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RPT-THSPT-001, Rev. 0

High Solids Performance Testing in a Scaled TSCR System

August 2021

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Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

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Richland, Washington 99354

Revision History

Revision Number	Date Issued	Description of Change
0	08.30.2021	Initial issue.

Summary

The Tank Side Cesium Removal (TSCR) project is a technology demonstration that will pretreat Hanford tank waste supernatant in support of the Direct Feed Low-Activity Waste (DFLAW) mission. The TSCR system employs two key separation technologies: dead-end filtration (DEF) and ion exchange (IX) using crystalline silicotitanate (CST) media. DEF will be used to remove undissolved solids from tank waste to protect the functionality of the IX columns, and the IX system will remove Cs-137 from tank waste.

The TSCR system has been designed and constructed by AVANTech Incorporated, for Washington River Protection Solutions (WRPS), and was recently installed adjacent to the Hanford AP Tank Farm. The separation technologies (DEF and IX) used in TSCR are technically mature and have also been successfully deployed at the Savannah River Site in a similar facility known as the Tank Closure Cesium Removal (TCCR) system. While testing with simulants and real waste with TSCR has been successfully performed under conditions expected during the initial operation of TSCR, test data are absent for assessing off-normal high-solids loading that may be in the TSCR waste feed. Accordingly, the purpose of this study was to evaluate the performance of the TSCR system with solids loading higher than the expected (normal) feed conditions.

Normal TSCR treatment operations are expected to handle wastes with solids content on the order of 200 ppm, and off-normal solids loading could be much larger than the nominal level. Previous testing at Pacific Northwest National Laboratory, as part of the Radioactive Test Platform program, demonstrated the DFLAW flow sheet, including small-scale DEF and IX, several times using various actual waste samples provided by WRPS. The previous testing, however, had a solids content near, or well below, the normal solids loading of 200 ppm. AVANTech Incorporated also conducted scaled filter testing when selecting the DEF media. This scaled filter testing was performed at a solids loading of 300 to 1,000 ppm, although the majority of tests were performed at ≤ 500 ppm. Operating data and process experience from TCCR can help inform TSCR operations, but there are sufficient differences between the TCCR and TSCR systems and waste feeds (e.g., different filter media, different backflushing protocol, and no appreciable solids for TCCR) that TSCR-specific data are needed.

The testing program described in this report was conducted to understand the consequence of operating the TSCR system at elevated solids loadings up to the high-solids limit of 15,000 ppm (i.e., 1.5-wt%) identified in the TSCR design basis. Although the system is not required to make throughput above the nominal solids loading, the testing was intended to provide important information related to potential off-normal operations. At off-normal levels near the high-solids limit, there are potential implications for TSCR performance in the areas of throughput, DEF pressure drop, filter backflush frequency, and IX column pressure drop. In addition, intrusion of solids into the IX column was postulated to impact the Cs-137 loading behavior by promoting channeling or flow maldistribution in the column; since the magnitude of the postulated effect was unknown, assessing it was also of interest. These performance topics are best assessed in an integrated system that is appropriately scaled and operated prototypically (to the extent practical). Since a prototypic, integrated TSCR system of any scale did not exist, an important element of the current testing program was the design and assembly of the test system used to conduct the high-solids performance assessment.

The design and scaling of the TSCR test system required consideration of the most important physical mechanisms and the dimensionless groups that describe their behavior. These scaling approaches are based on previous work and discussed in the report. The test system used a reduced flow rate that was 1/145th the full-scale flow, had two reduced-size DEFs that could be swapped to allow the off-line DEF to be backflushed in a prototypic manner, used a full-height cylindrical CST bed (the full-scale column has an annular geometry) with a reduced diameter, and reduced-size inlet distributor and screen and exit screen that used the full-scale screen slot and wire widths and matched, to the extent possible, the full-scale inlet and exit screen geometry.

A series of four tests were conducted using the scaled, prototypic TSCR system to assess filtration and ion exchange performance at higher-than-nominal solids loading. The testing used waste simulants with representative chemical constituents and solids generated by a dilution-precipitation process using dissolved $CaCl_2$. A baseline performance test was performed first using a 5.6M Na simulant with a chemical composition that is, approximately, an average of projected DFLAW feeds and contained only a trace number of solids. This was followed by three tests with solids loadings ranging from ~500 ppm to 3,000 ppm; the solids included a fraction of particles that were below the manufacturer's rating of the dead-end filters (< 5 microns). The solids loadings tested were greater than prior scaled testing but still below the maximum allowable value of 15,000 ppm. The test conducted at 3,000 ppm solids required a high frequency of backflushing (due to rapid fouling of the filters) to maintain throughput, which is not a preferred operational condition for TSCR, so tests at higher solids loadings were not performed.

All the test operations were similar: the flow rate was well-controlled at the target value and the feed temperature was held at 22 ± 1 °C. The dead-end filters retained the solid particles—no breakthrough or accumulation of particles downstream of the filters was observed—and backflushing was effective at restoring filter performance. The ion exchange column performed as expected and no significant change in hydraulic resistance was observed. Post-test observations did not reveal any unusual deposition of solids in the CST bed or inlet distributor; aside from an unexplained contamination event in the first test, the filters were successfully "cleaned" in place between tests.

Based on analysis of data and operational observation, the important conclusions drawn from the testing are the following:

- The dead-end filters successfully performed their primary function of protecting the IX column at all tested solids loadings. This was supported by several pieces of evidence collected during the testing, but primarily by the differential pressure drop (ΔP) measurements along the column only having a negligible increase over the duration of each test, indicating that there was no observable plugging of or solids build-up in the column during each test.
- The initial cesium loading behavior onto the CST was not discernably impacted.
- The filters exhibited a rapid rate of change in pressure differential even at modest solids loadings, i.e., ~1,000 ppm and greater. Though the target instantaneous throughput of the system was maintained, the observed system performance challenges the planned operational approach for TSCR because:
  - The ΔP across each DEF increased above the 2-psid (pounds per square inch differential) target in as little as ~10 to 15 minutes for the highest solids loading tested (~3,000 ppm). Swapping between filters when the 2-psid pressure target is reached demands rapid response by operators, requires operational vigilance, and generates an appreciable amount of flushed waste (which would ultimately collect in tank AP-108).
  - Above the 2-psid target, the rate of change in ΔP usually accelerated, especially above ~10 psid. This introduces a risk that the pressure could suddenly increase over the maximum allowed pressure differential of 25 psid and an interlock would be activated in the TSCR facility.
  - Rapid swapping would greatly reduce the duration of the 2-hour 0.1M NaOH soak time that is planned for TSCR. While there was not a noticeable impact on backflush efficacy when the soak time was shortened during the scaled testing, it is not certain that this would also be the case for full-scale radioactive operations.

  - The filter swapping frequency may significantly reduce the amount of "net" treated waste since every backflush evolution sends the equivalent of two DEF volumes to tank AP-108. The test system's DEF shell volume was not scaled to the full-scale TSCR shell volume, so the breakeven point cannot be projected directly from the test data.

- Despite pressure differentials that increased up to 25 psid over time periods of less than an hour, the DEFs were backflushed repeatedly and reliably during test operations. Backflushing and a 0.1M NaOH soak (even if the soak period was truncated) consistently returned the DEF to its baseline ΔP. DEF performance, as observed during these tests, is well-described by the term "cyclic."
- Following the completion of a test run, the system was readily returned to its baseline performance level (as determined by a 0.1M NaOH flow measurement conducted before each test) without any significant interventions. The only "cleaning" conducted between tests involved flushing out simulant material with 0.1M NaOH, water rinsing the pH down to ~7 or 8, and a handful of backflushes on each DEF.
- The scaled system tests were conducted in such a way as to be faithful to the planned full-size TSCR configuration and procedural steps as possible. No significant issues were identified with the operational configuration during testing. One minor observation was that when the CST was contacted initially with simulant after being loaded with 0.1M NaOH, a significant number of fines were released and flowed downstream. A similar effect would be anticipated when first contacting CST with actual waste feed.

Overall, the scaled TSCR testing demonstrated that the full-scale unit operations are expected to succeed in fulfilling their processing objectives in the presence of solids up to 3,000 ppm, but there are potential performance challenges to filtration operations at solids loadings as low as ~500 ppm. The severity of the challenge is likely to be dependent on the type and size distribution of solids, of which the current testing only examined a single type and size distribution. To provide some flexibility for future full-scale operations, the results of the testing suggest two possible risk-reduction strategies that can be implemented without any changes in TSCR design or configuration. One option would be to enact an administrative limit on the solids loading to protect TSCR from feeds that are likely to require an unacceptable DEF swap frequency; however, a quantitative measurement of solids content at the 10^2 – 10^3 ppm level requires a large sample (~1 L was used in this work). Another option is to permit operation of the DEFs at differential pressures greater than 2 psid before swapping filters. The selection of a higher differential pressure target is not anticipated to adversely impact DEF backflushing efficacy and would reduce both swap frequency and the amount of waste sent to tank AP-108.

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Acronyms and Abbreviations

APEL	Applied Process Engineering Laboratory
BV	bed volume
CST	crystalline silicotitanate
DEF	dead-end filtration/filter
DFLAW	Direct Feed Low-Activity Waste
DI	deionized
DP	differential pressure
EQL	estimated quantitation limit
ESL	Environmental Sciences Laboratory
FIO	For Information Only
FS	full-scale
HS(X)	high-solids (simulant)
IBC	intermediate bulk container
IC	ion chromatography
ICP-OES	inductively coupled plasma optical emission spectroscopy
ICP-MS	inductively coupled plasma mass spectrometry
ID	internal/inner/inside diameter *or* identification (determined by context)
IX	ion exchange
LAW	Low-Activity Waste
LS	laboratory-scale
NB	nominal batch (simulant)
OD	outside/outer diameter
PNNL	Pacific Northwest National Laboratory
PSD	particle size distribution
QA	quality assurance
R&D	research and development
Sch	Schedule (for pipe)
SOW	Statement of Work
SS	stainless steel
TC	total carbon
TCCR	Tank Closure Cesium Removal
TIC	total inorganic carbon
TOC	total organic carbon
THSPT	TSCR High Solids Performance Test(ing)
TSCR	Tank Side Cesium Removal
WRPS	Washington River Protection Solutions
WTP	Waste Treatment and Immobilization Plan
WWFTP	WRPS Waste Form Testing Program
XRD	x-ray diffraction

Contents

Figures

Tables

1.0 Introduction

The Tank Side Cesium Removal (TSCR) project is a technology demonstration that will pretreat Hanford tank waste supernatant in support of the Direct Feed Low-Activity Waste (DFLAW) mission. The TSCR system employs two key separation technologies: dead-end filtration (DEF) and ion exchange (IX) using crystalline silicotitanate (CST) media. DEF will be used to remove undissolved solids from tank waste to protect the functionality of the IX columns and the IX system will remove Cs-137 from tank waste. TSCR provides ICD-30 compliant feed (Reinemann 2015) to the Waste Treatment and Immobilization Plant (WTP) Low-Activity Waste (LAW) Vitrification facility as part of efforts to accelerate waste treatment and immobilization (Chamberlain and Eaton 2018).

The TSCR system has been designed and constructed by AVANTech Incorporated, for Washington River Protection Solutions (WRPS), and was recently installed in the Hanford AP Tank Farm. The separation technologies (DEF and IX) used in TSCR are technically mature and have also been successfully deployed at the Savannah River Site in a similar facility known as the Tank Closure Cesium Removal (TCCR) system (Beck et al. 2017, Keefer et al. 2019, Luzzati et al. 2021, Seeley et al. 2021). However, as was observed in both Statements of Work (SOWs)[1,2] provided by WRPS to Pacific Northwest National Laboratory (PNNL):

> “Testing with simulants and real waste has been successfully performed under conditions expected during the initial operation of TSCR and results indicate that the system will perform as planned. However, additional data has been requested to assess off normal high solids loading in the waste feed.”

The quoted statement refers to “off normal solids loading” in the waste feed to TSCR. For reference, “normal” TSCR treatment operations are expected to handle wastes with solids content on the order of 200 ppm.[3] An off-normal solids loading would be much larger than the nominal level of 200 ppm and, as mentioned in the SOW, was the parameter space where additional data were needed. Note that for a related parameter – the particle size of the solids – the feed to TSCR is expected to have predominantly small particles (nominally < 1 micron) but particles as large as 550 microns are permitted.

The successful testing referred to in the SOW has primarily been conducted at PNNL as part of the Radioactive Test Platform program, which has demonstrated the DFLAW flow sheet several times using various actual waste samples provided by WRPS. The scope of previous investigations has included extensive testing of both filtration (Geeting et al. 2018a, 2018b, 2019; Allred et al. 2020) and ion exchange with CST (Rovira et al. 2019; Fiskum et al. 2019a, 2021; Westesen et al. 2021a, 2021b). AVANTech Incorporated also conducted scaled filter testing to select the DEF media in the design phase. The scaled filter testing was performed at a solids loading of 300 to 1,000 ppm, although the majority of

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[1] Statement of Work Requisition #339013, Rev. 0. June 4, 2020. *TSCR High Solids Filtration and Ion Exchange Testing*. Washington River Protection Solutions, Richland, Washington.

[2] Statement of Work Requisition #343275, Rev. 0. October 26, 2020. *TSCR High Solids Filtration and Ion Exchange Testing*. Washington River Protection Solutions, Richland, Washington.

