P	
Balance piston leakage orifice meter	BP-T01	Temperature	
	BP-P01	Pressure	
	BP-PD01	Differential pressure	
1st section orifice meter	PD03	Differential pressure	16" suction line
	P26	Pressure	16" suction line (max suc. P = 55.5 psia)
	T24	Temperature	16" suction line (max suc. T = 115F)
1st section suction	P27	Pressure	16" suction line
	P28	Pressure	16" suction line
	P29	Pressure	16" suction line
	P30	Pressure	16" suction line
	T25	Temperature	16" suction line
	T26	Temperature	16" suction line
	T27	Temperature	16" suction line
	T28	Temperature	16" suction line
	P31	Pressure	Upstream of 16" suction strainer
	P32	Pressure	Downstream of 16" suction strainer
1st section discharge	P01	Pressure	10" discharge line (1st section max discharge P = 238 psia)
	P02	Pressure	10" discharge line
	P03	Pressure	10" discharge line
	P04	Pressure	10" discharge line
	T01	Temperature	10" discharge line (1st section max discharge T = 375F)
	T02	Temperature	10" discharge line
	T03	Temperature	10" discharge line
	T04	Temperature	10" discharge line
LP cooler inlet	P05	Pressure	
	T05	Temperature	
CV004			Valve actuator, LP cooler bypass
LP cooler outlet	P06	Pressure	
	T06	Temperature	
3" balance line	P07	Pressure	
	T07	Temperature	
Balance line orifice meter	PD01	Differential pressure	Orifice run
CV001			Valve actuator, 1st section throttle
2nd section orifice meter	PD02	Differential pressure	Orifice run
	P08	Pressure	10" suction line
	T08	Temperature	10" suction line
	P09	Pressure	Upstream of 10" suction strainer
	P10	Pressure	Downstream of 10" suction strainer
2nd section suction	P11	Pressure	10" suction line
	P12	Pressure	10" suction line
	P13	Pressure	10" suction line
	P14	Pressure	10" suction line
	T09	Temperature	10" suction line
	T10	Temperature	10" suction line
	T11	Temperature	10" suction line
	T12	Temperature	10" suction line
2nd section discharge	P15	Pressure	6" discharge line (line is rated to 3000 psia for future use)
	P16	Pressure	6" discharge line
	P17	Pressure	6" discharge line
	P18	Pressure	6" discharge line
	T13	Temperature	6" discharge line (2nd section max dis. T = 405.4F)
	T14	Temperature	6" discharge line
	T15	Temperature	6" discharge line
	T16	Temperature	6" discharge line
HP cooler inlet	P19	Pressure	
	T17	Temperature	
CV003			Valve actuator, HP cooler bypass line
HP cooler outlet	P20	Pressure	8" line is rated to 2000 psia
	P21	Pressure	
	P22	Pressure	
	P23	Pressure	
	T18	Temperature	
	T19	Temperature	
	T20	Temperature	
	T21	Temperature	
CV002 upstream	P24	Pressure	
	T22	Temperature	
CV002			Valve actuator, loop main throttle
CV002 downstream	P25	Pressure	
	T23	Temperature	
Cooling tower output		Annubar	Max cooling tower flow = 800 gpm
		Temperature	Max hot water temp = 115F
		Temperature	
Cooling tower return		Temperature	
LP cooler		Temperature	Inlet water temp
		Annubar	Water flow rate (LP max flow rate = 225 gpm)
		Temperature	Outlet temp
HP cooler		Temperature	Inlet water temp
		Annubar	Water flow rate (HP max flow rate = 800 gpm)
		Temperature	Outlet temp
Loop Fill/Purge/Vent			Valve actuator, fill valve
			Valve actuator, purge valve 1
			Valve actuator, purge valve 2
			Valve actuator, purge valve 3
			Valve actuator, purge valve 4
			Valve actuator, vent valve
		Pressure	CO2/N2 Supply Pump Discharge Pressure
		Level indicator	CO2 Tank Level
		Level indicator	N2 Tank Level

Table 4-17. Condition Monitoring Instrumentation

Location	Tag	Type	Description
Compressor	TE-701A	Temperature	DE Journal bearing RTD type PT100 (3 wires) (high alarm 245 F; shutdown 260 F)
	TE-701B	Temperature	DE Journal bearing RTD type PT100 (3 wires) (high alarm 245 F; shutdown 260 F)
	TE-702A	Temperature	NDE Journal bearing RTD type PT100 (3 wires) (high alarm 245 F; shutdown 260 F)
	TE-702B	Temperature	NDE Journal bearing RTD type PT100 (3 wires) (high alarm 245 F; shutdown 260 F)
	TE-703A	Temperature	Inboard thrust bearing RTD type PT100 (3 wires) (high alarm 245 F; shutdown 260 F)
	TE-703B	Temperature	Inboard thrust bearing RTD type PT100 (3 wires) (high alarm 245 F; shutdown 260 F)
	TE-704A	Temperature	Outboard thrust bearing RTD type PT100 (3 wires) (high alarm 245 F; shutdown 260 F)
	TE-704B	Temperature	Outboard thrust bearing RTD type PT100 (3 wires) (high alarm 245 F; shutdown 260 F)
Motor	TE-302A/X2-1R	Temperature	Phase T1 winding protection RTD type PT100 (3 wires) (alarm 266F; trip 311F)
	TE-302B/X2-4R	Temperature	Phase T1 winding protection RTD type PT100 (3 wires) (alarm 266F; trip 311F)
	TE-303A/X2-2R	Temperature	Phase T2 winding protection RTD type PT100 (3 wires) (alarm 266F; trip 311F)
	TE-303B/X2-5R	Temperature	Phase T2 winding protection RTD type PT100 (3 wires) (alarm 266F; trip 311F)
	TE-304A/X2-3R	Temperature	Phase T3 winding protection RTD type PT100 (3 wires) (alarm 266F; trip 311F)
	TE-304B/X2-6R	Temperature	Phase T3 winding protection RTD type PT100 (3 wires) (alarm 266F; trip 311F)
	TE-314A	Temperature	Motor Cooling Air Temperature RTD type PT100 (3 wires) (alarm ???F; trip ???F)
	X3-1PW	Pressure Switch	Cold Air Inlet Pressure Switch (alarm or shutdown)
	X3-2PW	Pressure Switch	Cold Air Inlet Pressure Switch (alarm or shutdown)
	X3-3PW	Pressure Switch	Hot Air Outlet Pressure Switch (alarm or shutdown)
	TE-300A/X3-9R	Temperature	DE roller bearing NU232 C3 type PT100 (6 wires) (alarm 230F; trip 248F)
	TE-300B/X3-9R	Temperature	DE roller bearing NU232 C3 type PT100 (6 wires) (alarm 230F; trip 248F)
	X3-10R	Temperature	DE roller bearing 6232 C3 type PT100 (6 wires) (alarm 230F; trip 248F)
	X3-10R	Temperature	DE roller bearing 6232 C3 type PT100 (6 wires) (alarm 230F; trip 248F)
	TE-301A/X3-11R	Temperature	NDE roller bearing NU232 C3 type PT100 (6 wires) (alarm 230F; trip 248F)
	TE-301B/X3-11R	Temperature	NDE roller bearing NU232 C3 type PT100 (6 wires) (alarm 230F; trip 248F)
Gearbox	TCM01	Torquemeter	
	TE-455A/TE1A	Temperature	HS DE radial bearing A RTD type PT100 (3 wires) (alarm ???F; trip ???F)
	TE-455B/TE1B	Temperature	HS DE radial bearing B RTD type PT100 (3 wires) (alarm ???F; trip ???F)
	TE-456A/TE2A	Temperature	HS NDE radial bearing A RTD type PT100 (3 wires) (alarm ???F; trip ???F)
	TE-456B/TE2B	Temperature	HS NDE radial bearing B RTD type PT100 (3 wires) (alarm ???F; trip ???F)
	TE-451A/TE3A	Temperature	LSP DE radial bearing A RTD type PT100 (3 wires) (alarm ???F; trip ???F)
	TE-451B/TE3B	Temperature	LSP DE radial bearing B RTD type PT100 (3 wires) (alarm ???F; trip ???F)
	TE-452A/TE4A	Temperature	LSP NDE radial bearing A RTD type PT100 (3 wires) (alarm ???F; trip ???F)
	TE-452B/TE4B	Temperature	LSP NDE radial bearing B RTD type PT100 (3 wires) (alarm ???F; trip ???F)
Gas seal panel	PDIT-1610	Differential pressure	Seal gas filter (high alarm at 15 psid)
	PDIT-1611	Differential pressure	Seal gas supply, DE (low alarm at 160.91; shutdown at 64.37)
	PDCV-611		Seal gas control valve positioner
	PDIT-1612	Differential pressure	Seal gas supply, NDE (low alarm at 160.91; shutdown at 64.37)
	PDIT-1651	Differential pressure	Separation gas filter (high alarm at 15psid)
	PDIT-1652A	Differential pressure	Separation gas supply (low alarm at 2psid; shutdown after 5sec at 2psid)
	PDIT-1694A	Differential pressure	Primary pressure vent, NDE (high alarm = 4psid; shutdown = 4.5psid)
	PDIT-1684A	Differential pressure	Primary pressure vent, DE (high alarm = 4psid; shutdown = 4.5psid)
Lube oil console	PIT-206	Pressure	Lube oil supply (alarm ???; shutdown ???)
	LIT-252	Level indicator	Lube oil reservoir level (input is 0-10 inches H2O)
	PDIT-258	Differential pressure	Lube oil filter (high alarm at 20psid)
	TIT-251	Temperature	Lube oil reservoir RTD w/transmitter (alarm at ???F)
	TIT-257	Temperature	Lube oil supply A RTD w/transmitter (low alarm at 70F; high alarm at 130F)
	TIT-257	Temperature	Lube oil supply B RTD w/transmitter (low alarm at 70F; high alarm at 130F)
	PIT-841	Level indicator	Lube oil rundown tank level (alarm ???)

Table 4-18. Vibration Monitoring Instrumentation

Compressor	VE-701X	Prox probe	Compressor DE X Prox Probe (high alarm 2.4 mil p-p; shutdown 2.92 mil p-p)
	VE-701Y	Prox probe	Compressor DE Y Prox Probe (high alarm 2.4 mil p-p; shutdown 2.92 mil p-p)
	VE-702X	Prox probe	Compressor NDE X Prox Probe (high alarm 2.4 mil p-p; shutdown 2.92 mil p-p)
	VE-702Y	Prox probe	Compressor NDE Y Prox Probe (high alarm 2.4 mil p-p; shutdown 2.92 mil p-p)
	ZE-703A	Prox probe	Compressor NDE Axial Prox Probe A (high alarm +/- 24 miles; shutdown +/- 32 mils)
	ZE-703B	Prox probe	Compressor NDE Axial Prox Probe B (high alarm +/- 24 miles; shutdown +/- 32 mils)
Motor	VE-310/X4-1VP	Acceleration	DE bearing accelerometer (alarm 4.5 mm/s; trip 7.0 mm/s, RMS)
	VE-312/X4-2VP	Acceleration	NDE bearing accelerometer (alarm 4.5 mm/s; trip 7.0 mm/s, RMS)
	VE-305X	Prox probe	Motor DE X Prox Probe
	VE-305Y	Prox probe	Motor DE Y Prox Probe
	VE-307X	Prox probe	Motor NDE X Prox Probe
	VE-307Y	Prox probe	Motor NDE Y Prox Probe
Gearbox	VE-467X/VX1	Prox probe	HS DE horizontal vibration probe, 3300XL 8mm
	VE-467Y/VY1	Prox probe	HS DE vertical vibration probe, 3300XL 8mm
	VE-469X	Prox probe	HS NDE horizontal vibration probe, 3300XL 8mm
	VE-469Y	Prox probe	HS NDE vertical vibration probe, 3300XL 8mm
	VE-459X/VX3	Prox probe	LSP DE horizontal vibration probe, 3300XL 8mm
	VE-459Y/VY3	Prox probe	LSP DE vertical vibration probe, 3300XL 8mm
	VE-461X	Prox probe	LSP NDE horizontal vibration probe, 3300XL 8mm
	VE-461Y	Prox probe	LSP NDE vertical vibration probe, 3300XL 8mm
	KE-472/KP1	Keyphasor	HS DE probe, 3300XL 8mm
	KE-464/KP3	Keyphasor	LSP DE probe, 3300XL 8mm
	AE-473/A1	Acceleration	HS DE accelerometer
	AE-466/A2	Acceleration	LSP DE accelerometer

Table 4-19. Compressor Diaphragm and Cooling Water Instrumentation

Location	Tag	Type	Description
Compressor diaphragm	CT1A	Temperature	Stage 1-2 temperature A (stage 2 max discharge T = 289F)
	CT1B	Temperature	Stage 1-2 temperature B
	CT2A	Temperature	Stage 2-3 temperature A (stage 3 max discharge T = 375F)
	CT2B	Temperature	Stage 2-3 temperature B
	CT4A	Temperature	Stage 4-5 temperature A (stage 5 max discharge T = 314F)
	CT4B	Temperature	Stage 4-5 temperature B
	CTP1	Combo (T+P)	Stage 1 return channel TOP (stage 1 max dis. P = 94psia)
	CTP2	Combo (T+P)	Stage 2 return channel TOP (stage 2 max dis. P = 154psia)
	CTP4	Combo (T+P)	Stage 4 return channel TOP (stage 4 max dis. P = 420psia)
	CTP5	Combo (T+P)	Stage 5 return channel TOP (stage 5 max dis. P = 679psia)
	CC11	Combo (T+P)	Stage 1 return channel circum. 1
	CC12	Combo (T+P)	Stage 1 return channel circum. 2
	CC13	Combo (T+P)	Stage 1 return channel circum. 3
	CC21	Combo (T+P)	Stage 2 return channel circum. 1
	CC22	Combo (T+P)	Stage 2 return channel circum. 2
	CC23	Combo (T+P)	Stage 2 return channel circum. 3
	CC41	Combo (T+P)	Stage 4 return channel circum. 1
	CC42	Combo (T+P)	Stage 4 return channel circum. 2
	CC43	Combo (T+P)	Stage 4 return channel circum. 3
	CC51	Combo (T+P)	Stage 5 return channel circum. 1
	CC52	Combo (T+P)	Stage 5 return channel circum. 2
	CC53	Combo (T+P)	Stage 5 return channel circum. 3
Compressor cooling water	CDT-1INA	Temperature	1st section inlet
	CDT-1INB	Temperature	1st section inlet
	CDT-2INA	Temperature	2nd section inlet
	CDT-2INB	Temperature	2nd section inlet
	CDT-1OUTA	Temperature	1st section oulet
	CDT-1OUTB	Temperature	1st section oulet
	CDT-2OUTA	Temperature	2nd section outlet
	CDT-2OUTB	Temperature	2nd section outlet
	CDT-FM1	Flow meter	Cooling water flow - 1st Section
	CDT-FM2	Flow meter	Cooling water flow - 2nd Section
	CP-P	Pressure	Cooling pump pressure
	CV		Cooling water flow control valve

Several different types of instrumentation were used to monitor the process. Each type of instrumentation was expected to maintain a prescribed accuracy in long-term outdoor conditions. All instrumentation outputs were 4-20 mA to match data acquisition needs. For cost control, each type of instrumentation was quoted from at least two (2) suppliers.

Process Temperature Monitoring

Thermocouples and RTDs (Resistance Temperature Detectors) were the two candidates for this application. RTDs, on average, have half the uncertainty of the T-type thermocouple with SLE (Special Limits of Error) wire. This comes at a 60% cost increase. Either type required a 4-20 mA transmitter.

Performance: $\pm$0.5°C

Vendor: Omega Engineering. $214.00 each

Absolute Pressure Monitoring

These transducers were used to measure gauge pressures throughout the loop. The very tight accuracy requirements limit the number of capable products. A 4-20 mA transmitter was required.

Performance: $\pm$0.050 % FS

Vendor: Honeywell. $600.00 - $1,200.00 each

Differential Pressure Monitoring

Differential pressure transmitters monitored the process pressure drop across an orifice plate. The very tight accuracy requirements limited the number of capable products. A 4-20 mA transmitter was required.

Performance: $\pm$0.025 % FS

Vendor: Rosemount. $1,261.92 each

The data acquisition program was completed, and some of the various user interface screens are shown in Figure 4-42 – Figure 4-46.

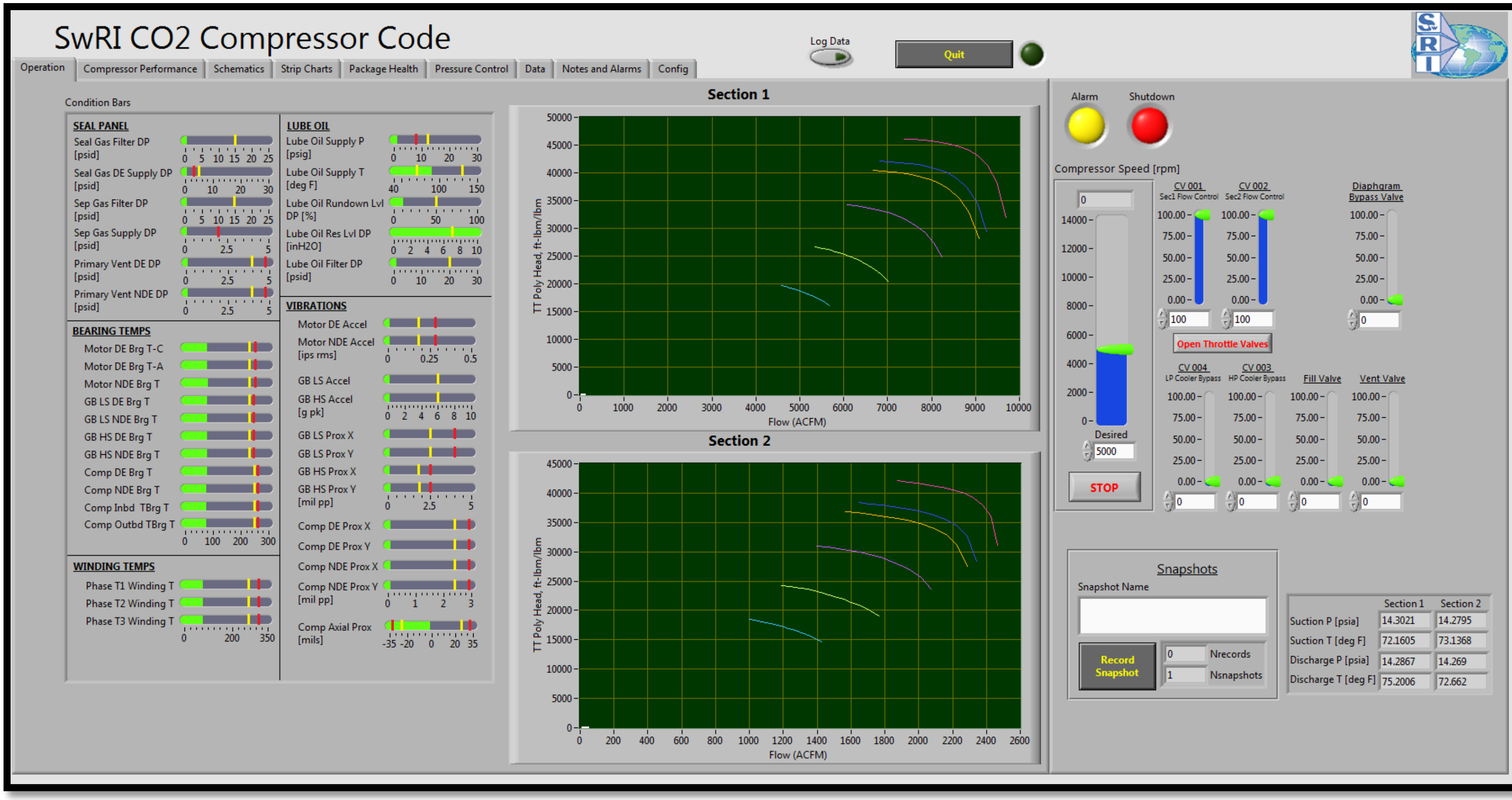


Figure 4-42. Data Acquisition Program for Compressor Testing, Operation Screen

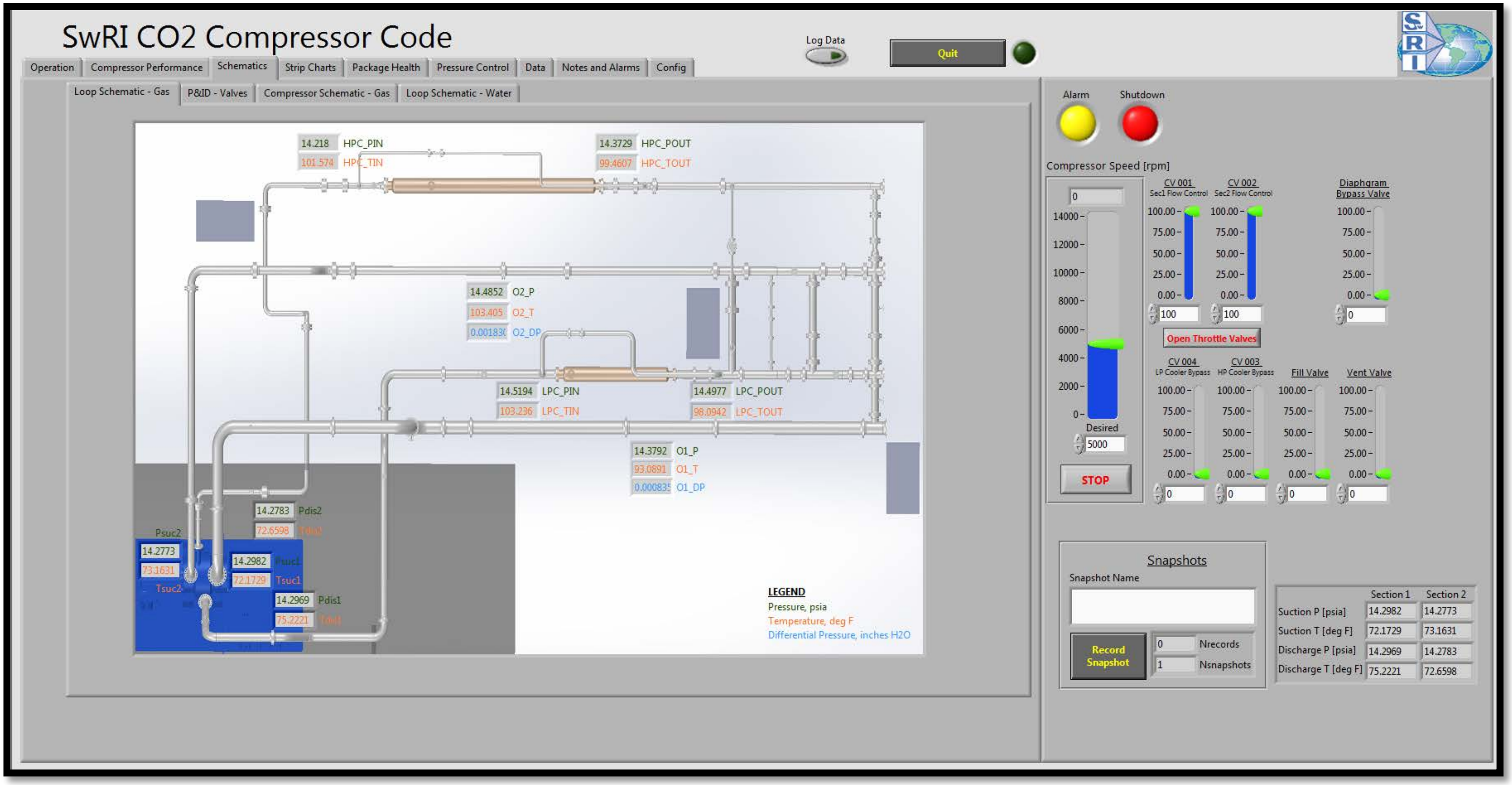


Figure 4-43. Data Acquisition Program for Compressor Testing, Loop Schematic Screen

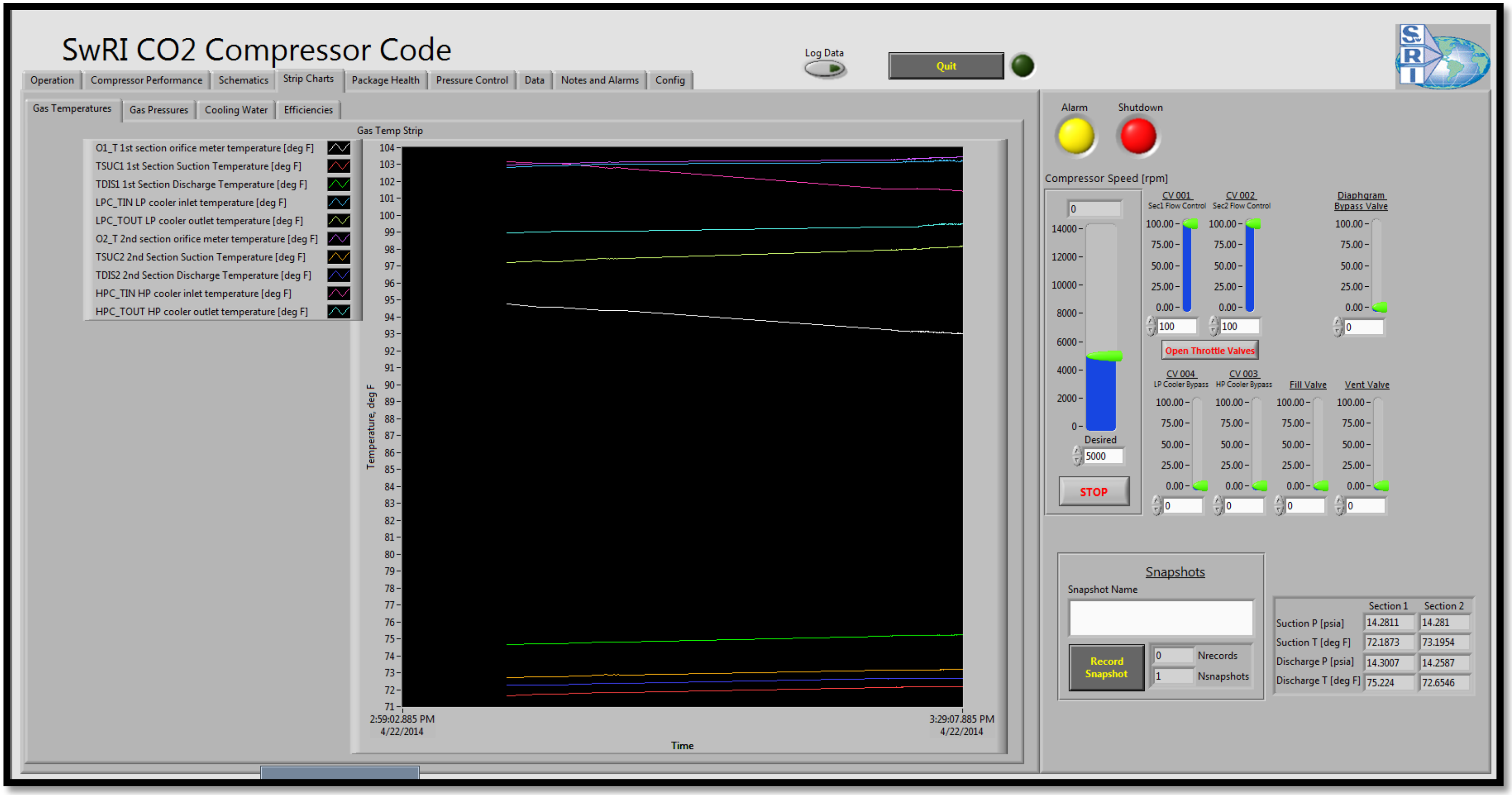


Figure 4-44. Data Acquisition Program for Compressor Testing, Strip Chart Screen

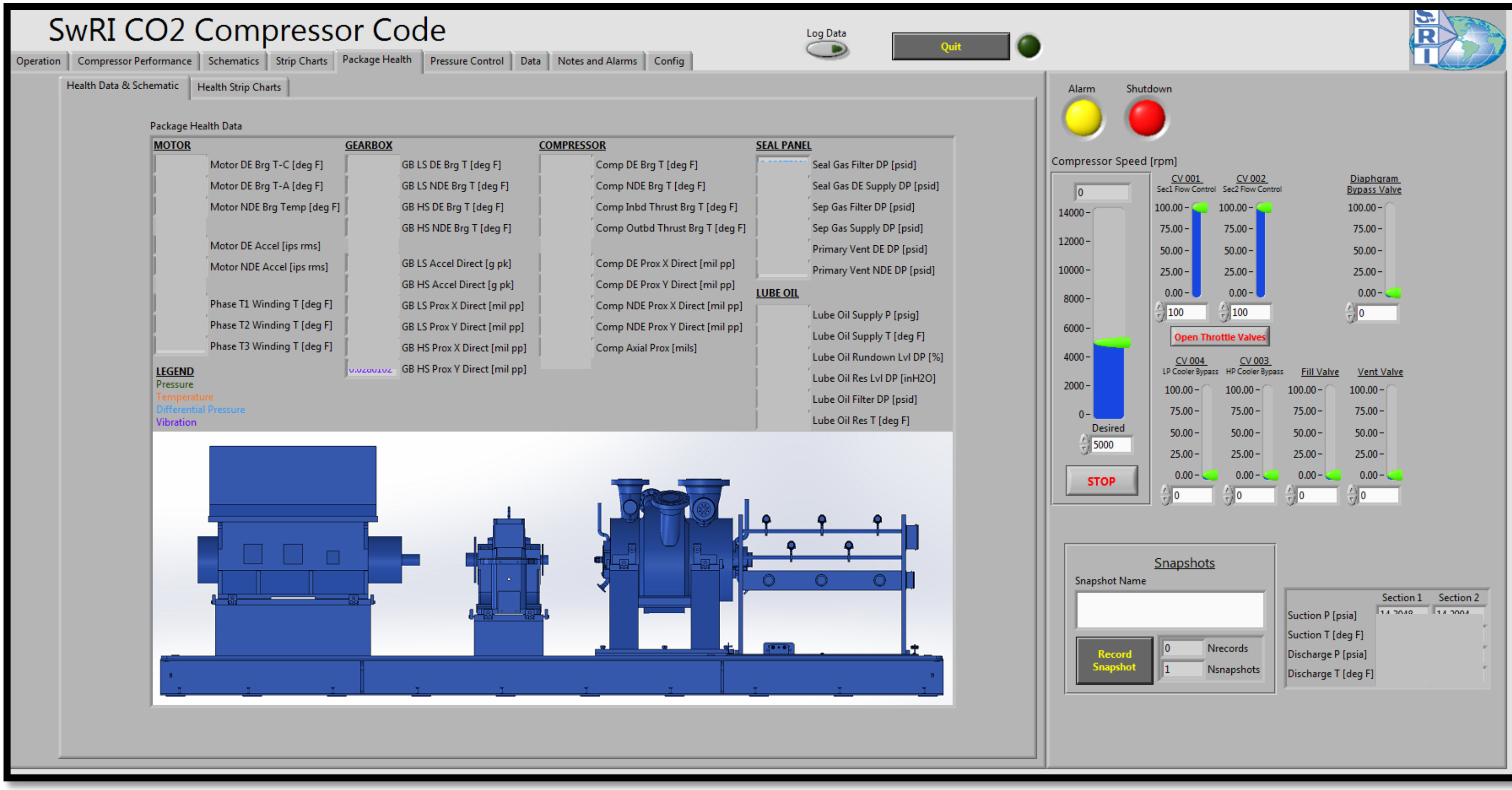


Figure 4-45. Data Acquisition Program for Compressor Testing, Package Health Monitoring Screen

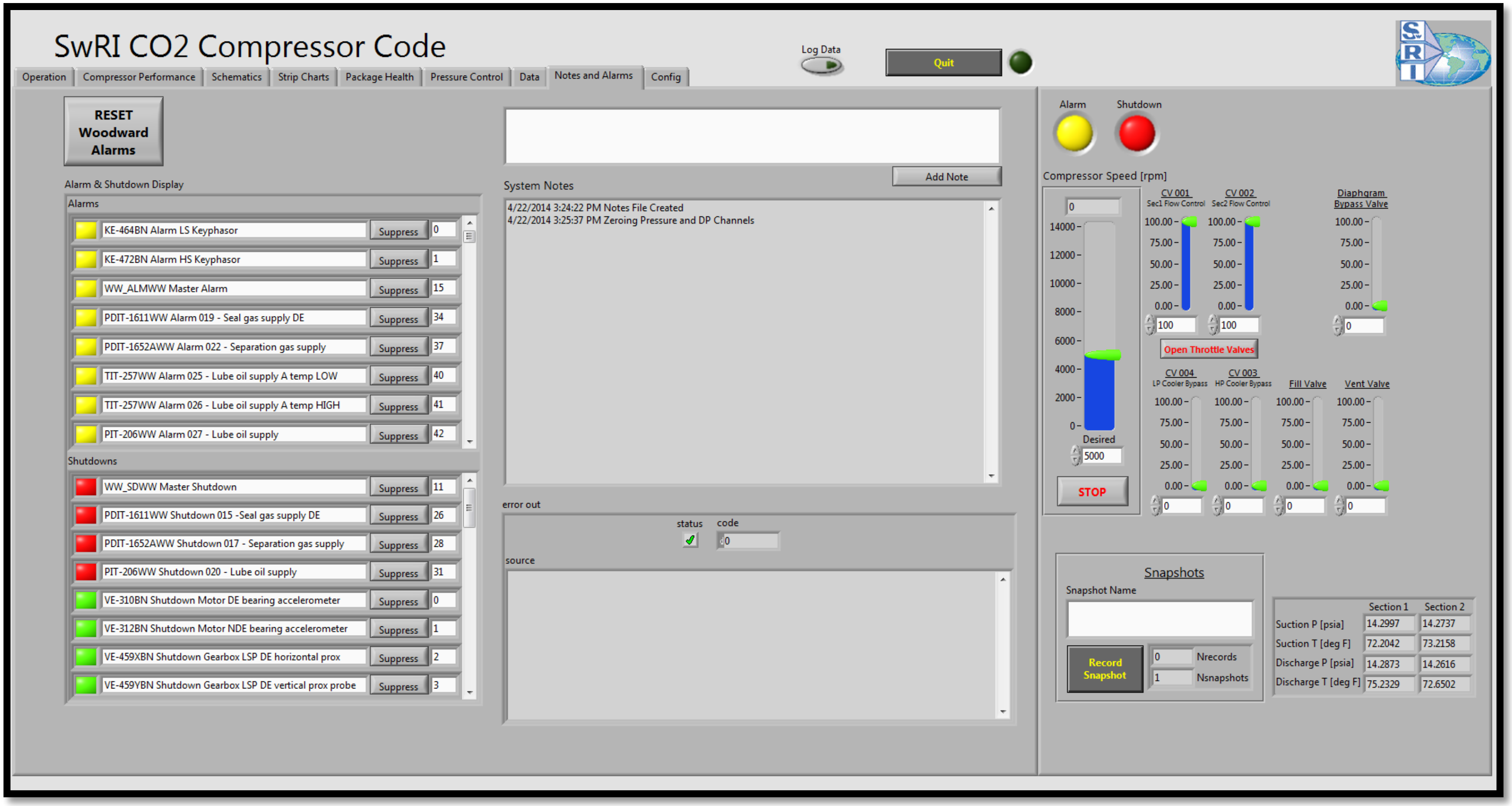


Figure 4-46. Data Acquisition Program for Compressor Testing, Notes and Alarms Screen

4.2.7 Subtask 2.7 – Prepare Site

The new facility that housed the new compressor package was completed. As of April 2014, all utilities were operational, including the electrical supply and compressed air supply, cooling water, and compressed CO_2 and N_2 at supply pressures up to 200-300 psi with provisions for higher pressure via an optional pumping station. Piping support and pipe loop construction was also completed and final connections to the compressor had been made. All hardware and instrumentation had been installed; insulation has been installed to minimize temperature changes between the compressor inlets/outlets and measurement locations.

4.2.8 Subtask 2.9 – Design of Generation 3 Cooled Diaphragm

In lieu of building a liquefaction and pumping system, a third generation-cooled diaphragm was developed to substantially improve the heat transfer in the diaphragm and also accommodate high pressure. The lessons learned from both the Gen 1 and 2 designs were leveraged. Substantial progress was made resulting in a design that could be manufactured with conventional machining and bonding methods. Preliminary CFD analysis showed less than desirable aerodynamic behavior with the new diaphragm concept. Therefore, additional design work was performed to improve the aerodynamic design. Next, the heat transfer effects of the integrated heat exchanger were analyzed.

4.3 Year 3: Task 3.0 – Test Loop Assembly, Commissioning, and Testing

4.3.1 Subtask 3.1 – Project Management and Reporting

All quarterly reports were submitted by their due date. The project cost summary is discussed below.

4.3.2 Subtask 3.2 – Compressor Procurement

The compressor, gearbox, motor, and variable frequency drive were all received and installed in SwRI's laboratory as discussed in Section 4.2.5.

4.3.3 Subtask 3.3 – Test Loop Assembly

The final assembly of the test loop was completed, as discussed in Section 4.2.5.

4.3.4 Subtask 3.4 – Testing

Mechanical testing of the compressor train was completed, with various successful test runs at speeds up to the design speed on both air and CO_2 with both parallel and series configurations of the test loop. These tests also served to validate the compressor and loop instrumentation and data acquisition and protection systems. During mechanical testing, multiple issues were experienced and resolved successfully as described below:

- **Gearbox rattle at low loads/speed.** The VFD/motor vendor came to the site and changed the VFD control mode such that rattling was not experienced at speeds above 5,000 rpm. The speed command signal was also changed from an analog signal to a digital (RS-485 Modbus) command in order to eliminate jitter in the speed control signal due to noise on the VFD's analog-to-digital conversion board.

- **Water supply and drain piping.** The water piping was upgraded from PVC to steel in order to survive startup and thermal loads from the water pump and heat exchangers. Several throttle valves were also changed from PVC to steel to allow for permanent throttling and overall water system balancing.

- **Dry gas seal supply line.** The dry gas seal supply was replumbed in order to allow feeding from the aftercooled compressor discharge gas during operation on CO_2. This setup significantly decreased the amount of CO_2 vented to atmosphere during a test.

- **Transformer winding temperature troubleshooting.** The transformer initially tripped on excessive winding temperature after approximately an hour of operation at full speed. The transformer OEM was brought onsite for a warranty visit and determined that the winding temperature sensor was malfunctioning. A replacement sensor was ordered and installed.

- **Trim balancing of gearbox output shaft.** During mechanical testing, high vibrations were observed (above alarm level) on the gearbox output shaft after heat soak. SwRI performed trim balancing and reduced vibration levels from approximately 2.7 mils pk-pk at full speed to 0.6 mils pk-pk, which is acceptable for continuous operation.

- **Torquemeter malfunctioning.** During testing, the torque meter was observed returning nonsensical values to the data acquisition program. After extensive troubleshooting, the torquemeter conditioning unit was replaced and the new unit then returned realistic values.

During the resolution of these issues, the compressor, gearbox, motor, and VFD were all tested up to the design speed and up to maximum power. Almost all of the previous operation had been at the high-flow side of the compressor map in order to minimize risk of surge. After the resolution of these mechanical issues and with successful and safe operation of the package achieved, aerodynamic testing of the compressor across its entire map was begun.

During the aerodynamics testing, internal elastomer seals were damaged, resulting in internal gas recycle thereby affecting the performance curves of the second section. These special-purpose seals were used to seal around the internal instrumentation leads that traveled from the high pressure section to the inlet of the compressor. Since the seals were elastomer with silicon sealant, no damage resulted when they liberated. Corrective action required removal of the bundle and the manufacturing of steel sealing blocks. Figure 4-47 shows the bundle being removed with the bundle cradle and lifting tooling supplied by Dresser-Rand.

Figure 4-47. Photo of Bundle Removal to Repair Internal Seals

4.4 Year 3: Task 4.0 – Aerodynamic Compressor Testing

4.4.1 Subtask 4.1 – Project Management and Reporting

All quarterly reports were submitted by their due date. The final project schedule and cost summary is discussed in Section 6.

4.4.2 Subtask 4.2 – Aerodynamic Compressor Testing Results

4.4.2.1.1 – Overview of Calculations

Computation of CO_2 thermodynamic and transport gas properties (such as viscosity, density, enthalpy, and ratio of specific heats) was required in order to calculate compressor performance. These properties were obtained directly from the National Institute of Standards and Technology (NIST) REFPROP software v9.0.

After initial reduction of the raw data, the flow rates in the first and second section inlet piping were calculated using orifice flow meters located in the loop. The orifice was instrumented with a differential pressure sensor across taps on both orifice flanges. Mass flow was calculated in accordance with API MPMS, Chapter 14.3 and ASME MFC-3M-1989 standards using the following equation:

$$q_m = \frac{\pi}{4} N_c C_d Y d^2 \sqrt{\frac{2\rho_{t,p}\Delta P}{1-\beta^4}}\,. \tag{4.5}$$

The terms in Eq. (4.5) are defined as:

q_m = mass flow rate, lbm/s
N_c = 323.279 (unit conversion constant for English units)

C_d = orifice plate coefficient of discharge, unitless
Y = expansion factor, unitless
d = orifice plate bore diameter, inches
$\rho_{t,p}$ = density of the fluid at flowing conditions upstream of the orifice, lbm/ft^3
ΔP = orifice differential pressure, inches H_2O
β = diameter ratio (orifice bore diameter/upstream piping internal diameter), unitless

In Eq. (4.5), the expansion factor is a function of the gas ratio of specific heats and the orifice diameter ratio. The coefficient of discharge is a function of Reynolds number and was calculated iteratively in accordance with the algorithm in API MPMS, Chapter 14.3 using the Reader-Harris/Gallagher Equation. The values were typically very close to 0.6. An additional orifice meter was installed on the balance piston leakage line to measure leakage flow, and this leakage flow was added to/subtracted from the first/second section orifice meter mass flows to obtain the actual inlet mass flow for each section.

Once the mass flows were determined, the volume flow in cubic feet per minute with respect to the suction density for each section was calculated as:

$$\dot{Q}_{1,2} = \frac{60\dot{m}_{1,2}}{\rho_{suc,1,2}}. \tag{4.6}$$

The flow rate of cooling water was measured directly with a turbine flow meter, but units were converted from gallons per minute to mass flow using the standard density of water as follows:

$$q_{m,H_2O} = \dot{Q}_{H_2O\ in\ gpm} \times \frac{0.1337\ ft^3}{gallon} \times \frac{62.3\ lbm}{ft^3} \times \frac{1\ minute}{60\ seconds}. \tag{4.7}$$

At all locations within the compressor, and at compressor suction and discharge locations, Keil head probes and half-shielded thermocouples were installed to measure the total pressure and temperature directly. On the suction and discharge lines, however, several types of probes were used as described in Table 4-20. Half-shielded thermocouples were used in the first section suction line due to the high flow velocities in order to measure the total temperature directly without converting the measured temperature to total temperature. The velocities in other lines were low enough that any gas power and efficiency errors associated with measuring a temperature below the total temperature were less than 0.25%.

Table 4-20. Suction and Discharge Probe Types

	Pressure	Temperature
Section 1 Suction	Kiel Head Probes (Total Pressure)	Half-Shielded Thermocouples (Total Temperature)
Section 1 Discharge	Kiel Head Probes (Total Pressure)	Shielded Grounded Thermocouples
Section 2 Suction	Kiel Head Probes (Total Pressure)	Shielded Grounded Thermocouples
Section 2 Discharge	Wall Taps (Static Pressure)	Shielded Grounded Thermocouples

After the mass flow rates were determined, the static pressure measurements in the second section discharge pipe were converted to total pressure using the methodology presented in ASME PTC-10, Section 5.4 for low Mach number flows. The first step in calculating total pressure was to determine the average flow velocity at the wall tap locations:

$$V_{avg} = \frac{\dot{m}}{\rho A}. \tag{4.8}$$

In Eq. (4.8), ρ is the density at the static pressure and measured temperature at the suction location and A was the cross-sectional flow area in the second section discharge line. Next, the total pressure was calculated from:

$$P_t = P_s + \frac{\rho V_{avg}^2}{2 \times 144 \times g_c}. \tag{4.9}$$

Internal temperature and pressure measurement probes were located in the return channel for Stages 1-2, 2-3, 4-5, and 5-6. Temperature measurements were also taken at the IGVs for Stages 2, 3, and 5. The internal measurement locations are shown in an example compressor schematic in Figure 4-48. When calculating stage performance, the locations listed in Table 4-21 were used as suction and discharge locations for each stage. Stage discharge temperatures could not be measured directly during cooled tests, but was calculated based on the stage inlet temperature and assuming the same stage isentropic efficiency for matched operating points from the adiabatic test, i.e., for tests with cooling the impeller exit temperature was calculated as:

$$T_{stage\ exit,cooled} = T_{stage\ inlet,cooled} \left(\frac{T_{stage\ exit}}{T_{stage\ inlet}}\right)_{adiabatic} \tag{4.10}$$

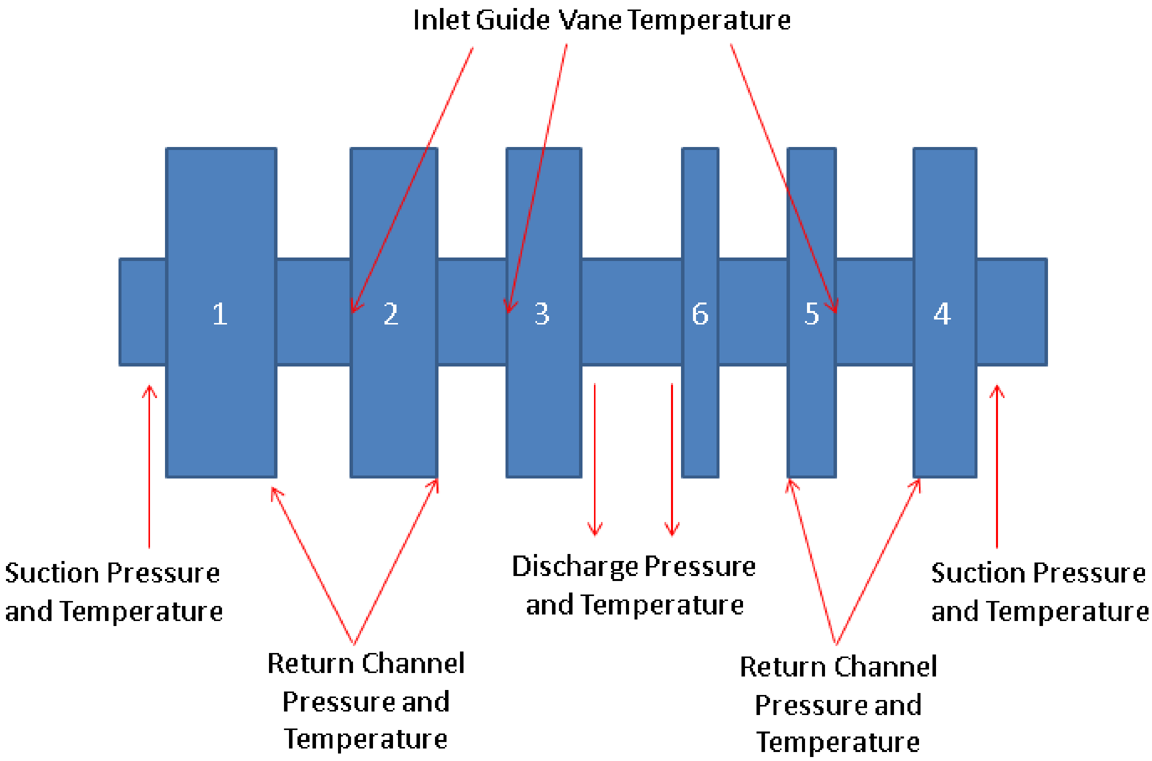


Figure 4-48. Locations of Internal Temperature Measurement Probes

Table 4-21. Stage Suction and Discharge Measurement Locations

	Suction	**Discharge**
Stage 1	1st Section Suction Pipe	Return Channel 1-2
Stage 2	Return Channel 1-2 (Pressure) IGV 2 (Temperature)	Return Channel 2-3
Stage 3	Return Channel 2-3 (Pressure) IGV 3 (Temperature)	1st Section Discharge Pipe
Stage 4	2nd Section Suction Pipe	Return Channel 4-5
Stage 5	Return Channel 4-5 (Pressure) IGV 5 (Temperature)	Return Channel 5-6
Stage 6	Return Channel 5-6	2nd Section Discharge Pipe

Total temperatures and pressures were used to calculate the actual head, polytropic head, and polytropic efficiency of the compressor during adiabatic tests. First, the total enthalpy, $h_{t,suc}$, and entropy, s_{suc}, of the CO_2 at the suction bridge-over were obtained from REFPROP. The total discharge enthalpy, $h_{t,dis}$, and density, $\rho_{t,dis}$, at the discharge bridge-over were also determined. Next, the isentropic discharge enthalpy, $h^*_{t,dis}$, and density, $\rho^*_{t,dis}$, were evaluated at the total discharge pressure and total suction entropy. Once these parameters were known, the actual head was calculated from:

$$H^a = h_{t,dis} - h_{t,suc}, \tag{4.11}$$

The isentropic head was calculated from:

$$H^* = h^*_{t,dis} - h_{t,suc}, \tag{4.12}$$

and the isentropic efficiency of the compressor was equal to:

$$\eta^* = \frac{H^*}{H^a}. \tag{4.13}$$

The polytropic performance of the compressor was calculated next. First, the isentropic exponent was defined as:

$$k = \frac{ln\frac{P_{t,dis}}{P_{t,suc}}}{ln\frac{\rho^*_{t,dis}}{\rho_{t,suc}}} \tag{4.14}$$

and the polytropic exponent was defined as:

$$n^P = \frac{ln\frac{P_{t,dis}}{P_{t,suc}}}{ln\frac{\rho_{t,dis}}{\rho_{t,suc}}}. \tag{4.15}$$

Next, the Schultz polytropic head correction factor was defined as:

$$f = \frac{H^*}{\left(\frac{k}{k-1}\right)\left(\frac{P_{t,dis}}{\rho^*_{t,dis}} - \frac{P_{t,suc}}{\rho_{t,suc}}\right)}. \tag{4.16}$$

Finally, the polytropic head was calculated from:

$$H^P = \left(\frac{n^P}{n^P-1}\right)\left[\left(\frac{P_{t,dis}}{P_{t,suc}}\right)^{\frac{n^P-1}{n^P}} - 1\right] \times f \times \frac{P_{t,suc}}{\rho_{t,suc}} \tag{4.17}$$

and the polytropic efficiency was calculated from:

$$\eta^P = \frac{H^P}{H^a}. \tag{4.18}$$

The final calculation for compressor performance was compressor gas power (i.e., power delivered to the gas). The actual gas power was equal to:

$$Pwr_{Gas} = \dot{m}H^a. \tag{4.19}$$

The actual power was calculated via speed and torque measurements on the shaft. The shaft power was equal to:

$$Pwr_{Shaft} = \frac{Torque\ (ft-lbf) \times Speed(rpm)}{5252}. \quad (4.20)$$

The power delivered to the gas was less than the shaft power because of bearing and windage losses:

$$Pwr_{Gas} = Pwr_{Shaft} - Losses. \quad (4.21)$$

The losses were determined from adiabatic test data because the gas power could be calculated accurately (the actual head measurement was not corrupted by cooling). During diabatic (cooled) tests, the actual head, isentropic efficiency, and polytropic efficiency could not be calculated due to the heat transfer.

Horsepower savings were calculated using data gathered from the torque meter. These values were normalized by dividing by the average mass flow rate for each section as follows:

$$TQHP_{normalized} = \frac{TQHP}{\dot{m_{avg}}} \quad (4.22)$$

The specific (normalized) torques were then converted to percentages.

$$Power\ Savings\ \% = \frac{TQHP_{adiabatic} - TQHP_{cooled}}{TQHP_{adiabatic}} \times 100 \quad (4.23)$$

The heat transfer effectiveness was calculated using the effectiveness-NTU method (Cengel, 2003), where dimensionless heat transfer effectiveness was defined as:

$$\varepsilon = \frac{\dot{Q}}{\dot{Q}_{max}} = \frac{Actual\ Heat\ Transfer\ Rate}{Maximum\ Possible\ Heat\ Transfer\ Rate}. \quad (4.24)$$

The actual heat transfer rate was computed from either the water or the CO_2 as

$$\dot{Q} = C_{H2O}\left(T_{H2O,out} - T_{H2O,in}\right) = C_{CO2}\left(T_{CO2,in} - T_{CO2,out}\right), \quad (4.25)$$

where $C_{H2O} = \dot{m}_{H2O}C_{p,H2O}$ and $C_{CO2} = \dot{m}_{CO2}C_{p,CO2}$ were the heat capacity rates of the cooling water and CO_2, respectively. Since most of the data points in Eq. (4.25) were measured, the actual heat transfer rate was calculated as the average value determined from both the water and the CO_2. The impeller exit temperature, however, was not directly measured. In the adiabatic tests, the impeller exit temperature equaled the temperature measured at the return channel. An isentropic efficiency could also be estimated for each impeller using the adiabatic test data. Theoretically, the impeller efficiency should not differ for adiabatic and cooled tests. By knowing the impeller efficiency, the impeller exit temperature was estimated for the cooled tests.

The maximum heat transfer rate was defined as

$$\dot{Q}_{max} = C_{min}\left(T_{CO2,in} - T_{H2O,in}\right), \quad (4.26)$$

where C_{min} was the smaller heat capacity rate of the two fluids. In this case, C_{CO2} was always smaller than C_{H2O}, so C_{CO2} was used. The above definition is the maximum heat transfer rate because it considers the case when the CO_2 is cooled to the inlet temperature of the water.

4.4.2.1.2 – Predicted Compressor Design Point Values

Dresser-Rand provided specification sheets for the compressor that outlined the design point for the compressor. The normal operating conditions for the design points are listed in Table 4-15.

Table 4-22. Compressor Design Point Values

Parameter	Design Point Value					
	Section 1	**Section 2**	**Section 3**	**Section 4**	**Section 5**	**Section 6**
Inlet Pressure (psia)	14.8	25.7	42.8	62.4	109.7	172.2
Discharge Pressure (psia)	25.7	42.8	67.6	109.7	172.2	250.0
Inlet Temperature (^oF)	115.0			115.0		

4.4.2.1.3 – Summary of Tests Completed

A total of three different loop configurations were tested in order to examine the effects of internal cooling water on compressor performance. These configurations are summarized in Table 4-23 and explained in greater detail below.

Table 4-23. Summary of Tests Completed

<table>
<tr><th>Test Number</th><th>Trial Description</th><th>Description</th></tr>
<tr><td rowspan="3">1</td><td>Adiabatic</td><td>Sections run in independent series mode with separate throttle valves for each section
Section 1 Suction Pressure = 15 psia, Section 1 and 2 Suction Temperature = 115°F
No internal cooling
Completed full design speed line (5 points) at 11403 rpm</td></tr>
<tr><td>Normal Flow</td><td>Identical loop configuration and suction conditions to adiabatic case above, but with internal cooling at total flow of 276 gpm split equally among both sections
Matched head with adiabatic run test points for each section (not pressure ratio or flow) at same operating speed</td></tr>
<tr><td>High Flow</td><td>Same as normal flow case above, but with increased internal cooling at total flow rate of 323 gpm, split 138 gpm in Section 1 and 185 gpm in Section 2 (the water supply system was insufficient to increase flow significantly in both sections simultaneously).</td></tr>
<tr><td rowspan="2">2</td><td>Adiabatic</td><td>Sections run in true series mode with single throttle valve for both sections
Section 1 Suction Pressure = 15 psia, Section 1 and 2 Suction Temperature = 115°F
No internal cooling
Completed full design speed line (6 points) at 11,403 rpm</td></tr>
<tr><td>Cooled Flow</td><td>Identical loop configuration and suction conditions to adiabatic case above, but with internal cooling at total flow of 276 gpm
Matched overall pressure ratio and flow with adiabatic run test points by varying speed and throttle valve position</td></tr>
<tr><td rowspan="3">3</td><td>Adiabatic</td><td>Sections run in true series mode with single throttle valve for both sections
No internal cooling or intercooling between sections 1 and 2 (imitating a straight-through compressor)
Obtained single operating point at 9,317 rpm</td></tr>
<tr><td>Cooled A</td><td>Identical loop configuration to adiabatic case above, but with internal cooling at total flow of 276 gpm
Matched overall pressure ratio and speed with adiabatic test point, but with a higher flow</td></tr>
<tr><td>Cooled B</td><td>Identical loop configuration to adiabatic case above, but with internal cooling at total flow of 276 gpm
Matched overall pressure ratio and flow with adiabatic test point at a lower speed of 8,881 rpm</td></tr>
</table>

Test 1

Test 1 was run with the piping loop in independent series configuration, meaning that discharge pressure of Section 1 was equal to the suction pressure of Section 2, but the sections were throttled individually via throttle valves CV-001 and CV-002. The loop configuration is illustrated in Figure 4-49. The suction temperature for each section was controlled to 115°F by adjusting the cooler bypass valves CV-003 and CV-004 and hand valves HV-009 and HV-010.Suction pressure was controlled to 15 psia by actuating the vent and fill valves.

During the adiabatic test, no cooling water was supplied to the internal diaphragms and a full design speed line of five points was completed at 11,403 rpm. Next, cooling water was supplied to the diaphragm at a normal flow (276 gpm split equally between all stages), and then a high flow of water (323 gpm total with 138 gpm in 1st section and 185 gpm in 2nd section, equal split among stages within each section). For the two different cooling flow rates, five additional points were obtained while matching speed and polytropic head with the test points from the adiabatic run for each section. There was no pressure ratio matching or flow matching between adiabatic and cooled tests.

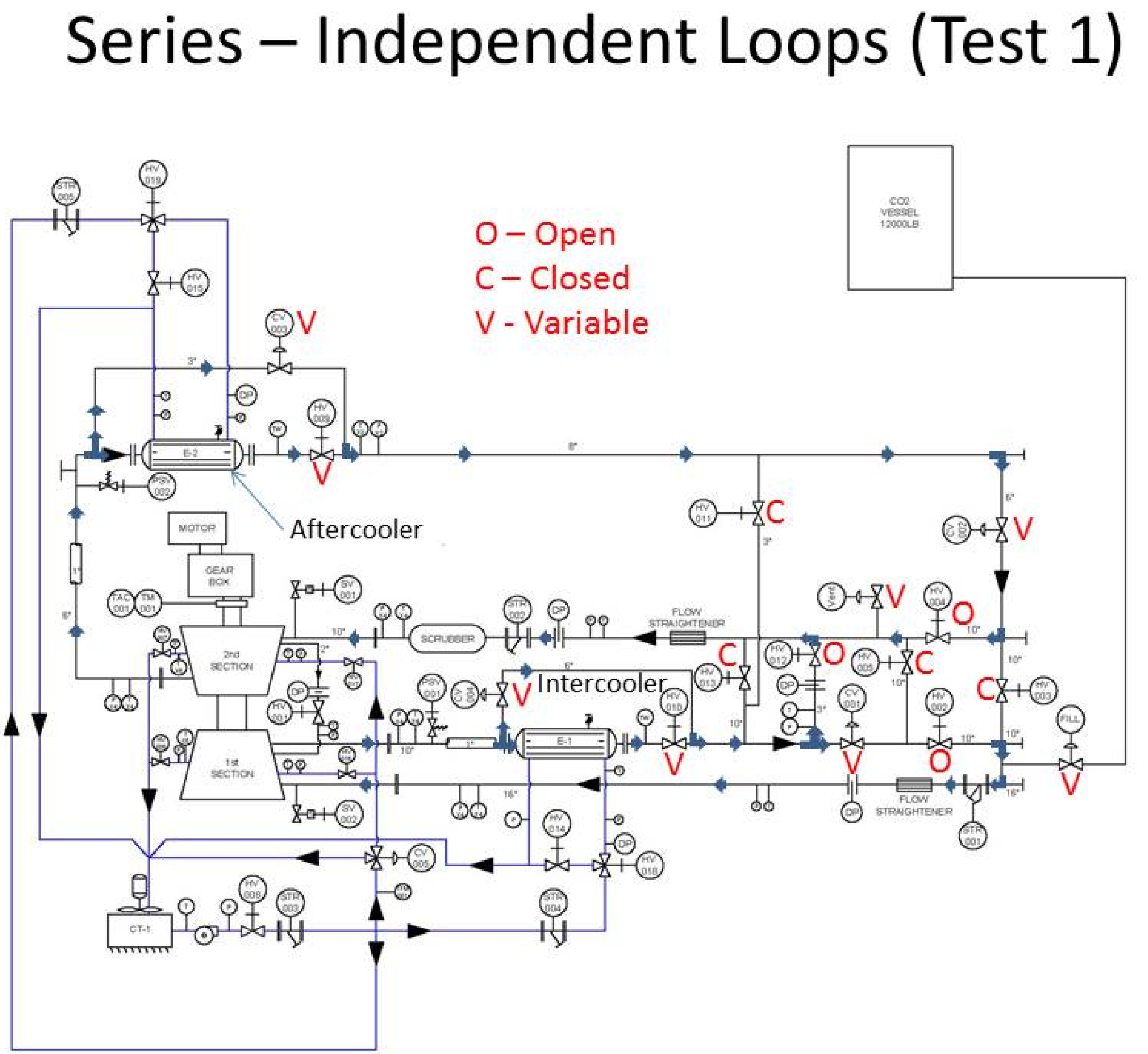


Figure 4-49. Test 1 Loop Configuration

The flow rates for different trials during Test 1 were expressed in terms of a percentage of the design point flow rate for each section. The throttle valve positions for each section were varied to obtain five different flow rates above and below the design point.

Table 4-24. Test 1 Flow Rates

	Section 1	Section 2
% Flow Rate, Trial 1	108.9%	104.3%
% Flow Rate, Trial 2	103.5%	104.2%
% Flow Rate, Trial 3	100.7%	99.6%
% Flow Rate, Trial 4	100.5%	92.6%
% Flow Rate, Trial 5	94.3%	92.2%

The polytropic head for varying flow rates from Test 1 is plotted below in Figure 4-50 and Figure 4-51 for the two sections. The polytropic efficiency from the adiabatic points in Test 1 are shown in Figure 4-52 and Figure 4-53 for sections 1 and 2, respectively. The adiabatic test points are shown in blue, and the data points for testing with cooling water at the two different flow rates are shown in red and green. The solid black line denotes the predicted adiabatic curve. All data are normalized with respect to the adiabatic test data at the design flow.

The measured adiabatic data were reasonably close to the predicted adiabatic curve, with polytropic head for Sections 1 and 2 measured to be slightly lower and higher than predicted near the design point, respectively. The data also showed that diaphragm cooling changed the characteristics of the speed line slightly by increasing the volume flow capacity for each section, particularly near the choke side of the map. This performance change is attributed to gas volume reduction that occurred as the gas was cooled in the diaphragm, which caused the latter stages in each section to stay out of choke and operate closer to their design point.

The polytropic head is a function of both suction and discharge conditions, so the introduction of diaphragm cooling also affected the head calculation. Thus, matching polytropic head for adiabatic and cooled test points did not result in the same overall pressure ratio. For this reason and, also, because the sections were throttled independently rather than together in series, performance data from Test 1 were not used to calculate power savings from diaphragm cooling.

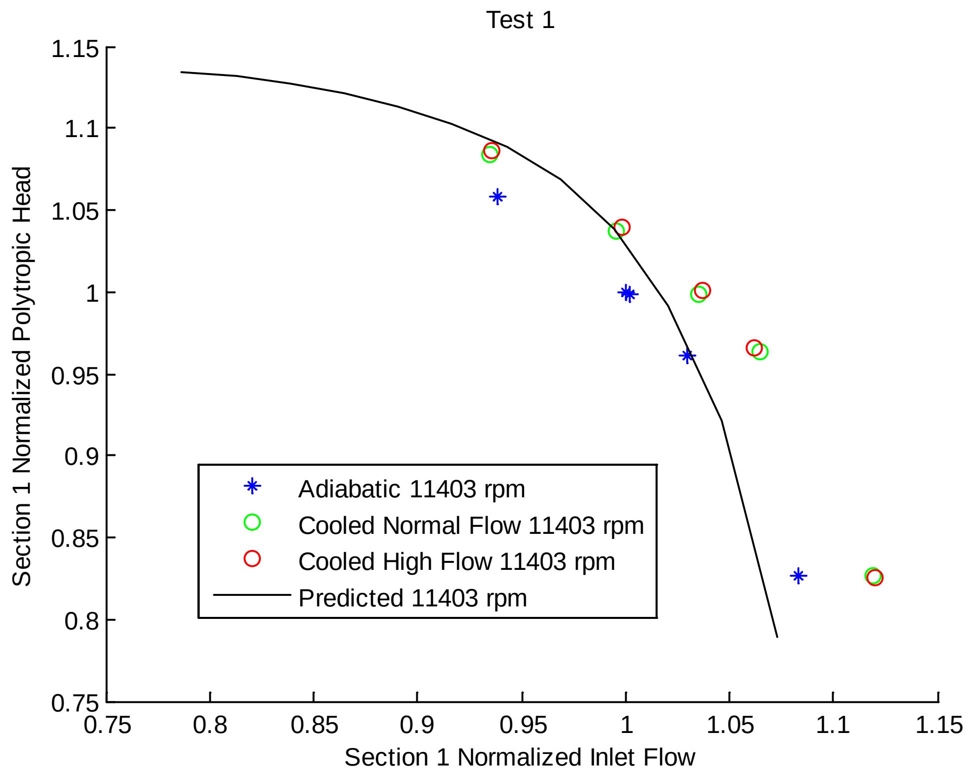


Figure 4-50. Section 1 Normalized Polytropic Head vs. Normalized Flow (Test 1)

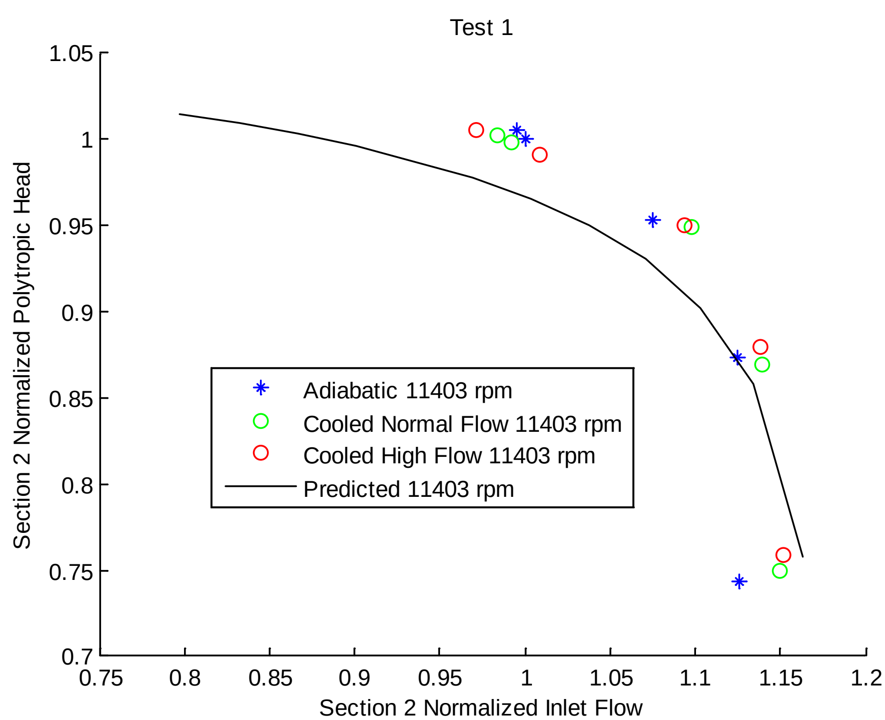


Figure 4-51. Section 2 Normalized Polytropic Head vs. Normalized Flow (Test 1)

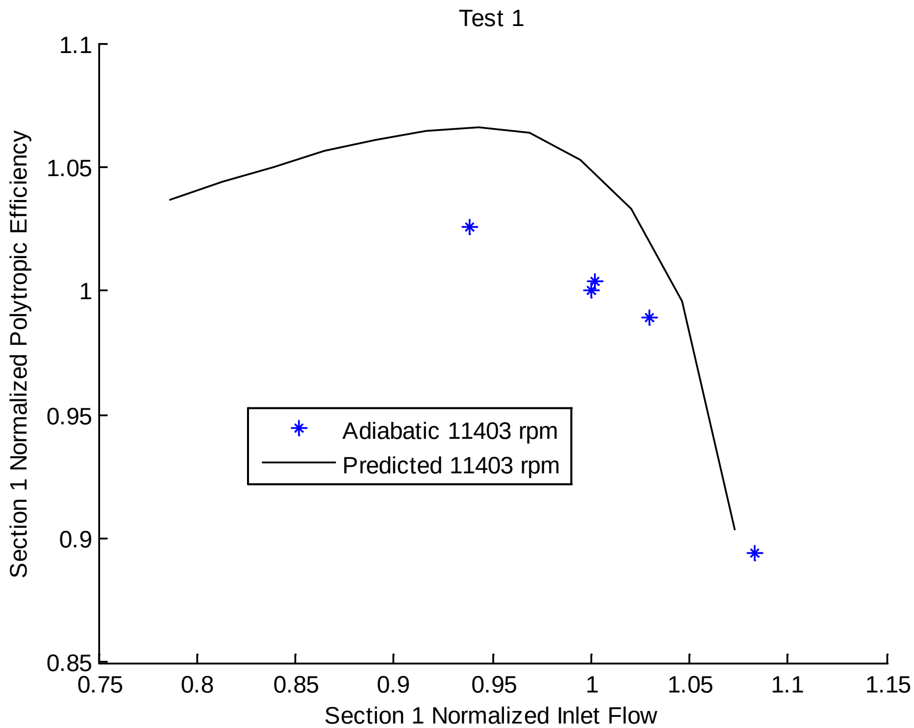


Figure 4-52. Section 1 Normalized Polytropic Efficiency vs. Normalized Flow for Adiabatic Case (Test 1)

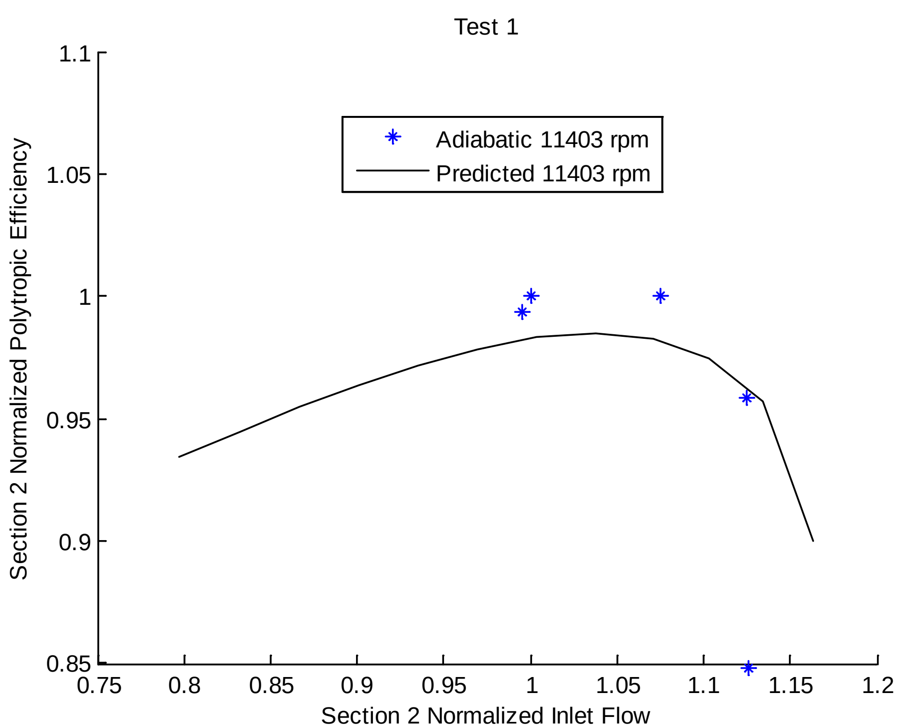


Figure 4-53. Section 2 Normalized Polytropic Efficiency vs. Normalizd Flow for Adiabatic Case (Test 1)

Test 2

Test 2 was a true series test, meaning that all of the discharge flow from Section 1 was sent to the inlet of Section 2 and that sections were throttled together with a single throttle valve CV-002. In this configuration, the operating points for each section were not controlled independently and were dictated by the relative capacities of each section. This is the configuration that would be used in the end application of CO_2 sequestration at a fossil fuel power plant. An adiabatic test was run with no internal cooling, and a full design speed line of six points at 11,403 rpm was completed. As in Test 1, loop temperature was controlled via hand valves HV-009 and HV-010 and control valves CV-003 and CV-004 (See diagram in Figure 4-54). Again, the first section suction pressure was maintained at 15 psia and the suction temperature for both sections was maintained at 115°F.

A cooled test was also run with 276 gpm cooling water split evenly between the six stages. This test kept the same suction conditions as the adiabatic test. The compressor speed and throttle valve position were varied to match the overall pressure and flow with the adiabatic test points. The flow rates for each point on the speed line in Test 2 are shown in Table 4-25. Because Section 1 flow rates were not directly controlled, Section 1 flow rates came close to but never surpassed the design flow rate. The flow rates were expressed in terms of a percentage of the flow rate at the adiabatic test design pressure ratio.

Table 4-25. Test 2 Flow Rates

	Section 1	Section 2	Cooled Test Speed, rpm
% Flow Rate, Trial 1	99.5%	104.1%	11133
% Flow Rate, Trial 2	98.2%	103.0%	11120
% Flow Rate, Trial 3	96.6%	99.3%	11100
% Flow Rate, Trial 4	93.3%	93.3%	11094
% Flow Rate, Trial 5	91.9%	90.9%	11094
% Flow Rate, Trial 6	88.5%	85.3%	11058

The overall pressure ratio and flow for all data points acquired during Test 2 are shown in Figure 4-54. These plots indicate the close matching of pressure ratio and flow between the two tests.