[3] The nominal solids loading is mentioned in Ard 2019 as 200 ppm in Table 3-4. The general waste acceptance criteria document (Russell and Chamberlain 2019) also mentions in Table 2 that up to 160 ppm is the bound for the system’s “normal operating parameters”.

tests were performed at ≤ 500 ppm (Wilson 2019b); PNNL staff supplied the solids content and particle size distribution analysis as part of AVANTech's test effort.[4]

As was mentioned, TSCR has many similarities to the TCCR unit operating on the Savannah River Site, and so it would be reasonable to expect that a question of this type may have already arisen during TCCR design, installation, commissioning, and operation. However, though operating data and process experience from TCCR can help inform TSCR, there are enough salient differences that TSCR-specific data are needed. The most important differences are:

- TCCR uses a different dead-end filter media than TSCR, i.e., it is not a sintered stainless-steel porous media manufactured by Mott Corporation;
- The TCCR backflushing protocol is operationally distinct from TSCR; and
- The dissolved saltcake fed to the TCCR system thus far has chemical and physical differences compared to the projected DFLAW feeds (for example: lower sodium concentration, lower density, no appreciable solids).

One result from prior technical studies associated with TCCR relevant to the testing reported herein is the observation of Mathurin and Taylor-Pashow (2019) that CST in contact with caustic and representative waste simulant solutions did not exhibit significant clumping or aggregation behavior over a period of several months. Although solutions fed to TCCR are not identical to DFLAW feeds, they are caustic and contain an array of the same dissolved salts. Thus, it is possible to conclude from their work that any aggregation or clumping behavior observed in the current testing is from solid particle deposition or interaction and not contact with the liquid solutions.

The testing program described in this report was conducted to understand the consequence of operating the TSCR system at elevated solids loadings up to the high-solids limit of 15,000 ppm (i.e., 1.5-wt%) identified in the TSCR design basis (Ard 2019). Although the system is not required to make throughput above the nominal solids loading, the testing was intended to provide important information related to potential off-normal operations. At off-normal levels near the high-solids limit, there are potential implications for TSCR performance in the areas of throughput, DEF pressure drop, filter backflush frequency, and IX column pressure drop. In addition, intrusion of solids into the IX column was postulated to impact the Cs-137 loading behavior by promoting channeling or flow maldistribution in the column; since the magnitude of the postulated effect was unknown, assessing it was also of interest. These performance topics are best assessed in an integrated system that is appropriately scaled and operated prototypically (to the extent practical). Since a prototypic, integrated TSCR system of any scale did not exist, an important element of the program was the design and assembly of the test system used to conduct the high-solids performance assessment.

The design and scaling of the TSCR test system required consideration of the most important physical mechanisms and the dimensionless groups that describe their behavior. Relevant information on scaled testing of waste treatment simulants and scaled system design is available in several prior PNNL studies, such as discussed in Daniel et al. 2009 and 2010, Scheele et al. 2009, and Kurath et al. 2009 (related treatment topics associated with the WTP Pretreatment facility), as well as Russell et al. 2017, Daniel et al. 2018, Gauglitz et al. 2018 and 2019, and Pease et al. 2019 (DFLAW-relevant test studies or analyses). The engineering considerations associated with the two major unit operations of TSCR are also described extensively in Schonewill 2020 (filtration) and Peterson et al. 2020 (ion exchange).

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[4] Refer to Attachment to LTR-72195-009: Burns CA, RC Daniel, and PP Schonewill. 2019. "TSS and PSD Analysis of TSCR Filter Performance Samples." Pacific Northwest National Laboratory, Richland, Washington.

The remainder of the report discusses the various elements of the TSCR High Solids Performance Testing (THSPT) program, beginning with a summary of quality assurance in Section 2.0. Section 3.0 describes the test objectives, the system design and scaling, and data collection methods. Section 4.0 presents the simulant selection process used to specify the material used in the testing. This is followed by a description of the test conditions and general procedure in Section 5.0. Section 6.0 presents the data collected during each test that was performed and some comparisons across test conditions. Section 7.0 discusses the test data and provides the conclusions of the testing. References are found in Section 8.0.

2.0 Quality Assurance

The THSPT project was conducted under two separate contracts and project numbers, but the same quality assurance approach was maintained across the separate contracts to maintain continuity in project records and associated documents. A crosswalk of the various project numbers associated with the THSPT project is shown in Table 2.1. This information is provided for completeness; the multiple contracts/project numbers did not have any bearing on the execution of the quality-affecting work.

Table 2.1. List of Project Numbers Associated with the THSPT Project.

PNNL Project Number	WRPS Project (Contract) Number	Description of Scope as Listed in the Statement of Work
77011	36437-308	*TSCR High Solids Performance Testing*; WRPS Requisition #339013, Rev. 0, dated 04 Jun 2020. In support of the Tank Side Cesium Removal (TSCR) technology testing activities, develop a simulant that addresses off normal high-solids loading in the TSCR waste feed, and perform filtration and ion exchange testing using the nominal simulant described in PNNL-26165, Rev. 0 (5.6M) and the simulant developed under this project.
77638	74916	*TSCR High Solids Performance Testing*; WRPS Requisition #343275, Rev. 0, dated 26 Oct 2020. Same as above. A change in the contracting process resulted in a new PNNL project number but the project scope, description, schedule, and deliverables were unchanged.

All research and development (R&D) work at PNNL is performed in accordance with PNNL's Laboratory-Level Quality Management Program, which is based on a graded application of NQA-1-2000, *Quality Assurance Requirements for Nuclear Facility Applications*, to R&D activities. To ensure that all client quality assurance (QA) expectations were addressed, the QA controls of the WRPS Waste Form Testing Program (WWFTP) QA program were also implemented for this work. The WWFTP QA program implements the requirements of NQA-1-2008, *Quality Assurance Requirements for Nuclear Facility Applications*, and NQA-1a-2009, *Addenda to ASME NQA-1-2008*, and consists of the WWFTP Quality Assurance Plan (QA-WWFTP-001) and associated QA-NSLW-numbered procedures that provide detailed instructions for implementing NQA-1 requirements for R&D work.

Specific details of this project's approach to assuring quality are contained in the TSCR High Solids Performance Testing Quality Assurance Plan (QA-THSPT-001, Rev. 1) and associated implementing procedures. The QA plan describes how the procedures of the WWFTP QA program were used when conducting the work. The work described in this report was assigned the technology level "Applied Research," and was planned, performed, documented, and reported in accordance with procedure QA-NSLW-1102, *Scientific Investigation for Applied Research*. All staff members contributing to the work received proper technical and QA training prior to performing quality-affecting work.

3.0 Test System Description

In this section, the system used to perform the high-solids performance testing is described. The design of the system arises out of the test objectives, which are presented in Section 3.1. The basis for the design is discussed in detail in Section 3.2, with special attention given to the parameters that are expected to be the most germane to TSCR's performance. Section 3.3 describes the scaling considerations involved in the IX column design, followed by a description of the scaling consideration for the DEFs and the feed system in Section 3.4. Then, Section 3.5 gives an overview of the system and its major test equipment and instrumentation. Finally, Section 3.6 describes the collection of data and the analyses performed in support of the testing.

3.1 Test Objectives

For the THSPT project, two high-level objectives were proposed to collect the required data:

1. Develop a simulant that addresses high solids (off-normal) loading in the TSCR waste feed. The simulant should be representative of a potential high-solids TSCR feed and address the entire range of solids concentrations identified in Ard 2019, Table 3-4.

2. Empirically determine the impact to DEF and IX performance of processing simulant (developed as part of Objective 1) with elevated levels of solids. Testing should be performed utilizing an appropriately scaled filtration and IX system.

Specific to the first objective, the solids loading target for the high-solids simulant was loadings of 20%, 60%, and 100% of the 15,000-ppm maximum, which spans the range of concentration that would be permitted in the feed. For comparison, a previously developed simulant (the 5.6 M "Nominal" simulant described in Russell et al. 2017) with the nominal solids loading of ~200 ppm was proposed to be tested to establish a performance baseline for the system. The simulant development process and scale-up of the selected recipe are discussed in detail in Section 4.0.

The second high-level objective has several other supporting objectives layered underneath it to define the parameters of the testing and collect the most pertinent empirical data. The supporting test objectives undergird the high-level objective to reduce uncertainty in the applicability of the results to the full-scale TSCR system. They include:

a. Conduct processing runs that mimic prototypic TSCR operations as much as feasible. Prototypic operations were considered to include:
    - Supplying simulant to the process equipment from a well-mixed feed tank.
    - Controlling to a target flow rate (as measured downstream of the IX column).
    - Switching processing between dual filters (one online and one offline) after reaching a target increase of 2-psi pressure drop in the online filter (or after 24 hours of operation).
    - Backflushing the filters using compressed air, with the flushed solids sent to a flush receipt vessel (not returned to the feed tank).
    - Soaking the filter that's not in active service, using 0.1M NaOH.
    - Feeding the filtrate directly into the IX column via a scaled distributor, i.e., integration of the unit operations.

- Conditioning CST media to remove fines prior to column loading.
- Operating without any temperature control of the process fluid downstream of the filter inlet.
- Collecting processed simulant in a product tank.

Some of the prototypic operations were not included in the scaled test system because they do not impact the filter and IX performance aspects being measured, they are not part of steady-state processing operations, or they have been previously demonstrated. These are:

- Controlling temperature of the ambient process space.
- Demonstrating filter and column blowdown.[5]
- Demonstrating IX column drying.[6]
- Processing through an IX column carousel.
- Implementing a scaled delay tank, gamma detectors, and media trap.[7]

b. Perform four tests with processing runs at different solids loadings that span the range from nominal (~200 ppm) to the upper limit of 15,000 ppm (1.5 wt%). If system performance prevents spanning the entire range of solids loadings, then testing will be performed at the highest solids loading that can be reasonably tested.

c. Collect key performance data during processing runs that permit assessment of the scaled system's performance relative to the baseline performance obtained at the nominal solids loading. The key performance metrics are the processing flow rate, pressure drop across the filters and IX column, frequency of backflushing, results of analyses of samples collected from process lines, and field observations during or post-test.

d. Analyze samples to compare filtration and IX performance across tests. Samples will be used to determine the presence (if any) of solids downstream of the filters and to characterize the cesium loading of the IX column to "initial" breakthrough (at least 0.1% of the cesium feed concentration). Particle size distribution (PSD) measurements will also be made on the feed simulant for each test.

e. Use trending and analysis tools to present test data for complete processing runs (meaning for the time that the system is trying to achieve the target flow rate) as a function of operating time or bed volumes (BVs) processed.

f. Based on test results, make recommendations for what operational changes could be implemented in the full-scale system if filter and/or column plugging becomes significant.

Accomplishing the objectives required the design and assembly of an appropriately scaled test system that could enable prototypic operations described in Objective 2a. The test system configuration and the relevant technical bases used to define the system are described in the next section.

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[5] Blowdowns are displacements of resident fluid with air used to either created a more stable operational configuration or prepare the equipment for removal.

[6] Air was used to displace process fluid at the conclusion of a test, but the process was not intended to be a quantitative measure of drying behavior. This has already been studied in Gauglitz et al. (2019).

[7] Note that the media trap's function will be accomplished using an in-line capture filter, but this is not prototypic.

3.2 Scaling Basis for Test System

In this section the scaling basis for the test system is summarized. Note that the test system is described in this section as the “laboratory-scale” system as opposed to the “full-scale” TSCR system. The TSCR system process flow diagram (as given in Langan 2019[8]) is shown in Figure 3.1 for reference. The flow diagram served as the model for the major process functions that needed to be replicated in the laboratory-scale test system. For a summary of the key selected parameters of the system in comparison to full-scale, see Table 3.1. Many of the planned parameters also have a specific scaling basis briefly summarized in Table 3.1. The subsequent sections discuss these in more detail; first, the implications for scaling a full-height IX column and its associated equipment are considered (Section 3.3), followed by a discussion of the filters and the feed system scaling (Section 3.4). The IX column is discussed first because the laboratory-scale test system was designed around its dimensions; the unit operations of the test system are integrated and thus are interdependent. Section 3.5 summarizes the test system configuration and key equipment and instruments that will be used.

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[8] An AVANTech-produced drawing entitled “TSCR Block Flow Diagram” (H-14-111241, Sheet 1, Rev. 0) also shows the same configuration.