Series – Dependent Loops (Test 2)

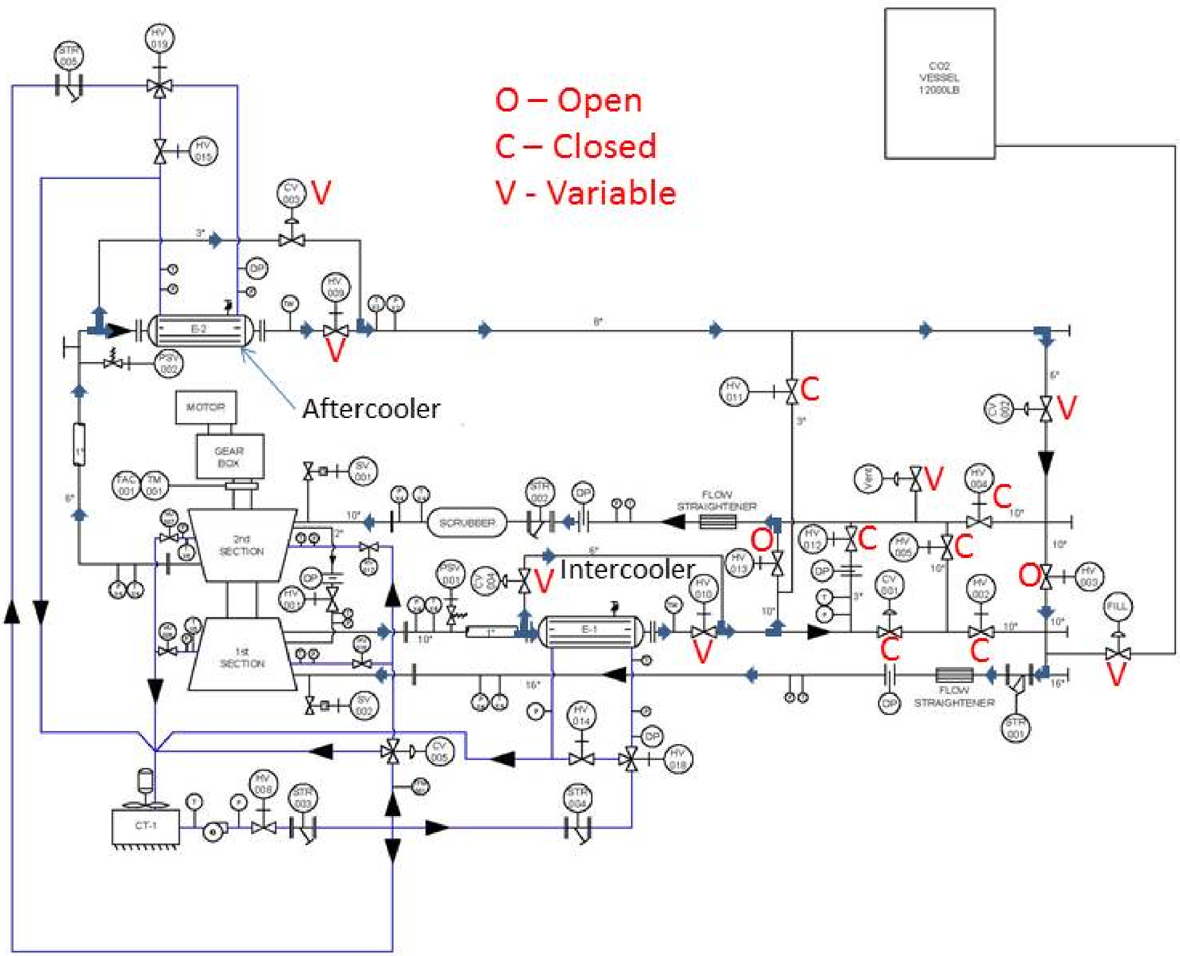


Figure 4-54. Test 2 Loop Configuration

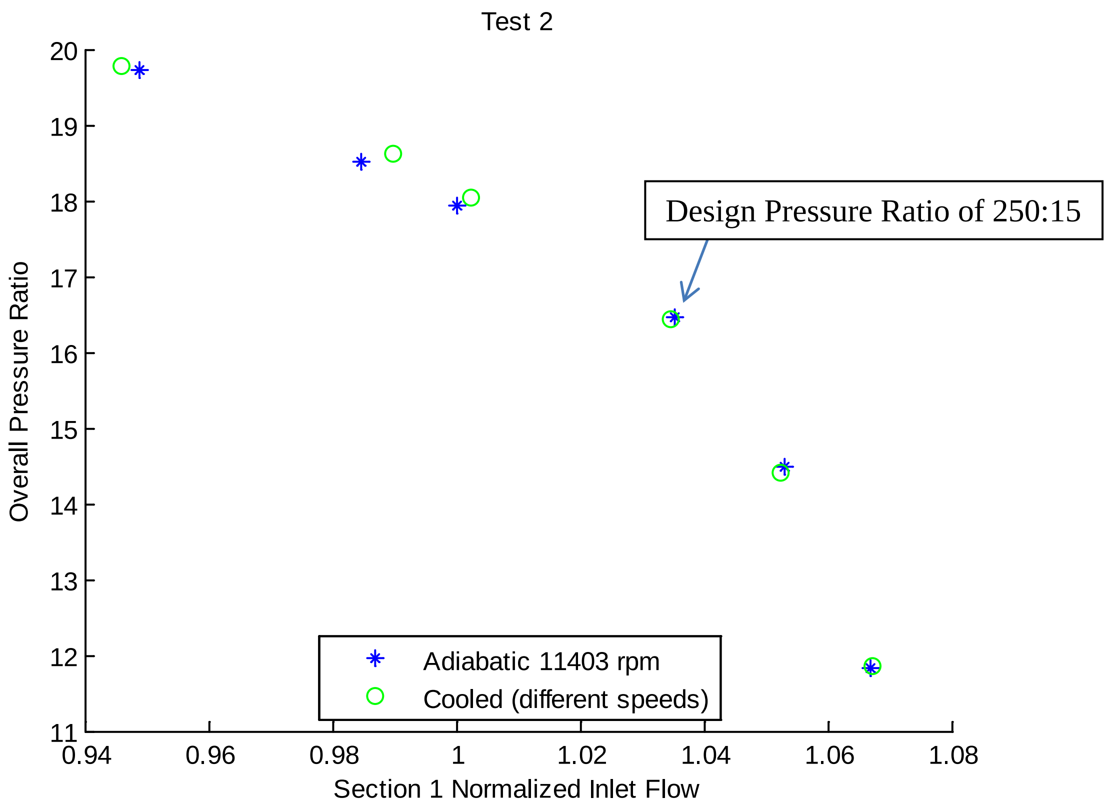


Figure 4-55. Overall Pressure Ratio vs. Normalized Flow (Test 2)

Test 3

Test 3 was a true series test (sections throttled together) similar to Test 2, but with the water supply to the intercooler shut off to simulate temperature rise through a six-stage straight-through compressor. The loop configuration for this test is shown in Figure 4-56. The compressor speed was lowered from 11,403 rpm to 9,317 rpm to keep operating temperatures in the second section below 420°F to prevent damage to compressor components. The first section suction pressure and temperature were increased to 20 psia and 160°F, respectively, in order to increase the overall horsepower (and corresponding accuracy of the horsepower savings measurement).

For Test 3, an adiabatic test was run at a single operating point at 9317 rpm. Two cooled test configurations were also performed that matched different operating characteristics of the adiabatic test. The cooling water flow rate for both cooled test points was 276 gpm split equally among the six stages. In cooled Configuration A, the overall pressure ratio and speed were matched with the adiabatic test point, but a higher flow rate was measured. In cooled Configuration B, the overall pressure ratio and flow were matched with the adiabatic test point, but the compressor was operated at a reduced speed of 8,881 rpm.

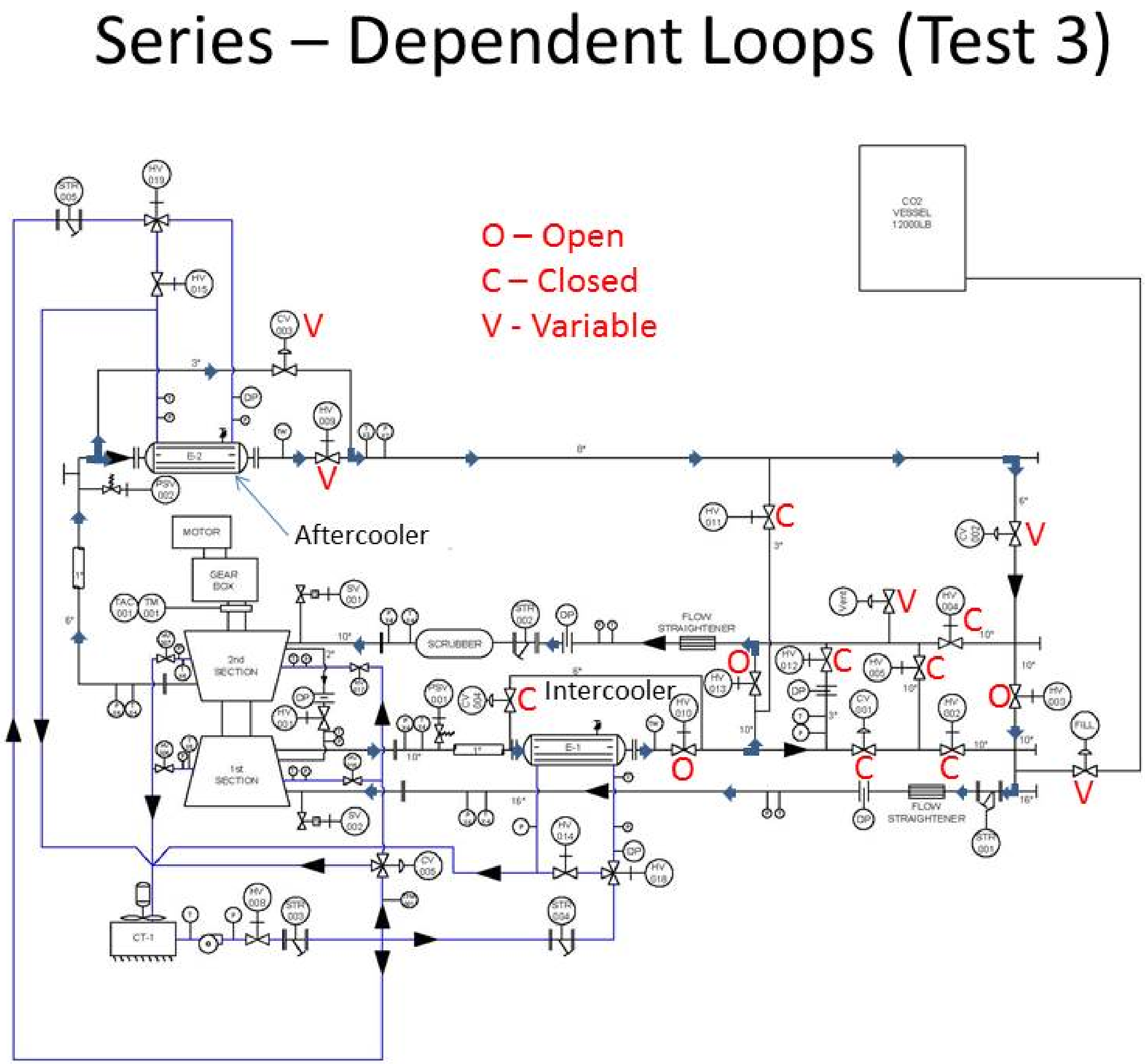


Figure 4-56. Test 3 Loop Configuration

The overall pressure ratio vs. flow plot for all Test 3 configurations is shown below in Figure 4-57. As shown, the pressure ratio for all three tests was very similar, but cooled Configuration A (at the adiabatic test speed) had significantly higher flow. The flow is normalized by the flow at the adiabatic test point.

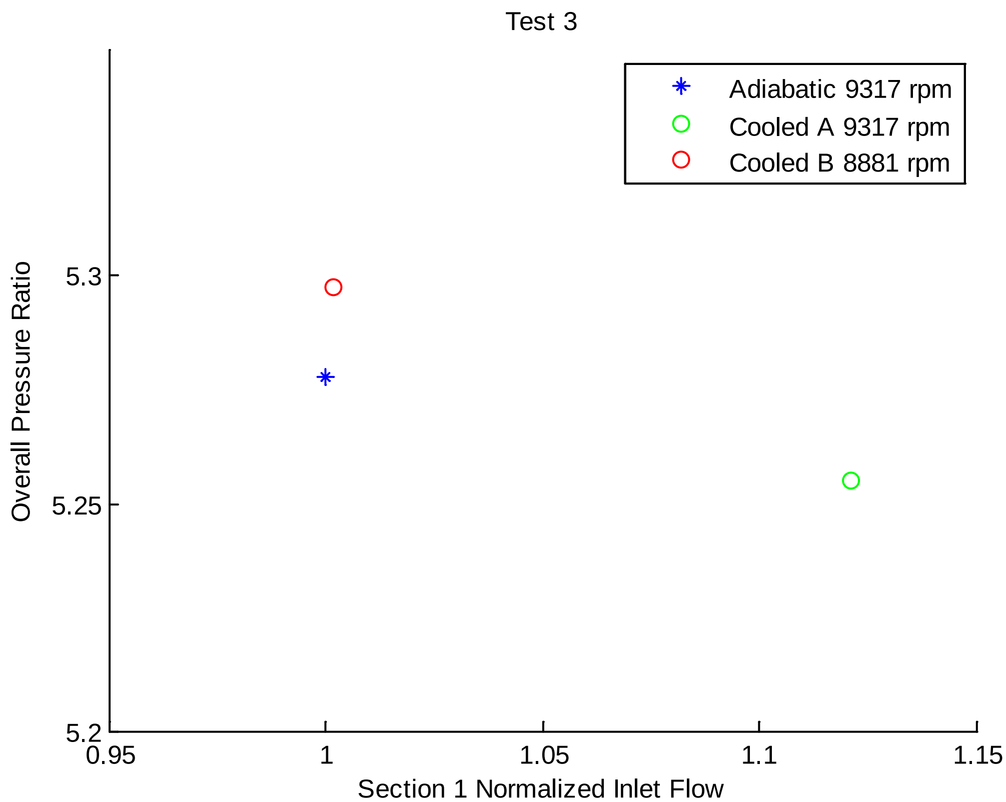


Figure 4-57. Overall Pressure Ratio vs. Normalized Flow (Test 3)

4.4.2.1.4 – Results

This section presents the results of the various tests shown above. The focus in this section is on the most important results, i.e., horsepower savings, temperature reduction from diaphragm cooling, diaphragm heat exchanger effectiveness. Additional calculated data (section and stage head, flow, and pressure ratio) are provided in Appendix E for completeness.

Percent Horsepower Savings

The horsepower savings (units of $HP \cdot s/lbm$), calculated as explained in Section 4.4.2.1.1, were as follows in Table 4-26 and Table 4-27 for Tests 2 and 3, respectively. Horsepower savings were not calculated for Test 1 since each section was throttled independently, so many variations could be employed to reach the same overall pressure ratio (i.e., the Section 1 pressure ratio was not naturally determined by the flow restriction imposed by Section 2). The results for Test 2 (with an intercooler) showed horsepower savings of 3-8% depending on the operating point. The Test 3 results (without an intercooler to simulate straight-through operation) showed even higher power savings of 9% when matching pressure ratio and speed.

Table 4-26. Test 2 Horsepower Percent Savings

Test 2 Horsepower Savings from Diaphragm Cooling	
Point	**Percent Difference (%)**
1	7.99
2	6.28
3	3.24
4	3.03
5	3.01
6	3.32

Table 4-27. Test 3 Horsepower Percent Savings

Test 3 Horsepower Savings from Diaphragm Cooling	
Cooled A Percent Difference (%): Matching speed and overall pressure ratio	**Cooled B Percent Difference (%): Matching flow and pressure ratio**
5.64	9.00

Temperature

Internal temperature measurements were taken at various points along the compressor, as is shown in Figure 4-48. At each of these points, several temperature and pressure measurements were taken at different circumferential locations. These data points were averaged to get a temperature and pressure at each location. The temperatures in each compressor section locations at all operating points for Test 2 are shown in Figure 4-58 and Figure 4-59 (normalized with respect to the adiabatic test discharge temperature at the design pressure ratio). As expected, the diaphragm cooling resulted in lower temperatures at all operating points.

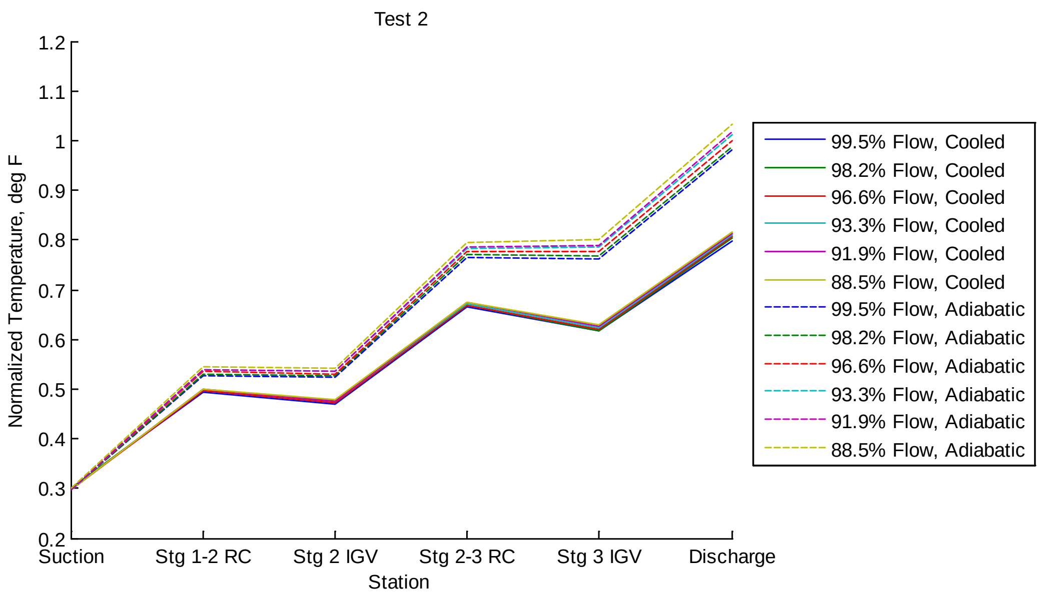


Figure 4-58. Section 1 Adiabatic and Cooled Diaphragm Normalized Internal Temperatures (Test 2)

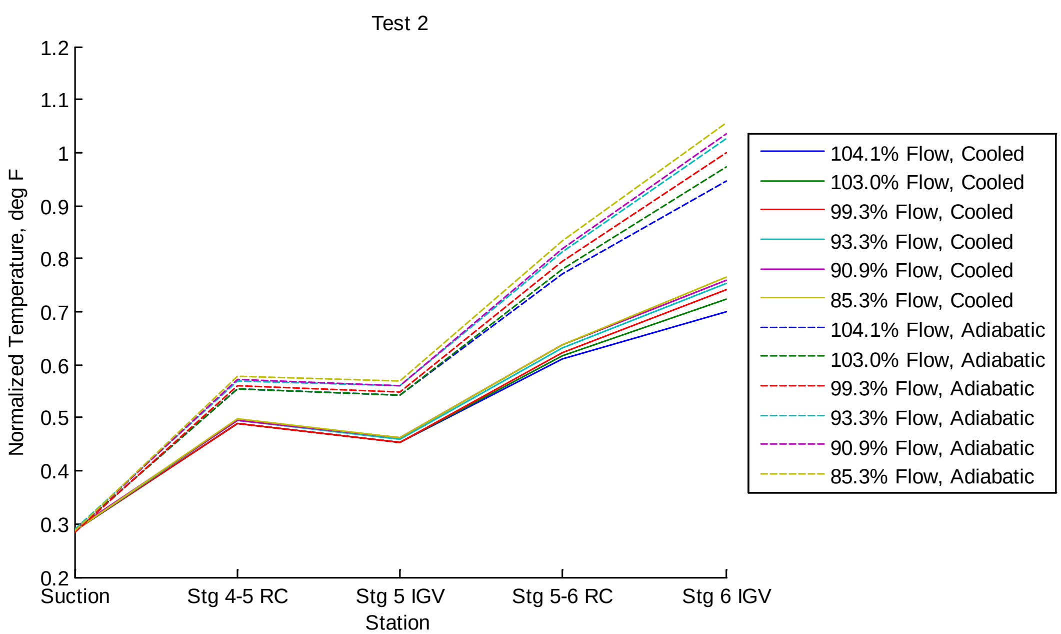


Figure 4-59. Section 2 Adiabatic and Cooled Diaphragm Normalized Internal Temperatures (Test 2)

Predicted design point temperatures were given on the compressor specifications sheet. For both the adiabatic and cooled cases in Test 2, the predicted design point temperature was plotted against the actual design point temperature in Figure 4-60 and Figure 4-61. The trial data used corresponds to Trial 3, which was the point that matched the overall pressure ratio. These results indicated that adiabatic temperature rise was very slightly higher than predicted and cooled temperatures were slightly lower than predicted.

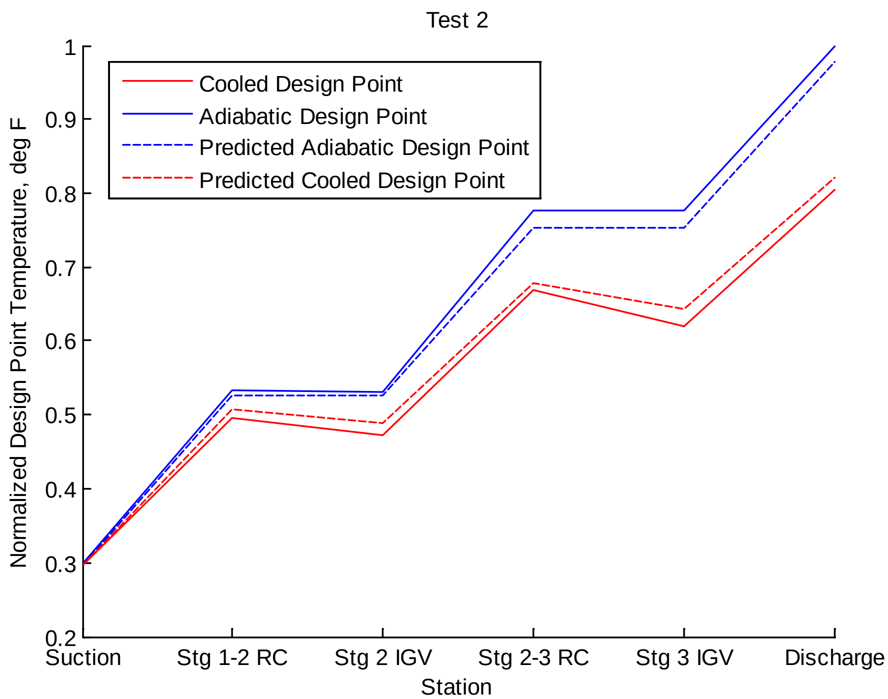


Figure 4-60. Section 1 Comparison with Predicted Normalized Temperature for Design Flow Conditions (Test 2)

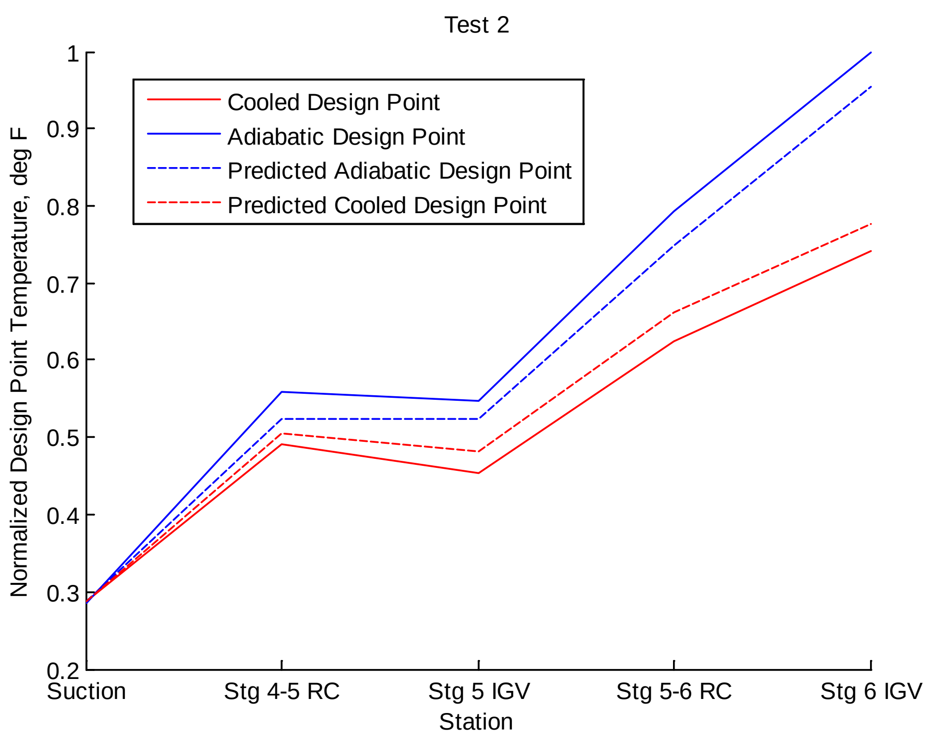


Figure 4-61. Section 2 Comparison with Predicted Normalized Temperature for Design Flow Conditions (Test 2)

To better analyze performance, the temperature differences between the cooled case and adiabatic case were calculated. Temperature differences at each location were determined by subtracting the cooled design point temperature from the adiabatic design point temperature. For the predicted temperature differences, the predicted cooled test temperature was subtracted from the predicted adiabatic temperature. The results, shown in Figure 4-62 and Figure 4-63, showed general agreement between predicted and measured temperature drop. The cooled diaphragms removed more heat than predicted in each section, particularly in the Stages 1-2 and 4-5 diaphragms.

The temperature differences for all six operating points in Test 2 are shown in Figure 4-64 and Figure 4-65. The data show that diaphragms reduced the gas temperature more towards the left of the map, when impeller exit temperatures were higher and gas velocities were lower.

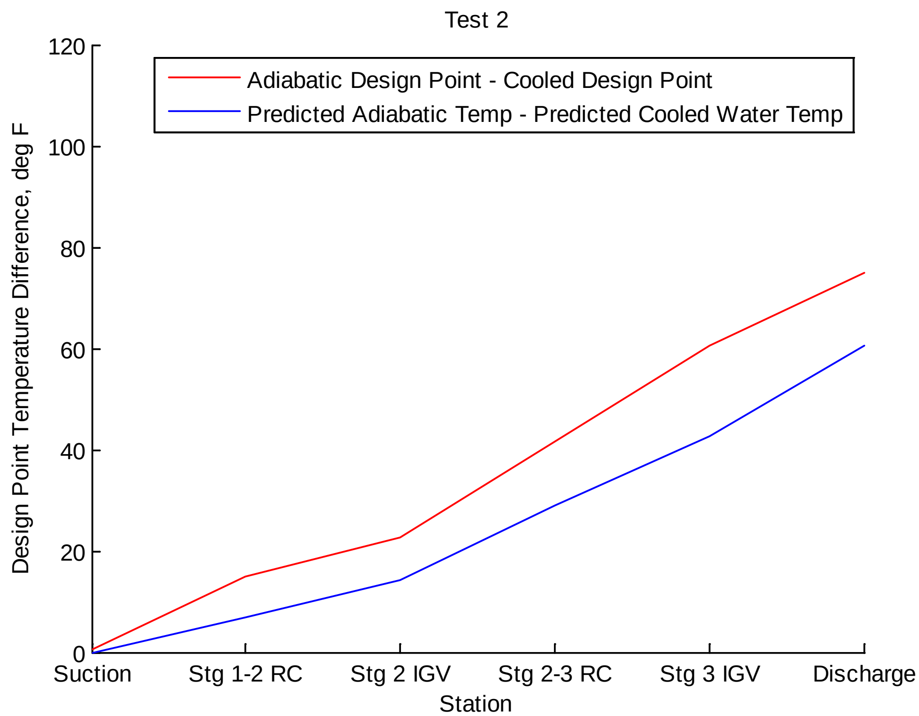


Figure 4-62. Section 1 Design Point Temperature Differences (Test 2)

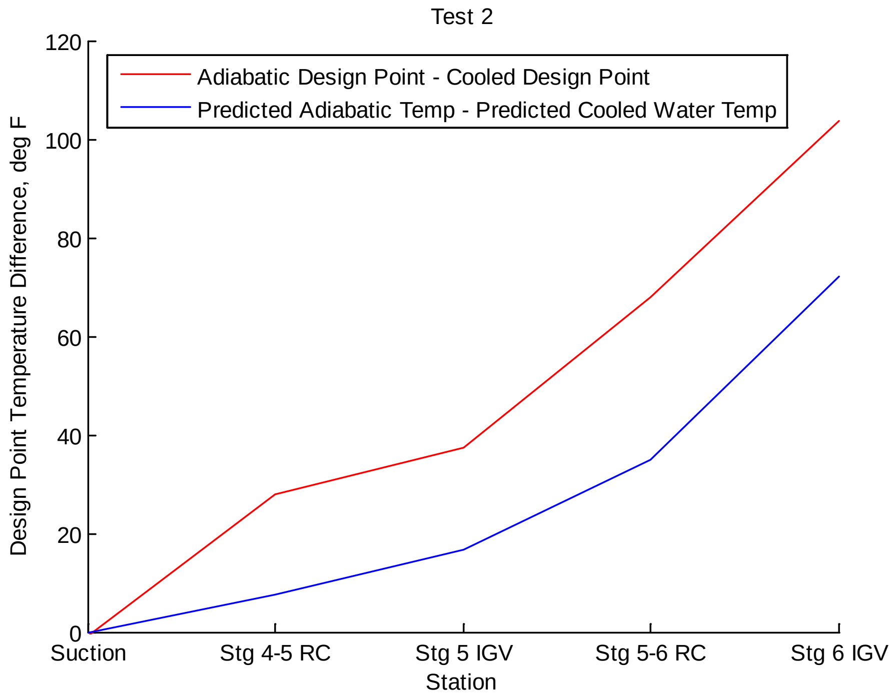


Figure 4-63. Section 2 Design Point Temperature Differences (Test 2)

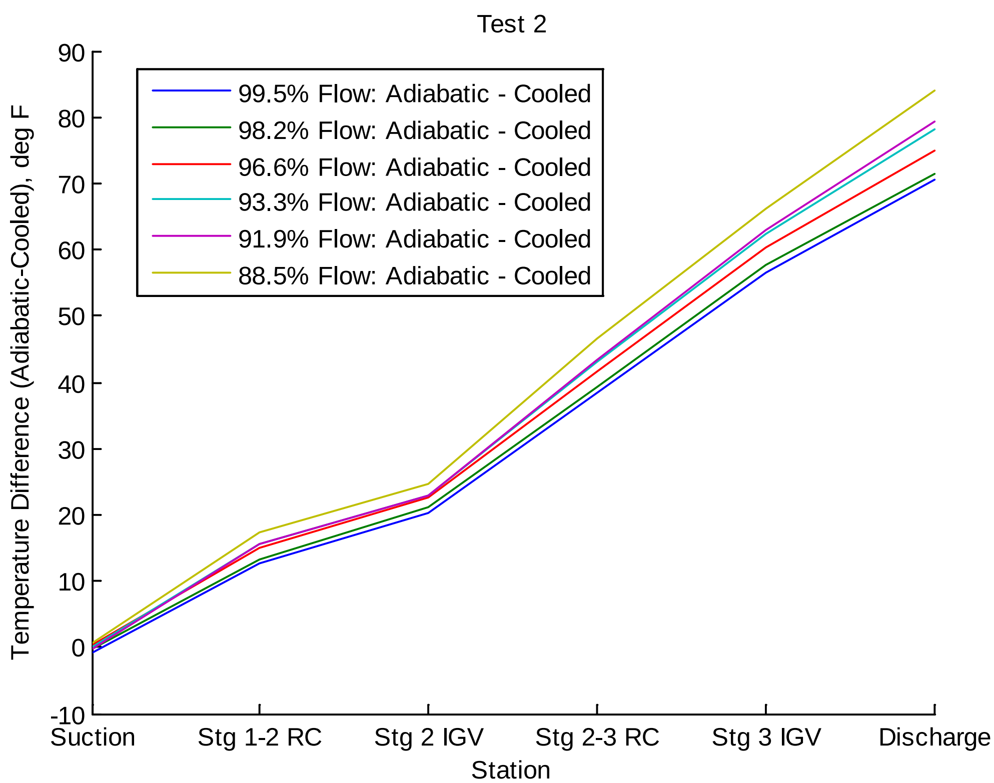


Figure 4-64. Section 1 Measured Temperature Differences between Adiabatic and Cooled Cases (Test 2)

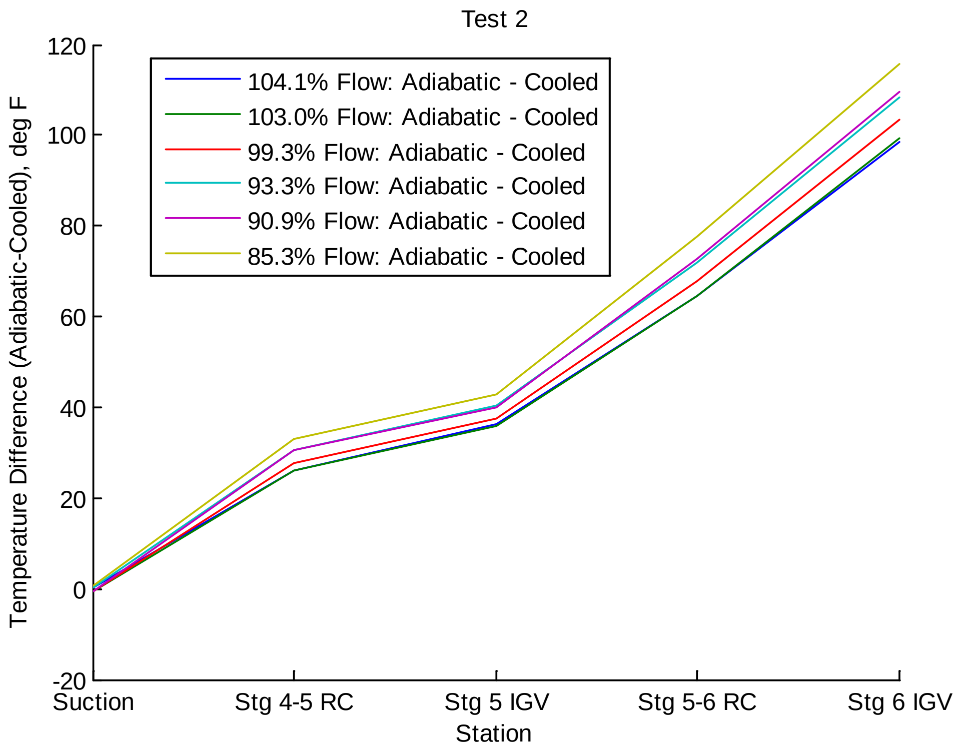


Figure 4-65. Section 2 Measured Differences between Adiabatic and Cooled Cases (Test 2)

Heat Exchanger Effectiveness

In Section 4.4.2.1.1, the maximum heat transfer rate was defined as:

$$\dot{Q}_{max} = C_{min}\left(T_{CO2,in} - T_{H2O,in}\right) \quad (4.26)$$

where C_{min} was the smaller heat capacity rate of the two fluids. In this case, C_{CO2} was always smaller than C_{H2O}. The effectiveness of the diaphragm was calculated for the CO_2 using the effectiveness-NTU method (Cengel, 2003). The gas inlet temperature into each stage was estimated using the measured pressure ratio and the same polytropic efficiency as the comparable adiabatic test point. Notably, no IGV temperatures were available for stage 6, so stage 5-6 return channel temperature was used for the stage 5 exit and stage 6 inlet temperature. This simplification is expected to artificially decrease the stage 5 heat exchanger effectiveness and artificially increase the stage 6 heat exchanger effectiveness. The effectiveness of each stage vs. flow rate is compared with the predicted effectiveness in Figure 4-66 for Test 2, Figure 4-67 for Test 3 cooled Configuration A, and Figure 4- for Test 3 cooled Configuration B. Flow data were normalized in the same manner as previous plots. The data showed that predicted and measured effectiveness values were reasonably close, but the measured effectiveness was typically higher than predicted. The measured effectiveness values showed the same trend as predicted values in that Stages 3 and 6 were typically the lowest (they did not have return channel cooling since they were the final stage in each section), followed by Stage 1 effectiveness. Stage 4 effectiveness showed the most disagreement with predictions in that it was significantly higher than predicted.

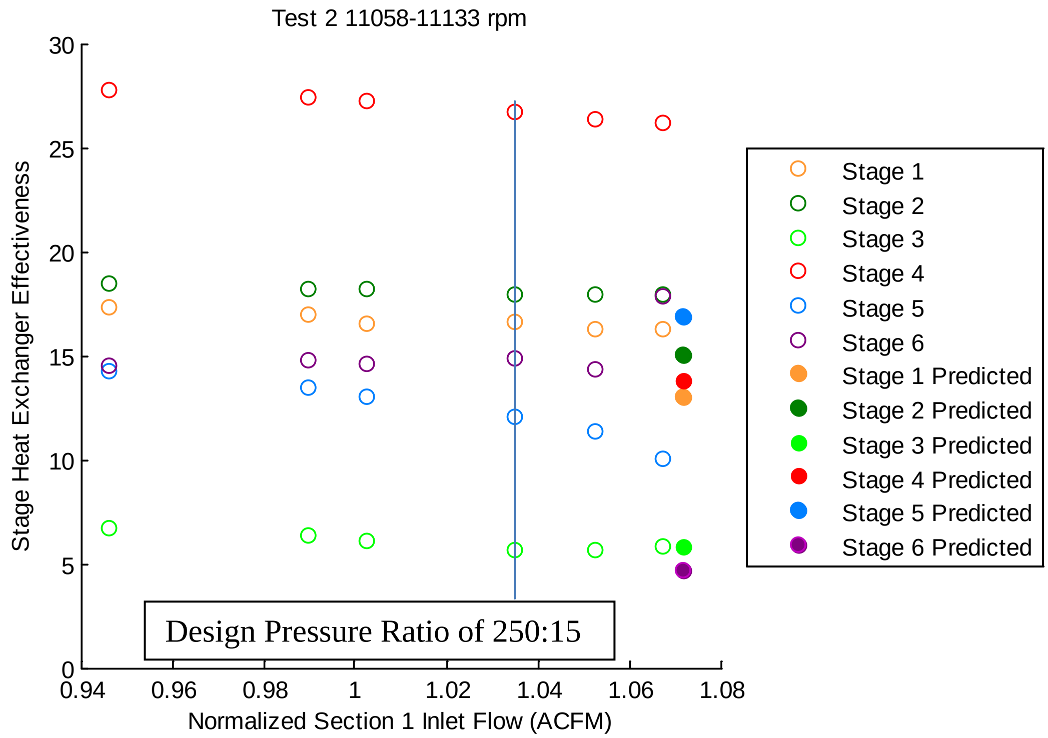


Figure 4-66. Heat Exchanger Effectiveness for CO_2 vs. Normalized Flow for Each Stage (Test 2)

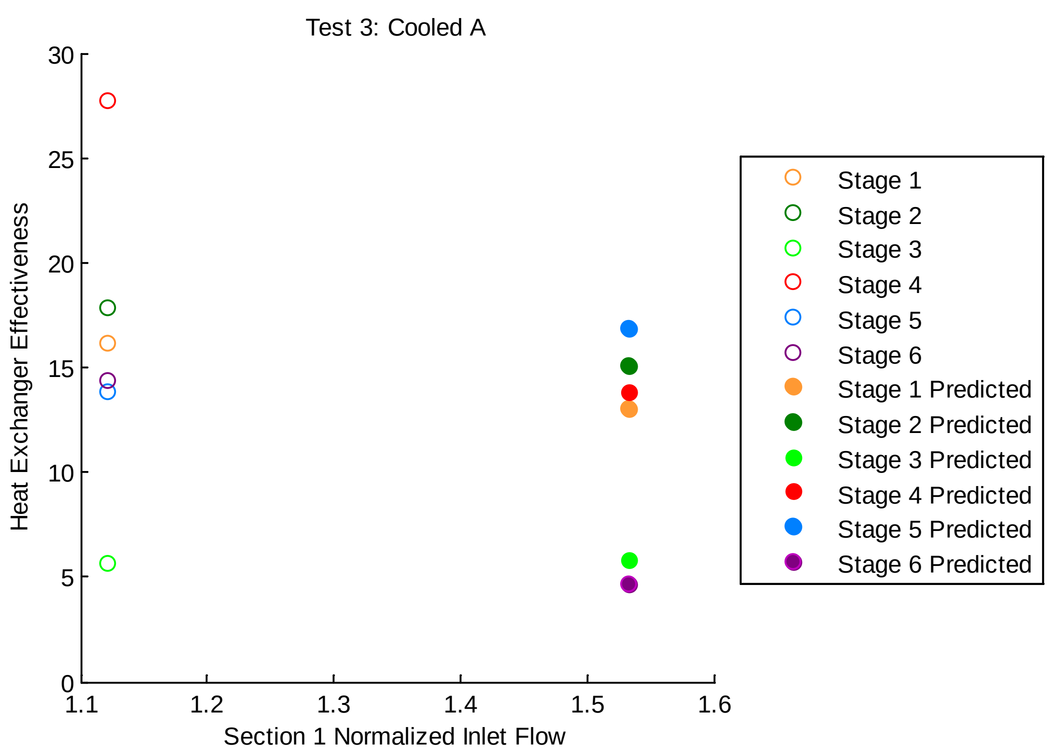


Figure 4-67. Heat Exchanger Effectiveness for CO_2 vs. Normalized Flow for Cooled A Trial (Test 3)

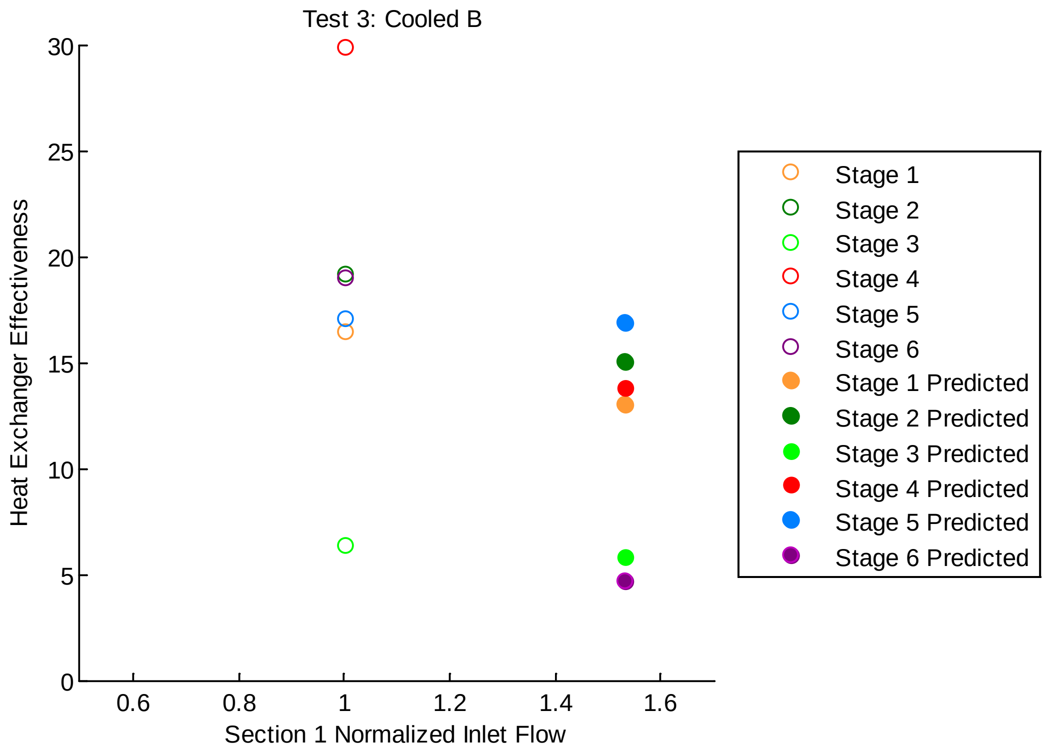


Figure 4-68. Heat Exchanger Effectiveness for CO_2 vs. Normalized Flow for Cooled B Trial (Test 3)

5. CONCLUSIONS

Phase III implemented the technology developed in Phase II into a full-scale demonstration compression plant with:

- A 3 MW Motor-driven compression train with variable speed drive.
- A 6-stage back-to-back inline centrifugal compressor equipped with cooled diaphragm technology.
- A piping loop interfacing with the compressor and incorporating valves to operate the compressor across its performance map and at multiple test configurations.
- Ancillary systems to support the compressor and loop, including lube oil system, CO_2 supply system, cooling water system with loop coolers and cooling tower, and electrical equipment for the motor.

All systems were designed, procured, and commissioned according to the proposed work scope and project plan. Aerodynamic testing of the compressor was completed with and without the cooling diaphragms activated and results showed that:

- The cooled diaphragm technology reduces compressor power consumption by 3.0% near surge to 8.0% near choke when compared with the adiabatic case with intercooling between the two sections.
- Up to 9.0% power savings were measured when the compressor was operated as a straight-through compressor with no intercooling, nearly achieving the project's goal of double-digit power reduction for CO_2 compression. This test was performed at the low-flow side of the map. Based on trends from the back-to-back test, horsepower savings at the high-flow side of the map is expected to be higher than 10%.
- The heat exchanger effectiveness for the cooled diaphragm was measured between 13-30%, depending on the stage and operating point.
- The cooled diaphragms removed 75-100°F (28-35%) of the temperature rise within each section when compared to the adiabatic case.
- The measured temperature drop, heat exchanger effectiveness, and power savings were all slightly higher than predicted values.
- Operation of the cooled diaphragms changed the characteristics of the multi-stage machine, increasing flow capacity and pressure ratio compared to adiabatic performance at the same speed. Additional performance gains may be realized by designing the compressor flow path for the cooled case rather than the adiabatic case.
- No reliability issues associated with the cooled diaphragm design were encountered during testing including diaphragm leakage.

6. SCHEDULE AND COST STATUS

The project was completed within 3.5 years from project initiation, which included a 6-month no-cost extension. The project phases and subtasks were sequential; namely:

YEAR 1 – Engineering conceptual design of multi-stage internally cooled compressor, test loop design, and liquefaction plant design.

YEAR 2 – Final detail design of test loop and cooled diaphragms, procurement of major equipment, pipe construction, and site preparation.

YEAR 3 – Test loop assembly, wiring, plumbing, commissioning, testing, and reporting.

The detailed project schedule, tollgates, and organization are presented in the Gantt chart. The schedule was revised to reflect the delay in the project start date. Due to the delay in site preparation and the delivery of the compressor, a revised six-month no-cost extension was granted. The project was completed on time by June 30, 2014, as shown below.

	Task Name	Duration	Start	Finish
1	**Year 1**	**125 days?**	**Mon 7/11/11**	**Fri 12/30/11**
2	**Multi-stage internally cooled diaphragm design**	**125 days?**	**Mon 7/11/11**	**Fri 12/30/11**
3	CFD Analysis	60 days?	Mon 7/11/11	Fri 9/30/11
4	Conceptual Design of Multi-stage Cooled Diaphragm	125 days?	Mon 7/11/11	Fri 12/30/11
5	Test loop conceptual design	125 days?	Mon 7/11/11	Fri 12/30/11
6	**Year 2**	**284 days?**	**Mon 1/2/12**	**Thu 1/31/13**
7	Detail Design of Multi-stage Cooled Diaphragm	65 days?	Mon 1/2/12	Fri 3/30/12
8	Test loop detail design	65 days?	Mon 1/2/12	Fri 3/30/12
9	Liquefaction plant design	65 days?	Mon 1/2/12	Fri 3/30/12
10	Procurement of major equipment	265 days?	Fri 1/27/12	Thu 1/31/13
11	Pipe construction	176 days?	Fri 4/27/12	Fri 12/28/12
12	Site preparation	176 days?	Fri 4/27/12	Fri 12/28/12
13	**Year 3**	**389 days?**	**Wed 1/2/13**	**Mon 6/30/14**
14	Test loop assembly	108 days?	Wed 1/2/13	Fri 5/31/13
15	Wiring and plumbing	65 days?	Mon 3/4/13	Fri 5/31/13
16	Commissioning	90 days	Mon 6/3/13	Fri 10/4/13
17	Performance Testing	170 days?	Mon 10/7/13	Fri 5/30/14
18	Reporting	20 days	Tue 6/3/14	Mon 6/30/14

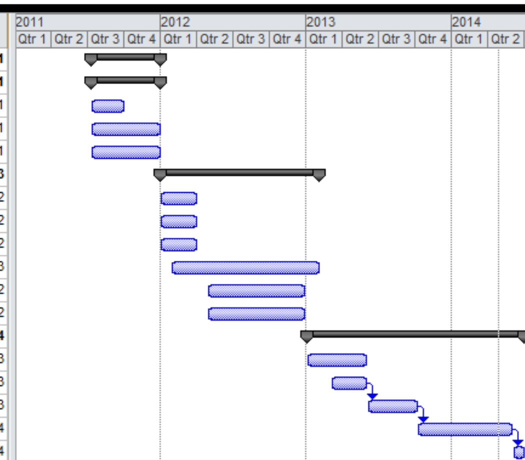


Figure 6-1. Project Schedule

7. REFERENCES

[1] Ramezan, et al., “Carbon Dioxide Capture from Existing Coal-Fired Power Plants,” DOE/NETL-401-110907, National Energy Technology Laboratory, Nov. 2007.

[2] Fan, Z., Fout, T., Seltzer, A. H.: An Optimized Oxygen-Fired Pulverized Coal Power Plant for CO_2 Capture. International Pittsburgh Coal Conference, Pittsburgh, PA, Sept. 12-15, 2005.

[3] Gampe, U., Hellfritsch, S.: Modern Coal-Fired Oxyfuel Power Plants with CO_2 Capture-Energetic and Economic Evaluation. ENERDAY Workshop on Energy Economics and Technology. Dresden, 2007.

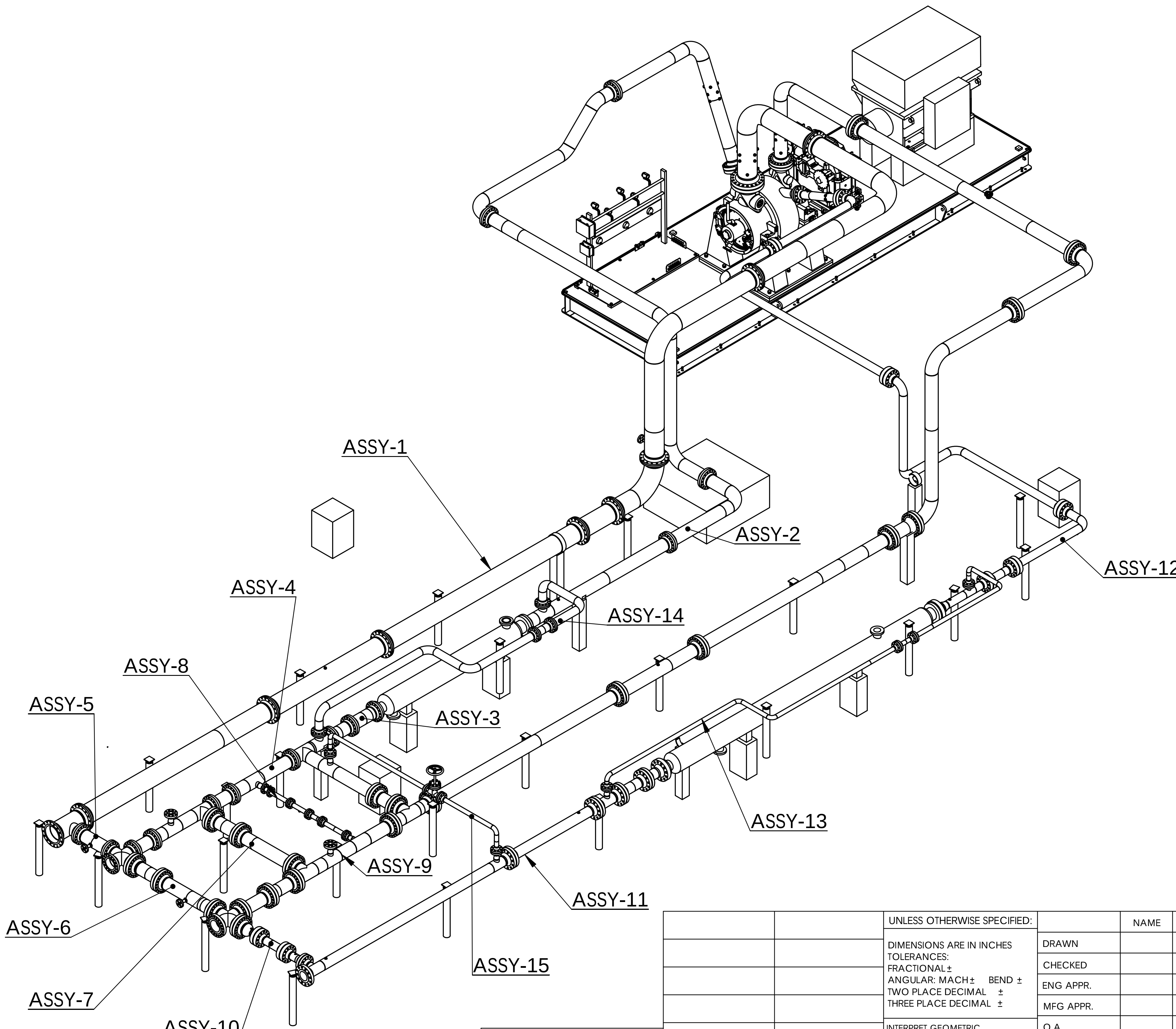
[4] National Energy Technology Laboratory, U.S. Department of Energy. Quality Guidelines for Energy System Studies: CO_2 Impurity Design Parameters (January 2012): COE/NETL-341/011212.

[5] Huber M.L., Lemmon, E.W., McLinden, M.O. (2010): REFPROP (Reference Fluid Thermodynamic and Transport Properties). NIST Standard Reference Database 23, Version 9.0.

[6] Lee, J., Keener, T.C., Yang, Y.J.,: Potential Flue Gas Impurities in Carbon Dioxide Streams Separated from Coal-Fired Power Plants. Journal of the Air & Waste Management Association, 59:6, 725-732, 2009.

[7] Breshears, M.J.,: Analysis of a Natural Gas Combined Cycle Power Plant Modeled for Carbon Capture with Variance of Oxy-Combustion Characteristics. Department of Mechanical Engineering, The University of Alabama, 2011.

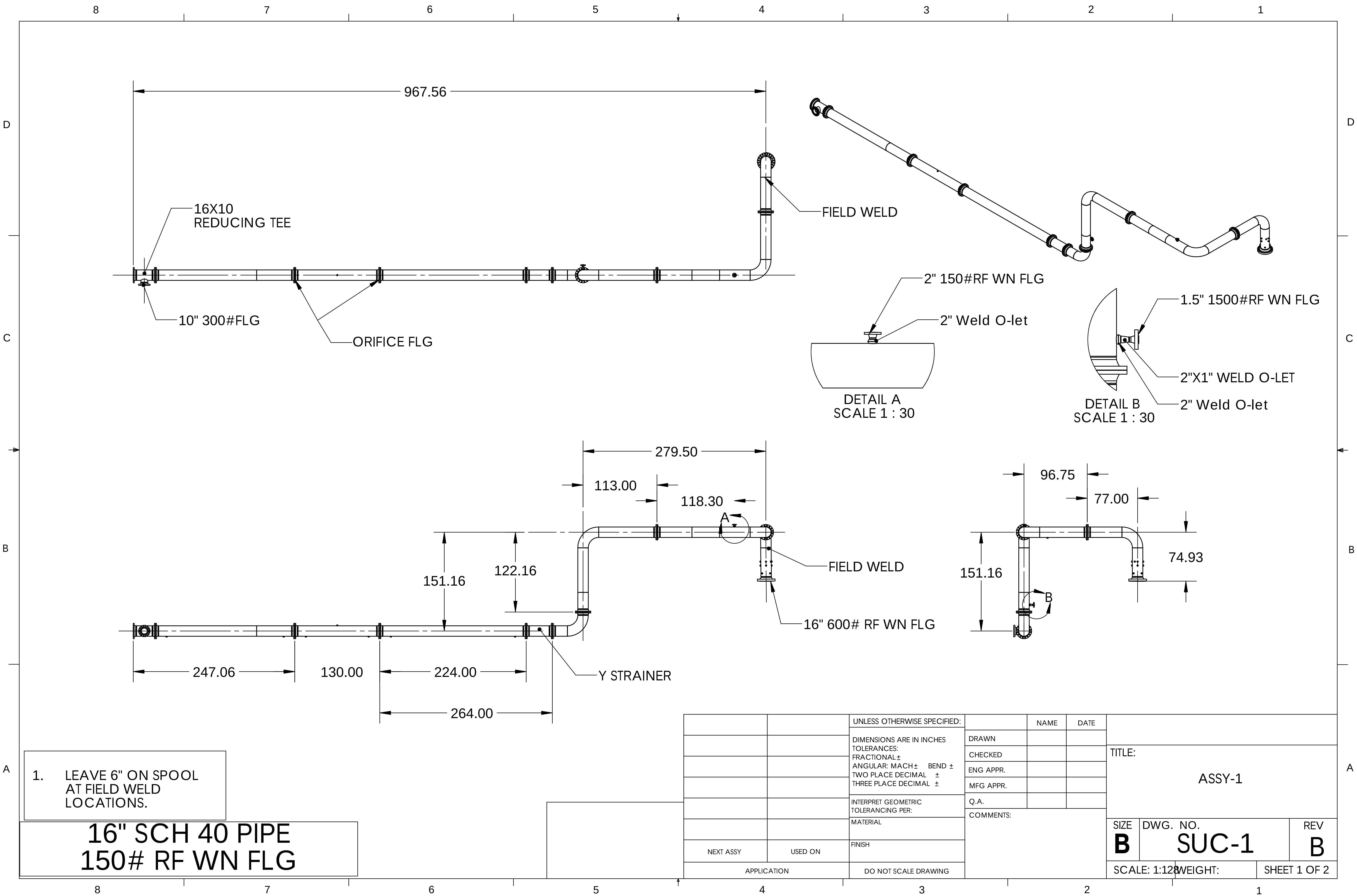
8. APPENDIX A: PIPE DRAWINGS AND RESTRAINT LOCATIONS

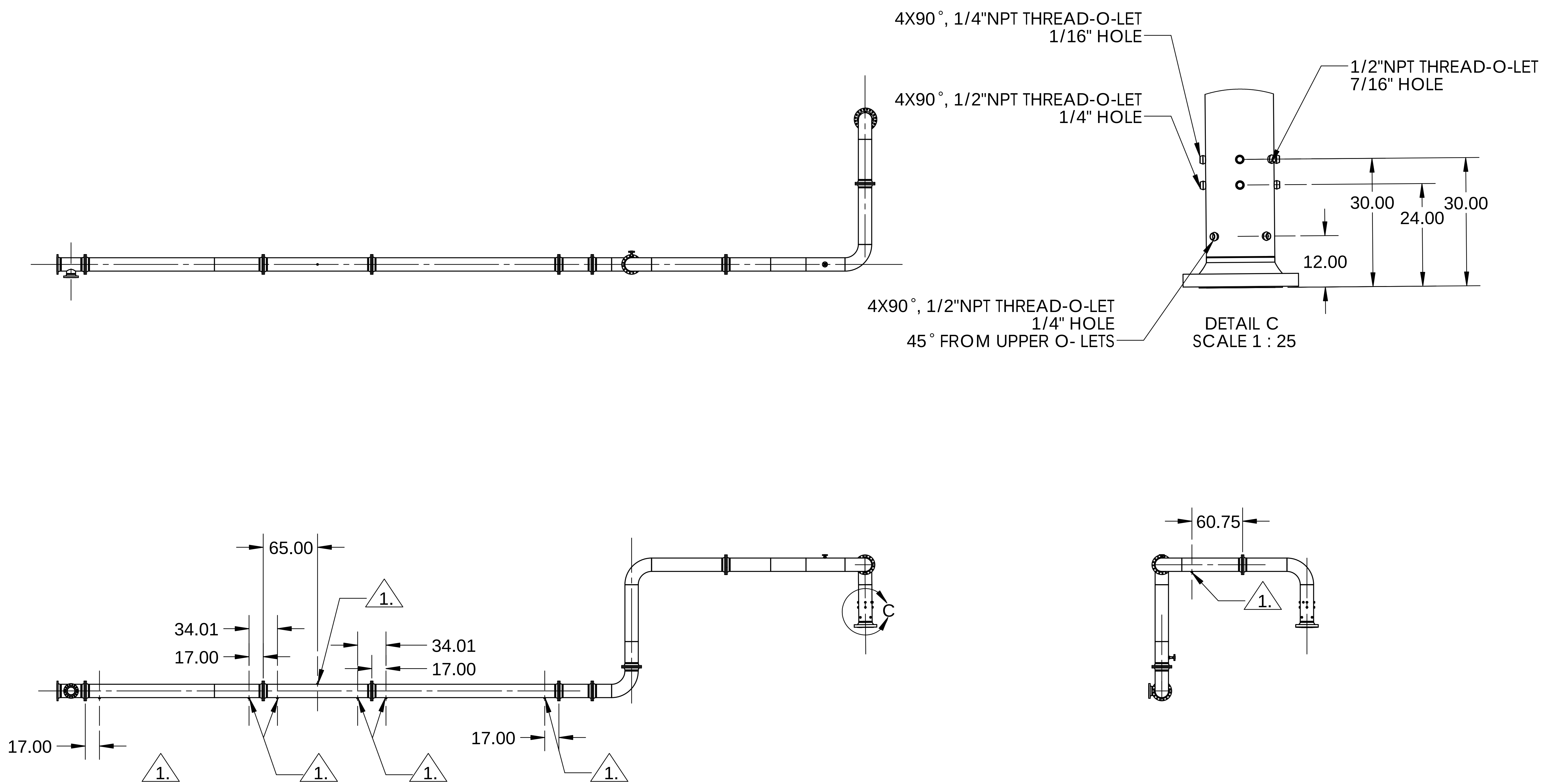


		UNLESS OTHERWISE SPECIFIED:		NAME	DATE
		DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL± ANGULAR: MACH± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±	DRAWN		
			CHECKED		
			ENG APPR.		
			MFG APPR.		
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
		MATERIAL	COMMENTS:		
NEXT ASSY	USED ON	FINISH			
APPLICATION		DO NOT SCALE DRAWING			

TITLE: ASSEMBLY LIST

SIZE	DWG. NO.	REV
B		
SCALE: 1:500	WEIGHT:	SHEET 1 OF 1


967.56
16X10 REDUCING TEE
10" 300#FLG
ORIFICE FLG
FIELD WELD
2" 150#RF WN FLG
2" Weld O-let
DETAIL A SCALE 1 : 30
1.5" 1500#RF WN FLG
2"X1" WELD O-LET
2" Weld O-let
DETAIL B SCALE 1 : 30
279.50
113.00
118.30
A
151.16
122.16
FIELD WELD
16" 600# RF WN FLG
Y STRAINER
247.06
130.00
224.00
264.00
96.75
77.00
74.93
151.16
B
1. LEAVE 6" ON SPOOL AT FIELD WELD LOCATIONS.
16" SCH 40 PIPE
150# RF WN FLG
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
NEXT ASSY
USED ON
APPLICATION
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
ASSY-1
SIZE B
DWG. NO. SUC-1
REV B
SCALE: 1:128
WEIGHT:
SHEET 1 OF 2



1. 3/4" NPT THREAD-O-LET

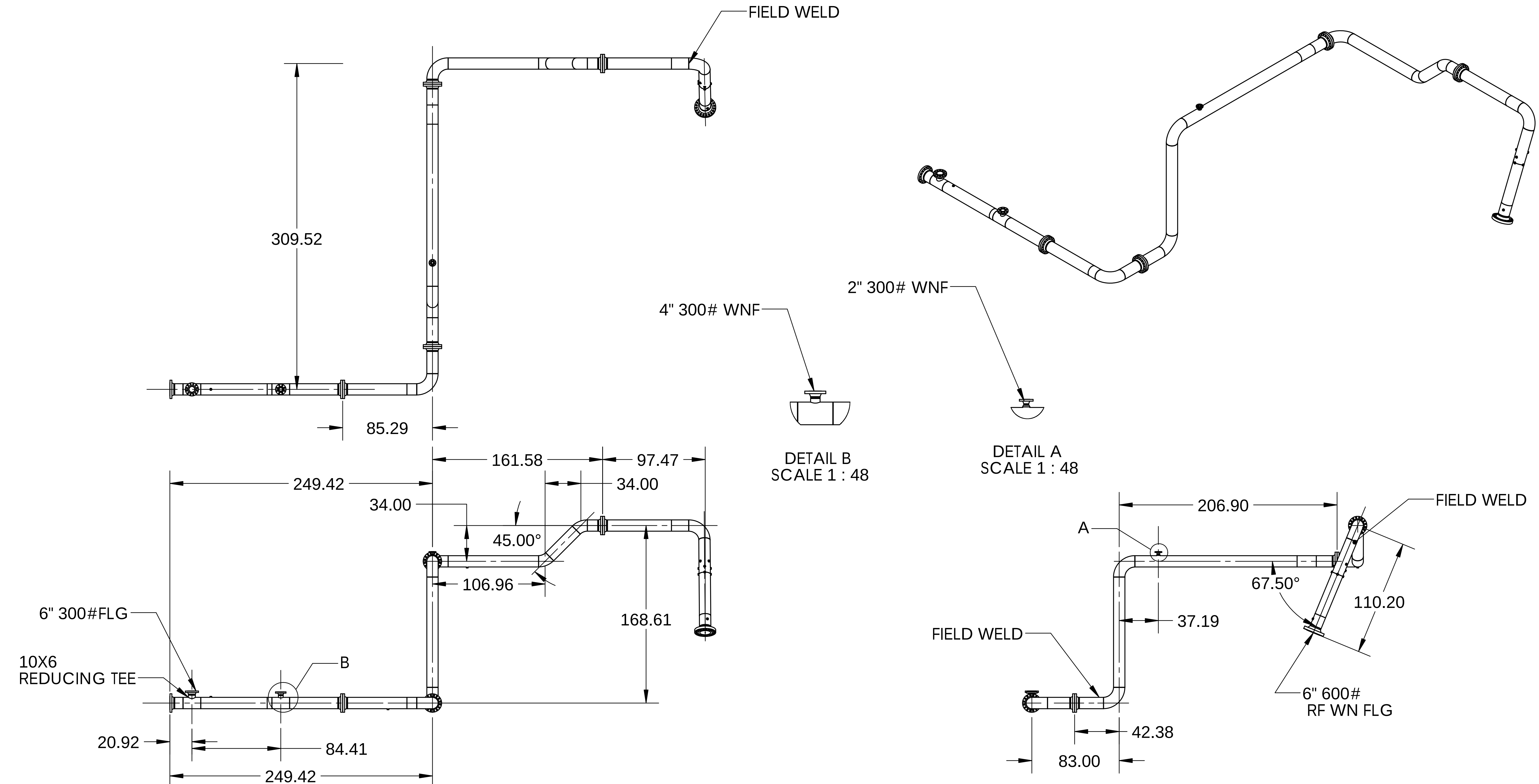
16" SCH 40 PIPE
150# RF WN FLG

UNLESS OTHERWISE SPECIFIED:	
DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL± ANGULAR: MACH± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±	
INTERPRET GEOMETRIC TOLERANCING PER:	
MATERIAL	
FINISH	
NEXT ASSY	USED ON
APPLICATION	DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		
COMMENTS:		

TITLE: ASSY-1 O-LET

SIZE	DWG. NO.	REV
B	SUC-1	B
SCALE: 1:128	WEIGHT:	SHEET 2 OF 2

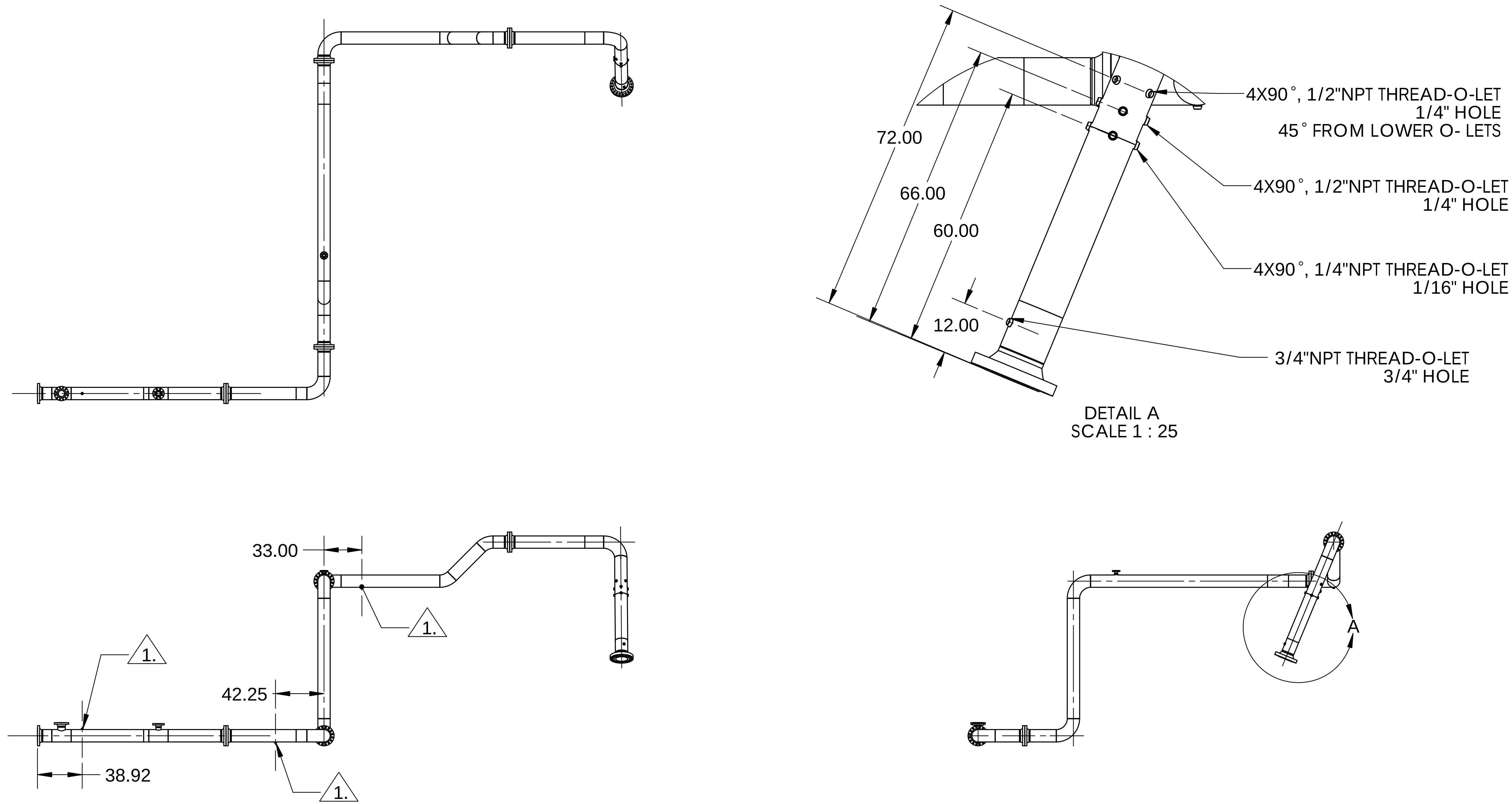


1. LEAVE 6" ON SPOOL AT FIELD WELD LOCATIONS.

10" SCH 80 PIPE
300# RF WN FLG

UNLESS OTHERWISE SPECIFIED:		NAME	DATE	TITLE:	ASSY-2
DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL± ANGULAR: MACH± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±	DRAWN				
	CHECKED				
	ENG APPR.				
	MFG APPR.				
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.				
MATERIAL	COMMENTS:			SIZE B	DWG. NO. Dis_1 · REV B
FINISH					
DO NOT SCALE DRAWING				SCALE: 1:96 · WEIGHT:	SHEET 1 OF 2

NEXT ASSY	USED ON
APPLICATION	

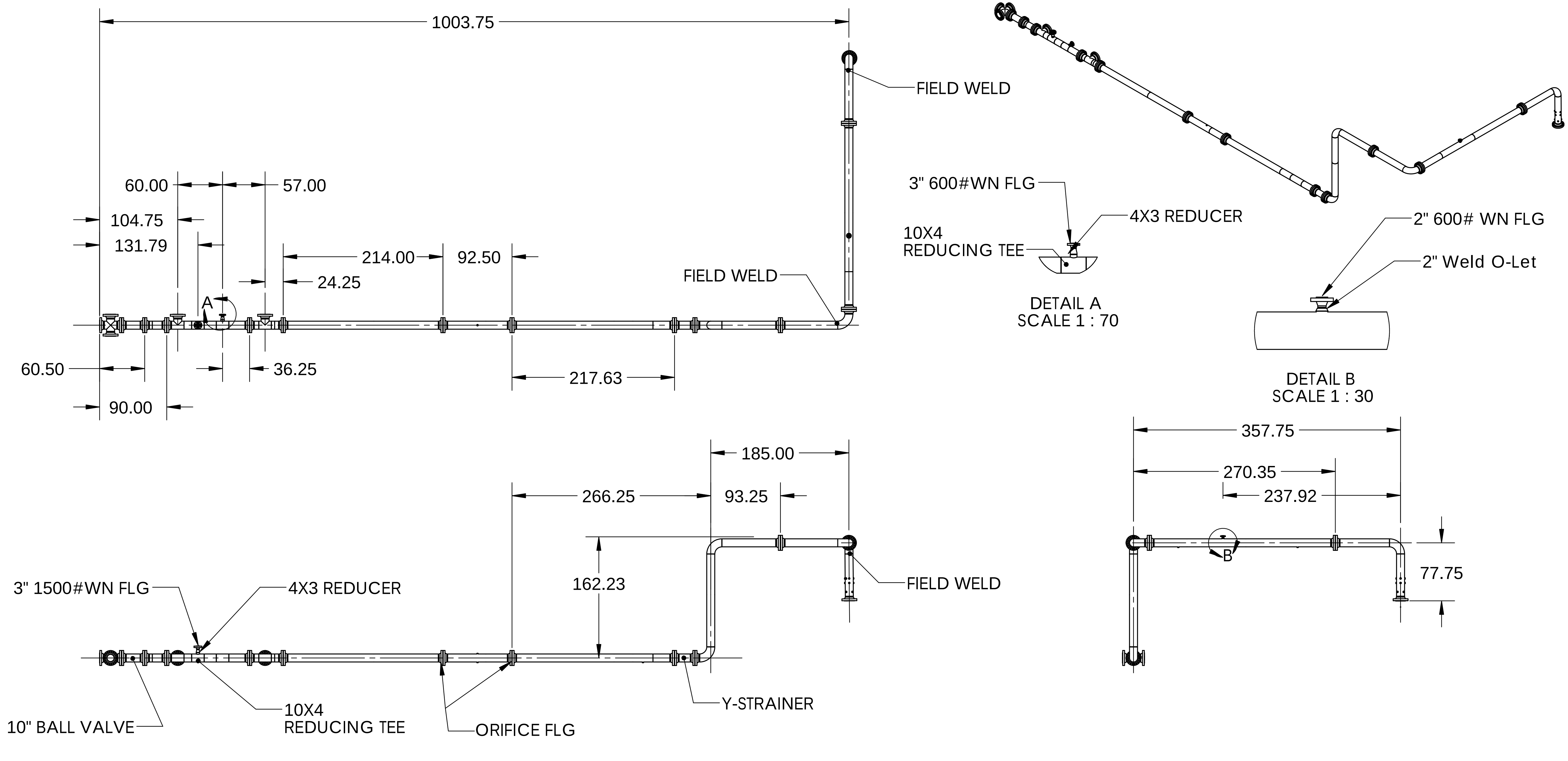


1. 3/4" NPT THREAD-O-LET

10" SCH 80 PIPE
300# RF WN FLG

UNLESS OTHERWISE SPECIFIED:		NAME	DATE	
DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±	DRAWN			TITLE: ASSY-2 O-LETS
	CHECKED			
	ENG APPR.			
	MFG APPR.			
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
MATERIAL	COMMENTS:			SIZE B / DWG. NO. Dis_1 / REV B
FINISH				
DO NOT SCALE DRAWING				SCALE: 1:96 / WEIGHT: / SHEET 2 OF 2

NEXT ASSY	USED ON
APPLICATION	

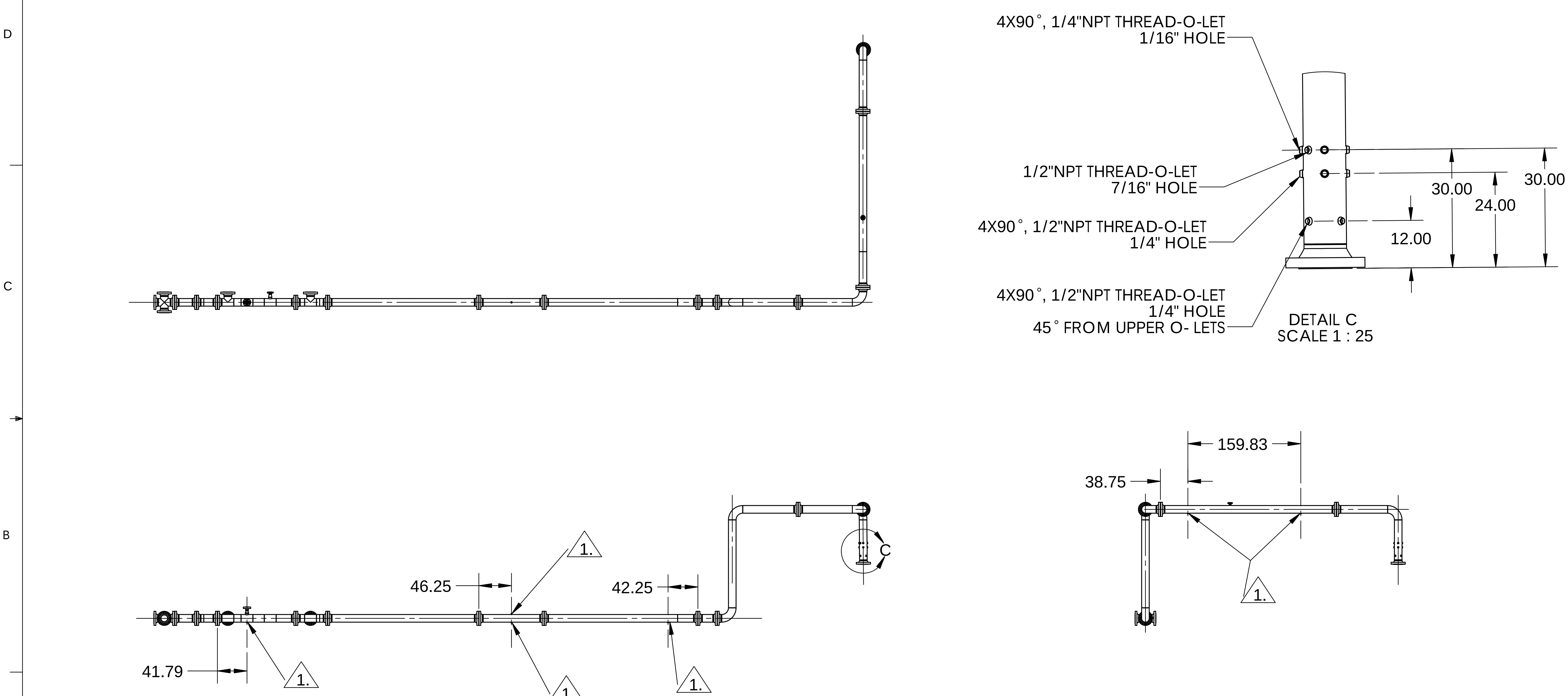


1. LEAVE 6" ON SPOOL AT FIELD WELD LOCATIONS.

10" SCH 80 PIPE
600# RF WN FLG

UNLESS OTHERWISE SPECIFIED:		NAME	DATE		
DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL± ANGULAR: MACH± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±	DRAWN			TITLE:	
	CHECKED			ASSY-9	
	ENG APPR.				
	MFG APPR.				
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.				
MATERIAL	COMMENTS:			SIZE B	DWG. NO. SUC-2	REV B
FINISH					
DO NOT SCALE DRAWING				SCALE: 1:192	WEIGHT:	SHEET 1 OF 2