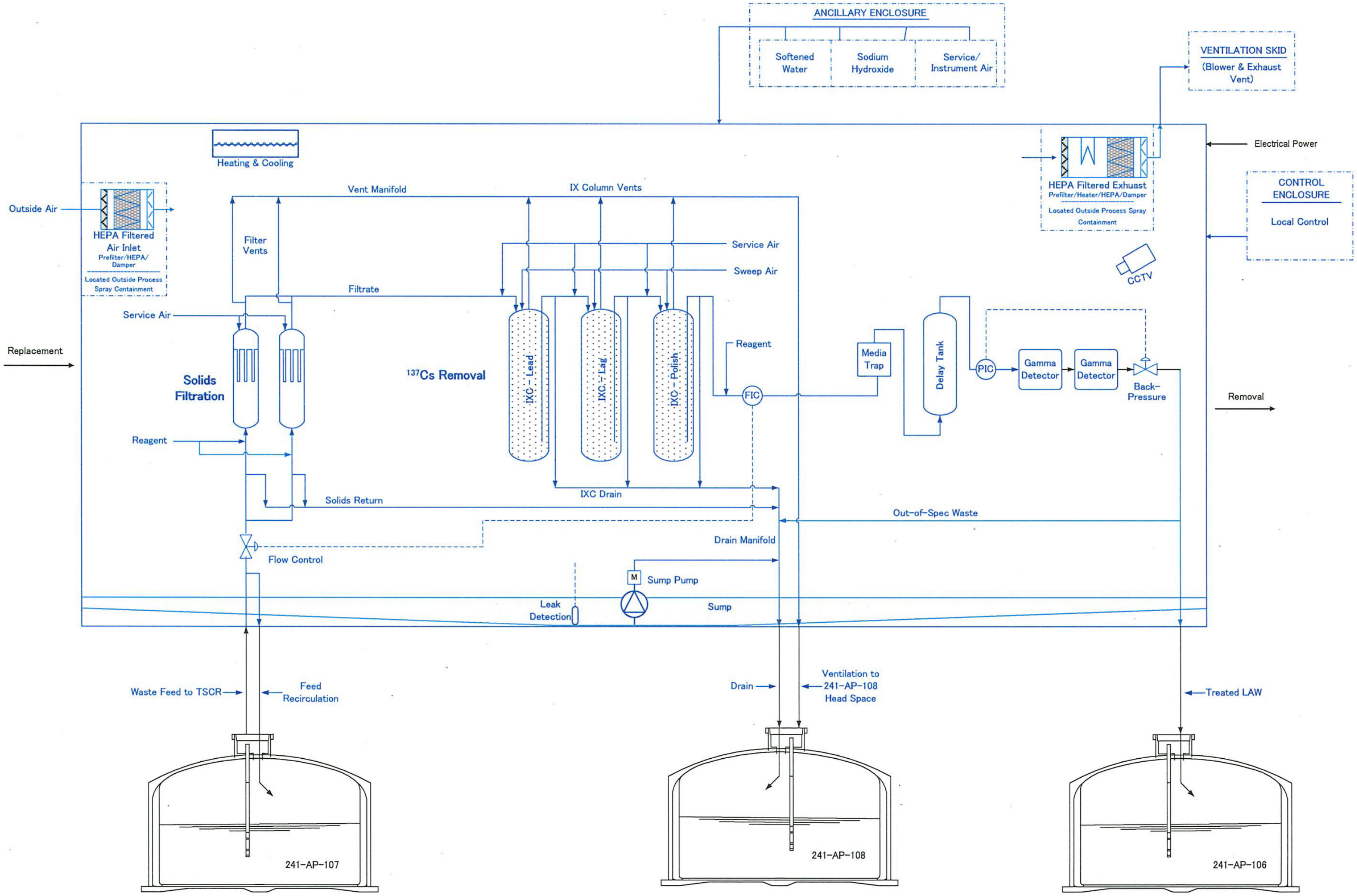

Figure 3.1. TSCR Process Flow Diagram (adapted from Langan 2019).

Table 3.1. Summary of Selected Parameters for the Scaled Test System.

System Parameter	Laboratory-Scale Value	TSCR (Full-Scale) Value	Scaling Basis
Column bed height	92 in.	92 in.	Full-height CST bed for characteristic hydraulic performance
Column inner diameter	1.87 in.	23 in. (with ~4.5-in. annulus)	Existing full-height column size that is large enough to keep wall effects small
Bed volume (BV)	1.09 gal	159.1 gal	Defined by column size parameters, ignoring excluded volume
Planned BVs to process	≥ 250	n/a – TSCR has a carousel and switches columns based on breakthrough, not BVs processed	Selected based on PNNL test data (see additional discussion in Section 3.3.1) to characterize initial cesium breakthrough (> 0.1% of the feed concentration) at an elevated feed concentration
Volume of simulant needed to process to BV target	273 gal	n/a – see note above	Minimum volume representing the BV target selected
Scaled process flow rate	0.0344 gpm (130.1 mL min^{-1})	5 gpm (18,927 mL min^{-1})	Flow rate that matches full-scale BV hr^{-1} processing rate based on bed cross-sectional area
Filter length needed to achieve flow rate	1 tube of 24.5 in.	98 tubes of 36 in.	Ratio of full-scale filter to scaled filter area needed to achieve the scaled flow rate
Operating time to process BV target	132.6 h	n/a	Defined by the BV and scaled process flow rate
Scaled filter housing volume	0.13 gal (1.5-in. diameter shell)	49.5 gal (18-in. diameter shell)	Maintain same superficial velocity between the shell and tube as the full-scale filter
Volume of air accumulator	0.13 gal (0.5 L)	20 gal (75.7 L)	Maintain same ratio of filter area to air volume as full-scale filter system (The initial pressure in the air accumulator will match full-scale system, so using same ratio of filter area to air volume should result in the same average flow rate through the filter in both the laboratory- and full-scale systems)
Criteria for switching filter unit	2 psig increase in pressure drop or at 24 h	2 psig increase in pressure drop or at 24 h	Criteria for switching filters is the same in both the laboratory- and full-scale systems
Solution for soaking filter not in use	0.1 M NaOH	0.1 M NaOH	Solution for soaking the filter not in use is the same for both laboratory- and full-scale systems
Range of Solids Concentration in Feed	200 – 15,000 ppm	0 – 15,000 ppm	Maximum solids concentration the same for both systems. For the low end of the range, laboratory-scale system will use 200 ppm, which is the TSCR nominal value.

3.3 Laboratory-Scale IX Column, Screens, and Inlet Distribution Ring Scaling

The selected laboratory scaling for the IX column is discussed before the rest of the system because its size fixed many aspects of the test, such as the relative amount of simulant needed and the surface area of the dead-end filters. One critical element only partly dependent on column size that is discussed first in the section below involves the measurement of cesium removal performance by the CST bed during the tests and its impact on the duration of the test. This was important to establish early during the test design so the amount of simulant required for the planned tests was well-defined.

3.3.1 Column Cesium Removal Performance

Cesium removal by CST is a well-studied phenomenon and its determination was not a primary objective of testing. The goal was to observe whether operation with higher solids loading in the feed had any impact on the cesium removal function of the IX column. This is an important distinction because the processing time needed to obtain the full cesium loading curve with CST is considerable and spans many more filtration cycles than are needed to collect an appreciable measure of filter performance.

Therefore, the analysis of CST cesium removal performance did not measure the complete cesium loading on the IX column during each test because the simulant volume used (a target value of at least 250 BVs) did not permit a full loading cycle to be conducted. The amount of simulant chosen to process, which is based on BV hr^{-1}, was balanced between the size of the experimental system and the volume of simulant required (larger systems require proportionally more simulant volume). In these tests, the decision was made to keep the simulant volume manageable to reduce test duration and material handling requirements, which reduced the number of BVs that could be processed. Based on historical data from simulant and actual waste testing at similar chemical compositions (to the simulants used in this testing) and flow rates (see Fiskum et al. 2019b, Rovira et al. 2019, Westesen et al. 2020), the effluent concentration was expected to reach a minimum of 0.1% C/C_o at the end of each test, where C is the cesium concentration in the effluent and C_o is the feed concentration of cesium. In the historical studies cited, 0.1% C/C_o was reached at between approximately 200 to 240 BVs depending on the waste or waste simulant processed. This evidence, in conjunction with using simulants that had slightly higher feed concentrations of cesium and potassium, suggested that achieving $\geq 0.1\%$ C/C_o at 250 BVs processed was achievable in the laboratory-scale system.

Therefore, as listed in Table 3.1, the tests were designed to process to an “initial” breakthrough at the 0.1% C/C_o level (or perhaps a bit past). This was deemed acceptable for the following reasons:

- The primary objective of the testing was measuring filter pressure drop and IX column hydraulic performance. Cesium removal performance was a postulated secondary effect of solids deposition in the IX column, which may not occur in significant amounts.
- If initial breakthrough occurred at approximately the same point in processing time for tests with simulants of the same or similar chemical composition, where only the solids loading is changed, it was expected that the rest of the breakthrough curve would be similar for a given flow rate and temperature.
- The initial breakthrough point determined in these tests can be compared to the initial breakthrough point measured in prior CST tests with both actual waste and simulants at multiple scales to help guide the assessment of performance.

The collection of C/C_o data is straightforward and depends only on liquid samples being measured for cesium concentration at discrete times; since the flow rate, temperature, and composition of the simulant's liquid phase were not varied, there are no other significant scaling considerations for cesium removal performance. However, there were several other considerations for the appropriate scaling with respect to the potential presence of solids in the CST column, and these are discussed in the next section.

3.3.2 IX Column Dimensional Scaling

Figure 3.2 shows dimensions and geometry of the planned full-scale CST column. For the IX and filtration tests, a scaled laboratory column was selected that allowed the use of the full height of the planned CST bed (92 in.) and was close to the full-scale column height (94 in.)[9] for several reasons. A full-height CST bed matches the hydraulic pressure loss across the column during flow when the superficial velocity in the laboratory-scale column matches that in the full-scale column. If CST bed plugging were to occur, the plugging was expected to occur primarily in the upstream portion of the bed. If a shorter height CST bed were used, multiple pressure measurements along the column would have been needed to estimate the pressure loss along the column and would have been complicated by the pressure loss potentially being different in the inlet and downstream regions of the bed. This would generate uncertainty in estimating the pressure loss for a full-height column. A full-height column also simplified the evaluation of the IX behavior, which represents CST loading and breakthrough behavior of the full-scale column without needing to estimate full-scale behavior from a shorter column. If bed plugging affected the IX behavior, estimating full-height bed performance from a shorter bed would also involve uncertainties. For these reasons, the laboratory column CST bed height for conducting the IX and plugging tests matched the CST bed height for the full-scale CST column.

As shown in Figure 3.2, the full-scale CST column has an annular configuration with an annulus outer diameter of 23 in. and a central pipe with an outer diameter of 4.5 in. (4-in. Schedule [Sch] 40 pipe). The laboratory column was selected to have a 1.87-in. internal diameter (ID) that was chosen as a compromise, giving acceptably small wall effects while keeping the volume of CST needed for testing reasonable. With smaller-diameter columns, wall effects for simulant flow can become significant under certain conditions. Though a rigorous analysis was not done, a 1.87-in. ID column is nominally 70 CST particle diameters (average CST particle diameter is 709 µm, Fiskum et al. 2019b)[10], which was considered sufficient to keep wall effects small for flow distribution: Dullien (1992) notes that it is generally concluded that wall effects in random-packed porous structures become negligible when the column diameter is more than 10 times the particle diameter. Cheng (2011) evaluated data and models for the effect of the ratio of column diameter to particle diameter on pressure drop during flow and his evaluation supports the statement that for column diameters more than 40 particle diameters, there is no difference in the measured pressure drop and values predicted from the Ergun equation, which is an equation that applies for column diameters infinitely larger than the particle diameter. While wall effects were not expected, the laboratory-scale column had a higher ratio of wall surface area to CST bed volume compared to the full-scale column. For preferential plugging occurring near the column wall, the laboratory-scale over-represents any negative impact of the plugging, which would be a conservative testing result.

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[9] In a recent study (Gauglitz et al. 2019) that used the same column components for a full-height column that were used in the current testing, the "as-built" height of the column was 94 ½ in. rather than the full-scale column height of 94 in. The slight difference was due to the thickness of gaskets where column sections were connected.

[10] Fiskum et al. (2019b) reported the d_{50} of two samples from CST Lot 2002009604, which is the lot of CST material that was used for the current filtration and column plugging study. The measured values were 695 µm and 722 µm, giving an average diameter of 709 µm.

The laboratory column was selected to have cylindrical geometry, rather than the annular geometry of the full-scale column. This change in configuration should not affect IX behavior or column plugging by fines. Stainless steel (SS) sanitary tubing, with tri-clamp fittings, was selected for fabricating the column. This tubing has an ID of 1.87 in. with a wall thickness of 0.065 in. The flow rate in the laboratory-scale column was selected to match the full-scale TSCR superficial velocity by scaling the full-scale flow rate by the ratio of cross-sectional areas of the small- and full-scale columns as follows:

$$Q_{Lab\text{-}S} = Q_{Full-S}\left(\frac{A_{Lab-S}}{A_{Full-S}}\right) \tag{3.1}$$

where

$A_{Lab\text{-}S}$ = cross-sectional area of laboratory-scale column
$A_{Full\text{-}S}$ = cross-sectional area of full-scale column
$Q_{Lab\text{-}S}$ = volumetric flow rate in laboratory-scale column
$Q_{Full\text{-}S}$ = volumetric flow rate in full-scale column

The full-scale flow rate is 5 gpm (all five screens, see Langan 2019) and the laboratory-scale flow rate was 0.0344 gpm (one screen); these values are included in Table 3.2. Table 3.2 lists both target values and planned design values for the laboratory-scale components to differentiate between the target values based on the scaling and the actual components that are planned for use in fabricating the column and components.

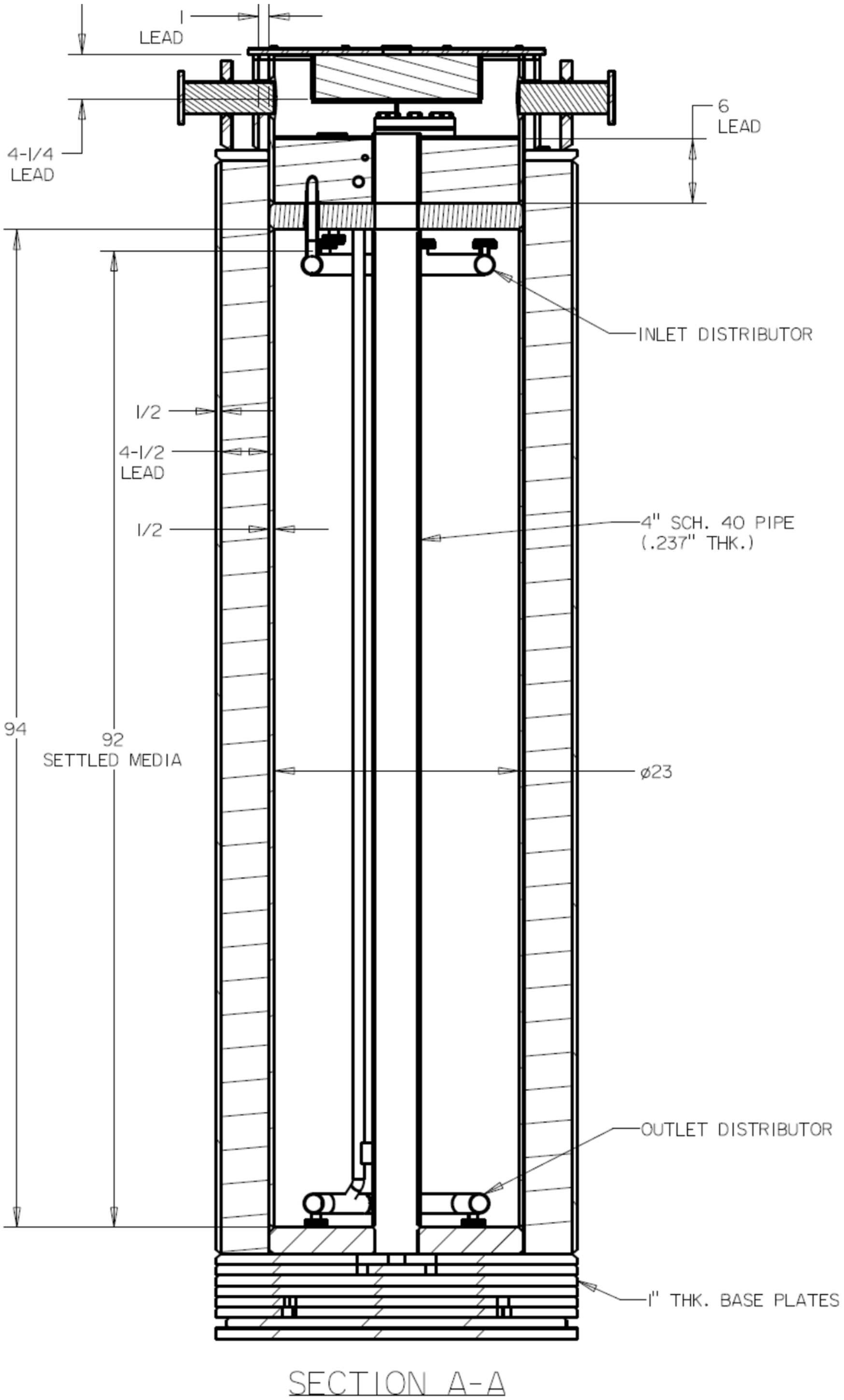

Figure 3.2. Full-scale CST bed configuration showing column and settled CST bed heights and inlet and outlet distributors (dimensions are in inches).[11]

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[11] AVANTech drawing H-14-111250, Sheet 1, Rev. 2. This schematic is a portion of that drawing.

Table 3.2. Full-Scale and Laboratory-Scale (both Target and Design) Flow Rates, Average Velocities, Dimensions, and Reynolds Numbers.

Component	Full-Scale	Laboratory-Scale Target	Laboratory-Scale Design
Column inner diameter (full-scale column is an annulus)	58.4 cm (outer) (23 in.) 11.4 cm (inner) (4.50 in.)	4.75 cm (1.87 in.)	4.75 cm (1.87 in.)
Volumetric flow rate (total)	315 mL/s (5 gpm)	2.17 mL/s (0.0344 gpm)	2.17 mL/s (0.0344 gpm)
Volumetric flow rate from each side of distribution ring to screen	31.5 mL/s (0.5 gpm)	1.084 mL/s (0.0172 gpm)	1.084 mL/s (0.0172 gpm)
Inlet distribution ring ID	4.09 cm (1.61 in.)	0.758 cm (0.298 in.)	0.775 cm (0.305 in.)
Average velocity in distribution ring	2.40 cm/s	2.40 cm/s	2.30 cm/s
Reynolds number in distribution ring	337	62.5	61.2
Volume of inlet distribution ring carrying flow to screen (last screen for full-scale)	697 cm^3	24.0 cm^3	4.98 cm^3
Vertical velocity from ring to screen	32.2 cm/s	32.2 cm/s	29.7 cm/s
ID of vertical pipe or tubing from distribution rings to screens and from bottom screen	1.58 cm (0.622 in.)	0.293 cm (0.115 in.)	0.305 cm (0.120 in.)
Screen slot width	0.0127 cm (0.005 in.)	0.0127 cm (0.005 in.)	0.0127 cm (0.005 in.)
Screen wire width	0.178 cm (0.070 in.)	0.178 cm (0.070 in.)	0.226 cm (0.089 in.)
Screen height	0.635 cm (0.25 in.)	0.635 cm (0.25 in.)	0.635 cm (0.25 in.)
Screen OD	5.28 cm (2.08 in.)	0.228 cm (0.0896 in.)	~ 2 cm (0.8 in.)

For the small diameter of the laboratory-scale column, a single inlet and exit screen was used. The inlet screen had a scaled distribution ring because this was a potential location for particle deposition and potential plugging. The exit screen did not have a distribution ring because particle deposition is unlikely at the column exit and this simplified the design. There were several considerations for designing the inlet and exit screens and inlet distribution ring on the laboratory-scale column to match the screens on the full-scale column for flow and potential plugging behavior. A design drawing from AVANTech shows details of the inlet and exit distribution rings and the five wedge wire screens that are attached to each of the rings.[12] Each screen has an outer diameter of 2.08 in. with a screen height of 0.25 in. and the screens have a slot width of 0.005 in. and a wire width of 0.070 in. (see Table 3.2). Figure 3.3 shows the full-scale inlet distribution ring from the AVANTech drawing with the estimated/approximate flows along the distribution ring assuming an equal flow of 1 gpm exiting each screen. The relatively small open area of each screen was expected to result in the screens providing the primary pressure loss for flow compared to the pressure loss in the much larger 1½-in. Sch 40 SS pipe that forms the distribution ring[13].

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[12] AVANTech drawing H-14-111255, Sheet 3, Rev. 1.

[13] AVANTech drawing H-14-111255, Sheet 3, Rev. 1.

Accordingly, it was expected that each screen will take an equal portion of the total flow of 5 gpm.[14] Although particle settling and deposition could occur anywhere in the distribution ring, the flow going to the last screen is the lowest, as highlighted in Figure 3.3, so the last screen is potentially the location of the most severe particle deposition and potential plugging. Accordingly, the laboratory-scale inlet screen and distribution ring were designed to match the average velocity, and potential particle deposition, of this last screen in the full-scale system.

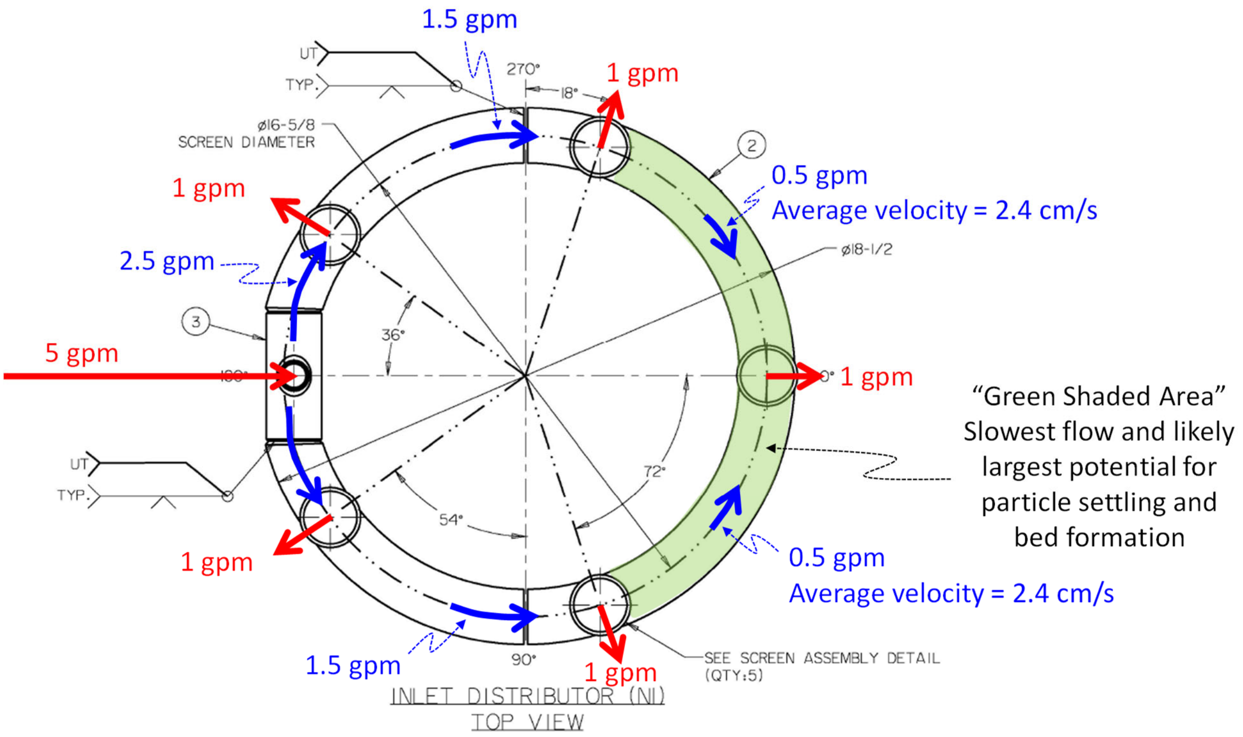

Figure 3.3. Inlet distribution ring for full-scale CST column showing approximate flow distribution assuming an inlet flow of 5 gpm and an equal flow of 1 gpm exiting each of the five screens.[15]

To match particle deposition behavior in the inlet distribution ring, the average velocity in the laboratory-scale distribution ring was targeted to match the average velocity in the full-scale distribution ring as it flows to the last screen. As shown in Figure 3.3, the full-scale flow rate is estimated to be 0.5 gpm from each direction flowing to the last screen. The full-scale distribution ring is 1½-in. Sch 40 SS pipe with an ID of 4.09 cm (1.61 in.). The target laboratory-scale velocity is given by

$$V_{target,Lab\text{-}S} = V_{Full-S} = \frac{Q_{Full-S}}{AR_{Full-S}} \tag{3.2}$$

where

$V_{target,\ Lab\text{-}S}$ = target average velocity in laboratory-scale distribution ring
$V_{Full\text{-}S}$ = average velocity in full-scale distribution ring

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[14] In RPP-CALC-63124, Rev. 1, "Service Air Pressure Setpoint Metrics", AVANTech, Inc., 2019, the pressure drop across a screen during air blowdown is calculated assuming equal flow to each of the five screens, which is consistent with the assumption of equal flow to each screen during liquid flow.

[15] The inlet distribution ring is a portion of AVANTech drawing H-14-111255, Sheet 3, Rev. 1.

$AR_{Full\text{-}S}$ = cross-sectional area of 1½-in. Sch 40 SS pipe in the full-scale distribution ring

The ID of the laboratory-scale inlet distribution ring is then given by

$$D_{target,Lab\text{-}S} = \left(\frac{4}{\pi}\frac{Q_{Lab-S}}{V_{target,Lab-S}}\right)^{1/2} \tag{3.3}$$

where

$D_{target,\ Lab\text{-}S}$ = internal diameter (target) of laboratory-scale distribution ring

With the values in Table 3.2, the target ID for the laboratory-scale distribution ring was 0.758 cm (0.298 in.). With an ID of 0.775 cm (0.305 in.), 3/8-in. tubing (0.035 in. wall thickness) provided a good match and was selected as the distribution ring tubing. Using this value, the average velocity in the laboratory-scale distribution ring is given by:

$$V_{Lab\text{-}S} = \frac{Q_{Lab-S}}{AR_{Lab-S}} \tag{3.4}$$

where

$Q_{Lab\text{-}S}$ = volumetric flow in laboratory-scale column
$V_{Lab\text{-}S}$ = average velocity in laboratory-scale distribution ring
$AR_{Lab\text{-}S}$ = cross-sectional area of 3/8-in. tubing in the laboratory-scale distribution ring

The full-scale and laboratory-scale average velocities and distribution ring IDs are summarized in Table 3.2.

The Reynolds numbers for the flow in the full- and laboratory-scale distribution rings are useful for understanding the deposition behavior of particles. For the full-scale and laboratory-scale distribution rings, the Reynolds number is given by (Denn 1980):

$$Re_{Full-S} = \left(\frac{\rho_L\, V_{Full-S}\, D_{Full-S}}{\mu_L}\right) \tag{3.5}$$

$$Re_{Lab-S} = \left(\frac{\rho_L\, V_{Lab-S}\, D_{Lab-S}}{\mu_L}\right) \tag{3.6}$$

where

ρ_L = liquid (or slurry) density
μ_L = liquid (or slurry) viscosity
$D_{Lab\text{-}S}$ = internal diameter of distribution ring in laboratory-scale column
$D_{Full\text{-}S}$ = internal diameter of distribution ring in full-scale column
$Re_{Full\text{-}S}$ = Reynolds number in full-scale distribution ring flowing towards last screen
$Re_{Lab\text{-}S}$ = Reynolds number in laboratory-scale distribution ring

For estimating the Reynolds numbers, the nominal liquid properties given by Ard (2019) were suitable estimates during the test system design: 1,270 kg/m^3 (1.27 g/mL) for density and 3.7 mPa·s (3.7 cP) for viscosity. With these values, the Reynolds number is 337 for the full-scale distribution ring and 61.2 for the planned laboratory-scale distribution ring using the ID for the planned 3/8-in. tubing. Both Reynolds numbers indicate laminar flow in the distribution rings and while the laboratory-scale Reynolds number is smaller, it should give similar particle deposition behavior (both are not turbulent).