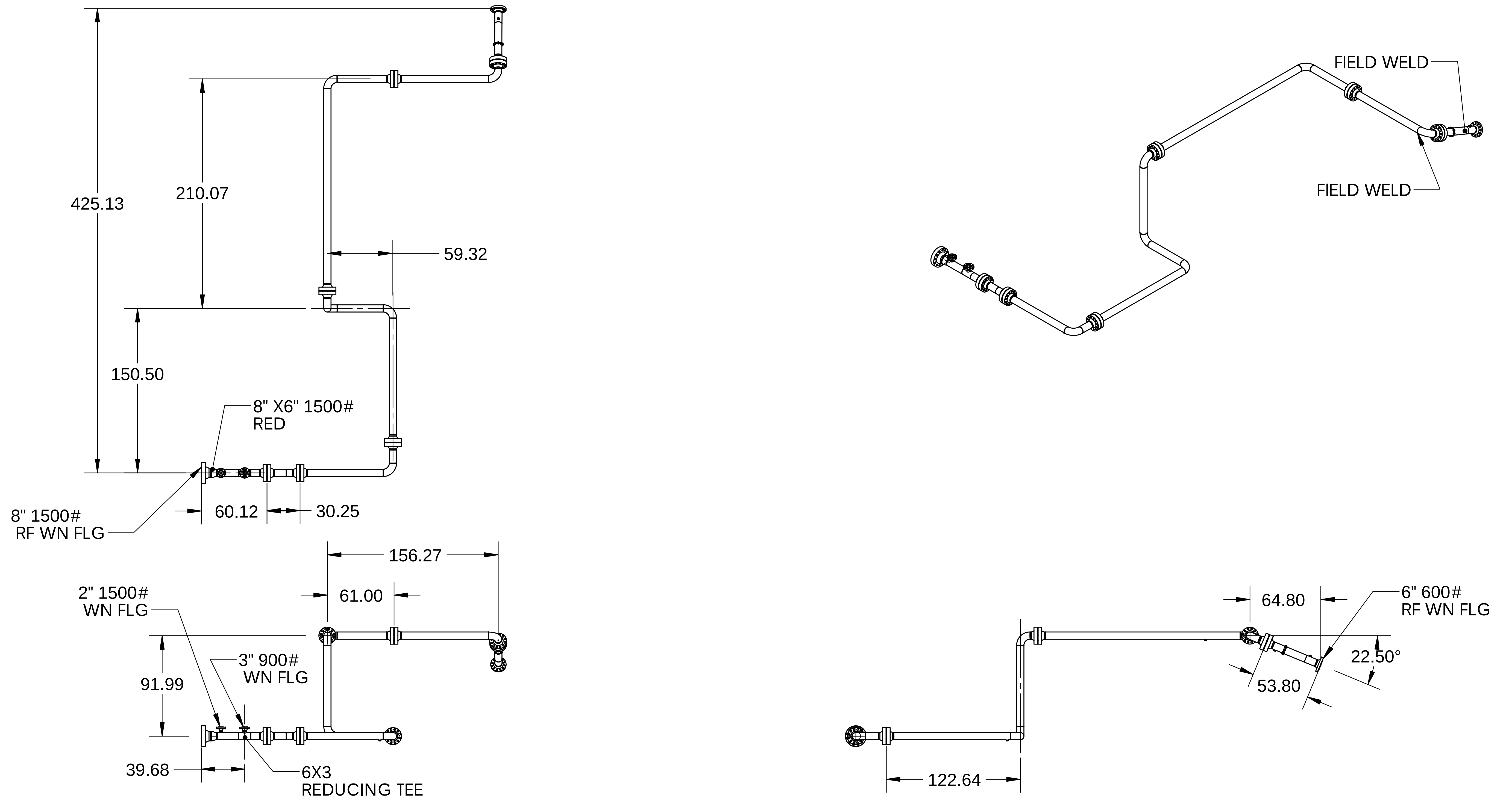
NEXT ASSY	USED ON
APPLICATION	



1. 3/4" NPT THREAD-O-LET

10" SCH 80 PIPE
600# RF WN FLG

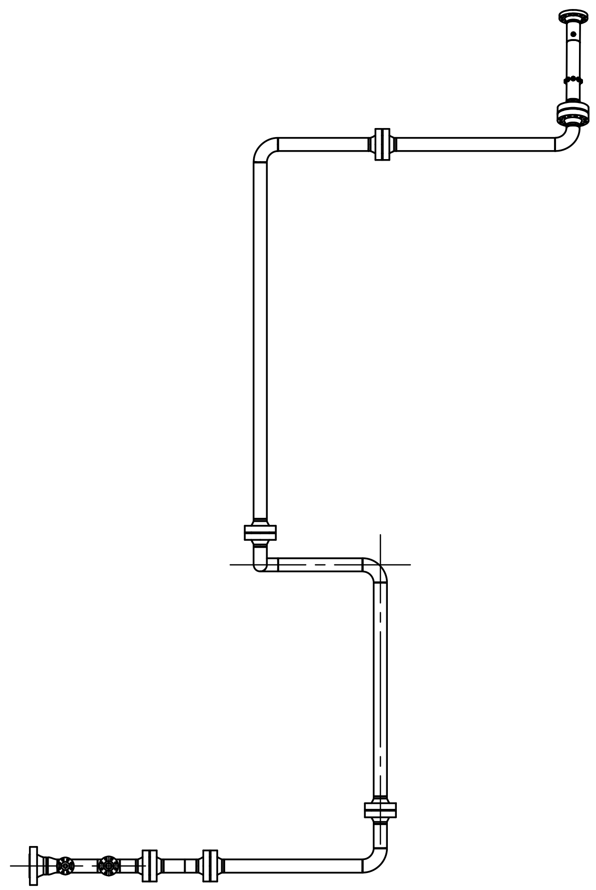
UNLESS OTHERWISE SPECIFIED:		NAME	DATE	TITLE:	
DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL± ANGULAR: MACH± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±	DRAWN			ASSY-9 O-LET	
	CHECKED				
	ENG APPR.				
	MFG APPR.				
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.				
MATERIAL	COMMENTS:			SIZE B	DWG. NO. SUC-2 — REV B
FINISH					
NEXT ASSY / USED ON — APPLICATION	DO NOT SCALE DRAWING			SCALE: 1:192	WEIGHT: — SHEET 2 OF 2

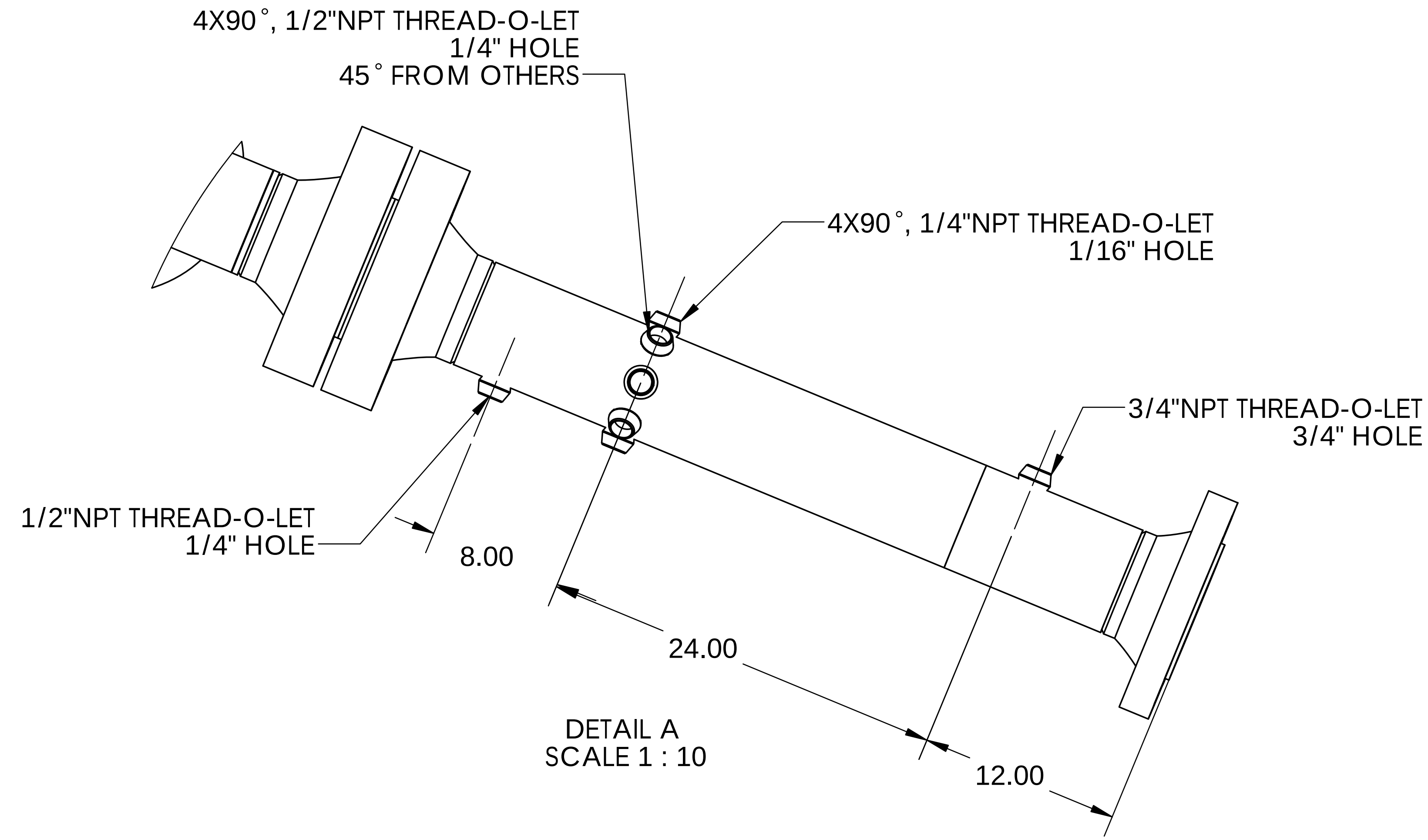


1. LEAVE 6" ON SPOOL AT FIELD WELD LOCATIONS.

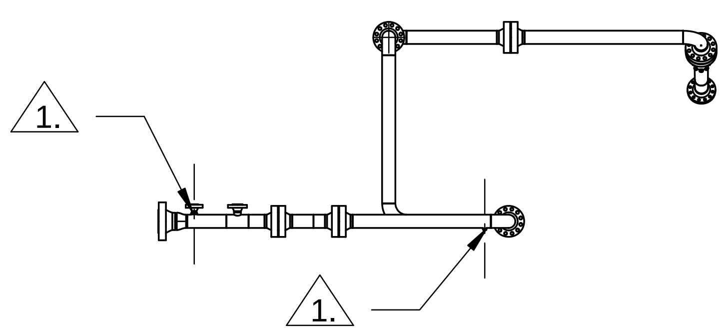
6" SCH 160 PIPE
1500# RF WN FLG

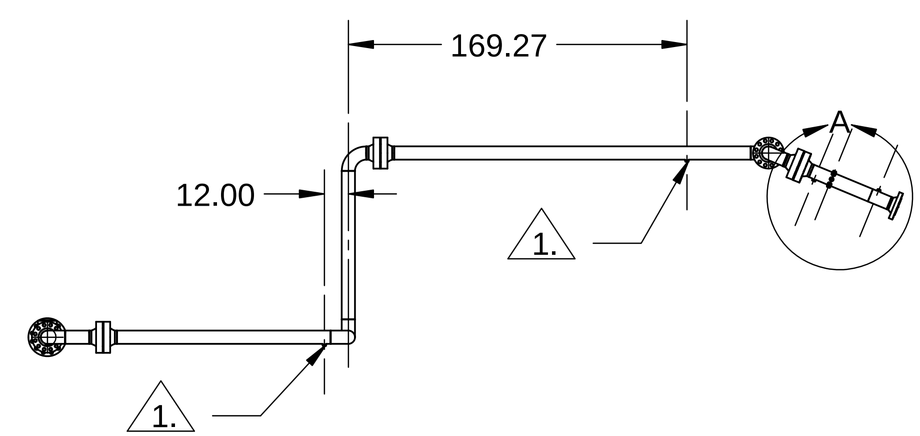
UNLESS OTHERWISE SPECIFIED:		NAME	DATE		
DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±	DRAWN			TITLE:	
	CHECKED			ASSY-12	
	ENG APPR.				
	MFG APPR.				
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.				
MATERIAL	COMMENTS:			SIZE B	DWG. NO. DIS_2	REV
FINISH					
NEXT ASSY / USED ON / APPLICATION	DO NOT SCALE DRAWING			SCALE: 1:96	WEIGHT:	SHEET 1 OF 2





DETAIL A
SCALE 1 : 10



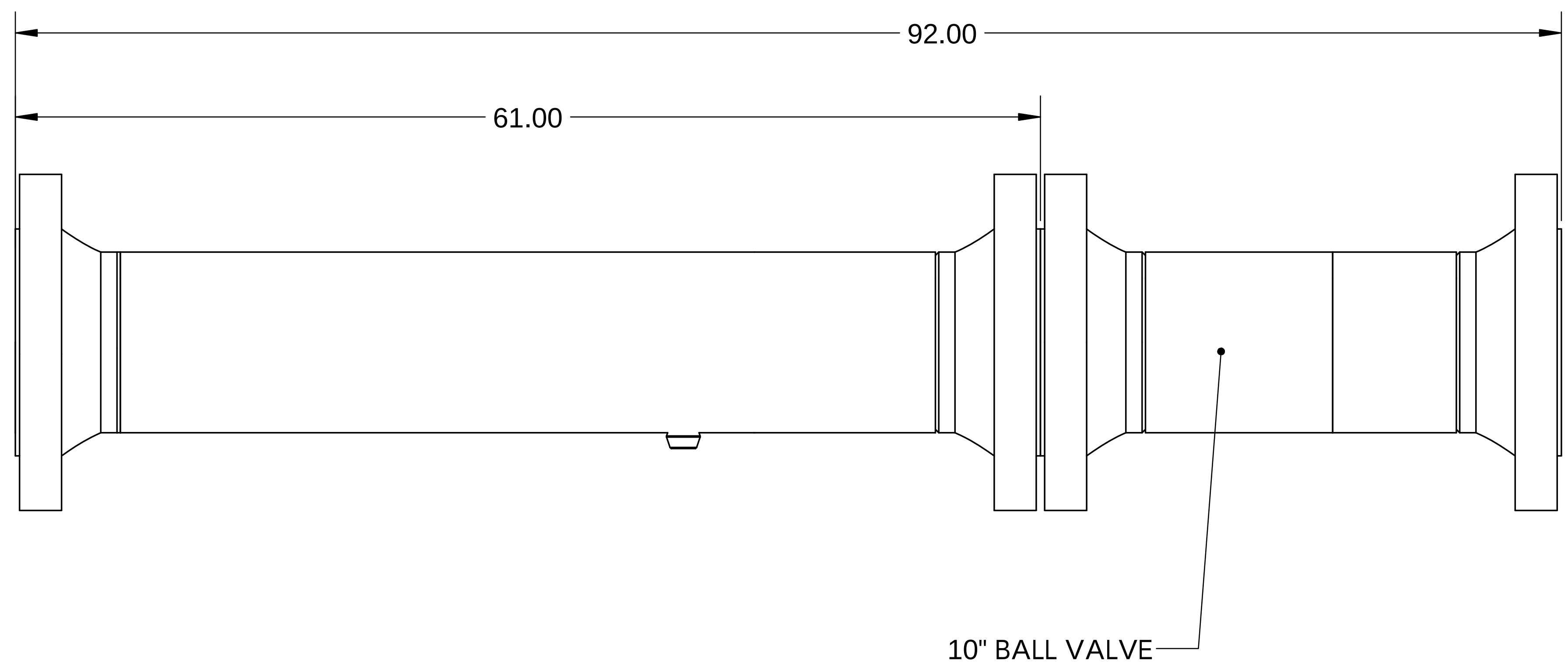


1. 3/4" NPT THREAD-O-LET

6" SCH 160 PIPE
1500# RF WN FLG

UNLESS OTHERWISE SPECIFIED:		NAME	DATE	
DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±	DRAWN			TITLE: ASSY-12 O-LET
	CHECKED			
	ENG APPR.			
	MFG APPR.			
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
MATERIAL	COMMENTS:			SIZE B · DWG. NO. DIS_2 · REV B
FINISH				
DO NOT SCALE DRAWING				SCALE: 1:96 · WEIGHT: · SHEET 2 OF 2

NEXT ASSY	USED ON
APPLICATION	



10" SCH 80 PIPE
600# RF WN FLG

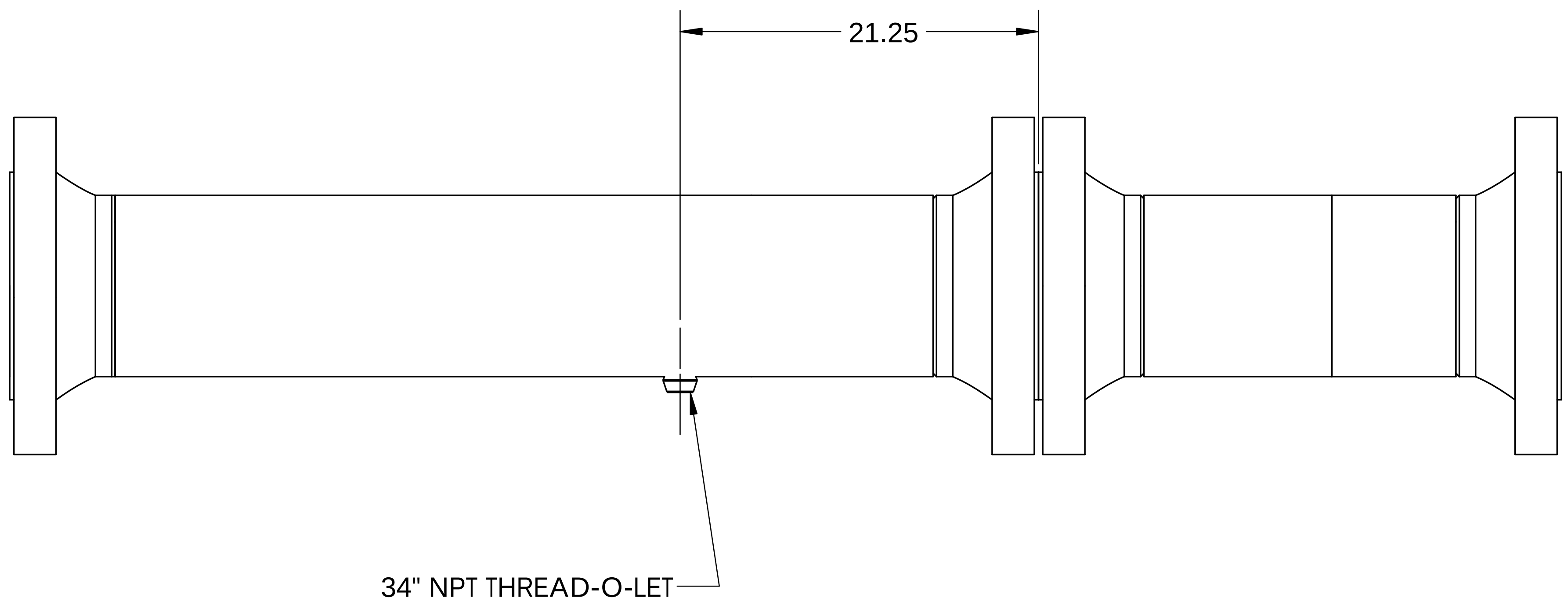
		UNLESS OTHERWISE SPECIFIED:		NAME	DATE
		DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL± ANGULAR: MACH± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±	DRAWN		
			CHECKED		
			ENG APPR.		
			MFG APPR.		
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
		MATERIAL	COMMENTS:		
NEXT ASSY	USED ON	FINISH			
APPLICATION		DO NOT SCALE DRAWING			

TITLE:

ASSEM-7

SIZE: B | DWG. NO.: 10IN BYPASS | REV

SCALE: 1:24 | WEIGHT: | SHEET 1 OF 2

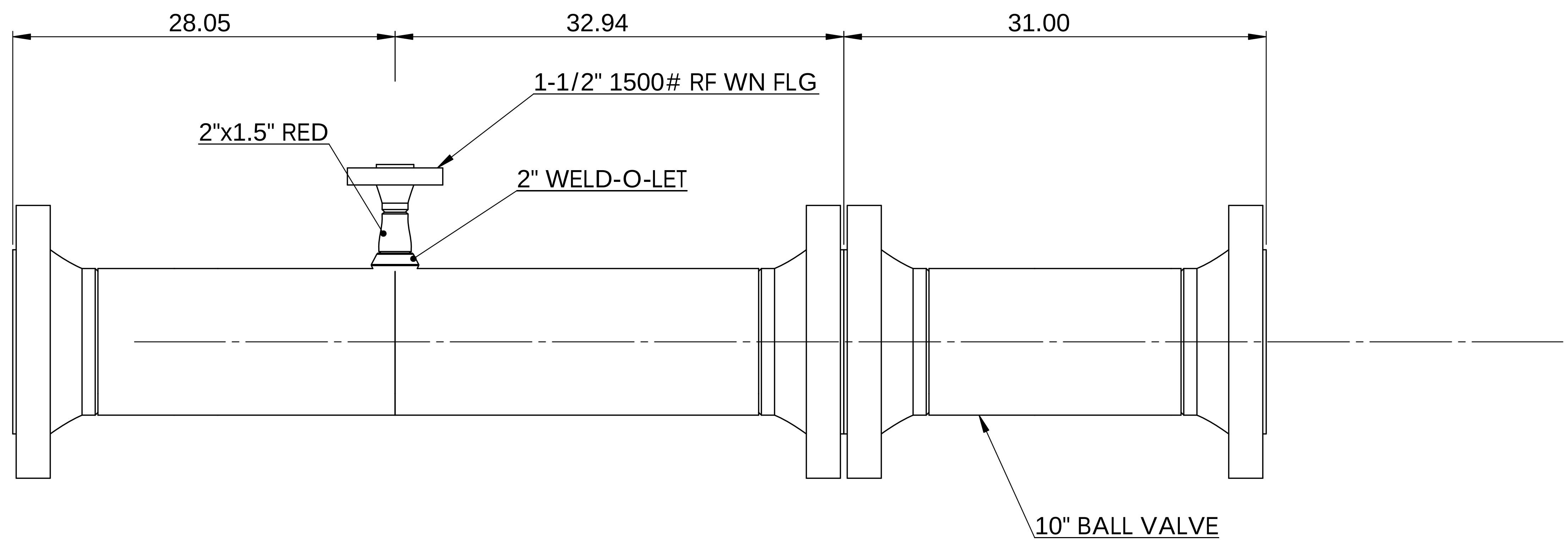


10" SCH 80 PIPE
600# RF WN FLG

		UNLESS OTHERWISE SPECIFIED:		NAME	DATE
		DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±	DRAWN		
			CHECKED		
			ENG APPR.		
			MFG APPR.		
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
		MATERIAL	COMMENTS:		
NEXT ASSY	USED ON	FINISH			
APPLICATION		DO NOT SCALE DRAWING			

TITLE: ASSEM-7 O-LET

SIZE	DWG. NO.	REV
B	10IN BYPASS	
SCALE: 1:24	WEIGHT:	SHEET 2 OF 2



10" SCH 80 PIPE
600# RF WN FLG

NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC
TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING

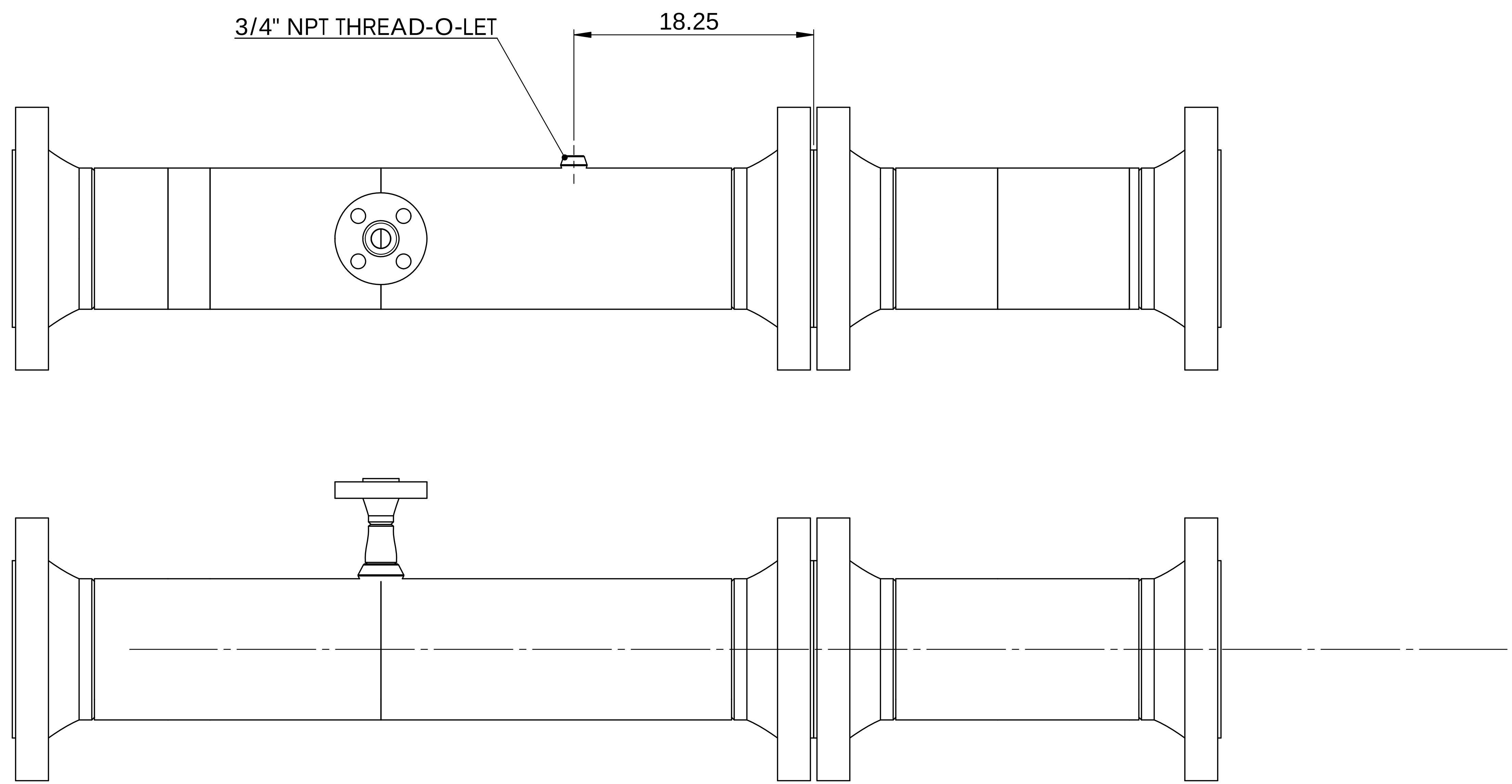
	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

TITLE:
ASSY-6

SIZE	DWG. NO.	REV
B	10IN BYPASS WITH FILL	

SCALE: 1:20 WEIGHT: SHEET 1 OF 2



10" SCH 80 PIPE
600# RF WN FLG

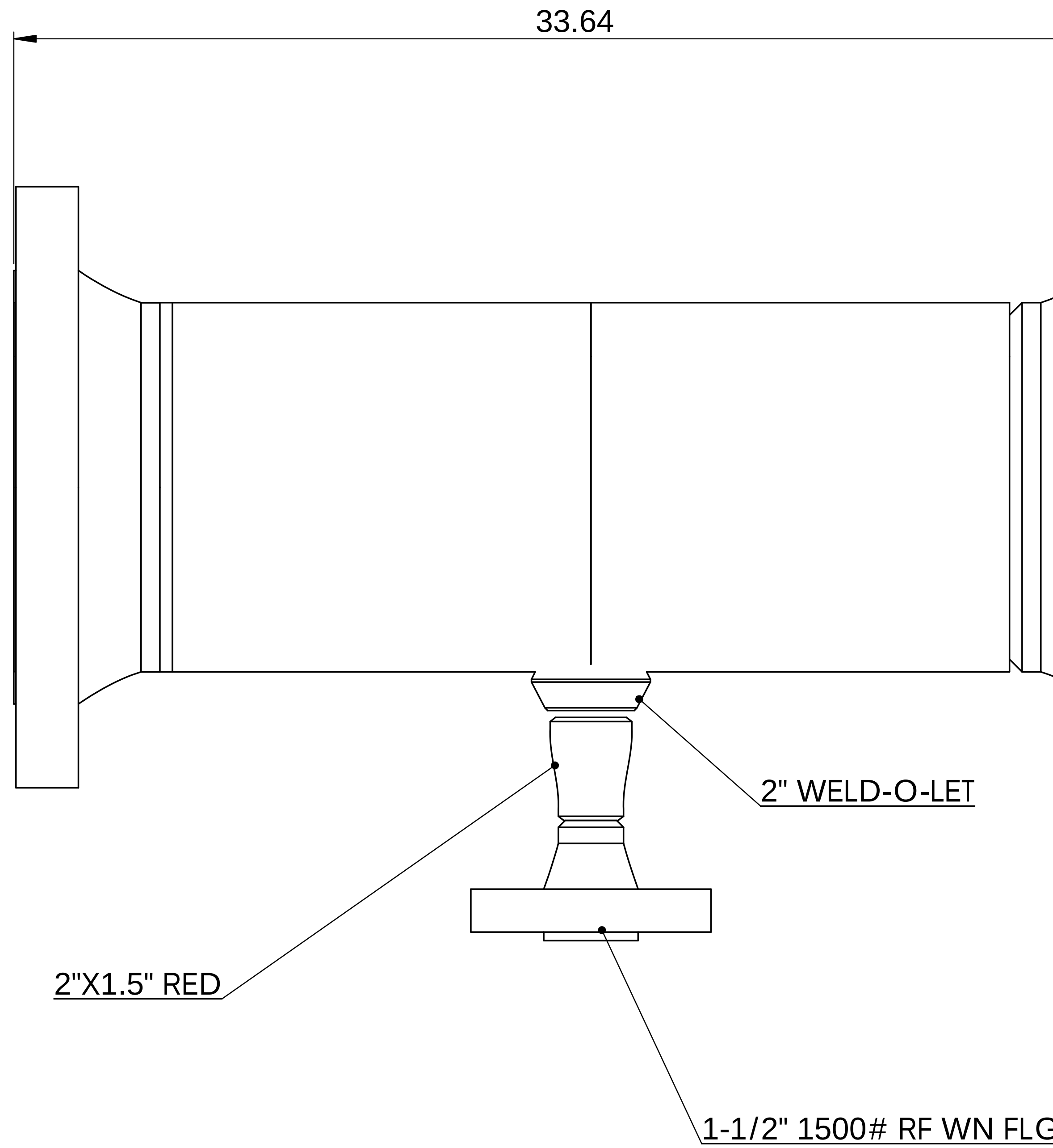
		UNLESS OTHERWISE SPECIFIED:		NAME	DATE
		DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL± ANGULAR: MACH± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±	DRAWN		
			CHECKED		
			ENG APPR.		
			MFG APPR.		
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
		MATERIAL	COMMENTS:		
NEXT ASSY	USED ON	FINISH			
APPLICATION		DO NOT SCALE DRAWING			

TITLE:

ASSY-6
O-LET

SIZE	DWG. NO.	REV
B	10IN BYPASS WITH FILL	

SCALE: 1:20 WEIGHT: SHEET 2 OF 2



10" SCH 80 PIPE
300# RF WN FLG

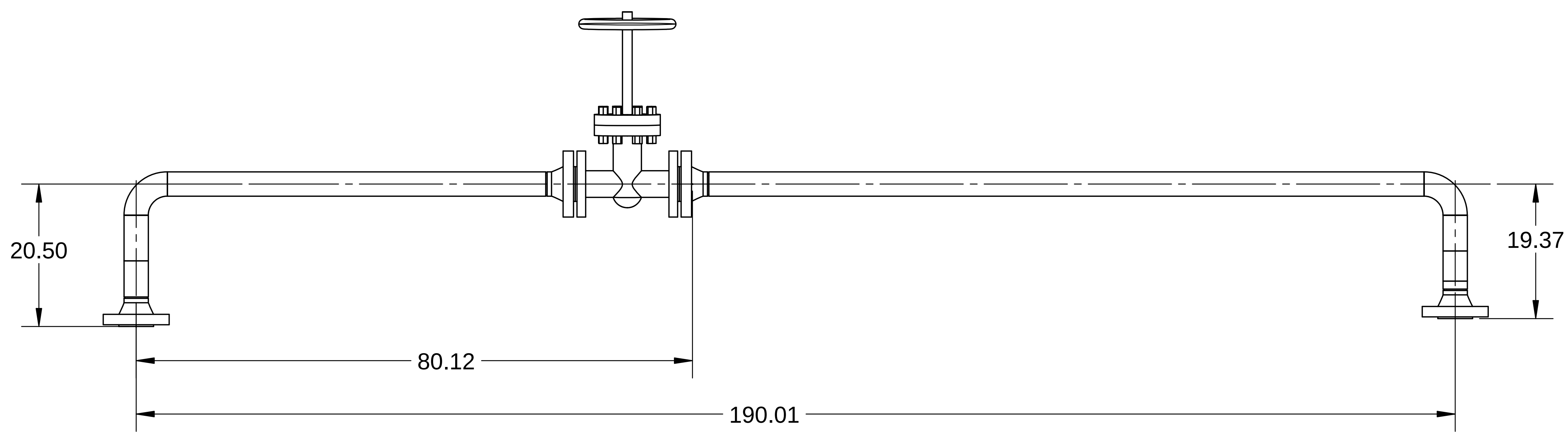
		UNLESS OTHERWISE SPECIFIED:	
		DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL± ANGULAR: MACH± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±	
		INTERPRET GEOMETRIC TOLERANCING PER:	
		MATERIAL	
NEXT ASSY	USED ON	FINISH	
APPLICATION		DO NOT SCALE DRAWING	

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		
COMMENTS:		

TITLE:

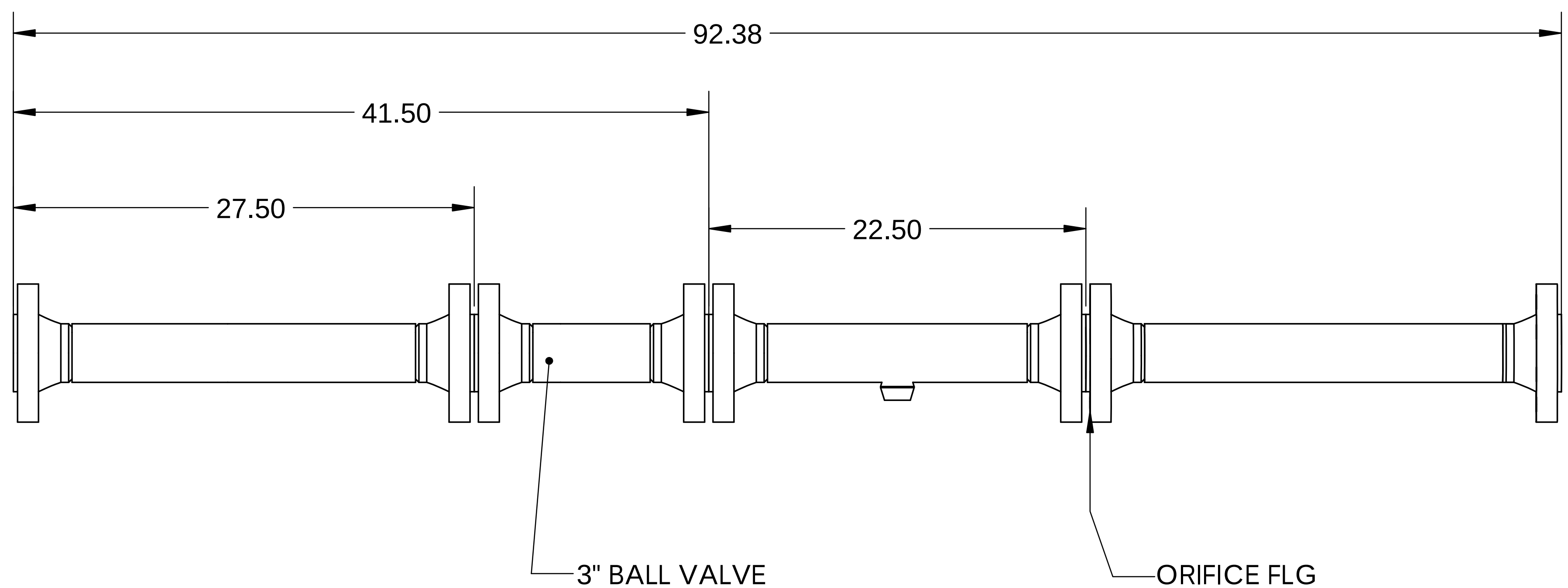
ASSY-5

SIZE	DWG. NO.	REV
B	10"SUC-DIS WITH FILL	
SCALE: 1:10	WEIGHT:	SHEET 1 OF 1



3" SCH 80 PIPE
900# RF WN FLG

		UNLESS OTHERWISE SPECIFIED:		NAME	DATE	
		DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL± ANGULAR: MACH± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±	DRAWN			TITLE: ASSY-15
			CHECKED			
			ENG APPR.			
			MFG APPR.			
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
		MATERIAL	COMMENTS:			SIZE B DWG. NO. 3IN BALANCE LINE REV
NEXT ASSY	USED ON	FINISH				
APPLICATION		DO NOT SCALE DRAWING				SCALE: 1:48 WEIGHT: SHEET 1 OF 1

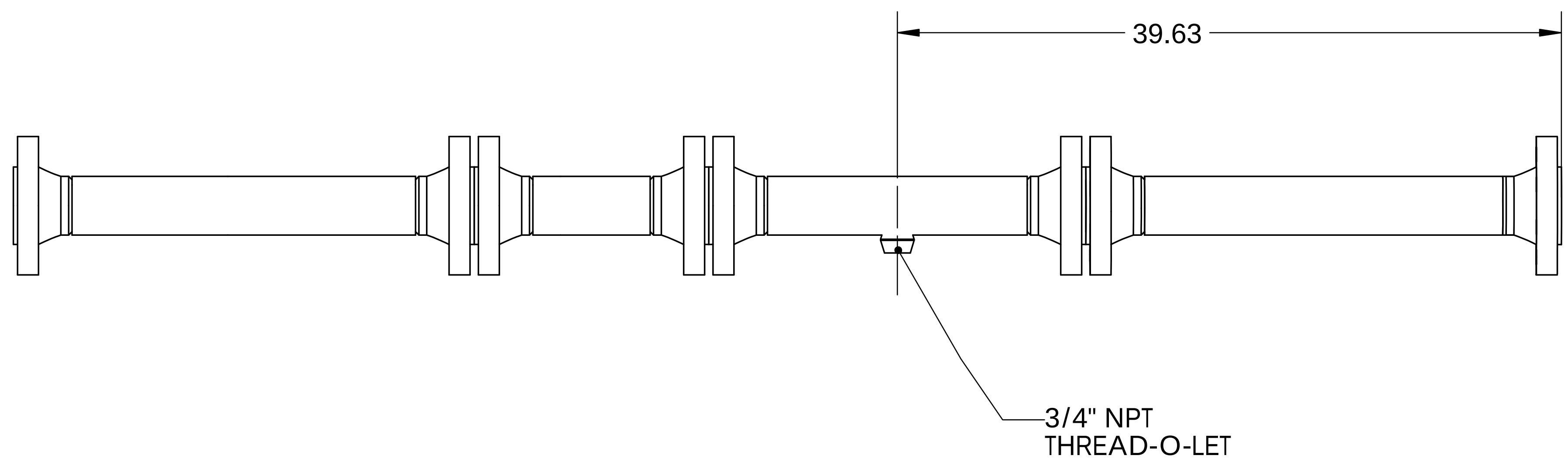


3" SCH 80 PIPE
600# RF WN FLG

		UNLESS OTHERWISE SPECIFIED:		NAME	DATE
		DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL± ANGULAR: MACH± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±	DRAWN		
			CHECKED		
			ENG APPR.		
			MFG APPR.		
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
		MATERIAL	COMMENTS:		
NEXT ASSY	USED ON	FINISH			
APPLICATION		DO NOT SCALE DRAWING			

TITLE: ASSY-8

SIZE	DWG. NO.	REV
B	3IN BY PASS	A
SCALE: 1:24	WEIGHT:	SHEET 1 OF 2



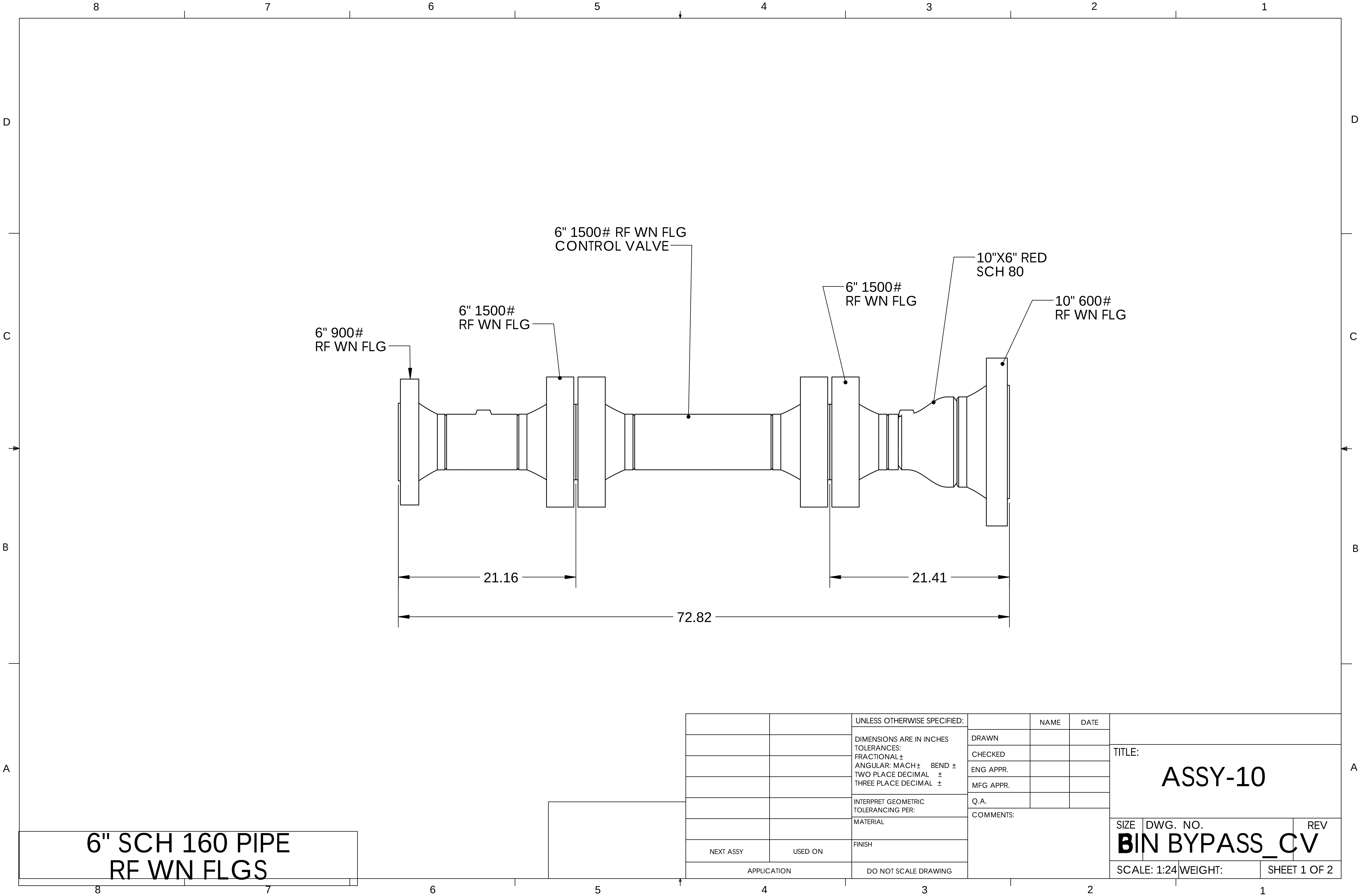
3" SCH 80 PIPE
600# RF WN FLG

		UNLESS OTHERWISE SPECIFIED:		NAME	DATE
		DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±	DRAWN		
			CHECKED		
			ENG APPR.		
			MFG APPR.		
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
		MATERIAL	COMMENTS:		
NEXT ASSY	USED ON	FINISH			
APPLICATION		DO NOT SCALE DRAWING			

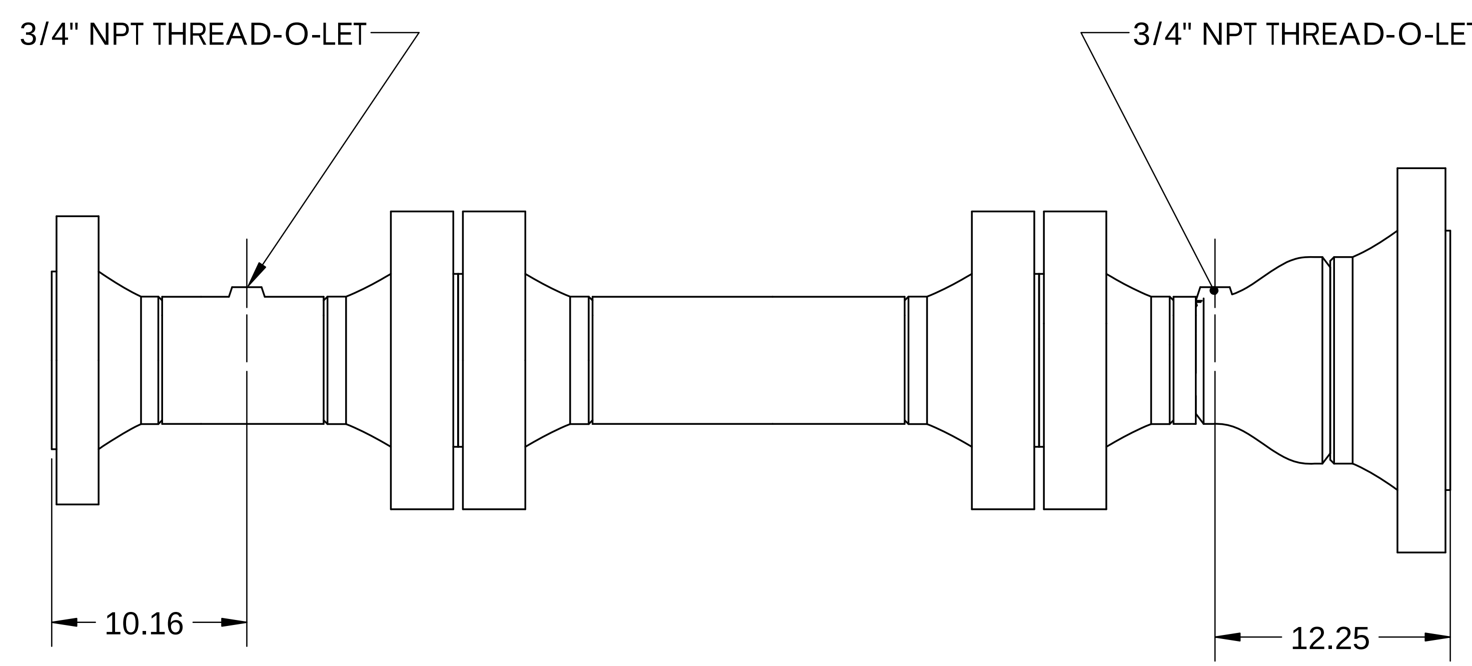
TITLE:

ASSY-8
O-LET

SIZE	DWG. NO.	REV
B	3IN BY PASS	A
SCALE: 1:24	WEIGHT:	SHEET 2 OF 2

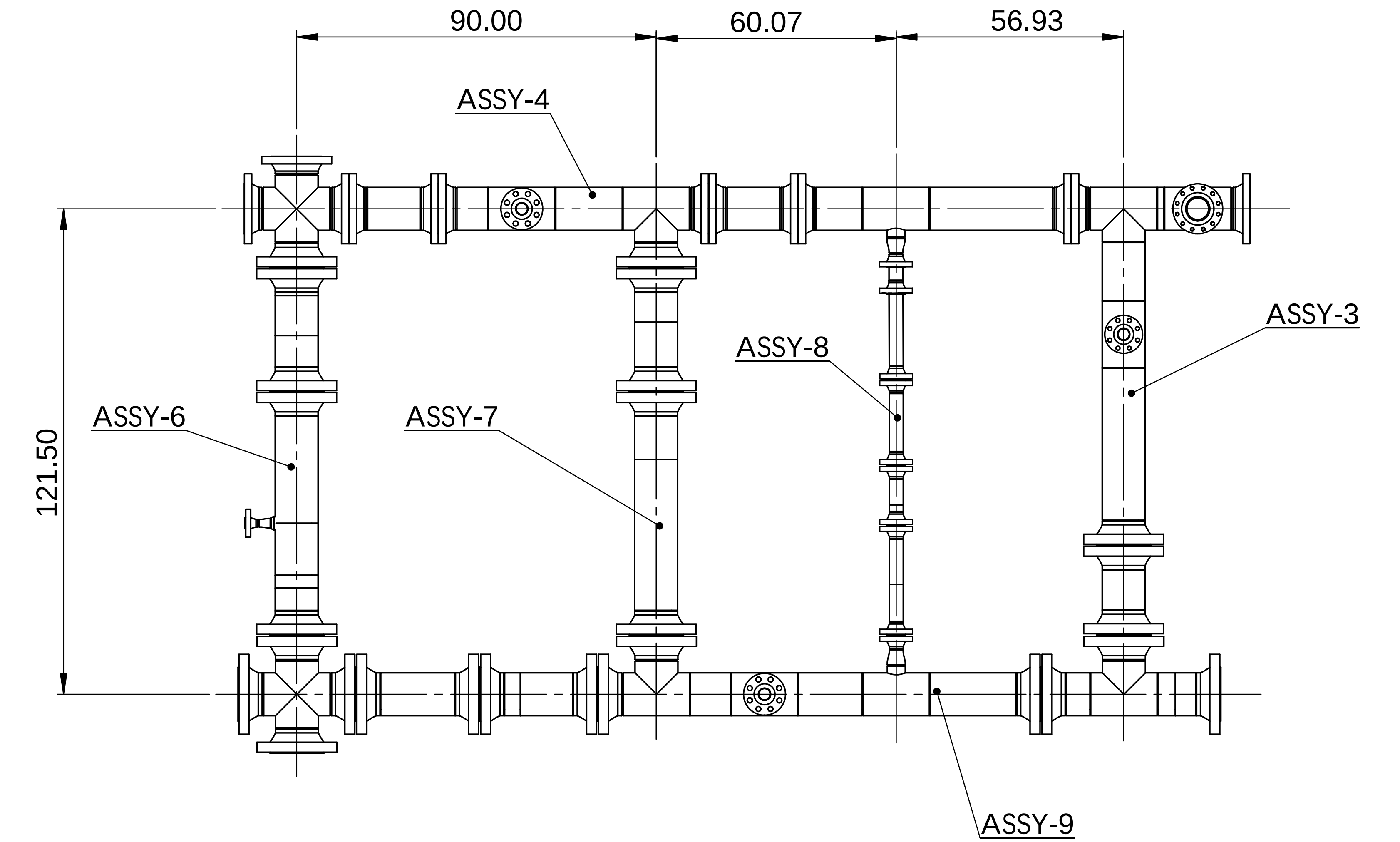


6" 1500# RF WN FLG
CONTROL VALVE
10"X6" RED
SCH 80
6" 1500#
RF WN FLG
10" 600#
RF WN FLG
6" 1500#
RF WN FLG
6" 900#
RF WN FLG
21.16
21.41
72.82
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC
TOLERANCING PER:
MATERIAL
FINISH
NEXT ASSY
USED ON
APPLICATION
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
ASSY-10
SIZE
DWG. NO.
REV
B
IN BYPASS_CV
SCALE: 1:24
WEIGHT:
SHEET 1 OF 2
6" SCH 160 PIPE
RF WN FLGS



		UNLESS OTHERWISE SPECIFIED:		NAME	DATE	
		DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL± ANGULAR: MACH± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±	DRAWN			TITLE:
			CHECKED			ASSY-10 O-LET
			ENG APPR.			
			MFG APPR.			
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
		MATERIAL	COMMENTS:			SIZE B; DWG. NO. IN BYPASS_CV; REV
NEXT ASSY	USED ON	FINISH				
APPLICATION		DO NOT SCALE DRAWING				SCALE: 1:24; WEIGHT:; SHEET 2 OF 2

6" SCH 160 PIPE
RF WN FLGS



BYPASS SECTION
TO BE ASSEMBLED
AT IMC AS ONE
PIECE AND
DELIVED TO SWRI.

NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC
TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

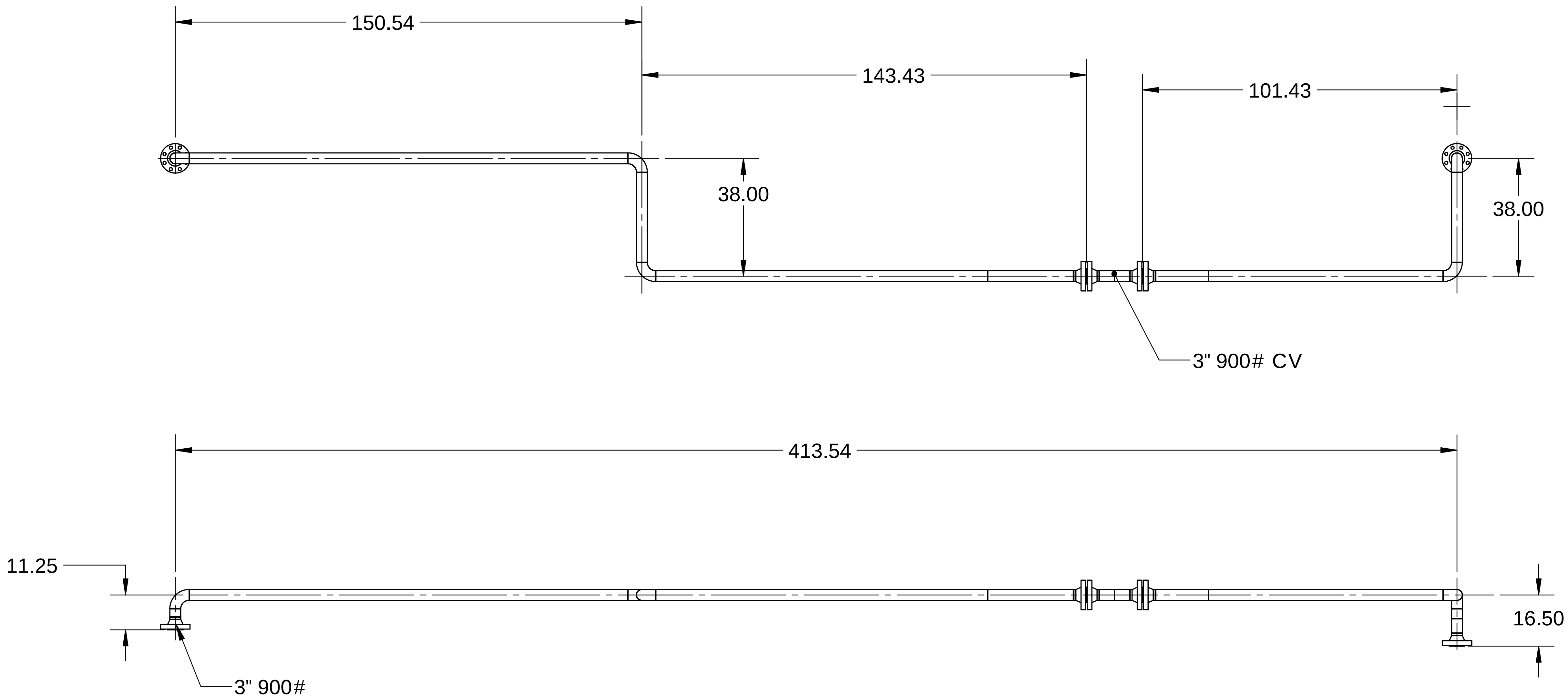
COMMENTS:

TITLE:

BYPASS SECTION

SIZE	DWG. NO.	REV
B	BYPASS SECTION	

SCALE: 1:200 WEIGHT: SHEET 1 OF 1



3" SCH 160 PIPE
900# RF WN FLG

NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

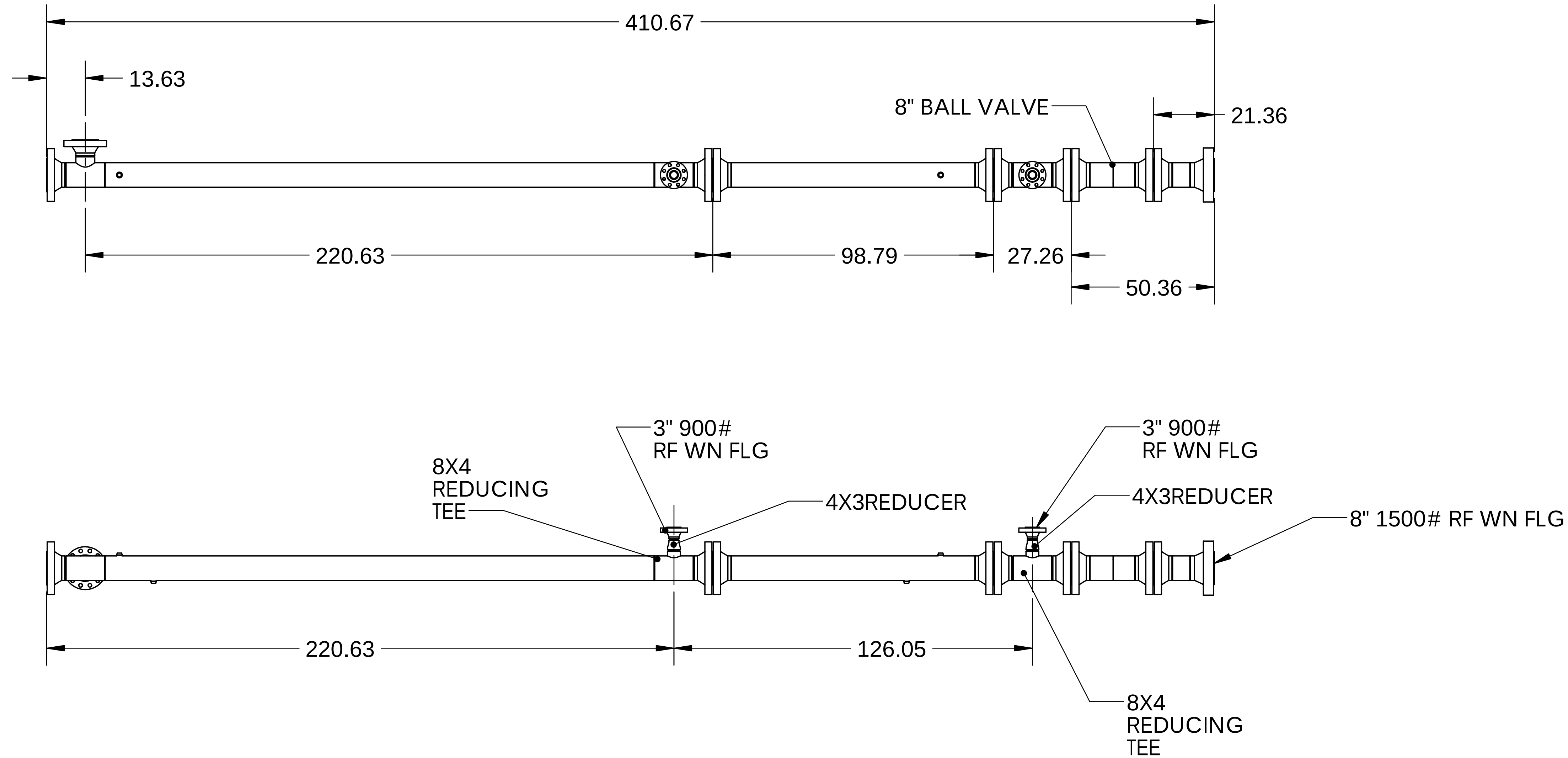
	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

TITLE: ASSY-13

SIZE	DWG. NO.	REV
B	HP-BYPASS	

SCALE: 1:64 WEIGHT: SHEET 1 OF 1



8" SCH 160 PIPE
900# RF WN FLG

NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

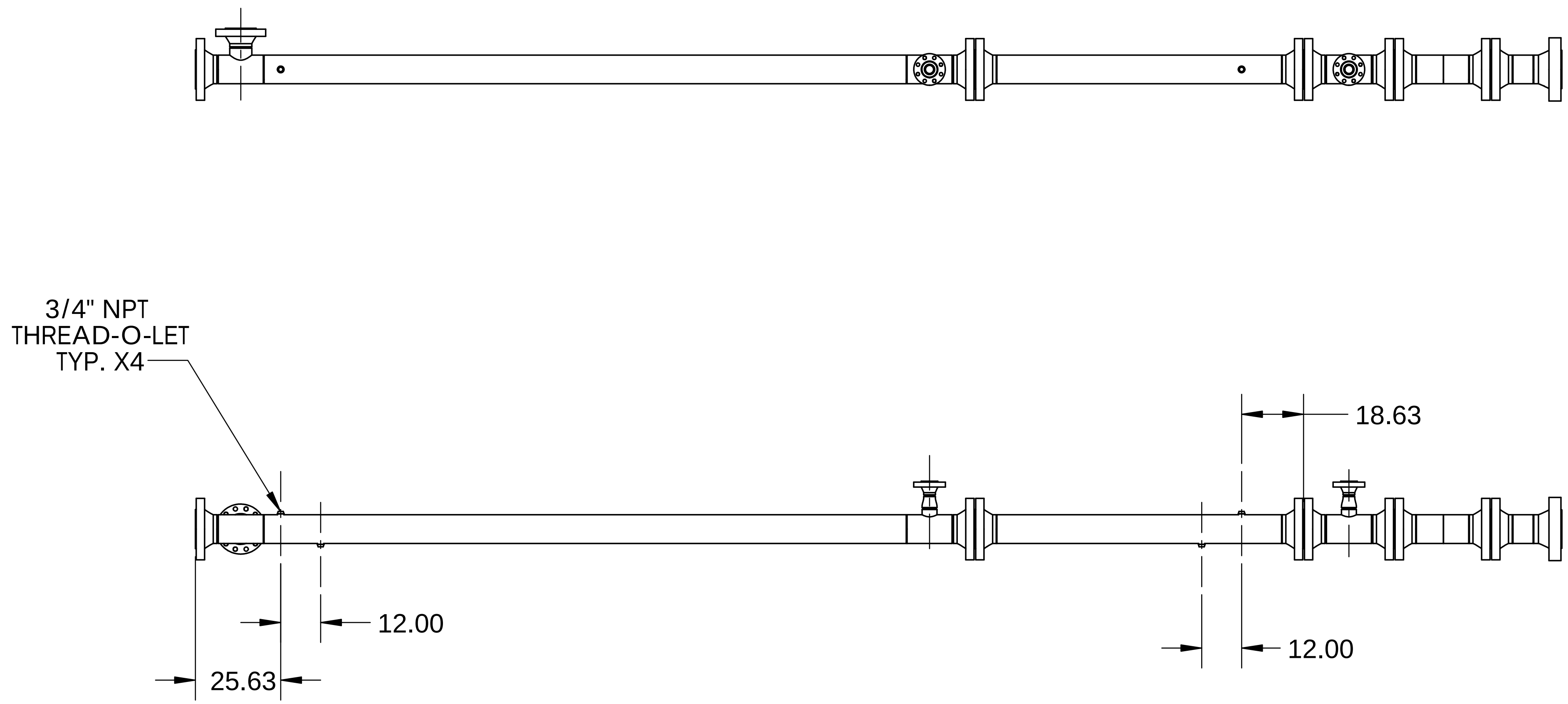
COMMENTS:

TITLE:

ASSY-11

SIZE	DWG. NO.	REV
B	IP-COOLER DIS	

SCALE: 1:48 WEIGHT: SHEET 1 OF 2



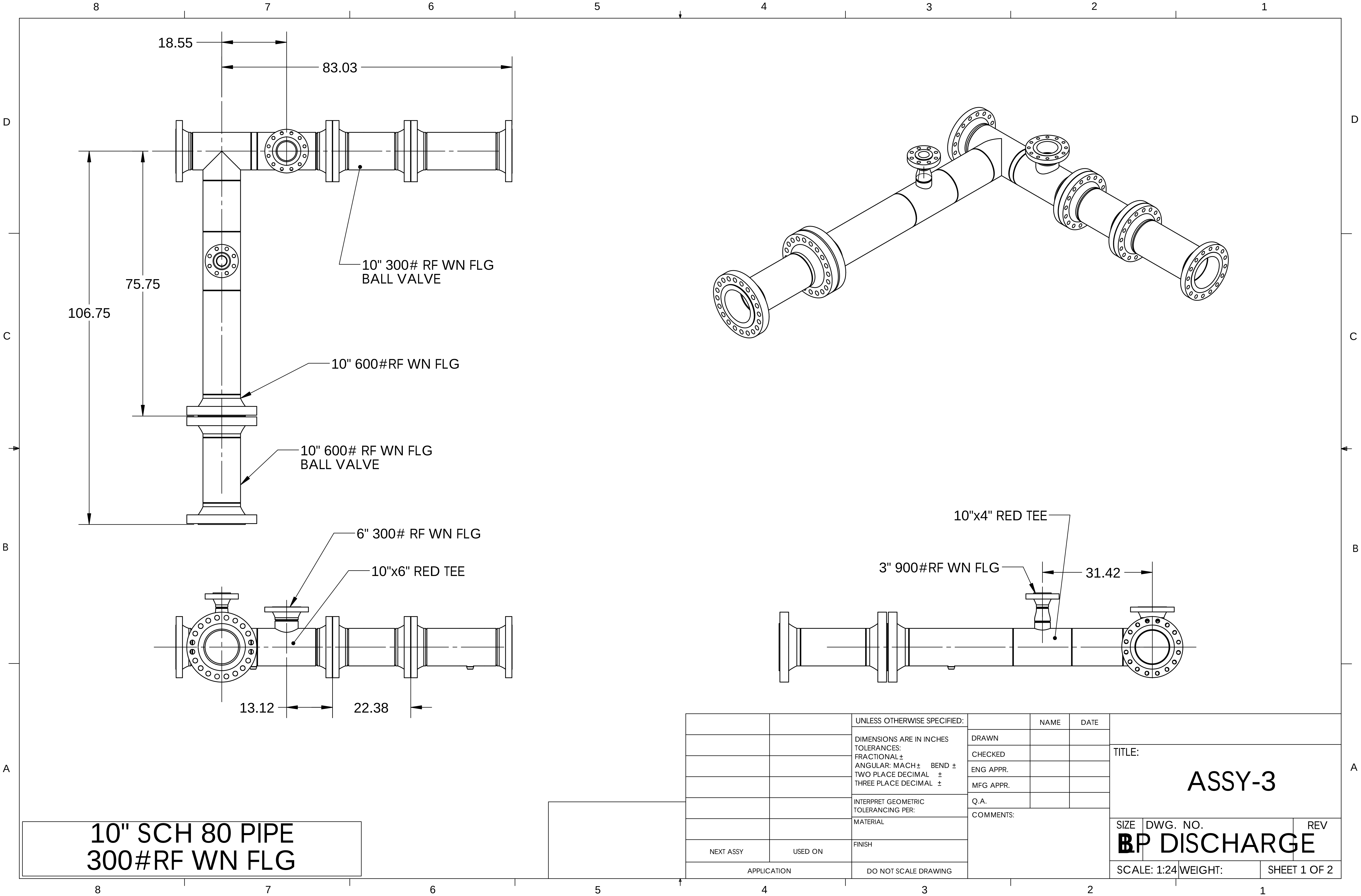
8" SCH 160 PIPE
900# RF WN FLG

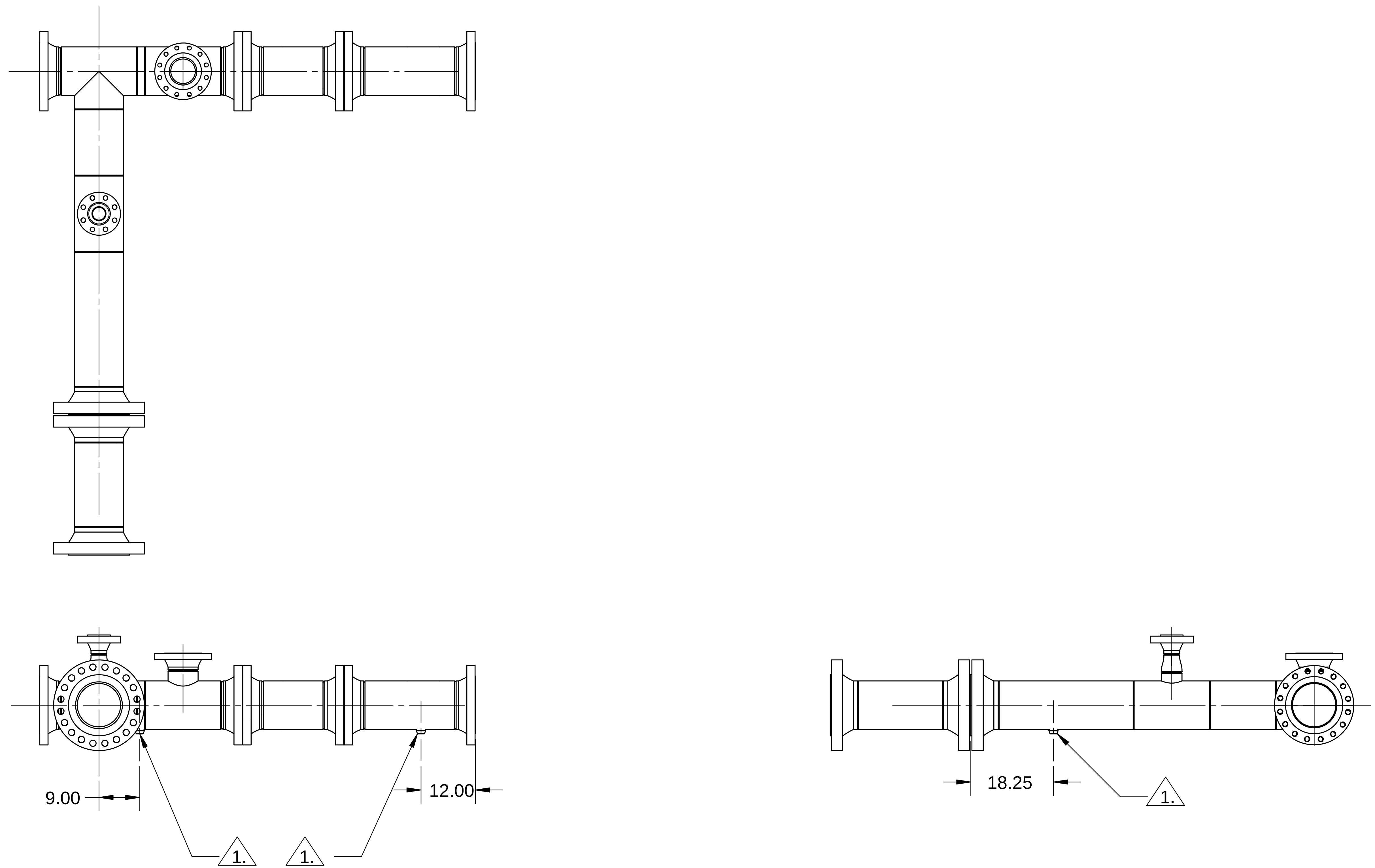
		UNLESS OTHERWISE SPECIFIED:		NAME	DATE
		DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±	DRAWN		
			CHECKED		
			ENG APPR.		
			MFG APPR.		
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
		MATERIAL	COMMENTS:		
NEXT ASSY	USED ON	FINISH			
APPLICATION		DO NOT SCALE DRAWING			

TITLE:

ASSY-11
O-LET

SIZE	DWG. NO.	REV
B	IP-COOLER DIS	
SCALE: 1:48	WEIGHT:	SHEET 2 OF 2


18.55
83.03
106.75
75.75
10" 300# RF WN FLG
BALL VALVE
10" 600#RF WN FLG
10" 600# RF WN FLG
BALL VALVE
6" 300# RF WN FLG
10"x6" RED TEE
13.12
22.38
10"x4" RED TEE
3" 900#RF WN FLG
31.42
10" SCH 80 PIPE
300#RF WN FLG
NEXT ASSY
USED ON
APPLICATION
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC
TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
ASSY-3
SIZE
DWG. NO.
REV
B
LP DISCHARGE
SCALE: 1:24
WEIGHT:
SHEET 1 OF 2



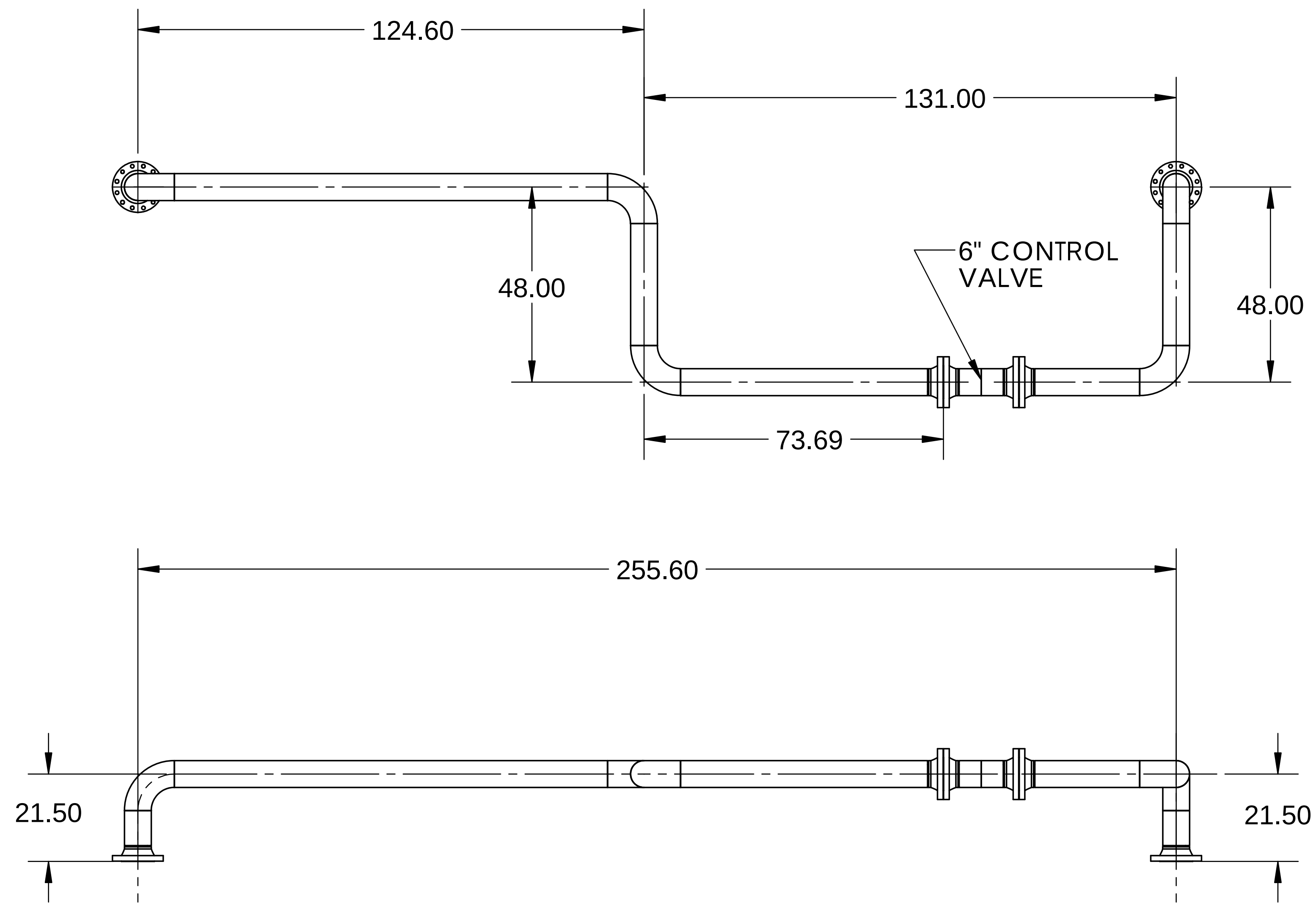
1. 3/4" NPT THREAD-O-LET

10" SCH 80 PIPE
300#RF WN FLG

		UNLESS OTHERWISE SPECIFIED:		NAME	DATE
		DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±	DRAWN		
			CHECKED		
			ENG APPR.		
			MFG APPR.		
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
		MATERIAL	COMMENTS:		
NEXT ASSY	USED ON	FINISH			
APPLICATION		DO NOT SCALE DRAWING			

TITLE: ASSY-3 O-LET

SIZE	DWG. NO.	REV
B	LP DISCHARGE	
SCALE: 1:24	WEIGHT:	SHEET 2 OF 2



6" SCH 80 PIPE
300# RF WN FLG

UNLESS OTHERWISE SPECIFIED:	NAME	DATE
DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL± ANGULAR: MACH± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±	DRAWN CHECKED ENG APPR. MFG APPR. Q.A.	
INTERPRET GEOMETRIC TOLERANCING PER:	COMMENTS:	
MATERIAL		
FINISH		
DO NOT SCALE DRAWING		