A second consideration for the laboratory-scale inlet distribution ring was the volume in the ring because this affects the volume of deposited particles needed to potentially plug the ring. The volume of the full-scale ring that carries flow to the last screen was estimated from the cross-sectional area of the pipe forming the ring, the ring circumference, and the observation that 2/5 of the ring circumference carries flow to the last screen, as follows:

$$Vol_{Full\text{-}S} = \left(\frac{2}{5}\right) \pi \, DC_{Full-S} \, AR_{Full-S} \tag{3.7}$$

where

$Vol_{Full\text{-}S}$ = volume of full-scale distribution ring that carries flow to the last screen
$DC_{Full\text{-}S}$ = diameter of full-scale distribution ring for determining ring circumference
$AR_{Full\text{-}S}$ = cross-sectional area of 1½-in. Sch 40 SS pipe in the full-scale distribution ring

With a full-scale ring diameter of 16 5/8 in. (diameter at center of 1.5-in. Sch 40 SS pipe)[16] the volume that carries flow to the last screen is 697 cm^3 and this value is included in Table 3.2.

The selected scaling approach for determining the target volume of the laboratory-scale ring was to multiply the full-scale ring volume that carries flow to the last screen by the ratio of flow rates, because the ratio of flow rates gives the reduced volume of particles entering the laboratory-scale ring for the same duration of flow. With this approach, the volume (target) of the laboratory-scale ring is the following:

$$Vol_{target,Lab\text{-}S} = Vol_{Full-S} \, \frac{Q_{Lab-S}}{Q_{Vert,Full-S}} \tag{3.8}$$

where

$Vol_{target,\ Lab\text{-}S}$ = volume (target) of laboratory-scale distribution ring
$Q_{Vert,\ Full\text{-}S}$ = flow rate going to last screen (1 gpm) of full-scale distribution ring
$Q_{Lab\text{-}S}$ = volumetric flow in laboratory-scale column

Using the full- and laboratory-scale flows in Table 3.2, the target volume of the laboratory-scale distribution ring is 24.0 cm^3. For the laboratory-scale column with an ID of 1.87 in. (see Table 3.2), the largest circular ring that could be accommodated did not give a volume this large. The design for the laboratory-scale distribution ring was to have an outer diameter of ~1.7 in. to give some clearance at the column wall. The diameter at the centerline of the planned 3/8-in. tubing is 3.37 cm (1.325 in.) ($DC_{Lab\text{-}S}$ = 1.7 – 3/8 in.) and the volume of the planned laboratory-scale distribution ring is given by

$$Vol_{Lab\text{-}S} = \pi \, DC_{Lab-S} \, AR_{Lab-S} \tag{3.9}$$

where

$Vol_{Lab\text{-}S}$ = volume (planned design) of laboratory-scale distribution ring
$DC_{Lab\text{-}S}$ = diameter of laboratory-scale distribution ring for determining ring circumference
$AR_{Lab\text{-}S}$ = cross-sectional area of 3/8-in. tubing in the laboratory-scale distribution ring

The volume of the planned laboratory-scale ring is 4.98 cm^3 and is included in Table 3.2. This volume is less than the target volume of 24.0 cm^3 but provided conservative (more likely) potential plugging behavior.

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[16] AVANTech drawing H-14-111255, Sheet 3, Rev. 1.

The vertical velocity in the pipe, or tubing, from the distribution ring upwards to the screens is important for matching the ability of the liquid to carry particles vertically. The scaling approach was to have the average vertical velocity in the laboratory-scale tubing, from the distribution ring to the screen, match the average vertical velocity in the full-scale system. For the full-scale system, the vertical pipe between the distribution ring and the screen is ½-in. Sch 40 SS[17] with an ID of 1.58 cm (0.622 in.) and the flow to the last screen was estimated to be 1 gpm (see Figure 3.3). The full-scale and target laboratory-scale vertical velocities are given by

$$V_{Vert,Lab\text{-}S} = V_{Vert,Full-S} = \frac{Q_{Vert,Full-S}}{A_{Vert,Full-S}} \tag{3.10}$$

where

$V_{Vert,\ Lab\text{-}S}$ = target average velocity in laboratory-scale distribution ring
$V_{Vert,\ Full\text{-}S}$ = average velocity in full-scale distribution ring
$Q_{Vert,\ Full\text{-}S}$ = vertical flow rate going to last screen (1 gpm) of full-scale distribution ring
$A_{Vert,\ Full\text{-}S}$ = cross-sectional area of ½-in. Sch 40 SS pipe connecting the full-scale distribution ring with the screen

Using the full-scale vertical flow rate to the screen of 1 gpm, the full-scale and target laboratory-scale vertical velocities are 32.2 cm/s and are included in Table 3.2.

The target ID for the laboratory-scale vertical tubing to give the target velocity is given by

$$D_{Vert,Lab\text{-}S} = \left(\frac{4}{\pi}\,\frac{Q_{Lab-S}}{V_{Vert,Lab-S}}\right)^{1/2} \tag{3.11}$$

where

$D_{Vert,\ Lab\text{-}S}$ = internal diameter (target) of laboratory-scale vertical tubing from ring to screen
$Q_{Lab\text{-}S}$ = volumetric flow in laboratory-scale column

Using the values in Table 3.2, the target ID of the vertical tubing in the laboratory-scale system was 0.293 cm (0.115 in.). With a wall thickness of 0.065 in., ¼-in. tubing provided a close match with an ID of 0.305 cm (0.120 in.). The average velocity in the laboratory-scale vertical tubing with this diameter is 29.7 cm/s. This was a close match to the target velocity of 32.2 cm/s. These values are included in Table 3.2. The full-scale exit screen assembly is the same as the inlet screens with ½-in. Sch 40 SS with an ID of 1.58 cm (0.622 in.).[18] Accordingly, the same ¼-in. tubing will be used at laboratory scale for the vertical exit from the bottom screen (see Figure 3.4 and associated discussion below).

The screens for the inlet and outlet of the laboratory column were selected to mimic, to the extent possible, the wedge-wire slotted screens on the inlet and outlet of the full-scale column as given in an AVANTech drawing.[19] For the laboratory-scale screen, the slot width (0.005 in.) and screen height (0.25 in.) matched the screens on the full-scale column. The wire in the laboratory-scale screen was #93 Johnson VEE-WIRE® with a width of 0.226 cm (0.089 in.) and is wider than the wire in the screen in the full-scale column (0.070 in.) but was the smallest wire width that could be used in fabricating the

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[17] AVANTech drawing H-14-111255, Sheet 3, Rev. 1.

[18] AVANTech drawing H-14-111255, Sheet 4, Rev. 1.

[19] AVANTech drawing H-14-111255, Sheet 3, Rev. 1.

laboratory-scale screen, according to the vendor (Johnson Screens, Aqseptence Group, Inc.). These values are given in Table 3.2. Figure 3.17 shows pictures of the assembled inlet and outlet screens.

The selected scaling approach for determining the target diameter of the laboratory-scale screen was to match the average velocity through the slots in the laboratory- and full-scale screens, because this matched the pressure loss through the screens and, correspondingly, the potential for particle collection and screen plugging. The average velocity through the slots is the flow rate divided by the open area of the slots. To match the average velocities, the open area of the laboratory-scale screen is as follows:

$$A_{Slot,Lab-S} = A_{Slot,Full-S} \left(\frac{Q_{Lab-S}}{Q_{Full-S}}\right) \tag{3.12}$$

where

$A_{Slot,\ Lab\text{-}S}$ = open area of slots in laboratory-scale screen
$A_{Slot,\ Full\text{-}S}$ = open area of slots in full-scale screen

The open area of the slots can be estimated from the number of turns of open slot for the screen height together with the circumference of the screens and the slot width as follows:

$$A_{Slot,Lab\text{-}S} = W_{Slot}\ \pi\ D_{screen,Lab-S}\ (\#Turns)_{Lab-S} \tag{3.13}$$

$$A_{Slot,Full\text{-}S} = W_{Slot}\ \pi\ D_{screen,Full-S}\ (\#Turns)_{Full-S} \tag{3.14}$$

where

W_{Slot} = slot width for both laboratory- and full-scale screens
$D_{Screen,\ Lab\text{-}S}$ = OD of laboratory-scale screen
$D_{Screen,\ Full\text{-}S}$ = OD of full-scale screen
$(\#\ Turns)_{Lab\text{-}S}$ = number of turns for laboratory-scale screen
$(\#\ Turns)_{Full\text{-}S}$ = number of turns for full-scale screen

Combining Eqs. (3.12) through (3.14) gives:

$$D_{Screen,Lab\text{-}S} = D_{Screen,Full-S} \left(\frac{Q_{Lab-S}}{Q_{Full-S}}\right) \left(\frac{(\#Turns)_{Full-S}}{(\#Turns)_{Lab-S}}\right) \tag{3.15}$$

The number of turns of open slot can be estimated by the ratio of screen height to the combined widths of the slot and wire as follows:

$$(\#\ Turns)_{Lab\text{-}S} = \left(\frac{H_{Screen}}{\left(W_{Slot} +\ W_{Wire,Lab-S}\right)}\right) \tag{3.16}$$

$$(\#\ Turns)_{Full\text{-}S} = \left(\frac{H_{Screen}}{\left(W_{Slot} +\ W_{Wire,Full-S}\right)}\right) \tag{3.17}$$

where

H_{Screen} = height of laboratory- and full-scale screen
$W_{Wire,\ Lab\text{-}S}$ = wire width for laboratory-scale screen
$W_{Wire,\ Full\text{-}S}$ = wire width for full-scale screen

Using the values in Table 3.2, the number of turns is 3.3 for the full-scale screen and 2.7 for the laboratory-scale screen that had a wider wire width. Using Eqs. (3.15) through (3.17) and the values in Table 3.2, the target diameter of the laboratory-scale screen was 0.228 cm (0.0896 in.). A screen of that small size could not be obtained from the vendor, so a screen with the smallest diameter available (~ 2 cm [0.8 in.]) was selected for use. The target and design diameters for the laboratory screen are given in Table 3.2. The design for the laboratory-scale screen had a lower average velocity through the slots, thus less pressure loss, and a larger open slot area. It was expected that this resulted in less potential plugging of the laboratory-scale screens in comparison to the full-scale system. Unfortunately, a more prototypic-sized laboratory-scale screen could not be fabricated by the screen vendor.

The same screen dimensions were used for both the inlet screen and exit screen for the laboratory-scale column; this is consistent with the design for the full-scale column. As discussed above, the inlet screen was attached to a scaled distribution ring. The exit screen, where particle deposition is not expected, did not have a distribution ring to simplify the design.

Figure 3.2 shows the position of the exit screens in the full-scale column, which has the screen assembly flush with the column bottom. Figure 3.4 shows the configuration of the exit screen for the laboratory-scale column, which had the screen flush with the column bottom and ¼-in. tubing carrying liquid from the screen to the column exit.

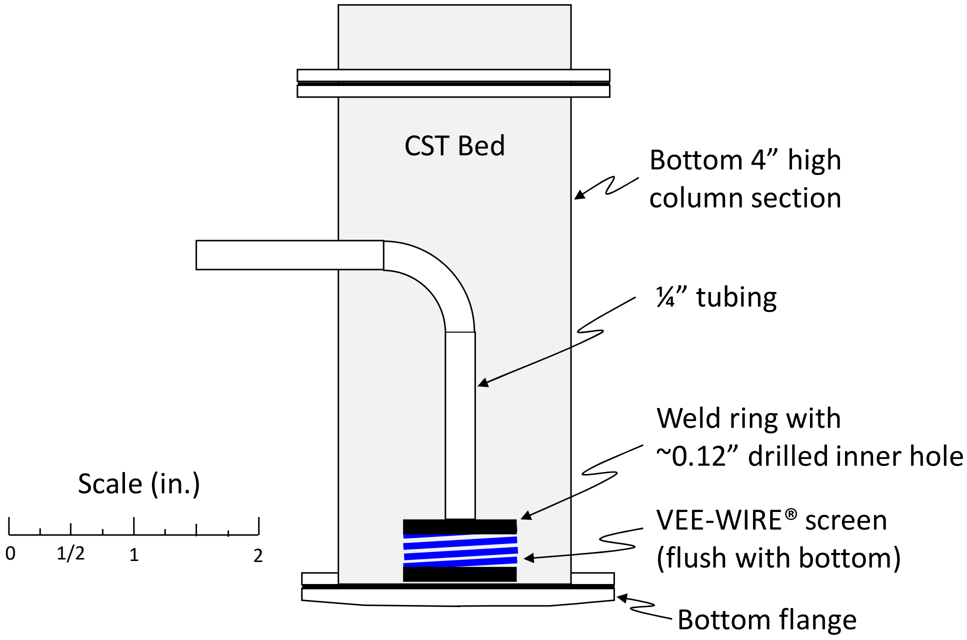

Figure 3.4. Configuration of the exit screen for the laboratory-scale column.

Figure 3.5 shows an expanded portion of the full-scale CST column (see Figure 3.2) focusing on the position of the upper (inlet) screens.[20] From a visual inspection of the drawing, the bottom of the VEE-WIRE® begins at about ½ in. above the top of the CST bed. The laboratory-scale inlet screen and distribution ring were positioned to also have the VEE-WIRE® begin at about ½ in. above the CST bed height. Figure 3.6 shows a schematic of the configuration of the inlet distribution ring and screen.

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[20] AVANTech drawing H-14-111250, Sheet 1, Rev 2. This schematic is a portion of that drawing.

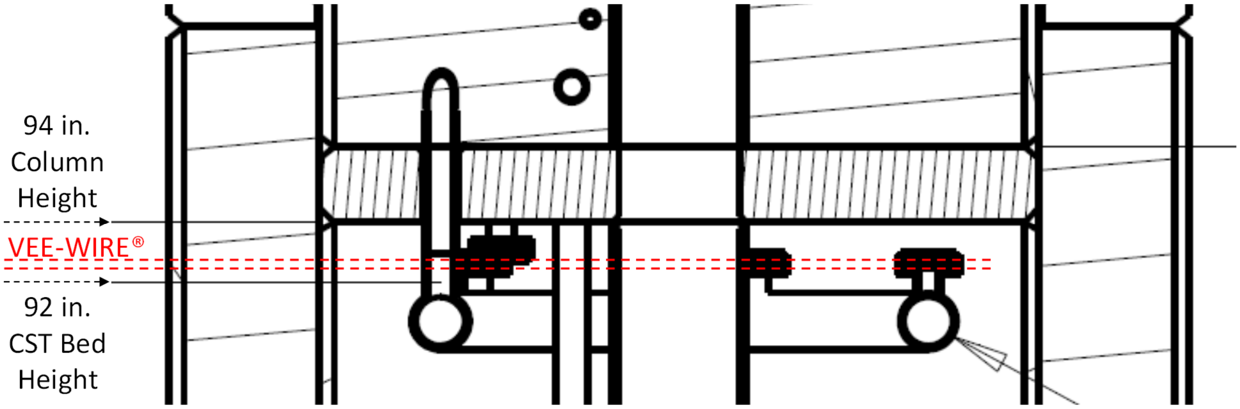

Figure 3.5. Estimated position of VEE-WIRE® interval compared with column height and bed height for the full-scale CST bed configuration showing column and settled CST bed heights and inlet distribution ring.[21]

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[21] AVANTech drawing H-14-111250, Sheet 1, Rev 2. This schematic is a portion of that drawing.

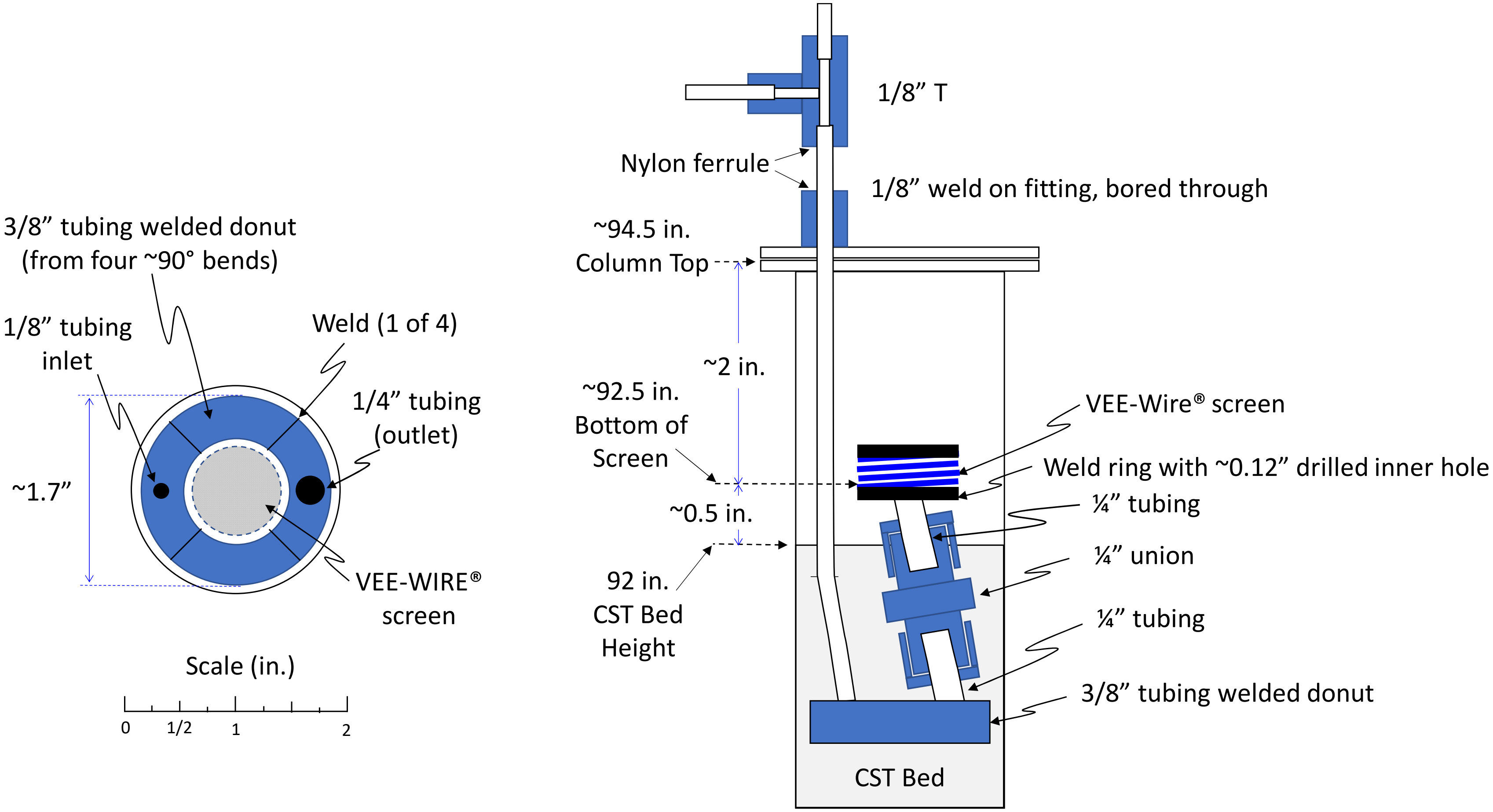

Figure 3.6. Configuration of the inlet distribution ring and screen for the laboratory-scale column.

3.4 Laboratory-Scale Filter and Feed System Scaling

The full-scale TSCR dead-end filters are pictured in Figure 3.7. The TSCR system has two identical units that will be operated in a cyclic manner: one filter actively filters the waste, while the other is either being backflushed, soaked, or on standby (Wilson 2019a). The filters swap roles if the initial pressure drop across the filter in use increases by 2 psid or every 24 hours, whichever comes first (Wilson 2019a). The laboratory-scale test system duplicated the dual-filter operating approach using an appropriately scaled pair of filters. The vertical orientation and flow path through the assembly shown in Figure 3.7 will also be used in the laboratory-scale system.

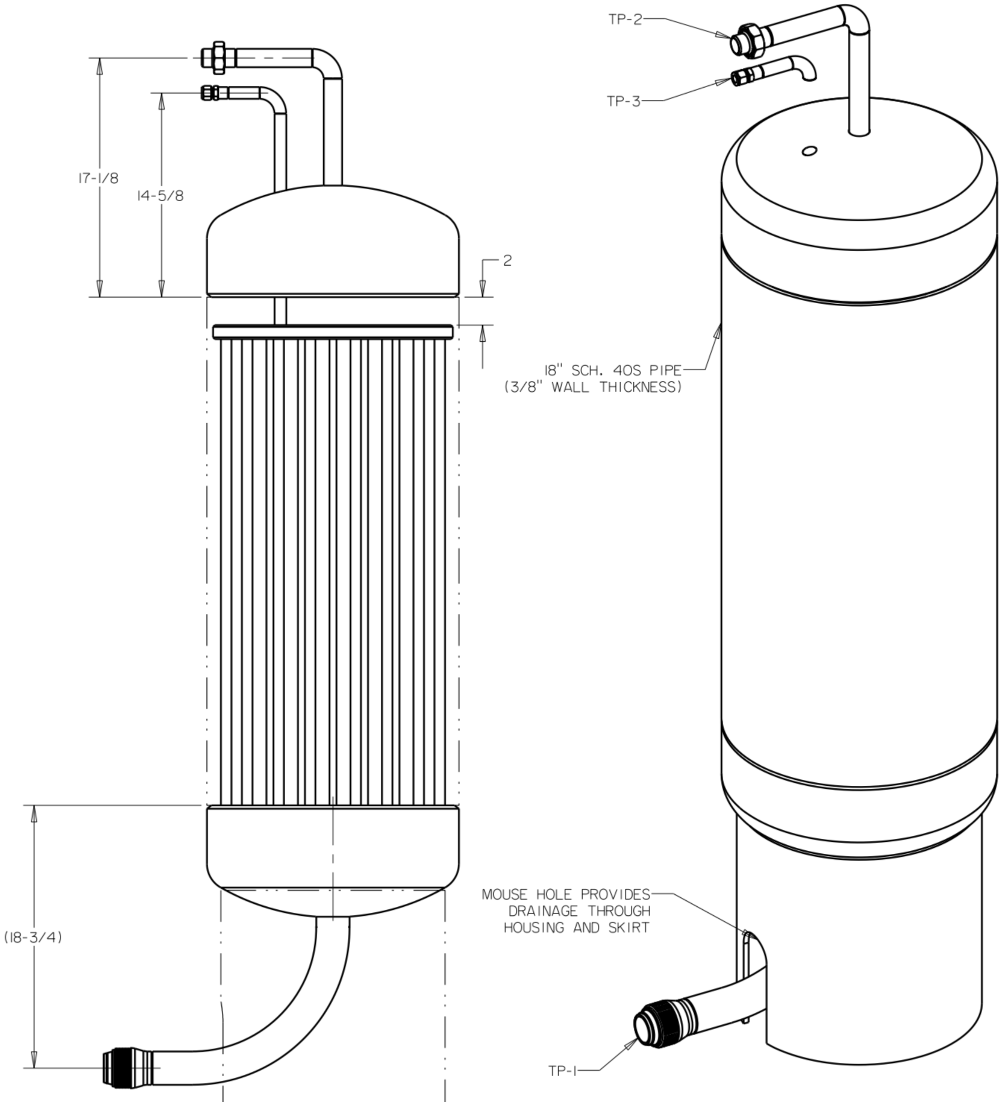

Figure 3.7. Side (left) and Isometric (right) Views of the TSCR Filter Assembly as Given in AVANTech Drawing H-14-111251, Sheet 2, Revision 2. This is only a portion of the original drawing. Note that the filter assembly is fed from the bottom with the filtrate leaving the assembly at the top.

As described in Section 3.3, the processing rate for the laboratory-scale system is defined by the ratio of laboratory-scale and full-scale IX column cross-sectional areas, i.e., matching the superficial velocity between the laboratory and full-scale columns and operating at essentially the same rate in terms of BV hr^{-1} (nominally ~1.9). This approach ignores the small difference in bed volumes between an IX column of constant cross-section (159.1 gal at full-scale) and the actual volume able to be packed with CST media due to excluded volume from internal components (157.5 gal at full-scale). The resultant difference in laboratory-scale flow rate is 1% (130.1 vs. 131.4 mL min^{-1}) and was considered to have negligible impact on the ion exchange performance. In addition, matching the superficial velocity was preferable for IX column hydraulic comparisons.

The processing rate of 0.0344 gal min^{-1} (130.1 mL min^{-1}) defined the required area for the filters in the laboratory-scale system, $A_{F,LS}$, via the following relationship:

$$A_{F,LS} = A_{F,FS}\left(\frac{Q_{Lab-S}}{Q_{Full-S}}\right) \tag{3.18}$$

where $A_{F,FS}$ is the filter area in the full-scale system (76.97 ft^2). The resultant value for $A_{F,LS}$ using Eq. (3.18) is 0.529 ft^2. The full-scale TSCR filter assembly consists of 98 tubes of 1-in. outer diameter (OD) and a length of 36 in. To avoid differences in performance due to the curvature of the filter tube used, a tube of 1-in. OD was selected for the laboratory-scale filters. Thus, the length of the tube(s) is defined by

$$L_{F,LS} = \left(\frac{A_{F,LS}}{n\pi D_F}\right) \tag{3.19}$$

where $L_{F,LS}$ is the tube length, n is the number of tubes, and D_F is the filter outer diameter. To simplify the fabrication of the laboratory-scale filters, n was chosen to be 1, which resulted in a tube length of 24.3 in. The target value for the porous tube length was rounded up to 24.5 in. to allow for the potential of porous length being lost from the welding process near both ends of the filter tube.

The shell of the laboratory-scale filter assembly was scaled to reproduce a matched "annular" velocity between the porous surface and the wall as would be present in the full-scale geometry (refer to Figure 3.8 for the tubesheet configuration in TSCR), i.e., $U_{F,an}$. Selecting the annular velocity as the basis for the shell size approximately maintained the characteristic shear (which is responsible for particle re-suspension and interaction of solids with the filter surface/cake surface) between the full-scale filter array and the single-tube laboratory-scale filter. The full-scale geometry has n = 98 tubes, with the annular velocity $U_{F,san}$ defined by the ratio of open area in the tube sheet to the cross-sectional area in the shell. Note that the TSCR shell ID is 18 inches, but the tubesheet diameter (D_{TS} = 16.41 inches) was used to compute the characteristic velocity. This has the consequence of ignoring the region outside of the tubes on the perimeter of the tubesheet. The perimeter tubes have a larger distance between them and the shell wall than most other (interior) tubes that have several tubes neighboring or surrounding them. Strictly speaking, using the tubesheet diameter as a basis means that the laboratory-scale filter was a better proxy for the filter behavior of the non-perimeter porous tubes (though the differences are likely not significant) because the perimeter tubes likely have reduced shear rates on some or all of their surfaces.