NEXT ASSY | USED ON

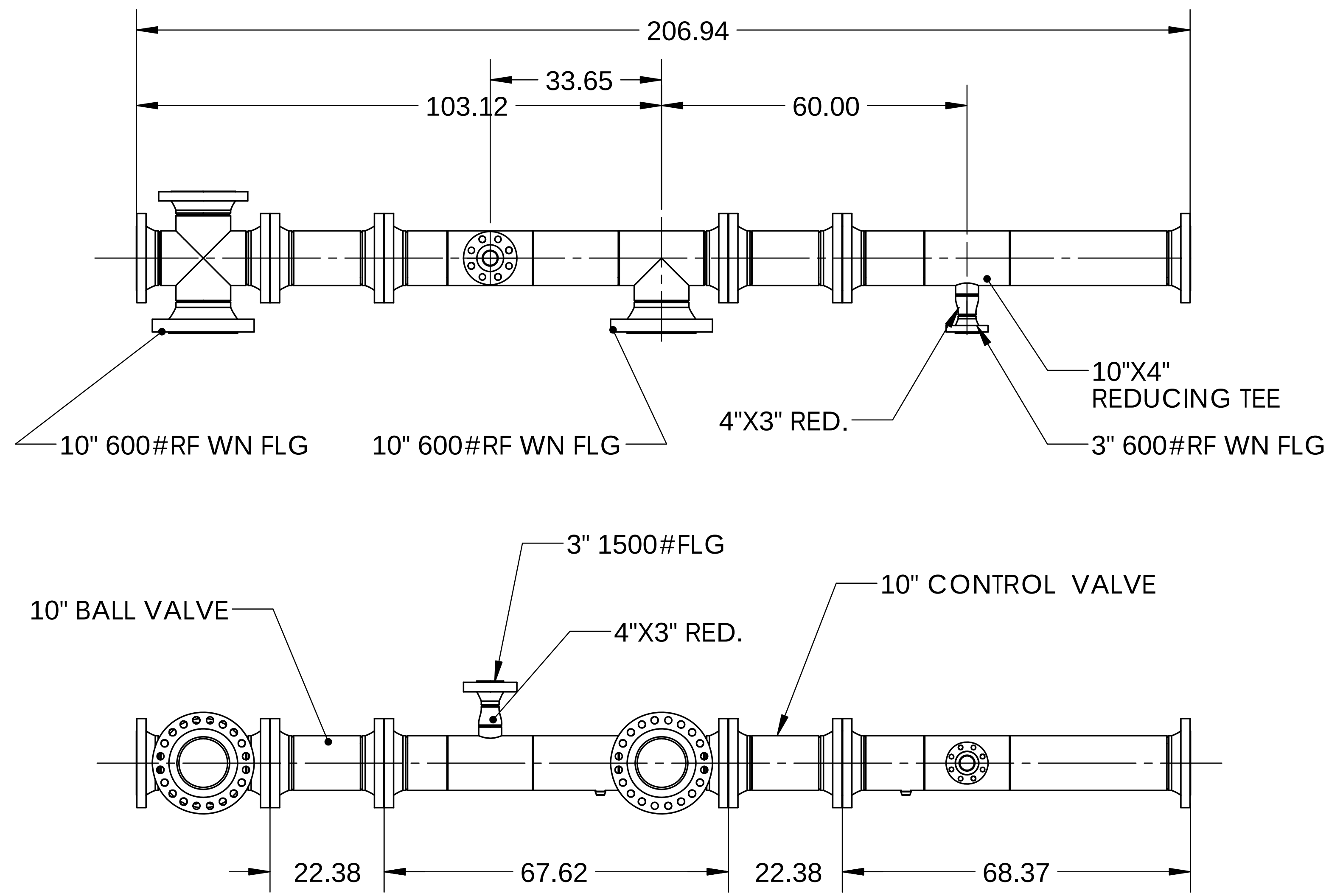
APPLICATION

TITLE:

ASSY-14

SIZE B | DWG. NO. LP_BYPASS | REV

SCALE: 1:48 | WEIGHT: | SHEET 1 OF 1



10" SCH 80 PIPE
300# RF WN FLG

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

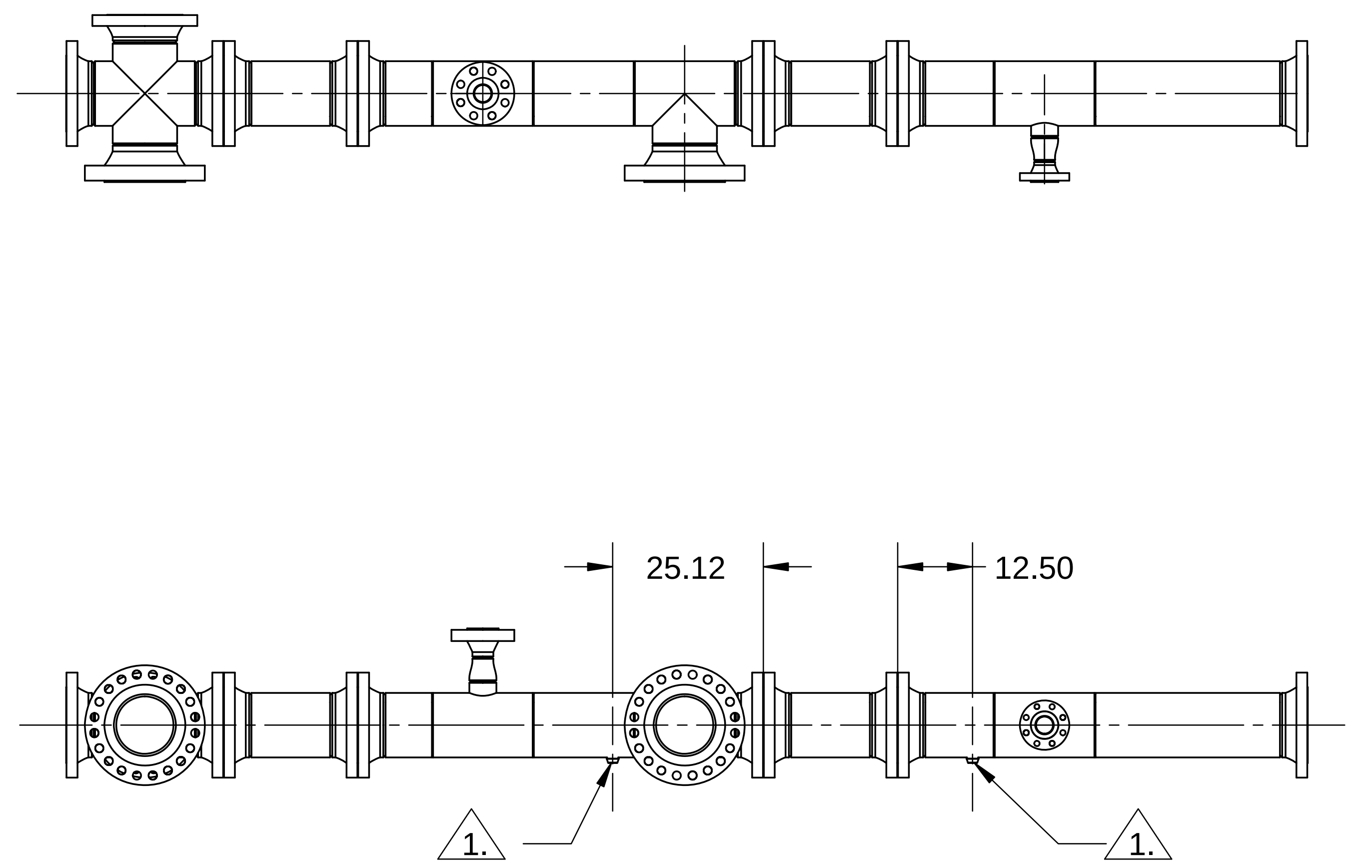
COMMENTS:

NEXT ASSY	USED ON
APPLICATION	

TITLE:
ASSY-4

SIZE B | DWG. NO. LP-DB_10IN BYPASSLOOP | REV

SCALE: 1:32 | WEIGHT: | SHEET 1 OF 2



1. 3/4" NPT THREAD-O-LET

10" SCH 80 PIPE
300# RF WN FLG

		UNLESS OTHERWISE SPECIFIED:		NAME	DATE
		DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL± ANGULAR: MACH± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±	DRAWN		
			CHECKED		
			ENG APPR.		
			MFG APPR.		
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
		MATERIAL	COMMENTS:		
NEXT ASSY	USED ON	FINISH			
APPLICATION		DO NOT SCALE DRAWING			

TITLE:

ASSY-4
O-LET

SIZE	DWG. NO.	REV
B	LP-DB_10IN BYPASSLOOP	
SCALE: 1:32	WEIGHT:	SHEET 2 OF 2

9. APPENDIX B: COMPONENT SPECIFICATIONS

HEAT EXCHANGER SPECIFICATION SHEET

US Units

		Job No.	
Customer	Southwest Research Institute	Reference No.	
Address		Proposal No.	13272
Plant Location		Date	2/10/2012 Rev
Service of Unit	LP CO2 Cooler, High Flow Condition	Item No.	
Size	18144 Type BEP Horz.	Connected In	1 Parallel 1 Series
Surf/Unit (Gross/Eff)	673.48 / 660.95 ft2 Shell/Unit 1	Surf/Shell (Gross/Eff)	673.48 / 660.95 ft2

PERFORMANCE OF ONE UNIT

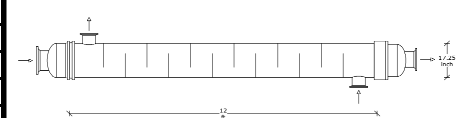
Fluid Allocation		Shell Side		Tube Side	
Fluid Name		water		CO2 vapor	
Fluid Quantity, Total	lb/hr	112500		72000.0	
Vapor (In/Out)				72000.0	72000.0
Liquid		112500	112500		
Steam					
Water		112500	112500		
Noncondensables					
Temperature (In/Out)	F	80.00	112.58	342.00	115.00
Specific Gravity		0.9971	0.9908		
Viscosity	cP	0.8571	0.5984	0.0213	0.0161
Molecular Weight, Vapor					
Molecular Weight, Noncondensables					
Specific Heat	Btu/lb-F	0.9993	0.9988	0.2344	0.2140
Thermal Conductivity	Btu/hr-ft-F	0.3527	0.3669	0.0170	0.0109
Latent Heat	Btu/lb				
Inlet Pressure	psia			97.700	
Velocity	ft/sec	1.14		60.75	
Pressure Drop, Allow/Calc	psi	10.000	1.284	2.000	1.837
Fouling Resistance (min)	ft2-hr-F/Btu	0.00100		0.00050	

Heat Exchanged Btu/hr	3661414		MTD (Corrected)	105.2 F	
Transfer Rate, Service	52.67 Btu/ft2-hr-F	Clean	59.71 Btu/ft2-hr-F	Actual	54.53 Btu/ft2-hr-F

CONSTRUCTION OF ONE SHELL

			Shell Side	Tube Side
Design/Test Pressure		psig	200 / per code	300 / per code
Design Temperature		F	200 / -20	500 / -20
No Passes per Shell			1	1
Corrosion Allowance		inch	0.0625 on CS	0.0625 on CS
Connections Size & Rating	In	inch	6"-150# ANSI RFSO	10"-300# ANSI RFSO
	Out	inch	6"-150# ANSI RFSO	8" companion flange
	Intermediate			

Sketch (Bundle/Nozzle Orientation)



Tube No. 343	OD 0.6250 inch	Thk(Avg) 0.0490 inch	Length 12.000 ft Pitch 0.7812 inch Layout 30
Tube Type	Plain		Material SA-214 WLD CARBON STEEL
Shell CS	ID 17.2500 inch	OD 18.00 inch	Shell Cover
Channel or Bonnet	CS		Channel Cover
Tubesheet-Stationary	CS		Tubesheet-Floating CS / CS skirt
Floating Head Cover			Impingement Plate None
Baffles-Cross CS	Type SINGLE-SEG.		
Baffles-Long		Seal Type	
Supports-Tube		U-Bend	Type
Bypass Seal Arrangement		Tube-Tubesheet Joint	roller expanded
Expansion Joint		Type	
Gaskets-Shell Side	compressed fiber	Tube Side	compressed fiber
-Floating Head			
Code Requirements	ASME Section VIII Div 1		TEMA Class C
Weight/Shell 4078.01	Filled with Water 5548.45		Bundle 1409.68 lb
Remarks:			

Reprinted with Permission (v6 SP3)

C:\Quotes\13272 Southwest Research\LP high flow.htri

HEAT EXCHANGER SPECIFICATION SHEET

US Units

		Job No.	
Customer	Southwest Research Institute	Reference No.	
Address		Proposal No.	13272
Plant Location		Date	11/1/2012 Rev
Service of Unit	HP CO2 Cooler, High Flow Condition	Item No.	
Size	16264 Type BEP Horz.	Connected In	1 Parallel 1 Series
Surf/Unit (Gross/Eff)	694.75 / 681.48 ft2 Shell/Unit 1	Surf/Shell (Gross/Eff)	694.75 / 681.48 ft2

PERFORMANCE OF ONE UNIT

Fluid Allocation		Shell Side		Tube Side	
Fluid Name		water		CO2 vapor	
Fluid Quantity, Total	lb/hr	112500		72000.0	
Vapor (In/Out)				72000.0	72000.0
Liquid		112500	112500		
Steam					
Water		112500	112500		
Noncondensables					
Temperature (In/Out)	F	80.00	113.29	336.00	115.00
Specific Gravity		0.9971	0.9906		
Viscosity	cP	0.8571	0.5943	0.0214	0.0167
Molecular Weight, Vapor					
Molecular Weight, Noncondensables					
Specific Heat	Btu/lb-F	0.9993	0.9988	0.2410	0.2327
Thermal Conductivity	Btu/hr-ft-F	0.3527	0.3671	0.0173	0.0115
Latent Heat	Btu/lb				
Inlet Pressure	psia			295.000	
Velocity	ft/sec	1.21		38.13	
Pressure Drop, Allow/Calc	psi	10.000	0.863		2.991
Fouling Resistance (min)	ft2-hr-F/Btu	0.00100		0.00050	

Heat Exchanged Btu/hr	3740485	MTD (Corrected)	102.2 F
Transfer Rate, Service	53.72 Btu/ft2-hr-F	Clean 95.04 Btu/ft2-hr-F	Actual 82.29 Btu/ft2-hr-F

CONSTRUCTION OF ONE SHELL — Sketch (Bundle/Nozzle Orientation)

		Shell Side	Tube Side
Design/Test Pressure	psig	200 / per code	2000 / per code
Design Temperature	F	200 / -20	500 / -20
No Passes per Shell		1	1
Corrosion Allowance	inch	0.0625 on CS	0.0625 on CS
Connections Size & Rating — In	inch	8"-150# ANSI RFSO	10"-1500# ANSI RFSO
Out	inch	8"-150# ANSI RFSO	8" companion flange
Intermediate			

Tube No. 193 OD 0.6250 inch	Thk(Avg) 0.0650 inch	Length 22.000 ft	Pitch 0.8125 inch Layout 30
Tube Type	Plain	Material	SA-214 WLD CARBON STEEL
Shell CS	ID 15.2500 inch OD 16.000 inch	Shell Cover	
Channel or Bonnet	CS	Channel Cover	
Tubesheet-Stationary	CS	Tubesheet-Floating	CS / CS skirt / CS flange
Floating Head Cover		Impingement Plate	None
Baffles-Cross CS	Type SINGLE-SEG.	%Cut (Diam) 40.00 Spacing(c/c) 12.0000	Inlet 15.4791 inch
Baffles-Long		Seal Type	
Supports-Tube		U-Bend	Type
Bypass Seal Arrangement		Tube-Tubesheet Joint	strength welded
Expansion Joint		Type	
Rho-V2-Inlet Nozzle			
Gaskets-Shell Side		Tube Side	
-Floating Head			
Code Requirements	ASME Section VIII Div 1	TEMA Class	C
Weight/Shell 5137.33	Filled with Water 6983.16	Bundle 1952.31	lb
Remarks:			

Reprinted with Permission (v6 SP3)

M:\GREG\Quotes\13272 Southwest Research\Rev 3\HP, 2000 PSIG, high flow condition.htri

DECO HEAVY-DUTY ADJUSTABLE ANCHORS

Deco Heavy-Duty Adjustable Anchor's durable, heavy-duty anchor studs and couplings are machined from mill-tested, C1144 (A-311) stress-proof, cold-rolled steel having a minimum tensile strength of 115,000 lbs. psi and yield strength of 100,000 lbs. psi. Special orders from alloy steel are available with a yield strength of 130,000 lbs. psi.

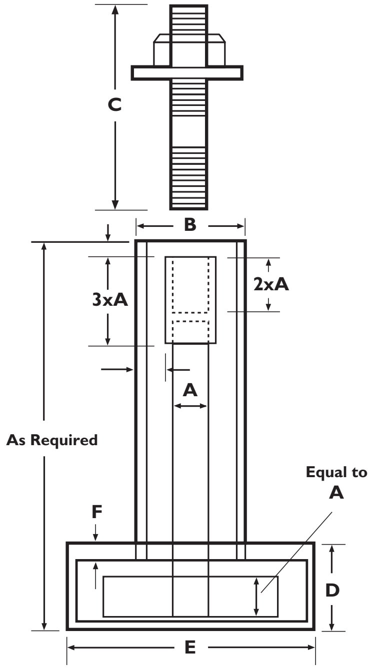
Deco Heavy-Duty Adjustable Anchors are also available in stainless or galvanized steel for specific industrial applications. To best meet our customers' needs, Deco also offers specialty steels and coatings.

Multiple anchors may be installed in sole plates to customers' specifications. Stepped couplings are available for jobs that require fastening studs and lower studs of different diameters.

Leveling plates of any size may be specified on Deco Heavy-Duty Adjustable Anchors.

DIMENSIONS

Bolt Diameter	A	½″	⅝″	¾″	⅞″	1″	1⅛″	1¼″	1⅜″	1½″	1¾″	2″	2¼″	2½″	2¾″	3″
Threads Per Inch		13	11	10	9	8	7	7	6	6	5	4½	4½	4	4	4
Tube Diameter	B	2″	2″	2½″	2½″	2¾″	3″	3″	3″	3″	3½″	4″	4½″	5″	5″	5½″
Fastening Stud *with 1 nut and washer*	C	Length to Specifications														
Box Height	D	1¼″	1¼″	1½″	1½″	1¾″	2¼″	2¼″	2¼″	2¼″	2¾″	2¾″	3¼″	3¾″	3¾″	4¾″
Box Square	E	3¾	3¾	4¾	4¾	5 5¾	5 5¾	5 5¾	5 5¾	5 5¾	5¾ 6¼	7¼	7¼	8¼	9¼	9¼
Plate Thickness	F	⅜	⅜	⅜	⅜	⅜	⅜	⅜	⅜	⅜	½	½	½	½	½	½



DECO
MANUFACTURING COMPANY

TOLL FREE 800-637-5861
PHONE 217-872-6450
FAX 217-872-6455
www.DECOanchors.com
DECOmfg@aol.com

DECO HEAVY-DUTY ADJUSTABLE ANCHORS PERFORMANCE

1 Safe working loads are based on a 4,000 lbs. psi concrete compressive strength at 28 days and a safety factor of 4 against predicted ultimate loads. Safe working loads are for anchors loaded in a static condition. For a dynamic loading condition, reduce loads by a minimum of 50%.

2 Shear safe working loads can only be obtained by fully grouting the annular space of the sleeve tube.

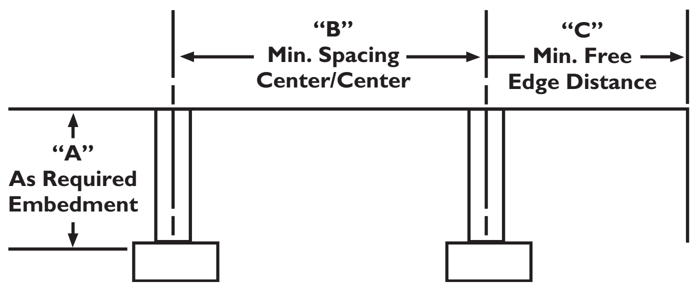
3 Allowable minimum center-to-center spacing of 12 times anchor diameter is permissible using a reduced safe working load of 50%.

4 Reduced minimum free edge distance spacing of ⅓ of minimum free edge distance "C" is permissible when shear reinforcement is supplied per ACI-318-95 Section II.7 Shear-Friction.

5 Anchor Bolt Combined Stress Interaction Formula:

$$\frac{\text{Actual Tension Applied}}{\text{Safe Working Load Allowable Pullout}} + \frac{\text{Actual Shear Applied}}{\text{Safe Working Load Allowable Shear}} \leq 1$$

6



ANCHOR SIZE	½″	⅝″	¾″	⅞″	1″	1⅛″	1¼″	1⅜″	1½″	1¾″	2″	2¼″	2½″	2¾″	3″
Pullout Safe Working Load (lbs.) (1)	4,047	6,441	9,519	13,167	17,271	21,746	27,617	32,918	40,043	54,122	71,193	92,568	113,972	140,619	170,060
Shear Safe Working Load (lbs.) (1) (2)	1,616	2,576	3,808	5,259	6,897	8,693	11,036	13,151	16,001	21,635	28,450	36,986	45,533	56,182	67,949
As Required Embedment ("A") (6)	9″	9″	9″	12″	12″	15″	15″	18″	18″	24″	24″	30″	30″	36″	42″
Minimum Spacing Center/Center ("B") (6)	11″	14″	17″	21″	24″	27″	30″	33″	37″	43″	49″	56″	62″	69″	76″
Minimum Free Edge Distance ("C") (6)	8″	10″	12″	14″	16″	18″	20″	21½″	24″	27½″	31″	35″	39″	43″	48″
Minimum Spacing Center/Center w/Reduced Safe Working Load (3)	6″	7½″	9″	10½″	12″	13½″	15″	16½″	18″	21″	24″	27″	30″	33″	36″
Min. Free Edge Distance w/Shear Reinforcement Per ACI-318 (4)	3″	3½″	4″	4½″	5″	6″	6½″	7″	8″	9″	10½″	11½″	13″	14″	15″

DECO: THE INDUSTRY STANDARD

Customer	**Southwest Research Institute**	Location	Date **9-Jan-13**
Project	**CO2 Loop**	Reference	
Item **1**	Qty **1**	Rev	

Service	**LP Throttle**	Actuator Style	**Spring & Diaphragm**
Tag	**CV001**	Size & Type	**DFR-220-O-10S3-G-RA1**
Size and Type	**10" Model 573 Rotary Valve**	Travel	**90 deg**
Body Style	**Flanged / V-Ball**	Spring Range	**0-18 / 0-33 psig**
Max Temp		Push Down to	
Max Press		Supply	**35 psig**
End Connection In	**300# RF**	To Actuator.	**6-30/0-33 psig**
& ANSI Class Out	**300# RF**	Failure Position	**Open**
Material	**WCC Carbon Steel**	Handwheel/Trav Stop	**None**
Ports	**One**	Positioner Type	**Siemens PS2 HART**
Flow Direction	**Forward**	Input Signal	**4-20 ma**
Trim		Accessories	**Airset**
Ball / Disk Material	**317 SST Chrome-Plated**	Gauges	**Yes**
Seal / Seat Material	**PTFE Composition**	Action	**Direct**
Retainer Material	**WCC Carbon Steel**	Certification	**NI Class 1 Div 2 Gr A,B,C,D**
Bushing / Bearing Mat'l	**316 SST/CPTFE**	Transducer	**None**
Shaft Material / Style	**Nitronic 50 (S20910) Splined**	Input/Output Signal	
Shaft Size	**1 1/4"**	Action	
Shutoff Class	**VI**	Mounting	
Port Size	**Reduced**	Airset	
Characteristic	**Equal Percent**	Certification	
		Solenoid Style	**None**
		Size & Type	
		Material	
		Power	
Bonnet Style	**Standard**	Controller Type	**None**
		Action	
Shaft Seal/Packing	**PTFE v-ring single**	Input Range	
Accessories		Output	
Bolting, Bonnet		Mounting	
Bolting, Packing Flange	**B7M/2HM**	Airset	
Valve	**573-10-EWC-PNT**	Inlet Pipe Diameter	**10"** Sch **80**
Actuator	**DFR-220-O-10S3-G-RA1**	Outlet Pipe Diameter	**10"** Sch **80**
Positioner	**6DR5210-0EN00-0AA3**	Insulation	
Controller		Process Fluid	**CO2**

Notes: **316 SST tubing and fittings**
SST Nametag w/Tag #

Sizing Calculation Information

	Units	Maximum	Normal	Minimum	
	Critical Press **1363** **psia**		Critical Temp **88** **degF**		
Flow	**LB/H**		**208,000**		
Inlet Pressure	**PSIA**		**200**		
Outlet Pressure			**179.8**		
Temperature	**DEGF**		**115**		
Viscosity/Sp Heat Ratio					
Spec Grav/Mol Weight			**1.52**		
Vapor Pressure					
Cv			**632**		
Deg Open			**48**		
Predicted Noise	**DB(A)**		**<70**		
Notes					
Max Rated Flow Coefficient	**Cv 2860**			Shutoff Pressure	**580 psig**

Customer	Southwest Research Institute	Location		Date	28-Dec-12
Project		Reference			
Item 2	Qty 1	Revision			
Service	HP Throttle	Actuator Style	Spring & Diaphragm		
Tag	CV-002	Size & Type	DFO-3220-FRN		
Size and Type	6" Model 390 Globe Valve	Travel	3"		
Body Style	Globe	Bench Set	6-17 psig		
Max Temp		Push Down to	Close		
Max Pressure		Supply	50 psig		
ANSI Class & In	1500# RF	To Actuator.	6-30/0-33 psig		
End Connect Out	1500# RF	Failure Position	Open		
Material	WCC Carbon Steel	Handwheel/Stop	None		
Ports	One	Positioner Type	Siemens PS2 HART		
Flow Direction	Down	Input Signal	4-20 ma		
Trim Number	Standard	Accessories	Airset		
Backup/Seal Ring Mat'l	None	Gauges	Yes		
Cage Material	17-4 PH SST	Action	Direct		
Retainer Material	316 SST	Certification	NI Class 1 Div 2 Gr A,B,C,D		
Bushing Material	None	Transducer	None		
Seat Ring Material	416 SST	Input/Output Signal			
Valve Plug Material	416 SST	Action			
Guiding	Cage	Mounting			
Balance/Unbalance	Balanced	Airset			
Stem Material	Nitronic 50	Certification			
Stem Size	3/4"	Solenoid Style	None		
Shutoff Class	IV	Size & Type			
Port Size	5 3/8"	Material			
Characteristic	Modified Equal Percent	Power			
Bonnet Style	Standard	Controller Type	None		
Boss Size	3 9/16"	Action			
Packing	PTFE v-ring single	Input Range			
Accessories		Output			
Bolting, Bonnet	B7/2H	Mounting			
Bolting, Packing Flange	B7/2H	Airset			
Valve	390-6EF-W3S -MP	Inlet Pipe Diameter	6"	Sch	160
Actuator	DFO-3220-FRN	Outlet Pipe Diameter	6"	Sch	160
Positioner	6DR5210-0EN00-0AA3	Insulation			
Controller		Process Fluid	Carbon dioxide		

Notes: **316 SST tubing and fittings**
SST Nametag w/Tag #

Sizing Calculation Information

	Units	Maximum	Normal	Minimum	
	Critical Press	1363	psia	Critical Temp	88 degf
Flow	LB/HR		208,000		
Inlet Pressure	PSIA		875		
Outlet Pressure	PSIA		857.3		
Temperature	DEGF		115		
Viscosity/Sp Heat Ratio					
Spec Grav/Mol Weight	SG		1.52		
Vapor Pressure	PSIA				
Cv			277		
% Open			77		
Predicted Noise	DB(a)		<70		
Notes					
Max Rated Coefficient - Cv	378			Shutoff Pressure	3000 psig

Customer	Southwest Research Institute		Location	Date	9-Jan-13
Project	CO2 Loop		Reference		
Item	3	Qty 1	Revision		

Service	HP Bypass	Actuator Style	Spring & Diaphragm
Tag	CV003	Size & Type	DFC-2105-CIN
Size and Type	3" Model 390 Globe Valve	Travel	1 1/2"
Body Style	Globe	Bench Set	9-30 psig
Max Temp		Push Down to	Close
Max Pressure		Supply	50 psig
ANSI Class & In	900# RF	To Actuator.	6-30/0-33 psig
End Connect Out	900# RF	Failure Position	Closed
Material	WCC Carbon Steel	Handwheel/Stop	None
Ports	One	Positioner Type	Siemens PS2 HART
Flow Direction	Down	Input Signal	4-20 ma
Trim Number	Standard	Accessories	Belgas P50 Airset Regulator
Backup/Seal Ring Mat'l	Viton	Gauges	Yes
Cage Material	17-4 PH SST	Action	Direct
Retainer Material	316 SST	Certification	NI Class 1 Div 2 Gr A,B,C,D
Bushing Material	None	Transducer	None
Seat Ring Material	416 SST	Input/Output Signal	
Valve Plug Material	416 SST	Action	
Guiding	Cage	Mounting	
Balance/Unbalance	Balanced	Airset	
Stem Material	Nitronic 50	Certification	
Stem Size	1/2"	Solenoid Style	None
Shutoff Class	IV	Size & Type	
Port Size	2 7/8"	Material	
Characteristic	Equal Percent	Power	
Bonnet Style	Standard	Controller Type	None
Boss Size	2 13/16"	Action	
Packing	PTFE v-ring single	Input Range	
Accessories		Output	
Bolting, Bonnet	B7/2H	Mounting	
Bolting, Packing Flange	B7/2H	Airset	

Valve	390-3DF-W2S -EP	Inlet Pipe Diameter	3"	Sch	160
Actuator	DFC-2105-CIN	Outlet Pipe Diameter	3"	Sch	160
Positioner	6DR5210-0EN00-0AA3	Insulation			
Controller		Process Fluid	CO2		

Notes: **316 SST tubing and fittings**
SST Nametag w/Tag #

Sizing Calculation Information

	Critical Press	1070	psia	Critical Temp	87.9 degf
	Units	Case 1	Case 2	Minimum	
Flow	LB/H	7,200	20,800		
Inlet Pressure	PSIA	885	1005		
Outlet Pressure	PSIA	875	990		
Temperature	DEGF	405	405		
Viscosity/Sp Heat Ratio					
Spec Grav/Mol Weight	SG	1.52	1.52		
Vapor Pressure					
Cv		17.2	38		
% Open		45	60		
Predicted Noise	DB(a)	<70	<70		
Notes					
Max Rated Coefficient - Cv	92.5			Shutoff Pressure	2220 psig

Customer	Southwest Research Institute	Location		Date	8-Nov-12
Project	CO2 Loop	Reference			
Item	4 Qty 1	Revision			

Service		LP Bypass		Actuator Style	Spring & Diaphragm	
Tag		CV004		Size & Type	DFC-3220-DMN	
Size and Type		6" Model 360 Globe Valve		Travel	2"	
Body Style		Globe		Bench Set	15-30 psig	
Max Temp				Push Down to	Close	
Max Pressure				Supply	50 psig	
ANSI Class &	In	300#	RF	To Actuator.	6-30/0-33 psig	
End Connect	Out	300#	RF	Failure Position	Closed	
Material		WCC Carbon Steel		Handwheel/Stop	None	
Ports		One		Positioner Type	Siemens PS2 HART	
Flow Direction		Down		Input Signal	4-20 ma	
Trim Number		D1		Accessories	Belgas P50 Airset Regulator	
Backup/Seal Ring Mat'l		Viton		Gauges	Yes	
Cage Material		17-4 PH SST		Action	Direct	
Retainer Material		316 SST		Certification	NI Class 1 Div 2 Gr A,B,C,D	
Bushing Material		None		Transducer	None	
Seat Ring Material		416 SST		Input/Output Signal		
Valve Plug Material		416 SST		Action		
Guiding		Cage		Mounting		
Balance/Unbalance		Balanced		Airset		
Stem Material		Nitronic 50		Certification		
Stem Size		3/4"		Solenoid Style	None	
Shutoff Class		IV		Size & Type		
Port Size		7"		Material		
Characteristic		Equal Percent		Power		
Bonnet Style		Standard		Controller Type	None	
Boss Size		3 9/16"		Action		
Packing		PTFE v-ring single		Input Range		
Accessories				Output		
Bolting, Bonnet		B7/2H		Mounting		
Bolting, Packing Flange		B7/2H		Airset		
Valve	360-6BFW-1FP3-VES			Inlet Pipe Diameter	6"	Sch 80
Actuator	DFC-3220-DMN			Outlet Pipe Diameter	6"	Sch 80
Positioner	6DR5210-0EN00-0AA3			Insulation		
Controller				Process Fluid	CO2	

Notes: 316 SST tubing and fittings
SST Nametag w/Tag #

Sizing Calculation Information

	Critical Press	1070	psia	Critical Temp	87.9 degf
	Units	Case 1	Case 2	Minimum	
Flow	LB/H	7,200	20,800		
Inlet Pressure	PSIA	97.7	238		
Outlet Pressure	PSIA	96.2	228		
Temperature	DEGF	377	377		
Viscosity/Sp Heat Ratio					
Spec Grav/Mol Weight	SG	1.52	1.52		
Vapor Pressure					
Cv		150	97.3		
% Open		58	48		
Predicted Noise	DB(a)	<70	<70		
Notes					
Max Rated Coefficient - Cv	394			Shutoff Pressure	700 psig

10. APPENDIX C: DENSITY, SPEED OF SOUND, AND SPECIFIC HEAT TEST RESULTS

Table 10-1. Mix 1 Density

Run No.	Pressure (psia)	Temp (degF)	Measured density (kg/m3)	Uncertainty - Meas rho (%)	Uncertainty - Ref rho (%)	Total Uncertainty (%)	Ref density - GERG (kg/m3)	Ref density - NIST (kg/m3)	Diff % - Meas vs. Ref rho GERG	Diff % - Meas vs. Ref rho NIST
1.100.200.1	200.63	100.96	23.564	0.072	2.650	2.651	25.346	25.346	-7.029	-7.029
1.100.200.2	200.15	100.12	25.337	0.071	2.651	2.652	25.331	25.331	0.022	0.022
1.100.200.3	199.35	100.08	25.347	0.071	2.663	2.664	25.224	25.225	0.486	0.482
1.100.200.4	200.79	100.32	25.492	0.071	2.643	2.644	25.406	25.406	0.338	0.338
1.100.200.5	200.99	99.17	24.686	0.071	2.635	2.636	25.502			
1.100.200.6	200.31	99.78	25.370	0.071	2.648	2.649	25.373	25.373	-0.013	-0.013
1.100.800.1	799.48	100.69	135.597	0.066	2.701	2.702	134.810		0.584	
1.100.800.2	798.68	100.66	136.376	0.066	2.701	2.702	134.620	134.620	1.305	1.305
1.100.800.3	801.52	101.34	130.673	0.066	2.699	2.699	134.850			
1.100.800.4	796.06	100.37	136.716	0.066	2.707	2.708	134.150	134.150	1.913	1.913
1.100.800.7	798.88	100.75	135.960	0.066	2.704	2.704	134.600		1.011	
1.100.800.8	800.95	100.14	136.512	0.066	2.697	2.698	135.610	135.620	0.665	0.657
1.100.1250.1	1266.66	101.35	484.172	0.066	13.970	13.970	485.920	486.170	-0.360	
1.100.1250.2	1244.66	100.62	455.634	0.066	15.841	15.841	456.810	458.210	-0.258	-0.562
1.100.1250.3	1247.42	101.06	442.439	0.066	15.283	15.283	448.640	449.960	-1.382	-1.671
1.100.1250.4	1241.47	100.62	441.040	0.066	15.858	15.858	448.410	449.690	-1.644	-1.924
1.100.1250.5	1252.92	100.97	458.234	0.066	15.213	15.213	465.710	466.710	-1.605	-1.816
1.100.1250.6	1251.80	101.81	418.663	0.066	14.214	14.214	435.400	436.570	-3.844	-4.102
1.100.1250.7	1248.75	100.98	452.383	0.066	15.372	15.373	454.750	456.020	-0.521	-0.798
1.100.1250.8	1252.08	100.68	464.380	0.066	15.329	15.329	473.960	474.690	-2.021	-2.172
1.100.1250.9	1261.50	101.30	465.079	0.066	14.504	14.504	475.420	476.200	-2.175	
1.100.1250.10	1255.52	104.56	368.376	0.066	9.649	9.649	379.240	379.360	-2.865	-2.895
1.100.1250.11	1259.69	102.82	394.294	0.066	12.885	12.885	424.480	425.380	-7.111	-7.308
1.100.1250.12	1256.80	104.81	367.020	0.066	9.398	9.398	376.980	377.080	-2.642	-2.668
1.100.1800.1	1801.37	99.56	766.264	0.066	1.414	1.415	756.130	756.170	1.340	1.335
1.100.1800.2	1798.67	99.65	772.188	0.066	1.417	1.419	755.430	755.480	2.218	2.212
1.100.1800.3	1800.27	99.95	770.000	0.066	1.386	1.387	774.340	754.340	-0.560	2.076
1.100.1800.4	1798.62	100.90	766.215	0.066	1.446	1.448	750.010	750.040	2.161	2.156
1.100.1800.5	1801.12	100.16	764.921	0.066	1.426	1.428	753.520	753.550	1.513	1.509

1.100.1800.6	1801.60	101.76	751.482	0.066	1.553	1.554	746.600	746.620	0.654	0.651
1.100.2500.1	2498.61	100.59	845.525	0.066	1.711	1.712	812.140	812.040	4.111	4.124
1.100.2500.2	2500.88	99.85	845.779	0.066	1.704	1.705	814.500	814.410	3.840	3.852
1.100.2500.3	2504.33	100.63	838.832	0.066	1.710	1.711	812.390	812.320	3.255	3.264
1.100.2500.4	2516.63	100.88	844.752	0.066	1.709	1.710	812.460	812.370	3.975	3.986
1.200.200.1	200.89	200.71	21.439	0.073	2.619	2.620	20.249	20.250	5.877	5.871
1.200.200.3	200.15	200.76	21.079	0.073	2.628	2.629	20.170	20.171	4.508	4.503
1.200.800.1	799.72	200.48	95.898	0.066	1.826	1.828	92.933	92.929	3.190	3.195
1.200.800.2	800.95	200.67	96.479	0.066	1.825	1.826	93.053	93.047	3.681	3.688
1.200.800.3	798.09	200.96	95.437	0.066	1.832	1.833	92.580	92.575	3.086	3.092
1.200.1250.1	1250.45	200.91	171.667	0.066	1.018	1.021	160.950	160.930	6.658	6.672
1.200.1250.2	1250.20	200.74	170.607	0.066	1.019	1.021	161.010	160.990	5.961	5.974
1.200.1250.3	1252.00	201.49	173.050	0.066	1.019	1.021	160.860	160.850	7.578	7.584
1.200.2500.1	2507.83	203.31	443.208	0.066	4.624	4.624	435.470	435.370	1.777	1.800
1.200.2500.2	2499.12	202.57	444.502	0.066	4.625	4.625	435.730	435.630	2.013	2.037
1.300.200.2	200.79	300.87	18.393	0.075	3.482	3.483	17.305	17.306	6.286	6.280
1.300.200.3	198.91	298.76	18.518	0.075	3.504	3.505	17.191	17.192	7.720	7.714
1.300.800.1	800.94	300.78	78.292	0.067	2.846	2.847	73.853	73.855	6.011	6.008
1.300.800.2	799.85	300.85	78.515	0.067	2.850	2.851	73.734	73.734	6.484	6.484
1.300.800.3	797.91	299.13	77.393	0.067	2.849	2.850	73.770	73.771	4.911	4.909
1.300.1250.1	1250.84	300.66	133.805	0.066	2.276	2.277	121.510	121.500	10.119	10.128
1.300.1250.2	1249.97	301.84	133.667	0.066	2.282	2.283	121.100	121.090	10.377	10.386
1.300.1250.3	1250.36	301.53	133.779	0.066	2.277	2.278	121.220	121.220	10.360	10.360
1.300.1800.1	1797.18	300.94	202.937	0.066	0.945	0.947	185.410	185.410	9.453	9.453
1.300.1800.2	1800.64	300.73	202.459	0.066	0.945	0.947	185.940	185.940	8.884	8.884
1.300.1800.3	1799.04	300.07	201.967	0.066	0.948	0.950	186.070	186.070	8.544	8.544
1.300.2500.1	2499.60	300.67	294.752	0.066	0.959	0.961	275.310	275.380	7.062	7.035
1.300.2500.2	2499.11	301.84	293.264	0.066	0.953	0.955	274.220	274.290	6.945	6.918
1.300.2500.3	2499.27	301.38	293.584	0.066	0.952	0.954	274.640	274.710	6.898	6.871

Table 10-2. Mix 1 Speed of Sound

Run No.	Pressure (psia)	Temp (degF)	Measured SOS (Ft/s)	Uncertainty - Meas SOS (%)	Uncertainty - Ref SOS (%)	Total Uncertainty (%)	Ref SOS GERG (ft/s)	Ref SOS NIST (ft/s)	Diff % - Meas vs. Ref SOS GERG	Diff % - Meas vs. Ref SOS NIST
1.100.200.1	200.79	100.80	892.000	0.249	7.394	7.398	869.890	869.810	2.542	2.551
1.100.200.2	199.83	99.81	892.000	0.249	7.400	7.404	869.150	869.070	2.629	2.638
1.100.200.3	199.35	99.85	892.000	0.249	7.399	7.403	869.270	869.180	2.615	2.625
1.100.200.4	200.15	100.77	892.000	0.249	7.393	7.397	869.970	869.890	2.532	2.542
1.100.800.2	799.35	99.63	776.040	0.273	8.520	8.525	756.230	756.040	2.620	2.645
1.100.800.3	797.75	99.02	774.256	0.274	8.531	8.535	755.320	755.120	2.507	2.534
1.100.800.4	795.02	98.14	773.364	0.274	8.545	8.549	754.090	753.890	2.556	2.583
1.100.1250.2	1267.68	101.25	695.760	0.296	10.941	10.945	651.480	657.520	6.797	5.816
1.100.1250.3	1261.41	100.68	690.408	0.298	11.265	11.269	650.660	656.830	6.109	5.112
1.100.1250.4	1246.33	99.89	692.192	0.297	11.181	11.185	639.280	646.530	8.277	7.063
1.100.1800.1	1801.35	99.48	1248.800	0.206	15.380	15.381	1263.300	1263.600	-1.148	-1.171
1.100.1800.2	1795.81	99.38	1248.800	0.206	15.406	15.407	1261.300	1261.700	-0.991	-1.022
1.100.1800.3	1807.32	99.58	1284.480	0.203	15.351	15.352	1265.500	1265.800	1.500	1.476
1.100.1800.4	1808.60	99.48	1286.710	0.203	15.323	15.324	1267.800	1268.000	1.492	1.476
1.100.2500.1	1999.16	104.63	1284.480	0.203	12.047	12.048	1306.000	1305.200	-1.648	-1.587
1.100.2500.2	1992.71	104.44	1284.480	0.203	12.057	12.059	1305.000	1304.200	-1.572	-1.512
1.100.2500.3	2006.65	105.01	1286.264	0.203	12.054	12.055	1305.100	1304.300	-1.443	-1.383
1.100.2500.4	2010.98	105.06	1287.156	0.203	12.037	12.038	1306.800	1305.900	-1.503	-1.435
1.200.200.4	200.16	199.58	963.360	0.237	0.161	0.287	951.690	951.610	1.226	1.235
1.200.200.5	200.64	199.86	967.820	0.236	0.161	0.286	951.860	951.790	1.677	1.684
1.200.200.6	200.80	199.05	966.928	0.237	0.161	0.286	951.230	951.150	1.650	1.659
1.200.200.7	199.84	197.67	966.928	0.237	0.161	0.286	950.260	950.180	1.754	1.763
1.200.800.1	802.40	200.32	892.000	0.249	0.249	0.352	901.650	901.810	-1.070	-1.088
1.200.800.2	800.63	198.67	896.460	0.248	0.251	0.353	899.950	900.100	-0.388	-0.404
1.200.800.3	804.96	199.31	897.352	0.248	0.251	0.353	900.330	900.480	-0.331	-0.347
1.200.800.4	801.11	199.86	892.000	0.249	0.250	0.353	901.240	901.390	-1.025	-1.042
1.200.800.5	802.56	200.48	892.000	0.249	0.250	0.352	901.820	901.970	-1.089	-1.105
1.200.800.6	799.03	199.31	892.000	0.249	0.250	0.353	900.790	900.940	-0.976	-0.992

1.200.1250.1	1249.22	198.37	865.240	0.254	0.324	0.412	869.390	869.560	-0.477	-0.497
1.200.1250.2	1250.82	199.41	865.240	0.254	0.323	0.410	870.760	870.930	-0.634	-0.653
1.200.1250.3	1250.66	199.05	863.456	0.254	0.323	0.411	870.270	870.440	-0.783	-0.802
1.200.1250.4	1248.90	199.13	864.348	0.254	0.323	0.411	870.470	870.640	-0.703	-0.723
1.200.1800.1	1803.31	199.95	838.480	0.259	0.326	0.417	862.620	862.480	-2.798	-2.783
1.200.1800.2	1806.04	200.76	874.160	0.252	0.326	0.412	863.830	863.700	1.196	1.211
1.200.1800.3	1802.19	199.65	868.808	0.253	0.326	0.413	862.160	862.020	0.771	0.787
1.200.1800.4	1807.64	200.73	869.700	0.253	0.325	0.412	863.840	863.700	0.678	0.695
1.200.2500.1	2496.17	204.19	963.360	0.237	0.272	0.361	946.190	947.070	1.815	1.720
1.200.2500.2	2488.88	204.60	958.008	0.238	0.265	0.356	944.630	945.510	1.416	1.322
1.200.2500.3	2487.52	204.51	955.332	0.238	0.265	0.357	944.380	945.260	1.160	1.066
1.200.2500.4	2492.97	205.43	959.792	0.238	0.262	0.354	945.280	946.150	1.535	1.442
1.300.200.1	203.88	301.94	1034.720	0.227	0.137	0.265	1025.100	1025.000	0.938	0.948
1.300.200.2	202.72	301.82	1029.368	0.228	0.137	0.266	1025.100	1025.000	0.416	0.426
1.300.200.3	202.72	301.65	1030.260	0.228	0.127	0.261	1025.000	1024.900	0.513	0.523
1.300.200.4	203.20	301.84	1029.368	0.228	0.127	0.261	1025.100	1025.000	0.416	0.426
1.300.800.1	805.85	300.77	999.040	0.232	0.173	0.289	998.920	999.050	0.012	-0.001
1.300.800.2	804.89	301.31	996.364	0.232	0.175	0.291	999.420	999.550	-0.306	-0.319
1.300.800.3	804.41	301.92	994.580	0.233	0.170	0.288	999.960	1000.100	-0.538	-0.552
1.300.800.4	804.08	301.60	996.364	0.232	0.178	0.292	999.690	999.820	-0.333	-0.346
1.300.1250.1	1255.15	297.89	981.200	0.234	0.200	0.308	984.190	984.460	-0.304	-0.331
1.300.1250.2	1250.50	298.84	978.524	0.235	0.199	0.308	985.210	985.470	-0.679	-0.705
1.300.1250.3	1250.02	299.38	977.632	0.235	0.199	0.308	985.750	986.010	-0.824	-0.850
1.300.1250.4	1247.30	298.81	978.524	0.235	0.199	0.308	985.240	985.500	-0.682	-0.708
1.300.1800.1	1799.95	295.06	981.200	0.234	0.217	0.319	979.120	979.160	0.212	0.208
1.300.1800.2	1797.06	294.87	978.524	0.235	0.218	0.320	978.880	978.920	-0.036	-0.040
1.300.1800.3	1794.66	294.96	977.632	0.235	0.218	0.320	978.950	978.990	-0.135	-0.139
1.300.1800.4	1793.38	294.85	977.632	0.235	0.218	0.320	978.820	978.860	-0.121	-0.125
1.300.2500.1	2445.74	289.77	999.040	0.232	0.203	0.308	997.110	996.900	0.194	0.215
1.300.2500.2	2442.65	289.70	999.932	0.232	0.203	0.308	996.850	996.640	0.309	0.330
1.300.2500.3	2440.69	289.55	999.932	0.232	0.205	0.309	996.580	996.380	0.336	0.356
1.300.2500.4	2441.85	289.57	999.932	0.232	0.205	0.309	996.680	996.470	0.326	0.347

Table 10-3. Mix 2 Density

Run No.	Pressure (psia)	Temp (degF)	Measured density (kg/m3)	Uncertainty - Meas rho (%)	Uncertainty - Ref rho (%)	Total Uncertainty (%)	Ref density - GERG (kg/m3)	Ref density - NIST (kg/m3)	Diff % - Meas vs. Ref rho GERG	Diff % - Meas vs. Ref rho NIST
2.100.200.1	205.93	97.58	24.934	0.071	1.010	1.012	25.434	25.434	-1.966	-1.966
2.100.200.2	208.90	100.10	25.561	0.071	1.006	1.008	25.683	25.684	-0.475	-0.478
2.100.200.3	204.32	98.55	25.211	0.071	1.014	1.017	25.169	25.169	0.168	0.167
2.100.800.2	805.33	99.14	128.686	0.066	2.512	2.513	126.950	126.948	1.368	1.369
2.100.800.3	798.16	100.68	123.611	0.066	2.533	2.534	124.410	124.400	-0.643	-0.635
2.100.1800.1	1792.76	102.16	645.690	0.066	7.205	7.205	634.390	634.228	1.781	1.807
2.100.1800.2	1793.00	100.05	658.771	0.066	7.000	7.001	649.910	649.625	1.363	1.408
2.100.1800.3	1809.75	102.78	645.536	0.066	7.183	7.183	635.090	634.914	1.645	1.673
2.100.2500.1	2491.32	99.13	783.000	0.066	3.203	3.204	768.350	768.356	1.907	1.906
2.100.2500.2	2492.35	100.75	776.865	0.066	3.232	3.233	762.350	762.353	1.904	1.904
2.200.200.1	200.92	199.61	19.201	0.074	1.467	1.469	20.378	20.379	-5.774	-5.778
2.200.200.3	201.63	200.01	21.083	0.073	1.462	1.464	20.438	20.439	3.153	3.148
2.200.800.1	799.43	198.39	92.587	0.066	2.403	2.404	90.482	90.481	2.327	2.328
2.200.800.2	806.19	198.58	91.358	0.066	2.384	2.385	91.325	91.323	0.036	0.038
2.200.800.3	803.71	199.33	92.348	0.066	2.395	2.396	90.833	90.830	1.668	1.672
2.200.1250.1	1250.70	199.01	157.954	0.066	3.483	3.484	155.010	154.985	1.899	1.916
2.200.1250.2	1252.45	200.03	156.832	0.066	3.488	3.488	154.760	154.740	1.339	1.352
2.200.1250.3	1253.15	200.96	150.010	0.066	3.493	3.494	154.410	154.399	-2.850	-2.843
2.200.1800.1	1796.64	200.46	257.980	0.066	4.143	4.143	249.080	249.154	3.573	3.542
2.200.1800.2	1805.90	200.30	258.838	0.066	4.115	4.115	251.040	251.102	3.106	3.081
2.200.1800.3	1797.34	200.38	257.419	0.066	4.140	4.141	249.310	249.368	3.253	3.229
2.200.2500.1	2496.72	200.86	399.965	0.066	7.110	7.110	389.730	389.850	2.626	2.595
2.200.2500.2	2500.22	200.81	403.469	0.066	7.095	7.096	390.540	390.662	3.310	3.278
2.200.2500.3	2491.14	202.22	398.904	0.066	7.180	7.180	385.660	385.785	3.434	3.401
2.300.200.1	199.19	296.69	16.241	0.078	1.377	1.380	17.376	17.378	-6.532	-6.541
2.300.200.1	202.41	299.06	17.198	0.076	1.362	1.364	17.603	17.604	-2.301	-2.308

2.300.800.1	805.30	297.28	75.686	0.067	1.839	1.841	74.398	74.401	1.732	1.727
2.300.800.2	804.39	296.69	75.152	0.067	1.840	1.841	74.385	74.388	1.031	1.027
2.300.800.3	805.51	298.70	75.396	0.067	1.842	1.844	74.233	74.236	1.567	1.562
2.300.1250.1	1251.97	296.77	126.914	0.066	2.273	2.274	120.700	120.832	5.148	5.034
2.300.1250.2	1250.77	296.88	124.954	0.066	2.276	2.277	120.550	120.675	3.653	3.546
2.300.1250.3	1240.18	295.87	123.465	0.066	2.291	2.292	119.660	119.783	3.180	3.074
2.300.1800.1	1807.14	299.90	188.320	0.066	2.852	2.853	181.730	181.981	3.626	3.483
2.300.1800.2	1805.67	296.77	191.188	0.066	2.835	2.836	182.940	183.202	4.509	4.359
2.300.1800.3	1801.76	297.32	190.413	0.066	2.845	2.846	182.240	182.497	4.484	4.337
2.300.2500.1	2508.88	299.34	277.769	0.066	3.523	3.524	265.450	265.986	4.641	4.430
2.300.2500.2	2499.62	299.67	275.690	0.066	3.539	3.540	264.090	264.622	4.392	4.182
2.300.2500.3	2490.24	301.35	273.106	0.066	3.570	3.570	261.720	262.240	4.350	4.143

Table 10-4. Mix 2 Speed of Sound

Run No.	Pressure (psia)	Temp (degF)	Measured SOS (Ft/s)	Uncertainty - Meas SOS (%)	Uncertainty - Ref SOS (%)	Total Uncertainty (%)	Ref SOS GERG (ft/s)	Ref SOS NIST (ft/s)	Diff % - Meas vs. Ref SOS GERG	Diff % - Meas vs. Ref SOS NIST
2.100.200.1	200.83	96.54	892.000	0.249	0.521	0.577	877.120	877.050	1.696	1.705
2.100.200.2	200.80	96.38	896.460	0.248	0.521	0.577	876.980	876.910	2.221	2.229
2.100.200.3	200.80	96.35	896.460	0.248	0.521	0.577	876.952	876.883	2.225	2.233
2.100.200.4	200.76	96.29	897.352	0.248	0.521	0.577	876.904	876.834	2.332	2.340
2.100.800.1	800.49	97.41	793.880	0.269	1.361	1.388	780.154	780.085	1.759	1.768
2.100.800.2	800.26	97.26	793.880	0.269	1.362	1.388	779.919	779.849	1.790	1.799
2.100.800.3	800.38	97.26	794.772	0.269	1.362	1.388	779.897	779.827	1.907	1.916
2.100.800.4	800.59	97.38	794.772	0.269	1.361	1.388	780.080	780.011	1.883	1.892
2.100.1800.1	1800.65	100.68	981.200	0.234	8.241	8.245	1017.130	1020.030	-3.532	-3.807
2.100.1800.2	1798.73	100.49	981.200	0.234	8.237	8.240	1018.210	1021.130	-3.635	-3.910
2.100.1800.3	1798.40	100.46	980.308	0.235	8.236	8.239	1018.360	1021.290	-3.737	-4.013
2.100.1800.4	1797.00	100.42	978.524	0.235	8.241	8.244	1017.820	1020.770	-3.861	-4.139
2.100.2000.1	2010.66	103.83	1150.680	0.214	11.156	11.159	1124.400	1123.600	2.337	2.410
2.100.2000.2	2007.45	103.97	1144.436	0.215	11.193	11.195	1120.700	1119.940	2.118	2.187

2.100.2000.3	2013.86	104.33	1134.624	0.216	11.193	11.195	1120.400	1119.600	1.270	1.342
2.100.2000.4	2014.18	104.26	1133.732	0.216	11.181	11.184	1121.500	1120.630	1.091	1.169
2.100.2500.1	2503.27	100.38	1489.640	0.190	8.832	8.834	1412.920	1410.920	5.430	5.579
2.100.2500.2	2502.94	100.25	1487.856	0.190	8.825	8.827	1414.130	1412.140	5.214	5.362
2.100.2500.3	2503.07	100.22	1487.856	0.190	8.822	8.824	1414.490	1412.510	5.187	5.334
2.100.2500.4	2503.04	100.23	1486.964	0.191	8.823	8.825	1414.380	1412.390	5.132	5.280
2.200.200.1	204.32	198.81	1007.960	0.231	0.863	0.893	961.600	961.543	4.821	4.827
2.200.200.2	203.68	198.50	1003.500	0.231	0.863	0.894	961.420	961.356	4.377	4.384
2.200.200.3	203.04	198.46	1007.960	0.231	0.863	0.893	961.440	961.376	4.839	4.846
2.200.200.4	204.48	198.65	1005.284	0.231	0.863	0.893	961.470	961.408	4.557	4.564
2.200.800.1	798.00	198.29	927.680	0.243	1.439	1.459	917.440	917.593	1.116	1.099
2.200.800.2	798.16	199.07	930.356	0.242	1.438	1.458	918.270	918.421	1.316	1.300
2.200.800.3	798.00	199.04	930.356	0.242	1.438	1.458	918.250	918.400	1.318	1.302
2.200.800.4	797.35	198.84	930.356	0.242	1.438	1.458	918.070	918.227	1.338	1.321
2.200.1250.1	1251.62	198.86	874.160	0.252	1.918	1.935	893.370	893.538	-2.150	-2.169
2.200.1250.2	1248.10	198.15	875.944	0.252	1.920	1.937	892.590	892.754	-1.865	-1.883
2.200.1250.3	1250.34	198.69	875.052	0.252	1.919	1.935	893.200	893.368	-2.032	-2.050
2.200.1250.4	1249.38	198.19	873.268	0.252	1.920	1.937	892.590	892.754	-2.165	-2.183
2.200.1800.1	1797.51	192.89	874.160	0.252	1.681	1.699	879.320	879.108	-0.587	-0.563
2.200.1800.2	1810.04	194.46	879.512	0.251	1.675	1.694	881.810	881.606	-0.261	-0.238
2.200.1800.3	1808.28	195.53	881.296	0.251	1.672	1.691	883.210	883.000	-0.217	-0.193
2.200.1800.4	1805.24	196.44	882.188	0.251	1.670	1.689	884.350	884.142	-0.244	-0.221
2.200.1800.5	1800.43	197.36	892.000	0.249	1.667	1.685	886.090	885.880	0.667	0.691
2.200.1800.6	1804.92	196.88	890.216	0.249	1.668	1.686	885.560	885.355	0.526	0.549
2.200.1800.7	1809.24	196.58	890.216	0.249	1.668	1.687	885.280	885.071	0.558	0.581
2.200.1800.8	1810.36	196.28	890.216	0.249	1.669	1.688	884.910	884.700	0.600	0.623
2.200.2500.1	2508.83	200.77	972.280	0.236	0.787	0.821	954.770	955.347	1.834	1.772
2.200.2500.2	2514.92	200.70	967.820	0.236	0.786	0.821	955.760	956.345	1.262	1.200
2.200.2500.3	2515.40	200.64	966.928	0.237	0.786	0.821	955.830	956.415	1.161	1.099
2.200.2500.4	2510.91	200.35	966.928	0.237	0.787	0.822	955.030	955.619	1.246	1.183
2.300.200.1	197.91	302.97	1052.560	0.225	0.804	0.835	1037.300	1037.170	1.471	1.484
2.300.200.2	198.23	303.10	1051.668	0.225	0.806	0.837	1037.300	1037.250	1.385	1.390
2.300.200.3	197.75	303.09	1052.560	0.225	0.804	0.835	1037.300	1037.260	1.471	1.475

2.300.200.4	197.43	302.82	1051.668	0.225	0.804	0.835	1037.200	1037.090	1.395	1.406
2.300.800.1	805.69	304.86	1025.800	0.228	1.119	1.142	1017.900	1017.970	0.776	0.769
2.300.800.2	804.41	305.20	1022.232	0.229	1.118	1.142	1018.200	1018.290	0.396	0.387
2.300.800.3	805.05	305.90	1023.124	0.229	1.118	1.141	1018.700	1018.860	0.434	0.419
2.300.800.4	804.08	305.85	1023.124	0.229	1.118	1.141	1018.700	1018.840	0.434	0.420
2.300.1250.1	1241.50	304.03	1025.800	0.228	1.342	1.362	1008.800	1009.000	1.685	1.665
2.300.1250.2	1242.49	304.32	1026.692	0.228	1.342	1.361	1009.000	1009.260	1.753	1.727
2.300.1250.3	1242.97	304.02	1023.124	0.229	1.342	1.362	1008.800	1008.970	1.420	1.403
2.300.1250.4	1242.81	304.47	1021.340	0.229	1.342	1.361	1009.200	1009.400	1.203	1.183
2.300.1800.1	1803.47	303.62	999.040	0.232	1.530	1.547	1009.300	1009.300	-1.017	-1.017
2.300.1800.2	1803.79	303.45	1003.500	0.231	1.530	1.548	1009.100	1009.130	-0.555	-0.558
2.300.1800.3	1802.99	303.25	1002.608	0.231	1.530	1.548	1008.900	1008.920	-0.624	-0.626
2.300.1800.4	1801.23	303.40	1003.500	0.231	1.530	1.548	1009.000	1009.040	-0.545	-0.549
2.300.2500.1	2503.38	296.18	1034.720	0.227	1.509	1.526	1027.000	1026.680	0.752	0.783
2.300.2500.2	2501.46	296.34	1034.720	0.227	1.508	1.525	1027.000	1026.710	0.752	0.780
2.300.2500.3	2504.18	295.42	1034.720	0.227	1.511	1.528	1026.300	1026.030	0.820	0.847
2.300.2500.4	2503.70	292.84	1027.584	0.228	1.514	1.531	1024.000	1023.650	0.350	0.384

Table 10-5. Mix 2 Specific Heat

Run No.	Temperature (degF)	Pressure (Mpa)	Measured Cv (J/kg-K)	Total Uncertainty (%)	Ref Cv GERG (J/kg-K)	Ref Cv NIST (J/kg-K)	Diff % - Meas vs Ref Cv GERG	Diff % - Meas vs Ref Cv NIST
2.100.200.1.cal1	99.452	163.678	691.077	1.017	689.006	688.896	0.301	0.317
2.100.200.1.cal2	99.452	163.678	689.642	1.017	689.006	688.896	0.092	0.108
2.100.200.1.cal3	99.452	163.678	671.478	1.017	689.006	688.896	-2.544	-2.528
2.100.200.1.cal4	99.452	163.678	683.694	1.017	689.006	688.896	-0.771	-0.755
2.100.200.2.cal1	99.554	163.672	700.863	1.017	689.043	688.933	1.715	1.732
2.100.200.2.cal2	99.554	163.672	699.408	1.017	689.043	688.933	1.504	1.520
2.100.200.2.cal3	99.554	163.672	680.986	1.017	689.043	688.933	-1.169	-1.154
2.100.200.2.cal4	99.554	163.672	693.375	1.017	689.043	688.933	0.629	0.645
2.100.200.3.cal1	99.724	163.651	686.834	1.017	689.104	688.994	-0.330	-0.314
2.100.200.3.cal2	99.724	163.651	692.809	1.017	689.104	688.994	0.538	0.554
2.100.200.3.cal3	99.724	163.651	674.561	1.017	689.104	688.994	-2.110	-2.095
2.100.200.3.cal4	99.724	163.651	686.834	1.017	689.104	688.994	-0.330	-0.314
2.100.200.4.cal1	99.744	163.515	699.129	1.017	689.093	688.983	1.456	1.473

2.100.200.4.cal2	99.744	163.515	697.678	1.017	689.093	688.983	1.246	1.262
2.100.200.4.cal3	99.744	163.515	679.301	1.017	689.093	688.983	-1.421	-1.405
2.100.200.4.cal4	99.744	163.515	691.660	1.017	689.093	688.983	0.373	0.389
2.100.800.1.cal1	99.957	634.956	775.086	2.559	766.312	766.928	1.145	1.064
2.100.800.1.cal2	99.957	634.956	762.247	2.560	766.312	766.928	-0.530	-0.610
2.100.800.1.cal3	99.957	634.956	769.291	2.559	766.312	766.928	0.389	0.308
2.100.800.1.cal4	99.957	634.956	769.554	2.559	766.312	766.928	0.423	0.342
2.100.800.2.cal1	100.123	634.666	765.465	2.560	766.174	766.783	-0.093	-0.172
2.100.800.2.cal2	100.123	634.666	752.785	2.560	766.174	766.783	-1.748	-1.826
2.100.800.2.cal3	100.123	634.666	759.742	2.560	766.174	766.783	-0.840	-0.918
2.100.800.2.cal4	100.123	634.666	760.002	2.560	766.174	766.783	-0.806	-0.884
2.100.800.3.cal1	100.001	634.361	772.484	2.559	766.171	766.784	0.824	0.743
2.100.800.3.cal2	100.001	634.361	759.688	2.560	766.171	766.784	-0.846	-0.925
2.100.800.3.cal3	100.001	634.361	766.708	2.560	766.171	766.784	0.070	-0.010
2.100.800.3.cal4	100.001	634.361	766.971	2.559	766.171	766.784	0.104	0.024
2.100.800.4.cal1	99.903	634.294	776.102	2.559	766.205	766.821	1.292	1.210
2.100.800.4.cal2	99.903	634.294	763.245	2.560	766.205	766.821	-0.386	-0.466
2.100.800.4.cal3	99.903	634.294	770.299	2.559	766.205	766.821	0.534	0.453
2.100.800.4.cal4	99.903	634.294	770.562	2.559	766.205	766.821	0.569	0.488
2.100.1250.1.cal1	101.036	989.837	819.903	3.389	854.869	856.702	-4.090	-4.295
2.100.1250.1.cal2	101.036	989.837	860.144	3.371	854.869	856.702	0.617	0.402
2.100.1250.1.cal3	101.036	989.837	860.201	3.371	854.869	856.702	0.624	0.408
2.100.1250.1.cal4	101.036	989.837	858.854	3.372	854.869	856.702	0.466	0.251
2.100.1250.2.cal1	101.348	989.906	825.945	3.386	854.151	855.965	-3.302	-3.507
2.100.1250.2.cal2	101.348	989.906	866.482	3.369	854.151	855.965	1.444	1.229
2.100.1250.2.cal3	101.348	989.906	866.540	3.369	854.151	855.965	1.450	1.235
2.100.1250.2.cal4	101.348	989.906	865.183	3.369	854.151	855.965	1.292	1.077
2.100.1250.3.cal1	101.221	989.506	818.904	3.390	854.321	856.142	-4.146	-4.350
2.100.1250.3.cal2	101.221	989.506	859.095	3.372	854.321	856.142	0.559	0.345
2.100.1250.3.cal3	101.221	989.506	859.153	3.372	854.321	856.142	0.566	0.352
2.100.1250.3.cal4	101.221	989.506	857.807	3.372	854.321	856.142	0.408	0.194
2.100.1250.4.cal1	101.503	989.380	833.663	3.383	853.621	855.420	-2.338	-2.543
2.100.1250.4.cal2	101.503	989.380	874.579	3.365	853.621	855.420	2.455	2.240
2.100.1250.4.cal3	101.503	989.380	874.637	3.365	853.621	855.420	2.462	2.247
2.100.1250.4.cal4	101.503	989.380	873.268	3.366	853.621	855.420	2.302	2.086
2.100.2500.1.cal2	100.084	1959.943	948.129	4.067	941.205	938.545	0.736	1.021
2.100.2500.1.cal3	100.084	1959.943	930.443	4.096	941.205	938.545	-1.143	-0.863
2.100.2500.1.cal4	100.084	1959.943	938.374	4.083	941.205	938.545	-0.301	-0.018

2.100.2500.1.cal5	100.084	1959.943	932.709	4.092	941.205	938.545	-0.903	-0.622
2.100.2500.2.cal2	99.846	1956.868	950.097	4.064	941.243	938.548	0.941	1.231
2.100.2500.2.cal3	99.846	1956.868	932.375	4.093	941.243	938.548	-0.942	-0.658
2.100.2500.2.cal4	99.846	1956.868	940.323	4.080	941.243	938.548	-0.098	0.189
2.100.2500.2.cal5	99.846	1956.868	934.646	4.089	941.243	938.548	-0.701	-0.416
2.100.2500.3.cal2	100.107	1957.443	955.451	4.056	941.477	938.771	1.484	1.777
2.100.2500.3.cal3	100.107	1957.443	937.629	4.084	941.477	938.771	-0.409	-0.122
2.100.2500.3.cal4	100.107	1957.443	945.621	4.071	941.477	938.771	0.440	0.730
2.100.2500.3.cal5	100.107	1957.443	939.912	4.081	941.477	938.771	-0.166	0.122
2.100.2500.4.cal2	100.010	1960.956	954.546	4.057	941.025	938.388	1.437	1.722
2.100.2500.4.cal3	100.010	1960.956	936.741	4.086	941.025	938.388	-0.455	-0.176
2.100.2500.4.cal4	100.010	1960.956	944.726	4.073	941.025	938.388	0.393	0.675
2.100.2500.4.cal5	100.010	1960.956	939.022	4.082	941.025	938.388	-0.213	0.067
2.200.200.1.cal1	199.356	162.649	730.438	1.469	729.523	729.456	0.125	0.135
2.200.200.1.cal3	199.356	162.649	757.480	1.469	729.523	729.456	3.832	3.842
2.200.200.1.cal4	199.356	162.649	746.865	1.469	729.523	729.456	2.377	2.387
2.200.200.1.cal5	199.356	162.649	749.768	1.469	729.523	729.456	2.775	2.785
2.200.200.2.cal1	199.249	162.632	736.975	1.469	729.477	729.410	1.028	1.037
2.200.200.2.cal3	199.249	162.632	764.259	1.469	729.477	729.410	4.768	4.778
2.200.200.2.cal4	199.249	162.632	753.548	1.469	729.477	729.410	3.300	3.309
2.200.200.2.cal5	199.249	162.632	756.478	1.469	729.477	729.410	3.701	3.711
2.200.200.3.cal1	199.501	162.643	688.785	1.469	729.584	729.516	-5.592	-5.583
2.200.200.3.cal3	199.501	162.643	714.285	1.469	729.584	729.516	-2.097	-2.088
2.200.200.3.cal4	199.501	162.643	704.275	1.469	729.584	729.516	-3.469	-3.460
2.200.200.3.cal5	199.501	162.643	707.013	1.469	729.584	729.516	-3.094	-3.085
2.200.200.4.cal1	199.488	162.598	703.240	1.469	729.575	729.508	-3.610	-3.601
2.200.200.4.cal3	199.488	162.598	729.275	1.469	729.575	729.508	-0.041	-0.032
2.200.200.4.cal4	199.488	162.598	719.055	1.469	729.575	729.508	-1.442	-1.433
2.200.200.4.cal5	199.488	162.598	721.850	1.469	729.575	729.508	-1.059	-1.050
2.200.800.1.cal1	199.397	631.677	761.641	2.420	762.217	761.970	-0.076	-0.043
2.200.800.1.cal2	199.397	631.677	762.724	2.420	762.217	761.970	0.067	0.099
2.200.800.1.cal3	199.397	631.677	755.696	2.420	762.217	761.970	-0.856	-0.823
2.200.800.1.cal4	199.397	631.677	768.682	2.419	762.217	761.970	0.848	0.881
2.200.800.2.cal1	199.598	631.249	768.004	2.419	762.224	761.977	0.758	0.791
2.200.800.2.cal2	199.598	631.249	769.096	2.419	762.224	761.977	0.902	0.934
2.200.800.2.cal3	199.598	631.249	762.009	2.420	762.224	761.977	-0.028	0.004
2.200.800.2.cal4	199.598	631.249	775.103	2.419	762.224	761.977	1.690	1.723
2.200.800.3.cal1	199.614	631.105	761.677	2.420	762.216	761.969	-0.071	-0.038
2.200.800.3.cal2	199.614	631.105	762.761	2.420	762.216	761.969	0.071	0.104

2.200.800.3.cal3	199.614	631.105	755.732	2.420	762.216	761.969	-0.851	-0.819
2.200.800.3.cal4	199.614	631.105	768.718	2.419	762.216	761.969	0.853	0.886
2.200.800.4.cal1	199.641	630.976	755.580	2.420	762.212	761.965	-0.870	-0.838
2.200.800.4.cal2	199.641	630.976	756.655	2.420	762.212	761.965	-0.729	-0.697
2.200.800.4.cal3	199.641	630.976	749.683	2.420	762.212	761.965	-1.644	-1.612
2.200.800.4.cal4	199.641	630.976	762.565	2.420	762.212	761.965	0.046	0.079
2.200.1250.1.cal1	200.026	985.102	793.146	3.555	788.950	788.619	0.532	0.574
2.200.1250.1.cal2	200.026	985.102	794.397	3.555	788.950	788.619	0.690	0.733
2.200.1250.1.cal3	200.026	985.102	796.738	3.555	788.950	788.619	0.987	1.030
2.200.1250.1.cal4	200.026	985.102	805.753	3.553	788.950	788.619	2.130	2.173
2.200.1250.2.cal1	199.675	984.616	781.069	3.557	788.922	788.592	-0.995	-0.954
2.200.1250.2.cal2	199.675	984.616	782.301	3.557	788.922	788.592	-0.839	-0.798
2.200.1250.2.cal3	199.675	984.616	784.606	3.556	788.922	788.592	-0.547	-0.505
2.200.1250.2.cal4	199.675	984.616	793.484	3.555	788.922	788.592	0.578	0.620
2.200.1250.3.cal1	200.034	985.416	793.648	3.555	788.974	788.643	0.592	0.635
2.200.1250.3.cal2	200.034	985.416	794.900	3.555	788.974	788.643	0.751	0.793
2.200.1250.3.cal3	200.034	985.416	797.242	3.555	788.974	788.643	1.048	1.090
2.200.1250.3.cal4	200.034	985.416	806.263	3.553	788.974	788.643	2.191	2.234
2.200.1250.4.cal1	199.994	984.519	785.411	3.556	788.906	788.575	-0.443	-0.401
2.200.1250.4.cal2	199.994	984.519	786.650	3.556	788.906	788.575	-0.286	-0.244
2.200.1250.4.cal3	199.994	984.519	788.968	3.556	788.906	788.575	0.008	0.050
2.200.1250.4.cal4	199.994	984.519	797.895	3.554	788.906	788.575	1.139	1.182
2.200.1800.1.cal1	200.021	1417.562	812.132	4.320	822.692	822.352	-1.284	-1.243
2.200.1800.1.cal2	200.021	1417.562	818.306	4.317	822.692	822.352	-0.533	-0.492
2.200.1800.1.cal3	200.021	1417.562	823.613	4.315	822.692	822.352	0.112	0.153
2.200.1800.1.cal4	200.021	1417.562	821.852	4.316	822.692	822.352	-0.102	-0.061
2.200.1800.2.cal1	199.465	1415.905	811.609	4.320	822.753	822.414	-1.354	-1.314
2.200.1800.2.cal2	199.465	1415.905	817.779	4.317	822.753	822.414	-0.605	-0.564
2.200.1800.2.cal3	199.465	1415.905	823.083	4.315	822.753	822.414	0.040	0.081
2.200.1800.2.cal4	199.465	1415.905	821.323	4.316	822.753	822.414	-0.174	-0.133
2.200.1800.3.cal1	199.746	1415.828	815.118	4.319	822.651	822.311	-0.916	-0.875
2.200.1800.3.cal2	199.746	1415.828	821.315	4.316	822.651	822.311	-0.162	-0.121
2.200.1800.3.cal3	199.746	1415.828	826.642	4.314	822.651	822.311	0.485	0.527
2.200.1800.3.cal4	199.746	1415.828	824.874	4.315	822.651	822.311	0.270	0.312
2.200.1800.4.cal1	199.630	1416.071	824.676	4.315	822.709	822.370	0.239	0.280
2.200.1800.4.cal2	199.630	1416.071	830.945	4.312	822.709	822.370	1.001	1.043
2.200.1800.4.cal3	199.630	1416.071	836.334	4.310	822.709	822.370	1.656	1.698
2.200.1800.4.cal4	199.630	1416.071	834.546	4.311	822.709	822.370	1.439	1.481

2.200.2500.1.cal2	199.672	1968.567	861.546	7.846	862.153	861.754	-0.070	-0.024
2.200.2500.1.cal3	199.672	1968.567	857.967	7.851	862.153	861.754	-0.486	-0.440
2.200.2500.1.cal4	199.672	1968.567	861.953	7.845	862.153	861.754	-0.023	0.023
2.200.2500.2.cal2	199.924	1969.065	863.861	7.842	862.010	861.614	0.215	0.261
2.200.2500.2.cal3	199.924	1969.065	860.273	7.848	862.010	861.614	-0.202	-0.156
2.200.2500.2.cal4	199.924	1969.065	864.270	7.842	862.010	861.614	0.262	0.308
2.200.2500.3.cal2	199.608	1967.760	862.483	7.844	862.148	861.749	0.039	0.085
2.200.2500.3.cal3	199.608	1967.760	858.900	7.850	862.148	861.749	-0.377	-0.331
2.200.2500.3.cal4	199.608	1967.760	862.891	7.844	862.148	861.749	0.086	0.132
2.200.2500.4.cal2	199.696	1967.938	864.778	7.841	862.098	861.701	0.311	0.357
2.200.2500.4.cal3	199.696	1967.938	861.186	7.846	862.098	861.701	-0.106	-0.060
2.200.2500.4.cal4	199.696	1967.938	865.187	7.840	862.098	861.701	0.358	0.405
2.300.200.1.cal1	299.395	162.634	776.465	1.380	770.626	770.643	0.758	0.755
2.300.200.1.cal2	299.395	162.634	796.075	1.380	770.626	770.643	3.302	3.300
2.300.200.1.cal3	299.395	162.634	758.481	1.380	770.626	770.643	-1.576	-1.578
2.300.200.1.cal4	299.395	162.634	774.983	1.380	770.626	770.643	0.565	0.563
2.300.200.2.cal1	299.343	162.524	763.691	1.380	770.601	770.619	-0.897	-0.899
2.300.200.2.cal2	299.343	162.524	782.978	1.380	770.601	770.619	1.606	1.604
2.300.200.2.cal3	299.343	162.524	746.003	1.380	770.601	770.619	-3.192	-3.194
2.300.200.2.cal4	299.343	162.524	762.234	1.380	770.601	770.619	-1.086	-1.088
2.300.200.3.cal1	299.385	162.671	790.625	1.380	770.623	770.641	2.596	2.593
2.300.200.3.cal2	299.385	162.671	810.592	1.380	770.623	770.641	5.187	5.184
2.300.200.3.cal3	299.385	162.671	772.313	1.380	770.623	770.641	0.219	0.217
2.300.200.3.cal4	299.385	162.671	789.116	1.380	770.623	770.641	2.400	2.397
2.300.200.4.cal1	299.321	162.683	753.434	1.380	770.598	770.616	-2.227	-2.230
2.300.200.4.cal2	299.321	162.683	772.462	1.380	770.598	770.616	0.242	0.240
2.300.200.4.cal3	299.321	162.683	735.983	1.380	770.598	770.616	-4.492	-4.494
2.300.200.4.cal4	299.321	162.683	751.996	1.380	770.598	770.616	-2.414	-2.416
2.300.800.2.cal1	299.776	631.841	790.636	1.851	788.180	788.176	0.312	0.312
2.300.800.2.cal2	299.776	631.841	788.072	1.851	788.180	788.176	-0.014	-0.013
2.300.800.2.cal3	299.776	631.841	784.131	1.851	788.180	788.176	-0.514	-0.513
2.300.800.2.cal4	299.776	631.841	799.310	1.851	788.180	788.176	1.412	1.413
2.300.800.3.cal1	299.602	631.622	786.539	1.851	788.119	788.115	-0.201	-0.200
2.300.800.3.cal2	299.602	631.622	783.988	1.851	788.119	788.115	-0.524	-0.524
2.300.800.3.cal3	299.602	631.622	780.067	1.851	788.119	788.115	-1.022	-1.021
2.300.800.3.cal4	299.602	631.622	795.167	1.851	788.119	788.115	0.894	0.895
2.300.800.4.cal1	299.580	631.851	787.669	1.851	788.121	788.117	-0.057	-0.057
2.300.800.4.cal2	299.580	631.851	785.115	1.851	788.121	788.117	-0.381	-0.381
2.300.800.4.cal3	299.580	631.851	781.188	1.851	788.121	788.117	-0.880	-0.879

2.300.800.4.cal4	299.580	631.851	796.310	1.851	788.121	788.117	1.039	1.040
2.300.1250.1.cal1	299.291	985.351	772.563	2.317	801.486	801.415	-3.609	-3.600
2.300.1250.1.cal2	299.291	985.351	803.086	2.315	801.486	801.415	0.200	0.209
2.300.1250.1.cal3	299.291	985.351	811.915	2.315	801.486	801.415	1.301	1.310
2.300.1250.1.cal4	299.291	985.351	810.722	2.315	801.486	801.415	1.152	1.161
2.300.1250.2.cal1	299.049	985.107	768.185	2.317	801.423	801.351	-4.147	-4.139
2.300.1250.2.cal2	299.049	985.107	798.535	2.315	801.423	801.351	-0.360	-0.351
2.300.1250.2.cal3	299.049	985.107	807.314	2.315	801.423	801.351	0.735	0.744
2.300.1250.2.cal4	299.049	985.107	806.128	2.315	801.423	801.351	0.587	0.596
2.300.1250.3.cal1	299.511	985.940	777.222	2.317	801.557	801.486	-3.036	-3.027
2.300.1250.3.cal2	299.511	985.940	807.930	2.315	801.557	801.486	0.795	0.804
2.300.1250.3.cal3	299.511	985.940	816.812	2.314	801.557	801.486	1.903	1.912
2.300.1250.3.cal4	299.511	985.940	815.612	2.314	801.557	801.486	1.754	1.762
2.300.1250.4.cal1	299.758	985.282	781.165	2.316	801.586	801.517	-2.548	-2.539
2.300.1250.4.cal2	299.758	985.282	812.028	2.315	801.586	801.517	1.303	1.311
2.300.1250.4.cal3	299.758	985.282	820.956	2.314	801.586	801.517	2.416	2.425
2.300.1250.4.cal4	299.758	985.282	819.750	2.314	801.586	801.517	2.266	2.275
2.300.1800.1.cal1	299.618	1417.011	823.297	2.917	817.799	817.620	0.672	0.694
2.300.1800.1.cal2	299.618	1417.011	813.515	2.918	817.799	817.620	-0.524	-0.502
2.300.1800.1.cal3	299.618	1417.011	814.504	2.918	817.799	817.620	-0.403	-0.381
2.300.1800.1.cal4	299.618	1417.011	805.041	2.920	817.799	817.620	-1.560	-1.538
2.300.1800.2.cal1	299.897	1417.160	825.826	2.916	817.839	817.661	0.977	0.999
2.300.1800.2.cal2	299.897	1417.160	816.015	2.918	817.839	817.661	-0.223	-0.201
2.300.1800.2.cal3	299.897	1417.160	817.006	2.918	817.839	817.661	-0.102	-0.080
2.300.1800.2.cal4	299.897	1417.160	807.515	2.919	817.839	817.661	-1.262	-1.241
2.300.1800.3.cal1	299.780	1416.843	847.716	2.913	817.813	817.635	3.656	3.679
2.300.1800.3.cal2	299.780	1416.843	837.644	2.915	817.813	817.635	2.425	2.447
2.300.1800.3.cal3	299.780	1416.843	838.662	2.915	817.813	817.635	2.549	2.572
2.300.1800.3.cal4	299.780	1416.843	828.919	2.916	817.813	817.635	1.358	1.380
2.300.1800.4.cal1	299.526	1416.743	812.383	2.919	817.778	817.599	-0.660	-0.638
2.300.1800.4.cal2	299.526	1416.743	802.731	2.920	817.778	817.599	-1.840	-1.819
2.300.1800.4.cal3	299.526	1416.743	803.706	2.920	817.778	817.599	-1.721	-1.699
2.300.1800.4.cal4	299.526	1416.743	794.369	2.922	817.778	817.599	-2.862	-2.841
2.300.2500.1.cal1	299.738	1962.779	832.225	3.734	837.003	836.740	-0.571	-0.540
2.300.2500.1.cal2	299.738	1962.779	835.091	3.733	837.003	836.740	-0.228	-0.197
2.300.2500.1.cal3	299.738	1962.779	842.723	3.730	837.003	836.740	0.683	0.715
2.300.2500.1.cal4	299.738	1962.779	827.445	3.736	837.003	836.740	-1.142	-1.111
2.300.2500.2.cal1	299.459	1962.207	834.961	3.733	836.981	836.718	-0.241	-0.210

2.300.2500.2.cal2	299.459	1962.207	837.836	3.732	836.981	836.718	0.102	0.134
2.300.2500.2.cal3	299.459	1962.207	845.494	3.729	836.981	836.718	1.017	1.049
2.300.2500.2.cal4	299.459	1962.207	830.165	3.735	836.981	836.718	-0.814	-0.783
2.300.2500.3.cal1	299.606	1962.310	837.452	3.732	836.986	836.723	0.056	0.087
2.300.2500.3.cal2	299.606	1962.310	840.336	3.731	836.986	836.723	0.400	0.432
2.300.2500.3.cal3	299.606	1962.310	848.017	3.728	836.986	836.723	1.318	1.350
2.300.2500.3.cal4	299.606	1962.310	832.642	3.734	836.986	836.723	-0.519	-0.488

Table 10-6. Mix 3 Density

Run No.	Pressure (psia)	Temp (degF)	Measured density (kg/m3)	Uncertainty - Meas rho (%)	Uncertainty - Ref rho (%)	Total Uncertainty (%)	Ref density - GERG (kg/m3)	Ref density - NIST (kg/m3)	Diff % - Meas vs. Ref rho GERG	Diff % - Meas vs. Ref rho NIST
3.100.200.2	207.06	103.89	26.003	0.071	2.215	2.216	26.456	26.460	-1.711	-1.726
3.100.200.3	203.96	103.60	26.059	0.071	2.246	2.247	26.047	26.051	0.048	0.032
3.100.800.1	802.14	104.83	139.360	0.066	5.756	5.757	139.120	138.720	0.172	0.461
3.100.800.2	797.63	103.73	138.162	0.066	5.772	5.772	138.780	138.370	-0.446	-0.151
3.100.800.3	807.22	104.92	139.389	0.066	5.706	5.707	140.500	140.070	-0.790	-0.486
3.100.1800.1	1809.14	105.81	777.449	0.066	1.366	1.368	726.390	726.360	7.029	7.034
3.100.1800.2	1804.96	100.89	804.848	0.066	1.239	1.241	748.490	748.470	7.530	7.532
3.100.1800.3	1800.02	100.86	807.733	0.066	1.245	1.247	747.980	747.980	7.989	7.989
3.100.2500.1	2503.63	100.27	875.320	0.066	0.919	0.921	815.650	815.590	7.316	7.324
3.100.2500.2	2508.50	97.96	880.980	0.066	0.901	0.904	822.890	822.800	7.059	7.071
3.100.2500.3	2505.24	101.76	864.092	0.066	0.930	0.932	811.250	811.200	6.514	6.520
3.200.200.1	206.05	204.33	21.680	0.073	2.033	2.034	21.643	21.643	0.170	0.170
3.200.200.2	207.11	203.78	21.805	0.073	2.022	2.023	21.779	21.780	0.121	0.116
3.200.200.3	207.25	204.41	21.759	0.073	2.023	2.024	21.771	21.771	-0.055	-0.055
3.200.800.1	803.91	205.38	96.558	0.066	2.921	2.921	95.559	95.465	1.045	1.145
3.200.800.2	803.29	204.78	96.455	0.066	2.919	2.920	95.620	95.527	0.874	0.972
3.200.800.3	804.26	205.59	96.386	0.066	2.921	2.922	95.556	95.462	0.869	0.968
3.200.1250.1	1240.74	204.46	173.568	0.066	3.898	3.899	165.320	164.670	4.989	5.403

3.200.1800.1	1797.47	204.96	285.125	0.066	5.141	5.141	277.010	277.070	2.930	2.907
3.200.1800.2	1765.42	206.31	274.508	0.066	5.294	5.294	268.000	268.050	2.428	2.409
3.200.2500.1	2507.23	195.01	490.363	0.066	4.018	4.019	471.940	471.840	3.904	3.926
3.200.2500.2	2506.36	196.13	493.911	0.066	4.044	4.045	468.250	468.150	5.480	5.503
3.200.2500.3	2505.29	198.73	474.277	0.066	4.102	4.103	460.070	459.960	3.088	3.113
3.300.200.1	207.17	298.50	18.805	0.075	1.914	1.915	18.789	18.788	0.087	0.092
3.300.200.2	200.43	296.85	17.970	0.076	1.967	1.969	18.207	18.207	-1.300	-1.300
3.300.200.3	206.29	295.60	20.422	0.073	1.913	1.914	18.786	18.785	8.711	8.717
3.300.800.1	804.39	304.97	78.106	0.067	2.361	2.362	77.263	77.187	1.091	1.190
3.300.800.2	805.14	304.33	76.389	0.067	2.357	2.358	77.431	77.356	-1.345	-1.249
3.300.800.3	806.45	299.52	78.752	0.067	2.333	2.334	78.356	78.276	0.506	0.609
3.300.1250.1	1247.79	297.79	136.736	0.066	2.636	2.637	128.290	127.950	6.584	6.867
3.300.1250.2	1244.27	306.23	133.284	0.066	2.686	2.687	125.530	125.210	6.177	6.448
3.300.1250.3	1242.82	303.20	128.055	0.066	2.674	2.675	126.190	125.860	1.478	1.744
3.300.1800.1	1797.09	304.39	201.614	0.066	2.988	2.988	193.080	192.050	4.420	4.980
3.300.1800.2	1791.27	299.40	204.472	0.066	2.965	2.966	194.920	193.860	4.900	5.474
3.300.1800.3	1810.22	298.89	205.465	0.066	2.928	2.929	197.670	196.570	3.944	4.525
3.300.2500.1	2504.64	300.34	305.901	0.066	3.073	3.074	287.840	287.900	6.275	6.253
3.300.2500.2	2495.01	301.39	300.211	0.066	3.095	3.095	285.590	285.660	5.120	5.094
3.300.2500.3	2500.13	300.68	300.997	0.066	3.082	3.082	286.920	286.980	4.906	4.884

Table 10-7. Mix 3 Speed of Sound

Run No.	Pressure (psia)	Temp (degF)	Measured SOS (Ft/s)	Uncertainty - Meas SOS (%)	Uncertainty - Ref SOS (%)	Total Uncertainty (%)	Ref SOS GERG (ft/s)	Ref SOS NIST (ft/s)	Diff % - Meas vs. Ref SOS GERG	Diff % - Meas vs. Ref SOS NIST
3.100.200.1	204.75	97.24	883.080	0.250	1.172	1.199	853.540	853.460	3.461	3.471
3.100.200.2	204.73	97.33	882.188	0.251	1.172	1.198	853.630	853.540	3.345	3.356
3.100.200.3	204.73	97.39	882.188	0.251	1.172	1.198	853.680	853.600	3.339	3.349
3.100.200.4	204.75	97.40	883.080	0.250	1.172	1.198	853.690	853.600	3.443	3.454
3.100.800.1	798.19	101.26	758.200	0.278	2.629	2.644	737.530	737.320	2.803	2.832
3.100.800.2	805.66	101.71	759.984	0.277	2.633	2.648	736.700	736.490	3.161	3.190

3.100.800.3	793.70	101.89	759.092	0.278	2.617	2.632	740.040	739.840	2.574	2.602
3.100.800.4	794.32	101.85	760.876	0.277	2.618	2.633	739.800	739.600	2.849	2.877
3.100.1800.1	1808.01	103.27	1204.200	0.209	4.953	4.958	1286.700	1286.400	-6.412	-6.390
3.100.1800.2	1807.01	103.22	1206.876	0.209	4.953	4.957	1286.800	1286.500	-6.211	-6.189
3.100.1800.3	1806.40	103.21	1205.984	0.209	4.954	4.958	1286.500	1286.300	-6.259	-6.244
3.100.1800.4	1806.04	103.22	1205.092	0.209	4.956	4.960	1286.200	1285.900	-6.306	-6.284
3.100.2500.1	2509.63	100.80	1754.296	0.180	2.881	2.886	1631.800	1632.100	7.507	7.487
3.100.2500.2	2506.80	101.38	1749.212	0.180	2.893	2.899	1624.700	1625.000	7.664	7.644
3.100.2500.3	2501.68	101.76	1746.536	0.180	2.903	2.909	1618.800	1619.100	7.891	7.871
3.100.2500.4	2501.47	102.08	1743.860	0.180	2.910	2.915	1615.400	1615.600	7.952	7.939
3.200.200.1	201.78	195.36	963.360	0.237	1.044	1.070	936.000	935.930	2.923	2.931
3.200.200.2	201.90	196.11	964.252	0.237	1.043	1.070	936.560	936.490	2.957	2.964
3.200.200.3	201.92	196.31	965.144	0.237	1.043	1.070	936.710	936.640	3.036	3.043
3.200.200.4	201.92	196.60	965.144	0.237	1.043	1.069	936.930	936.870	3.011	3.018
3.200.800.1	797.60	198.81	900.920	0.247	1.379	1.401	885.200	885.360	1.776	1.757
3.200.800.2	797.01	198.32	901.812	0.247	1.380	1.402	884.690	884.850	1.935	1.917
3.200.800.3	796.63	198.12	901.812	0.247	1.381	1.403	884.490	884.650	1.958	1.940
3.200.800.4	796.18	197.90	902.704	0.247	1.381	1.403	884.280	884.440	2.084	2.065
3.200.1250.1	1241.50	196.30	856.320	0.256	1.508	1.530	851.050	851.160	0.619	0.606
3.200.1250.2	1245.08	197.10	858.996	0.255	1.506	1.528	852.030	852.140	0.818	0.805
3.200.1250.3	1246.13	197.38	858.996	0.255	1.506	1.527	852.380	852.490	0.776	0.763
3.200.1250.4	1246.88	197.55	858.996	0.255	1.505	1.526	852.580	852.700	0.753	0.738
3.200.1800.1	1794.98	195.75	838.480	0.259	1.538	1.560	847.930	847.890	-1.114	-1.110
3.200.1800.2	1805.40	197.18	844.724	0.258	1.533	1.554	850.410	850.380	-0.669	-0.665
3.200.1800.3	1800.66	198.21	846.508	0.258	1.531	1.553	851.450	851.400	-0.580	-0.575
3.200.1800.4	1803.66	198.73	845.616	0.258	1.530	1.551	852.300	852.250	-0.784	-0.778
3.200.2500.1	2503.36	203.40	963.360	0.237	1.374	1.394	967.720	968.530	-0.451	-0.534
3.200.2500.2	2502.29	204.80	961.576	0.237	1.372	1.392	966.150	966.970	-0.473	-0.558
3.200.2500.3	2495.88	204.25	959.792	0.238	1.374	1.394	965.060	965.870	-0.546	-0.629
3.200.2500.4	2494.81	204.29	959.792	0.238	1.374	1.394	964.760	965.570	-0.515	-0.598
3.300.200.1	199.33	294.97	1025.800	0.228	1.273	1.294	1008.100	1008.100	1.756	1.756
3.300.200.2	199.89	295.30	1026.692	0.228	1.273	1.293	1008.300	1008.200	1.824	1.834
3.300.200.3	200.06	295.98	1027.584	0.228	1.273	1.294	1008.800	1008.700	1.862	1.872

3.300.200.4	200.10	296.34	1027.584	0.228	1.273	1.294	1009.000	1008.900	1.842	1.852
3.300.800.1	796.82	296.45	990.120	0.233	1.313	1.333	981.890	982.030	0.838	0.824
3.300.800.2	796.02	295.88	989.228	0.233	1.313	1.334	981.420	981.560	0.796	0.781
3.300.800.3	795.43	295.43	989.228	0.233	1.314	1.334	981.050	981.190	0.834	0.819
3.300.800.4	794.50	294.65	988.336	0.233	1.315	1.335	980.400	980.540	0.809	0.795
3.300.1250.1	1247.20	299.80	972.280	0.236	1.329	1.349	972.690	972.930	-0.042	-0.067
3.300.1250.2	1245.32	299.34	968.712	0.236	1.329	1.350	972.270	972.510	-0.366	-0.391
3.300.1250.3	1243.77	298.90	968.712	0.236	1.330	1.351	971.860	972.100	-0.324	-0.349
3.300.1250.4	1242.18	298.64	968.712	0.236	1.330	1.351	971.630	971.870	-0.300	-0.325
3.300.1800.1	1790.52	300.82	972.280	0.236	1.329	1.350	973.630	973.610	-0.139	-0.137
3.300.1800.2	1798.62	300.63	973.172	0.236	1.329	1.350	973.580	973.560	-0.042	-0.040
3.300.1800.3	1796.79	300.41	972.280	0.236	1.330	1.350	973.310	973.290	-0.106	-0.104
3.300.1800.4	1795.30	300.13	972.280	0.236	1.330	1.351	972.990	972.970	-0.073	-0.071
3.300.2500.1	2500.16	297.60	1007.960	0.231	1.287	1.308	1003.700	1003.600	0.424	0.434
3.300.2500.2	2504.94	298.24	1004.392	0.231	1.286	1.307	1004.600	1004.500	-0.021	-0.011
3.300.2500.3	2495.14	298.76	1003.500	0.231	1.287	1.307	1004.300	1004.200	-0.080	-0.070
3.300.2500.4	2497.23	299.19	1004.392	0.231	1.285	1.306	1004.800	1004.700	-0.041	-0.031

Table 10-8. Mix 4 Density

Run No.	Pressure (psia)	Temp (degF)	Measured density (kg/m3)	Uncertainty - Meas rho (%)	Uncertainty - Ref rho (%)	Total Uncertainty (%)	Ref density - GERG (kg/m3)	Ref density - NIST (kg/m3)	Diff % - Meas vs. Ref rho GERG	Diff % - Meas vs. Ref rho NIST
4.100.200.1	196.85	99.35	24.198	0.071	1.157	1.159	23.149	23.149	4.532	4.532
4.100.200.2	209.24	100.17	24.294	0.071	1.111	1.113	24.645	24.645	-1.425	-1.425
4.100.200.3	200.93	101.35	23.053	0.072	1.142	1.144	23.555	23.556	-2.132	-2.134
4.100.800.1	805.17	99.18	116.356	0.066	2.127	2.128	115.470	115.461	0.768	0.776
4.100.800.2	806.27	101.15	115.508	0.066	2.133	2.134	114.770	114.760	0.643	0.652
4.100.800.3	805.63	101.28	115.908	0.066	2.134	2.135	114.590	114.585	1.150	1.154
4.100.1250.1	1247.14	102.73	221.677	0.066	4.499	4.500	216.140	216.116	2.562	2.573
4.100.1250.2	1243.90	99.84	224.401	0.066	4.464	4.464	219.850	219.831	2.070	2.079
4.100.1250.3	1244.09	100.08	223.604	0.066	4.467	4.467	219.510	219.495	1.865	1.872
4.100.2500.1	2499.61	101.60	633.053	0.066	9.878	9.879	615.641	615.684	2.828	2.821

4.100.2500.2	2499.14	99.21	640.759	0.066	9.697	9.697	627.159	625.439	2.169	2.449
4.100.2500.3	2489.27	100.21	632.482	0.066	9.789	9.789	621.333	619.637	1.794	2.073
4.200.200.1	204.81	197.30	20.422	0.073	1.034	1.037	20.047	20.048	1.873	1.866
4.200.200.2	208.81	199.41	20.287	0.074	1.024	1.027	20.378	20.379	-0.446	-0.452
4.200.200.3	201.60	197.61	18.502	0.075	1.045	1.048	19.714	19.716	-6.150	-6.157
4.200.800.1	801.37	200.39	88.389	0.066	1.432	1.433	85.131	85.130	3.828	3.829
4.200.800.2	798.65	199.91	85.827	0.066	1.434	1.436	84.899	84.897	1.093	1.095
4.200.800.3	799.02	198.78	86.010	0.066	1.433	1.434	85.163	85.161	0.994	0.997
4.200.1250.1	1250.97	200.51	144.053	0.066	1.834	1.836	142.450	142.429	1.125	1.140
4.200.1250.2	1253.21	202.32	143.980	0.066	1.838	1.839	142.020	141.999	1.380	1.395
4.200.1250.3	1254.65	201.75	144.644	0.066	1.832	1.834	142.440	142.424	1.547	1.558
4.200.1800.1	1806.23	203.34	227.696	0.066	2.448	2.449	221.520	221.527	2.788	2.785
4.200.1800.2	1799.62	202.18	232.413	0.066	2.450	2.451	221.440	221.441	4.955	4.955
4.200.1800.3	1798.02	204.03	219.640	0.066	2.463	2.464	219.720	219.721	-0.036	-0.037
4.200.2500.1	2500.82	200.78	343.584	0.066	3.107	3.108	335.490	335.564	2.413	2.390
4.200.2500.2	2496.97	200.58	343.538	0.066	3.111	3.112	335.170	335.238	2.497	2.476
4.200.2500.3	2496.33	202.35	341.838	0.066	3.130	3.131	332.490	332.557	2.812	2.791
4.300.200.1	205.38	302.20	16.531	0.077	1.716	1.718	17.098	17.099	-3.314	-3.317
4.300.200.2	207.60	300.59	17.208	0.076	1.695	1.696	17.324	17.326	-0.670	-0.680
4.300.200.3	200.43	299.07	16.743	0.077	1.747	1.749	16.752	16.754	-0.056	-0.066
4.300.800.1	808.70	302.86	71.657	0.067	2.164	2.165	70.374	70.373	1.823	1.825
4.300.800.2	803.16	300.06	71.059	0.067	2.169	2.170	70.193	70.193	1.234	1.235
4.300.800.3	807.98	299.12	72.086	0.067	2.154	2.155	70.752	70.752	1.885	1.886
4.300.1250.1	1248.84	304.49	114.624	0.066	2.569	2.570	111.780	111.762	2.544	2.561
4.300.1250.2	1245.72	303.37	115.927	0.066	2.567	2.568	111.710	111.697	3.775	3.787
4.300.1250.3	1248.92	302.95	115.106	0.066	2.560	2.561	112.110	112.096	2.672	2.685
4.300.1800.1	1808.48	305.03	173.149	0.066	3.038	3.039	167.420	167.402	3.422	3.433
4.300.1800.2	1802.09	303.96	179.693	0.066	3.043	3.044	167.150	167.139	7.504	7.511
4.300.1800.3	1796.45	302.56	173.624	0.066	3.047	3.047	167.080	167.068	3.917	3.924
4.300.2500.1	2495.08	297.37	251.878	0.066	3.580	3.581	243.030	243.062	3.641	3.627
4.300.2500.2	2506.25	297.23	252.802	0.066	3.563	3.563	244.310	244.341	3.476	3.463

4.300.2500.3	2510.55	302.76	246.426	0.066	3.601	3.602	241.430	241.456	2.069	2.058

Table 10-9. Mix 4 Speed of Sound

Run No.	Pressure (psia)	Temp (degF)	Measured SOS (Ft/s)	Uncertainty - Meas SOS (%)	Uncertainty - Ref SOS (%)	Total Uncertainty (%)	Ref SOS GERG (ft/s)	Ref SOS NIST (ft/s)	Diff % - Meas vs. Ref SOS NIST	Diff % - Meas vs. Ref SOS GERG
4.100.200.1	205.12	101.42	936.600	0.241	0.596	0.643	904.470	904.428	3.552	3.557
4.100.200.2	205.77	101.00	936.600	0.241	0.597	0.644	904.020	903.971	3.604	3.610
4.100.200.3	205.77	101.26	938.384	0.241	0.596	0.643	904.250	904.206	3.775	3.780
4.100.200.4	205.93	101.13	936.600	0.241	0.597	0.644	904.120	904.070	3.592	3.598
4.100.800.1	795.11	102.45	856.320	0.256	1.166	1.194	834.310	834.435	2.638	2.623
4.100.800.2	794.47	101.74	861.672	0.254	1.168	1.196	833.310	833.426	3.404	3.389
4.100.800.3	792.87	102.44	858.104	0.255	1.166	1.193	834.560	834.685	2.821	2.806
4.100.800.4	793.03	101.52	858.104	0.255	1.169	1.196	833.140	833.261	2.996	2.981
4.100.1250.5	1246.53	97.46	784.960	0.271	3.646	3.656	777.300	777.297	0.985	0.986
4.100.1250.6	1247.90	97.59	784.068	0.271	3.645	3.655	777.490	777.490	0.846	0.846
4.100.1250.7	1248.88	97.59	784.960	0.271	3.645	3.655	777.420	777.419	0.970	0.970
4.100.1250.8	1249.92	97.61	784.960	0.271	3.645	3.655	777.390	777.390	0.974	0.974
4.100.2500.1	2504.18	104.30	1079.320	0.222	7.354	7.358	1113.500	1113.550	-3.070	-3.074
4.100.2500.2	2500.34	104.22	1079.320	0.222	7.360	7.364	1112.400	1112.390	-2.974	-2.973
4.100.2500.3	2487.20	103.65	1079.320	0.222	7.378	7.381	1110.100	1110.060	-2.773	-2.769
4.100.2500.4	2492.16	103.95	1081.104	0.222	7.374	7.377	1110.500	1110.460	-2.647	-2.644
4.200.200.1	203.84	202.78	1016.880	0.230	1.066	1.090	989.310	989.242	2.787	2.794
4.200.200.2	203.40	203.17	1008.852	0.231	1.066	1.090	989.630	989.569	1.942	1.949
4.200.200.3	202.56	203.75	1009.744	0.230	1.065	1.090	990.130	990.066	1.981	1.988
4.200.200.4	202.88	203.50	1007.068	0.231	1.065	1.090	989.920	989.855	1.732	1.739
4.200.800.1	801.20	203.46	972.280	0.236	1.556	1.573	958.040	958.182	1.486	1.471
4.200.800.2	800.88	203.54	975.848	0.235	1.555	1.573	958.130	958.277	1.849	1.834
4.200.800.3	800.56	203.58	973.172	0.236	1.555	1.573	958.190	958.332	1.564	1.549
4.200.800.4	800.56	203.62	974.064	0.235	1.555	1.573	958.230	958.373	1.652	1.637
4.200.1250.1	1240.57	202.55	945.520	0.240	1.943	1.958	942.370	942.546	0.334	0.316

4.200.1250.2	1240.89	202.31	949.980	0.239	1.944	1.959	942.080	942.255	0.839	0.820
4.200.1250.3	1243.45	202.73	949.088	0.239	1.943	1.958	942.530	942.698	0.696	0.678
4.200.1250.4	1241.85	202.43	947.304	0.240	1.944	1.958	942.200	942.377	0.542	0.523
4.200.1800.1	1800.27	197.95	990.120	0.233	2.249	2.261	937.830	937.672	5.576	5.593
4.200.1800.2	1804.43	198.53	974.064	0.235	2.247	2.259	938.670	938.511	3.771	3.788
4.200.1800.3	1803.31	198.67	972.280	0.236	2.246	2.259	938.810	938.651	3.565	3.583
4.200.1800.4	1806.04	198.57	970.496	0.236	2.247	2.259	938.770	938.608	3.380	3.397
4.200.2500.1	2509.31	196.24	990.120	0.233	1.791	1.806	987.920	988.125	0.223	0.202
4.200.2500.2	2516.84	196.66	989.228	0.233	1.788	1.804	989.120	989.323	0.011	-0.010
4.200.2500.3	2507.23	198.88	990.120	0.233	1.788	1.803	989.370	989.538	0.076	0.059
4.200.2500.4	2513.96	197.64	989.228	0.233	1.788	1.803	989.380	989.570	-0.015	-0.035
4.300.200.1	203.04	297.97	1070.400	0.223	1.032	1.056	1058.800	1058.760	1.096	1.099
4.300.200.2	201.44	298.04	1073.968	0.222	1.032	1.056	1058.900	1058.860	1.423	1.427
4.300.200.3	201.92	298.46	1074.860	0.222	1.032	1.056	1059.200	1059.140	1.478	1.484
4.300.200.4	201.44	298.44	1073.968	0.222	1.032	1.056	1059.200	1059.140	1.394	1.400
4.300.800.1	801.52	298.51	1052.560	0.225	1.330	1.349	1045.100	1045.200	0.714	0.704
4.300.800.2	802.48	299.22	1053.452	0.225	1.331	1.350	1045.700	1045.780	0.741	0.734
4.300.800.3	802.16	300.00	1053.452	0.225	1.330	1.349	1046.300	1046.430	0.684	0.671
4.300.800.4	801.68	300.68	1053.452	0.225	1.328	1.347	1046.900	1047.000	0.626	0.616
4.300.1250.1	1256.11	296.27	1043.640	0.226	1.547	1.564	1039.300	1039.450	0.418	0.403
4.300.1250.2	1255.31	296.91	1040.072	0.227	1.547	1.563	1039.800	1040.040	0.026	0.003
4.300.1250.3	1255.95	297.18	1042.748	0.226	1.545	1.562	1040.100	1040.290	0.255	0.236
4.300.1250.4	1255.79	297.44	1042.748	0.226	1.546	1.562	1040.300	1040.530	0.235	0.213
4.300.1800.1	1799.15	294.46	1052.560	0.225	1.749	1.763	1042.400	1042.430	0.975	0.972
4.300.1800.2	1796.74	294.74	1053.452	0.225	1.748	1.763	1042.700	1042.650	1.031	1.036
4.300.1800.3	1797.54	294.70	1057.020	0.224	1.749	1.763	1042.600	1042.630	1.383	1.380
4.300.1800.4	1796.42	294.62	1056.128	0.225	1.749	1.763	1042.500	1042.520	1.307	1.305
4.300.2500.1	2493.61	287.54	1052.560	0.225	1.830	1.844	1064.000	1063.670	-1.075	-1.044
4.300.2500.2	2494.89	288.70	1054.344	0.225	1.828	1.842	1065.100	1064.790	-1.010	-0.981
4.300.2500.3	2494.73	288.55	1054.344	0.225	1.828	1.842	1065.000	1064.650	-1.001	-0.968
4.300.2500.4	2496.17	288.68	1053.452	0.225	1.828	1.842	1065.200	1064.850	-1.103	-1.070

Table 10-10. Mix 4 Specific Heat

Run No.	Temperature (degC)	Pressure (Mpa)	Measured Cv (J/kg-K)	Total Uncertainty (%)	Ref Cv GERG (J/kg-K)	Ref Cv NIST (J/kg-K)	Diff % - Meas vs Ref Cv GERG	Diff % - Meas vs Ref Cv NIST
4.100.200.1.cal1	99.36	164.09	714.305	1.160	692.390	692.257	3.165	3.185
4.100.200.1.cal2	99.36	164.09	701.946	1.160	692.390	692.257	1.380	1.400
4.100.200.1.cal3	99.36	164.09	682.940	1.160	692.390	692.257	-1.365	-1.346
4.100.200.1.cal4	99.36	164.09	699.882	1.160	692.390	692.257	1.082	1.102
4.100.200.2.cal1	99.76	163.87	703.502	1.160	692.502	692.369	1.588	1.608
4.100.200.2.cal2	99.76	163.87	691.330	1.160	692.502	692.369	-0.169	-0.150
4.100.200.2.cal3	99.76	163.87	672.612	1.160	692.502	692.369	-2.872	-2.854
4.100.200.2.cal4	99.76	163.87	689.297	1.160	692.502	692.369	-0.463	-0.444
4.100.200.3.cal1	99.74	163.89	705.463	1.160	692.497	692.364	1.872	1.892
4.100.200.3.cal2	99.74	163.89	693.257	1.160	692.497	692.364	0.110	0.129
4.100.200.3.cal3	99.74	163.89	674.486	1.160	692.497	692.364	-2.601	-2.582
4.100.200.3.cal4	99.74	163.89	691.218	1.160	692.497	692.364	-0.185	-0.165
4.100.200.4.cal1	99.78	163.76	704.979	1.160	692.493	692.360	1.803	1.823
4.100.200.4.cal2	99.78	163.76	692.782	1.160	692.493	692.360	0.042	0.061
4.100.200.4.cal3	99.78	163.76	674.024	1.160	692.493	692.360	-2.667	-2.648
4.100.200.4.cal4	99.78	163.76	690.744	1.160	692.493	692.360	-0.253	-0.233
4.100.800.1.cal1	99.98	636.17	751.671	2.154	759.124	759.102	-0.982	-0.979
4.100.800.1.cal2	99.98	636.17	754.228	2.154	759.124	759.102	-0.645	-0.642
4.100.800.1.cal3	99.98	636.17	761.469	2.153	759.124	759.102	0.309	0.312
4.100.800.1.cal4	99.98	636.17	751.671	2.154	759.124	759.102	-0.982	-0.979
4.100.800.2.cal1	100.26	636.10	743.215	2.154	759.032	759.006	-2.084	-2.080
4.100.800.2.cal2	100.26	636.10	741.364	2.154	759.032	759.006	-2.328	-2.324
4.100.800.2.cal3	100.26	636.10	748.482	2.154	759.032	759.006	-1.390	-1.387
4.100.800.2.cal4	100.26	636.10	738.851	2.154	759.032	759.006	-2.659	-2.655
4.100.800.3.cal1	100.01	634.72	765.944	2.153	758.885	758.862	0.930	0.933
4.100.800.3.cal2	100.01	634.72	764.037	2.153	758.885	758.862	0.679	0.682
4.100.800.3.cal3	100.01	634.72	771.372	2.153	758.885	758.862	1.645	1.649
4.100.800.3.cal4	100.01	634.72	761.447	2.153	758.885	758.862	0.338	0.341
4.100.800.4.cal1	99.68	635.78	777.266	2.153	759.148	759.129	2.387	2.389
4.100.800.4.cal2	99.68	635.78	775.331	2.153	759.148	759.129	2.132	2.134
4.100.800.4.cal3	99.68	635.78	782.774	2.152	759.148	759.129	3.112	3.115
4.100.800.4.cal4	99.68	635.78	772.702	2.153	759.148	759.129	1.785	1.788
4.100.1250.1.cal2*	100.46	989.70	806.586	4.637	821.522	821.885	-1.818	-1.861
4.100.1250.1.cal3*	100.46	989.70	806.640	4.637	821.522	821.885	-1.812	-1.855

4.100.1250.1.cal4*	100.46	989.70	805.377	4.637	821.522	821.885	-1.965	-2.009
4.100.1250.3.cal1*	100.31	989.14	796.291	4.641	821.585	821.952	-3.079	-3.122
4.100.1250.3.cal2*	100.31	989.14	835.373	4.628	821.585	821.952	1.678	1.633
4.100.1250.3.cal3*	100.31	989.14	835.428	4.628	821.585	821.952	1.685	1.640
4.100.1250.3.cal4*	100.31	989.14	834.120	4.628	821.585	821.952	1.526	1.480
4.100.1250.4.cal1*	100.25	988.55	801.150	4.639	821.548	821.915	-2.483	-2.526
4.100.1250.4.cal2*	100.25	988.55	840.470	4.626	821.548	821.915	2.303	2.257
4.100.1250.4.cal3*	100.25	988.55	840.526	4.626	821.548	821.915	2.310	2.264
4.100.1250.4.cal4*	100.25	988.55	839.210	4.627	821.548	821.915	2.150	2.104
4.100.2500.1.cal1	99.45	1965.68	975.837	11.647	956.131	964.333	2.061	1.193
4.100.2500.1.cal2	99.45	1965.68	972.922	11.657	956.131	964.333	1.756	0.891
4.100.2500.1.cal3	99.45	1965.68	958.649	11.706	956.131	964.333	0.263	-0.589
4.100.2500.1.cal4	99.45	1965.68	966.809	11.678	956.131	964.333	1.117	0.257
4.100.2500.1.cal5	99.45	1965.68	960.535	11.700	956.131	964.333	0.461	-0.394
4.100.2500.2.cal1	99.35	1964.34	983.964	11.620	956.295	964.541	2.893	2.014
4.100.2500.2.cal2	99.35	1964.34	981.025	11.630	956.295	964.541	2.586	1.709
4.100.2500.2.cal3	99.35	1964.34	966.634	11.678	956.295	964.541	1.081	0.217
4.100.2500.2.cal4	99.35	1964.34	974.861	11.651	956.295	964.541	1.941	1.070
4.100.2500.2.cal5	99.35	1964.34	968.535	11.672	956.295	964.541	1.280	0.414
4.100.2500.3.cal1	99.30	1964.99	955.814	11.716	956.306	964.561	-0.051	-0.907
4.100.2500.3.cal2	99.30	1964.99	952.959	11.726	956.306	964.561	-0.350	-1.203
4.100.2500.3.cal3	99.30	1964.99	938.980	11.777	956.306	964.561	-1.812	-2.652
4.100.2500.3.cal4	99.30	1964.99	946.971	11.748	956.306	964.561	-0.976	-1.824
4.100.2500.3.cal5	99.30	1964.99	940.826	11.771	956.306	964.561	-1.619	-2.461
4.100.2500.4.cal1	99.35	1967.02	945.576	11.753	956.151	964.369	-1.106	-1.949
4.100.2500.4.cal2	99.35	1967.02	942.752	11.763	956.151	964.369	-1.401	-2.242
4.100.2500.4.cal3	99.35	1967.02	928.922	11.815	956.151	964.369	-2.848	-3.676
4.100.2500.4.cal4	99.35	1967.02	936.828	11.785	956.151	964.369	-2.021	-2.856
4.100.2500.4.cal5	99.35	1967.02	930.748	9.879	956.151	964.369	-2.657	-3.486
4.200.200.1.cal1	199.02	162.90	691.863	1.048	730.282	730.253	-5.261	-5.257
4.200.200.1.cal2	199.02	162.90	741.096	1.048	730.282	730.253	1.481	1.485
4.200.200.1.cal3	199.02	162.90	717.477	1.048	730.282	730.253	-1.753	-1.749
4.200.200.1.cal4	199.02	162.90	707.423	1.048	730.282	730.253	-3.130	-3.126
4.200.200.1.cal5	199.02	162.90	710.173	1.048	730.282	730.253	-2.754	-2.750
4.200.200.2.cal1	199.35	162.90	707.407	1.048	730.412	730.383	-3.150	-3.146
4.200.200.2.cal2	199.35	162.90	757.745	1.048	730.412	730.383	3.742	3.746
4.200.200.2.cal3	199.35	162.90	733.596	1.048	730.412	730.383	0.436	0.440
4.200.200.2.cal4	199.35	162.90	723.315	1.048	730.412	730.383	-0.972	-0.968
4.200.200.2.cal5	199.35	162.90	726.127	1.048	730.412	730.383	-0.587	-0.583

4.200.200.3.cal1	199.44	162.89	721.504	1.048	730.444	730.415	-1.224	-1.220
4.200.200.3.cal2	199.44	162.89	772.846	1.048	730.444	730.415	5.805	5.809
4.200.200.3.cal3	199.44	162.89	748.215	1.048	730.444	730.415	2.433	2.437
4.200.200.3.cal4	199.44	162.89	737.730	1.048	730.444	730.415	0.997	1.001
4.200.200.3.cal5	199.44	162.89	740.598	1.048	730.444	730.415	1.390	1.394
4.200.200.4.cal1	199.43	162.92	713.886	1.058	730.442	730.413	-2.267	-2.263
4.200.200.4.cal2	199.43	162.92	764.685	1.057	730.442	730.413	4.688	4.692
4.200.200.4.cal3	199.43	162.92	740.315	1.057	730.442	730.413	1.352	1.356
4.200.200.4.cal4	199.43	162.92	729.940	1.058	730.442	730.413	-0.069	-0.065
4.200.200.4.cal5	199.43	162.92	732.778	1.058	730.442	730.413	0.320	0.324
4.200.800.1.cal1	199.62	632.40	763.549	1.443	760.239	760.073	0.435	0.457
4.200.800.1.cal2	199.62	632.40	764.635	1.443	760.239	760.073	0.578	0.600
4.200.800.1.cal3	199.62	632.40	748.527	1.443	760.239	760.073	-1.541	-1.519
4.200.800.1.cal4	199.62	632.40	770.607	1.442	760.239	760.073	1.364	1.386
4.200.800.2.cal1	199.71	631.97	752.139	1.443	760.227	760.061	-1.064	-1.042
4.200.800.2.cal2	199.71	631.97	753.209	1.443	760.227	760.061	-0.923	-0.901
4.200.800.2.cal3	199.71	631.97	737.341	1.443	760.227	760.061	-3.010	-2.989
4.200.800.2.cal4	199.71	631.97	759.092	1.443	760.227	760.061	-0.149	-0.127
4.200.800.3.cal1	199.62	632.61	762.331	1.443	760.252	760.085	0.273	0.295
4.200.800.3.cal2	199.62	632.61	763.415	1.443	760.252	760.085	0.416	0.438
4.200.800.3.cal3	199.62	632.61	747.332	1.469	760.252	760.085	-1.699	-1.678
4.200.800.3.cal4	199.62	632.61	769.378	1.468	760.252	760.085	1.200	1.223
4.200.800.4.cal1	199.75	632.61	770.415	1.468	760.277	760.111	1.333	1.356
4.200.800.4.cal2	199.75	632.61	771.511	1.467	760.277	760.111	1.478	1.500
4.200.800.4.cal3	199.75	632.61	755.257	1.469	760.277	760.111	-0.660	-0.639
4.200.800.4.cal4	199.75	632.61	777.536	1.467	760.277	760.111	2.270	2.293
4.200.1250.1.cal1	199.86	988.23	784.000	1.863	783.675	783.398	0.042	0.077
4.200.1250.1.cal2	199.86	988.23	785.237	1.863	783.675	783.398	0.199	0.235
4.200.1250.1.cal3	199.86	988.23	787.551	1.863	783.675	783.398	0.495	0.530
4.200.1250.1.cal4	199.86	988.23	796.461	1.862	783.675	783.398	1.632	1.668
4.200.1250.2.cal1	199.91	988.14	777.297	1.863	783.670	783.393	-0.813	-0.778
4.200.1250.2.cal2	199.91	988.14	778.523	1.863	783.670	783.393	-0.657	-0.622
4.200.1250.2.cal3	199.91	988.14	780.817	1.863	783.670	783.393	-0.364	-0.329
4.200.1250.2.cal4	199.91	988.14	789.652	1.863	783.670	783.393	0.763	0.799
4.200.1250.3.cal1	199.91	989.14	776.293	1.863	783.736	783.459	-0.950	-0.915
4.200.1250.3.cal2	199.91	989.14	777.517	1.863	783.736	783.459	-0.793	-0.758
4.200.1250.3.cal3	199.91	989.14	779.808	1.947	783.736	783.459	-0.501	-0.466
4.200.1250.3.cal4	199.91	989.14	788.631	1.945	783.736	783.459	0.625	0.660
4.200.1250.4.cal1	199.73	988.87	780.224	1.947	783.716	783.439	-0.446	-0.410

4.200.1250.4.cal2	199.73	988.87	781.455	1.947	783.716	783.439	-0.289	-0.253
4.200.1250.4.cal3	199.73	988.87	783.757	1.946	783.716	783.439	0.005	0.041
4.200.1250.4.cal4	199.73	988.87	792.625	1.944	783.716	783.439	1.137	1.173
4.200.1800.1.cal1	199.79	1417.00	792.268	2.543	811.851	811.499	-2.412	-2.370
4.200.1800.1.cal2	199.79	1417.00	798.291	2.542	811.851	811.499	-1.670	-1.628
4.200.1800.1.cal3	199.79	1417.00	803.468	2.541	811.851	811.499	-1.032	-0.990
4.200.1800.1.cal4	199.79	1417.00	801.750	2.541	811.851	811.499	-1.244	-1.201
4.200.1800.2.cal1	199.74	1416.39	811.257	2.540	811.821	811.470	-0.069	-0.026
4.200.1800.2.cal2	199.74	1416.39	817.424	2.539	811.821	811.470	0.690	0.734
4.200.1800.2.cal3	199.74	1416.39	822.726	2.538	811.821	811.470	1.343	1.387
4.200.1800.2.cal4	199.74	1416.39	820.966	2.538	811.821	811.470	1.127	1.170
4.200.1800.3.cal1	199.58	1415.43	811.973	2.540	811.795	811.443	0.022	0.065
4.200.1800.3.cal2	199.58	1415.43	818.145	2.538	811.795	811.443	0.782	0.826
4.200.1800.3.cal3	199.58	1415.43	823.451	2.736	811.795	811.443	1.436	1.480
4.200.1800.3.cal4	199.58	1415.43	821.691	2.737	811.795	811.443	1.219	1.263
4.200.2500.1.cal2	200.01	1966.14	842.302	3.340	844.209	843.972	-0.226	-0.198
4.200.2500.1.cal3	200.01	1966.14	838.081	3.342	844.209	843.972	-0.726	-0.698
4.200.2500.1.cal4	200.01	1966.14	843.815	3.339	844.209	843.972	-0.047	-0.019
4.200.2500.2.cal2	199.83	1966.17	844.726	3.338	844.294	844.058	0.051	0.079
4.200.2500.2.cal3	199.83	1966.17	840.493	3.341	844.294	844.058	-0.450	-0.422
4.200.2500.2.cal4	199.83	1966.17	846.244	3.338	844.294	844.058	0.231	0.259
4.200.2500.3.cal2	199.97	1966.35	852.076	3.335	844.238	844.002	0.928	0.957
4.200.2500.3.cal3	199.97	1966.35	847.806	3.337	844.238	844.002	0.423	0.451
4.200.2500.3.cal4	199.97	1966.35	853.606	3.334	844.238	844.002	1.110	1.138
4.200.2500.4.cal2	199.95	1966.05	841.599	3.340	844.231	843.995	-0.312	-0.284
4.200.2500.4.cal3	199.95	1966.05	837.382	3.342	844.231	843.995	-0.811	-0.783
4.200.2500.4.cal4	199.95	1966.05	843.111	3.339	844.231	843.995	-0.133	-0.105
4.300.200.1.cal1	299.34	162.66	767.656	1.749	769.030	769.066	-0.179	-0.183
4.300.200.1.cal2	299.34	162.66	787.043	1.749	769.030	769.066	2.342	2.338
4.300.200.1.cal3	299.34	162.66	749.876	1.749	769.030	769.066	-2.491	-2.495
4.300.200.1.cal4	299.34	162.66	766.191	1.749	769.030	769.066	-0.369	-0.374
4.300.200.2.cal1	299.29	162.67	771.411	1.749	769.010	769.046	0.312	0.308
4.300.200.2.cal2	299.29	162.67	790.893	1.749	769.010	769.046	2.846	2.841
4.300.200.2.cal3	299.29	162.67	753.544	1.749	769.010	769.046	-2.011	-2.016
4.300.200.2.cal4	299.29	162.67	769.939	1.749	769.010	769.046	0.121	0.116
4.300.200.3.cal1	299.36	162.55	769.639	1.749	769.033	769.069	0.079	0.074
4.300.200.3.cal2	299.36	162.55	789.077	1.749	769.033	769.069	2.606	2.602
4.300.200.3.cal3	299.36	162.55	751.813	1.749	769.033	769.069	-2.239	-2.244

4.300.200.3.cal4	299.36	162.55	768.171	1.749	769.033	769.069	-0.112	-0.117
4.300.200.4.cal1	299.48	162.56	768.218	1.749	769.080	769.116	-0.112	-0.117
4.300.200.4.cal2	299.48	162.56	787.620	1.749	769.080	769.116	2.411	2.406
4.300.200.4.cal3	299.48	162.56	750.425	1.749	769.080	769.116	-2.426	-2.430
4.300.200.4.cal4	299.48	162.56	766.752	1.749	769.080	769.116	-0.303	-0.307
4.300.800.2.cal1	299.46	632.84	781.231	2.178	785.173	785.242	-0.502	-0.511
4.300.800.2.cal2	299.46	632.84	778.698	2.178	785.173	785.242	-0.825	-0.833
4.300.800.2.cal3	299.46	632.84	774.803	2.179	785.173	785.242	-1.321	-1.329
4.300.800.2.cal4	299.46	632.84	789.802	2.178	785.173	785.242	0.590	0.581
4.300.800.3.cal1	299.60	632.77	794.584	2.178	785.212	785.280	1.194	1.185
4.300.800.3.cal2	299.60	632.77	792.007	2.178	785.212	785.280	0.865	0.857
4.300.800.3.cal3	299.60	632.77	788.046	2.178	785.212	785.280	0.361	0.352
4.300.800.3.cal4	299.60	632.77	803.301	2.178	785.212	785.280	2.304	2.295
4.300.800.4.cal1	299.73	632.80	781.975	2.178	785.250	785.319	-0.417	-0.426
4.300.800.4.cal2	299.73	632.80	779.439	2.178	785.250	785.319	-0.740	-0.749
4.300.800.4.cal3	299.73	632.80	775.541	2.179	785.250	785.319	-1.236	-1.245
4.300.800.4.cal4	299.73	632.80	790.553	2.178	785.250	785.319	0.675	0.666
4.300.800.4.cal1	299.64	632.63	783.758	2.178	785.218	785.287	-0.186	-0.195
4.300.800.4.cal2	299.64	632.63	781.217	2.178	785.218	785.287	-0.510	-0.518
4.300.800.4.cal3	299.64	632.63	777.309	2.178	785.218	785.287	-1.007	-1.016
4.300.800.4.cal4	299.64	632.63	792.356	2.178	785.218	785.287	0.909	0.900
4.300.1250.1.cal1	299.70	986.57	777.646	2.595	797.303	797.344	-2.465	-2.470
4.300.1250.1.cal2	299.70	986.57	808.370	2.593	797.303	797.344	1.388	1.383
4.300.1250.1.cal3	299.70	986.57	817.257	2.592	797.303	797.344	2.503	2.497
4.300.1250.1.cal4	299.70	986.57	816.057	2.592	797.303	797.344	2.352	2.347
4.300.1250.2.cal1	299.60	985.75	757.535	2.596	797.254	797.295	-4.982	-4.987
4.300.1250.2.cal2	299.60	985.75	787.464	2.594	797.254	797.295	-1.228	-1.233
4.300.1250.2.cal3	299.60	985.75	796.121	2.593	797.254	797.295	-0.142	-0.147
4.300.1250.2.cal4	299.60	985.75	794.952	2.593	797.254	797.295	-0.289	-0.294
4.300.1250.3.cal1	299.67	985.97	772.270	2.595	797.277	797.318	-3.137	-3.142
4.300.1250.3.cal2	299.67	985.97	802.782	2.593	797.277	797.318	0.690	0.685
4.300.1250.3.cal3	299.67	985.97	811.607	2.593	797.277	797.318	1.797	1.792
4.300.1250.3.cal4	299.67	985.97	810.415	2.593	797.277	797.318	1.648	1.643
4.300.1250.4.cal1	299.57	985.88	775.488	2.595	797.253	797.293	-2.730	-2.735
4.300.1250.4.cal2	299.57	985.88	806.127	2.593	797.253	797.293	1.113	1.108
4.300.1250.4.cal3	299.57	985.88	814.989	2.592	797.253	797.293	2.225	2.219
4.300.1250.4.cal4	299.57	985.88	813.792	2.592	797.253	797.293	2.075	2.069
4.300.1800.1.cal1	299.39	1416.28	811.982	3.108	811.552	811.515	0.053	0.057

4.300.1800.1.cal2	299.39	1416.28	802.334	3.109	811.552	811.515	-1.136	-1.131
4.300.1800.1.cal3	299.39	1416.28	803.310	3.109	811.552	811.515	-1.016	-1.011
4.300.1800.1.cal4	299.39	1416.28	793.977	3.110	811.552	811.515	-2.166	-2.161
4.300.1800.2.cal1	299.81	1417.06	818.549	3.107	811.634	811.598	0.852	0.856
4.300.1800.2.cal2	299.81	1417.06	808.824	3.108	811.634	811.598	-0.346	-0.342
4.300.1800.2.cal3	299.81	1417.06	809.807	3.108	811.634	811.598	-0.225	-0.221
4.300.1800.2.cal4	299.81	1417.06	800.399	3.109	811.634	811.598	-1.384	-1.380
4.300.1800.3.cal1	299.77	1417.18	818.088	3.107	811.632	811.597	0.795	0.800
4.300.1800.3.cal2	299.77	1417.18	808.368	3.108	811.632	811.597	-0.402	-0.398
4.300.1800.3.cal3	299.77	1417.18	809.351	3.108	811.632	811.597	-0.281	-0.277
4.300.1800.3.cal4	299.77	1417.18	799.948	3.110	811.632	811.597	-1.440	-1.435
4.300.1800.4.cal1	299.75	1416.84	835.098	3.104	811.619	811.584	2.893	2.897
4.300.1800.4.cal2	299.75	1416.84	825.176	3.106	811.619	811.584	1.670	1.675
4.300.1800.4.cal3	299.75	1416.84	826.179	3.106	811.619	811.584	1.794	1.798
4.300.1800.4.cal4	299.75	1416.84	816.581	3.107	811.619	811.584	0.611	0.616
4.300.2500.1.cal1	299.50	1965.20	826.460	3.746	828.544	828.413	-0.252	-0.236
4.300.2500.1.cal2	299.50	1965.20	829.306	3.745	828.544	828.413	0.092	0.108
4.300.2500.1.cal3	299.50	1965.20	836.885	3.743	828.544	828.413	1.007	1.023
4.300.2500.1.cal4	299.50	1965.20	821.713	3.748	828.544	828.413	-0.824	-0.809
4.300.2500.2.cal1	299.26	1965.45	826.666	3.746	828.543	828.411	-0.226	-0.211
4.300.2500.2.cal2	299.26	1965.45	829.513	3.745	828.543	828.411	0.117	0.133
4.300.2500.2.cal3	299.26	1965.45	837.094	3.743	828.543	828.411	1.032	1.048
4.300.2500.2.cal4	299.26	1965.45	821.918	3.748	828.543	828.411	-0.800	-0.784
4.300.2500.3.cal1	299.73	1964.96	826.222	3.746	828.546	828.416	-0.280	-0.265
4.300.2500.3.cal2	299.73	1964.96	829.068	3.745	828.546	828.416	0.063	0.079
4.300.2500.3.cal3	299.73	1964.96	836.645	3.743	828.546	828.416	0.978	0.993
4.300.2500.3.cal4	299.73	1964.96	821.477	3.748	828.546	828.416	-0.853	-0.838
4.300.2500.4.cal1	299.42	1965.03	828.500	3.745	828.536	828.405	-0.004	0.011
4.300.2500.4.cal2	299.42	1965.03	831.353	3.744	828.536	828.405	0.340	0.356
4.300.2500.4.cal3	299.42	1965.03	838.952	3.742	828.536	828.405	1.257	1.273
4.300.2500.4.cal4	299.42	1965.03	823.742	3.747	828.536	828.405	-0.579	-0.563

Table 10-11. Mix 5 Density

Run No.	Pressure (psia)	Temp (degF)	Measured density (kg/m3)	Uncertainty - Meas rho (%)	Uncertainty - Ref rho (%)	Total Uncertainty (%)	Ref density - GERG (kg/m3)	Ref density - NIST (kg/m3)	Diff % - Meas vs. Ref rho GERG	Diff % - Meas vs. Ref rho NIST
5.100.2000.1	1983.09	108.24	674.967	0.066	5.973	5.973	665.350	665.142	1.445	1.477

5.100.2000.2	2009.31	105.95	686.257	0.066	5.787	5.787	683.330	683.118	0.428	0.460
5.100.2000.3	1999.58	106.27	684.620	0.066	5.824	5.825	679.710	679.503	0.722	0.753
5.100.4000.1	4002.79	105.65	864.092	0.066	2.376	2.377	854.790	854.669	1.088	1.103
5.100.4000.2	3613.91	104.16	846.518	0.066	2.433	2.434	838.760	838.682	0.925	0.934
5.100.4000.3	4007.36	106.29	862.327	0.066	2.380	2.381	853.520	853.402	1.032	1.046
5.100.6000.1	6000.30	100.06	924.459	0.066	1.756	1.757	937.760	937.700	-1.418	-1.412
5.100.6000.2	5999.73	100.79	937.683	0.066	1.758	1.760	936.460	936.380	0.131	0.139
5.100.6000.3	6007.11	101.66	958.459	0.066	1.761	1.762	935.120	935.050	2.496	2.503
5.100.8000.1	7993.28	102.01	996.624	0.066	1.495	1.497	981.680	981.820	1.522	1.508
5.100.8000.2	8000.56	102.72	974.224	0.066	1.497	1.498	980.770	980.900	-0.667	-0.681
5.100.8000.3	8005.06	101.45	997.046	0.066	1.493	1.495	982.770	982.920	1.453	1.437
5.100.10000.1	9996.54	105.23	1031.762	0.066	1.342	1.343	1014.700	1015.000	1.682	1.651
5.100.10000.2	10004.03	103.75	1025.020	0.066	1.339	1.340	1016.810	1017.120	0.807	0.777
5.100.10000.3	9998.96	104.17	1030.023	0.066	1.339	1.341	1016.240	1016.540	1.356	1.326
5.200.2000.1	1941.87	205.06	281.967	0.066	3.618	3.618	276.803	276.862	1.866	1.844
5.200.2000.2	2005.86	207.50	290.772	0.066	3.514	3.514	286.092	286.166	1.636	1.610
5.200.2000.3	2005.75	203.97	295.977	0.066	3.471	3.472	291.177	291.249	1.648	1.623
5.200.4000.1	3775.65	202.54	602.343	0.066	3.254	3.255	595.487	595.478	1.151	1.153
5.200.4000.2	4002.97	203.47	624.238	0.066	3.140	3.141	615.237	615.225	1.463	1.465
5.200.4000.3	3992.14	204.93	620.614	0.066	3.163	3.163	610.777	610.753	1.611	1.615
5.200.6000.1	6001.30	199.76	758.891	0.066	2.104	2.105	759.280	759.280	-0.051	-0.051
5.200.6000.2	5999.48	200.48	768.479	0.066	2.107	2.108	757.930	757.930	1.392	1.392
5.200.6000.3	6002.07	202.13	766.743	0.066	2.115	2.116	755.160	755.170	1.534	1.532
5.200.8000.1	8010.44	200.57	848.657	0.066	1.685	1.686	835.240	835.070	1.606	1.627
5.200.8000.2	7999.64	202.69	845.597	0.066	1.691	1.693	831.830	831.660	1.655	1.676
5.200.8000.3	8001.27	202.02	845.422	0.066	1.689	1.691	832.850	832.680	1.510	1.530
5.200.10000.1	10003.91	200.27	903.617	0.066	1.456	1.457	888.820	888.615	1.665	1.688
5.200.10000.2	10007.43	200.54	889.512	0.066	1.456	1.458	888.559	888.354	0.107	0.130
5.200.10000.3	9985.85	202.98	903.389	0.066	1.462	1.464	884.951	884.737	2.084	2.108
5.300.2000.1	1999.55	302.67	209.479	0.066	1.877	1.878	204.663	204.656	2.353	2.356
5.300.2000.2	2001.00	302.79	214.304	0.066	1.876	1.877	204.771	204.766	4.655	4.658

5.300.2000.3	1998.40	307.32	208.426	0.066	1.892	1.893	202.120	202.113	3.120	3.123
5.300.4000.1	3985.23	305.75	442.921	0.066	2.482	2.483	431.561	431.552	2.632	2.634
5.300.4000.2	4010.59	307.56	442.845	0.066	2.479	2.480	431.817	431.803	2.554	2.557
5.300.4000.3	3991.70	305.79	438.050	0.066	2.478	2.479	432.163	432.151	1.362	1.365
5.300.6000.1	6005.16	302.83	608.795	0.066	2.089	2.090	596.420	596.330	2.075	2.090
5.300.6000.2	5992.45	303.15	602.660	0.066	2.093	2.094	595.200	595.110	1.253	1.269
5.300.6000.3	6008.42	304.41	611.914	0.066	2.095	2.096	594.480	594.390	2.933	2.948
5.300.8000.1	7989.71	301.65	717.653	0.066	1.737	1.739	697.400	697.240	2.904	2.928
5.300.8000.2	7995.77	303.53	700.706	0.066	1.742	1.743	695.340	695.170	0.772	0.796
5.300.8000.3	7990.53	300.87	726.607	0.066	1.735	1.736	698.400	698.250	4.039	4.061
5.300.10000.1	9986.99	297.32	773.762	0.066	1.499	1.500	772.000	771.770	0.228	0.258
5.300.10000.2	10011.26	297.70	787.267	0.066	1.498	1.499	772.290	772.050	1.939	1.971
5.300.10000.3	9981.53	299.19	791.525	0.066	1.503	1.505	769.740	769.500	2.830	2.862

Table 10-12. Mix 5 Speed of Sound

Run No.	Pressure (psia)	Temp (degF)	Measured SOS (Ft/s)	Uncertainty - Meas SOS (%)	Uncertainty - Ref SOS (%)	Total Uncertainty (%)	Ref SOS GERG (ft/s)	Ref SOS NIST (ft/s)	Diff % - Meas vs. Ref SOS GERG	Diff % - Meas vs. Ref SOS NIST
5.100.2000.5	2007.62	99.91	1186.360	0.211	8.210	8.213	1213.900	1213.120	-2.269	-2.206
5.100.2000.6	2006.79	101.84	1186.360	0.211	8.394	8.396	1189.500	1188.760	-0.264	-0.202
5.100.2000.7	2003.68	102.05	1185.468	0.211	8.426	8.428	1185.100	1184.350	0.031	0.094
5.100.2000.8	2004.80	102.09	1189.036	0.211	8.425	8.428	1185.200	1184.520	0.324	0.381
5.100.4000.5	4005.19	101.48	2039.201	0.172	3.549	3.553	1902.800	1903.130	7.168	7.150
5.100.4000.6	3999.56	101.65	2036.971	0.172	3.557	3.561	1900.100	1900.420	7.203	7.185
5.100.4000.7	4005.26	101.72	2036.079	0.172	3.555	3.559	1900.900	1901.250	7.111	7.092
5.100.4000.8	4008.70	101.08	2035.187	0.172	3.543	3.547	1906.900	1907.150	6.728	6.714
5.100.6000.1	6001.54	103.89	2399.480	0.166	2.566	2.572	2289.410	2286.400	4.808	4.946
5.100.6000.2	6004.72	103.93	2400.372	0.166	2.566	2.571	2289.680	2286.680	4.834	4.972
5.100.6000.3	6007.26	103.97	2401.264	0.166	2.566	2.572	2289.850	2286.850	4.866	5.003
5.100.6000.4	6007.90	104.06	2399.480	0.166	2.567	2.572	2289.350	2286.370	4.811	4.947

5.100.8000.1	8000.65	101.94	2720.600	0.162	2.080	2.086	2605.940	2601.980	4.400	4.559
5.100.8000.2	8000.33	102.05	2715.248	0.162	2.081	2.087	2605.230	2601.280	4.223	4.381
5.100.8000.3	8006.06	102.31	2713.464	0.162	2.082	2.088	2604.420	2600.490	4.187	4.344
5.100.8000.4	8004.79	102.38	2711.680	0.162	2.082	2.089	2603.820	2599.900	4.142	4.299
5.100.10000.1	10001.86	98.55	2970.360	0.160	1.792	1.799	2873.610	2871.690	3.367	3.436
5.100.10000.2	10004.52	98.47	2973.928	0.160	1.791	1.798	2874.370	2872.450	3.464	3.533
5.100.10000.3	10009.27	98.49	2972.144	0.160	1.791	1.798	2874.790	2872.880	3.386	3.455
5.100.10000.4	10006.12	98.49	2971.252	0.160	1.791	1.798	2874.440	2872.520	3.368	3.437
5.200.2000.5	1997.63	198.36	909.840	0.246	1.319	1.341	890.990	890.979	2.116	2.117
5.200.2000.6	1997.39	198.21	913.408	0.245	1.319	1.342	890.800	890.788	2.538	2.539
5.200.2000.7	1997.32	198.02	921.436	0.244	1.320	1.342	890.570	890.563	3.466	3.467
5.200.2000.8	1996.93	198.00	925.004	0.243	1.320	1.342	890.520	890.512	3.872	3.873
5.200.4000.5	3996.32	198.96	1346.920	0.199	2.763	2.770	1329.100	1329.580	1.341	1.304
5.200.4000.6	4002.48	199.11	1346.028	0.199	2.761	2.768	1330.200	1330.660	1.190	1.155
5.200.4000.7	4004.97	199.25	1345.136	0.199	2.762	2.769	1330.300	1330.830	1.115	1.075
5.200.4000.8	4000.79	199.30	1344.244	0.199	2.763	2.770	1329.100	1329.600	1.139	1.101
5.200.6000.1	6010.72	202.06	1870.078	0.176	2.455	2.461	1762.030	1764.590	6.132	5.978
5.200.6000.2	6003.13	202.65	1871.059	0.176	2.459	2.465	1758.290	1760.820	6.414	6.261
5.200.6000.3	6009.49	202.80	1866.599	0.176	2.458	2.464	1758.920	1761.450	6.122	5.969
5.200.6000.4	6003.44	202.88	1871.059	0.176	2.459	2.466	1757.460	1759.970	6.464	6.312
5.200.8000.1	7998.74	200.70	2083.801	0.171	2.133	2.140	2104.260	2108.000	-0.972	-1.148
5.200.8000.2	8007.97	201.01	2086.923	0.171	2.134	2.140	2104.430	2108.170	-0.832	-1.008
5.200.8000.3	8007.65	201.25	2085.139	0.171	2.134	2.141	2103.430	2107.180	-0.870	-1.046
5.200.8000.4	8006.38	201.27	2085.139	0.171	2.135	2.142	2103.150	2106.910	-0.856	-1.033
5.200.10000.1	9995.31	200.61	2310.280	0.167	1.914	1.921	2381.890	2384.380	-3.006	-3.108
5.200.10000.2	10007.40	200.75	2307.604	0.167	1.913	1.921	2382.880	2385.370	-3.159	-3.260
5.200.10000.3	9999.76	200.85	2306.712	0.167	1.914	1.921	2381.510	2384.020	-3.141	-3.243
5.200.10000.4	10002.94	200.94	2304.036	0.167	1.914	1.922	2381.570	2384.070	-3.256	-3.357
5.300.2000.1	2005.56	295.46	999.040	0.232	0.985	1.012	1001.310	1001.200	-0.227	-0.216
5.300.2000.2	2006.61	295.46	1002.608	0.231	0.985	1.012	1001.340	1001.230	0.127	0.138
5.300.2000.3	2005.66	295.51	1002.608	0.231	0.985	1.012	1001.370	1001.260	0.124	0.135
5.300.2000.4	2005.34	295.54	1002.608	0.231	0.985	1.012	1001.390	1001.280	0.122	0.133
5.300.4000.5	3997.39	296.35	1204.200	0.209	1.541	1.555	1190.800	1191.040	1.125	1.105

5.300.4000.6	3996.71	296.09	1203.308	0.209	1.550	1.564	1190.700	1190.980	1.059	1.035
5.300.4000.7	3996.84	296.02	1204.200	0.209	1.541	1.555	1190.700	1191.020	1.134	1.107
5.300.4000.8	3996.56	295.96	1203.308	0.209	1.550	1.564	1190.700	1190.990	1.059	1.034
5.300.6000.1	6005.67	304.63	1469.302	0.191	1.927	1.936	1502.820	1504.550	-2.230	-2.343
5.300.6000.2	6008.22	304.63	1471.532	0.191	1.927	1.936	1503.220	1504.950	-2.108	-2.221
5.300.6000.3	6005.99	304.70	1471.532	0.191	1.927	1.936	1502.770	1504.500	-2.079	-2.191
5.300.6000.4	6006.31	304.74	1472.424	0.191	1.926	1.935	1502.770	1504.500	-2.019	-2.132
5.300.8000.1	8004.47	299.76	1855.360	0.176	1.962	1.970	1812.090	1814.850	2.388	2.232
5.300.8000.2	7995.24	299.99	1857.144	0.176	1.963	1.971	1810.320	1813.070	2.587	2.431
5.300.8000.3	8000.65	300.25	1855.360	0.176	1.962	1.970	1810.560	1813.310	2.474	2.319
5.300.8000.4	8004.47	300.49	1855.360	0.176	1.962	1.970	1810.610	1813.370	2.472	2.316
5.300.10000.1	9998.17	299.71	2051.600	0.172	1.888	1.896	2077.330	2081.310	-1.239	-1.427
5.300.10000.2	10007.08	300.36	2050.708	0.172	1.888	1.896	2076.950	2080.920	-1.263	-1.452
5.300.10000.3	10003.26	300.47	2049.816	0.172	1.888	1.896	2076.220	2080.180	-1.272	-1.460
5.300.10000.4	10002.54	300.48	2048.924	0.172	1.889	1.896	2076.110	2080.070	-1.309	-1.497

Table 10-13. Mix 5 Specific Heat

Run No.	Temperature (degC)	Pressure (Mpa)	Measured Cv (J/kg-K)	Total Uncertainty (%)	Ref Cv GERG (J/kg-K)	Ref Cv NIST (J/kg-K)	Diff % - Meas vs Ref Cv GERG	Diff % - Meas vs Ref Cv NIST
5.100.4000.2.cal1	101.294	3132.511	899.121	3.278	911.720	912.888	-1.382	-1.508
5.100.4000.2.cal2	101.294	3132.511	905.699	3.267	911.720	912.888	-0.660	-0.787
5.100.4000.2.cal3	101.294	3132.511	900.690	3.275	911.720	912.888	-1.210	-1.336
5.100.4000.2.cal4	101.294	3132.511	915.801	3.251	911.720	912.888	0.448	0.319
5.100.4000.3.cal1	101.849	3130.649	914.636	3.253	911.774	912.902	0.314	0.190
5.100.4000.3.cal2	101.849	3130.649	921.328	3.243	911.774	912.902	1.048	0.923
5.100.4000.3.cal3	101.849	3130.649	916.232	3.250	911.774	912.902	0.489	0.365
5.100.4000.3.cal4	101.849	3130.649	931.604	3.227	911.774	912.902	2.175	2.049
5.100.4000.4.cal1	101.960	3130.097	913.477	3.255	911.787	912.907	0.185	0.062
5.100.4000.4.cal2	101.960	3130.097	920.161	3.244	911.787	912.907	0.918	0.795
5.100.4000.4.cal3	101.960	3130.097	915.071	3.252	911.787	912.907	0.360	0.237
5.100.4000.4.cal4	101.960	3130.097	930.424	3.229	911.787	912.907	2.044	1.919
5.100.6000.1.cal1	100.984	4703.879	897.525	2.512	905.586	906.516	-0.890	-0.992
5.100.6000.1.cal2	100.984	4703.879	893.485	2.517	905.586	906.516	-1.336	-1.437
5.100.6000.1.cal3	100.984	4703.879	905.265	2.501	905.586	906.516	-0.035	-0.138

5.100.6000.1.cal4	100.984	4703.879	899.978	2.508	905.586	906.516	-0.619	-0.721
5.100.6000.2.cal1	100.852	4705.418	918.423	2.483	905.602	906.539	1.416	1.311
5.100.6000.2.cal2	100.852	4705.418	914.289	2.488	905.602	906.539	0.959	0.855
5.100.6000.2.cal3	100.852	4705.418	926.344	2.472	905.602	906.539	2.290	2.185
5.100.6000.2.cal4	100.852	4705.418	920.933	2.479	905.602	906.539	1.693	1.588
5.100.6000.3.cal1	101.011	4703.041	897.780	2.511	905.584	906.511	-0.862	-0.963
5.100.6000.3.cal2	101.011	4703.041	893.739	2.517	905.584	906.511	-1.308	-1.409
5.100.6000.3.cal3	101.011	4703.041	905.523	2.500	905.584	906.511	-0.007	-0.109
5.100.6000.3.cal4	101.011	4703.041	900.234	2.508	905.584	906.511	-0.591	-0.692
5.100.6000.4.cal1	100.990	4707.744	902.830	2.504	905.585	906.513	-0.304	-0.406
5.100.6000.4.cal2	100.990	4707.744	898.766	2.510	905.585	906.513	-0.753	-0.855
5.100.6000.4.cal3	100.990	4707.744	910.616	2.493	905.585	906.513	0.555	0.453
5.100.6000.4.cal4	100.990	4707.744	905.297	2.501	905.585	906.513	-0.032	-0.134
5.100.8000.1.cal1	100.362	6271.188	906.731	2.179	907.589	907.977	-0.095	-0.137
5.100.8000.1.cal2	100.362	6271.188	905.030	2.181	907.589	907.977	-0.282	-0.325
5.100.8000.1.cal3	100.362	6271.188	903.936	2.182	907.589	907.977	-0.403	-0.445
5.100.8000.1.cal4	100.362	6271.188	905.010	2.181	907.589	907.977	-0.284	-0.327
5.100.8000.2.cal1	100.843	6269.099	903.548	2.183	907.506	907.872	-0.436	-0.476
5.100.8000.2.cal2	100.843	6269.099	901.853	2.185	907.506	907.872	-0.623	-0.663
5.100.8000.2.cal3	100.843	6269.099	900.763	2.186	907.506	907.872	-0.743	-0.783
5.100.8000.2.cal4	100.843	6269.099	901.833	2.185	907.506	907.872	-0.625	-0.665
5.100.8000.3.cal1	101.205	6269.222	917.051	2.166	907.447	907.797	1.058	1.019
5.100.8000.3.cal2	101.205	6269.222	915.331	2.168	907.447	907.797	0.869	0.830
5.100.8000.3.cal3	101.205	6269.222	914.224	2.169	907.447	907.797	0.747	0.708
5.100.8000.3.cal4	101.205	6269.222	915.311	2.168	907.447	907.797	0.867	0.828
5.100.10000.1.cal1	100.423	7837.752	904.800	1.993	911.609	911.206	-0.747	-0.703
5.100.10000.1.cal2	100.423	7837.752	890.335	2.011	911.609	911.206	-2.334	-2.290
5.100.10000.1.cal3	100.423	7837.752	892.393	2.008	911.609	911.206	-2.108	-2.065
5.100.10000.1.cal4	100.423	7837.752	895.600	2.004	911.609	911.206	-1.756	-1.713
5.100.10000.2.cal1	100.573	7836.198	927.665	1.966	911.576	911.169	1.765	1.810
5.100.10000.2.cal2	100.573	7836.198	912.835	1.983	911.576	911.169	0.138	0.183
5.100.10000.2.cal3	100.573	7836.198	914.944	1.981	911.576	911.169	0.369	0.414
5.100.10000.2.cal4	100.573	7836.198	918.232	1.977	911.576	911.169	0.730	0.775
5.100.10000.3.cal1	100.431	7834.408	927.345	1.967	911.597	911.196	1.727	1.772
5.100.10000.3.cal2	100.431	7834.408	912.520	1.984	911.597	911.196	0.101	0.145
5.100.10000.3.cal3	100.431	7834.408	914.628	1.981	911.597	911.196	0.333	0.377
5.100.10000.3.cal4	100.431	7834.408	917.915	1.977	911.597	911.196	0.693	0.737
5.100.10000.4.cal1	101.045	7831.331	923.684	1.971	911.475	911.054	1.340	1.386
5.100.10000.4.cal2	101.045	7831.331	908.918	1.988	911.475	911.054	-0.281	-0.234