As just described, the laboratory-scale shell diameter $D_{Shell,LS}$ can be established by the following two expressions:

$$U_{F,an} = \left(\frac{Q_{Full-S}}{\frac{\pi}{4}\left[{D_{TS}}^2 - n{D_F}^2\right]}\right) \tag{3.20}$$

$$D_{Shell,LS} = \left(\frac{4Q_{Lab-S}}{\pi U_{F,an}} + {D_F}^2 \right)^{1/2} \tag{3.21}$$

The superficial velocity was solved-for in Eq. (3.20) and inserted into Eq. (3.21) to give a result of ~1.48 inches. Based on that analysis, a filter shell ID of 1.5 in. was selected as the target size for the laboratory-scale filters.

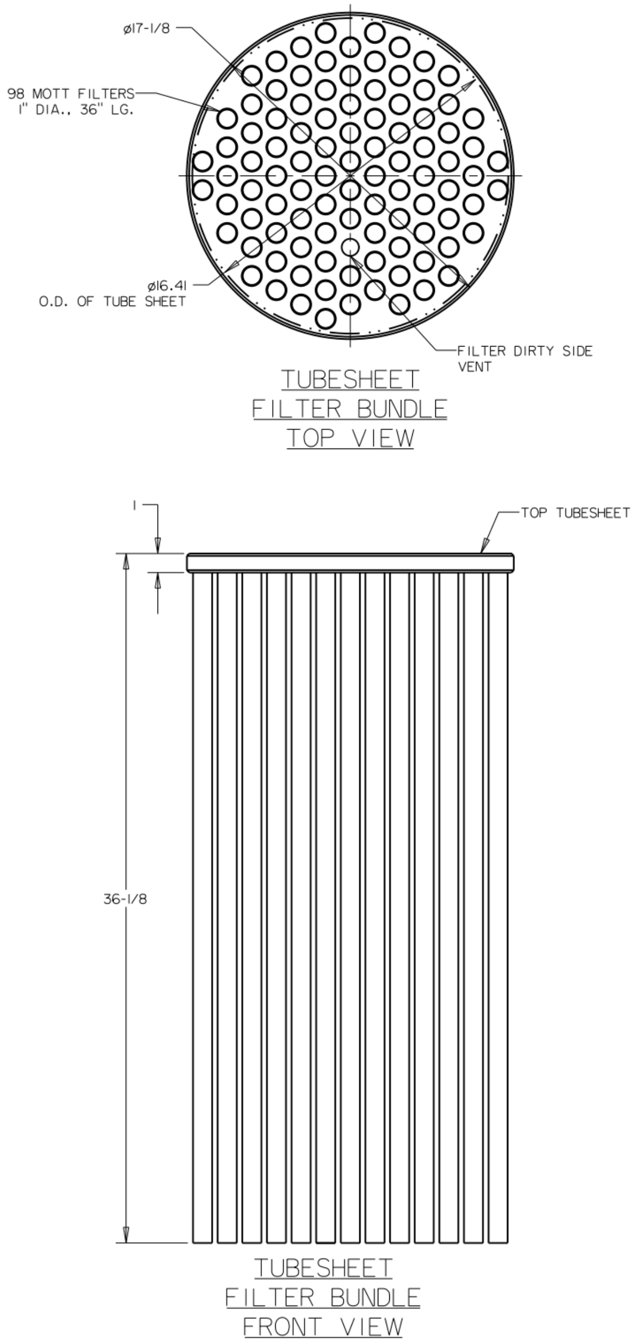

Figure 3.8. Tubesheet Assembly for the TSCR filters as Presented in AVANTech Drawing H-14-111251, Sheet 2, Revision 2. This is only a portion of the drawing.

The configuration of the laboratory-scale filter assembly based on these scaled parameters is shown in Figure 3.9. The filter used the same Mott Grade 5 sintered stainless steel filter media used in the TSCR filters. The target shell size was readily achieved with 1.5-in. Sch 80 steel pipe, which had an ID of 1.5 in. Once the porous tube was welded to a bored-through flange as shown, its position in the shell created an annular gap around the porous surface of approximately 0.25 in. The Mott porous tube had a single 4-in. non-porous section at the top of the filter; the length of the non-porous section was not selected to satisfy any dimensional consistency with the full-scale filter; however, a non-zero distance between the porous area and the top of the shell was expected to prevent significant solids impaction on the bottom surface of the flange. The distance the porous tube stands off the shell bottom was not considered critical to specify, but it was selected to be at least as large as the annular distance and was minimized as much as practical to reduce the probability that solids settle out in the shell. Although it is not shown, for Test HS1 and subsequent tests, the shell was vented to assist with filling it with flush/rinse fluid during operations. The filtrate from the filter was fed directly into the IX column discussed in Section 3.3.

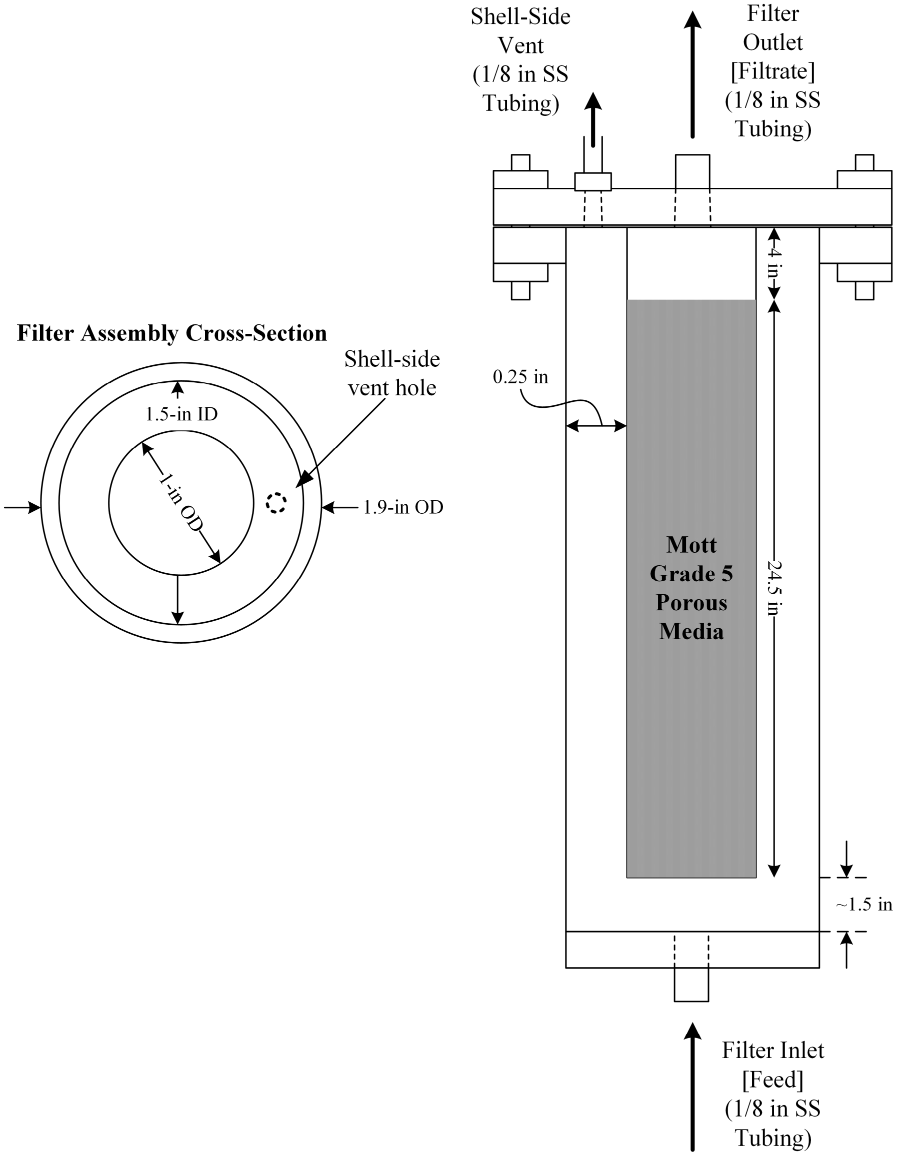

Figure 3.9. Diagram of the Laboratory-Scale Filter Configuration. The shell-side vent was added for Test HS1 and subsequent tests to assist with operations.

The process by which feed was supplied to the laboratory-scale filters had a series of considerations that are discussed in the remainder of this section. Important considerations included (1) creating sufficient mixing energy in the feed vessel, (2) avoiding settling of solid particles in process lines, (3) minimizing the variation in feed temperature, and (4) feeding a pseudo-homogeneous suspension of particles to the filter assembly.[22] In conceiving a feed approach for the laboratory-scale test system, it was preferred to have a similar approach to that used at full-scale. The advantage of keeping the feed system as prototypic as possible is that it reduces the potential attribution of test data abnormalities to the differences in feed approaches between laboratory- and full-scale.

Therefore, the feed strategy selected for testing was to reproduce (as much as practical) the TSCR approach as shown in Figure 3.1, where supernatant from a feed tank is pumped through a recirculation line back to the feed tank and a smaller-flow slip stream provides feed to the filters and IX columns. For the laboratory-scale system, the feed vessel also had a recirculation loop of significantly higher flow rate and larger-diameter tubing with a smaller-diameter, smaller-flow slip stream taken from the recirculation loop as the process feed line to the filters and IX column. The feed line supplied the required pressure for the entire system and removed only a fraction of the total recirculation flow. In the laboratory-scale system, the recirculation line also imparted mixing energy into the feed vessel. Based on observations during testing, the recirculation return appeared to keep the solids suspended; this was performed using a return line terminating in a horizontally-oriented line on a pivot that rotated in the vessel bottom (pictured in Figure 3.10). The horizontal line had a nozzle on its end to enhance local volumetric flow and “drive” the pivot arm around the tank bottom via the thrust provided by the recirculating flow. This device is referred to as the “pivot nozzle mixer” for short. A second, open-ended recirculation return line that ended near the tank bottom (also pictured in Figure 3.10) was used when the simulant level became low, to limit the amount of air entrainment into the suction of the recirculation line. If it was insufficient, a second recirculation line dedicated to mixing (or a mechanical agitator) could be added. The recirculation line configuration is illustrated with some additional details in Figure 3.11, along with the slip stream approach for the testing that is discussed in more detail later in the section.

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[22] The term “pseudo-homogeneous” is intended to imply that the solids concentration was approximately constant so that significant “slugs” of solids are not passing through the system. However, some variation can be tolerated and, if present, was likely more representative of full-scale processing.

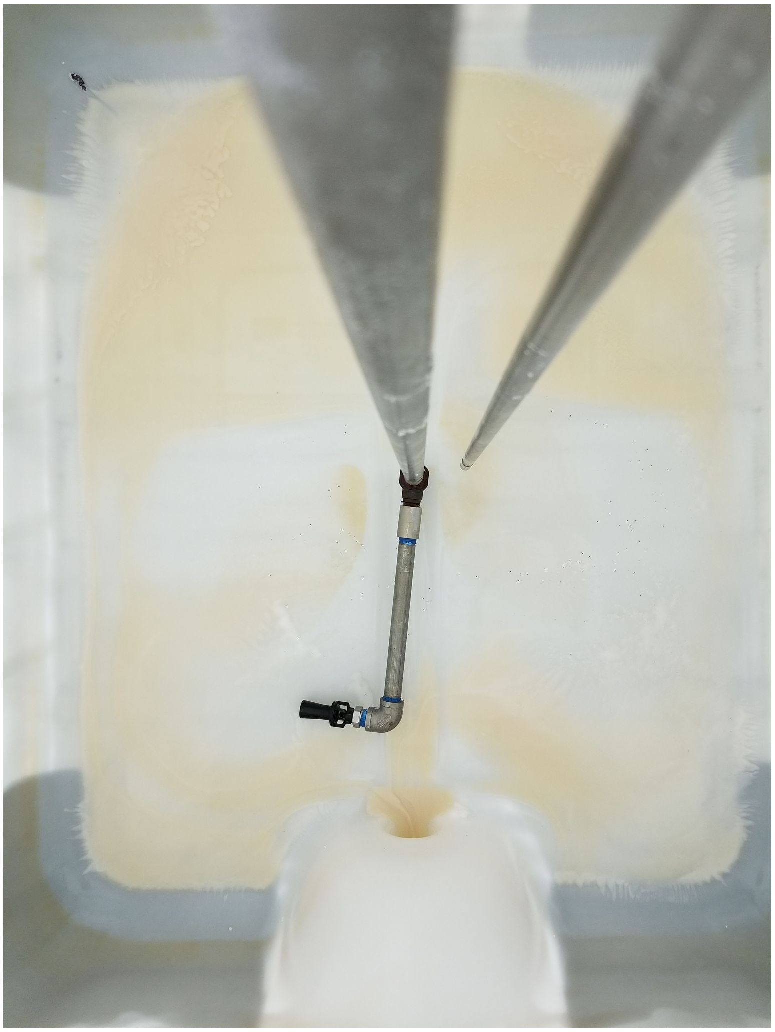

Figure 3.10. Image of Recirculation Return Lines Looking Down into TK-01 (Laboratory-Scale System Feed Vessel). The “pivot nozzle mixer” return line is shown at rest, with the second return line just to its right in the image.