5.100.10000.4.cal3	101.045	7831.331	911.018	1.985	911.475	911.054	-0.050	-0.004
5.100.10000.4.cal4	101.045	7831.331	914.292	1.982	911.475	911.054	0.309	0.355
5.200.2000.1.cal2	201.508	1573.796	816.826	3.799	847.505	846.984	-3.620	-3.561
5.200.2000.1.cal3	201.508	1573.796	814.812	3.800	847.505	846.984	-3.857	-3.798
5.200.2000.2.cal2	201.927	1573.881	811.955	3.801	847.287	846.765	-4.170	-4.111
5.200.2000.2.cal3	201.927	1573.881	809.953	3.802	847.287	846.765	-4.406	-4.347
5.200.2000.3.cal2	201.550	1572.192	885.361	3.772	847.355	846.831	4.485	4.550
5.200.2000.3.cal3	201.550	1572.192	883.178	3.773	847.355	846.831	4.228	4.292
5.200.2000.3.cal4	201.550	1572.192	865.852	3.779	847.355	846.831	2.183	2.246
5.200.2000.4.cal2	201.489	1571.516	885.481	3.772	847.333	846.809	4.502	4.567
5.200.2000.4.cal3	201.489	1571.516	883.298	3.773	847.333	846.809	4.245	4.309
5.200.2000.4.cal4	201.489	1571.516	865.969	3.779	847.333	846.809	2.199	2.263
5.200.4000.1.cal1	201.251	3142.629	914.501	3.841	905.953	904.404	0.944	1.116
5.200.4000.1.cal2	201.251	3142.629	910.957	3.845	905.953	904.404	0.552	0.725
5.200.4000.1.cal3	201.251	3142.629	898.247	3.861	905.953	904.404	-0.851	-0.681
5.200.4000.1.cal4	201.251	3142.629	901.766	3.856	905.953	904.404	-0.462	-0.292
5.200.4000.2.cal1	200.964	3141.642	918.243	3.836	906.044	904.487	1.346	1.521
5.200.4000.2.cal2	200.964	3141.642	914.685	3.841	906.044	904.487	0.954	1.127
5.200.4000.2.cal3	200.964	3141.642	901.922	3.856	906.044	904.487	-0.455	-0.284
5.200.4000.2.cal4	200.964	3141.642	905.457	3.852	906.044	904.487	-0.065	0.107
5.200.4000.3.cal1	201.055	3143.094	910.377	3.846	906.012	904.458	0.482	0.654
5.200.4000.3.cal2	201.055	3143.094	906.849	3.850	906.012	904.458	0.092	0.264
5.200.4000.3.cal3	201.055	3143.094	894.196	3.866	906.012	904.458	-1.304	-1.135
5.200.4000.3.cal4	201.055	3143.094	897.700	3.861	906.012	904.458	-0.917	-0.747
5.200.4000.4.cal1	201.568	3142.908	913.489	3.842	905.854	904.313	0.843	1.015
5.200.4000.4.cal2	201.568	3142.908	909.949	3.846	905.854	904.313	0.452	0.623
5.200.4000.4.cal3	201.568	3142.908	897.253	3.862	905.854	904.313	-0.950	-0.781
5.200.4000.4.cal4	201.568	3142.908	900.768	3.857	905.854	904.313	-0.561	-0.392
5.200.6000.1.cal1	201.228	4714.171	873.038	2.763	899.618	898.647	-2.955	-2.850
5.200.6000.1.cal2	201.228	4714.171	888.161	2.744	899.618	898.647	-1.274	-1.167
5.200.6000.1.cal3	201.228	4714.171	898.873	2.730	899.618	898.647	-0.083	0.025
5.200.6000.1.cal4	201.228	4714.171	897.610	2.732	899.618	898.647	-0.223	-0.115
5.200.6000.2.cal1	201.121	4712.486	893.836	2.737	899.626	898.656	-0.644	-0.536
5.200.6000.2.cal2	201.121	4712.486	909.319	2.718	899.626	898.656	1.077	1.187
5.200.6000.2.cal3	201.121	4712.486	920.286	2.705	899.626	898.656	2.297	2.407
5.200.6000.2.cal4	201.121	4712.486	918.994	2.707	899.626	898.656	2.153	2.263
5.200.6000.3.cal1	200.554	4715.745	884.015	2.749	899.647	898.676	-1.738	-1.631
5.200.6000.3.cal2	200.554	4715.745	899.328	2.730	899.647	898.676	-0.036	0.073

5.200.6000.3.cal3	200.554	4715.745	910.174	2.717	899.647	898.676	1.170	1.279
5.200.6000.3.cal4	200.554	4715.745	908.896	2.718	899.647	898.676	1.028	1.137
5.200.6000.4.cal1	201.512	4716.188	882.051	2.751	899.602	898.629	-1.951	-1.845
5.200.6000.4.cal2	201.512	4716.188	897.330	2.732	899.602	898.629	-0.253	-0.145
5.200.6000.4.cal3	201.512	4716.188	908.152	2.719	899.602	898.629	0.950	1.060
5.200.6000.4.cal4	201.512	4716.188	906.876	2.721	899.602	898.629	0.809	0.918
5.200.8000.1.cal1	202.226	6279.119	899.615	2.278	899.592	897.804	0.003	0.202
5.200.8000.1.cal2	202.226	6279.119	903.646	2.273	899.592	897.804	0.451	0.651
5.200.8000.1.cal3	202.226	6279.119	898.144	2.279	899.592	897.804	-0.161	0.038
5.200.8000.1.cal4	202.226	6279.119	887.397	2.292	899.592	897.804	-1.356	-1.159
5.200.8000.2.cal1	201.960	6280.990	899.857	2.277	899.600	897.812	0.029	0.228
5.200.8000.2.cal2	201.960	6280.990	903.889	2.273	899.600	897.812	0.477	0.677
5.200.8000.2.cal3	201.960	6280.990	898.385	2.279	899.600	897.812	-0.135	0.064
5.200.8000.2.cal4	201.960	6280.990	887.635	2.291	899.600	897.812	-1.330	-1.134
5.200.8000.3.cal1	201.555	6279.093	906.749	2.270	899.607	897.822	0.794	0.994
5.200.8000.3.cal2	201.555	6279.093	910.811	2.265	899.607	897.822	1.245	1.447
5.200.8000.3.cal3	201.555	6279.093	905.265	2.271	899.607	897.822	0.629	0.829
5.200.8000.3.cal4	201.555	6279.093	894.433	2.284	899.607	897.822	-0.575	-0.377
5.200.8000.4.cal1	201.901	6278.357	906.523	2.270	899.598	897.812	0.770	0.970
5.200.8000.4.cal2	201.901	6278.357	910.585	2.265	899.598	897.812	1.221	1.423
5.200.8000.4.cal3	201.901	6278.357	905.040	2.272	899.598	897.812	0.605	0.805
5.200.8000.4.cal4	201.901	6278.357	894.211	2.284	899.598	897.812	-0.599	-0.401
5.200.10000.1.cal1	201.991	7842.923	902.754	2.025	902.277	899.925	0.053	0.314
5.200.10000.1.cal3	201.991	7842.923	909.611	2.018	902.277	899.925	0.813	1.076
5.200.10000.1.cal4	201.991	7842.923	898.723	2.029	902.277	899.925	-0.394	-0.134
5.200.10000.2.cal1	201.690	7844.652	898.060	2.030	902.287	899.937	-0.469	-0.209
5.200.10000.2.cal3	201.690	7844.652	904.881	2.023	902.287	899.937	0.288	0.549
5.200.10000.2.cal4	201.690	7844.652	894.049	2.034	902.287	899.937	-0.913	-0.654
5.200.10000.3.cal1	200.963	7845.070	896.726	2.032	902.304	899.959	-0.618	-0.359
5.200.10000.3.cal3	200.963	7845.070	903.537	2.024	902.304	899.959	0.137	0.398
5.200.10000.3.cal4	200.963	7845.070	892.721	2.036	902.304	899.959	-1.062	-0.804
5.200.10000.4.cal1	201.799	7843.222	908.024	2.019	902.282	899.931	0.636	0.899
5.200.10000.4.cal3	201.799	7843.222	914.921	2.012	902.282	899.931	1.401	1.666
5.200.10000.4.cal4	201.799	7843.222	903.969	2.024	902.282	899.931	0.187	0.449
5.300.2000.1.cal2	301.170	1573.533	829.656	1.940	831.895	831.580	-0.269	-0.231
5.300.2000.1.cal3	301.170	1573.533	833.751	1.939	831.895	831.580	0.223	0.261
5.300.2000.1.cal4	301.170	1573.533	825.098	1.940	831.895	831.580	-0.817	-0.779
5.300.2000.2.cal2	301.365	1572.810	841.751	1.938	831.880	831.566	1.187	1.225

5.300.2000.2.cal3	301.365	1572.810	845.905	1.938	831.880	831.566	1.686	1.724
5.300.2000.2.cal4	301.365	1572.810	837.127	1.939	831.880	831.566	0.631	0.669
5.300.2000.3.cal2	301.187	1572.448	831.942	1.939	831.855	831.540	0.011	0.048
5.300.2000.3.cal3	301.187	1572.448	836.048	1.939	831.855	831.540	0.504	0.542
5.300.2000.3.cal4	301.187	1572.448	827.372	1.940	831.855	831.540	-0.539	-0.501
5.300.2000.4.cal2	301.157	1572.452	824.990	1.940	831.852	831.538	-0.825	-0.787
5.300.2000.4.cal3	301.157	1572.452	829.062	1.940	831.852	831.538	-0.335	-0.298
5.300.2000.4.cal4	301.157	1572.452	820.458	1.941	831.852	831.538	-1.370	-1.332
5.300.4000.1.cal1	301.977	3141.819	872.712	2.744	878.088	877.914	-0.612	-0.593
5.300.4000.1.cal2	301.977	3141.819	868.926	2.747	878.088	877.914	-1.043	-1.024
5.300.4000.1.cal3	301.977	3141.819	857.408	2.753	878.088	877.914	-2.355	-2.336
5.300.4000.1.cal4	301.977	3141.819	863.738	2.750	878.088	877.914	-1.634	-1.615
5.300.4000.2.cal1	302.101	3142.206	896.821	2.731	878.079	877.905	2.134	2.155
5.300.4000.2.cal2	302.101	3142.206	892.931	2.733	878.079	877.905	1.691	1.712
5.300.4000.2.cal3	302.101	3142.206	881.094	2.740	878.079	877.905	0.343	0.363
5.300.4000.2.cal4	302.101	3142.206	887.599	2.736	878.079	877.905	1.084	1.104
5.300.4000.3.cal1	302.350	3140.683	884.372	2.738	878.018	877.843	0.724	0.744
5.300.4000.3.cal2	302.350	3140.683	880.536	2.740	878.018	877.843	0.287	0.307
5.300.4000.3.cal3	302.350	3140.683	868.864	2.747	878.018	877.843	-1.043	-1.023
5.300.4000.3.cal4	302.350	3140.683	875.278	2.743	878.018	877.843	-0.312	-0.292
5.300.4000.4.cal1	302.284	3143.094	887.308	2.736	878.072	877.897	1.052	1.072
5.300.4000.4.cal2	302.284	3143.094	883.460	2.738	878.072	877.897	0.614	0.634
5.300.4000.4.cal3	302.284	3143.094	871.749	2.745	878.072	877.897	-0.720	-0.700
5.300.4000.4.cal4	302.284	3143.094	878.185	2.741	878.072	877.897	0.013	0.033
5.300.6000.1.cal1	300.962	4708.269	888.832	2.495	894.455	893.947	-0.629	-0.572
5.300.6000.1.cal2	300.962	4708.269	887.000	2.496	894.455	893.947	-0.833	-0.777
5.300.6000.1.cal3	300.962	4708.269	886.580	2.496	894.455	893.947	-0.880	-0.824
5.300.6000.2.cal1	302.026	4705.831	900.822	2.485	894.398	893.897	0.718	0.775
5.300.6000.2.cal2	302.026	4705.831	898.966	2.486	894.398	893.897	0.511	0.567
5.300.6000.2.cal3	302.026	4705.831	898.541	2.487	894.398	893.897	0.463	0.520
5.300.6000.3.cal1	301.668	4703.877	898.222	2.487	894.403	893.901	0.427	0.483
5.300.6000.3.cal2	301.668	4703.877	896.371	2.488	894.403	893.901	0.220	0.276
5.300.6000.3.cal3	301.668	4703.877	895.947	2.489	894.403	893.901	0.173	0.229
5.300.6000.4.cal1	301.501	4705.595	895.379	2.489	894.419	893.915	0.107	0.164
5.300.6000.4.cal2	301.501	4705.595	893.534	2.491	894.419	893.915	-0.099	-0.043
5.300.6000.4.cal3	301.501	4705.595	893.111	2.491	894.419	893.915	-0.146	-0.090
5.300.8000.1.cal2	301.967	6276.804	901.731	2.176	899.926	898.523	0.201	0.357
5.300.8000.1.cal3	301.967	6276.804	898.783	2.179	899.926	898.523	-0.127	0.029

5.300.8000.1.cal4	301.967	6276.804	902.054	2.176	899.926	898.523	0.237	0.393
5.300.8000.2.cal2	301.150	6278.170	906.920	2.172	899.909	898.498	0.779	0.937
5.300.8000.2.cal3	301.150	6278.170	903.954	2.174	899.909	898.498	0.450	0.607
5.300.8000.2.cal4	301.150	6278.170	907.245	2.172	899.909	898.498	0.815	0.973
5.300.8000.3.cal2	302.016	6276.963	898.506	2.179	899.927	898.525	-0.158	-0.002
5.300.8000.3.cal3	302.016	6276.963	895.568	2.182	899.927	898.525	-0.484	-0.329
5.300.8000.3.cal4	302.016	6276.963	898.828	2.179	899.927	898.525	-0.122	0.034
5.300.8000.4.cal2	301.220	6278.195	896.095	2.181	899.911	898.501	-0.424	-0.268
5.300.8000.4.cal3	301.220	6278.195	893.165	2.184	899.911	898.501	-0.750	-0.594
5.300.8000.4.cal4	301.220	6278.195	896.416	2.181	899.911	898.501	-0.388	-0.232
5.300.10000.1.cal1	301.217	7841.748	913.226	2.088	903.976	901.959	1.023	1.249
5.300.10000.1.cal3	301.217	7841.748	914.487	2.087	903.976	901.959	1.163	1.389
5.300.10000.1.cal4	301.217	7841.748	924.241	2.080	903.976	901.959	2.242	2.470
5.300.10000.2.cal1	301.318	7840.901	900.928	2.098	903.979	901.963	-0.338	-0.115
5.300.10000.2.cal3	301.318	7840.901	902.172	2.097	903.979	901.963	-0.200	0.023
5.300.10000.2.cal4	301.318	7840.901	911.795	2.089	903.979	901.963	0.865	1.090
5.300.10000.3.cal1	301.553	7841.810	886.182	2.111	903.992	901.978	-1.970	-1.751
5.300.10000.3.cal3	301.553	7841.810	887.405	2.110	903.992	901.978	-1.835	-1.616
5.300.10000.3.cal4	301.553	7841.810	896.871	2.101	903.992	901.978	-0.788	-0.566
5.300.10000.4.cal1	301.591	7841.215	898.917	2.100	903.993	901.979	-0.561	-0.340
5.300.10000.4.cal3	301.591	7841.215	900.158	2.099	903.993	901.979	-0.424	-0.202
5.300.10000.4.cal4	301.591	7841.215	909.760	2.091	903.993	901.979	0.638	0.863

11. APPENDIX D: PRESSURE-ENTHALPY DIAGRAM FOR PURE CO_2

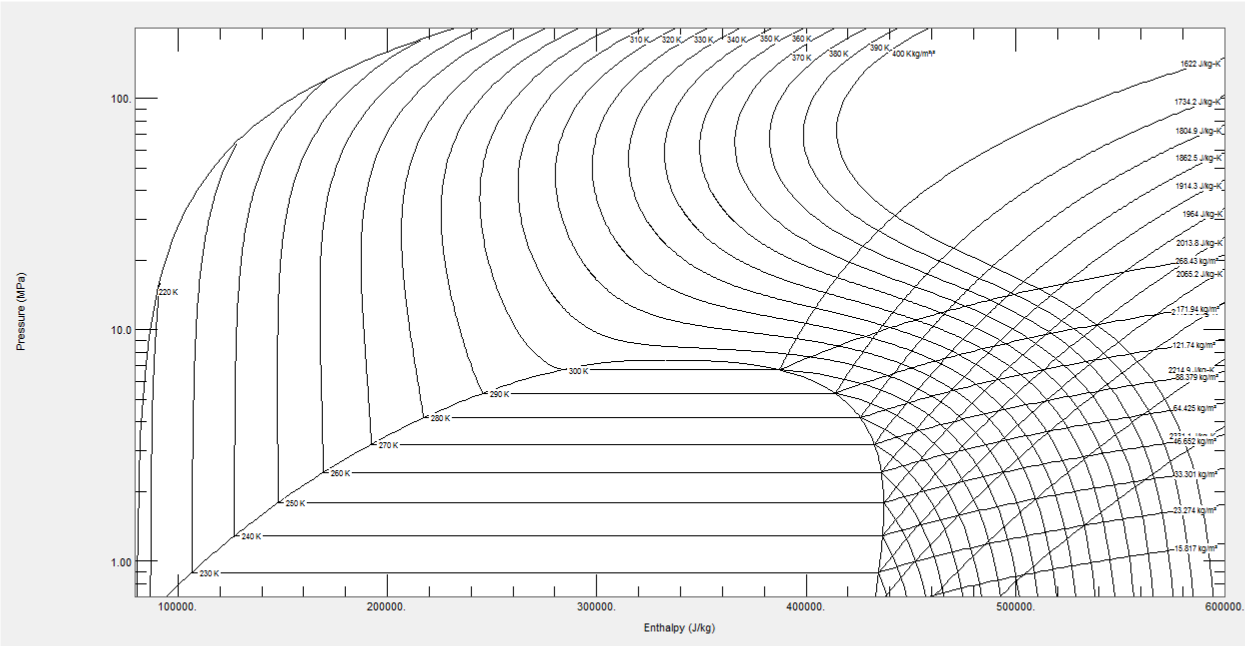


Figure 11-1. Pressure-Enthalpy Diagram for CO_2 (GERG EOS Model)

12. APPENDIX E: REDUCED DATA

This section presents the reduced data gathered during testing.

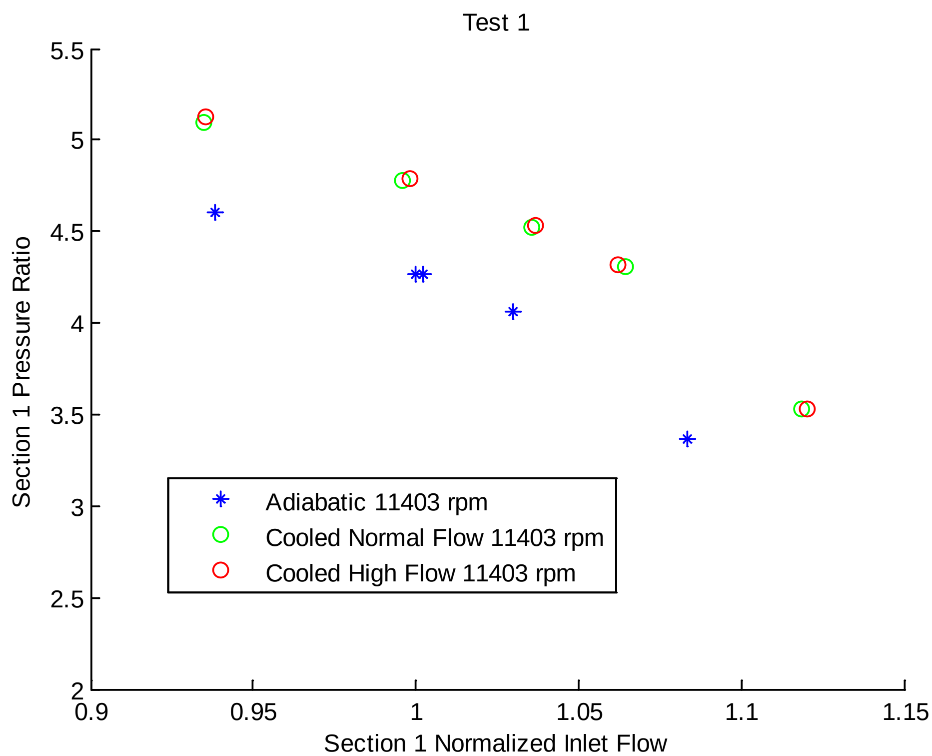


Figure 12-1. Section 1 Pressure Ratio vs. Normalized Flow (Test 1)

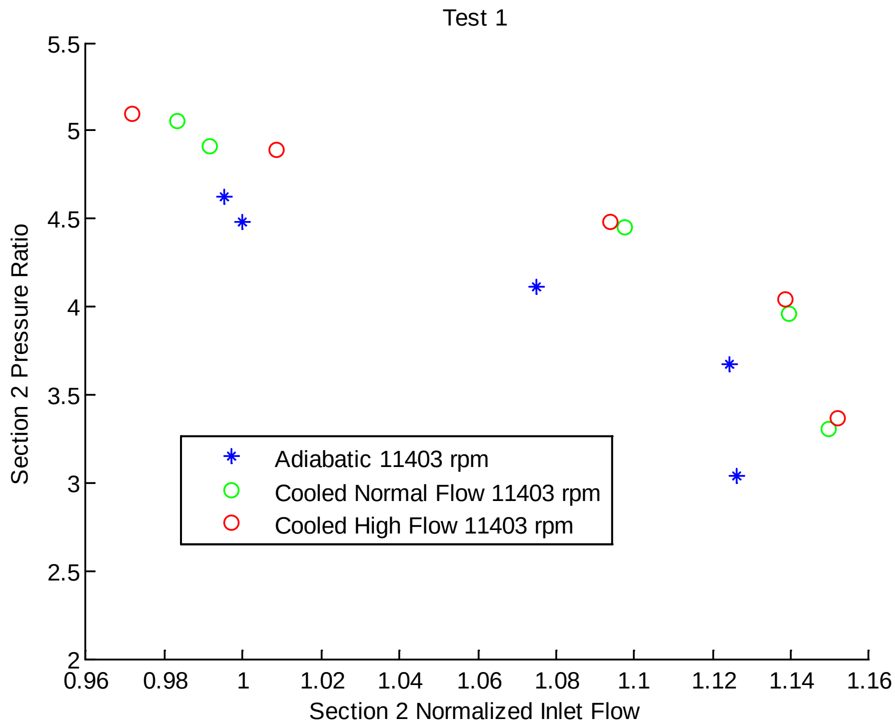


Figure 12-2. Section 2 Pressure Ratio vs. Normalized Flow (Test 1)

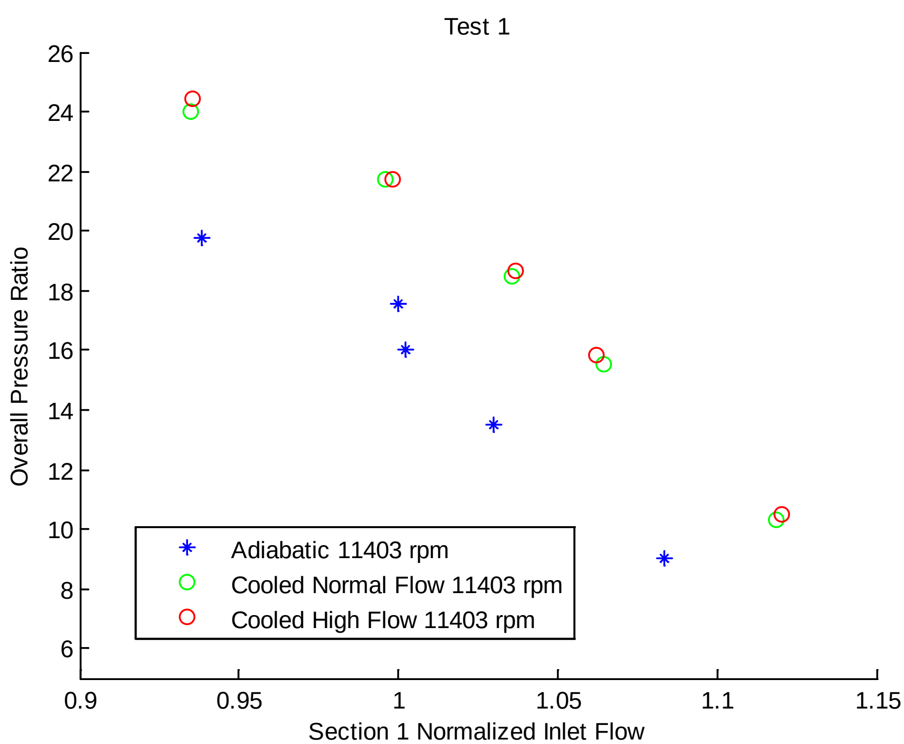


Figure 12-3. Overall Pressure Ratio vs. Normalized Flow (Test 1)

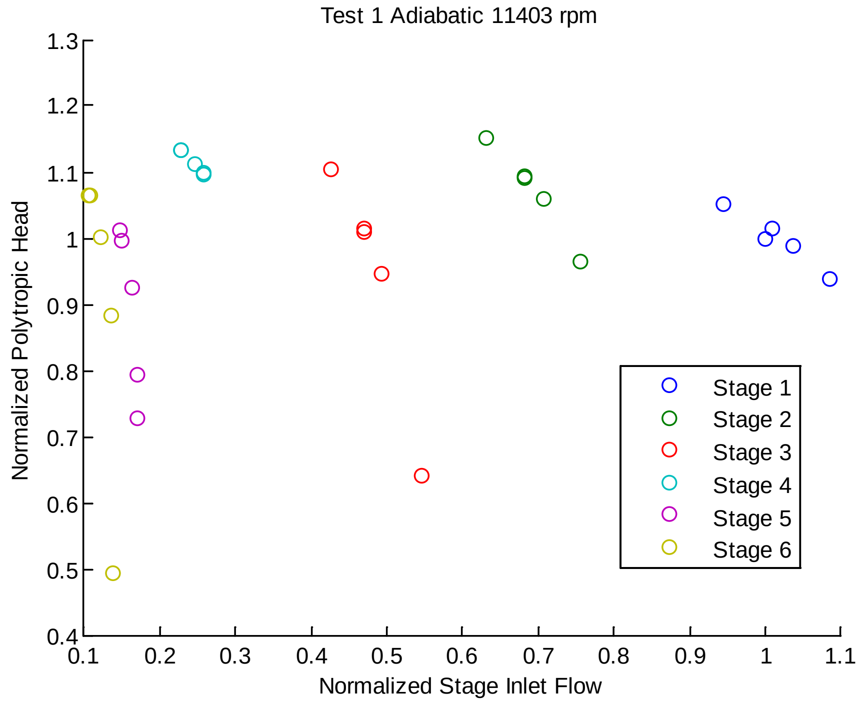


Figure 12-4. Polytropic Head vs. Inlet Flow for Adiabatic Case (Test 1)

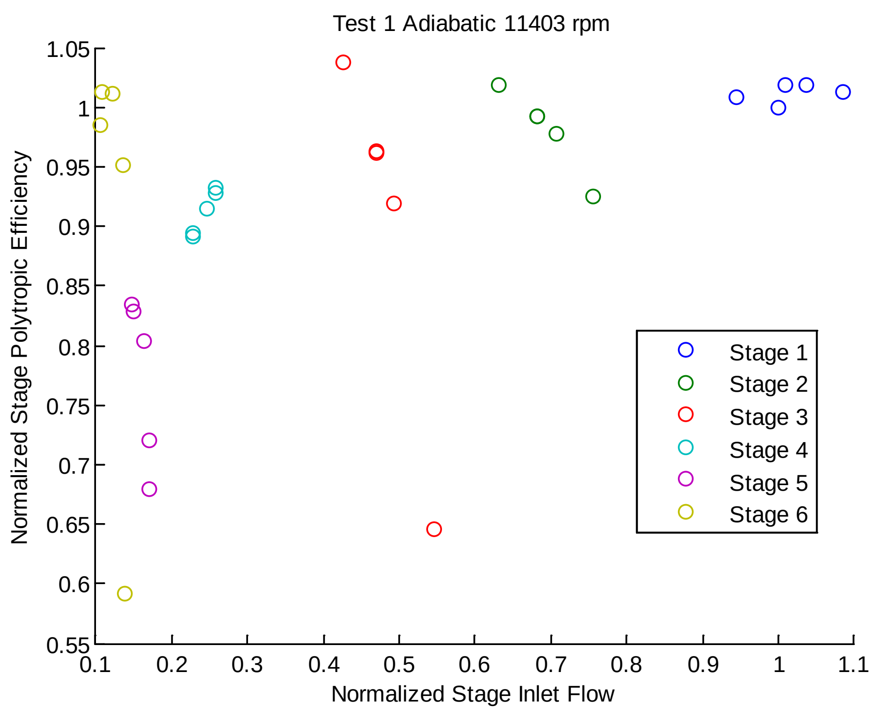


Figure 12-5. Stage Efficiency vs. Inlet Flow for Adiabatic Case (Test 1)

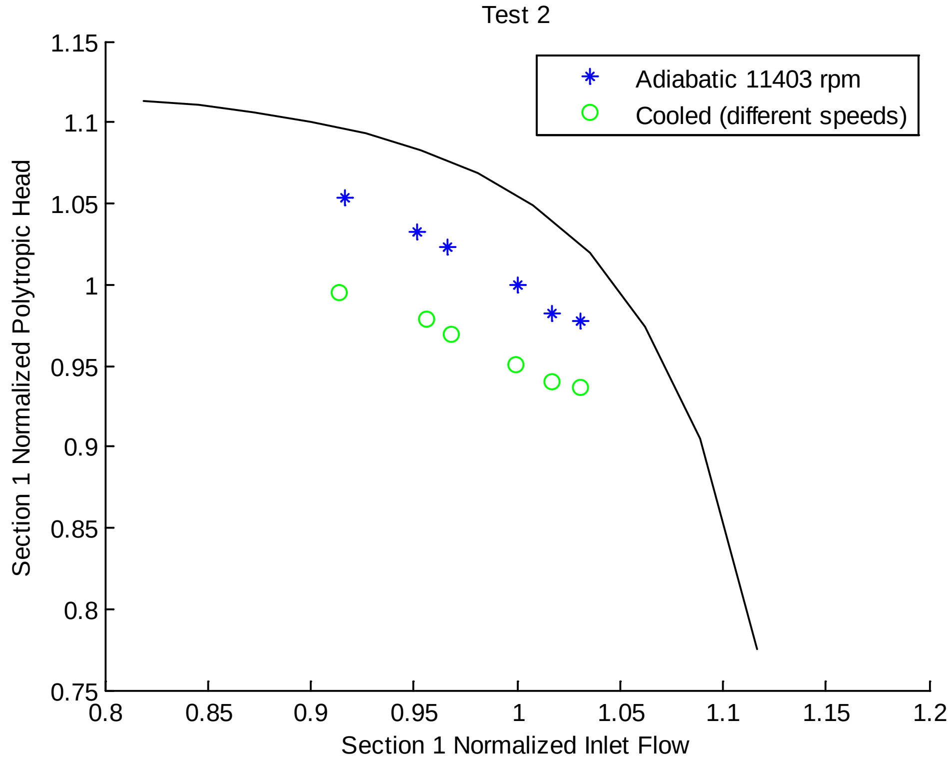


Figure 12-6. Section 1 Normalized Polytropic Head vs. Normalized Flow (Test 2)

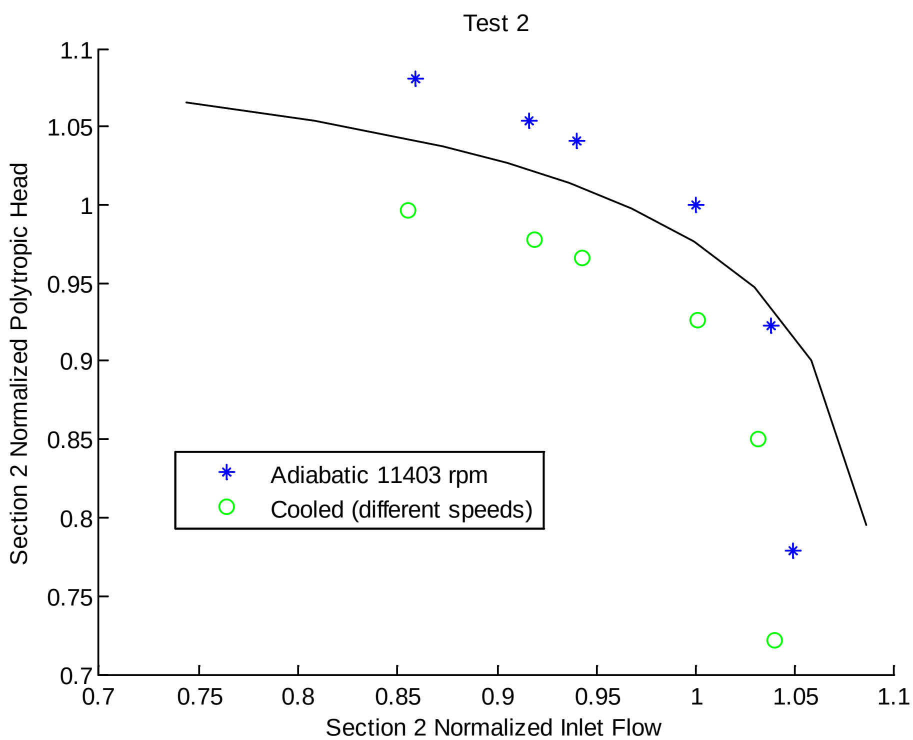


Figure 12-7. Section 2 Normalized Polytropic Head vs. Normalized Flow (Test 2)

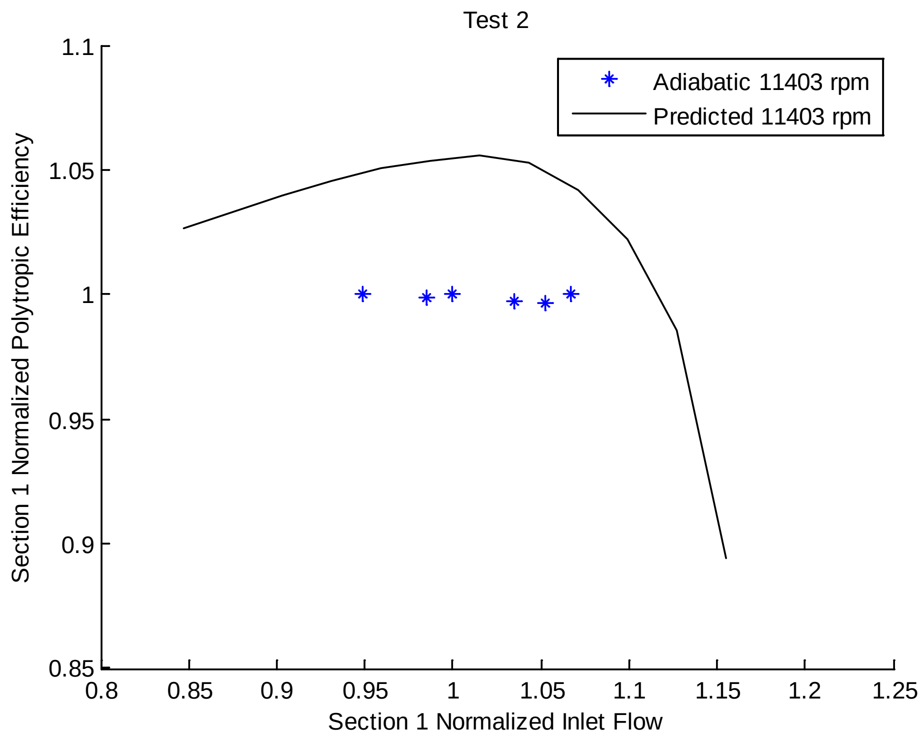


Figure 12-8. Section 1 Normalized Polytropic Efficiency vs. Normalized Flow (Test 2)

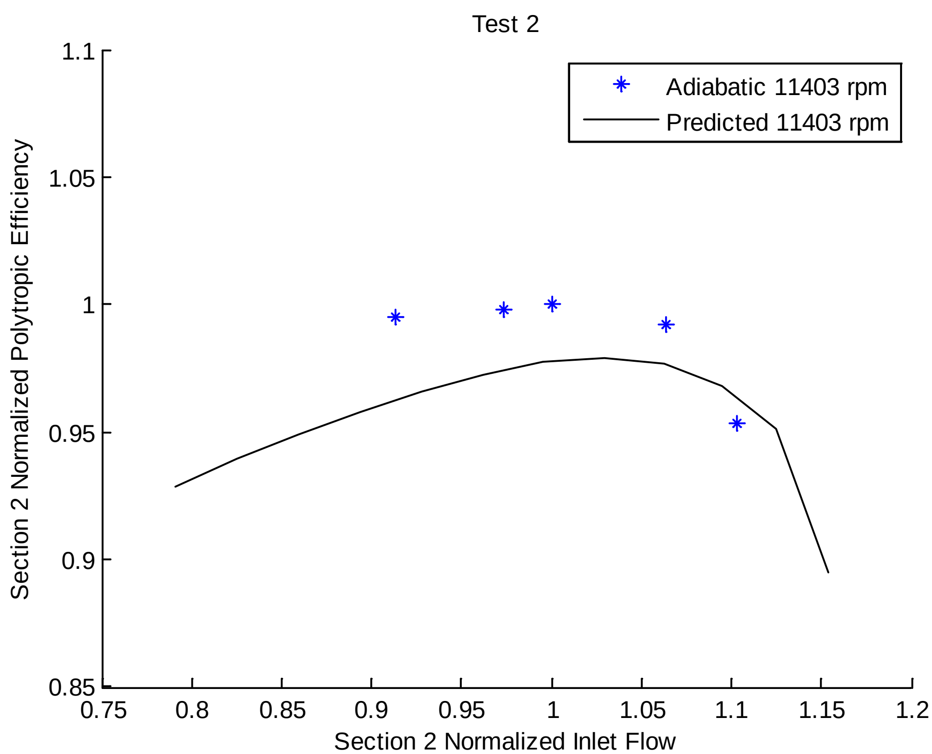


Figure 12-9. Section 2 Normalized Polytropic Efficiency vs. Normalized Flow (Test 2)

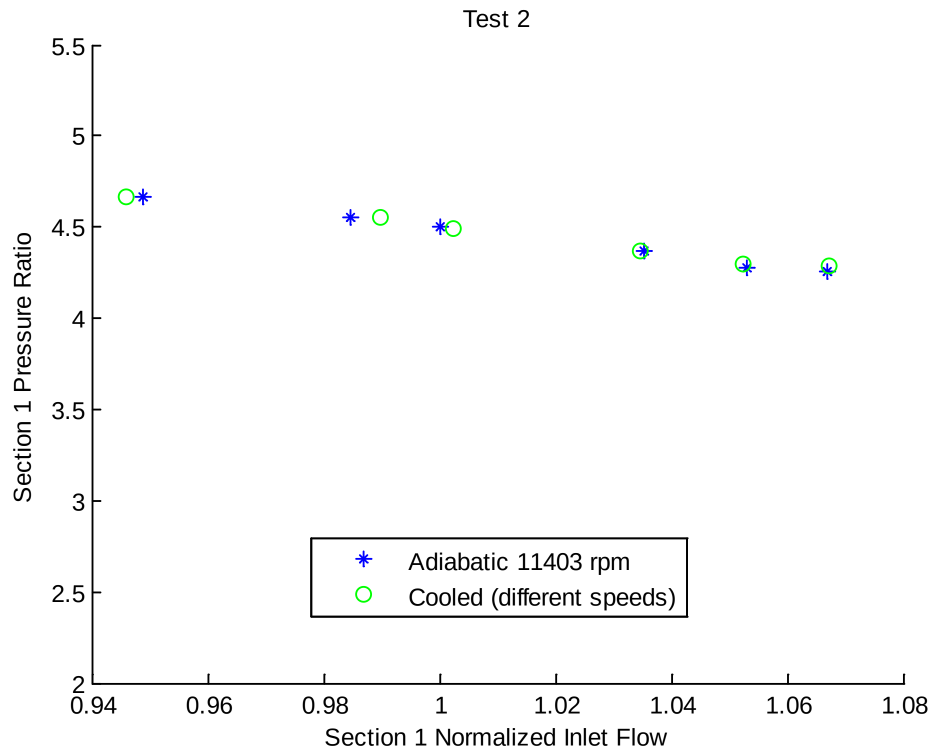


Figure 12-10. Section 1 Pressure Ratio vs. Normalized Flow (Test 2)

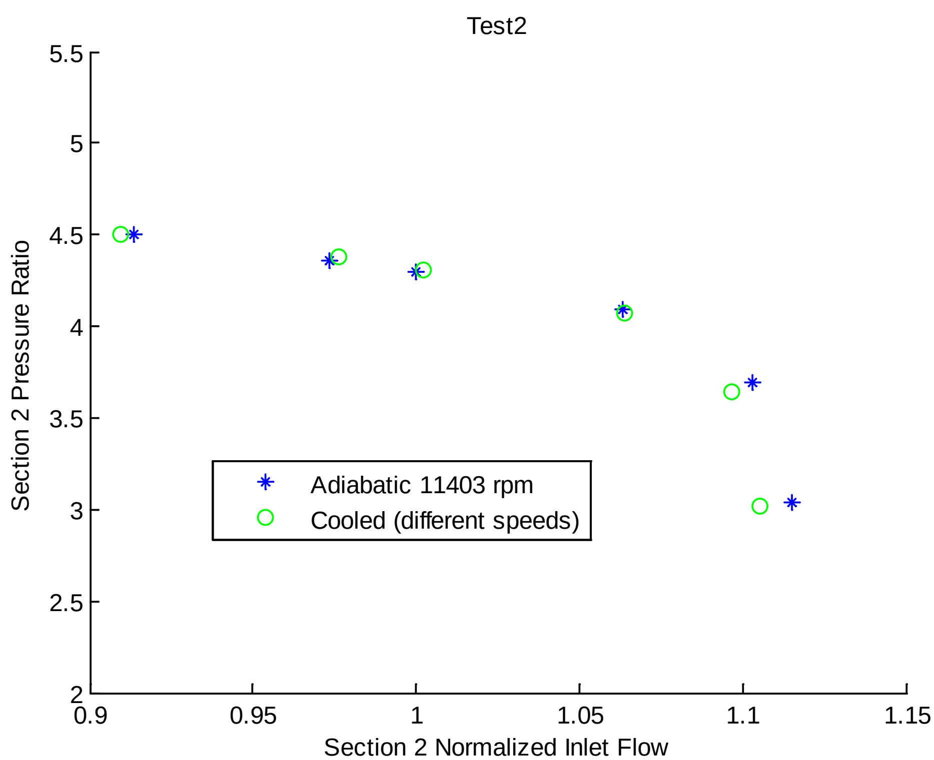


Figure 12-11. Section 2 Pressure Ratio vs. Normalized Flow (Test 2)

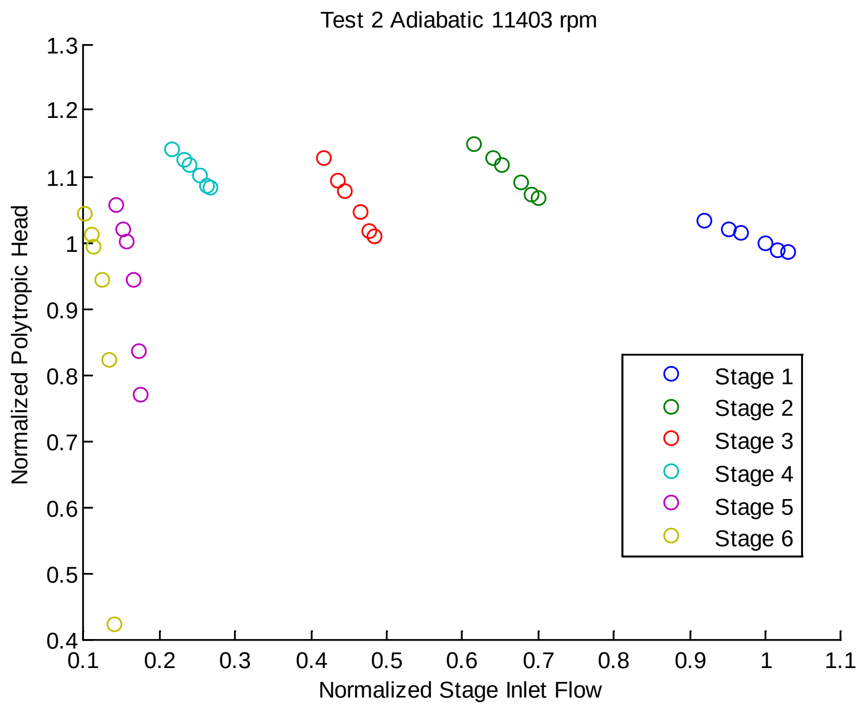


Figure 12-12. Stage Polytropic Head vs. Inlet Flow for Adiabatic Case (Test 2)

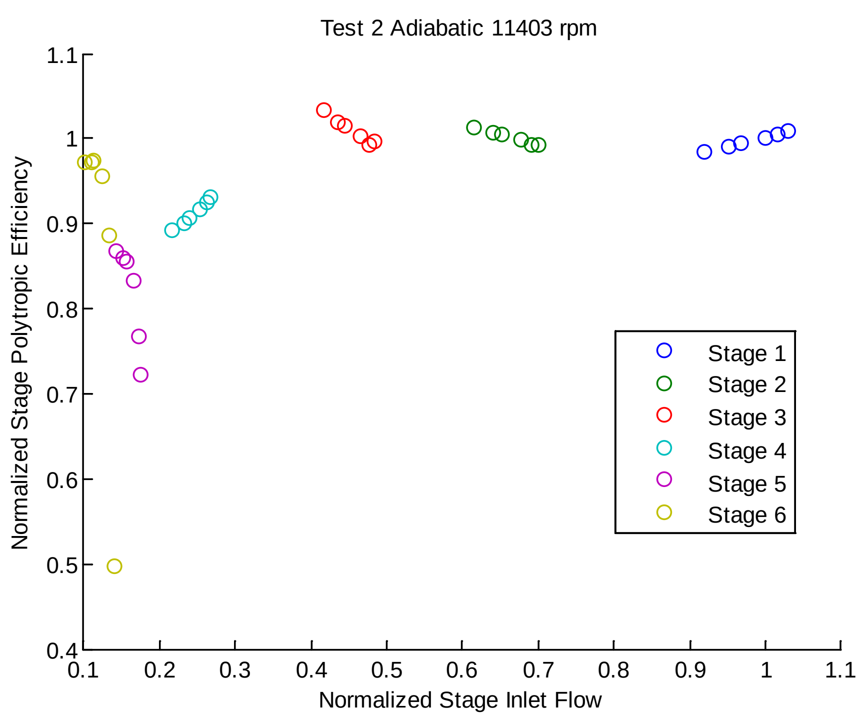


Figure 12-13. Stage Efficiency vs. Inlet Flow for Adiabatic Case (Test 2)

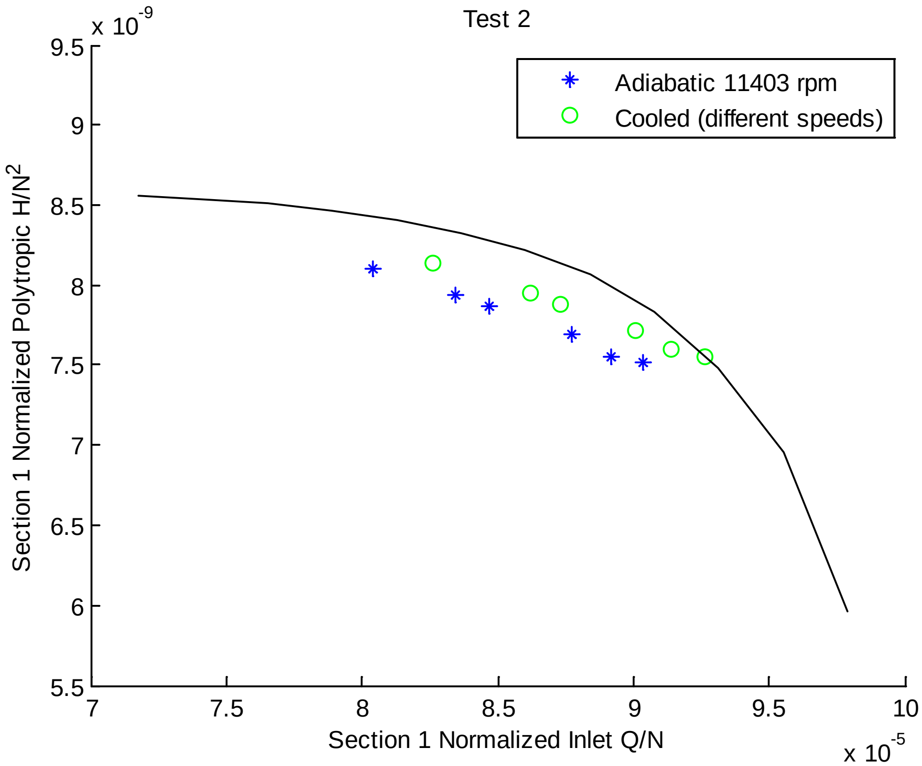


Figure 12-14. Section 1 Normalized Polytropic H/N^2 vs. Normalized Q/N (Test 2)

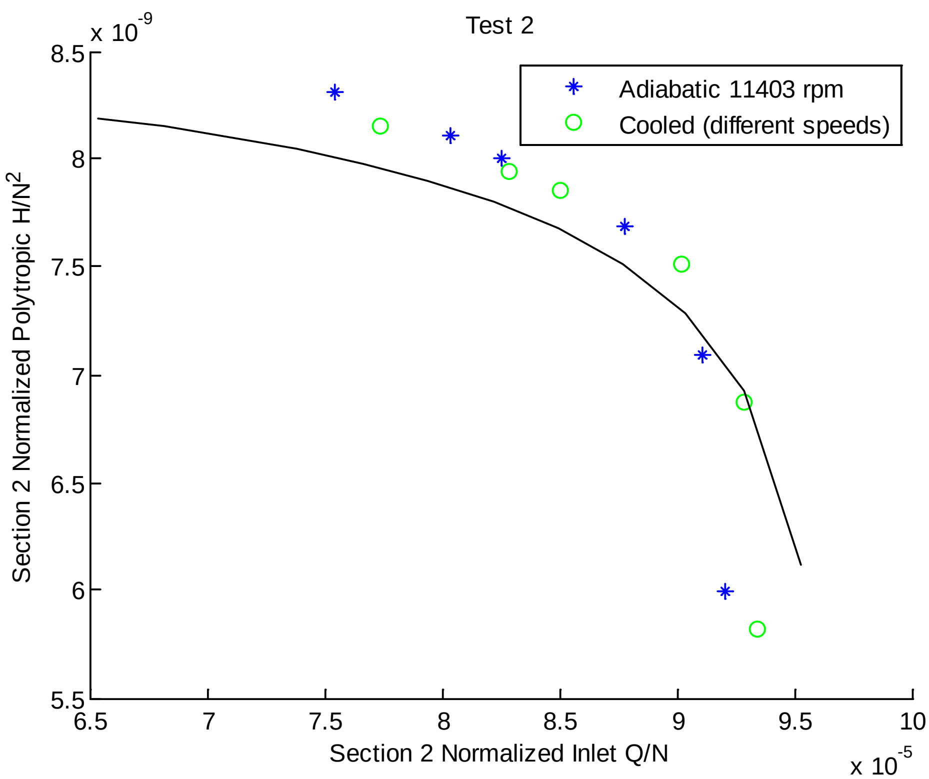


Figure 12-15. Section 2 Normalized Polytropic H/N^2 vs. Normalized Q/N (Test 2)

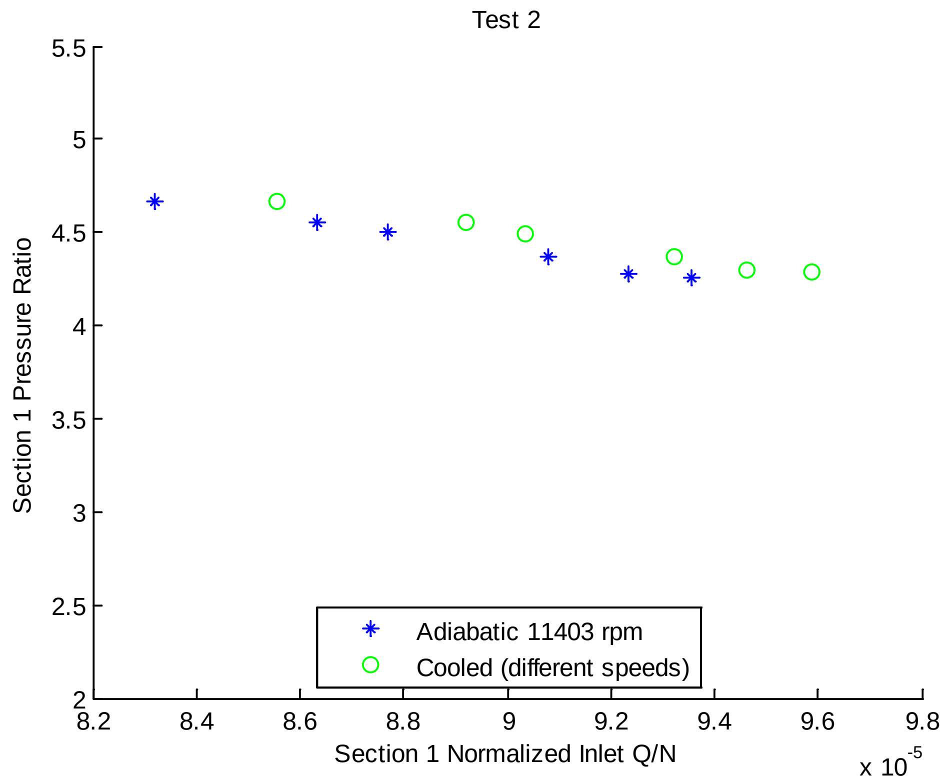


Figure 12-16. Section 1 Pressure Ratio vs. Normalized Inlet Q/N (Test 2)

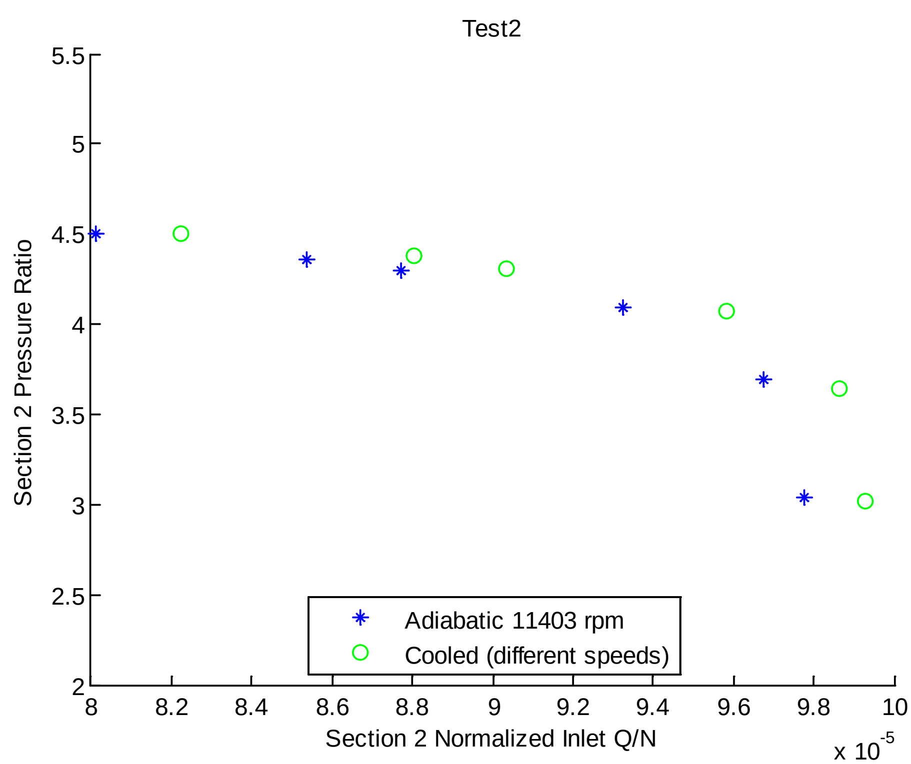


Figure 12-17. Section 2 Pressure Ratio vs. Normalized Inlet Q/N (Test 2)

The following table compares calculated data to the design point prediction values given on the compressor specifications sheet. Blue columns contain predicted values, and grey columns list the measured values. A parameter marked with an asterisk (*) means that the values were estimated by assuming the same polytropic efficiency as the adiabatic point with the same flow and overall pressure ratio case. A field listed as “N/A” indicates that the specified measurement was not available. Notably, no IGV temperatures were available for stage 6, so stage 5-6 return channel temperature was used for the stage 5 exit and stage 6 inlet temperature. This simplification is expected to artificially decrease the stage 5 horsepower, polytropic head, and heat exchanger effectiveness and artificially increase the stage 6 horsepower, polytropic head, and heat exchanger effectiveness.

Table 12-1. Comparison of Actual Values to Predicted Values (Test 2)

Test 2: Adiabatic Design Point, 11403 RPM

Stage	***1***		***2***		***3***		***4***		***5***		***6***	
Specification												
Inlet Pressure (psia)	14.8	14.99	25.7	25.6	42.8	42.6	62.4	60.3	109.7	108.6	172.7	167.9
Discharge Pressure (psia)	25.7	25.6	42.8	42.6	67.6	65.6	109.7	108.6	172.7	167.9	250	247.05
Inlet Temperature (°F)	115	115.4					115	114.4				

Test 2: Cooled, Lower Speed to Match Overall Pressure Ratio and Mass Flow

Stage	***1***		***2***		***3***		***4***		***5***		***6***	
Specification												
Inlet Pressure (psia)	14.8	15	25.7	25.2	42.8	41.8	62.4	60.6	109.7	106.3	172.7	162.1
Discharge Pressure (psia)	25.7	25.2	42.8	41.8	67.6	65.6	109.7	106.3	172.7	162.1	250	246.8
Inlet Temperature (°F)	115	115					115	115				
Head Percent of Uncooled (%)*	100.0%	96.8%	98.0%	95.8%	94.4%	96.5%	100.0%	95.3%	97.3%	91.0%	92.9%	99.5%
Cooled Diaphragm Effectiveness*	13.03%	16.62%	15.06%	17.95%	5.81%	5.70 %	13.85%	26.75%	16.86%	12.10%	4.68%	14.87%

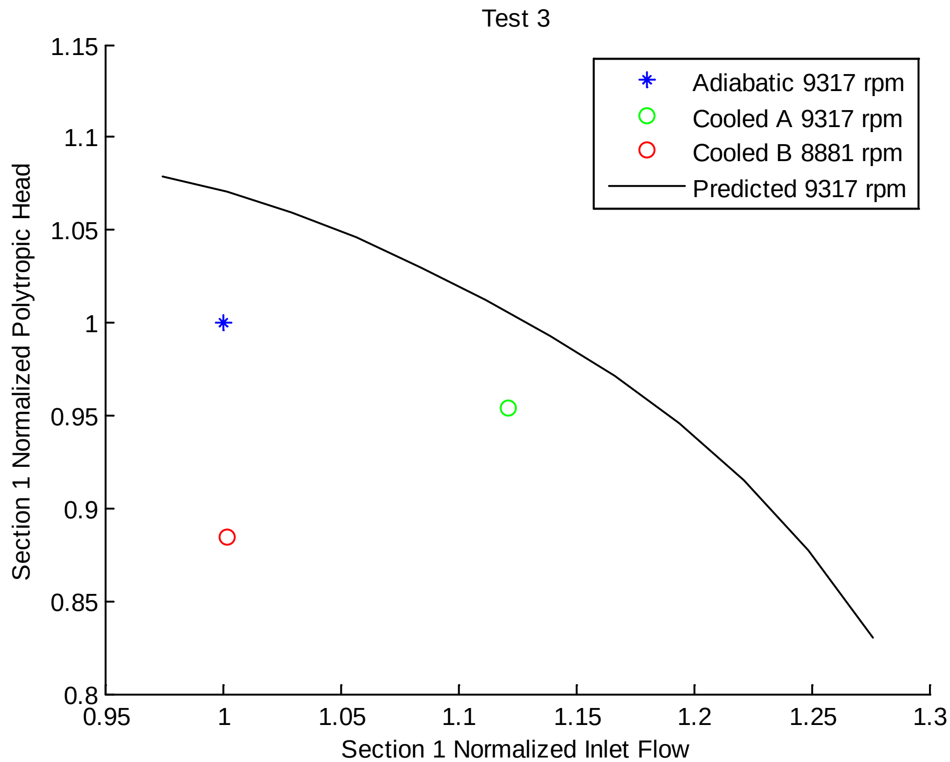


Figure 12-18. Section 1 Normalized Polytropic Head vs. Normalized Flow (Test 3)

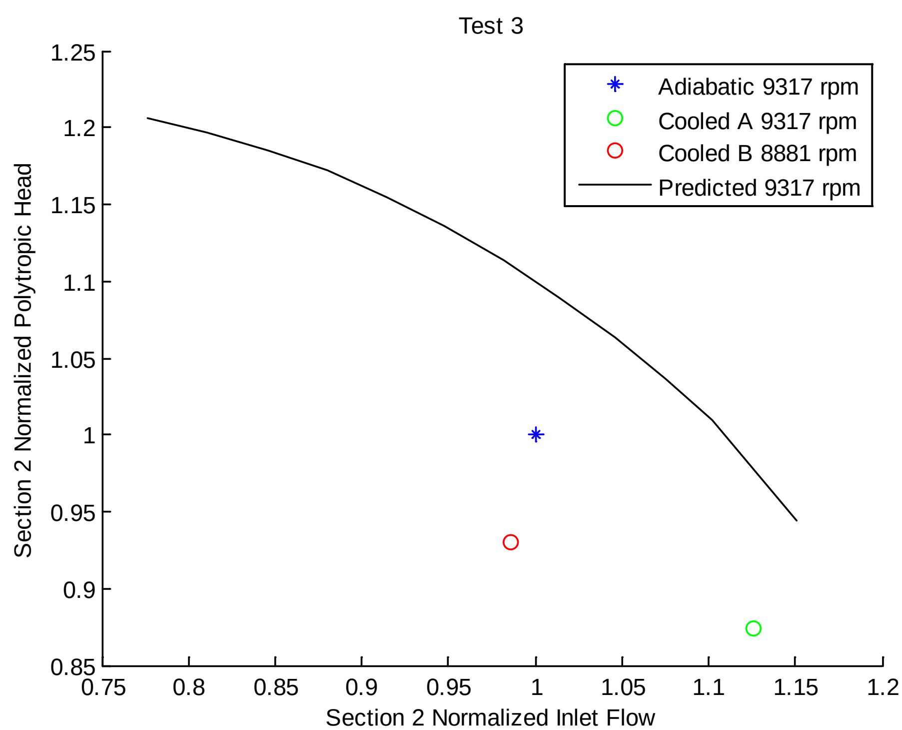


Figure 12-19. Section 2 Normalized Polytropic Head vs. Normalized Flow (Test 3)

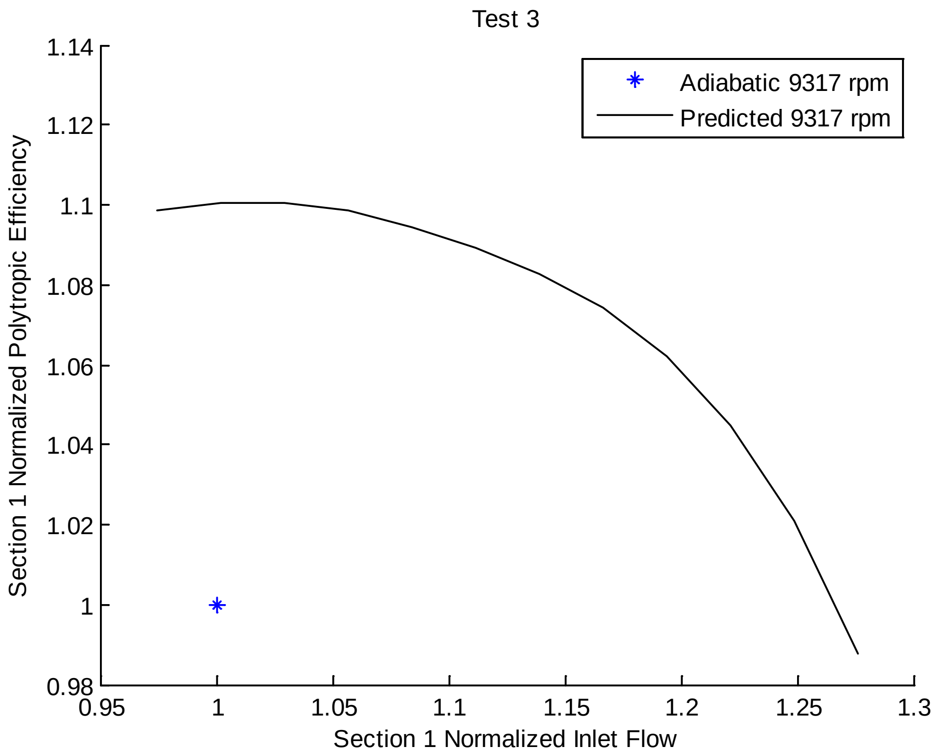


Figure 12-20. Section 1 Normalized Polytropic Efficiency vs. Normalized Flow (Test 3)

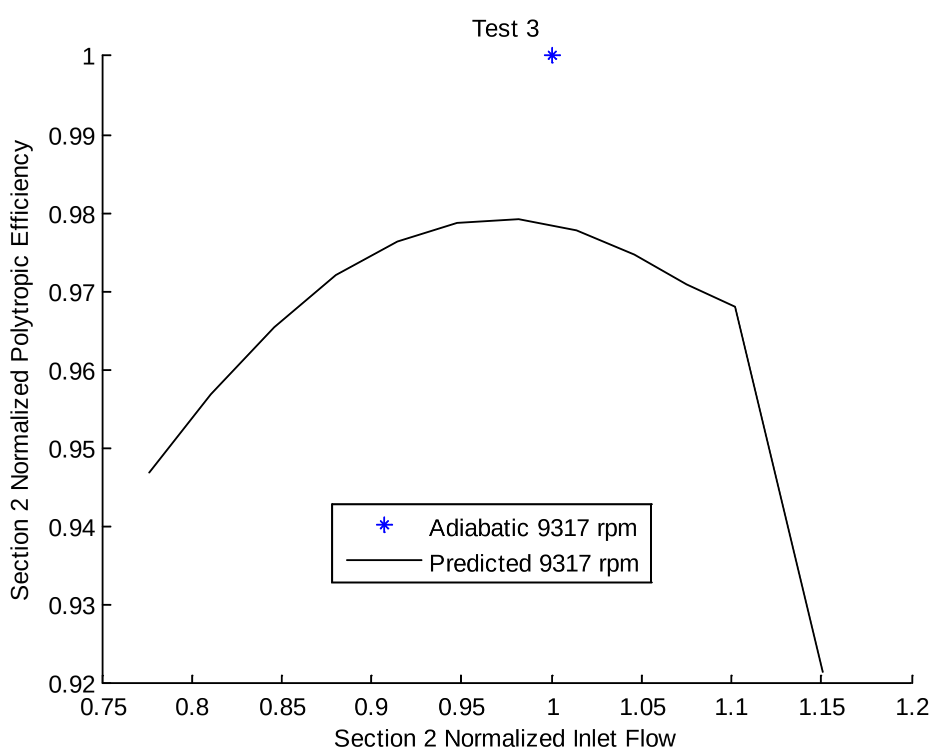


Figure 12-21. Section 2 Normalized Polytropic Efficiency vs. Normalized Flow (Test 3)

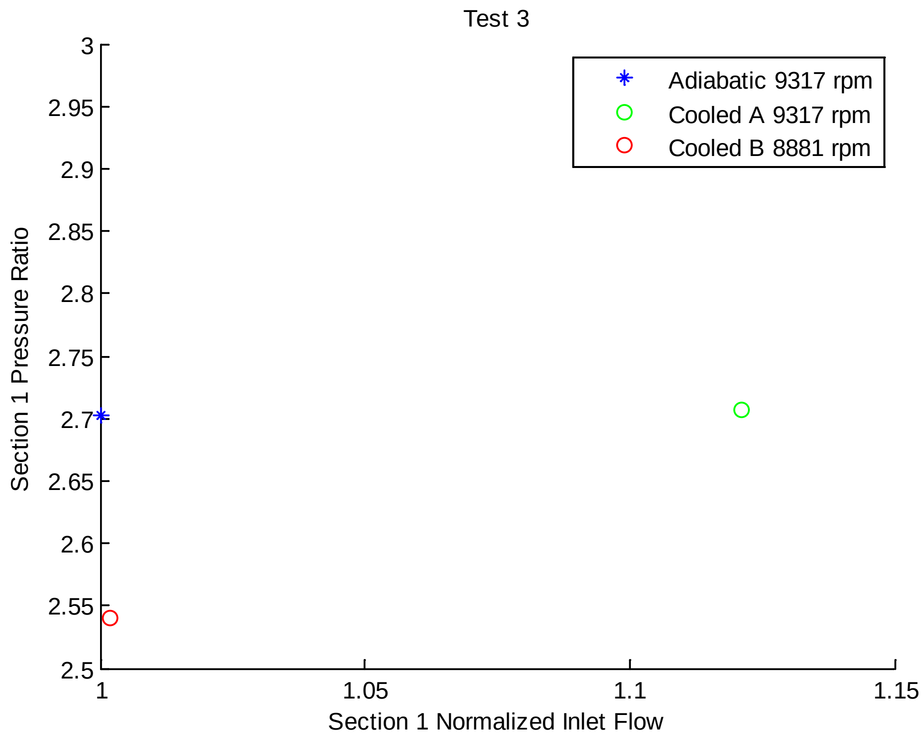


Figure 12-22. Section 1 Pressure Ratio vs. Normalized Flow (Test 3)

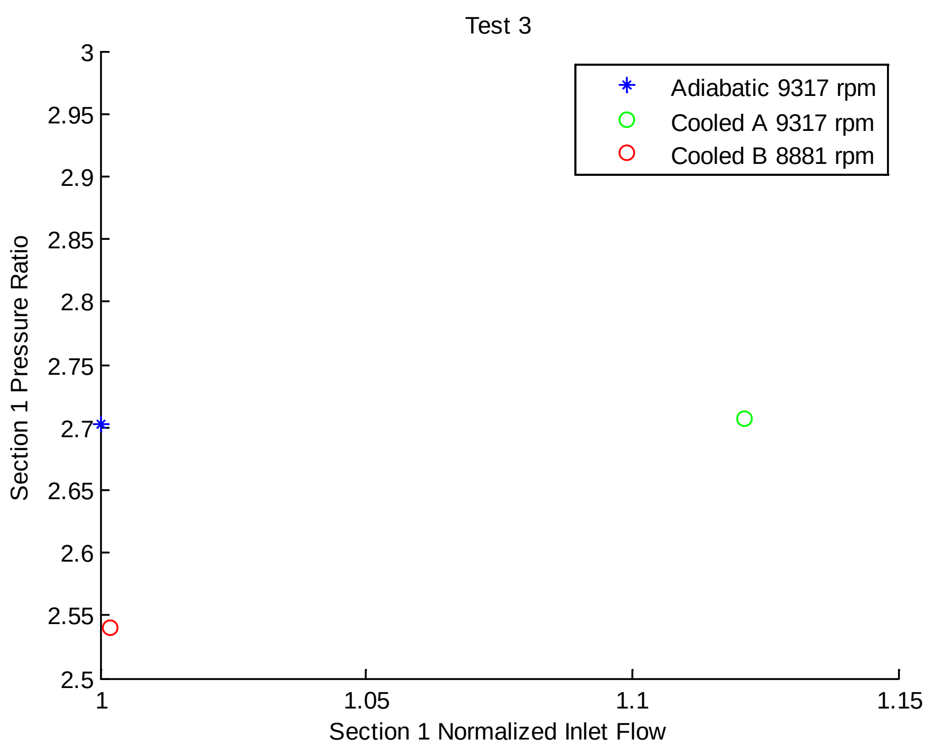


Figure 12-23. Section 2 Pressure Ratio vs. Flow (Test 3)

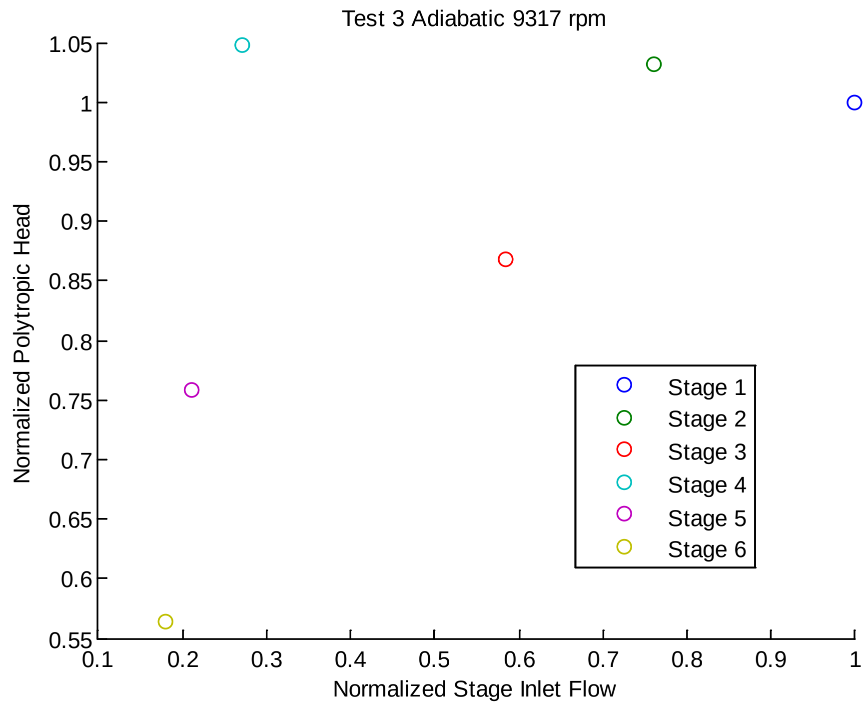


Figure 12-24. Normalized Stage Head vs. Inlet Flow for Adiabatic Case (Test 3)

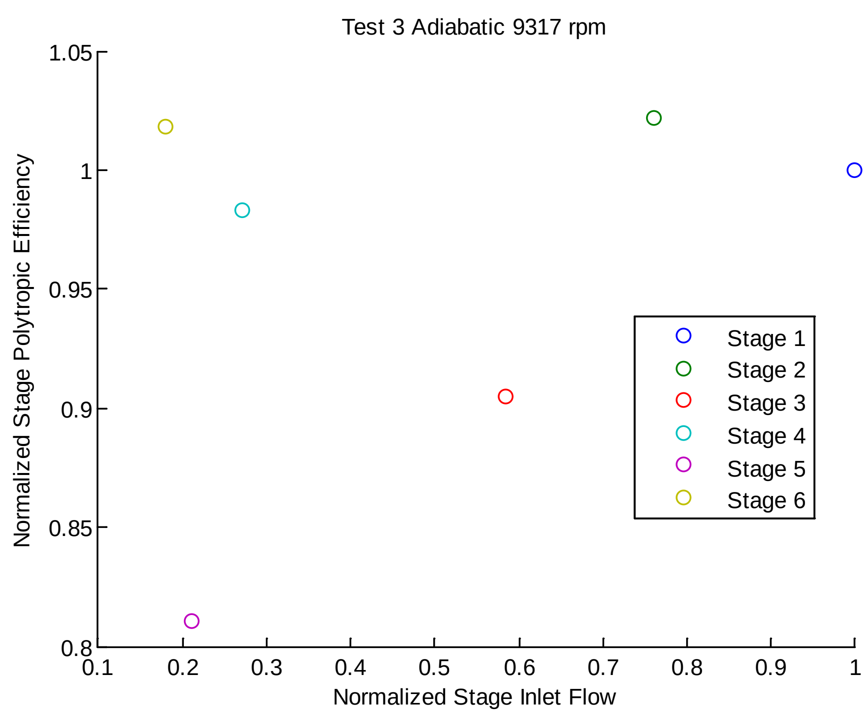


Figure 12-25. Normalized Stage Efficiency vs. Inlet Flow for Adiabatic Case (Test 3)

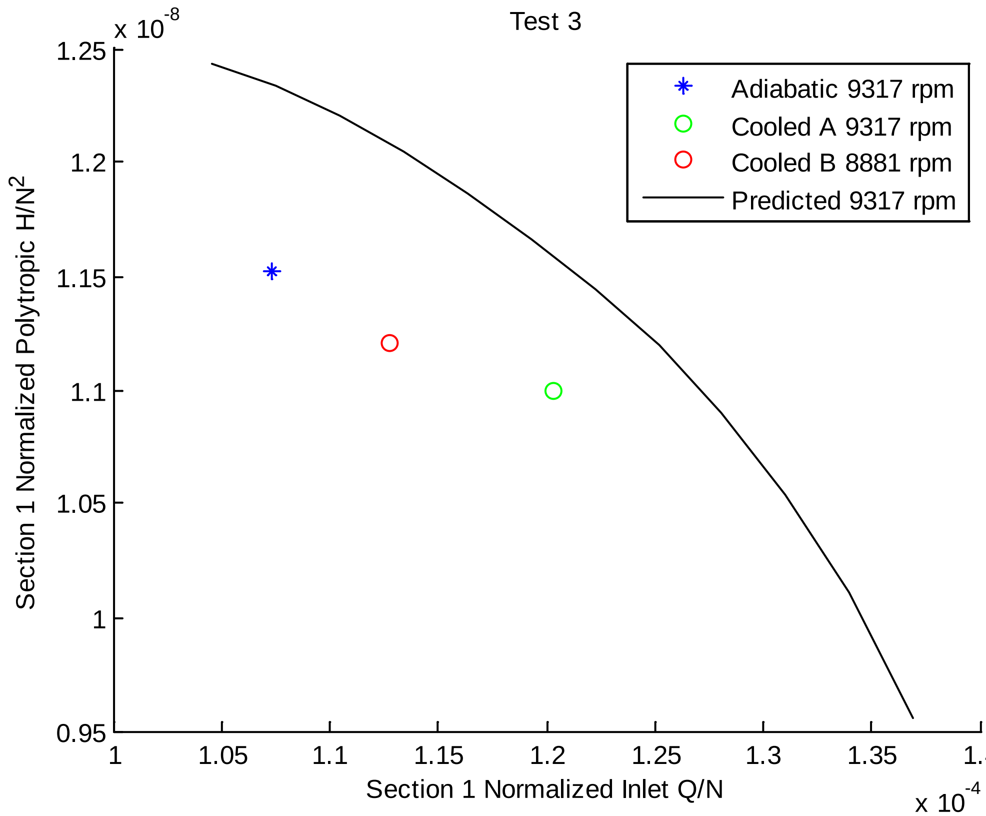


Figure 12-26. Section 1 Normalized Polytropic H/N^2 vs. Normalized Q/N (Test 3)

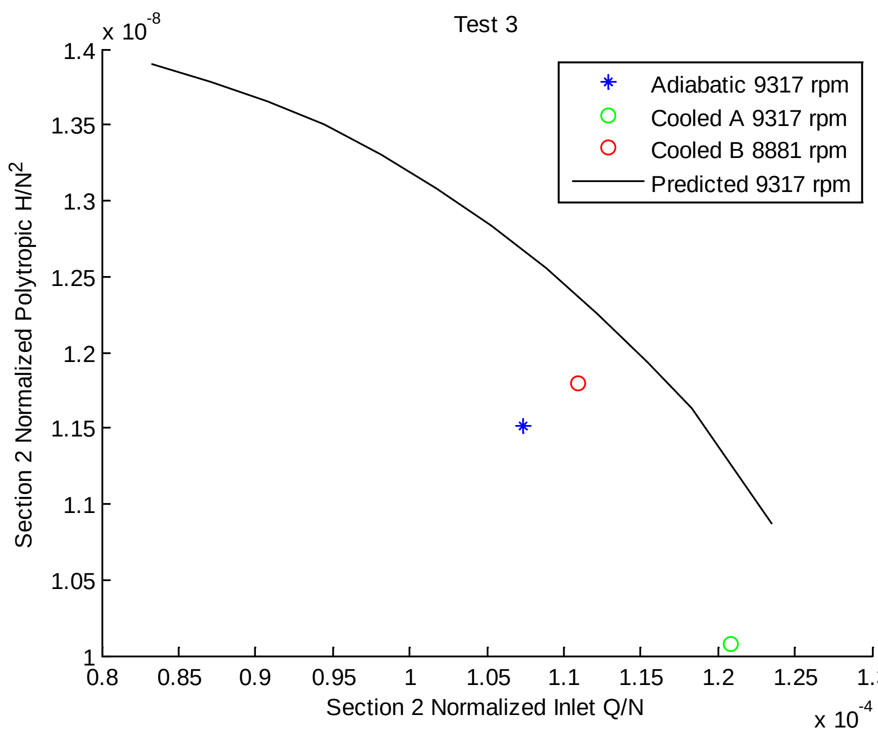


Figure 12-27. Section 2 Normalized Polytropic H/N^2 vs. Normalized Q/N (Test 3)

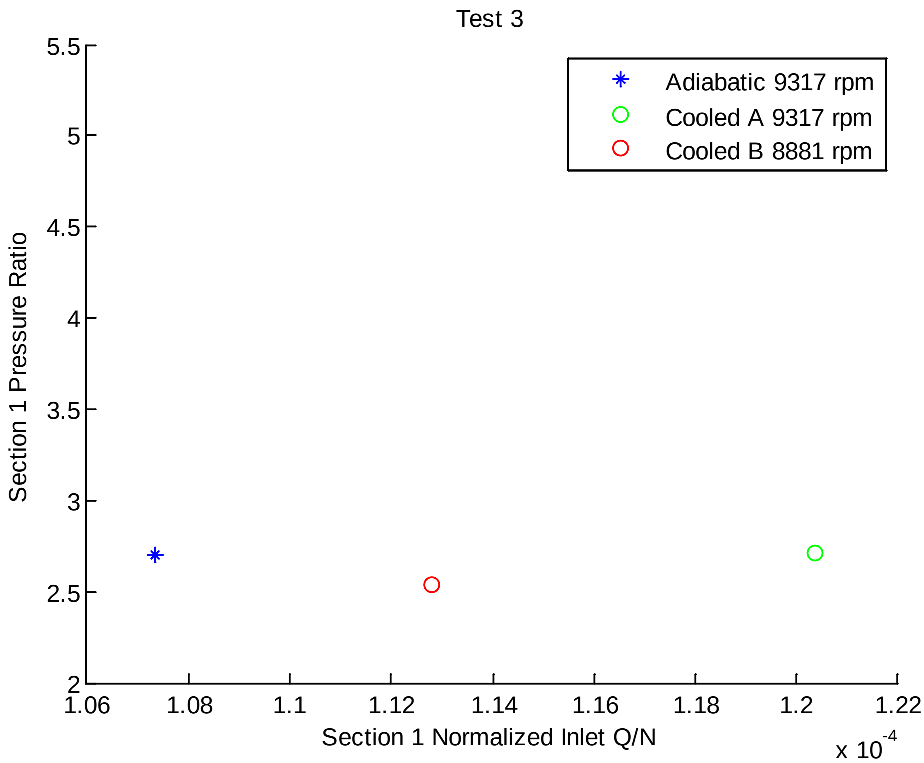


Figure 12-28. Section 1 Pressure Ratio vs. Normalized Inlet Q/N (Test 3)

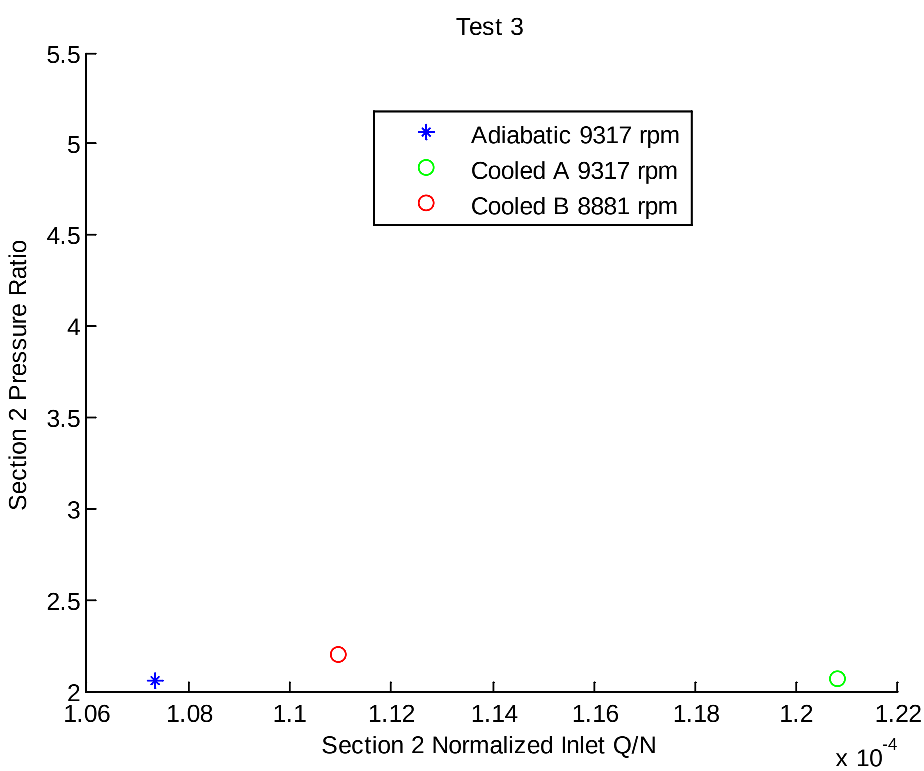


Figure 12-29. Section 2 Pressure Ratio vs. Inlet Q/N (Test 3)

13. APPENDIX F: RAW DATA

This section presents raw data gathered during testing. As described previously, multiple temperature and pressure probes were present at each location. This section contains plots showing the difference between the averaged and the actual measurements for each temperature and pressure probe at the suction and discharge locations.

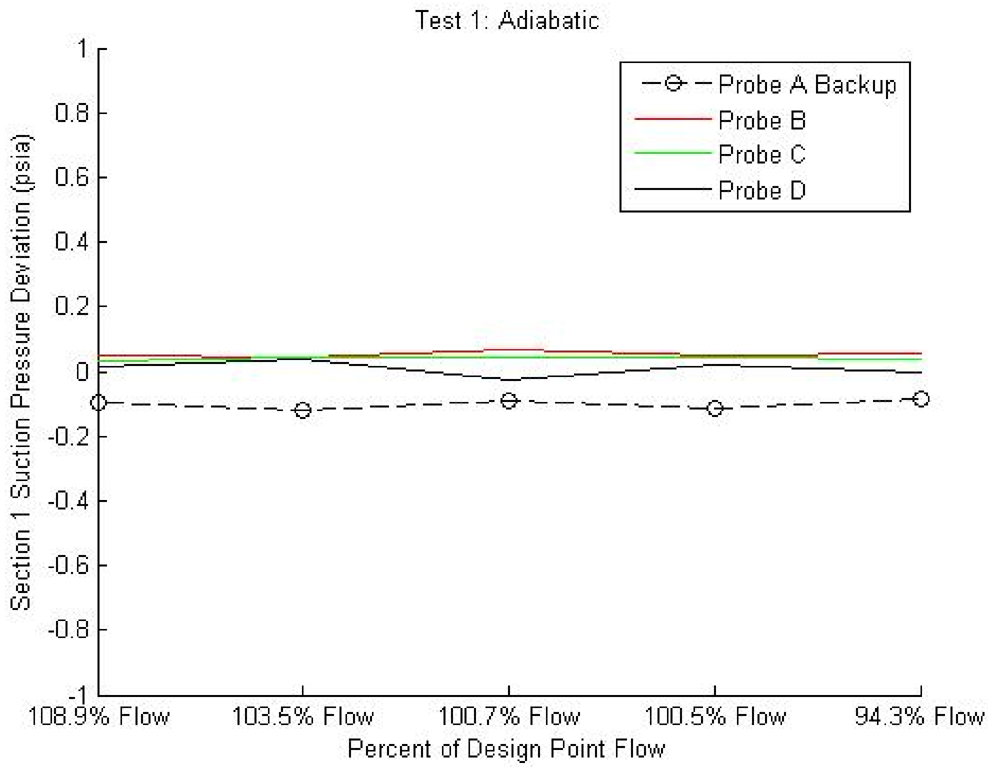


Figure 13-1. Section 1 Suction Pressure Deviation (Test 1, Adiabatic)

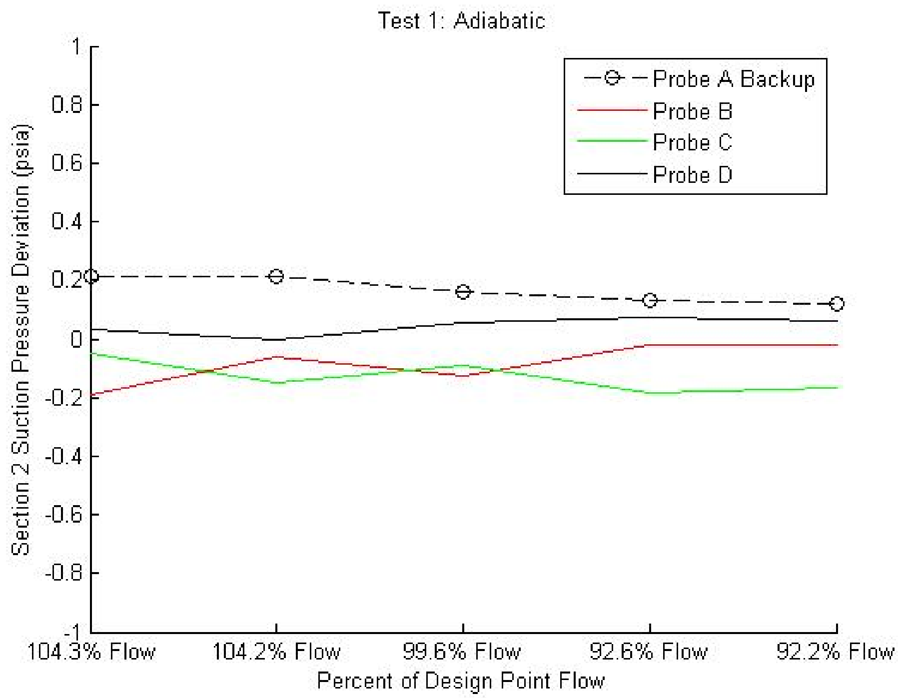


Figure 13-2. Section 2 Suction Pressure Deviation (Test 1, Adiabatic)

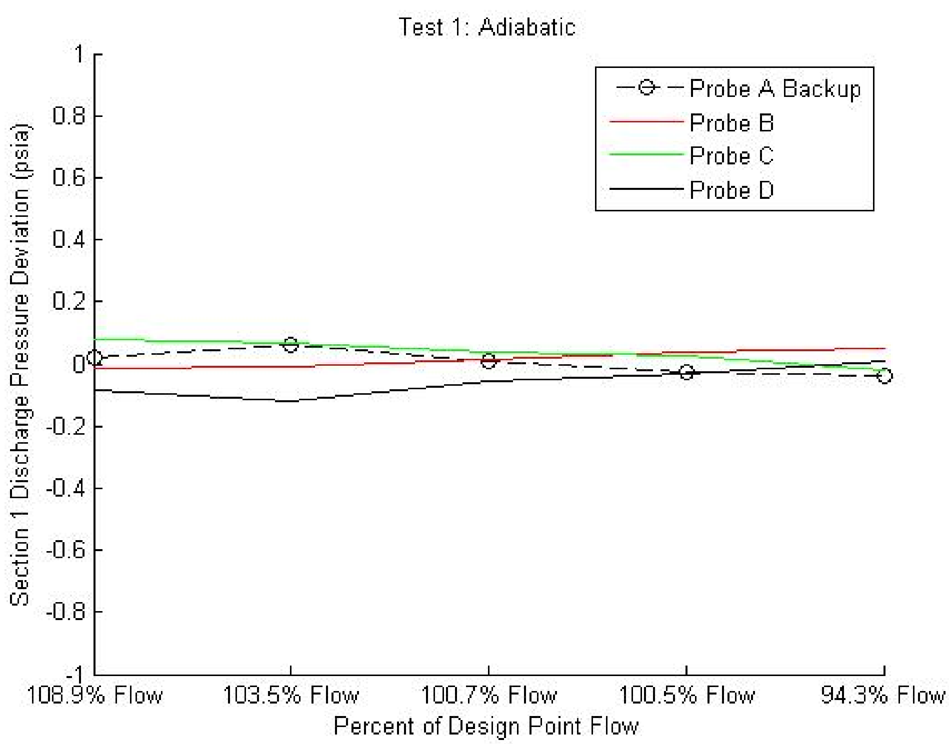


Figure 13-3. Section 1 Discharge Pressure Deviation (Test 1, Adiabatic)

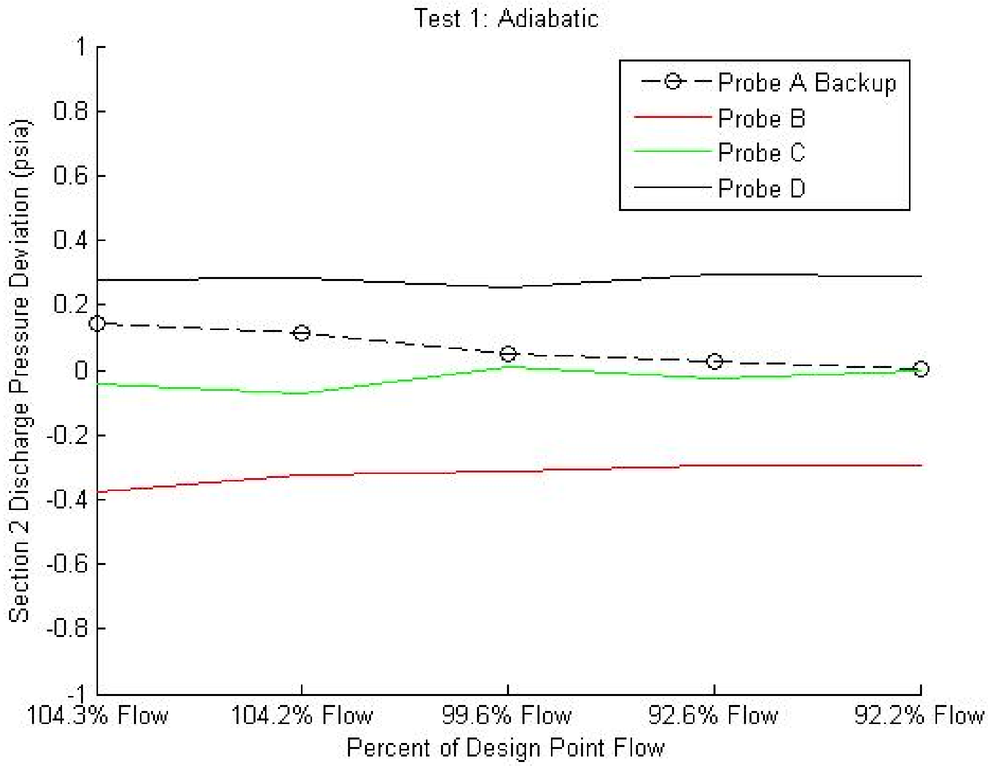


Figure 13-4. Section 2 Discharge Pressure Deviation (Test 1, Adiabatic)

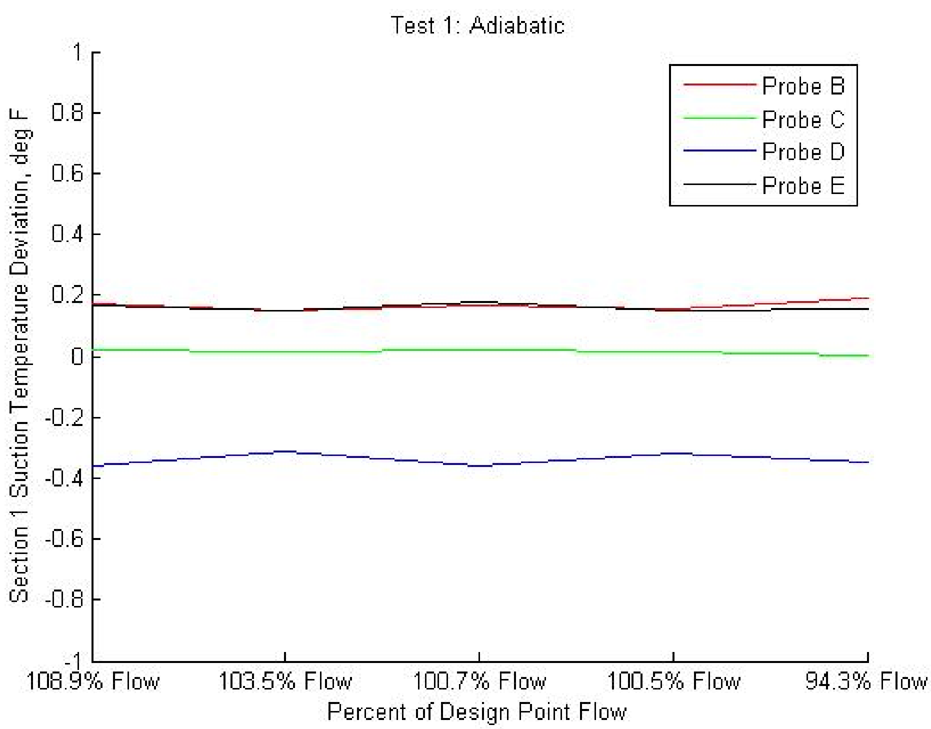


Figure 13-5. Section 1 Suction Temperature Deviation (Test 1, Adiabatic)

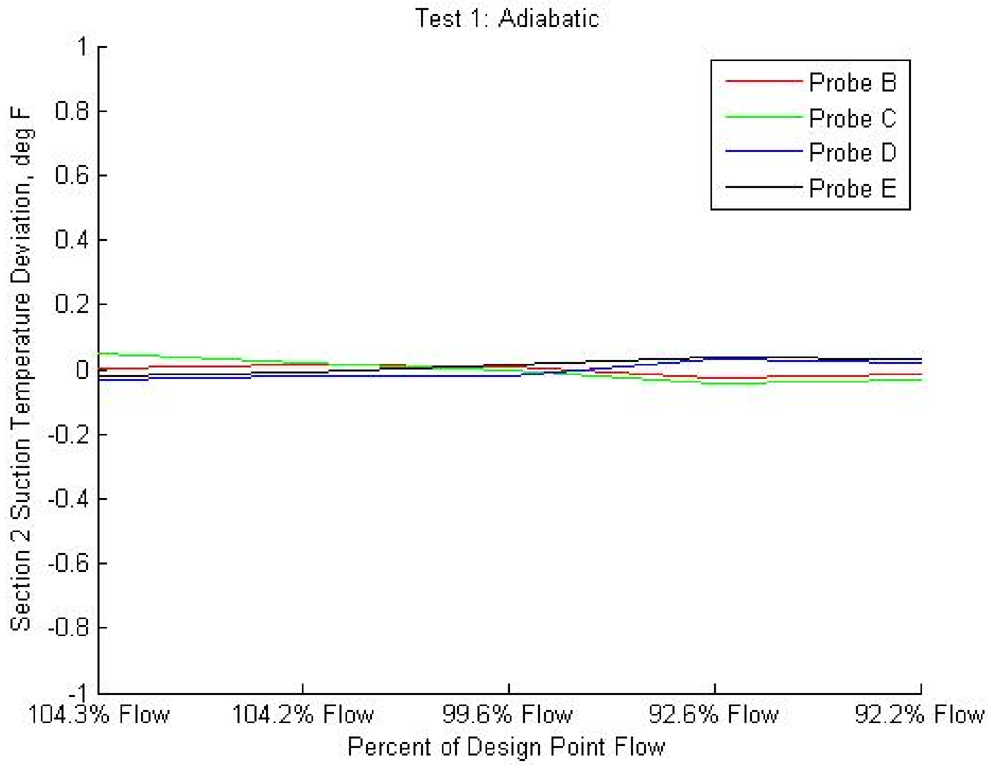


Figure 13-6. Section 2 Suction Temperature Deviation (Test 1, Adiabatic)

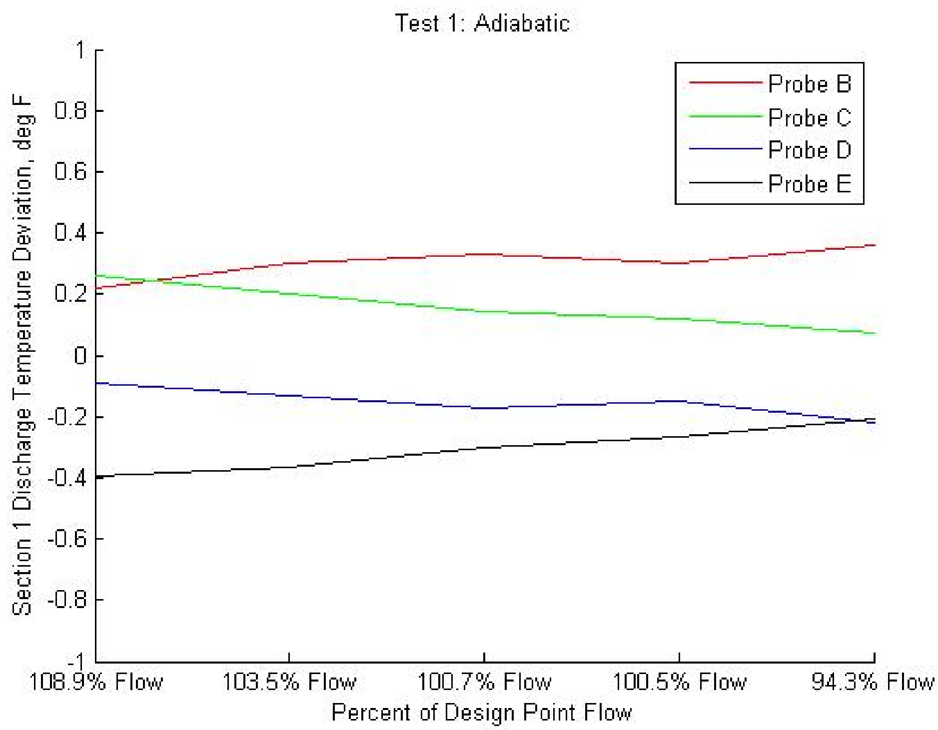


Figure 13-7. Section 1 Discharge Temperature Deviation (Test 1, Adiabatic)

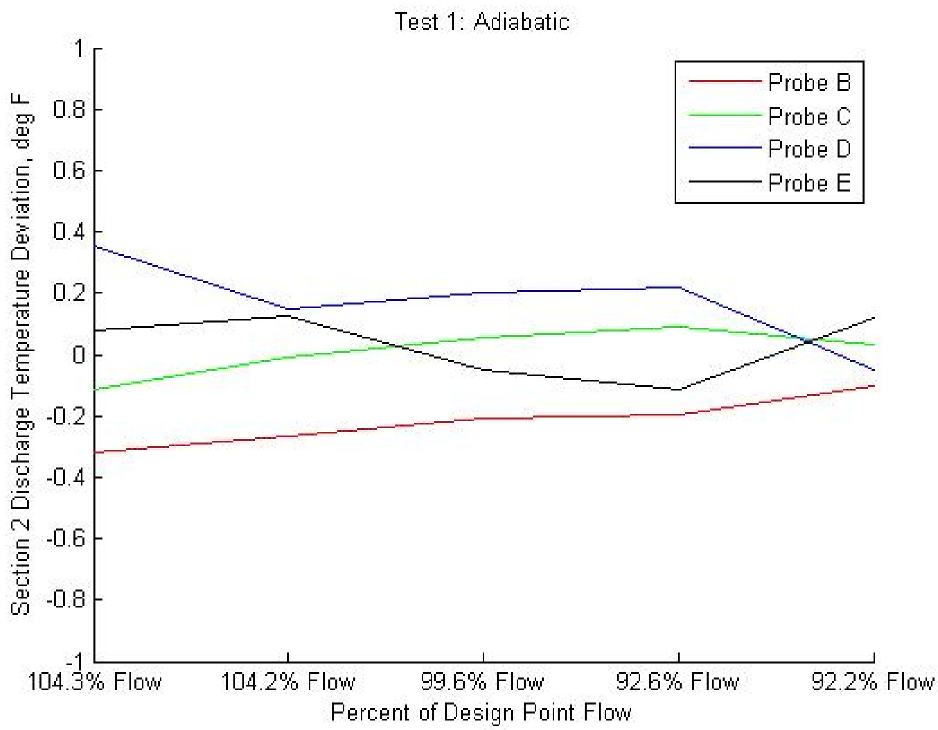


Figure 13-8. Section 2 Discharge Temperature Deviation (Test 1, Adiabatic)

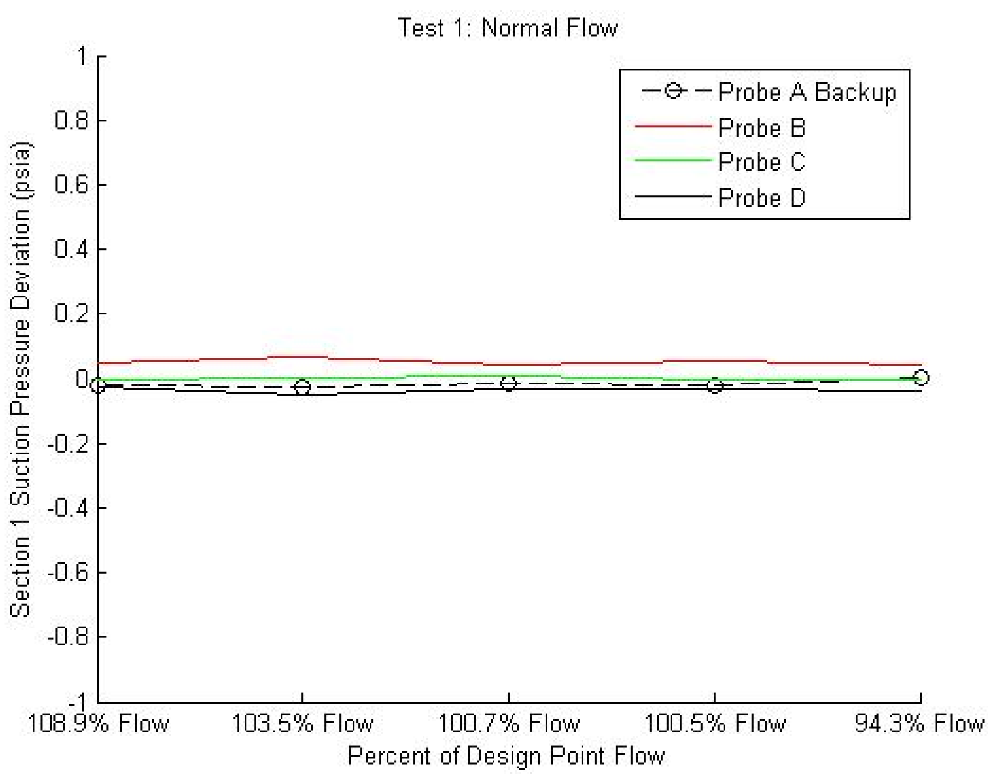


Figure 13-9. Section 1 Suction Pressure Deviation (Test 1, Normal Flow)

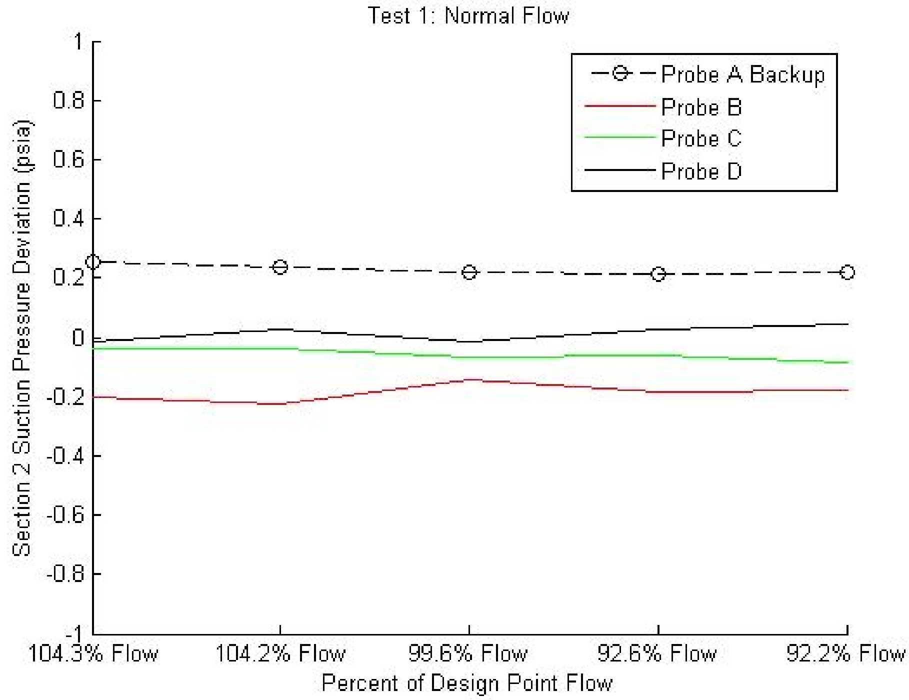


Figure 13-10. Section 2 Suction Pressure Deviation (Test 1, Normal Flow)

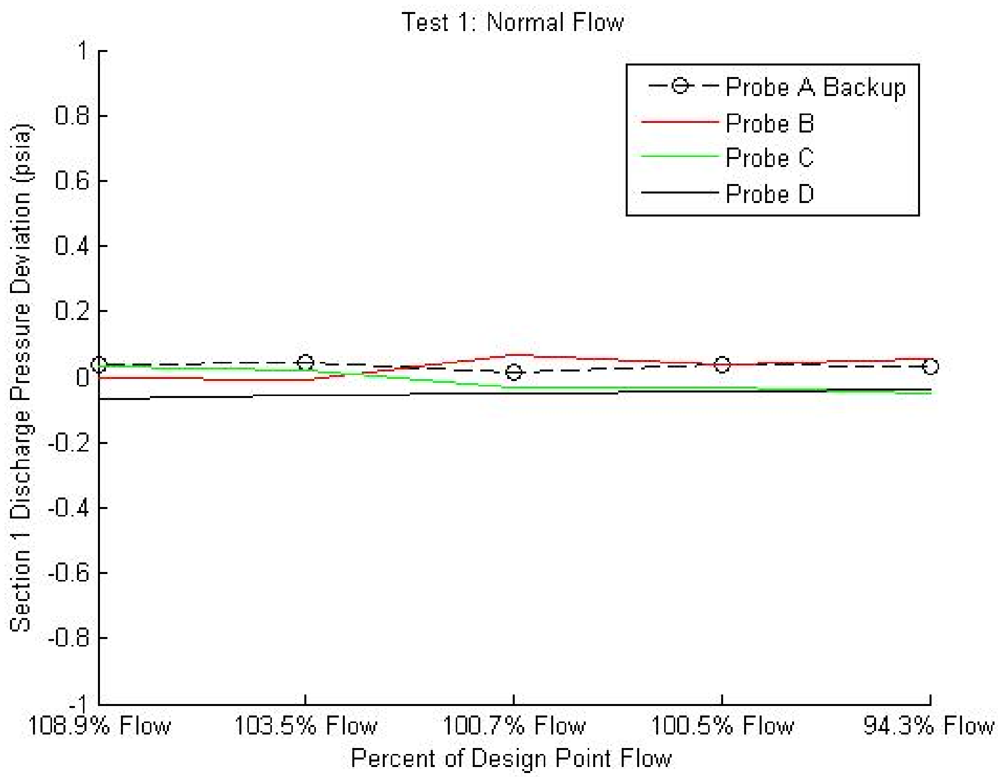


Figure 13-11. Section 1 Discharge Pressure Deviation (Test 1, Normal Flow)

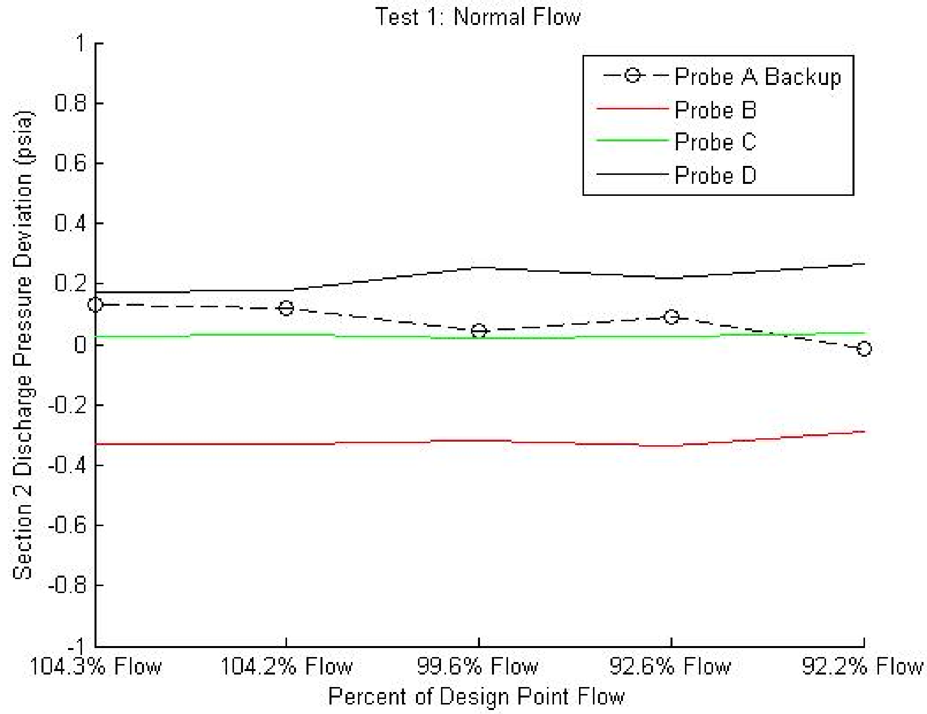


Figure 13-12. Section 2 Discharge Pressure Deviation (Test 1, Normal Flow)

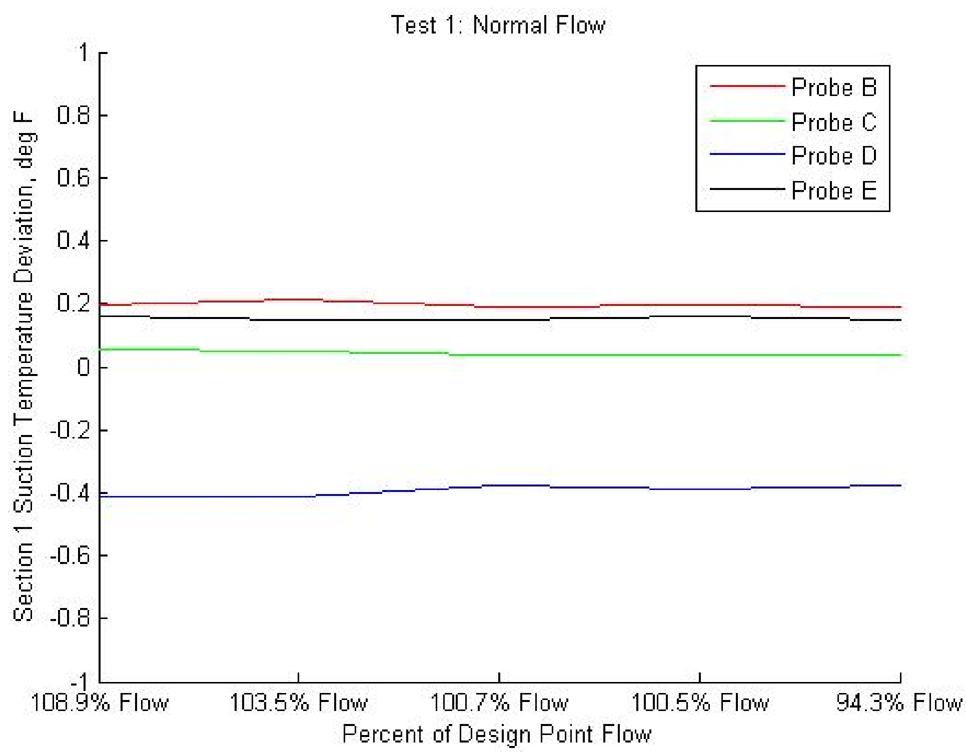


Figure 13-13. Section 1 Suction Temperature Deviation (Test 1, Normal Flow)

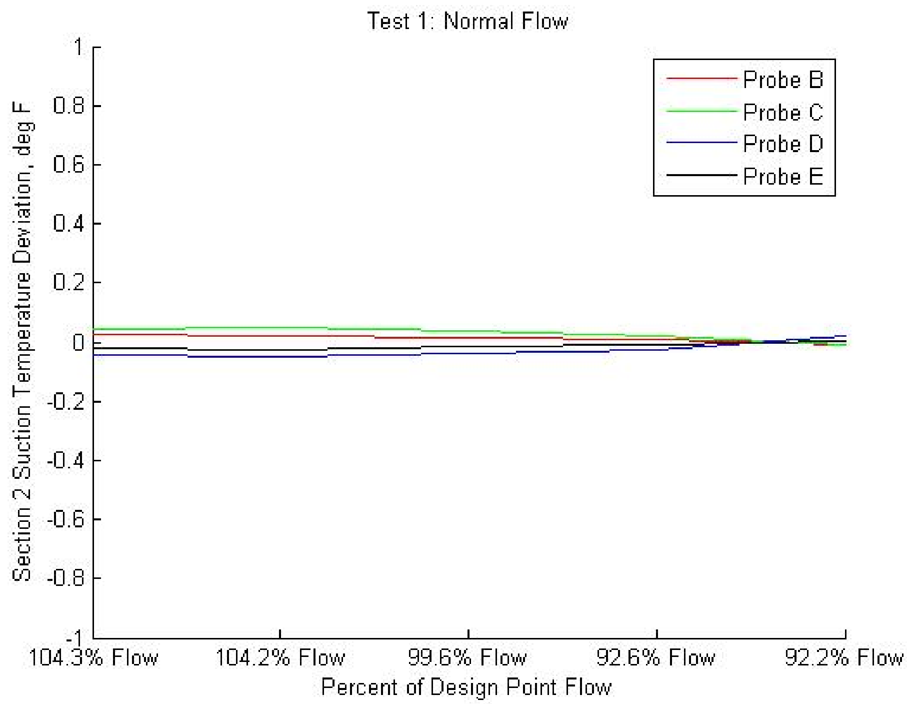


Figure 13-14. Section 2 Suction Temperature Deviation (Test 1, Normal Flow)

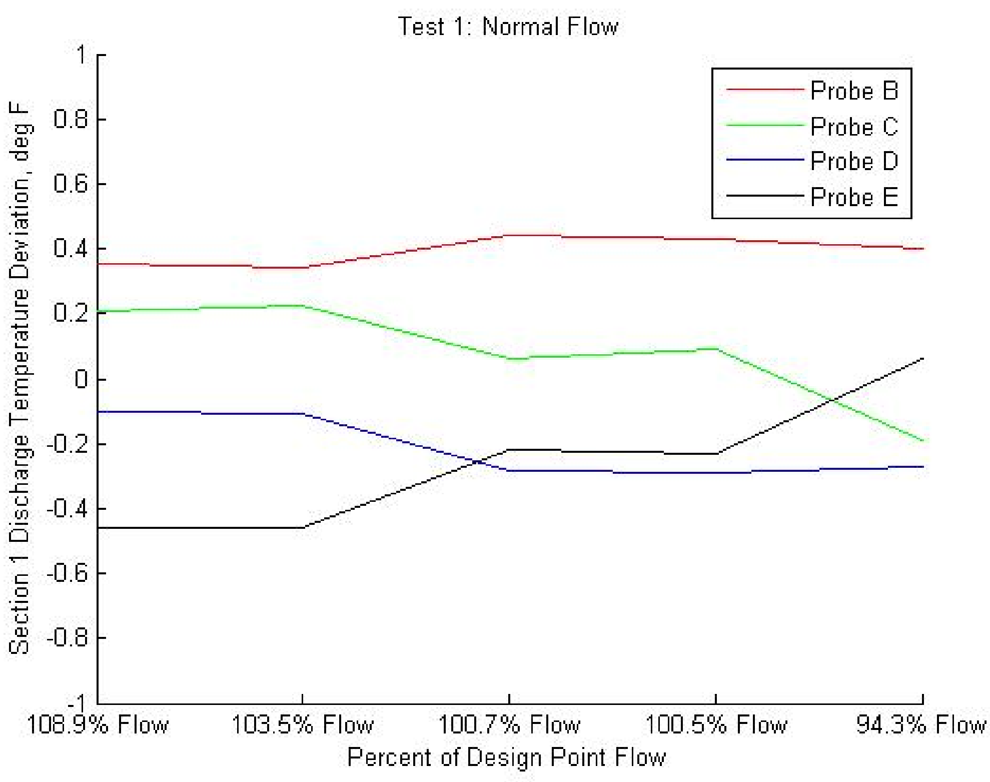


Figure 13-15. Section 1 Discharge Temperature Deviation (Test 1, Normal Flow)

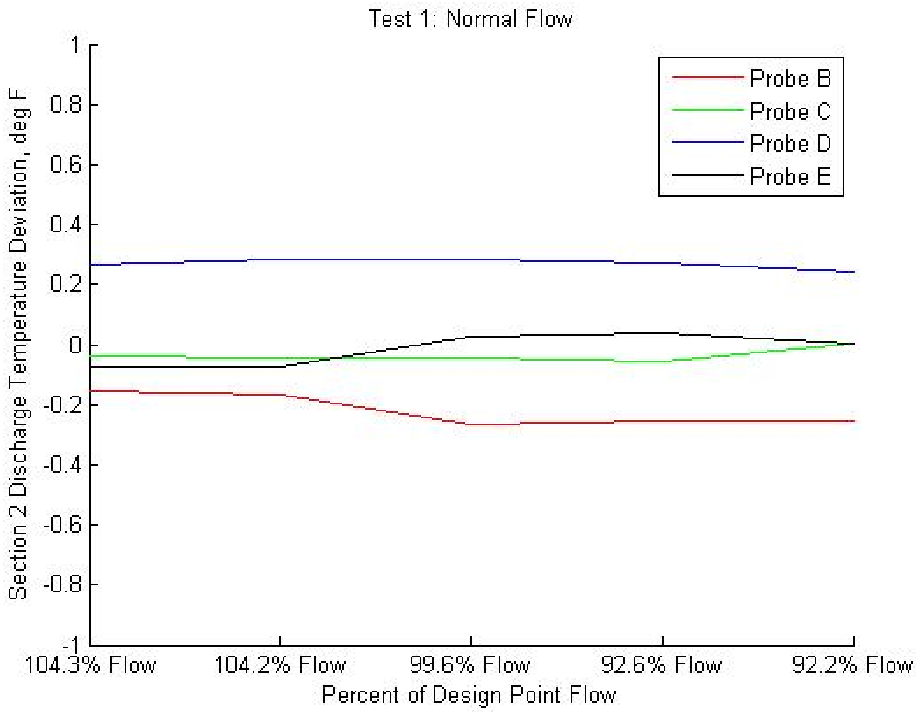


Figure 13-16. Section 2 Discharge Temperature Deviation (Test 1, Normal Flow)

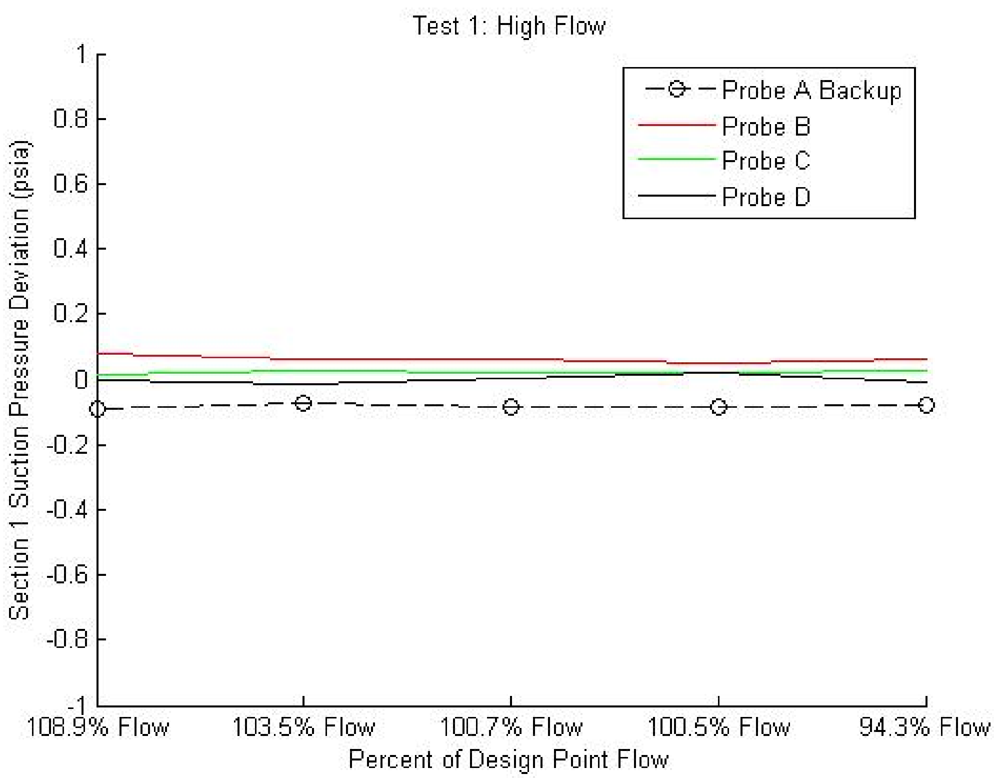


Figure 13-17. Section 1 Suction Pressure Deviation (Test 1, High Flow)

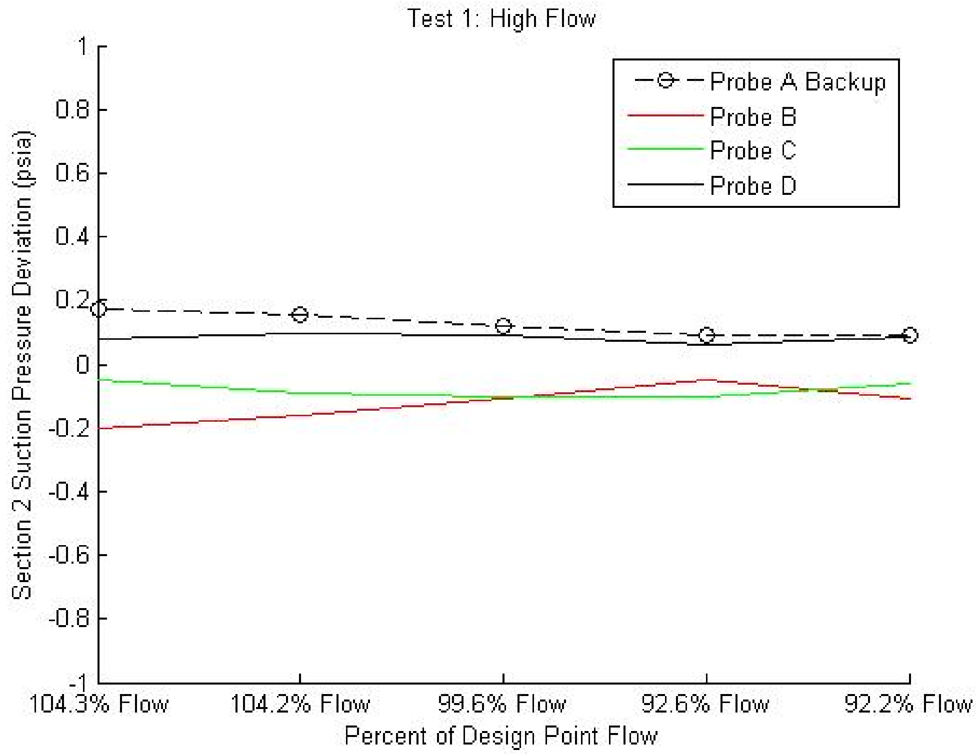


Figure 13-18. Section 2 Suction Pressure Deviation (Test 1, High Flow)

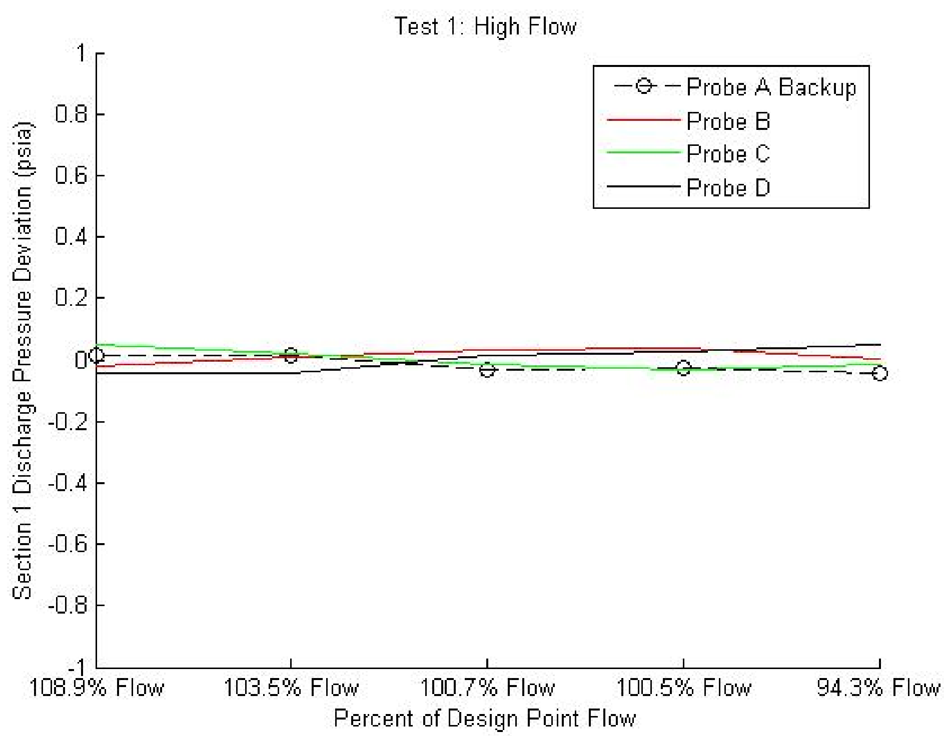


Figure 13-19. Section 1 Discharge Pressure Deviation (Test 1, High Flow)

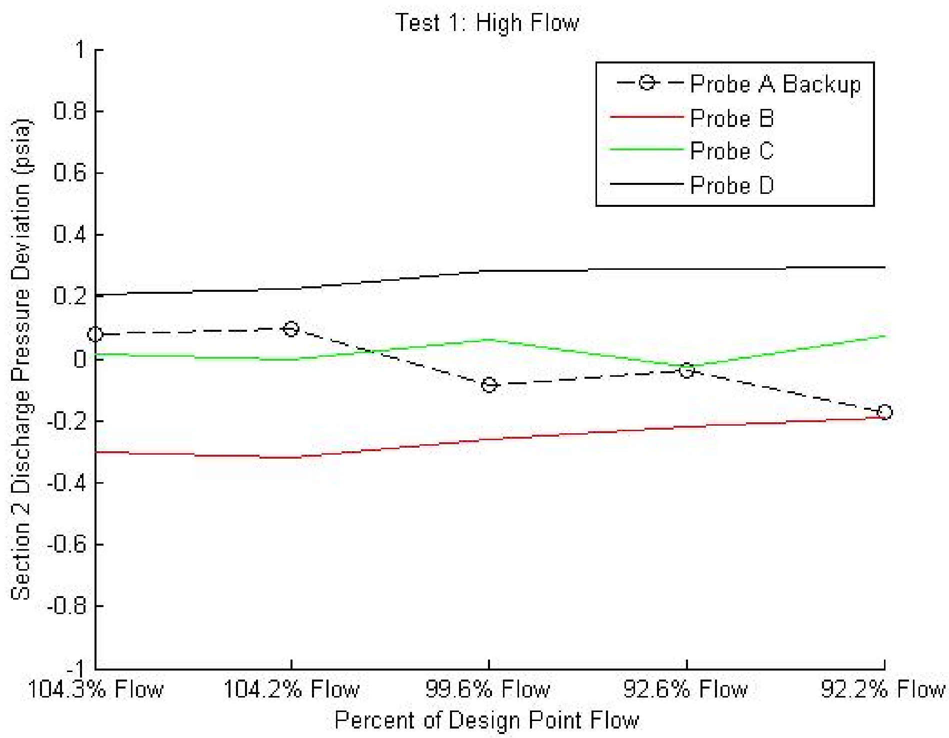


Figure 13-20. Section 2 Discharge Pressure Deviation (Test 1, High Flow)

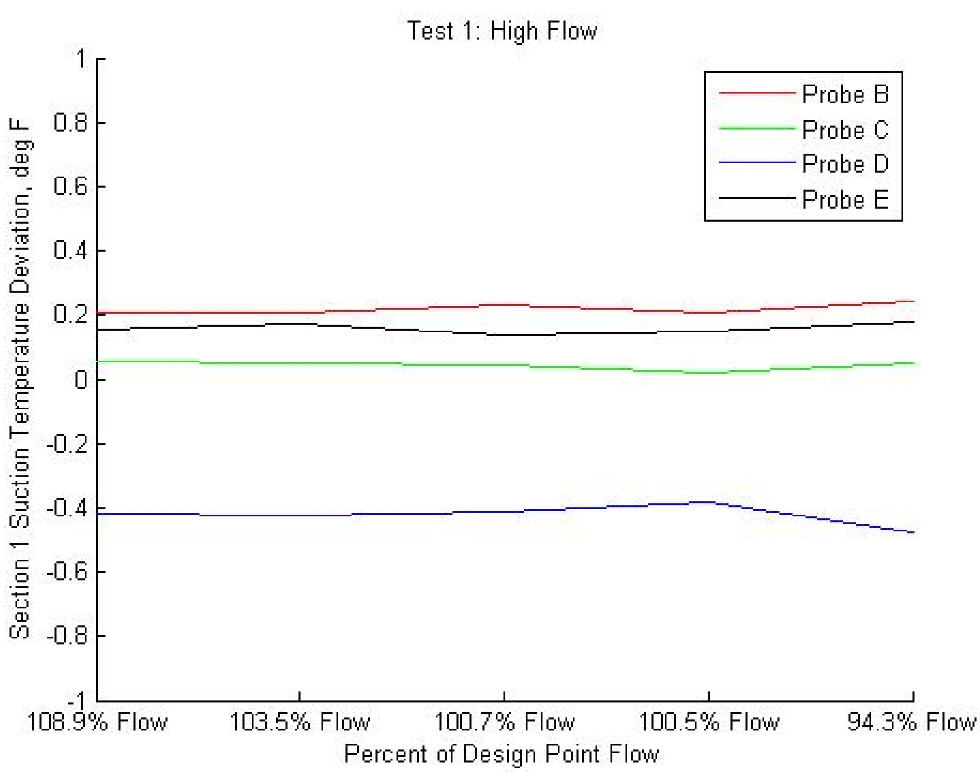


Figure 13-21. Section 1 Suction Temperature Deviation (Test 1, High Flow)

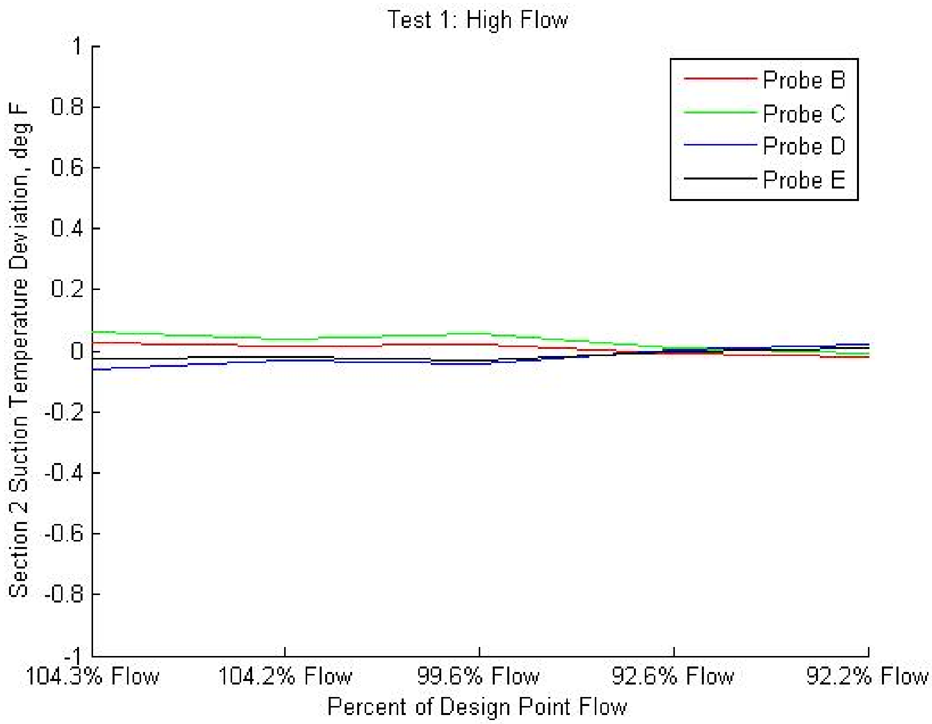


Figure 13-22. Section 2 Suction Temperature Deviation (Test 1, High Flow)

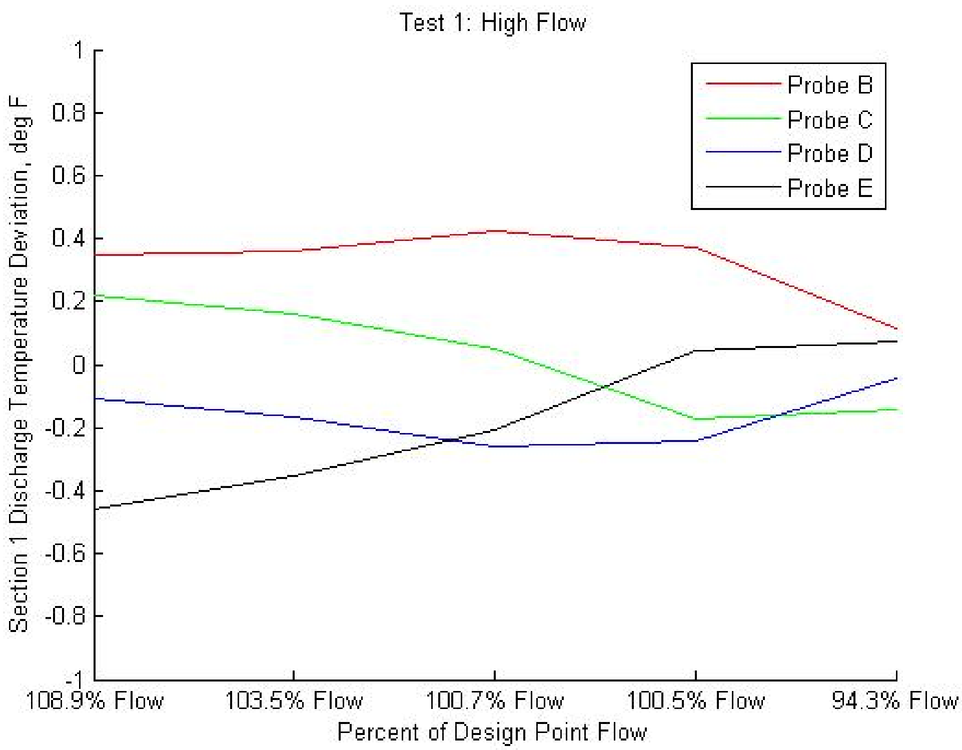


Figure 13-23. Section 1 Discharge Temperature Deviation (Test 1, High Flow)

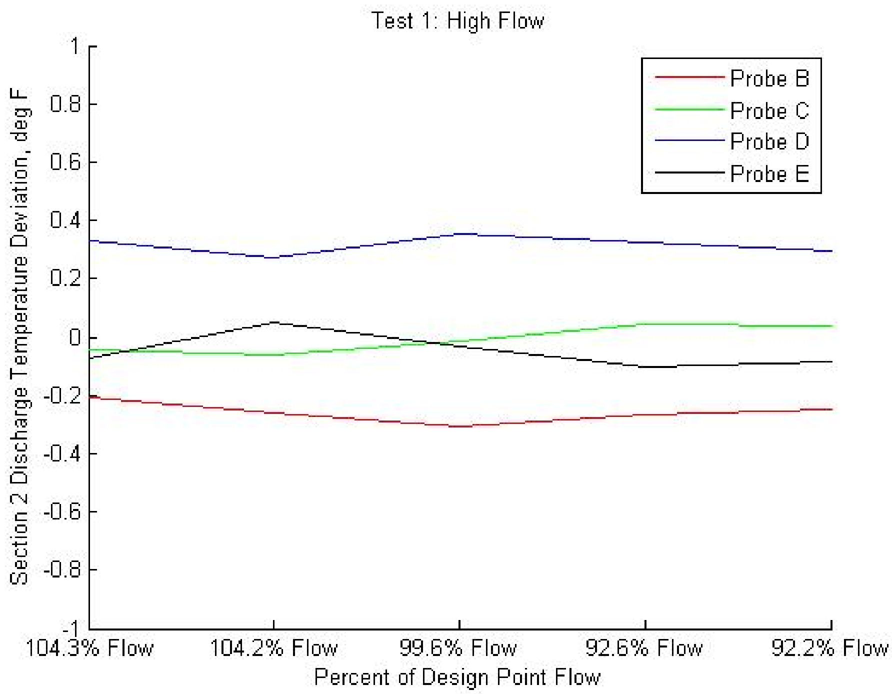


Figure 13-24. Section 2 Discharge Temperature Deviation (Test 1, High Flow)

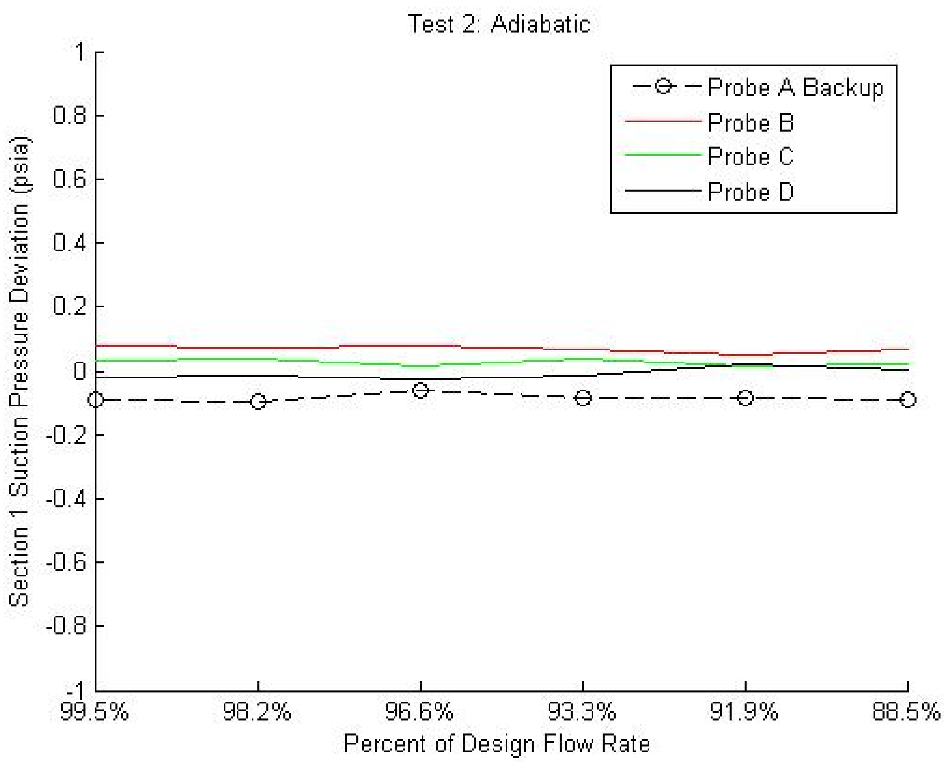


Figure 13-25. Section 1 Suction Pressure Deviation (Test 2, Adiabatic)

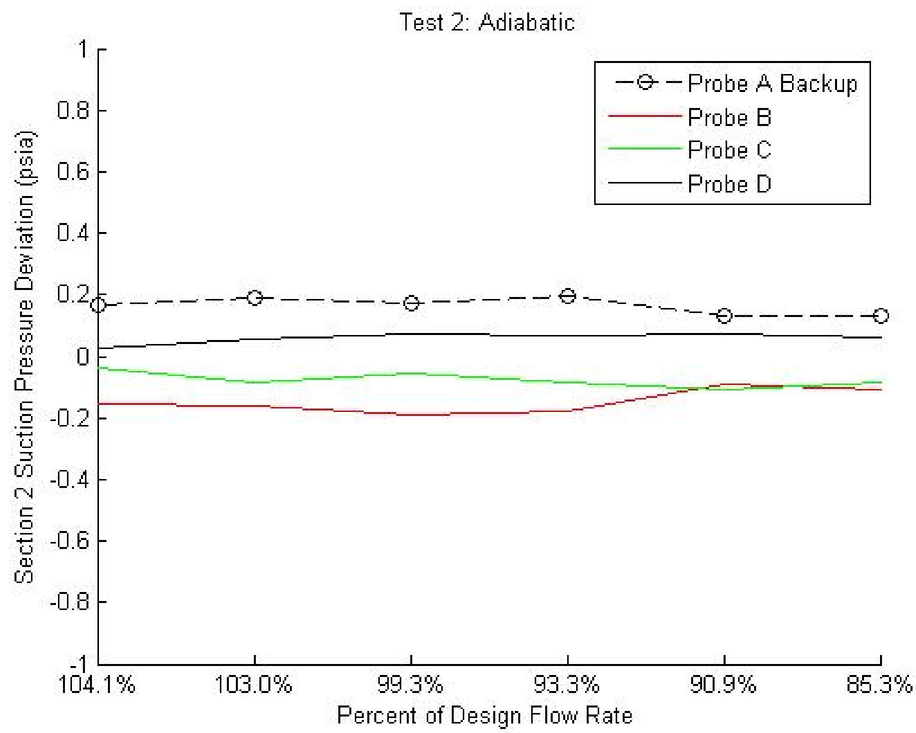


Figure 13-26. Section 2 Suction Pressure Deviation (Test 2, Adiabatic)

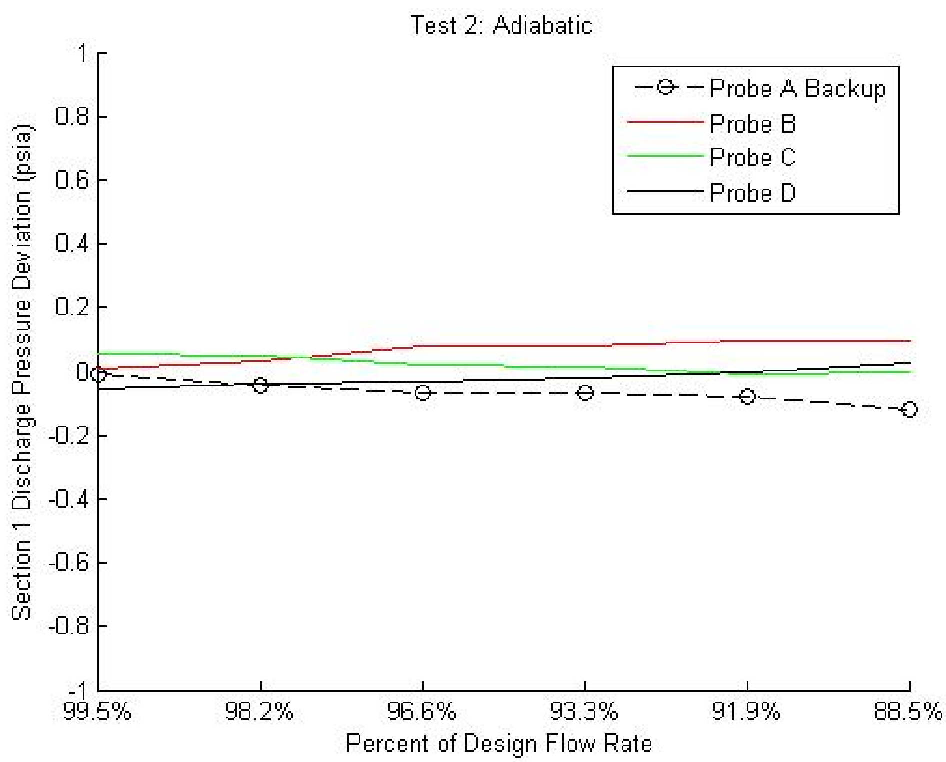


Figure 13-27. Section 1 Discharge Pressure Deviation (Test 2, Adiabatic)

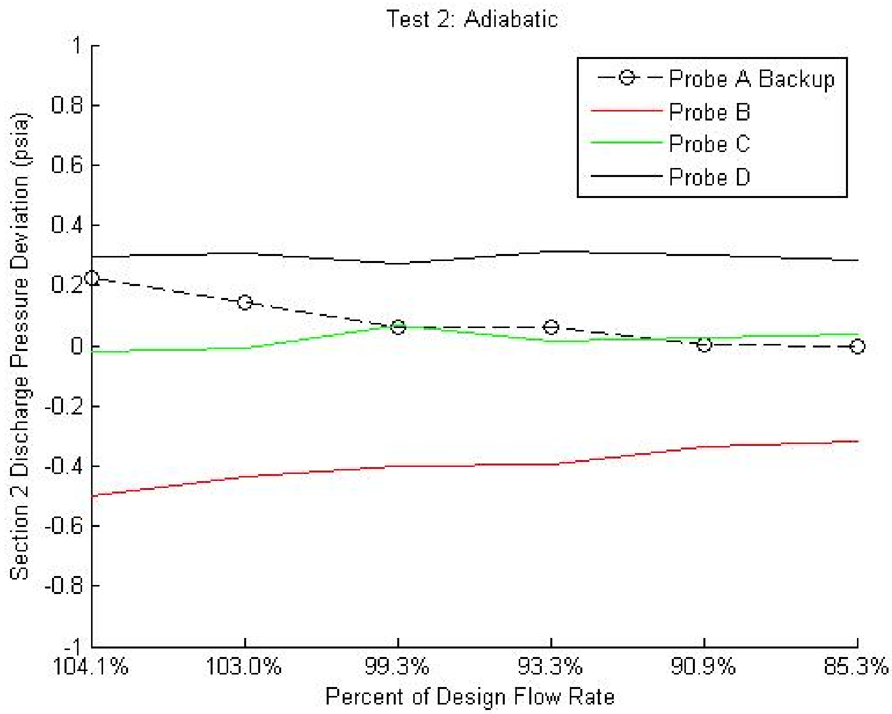


Figure 13-28. Section 2 Discharge Pressure Deviation (Test 2, Adiabatic)

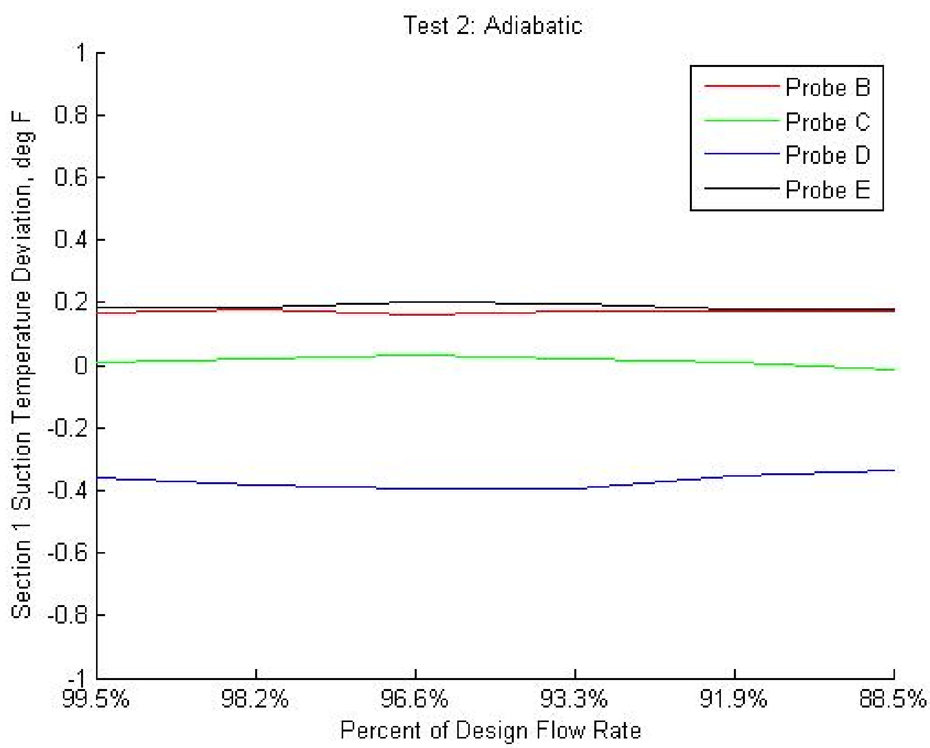


Figure 13-29. Section 1 Temperature Deviation (Test 2, Adiabatic)

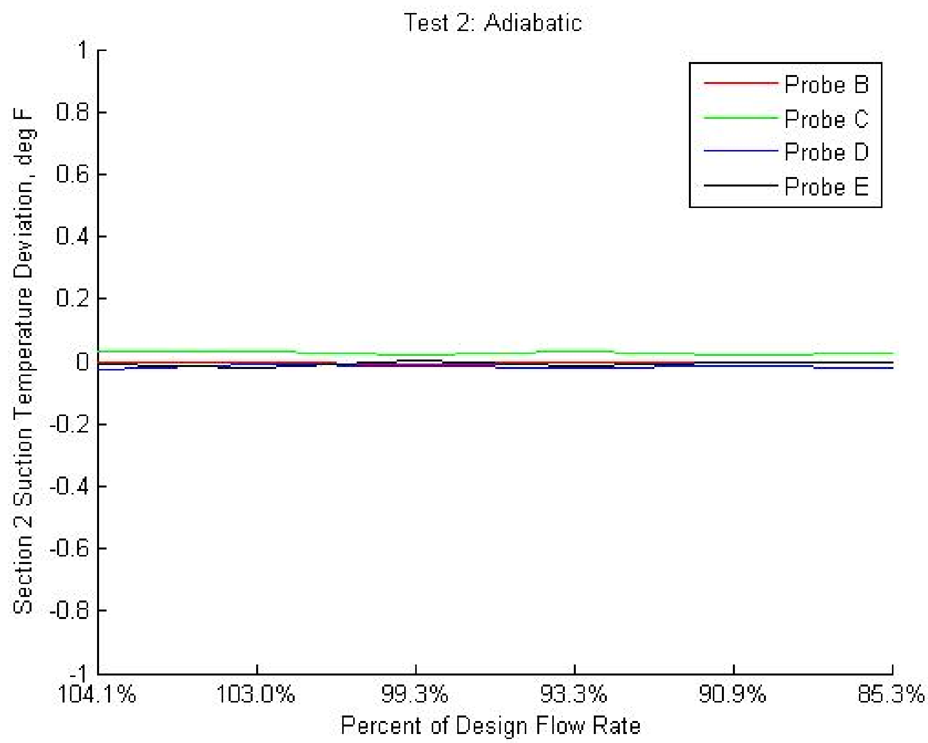


Figure 13-30. Section 2 Suction Temperature Deviation (Test 2, Adiabatic)

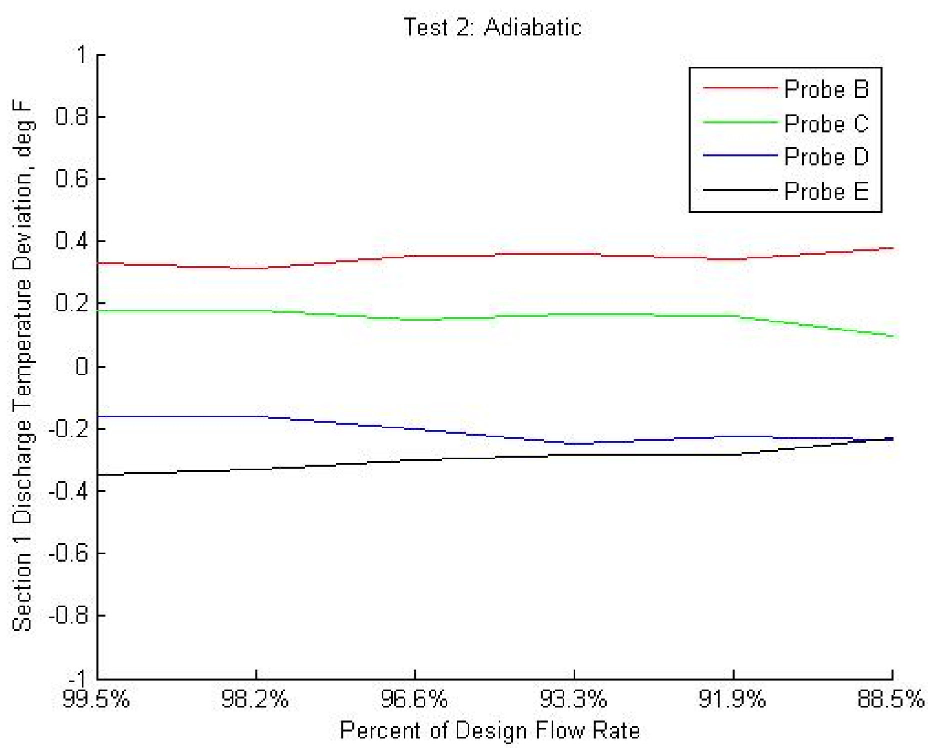


Figure 13-31. Section 1 Discharge Temperature Deviation (Test 2, Adiabatic)

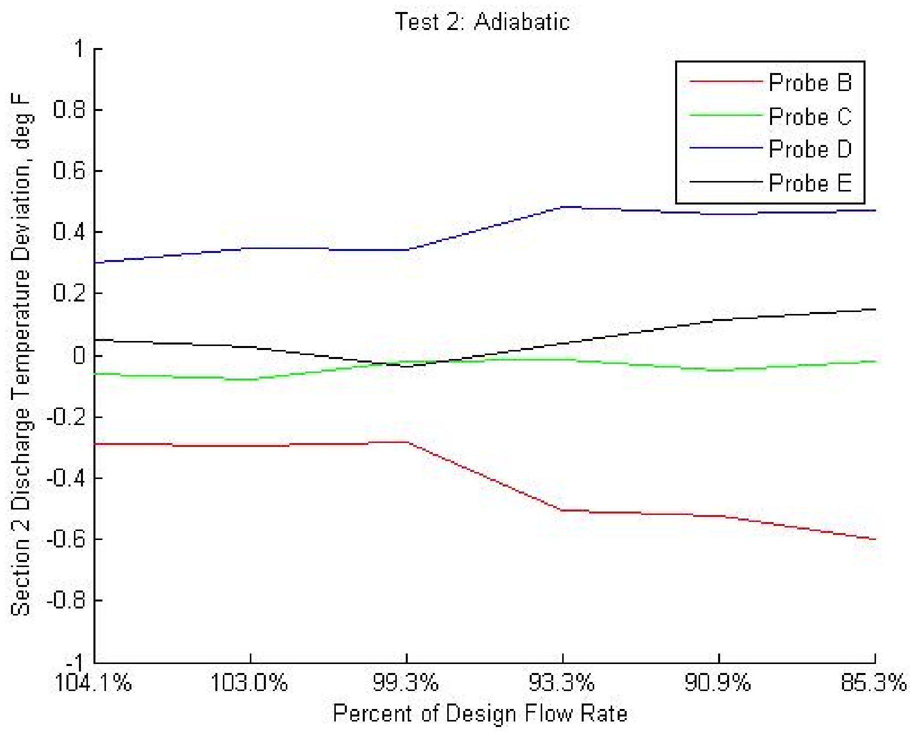


Figure 13-32. Section 2 Discharge Temperature Deviation (Test 2, Adiabatic)

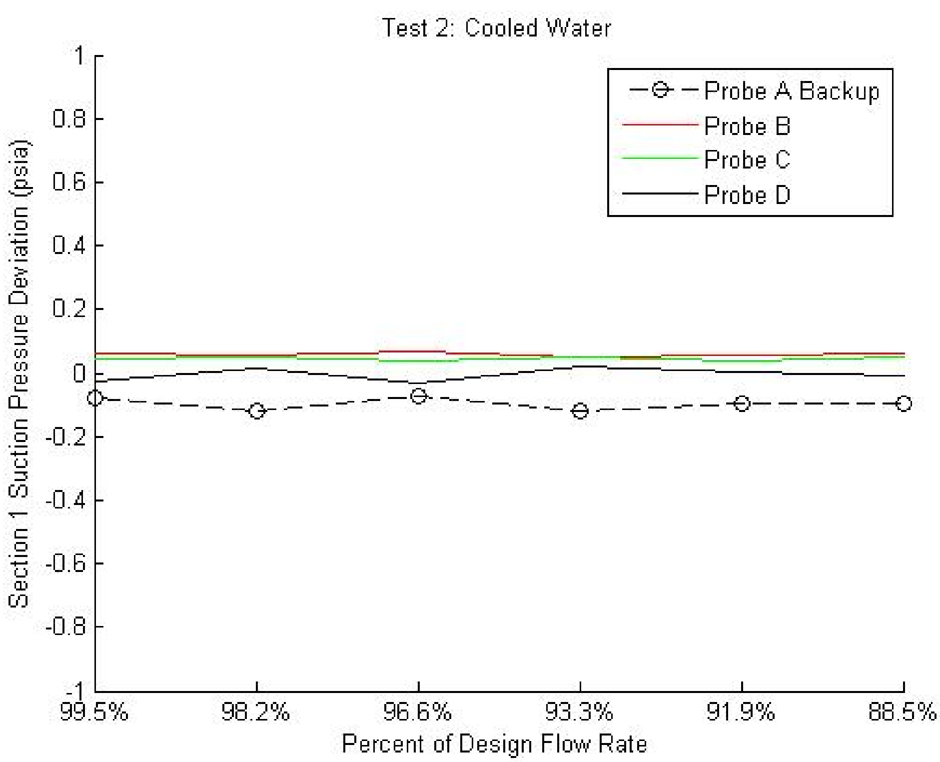


Figure 13-33. Section 1 Suction Pressure Deviation (Test 2, Cooled Water)

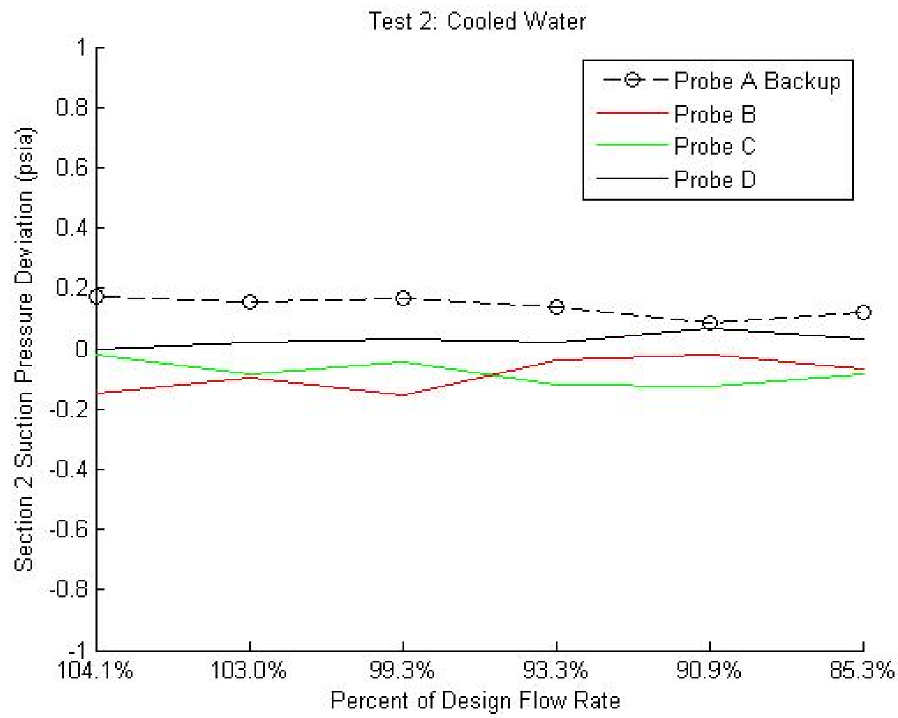


Figure 13-34. Section 2 Suction Pressure Deviation (Test 2, Cooled Water)

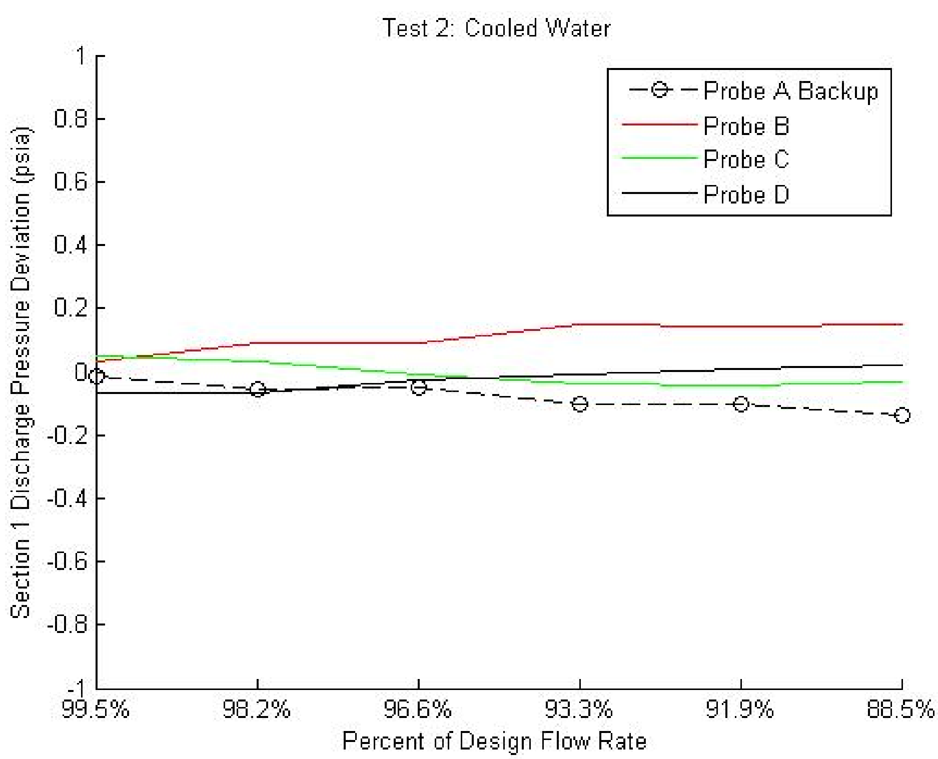


Figure 13-35. Section 1 Discharge Pressure Deviation (Test 2, Cooled Water)

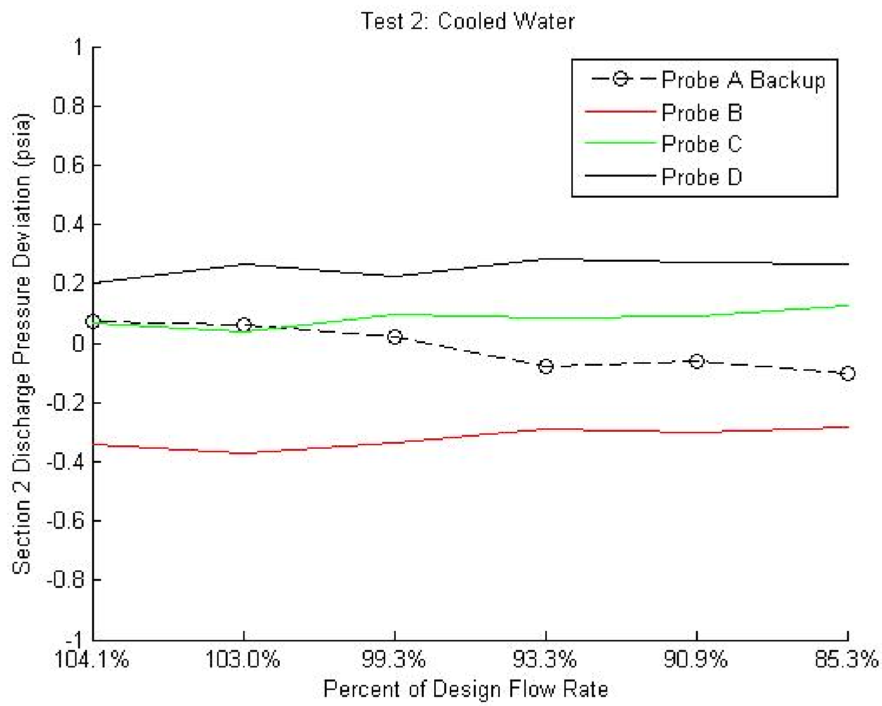


Figure 13-36. Section 2 Discharge Pressure Deviation (Test 2, Cooled Water)

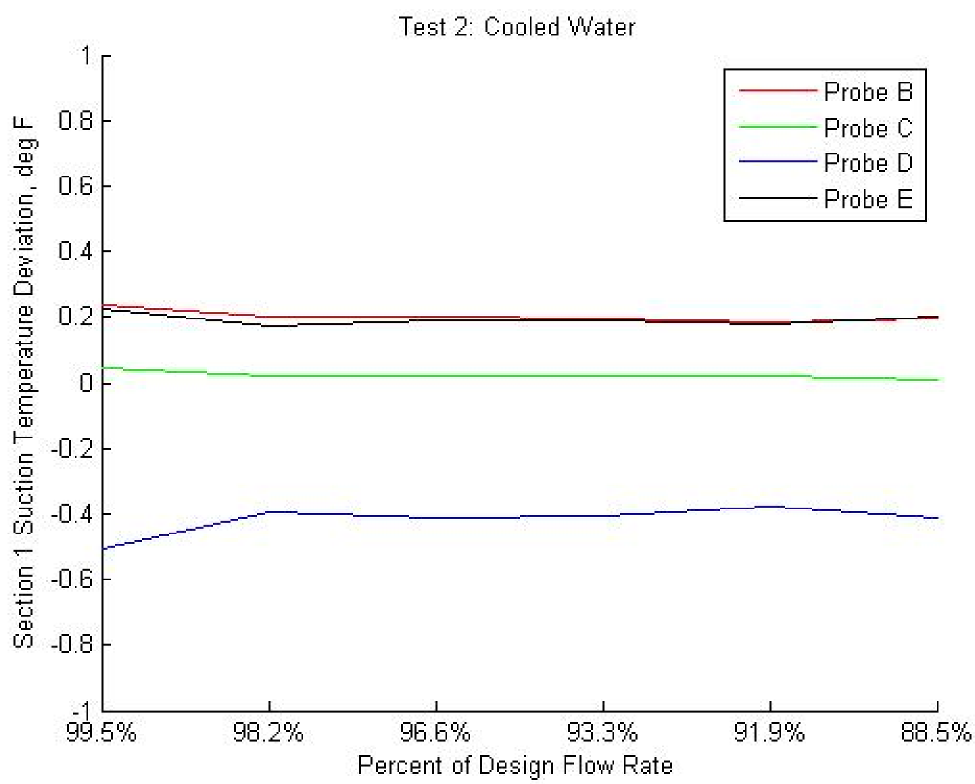


Figure 13-37. Section 1 Suction Temperature Deviation (Test 2, Cooled Water)

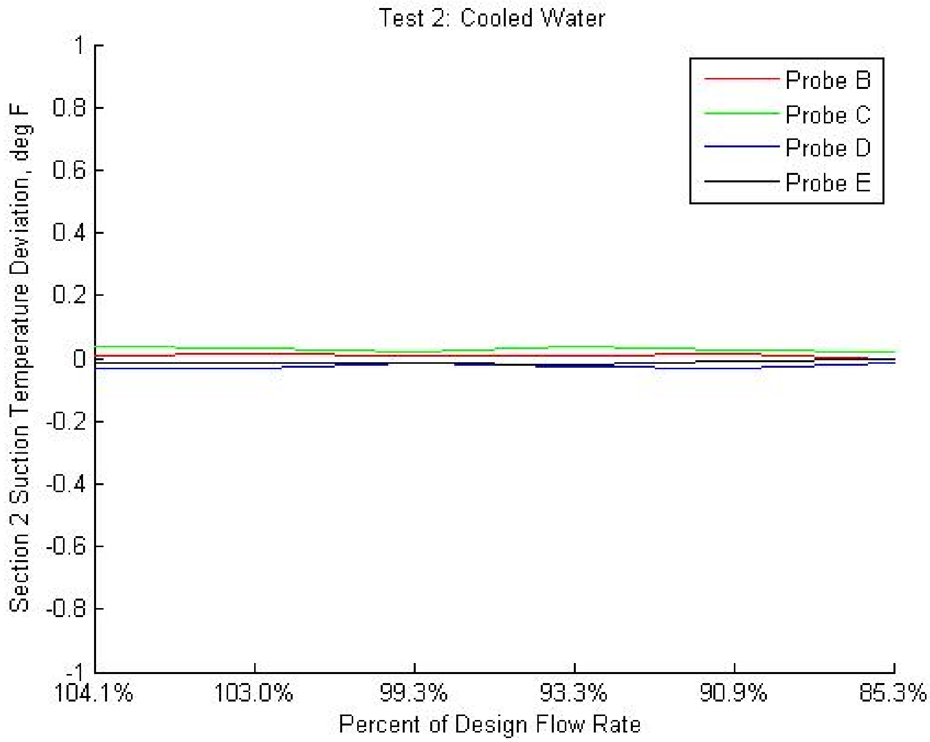


Figure 13-38. Section 2 Suction Temperature Deviation (Test 2, Cooled Water)

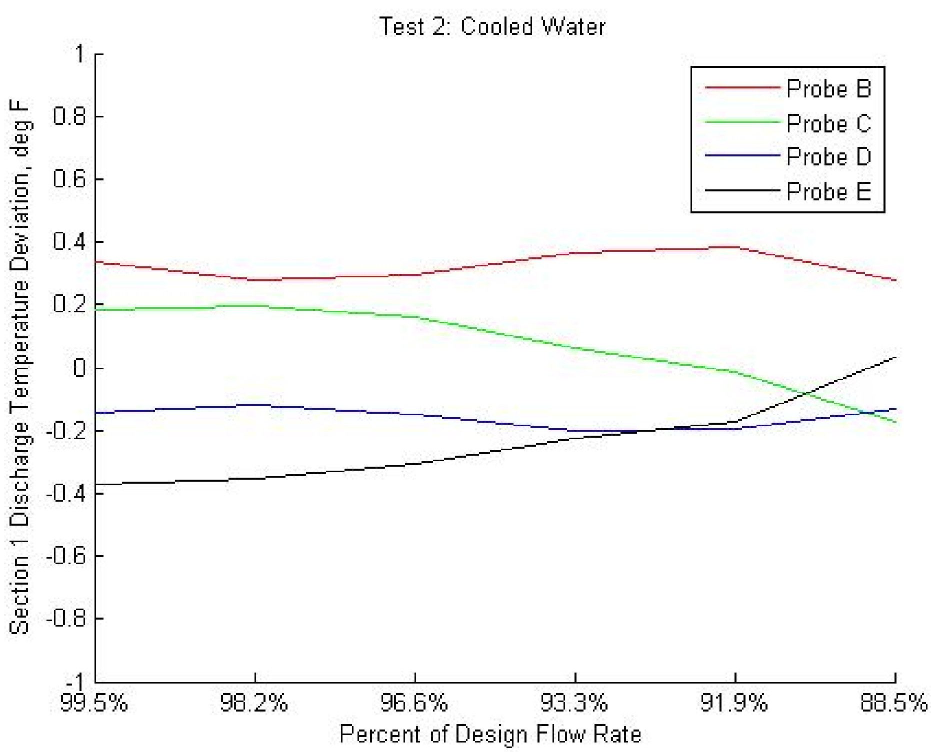


Figure 13-39. Section 1 Discharge Temperature Deviation (Test 2, Cooled Water)

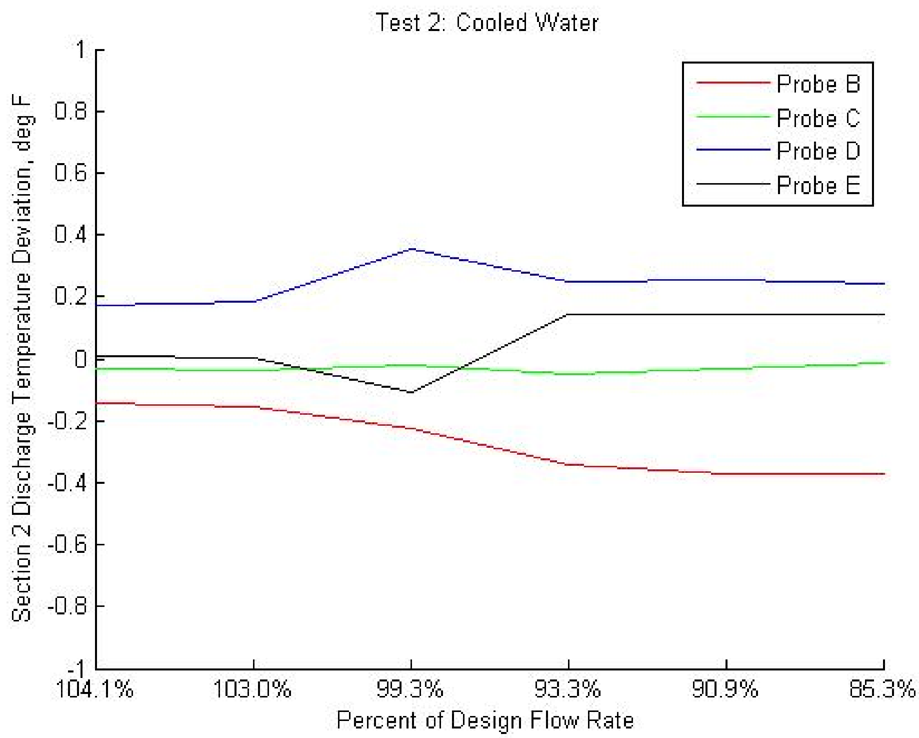


Figure 13-40. Section 2 Discharge Temperature Deviation (Test 2, Cooled Water)

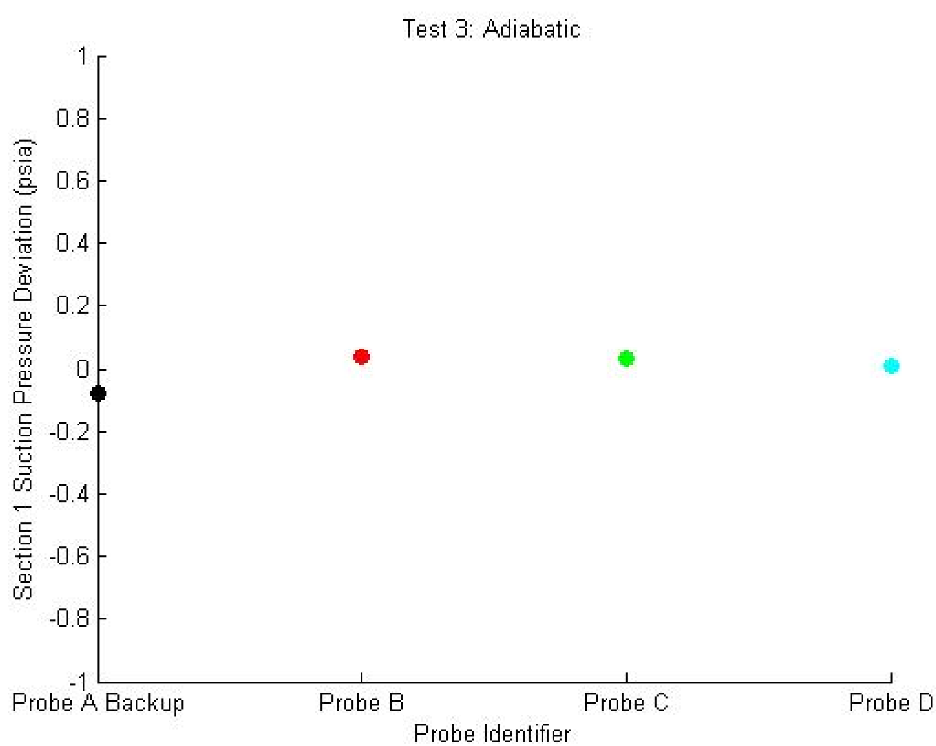


Figure 13-41. Section 1 Suction Pressure Deviation (Test 3, Adiabatic)

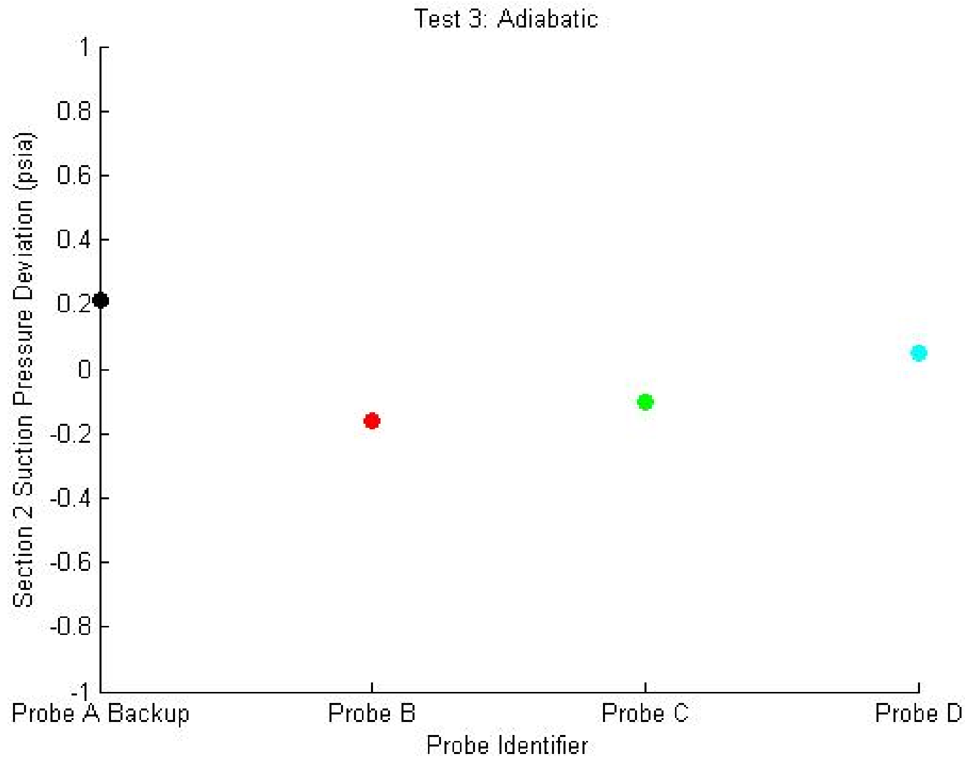


Figure 13-42. Section 2 Suction Pressure Deviation (Test 3, Adiabatic)

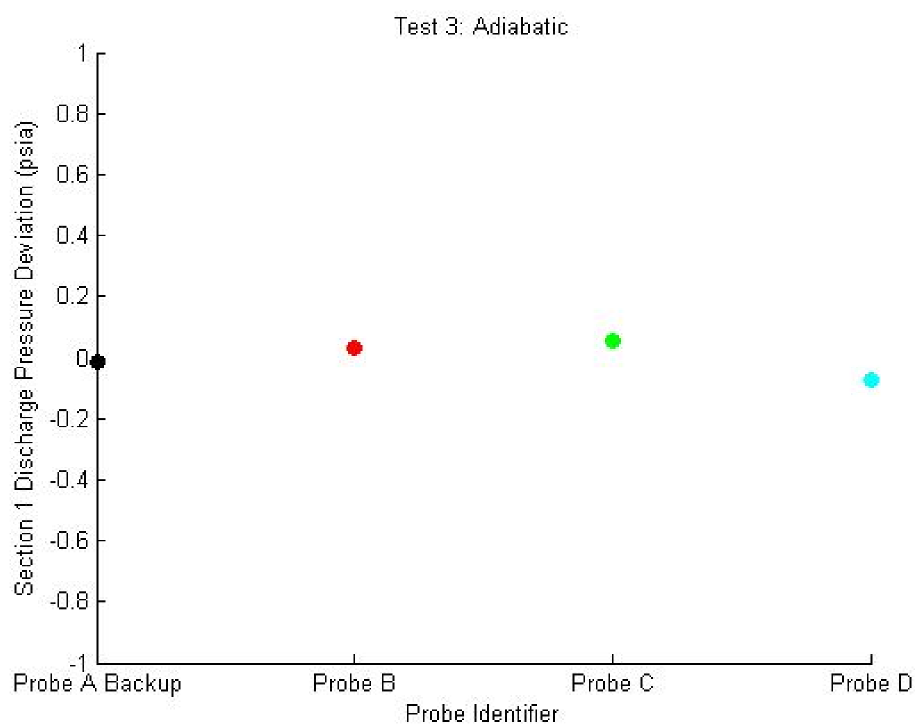


Figure 13-43. Section 1 Discharge Pressure Deviation (Test 3, Adiabatic)

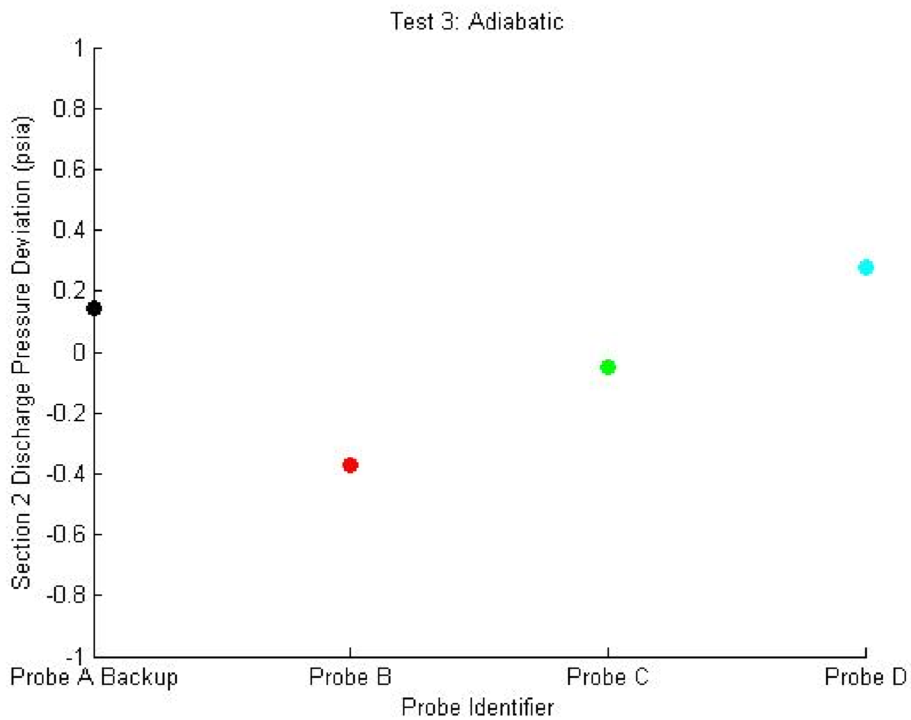


Figure 13-44. Section 2 Discharge Pressure Deviation (Test 3, Adiabatic)

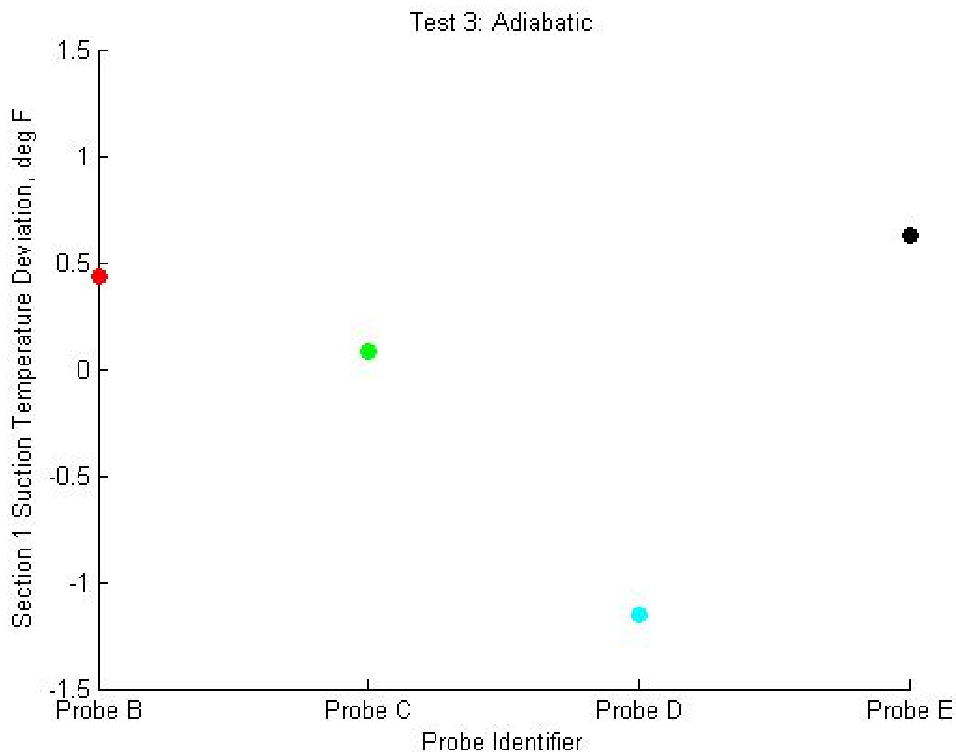


Figure 13-45. Section 1 Suction Temperature Deviation (Test 3, Adiabatic)

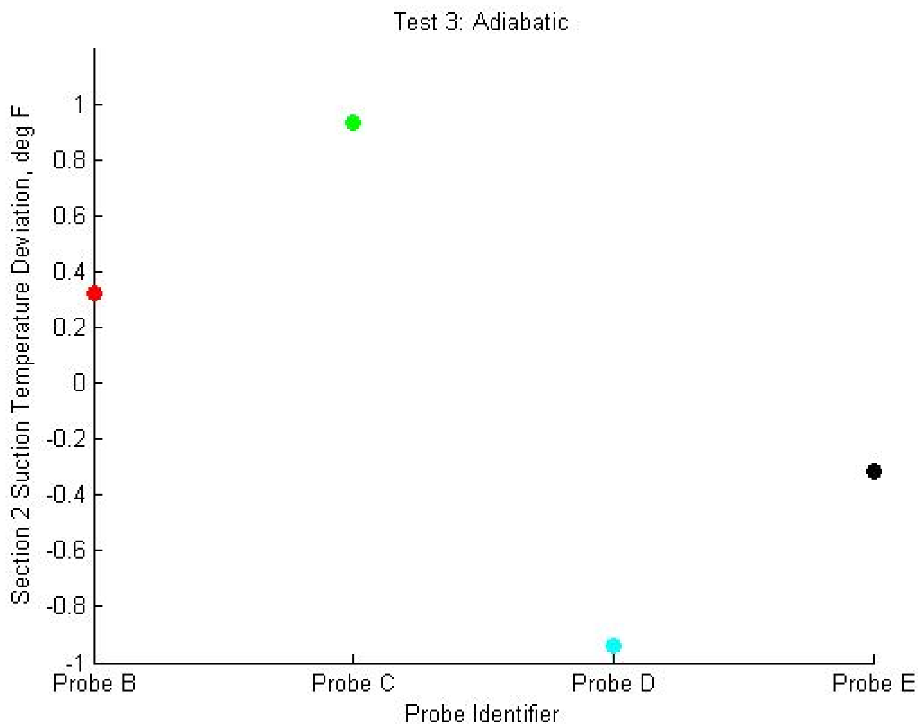


Figure 13-46. Section 2 Suction Temperature Deviation (Test 3, Adiabatic)

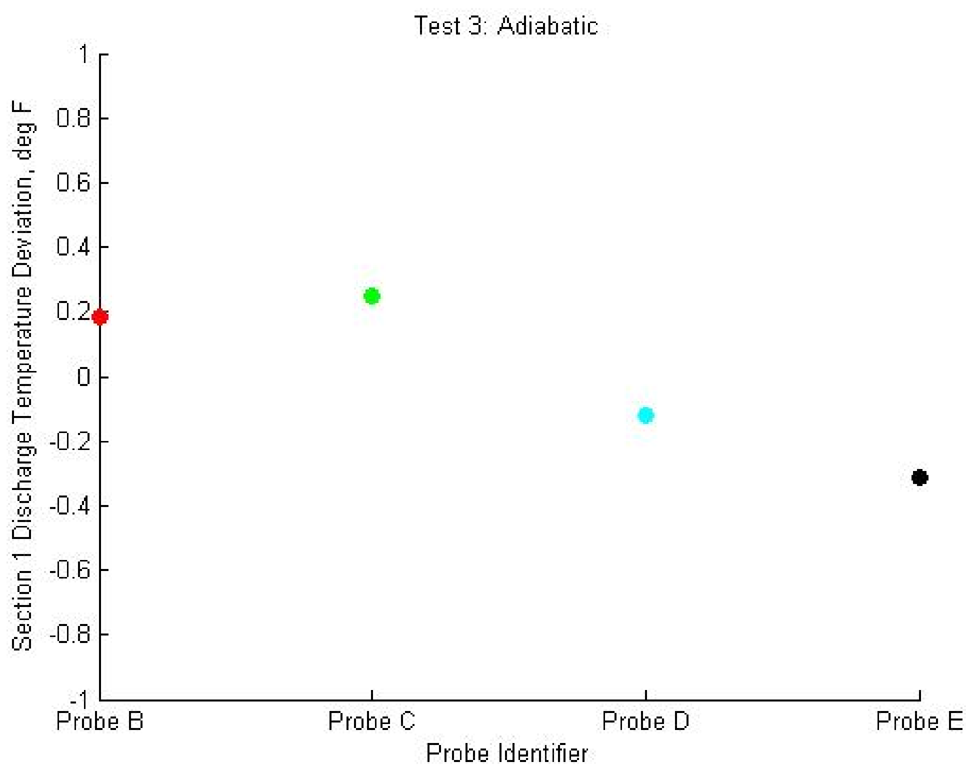


Figure 13-47. Section 1 Discharge Temperature Deviation (Test 3, Adiabatic)

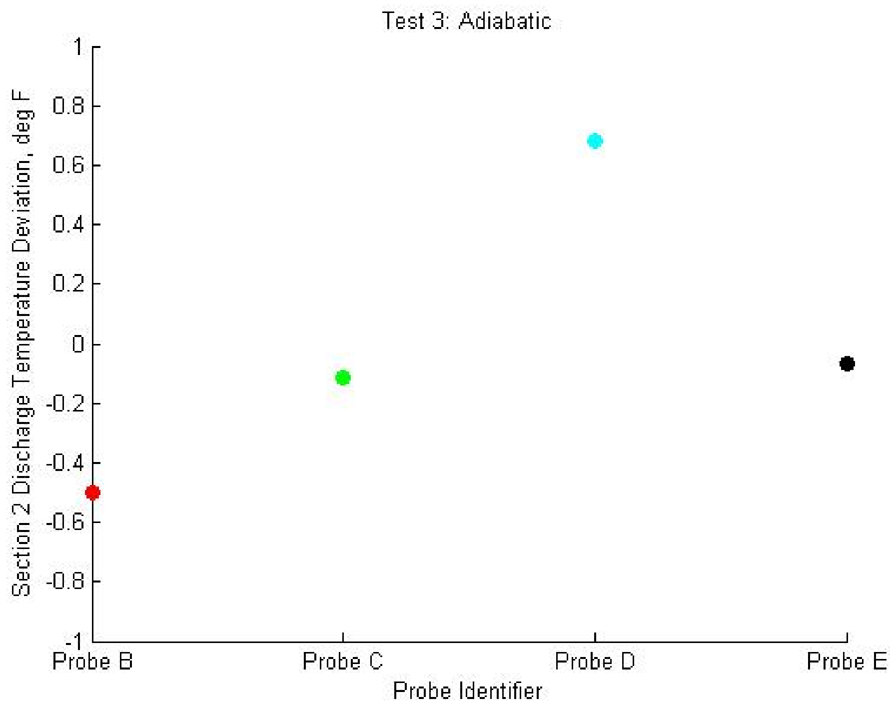


Figure 13-48. Section 2 Discharge Temperature Deviation (Test 3, Adiabatic)

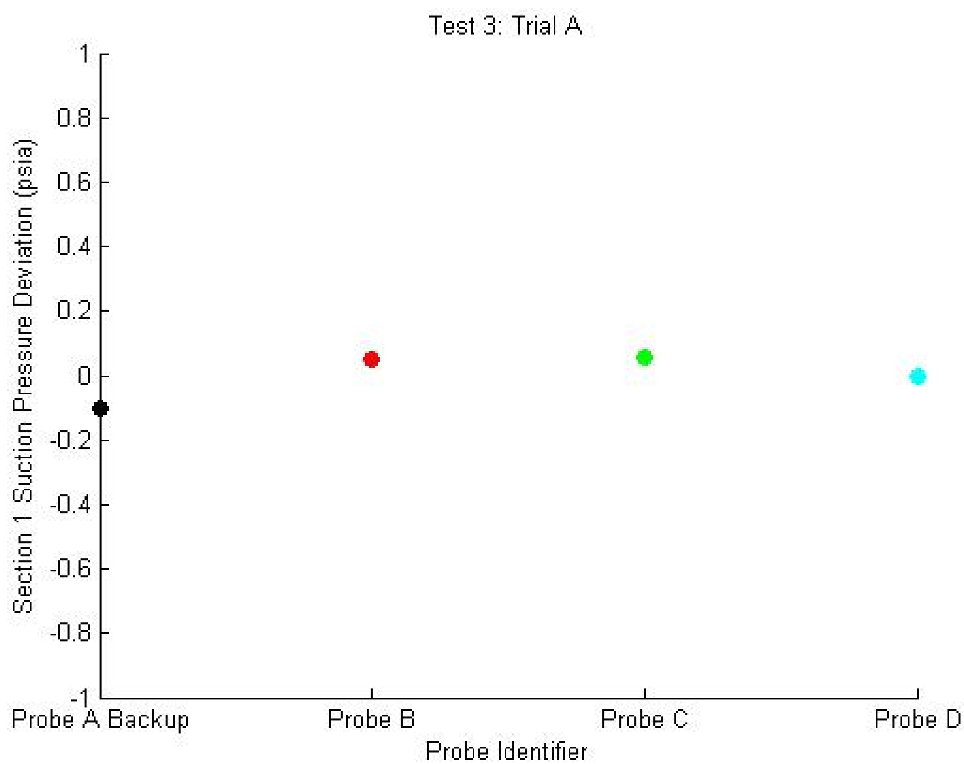


Figure 13-49. Section 1 Suction Pressure Deviation (Test 3, Trial A)

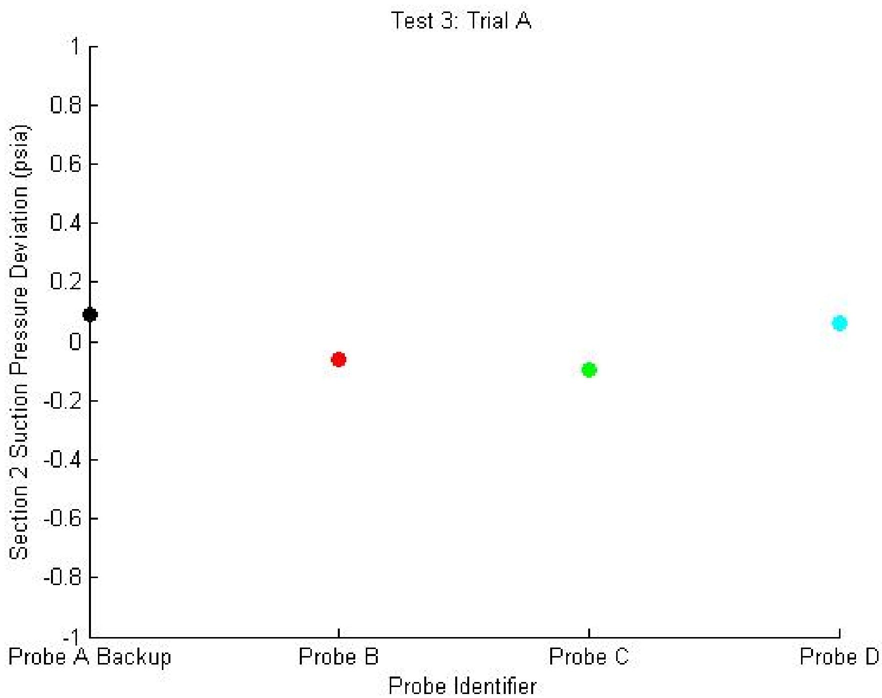


Figure 13-50. Section 2 Suction Pressure Deviation (Test 3, Trial A)

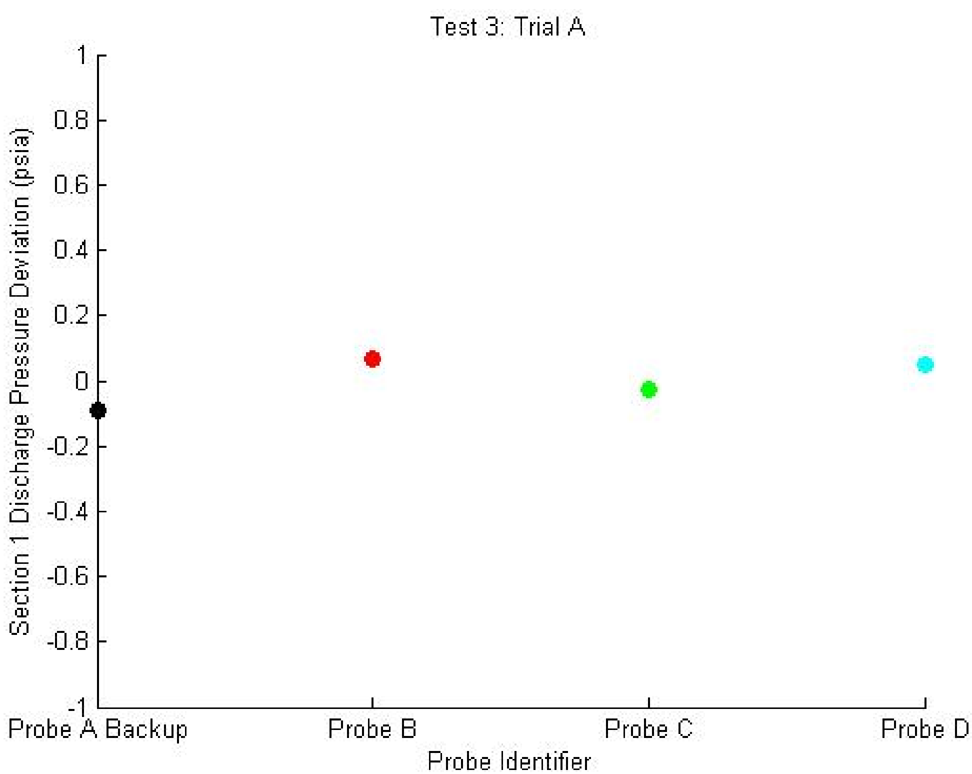


Figure 13-51. Section 1 Discharge Pressure Deviation (Test 3, Trial A)

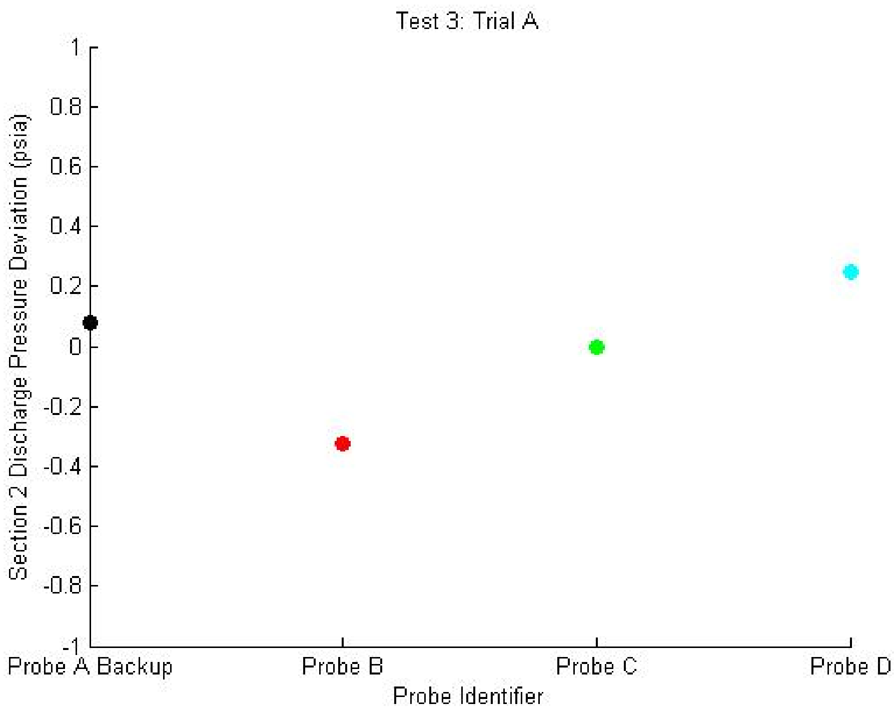


Figure 13-52. Section 2 Discharge Pressure Deviation (Test 3, Trial A)

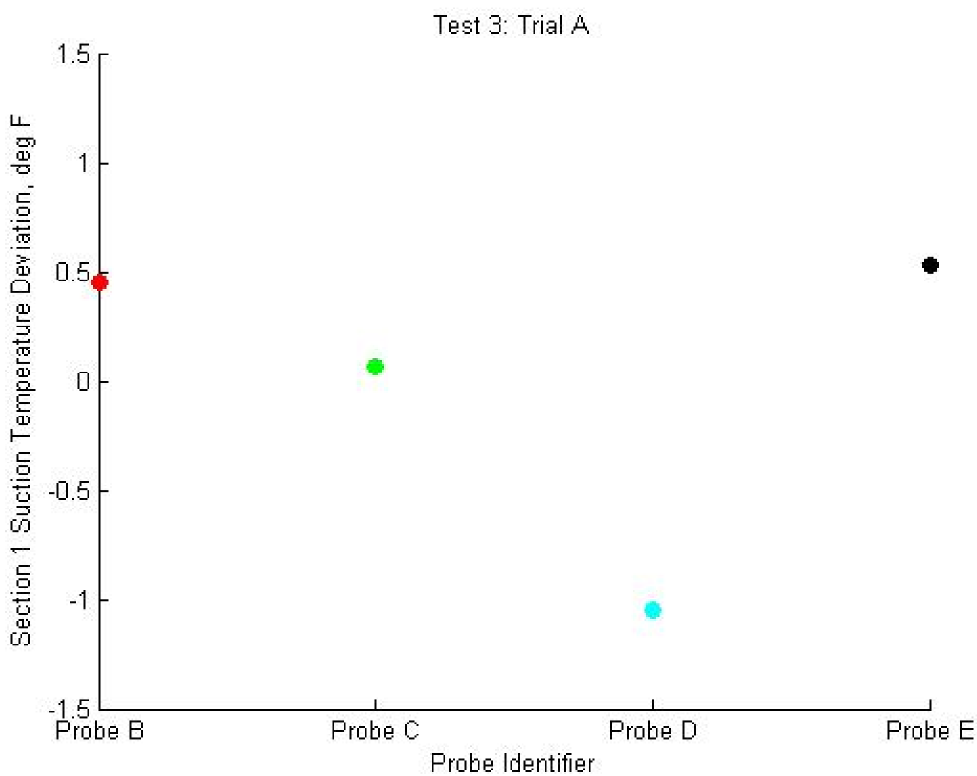


Figure 13-53. Section 1 Suction Temperature Deviation (Test 3, Trial A)

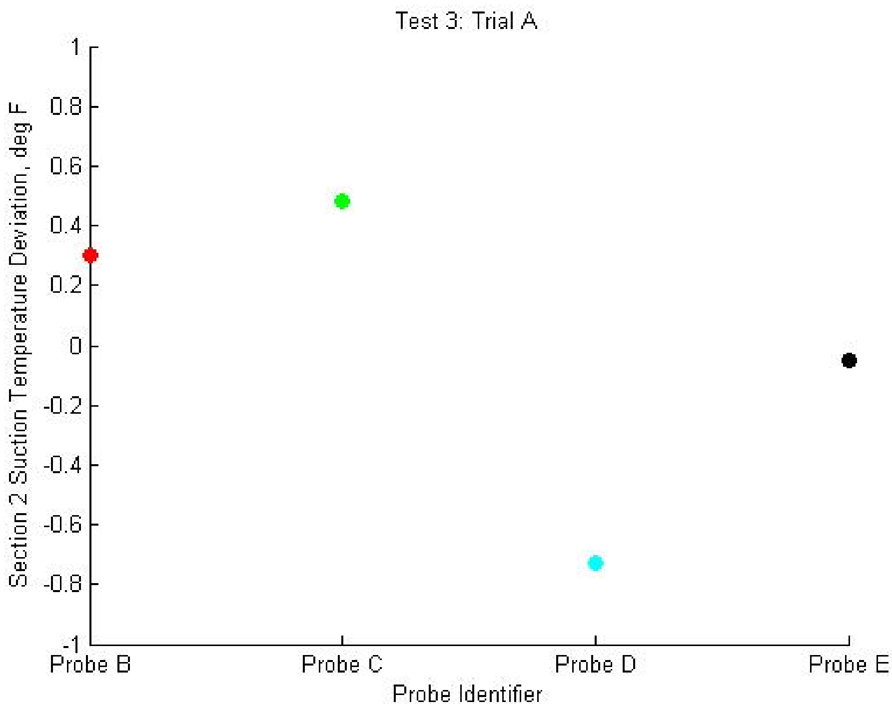


Figure 13-54. Section 2 Suction Temperature Deviation (Test 3, Trial A)

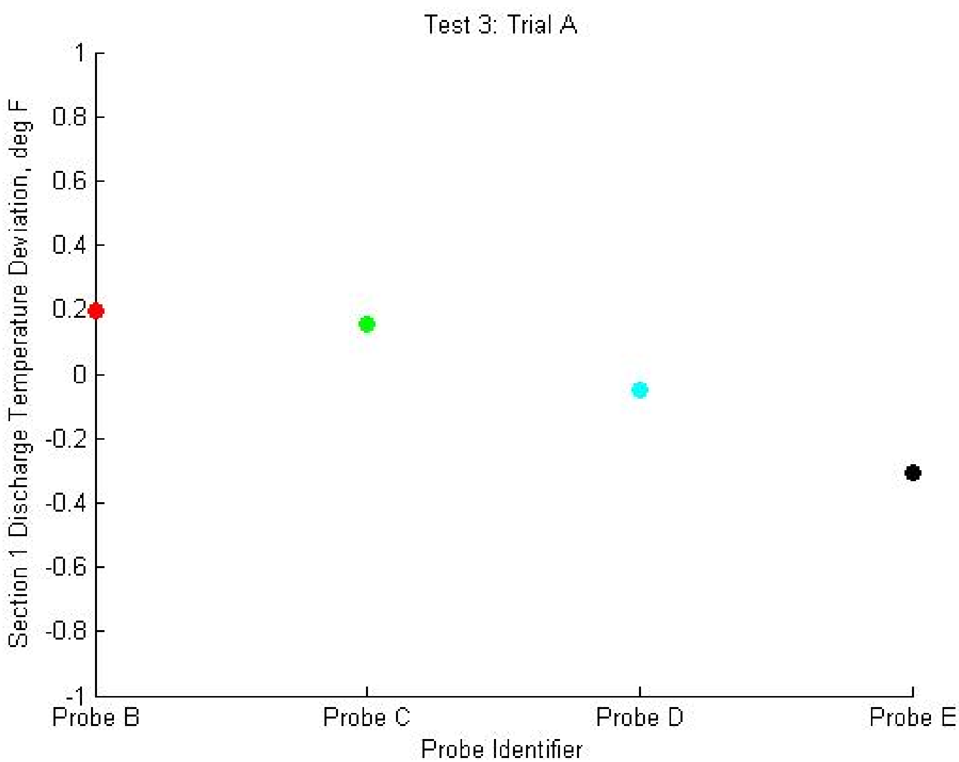


Figure 13-55. Section 1 Discharge Temperature Deviation (Test 3, Trial A)

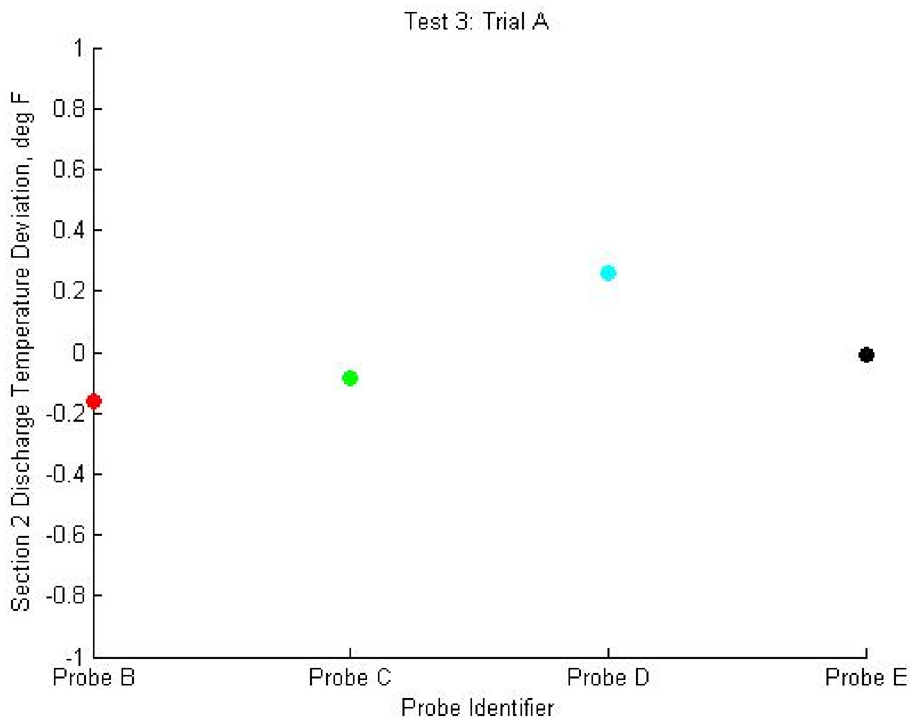


Figure 13-56. Section 2 Discharge Temperature Deviation (Test 3, Trial A)

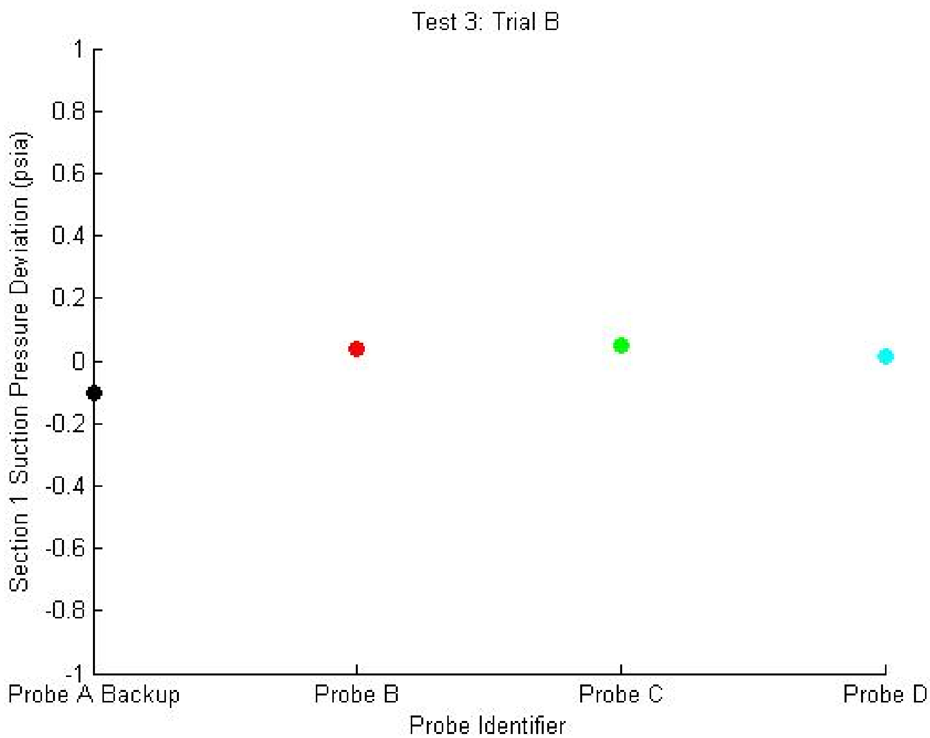


Figure 13-57. Section 1 Suction Pressure Deviation (Test 3, Trial B)

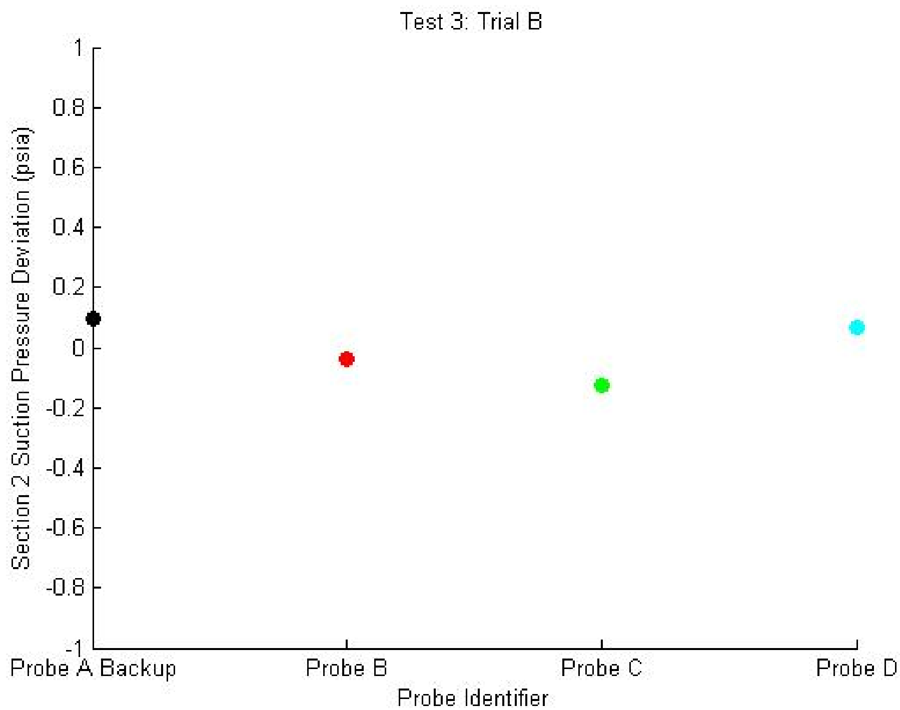


Figure 13-58. Section 2 Suction Pressure Deviation (Test 3, Trial B)

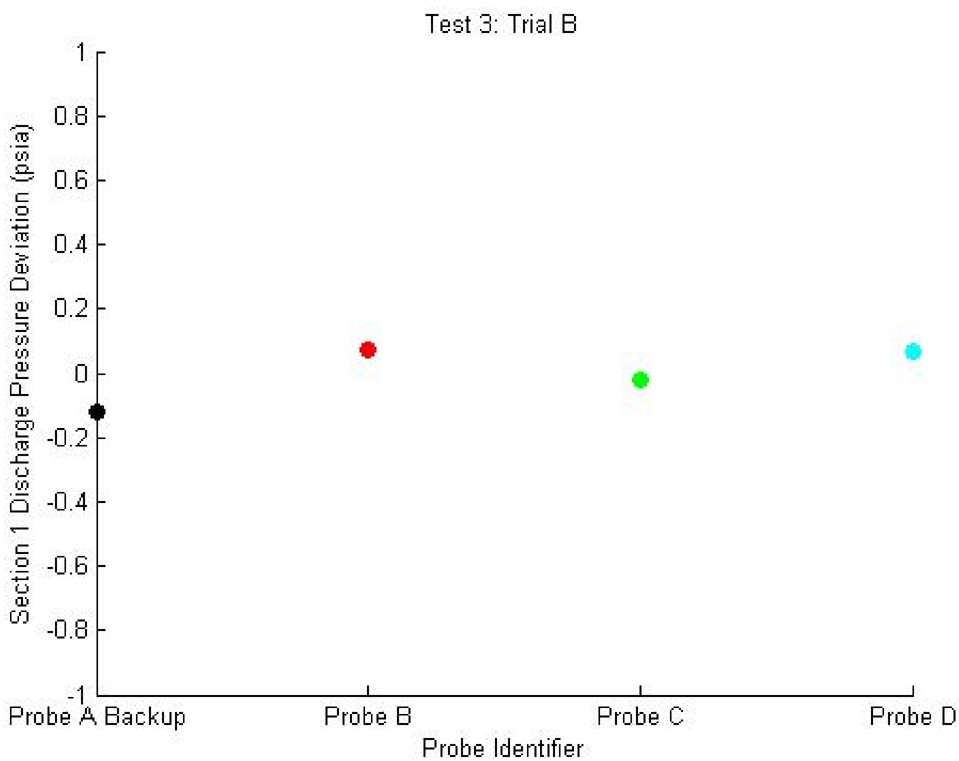


Figure 13-59. Section 1 Discharge Pressure Deviation (Test 3, Trial B)

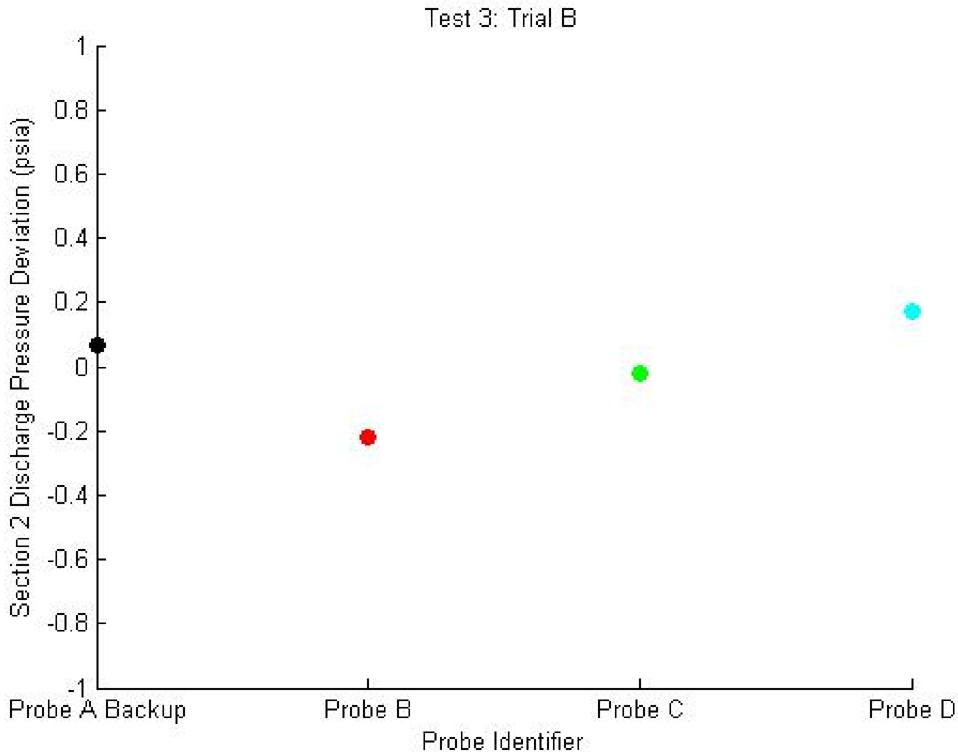


Figure 13-60. Section 2 Discharge Pressure Deviation (Test 3, Trial B)

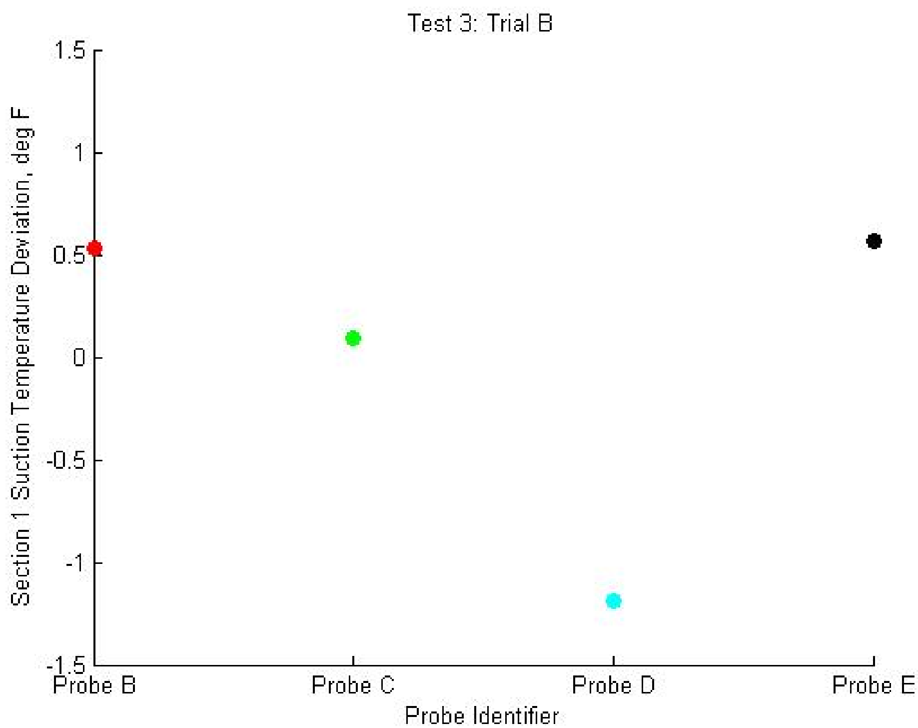


Figure 13-61. Section 1 Suction Temperature Deviation (Test 3, Trial B)

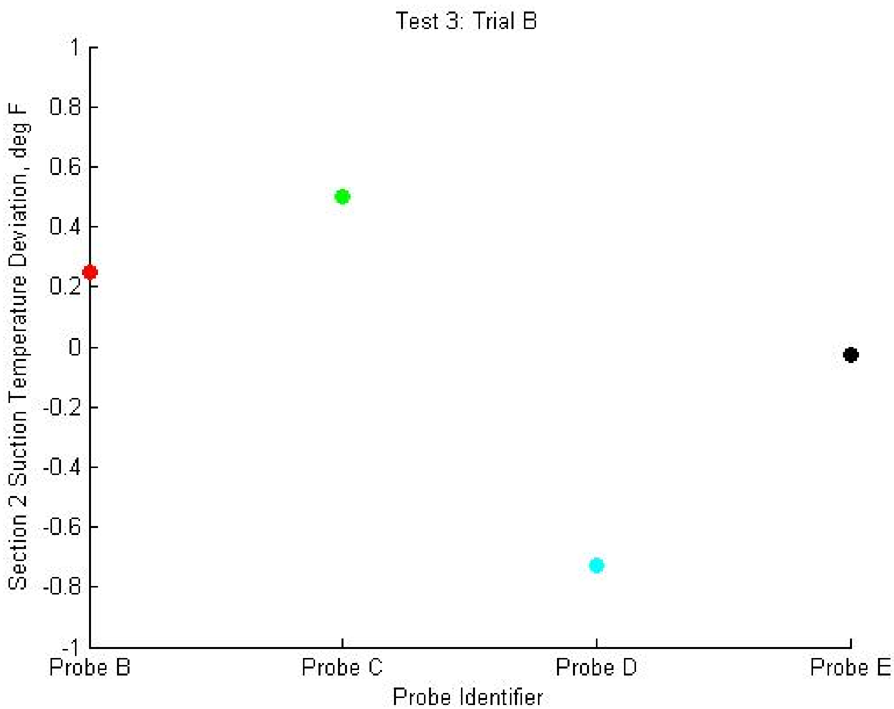


Figure 13-62. Section 2 Suction Temperature Deviation (Test 3, Trial B)

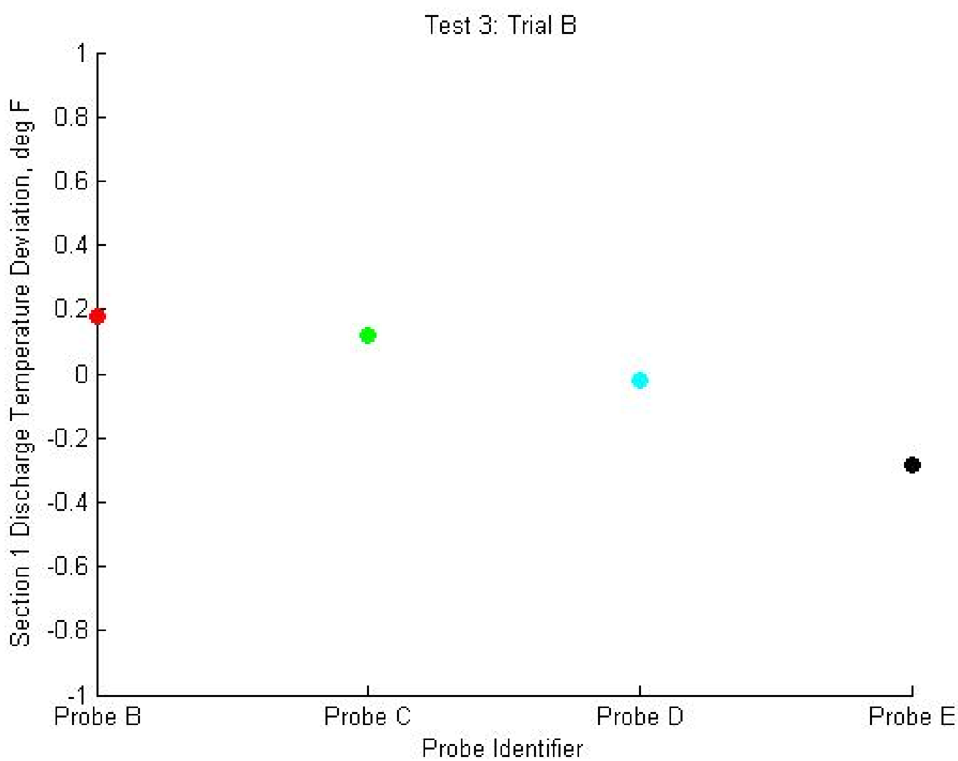


Figure 13-63. Section 1 Discharge Temperature Deviation (Test 3, Trial B)

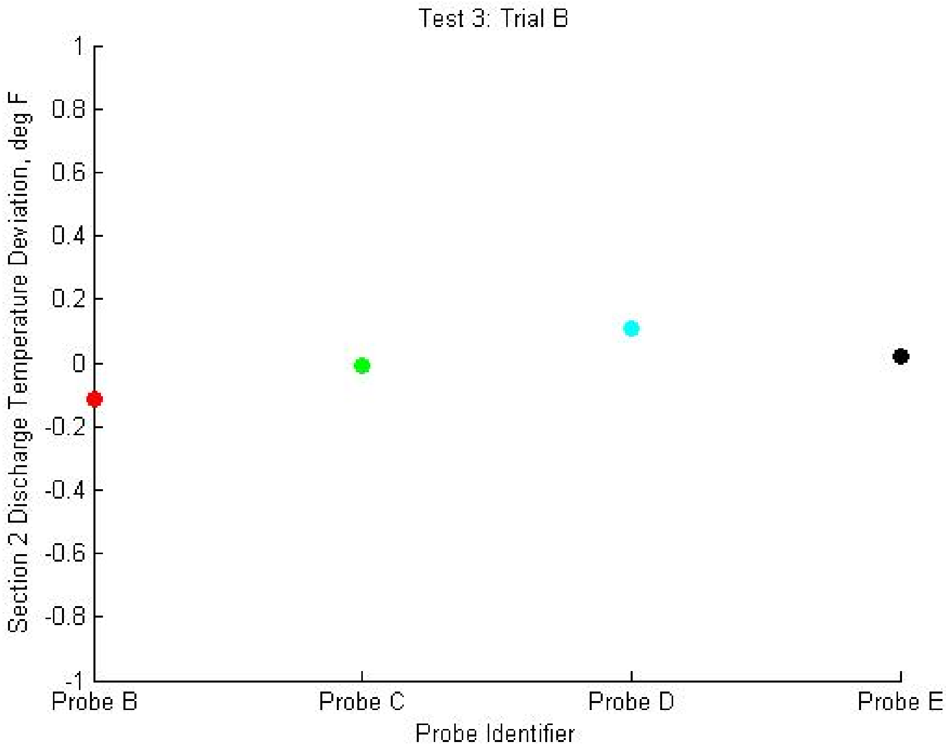


Figure 13-64. Section 2 Discharge Temperature Deviation (Test 3, Trial B)