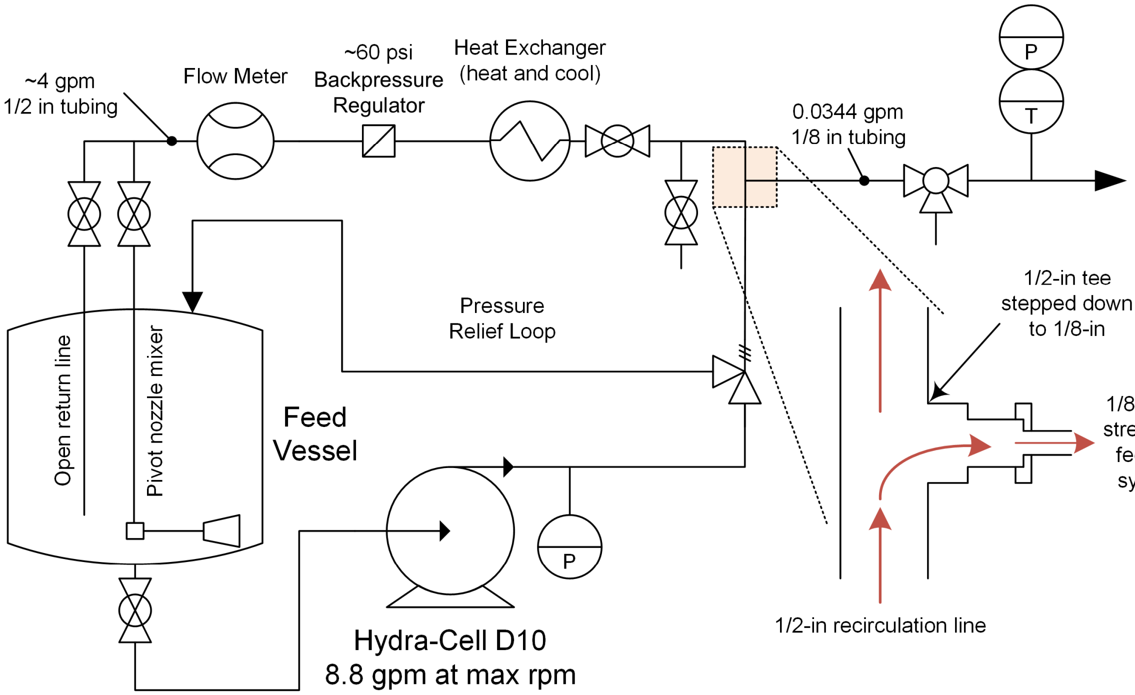

Figure 3.11. Schematic of Laboratory-Scale Feed System Configuration and Equipment.

The recirculation loop had a backpressure regulator to set the system feed pressure. During test operations, a set-point of at least 60 psig was used because the feed pressure needed to be high enough to exceed the summation of pressure drop across the active dead-end filter, the IX column, the flow control system, and all the valves, fittings, and process piping. The loop also had a heat exchanger/water bath to control feed temperature, which was nominally targeted for 22 °C. In the full-scale TSCR system, it is expected that the temperature in the feed tank (AP-107) will remain relatively constant; controlling the temperature in the laboratory-scale system was intended to mimic the anticipated temperature control strategy of the full-scale system. The heating/cooling capacity was in place to both reduce the possibility of unrepresentative phase changes in the simulant and avoid changes in feed temperature over the test period (from pump heat not being removed or fluctuations in ambient conditions).

Determining the process line size for the slip stream/process feed line was dominated by selecting a size most likely to avoid settling in the line before the suspension reaches the filter, which would result in unrepresentative test data being collected. The goal for the laboratory-scale system was to obtain a ratio of the average velocity $U_{i,PL}$ to the predicted critical velocity $U_{Crit,i}$ on the same order as the full-scale system, i.e.,

$$\left(\frac{U_{LS,PL}}{U_{Crit,LS}}\right) \approx \left(\frac{U_{FS,PL}}{U_{Crit,FS}}\right) \tag{3.22}$$

where subscript *i* has been replaced with *LS* (laboratory-scale) or *FS* (full-scale) as appropriate. The full-scale ratio became fixed once a critical velocity prediction method was selected. In this case, the recommendations of Wells et al. (2011) were followed, and three approaches were applied: (1) Thomas (1979), (2) Wasp and Slater (2004), and (3) Poloski et al. (2009). These three models are all appropriate for turbulent deposition – the TSCR process feed line has a Reynolds number (computed as defined in

Eq. (3.5)[23]) of approximately 1.0×10^4 – but each model depends on slightly different underlying physical parameters.[24] Using these three approaches and some bounding values for the physical parameters of the test simulant, the ratio on the right-hand side of Eq. (3.22) varied from 2.6 to 10.3.

Unfortunately, a direct comparison using the same critical velocity methods was not possible for the laboratory-scale system due to its relatively low processing flow rate. For tube diameters of 1/8 in. and larger, the flow is laminar. Using a tube smaller than 1/8 in. had structural and assembly concerns that are separate from the critical velocity issue, so smaller tubes were not considered. Thus, the critical velocity prediction method used was from Gillies et al. (2007), as related by Poloski et al. (2009), with adaptation by Bbosa et al. (2017). Gillies et al. stated that settling in a laminar flow of suspension would be greatly reduced when $\alpha > 60$ and nearly eliminated when $\alpha > 100$, with α defined by

$$\alpha = \frac{\tau_w}{\tau_p} = \frac{\left(\frac{8U_{crit}\mu_L}{D_t}\right)}{\left(\frac{(\rho_s - \rho_L)gd_p}{6}\right)}; \tag{3.23}$$

where

α = critical velocity parameter
τ_w = wall shear stress (as shown, written for tube flow)
τ_p = average surficial particle shear stress
ρ_s = density of solid particles
d_p = diameter of solid particles
g = acceleration due to gravity
D_t = diameter of the tube

Based on representative values for the parameters in Eq. (3.23), U_{crit} was solved-for as a function of D_t for $\alpha = 60$ and 100.[25] It was found that a value of $D_t = 0.069$ in. (0.18 cm) gave ratios of 2.7 and 4.6, which were consistent with the range for the turbulent-based TSCR system estimates. This represents a tube diameter of a 1/8-in. diameter SS tube with a 0.028-in. wall. Increasing the line size to 1/4-in. diameter tubing resulted in velocity ratios [Eq. (3.22)] that are < 1; this indicated a high risk of settling so 1/8-in. tubing was selected as the laboratory-scale process line diameter. During testing, samples taken from the process feed line were assessed to detect any significant accumulation of solid particles upstream of the filters over time, although feed line plugging was often a more obvious indicator of trouble.

With the process line size defined (1/8-in. diameter tubing) to minimize impacts of settling during test operations, another important consideration was the ability of the recirculating suspension to be appropriately "sampled" by the process feed line. The full-scale system contains a 1.61-in. ID recirculation loop flowing at about 60 gpm with a 0.622-in. ID feed line flowing at 5 gpm (see reference

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[23] Calculated with the substitutions of $U_{FS,PL}$ (= 1.61 m s^{-1} based on a 5 gpm flow) for $V_{Full\text{-}S}$, and $D_{Full\text{-}S}$ = 0.622 in. (0.016 m), which is the inner diameter of the process line (0.5-in. Sch 40 pipe) for TSCR.

[24] Note that Wasp and Slater's model depends on a d_{95} for the solid particles, which was assumed to be 30 µm. Their model is also solids-concentration-dependent, so a value of 1.5 wt% was used (the upper limit for TSCR and this testing) and converted to a volume concentration.

[25] For this calculation: liquid viscosity (μ_L) = 0.003 Pa s; liquid density (ρ_L) = 1250 kg m^{-3}; solid density (ρ_s) = 4000 kg m^{-3}; and particle diameter (d_p) = 10 µm. These values are all reasonably representative of the test simulants for the critical velocity evaluation and were also more conservative than the nominal liquid properties given by Ard (2019) that were used with Eqs. (3.5) and (3.6).

drawing H-14-111242, Sheet 1, Rev. 2). Where these lines meet, the ratio of cross-sectional areas is ~7.[26] For particles to make the "turn" at the tee junction of these lines and be fed to the filter, the characteristic relaxation time τ_r of the particle as it travels in proximity to the relevant capture dimension (the process line opening at the tee) needs to be dominated by the local convective time τ_c of that capture dimension. This is the Stokes number *St*, defined as

$$St = \frac{\tau_r}{\tau_c} = \frac{\left(\frac{\rho_s {d_p}^2}{18\mu_L}\right)}{\left(\frac{D_t}{U_{i,RL}}\right)} = \left(\frac{U_{i,RL}\rho_s {d_p}^2}{18\mu_L D_t}\right) \tag{3.24}$$

where $U_{i,RL}$ is the velocity in the recirculation line at scale *i*. In some representations of *St*, the relaxation time of the particle is dependent on the density difference ($\rho_s - \rho_L$); in Eq. (3.24) only ρ_s is used, which was conservative. The Stokes number as defined in Eq. (3.24) is consistent with its use in slurry flow work studying solids distribution in tee junctions (see Nasr-El-Din et al. 1989, 1992). The Stokes number is ~1.3×10^{-3} for particles that have a bounding density (4,000 kg/m^3) and nominal particle size (diameter of 10 μm) for the TSCR system, which are the more difficult particles to make the turn into the side stream at the tee. Particles that are significantly larger than 10 μm are of less interest because they will be readily filtered out and are unlikely to break through the filter.

The requirements for the laboratory-scale recirculation loop were to achieve turbulence and generate the feed pressure, which required a significant amount of flow and pumping power. Turbulence was expected to keep solid particles well-suspended and promote mixing in the feed vessel. Matching the cross-sectional area ratio of the TSCR system was challenging to do while accommodating the pump power and flow needed in the laboratory-scale recirculation line. For a flow rate of about 4 gpm in the ½-in. recirculation line, the linear velocity (and thus, the Reynolds number) is similar between the laboratory- and full-scale systems (full-scale $Re = 4.8\times10^4$, laboratory-scale $Re = 1.3\times10^4$); for this reason, a target recirculation rate of 4 gpm was preferred. For the ½-in. ID recirculation line, the ratio of cross-sectional areas is ~34.[27] However, if a similar configuration was used in the laboratory-scale test system with a recirculation flow of ~4 gpm in ½-in. tubing and a flow of 0.0344 gpm taken from a tee in the line, the Stokes number for turning at the tee is ~1.3×10^{-2}.

The critical value for the Stokes number varies in the multiphase flow literature and is geometry sensitive. Relevant work on particles turning around cylinders or 90-degree elbows suggest that particles turn corners without impacting the wall if $St < 1/16$ (~0.06) (Friedlander 1977), $St < 0.05$ (Brown 2002), $St < 1/12$ (~0.08) (Russel et al. 1989), or $St < 0.01$ (Brandon and Aggarwal 2001).[28] The most relevant studies applicable to the current situation are the work of Nasr-El-Din and Shook (1986), Nasr-El-Din et al. (1989), and Nasr-El-Din et al. (1992). Their studies are concerned with slurry flow in tee junctions. Though the particle sizes and solids concentrations used in the experimental work were larger than the values expected of the laboratory-scale testing simulant, Nasr-El-Din et al. (1992) concluded that small Stokes numbers will result in a "branch concentration ratio approach[ing] unity"[29] because the inertial forces are negligible and particle streamlines coincide with fluid streamlines. Nasr-El-Din et al. (1989)

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[26] As calculated by: Ratio = (1.61 in./0.622 in.)^2.

[27] As calculated by: Ratio = (0.402 in./0.069 in.)^2.

[28] The *St* numbers calculated here for the laboratory-scale system approximately satisfy all these criteria – though these criteria were either developed based on gas-solid flows or Stokes flow, i.e., low Reynolds number.

[29] Meaning that the concentration of solids downstream of the branch of the tee, i.e., the portion of the flow that has to make a 90-degree turn, is similar (or even identical) to the concentration of solids in the stream downstream of the straight-through part of the tee.

tested systems down to a Stokes number of 0.06 and measured a branch concentration ratio of about 0.85 for an upward branch in a horizontal line with a similar flow ratio to the proposed laboratory-scale system. Thus, it would be expected that Stokes numbers closer to 0.01 would improve on that concentration ratio. Given that both the full- and lab-scale systems have similar Stokes numbers that are on the order of 0.01 or less, the qualitative expectation based on a survey of available literature was that the side (process feed line) streams should each get a representative quantity of slurry particles in the recirculation line in both systems. Even conservative physical parameters (μ_L = 4 cP, d_p = 30 μm) still result in $St < 0.1$ for both geometries.

In summary, Table 3.3 compares all the various parameters relevant to the feed system configuration that have been discussed in the preceding paragraphs. The laboratory-scale dimensions listed represent the design values for system assembly. Because the recirculation line flow rate was important to establish at approximately 4 gpm (assumed in most calculations), the line had the ability to throttle the flow using ball valves and contained a flow meter (see Figure 3.11) so that the recirculation flow could be established at or near the target during operations.

Table 3.3. Comparison Between Laboratory-Scale and Full-Scale Feed System Parameters.

Parameter	Laboratory-Scale	Full-Scale (TSCR)
Recirculation line size	½-in. SS tubing (0.402 in. ID)	1.5-in. Sch 40 pipe (1.61 in. ID)
Recirculation line flow rate	4.0 gpm [target]	58.2 gpm
Recirculation line average velocity	3.1 m s^{-1}	2.8 m s^{-1}
Recirculation line *Re*	1.3×10^4 [fully turbulent]	4.8×10^4 [fully turbulent]
Process feed line size	1/8-in. SS tubing (0.069 in. ID)	0.5-in. Sch 40 pipe (0.622 in. ID)
Process feed line flow rate	0.034 gpm	5.0 gpm
Process feed line average velocity ($U_{i,PL}$)	0.9 m s^{-1}	1.6 m s^{-1}
Process feed line *Re*	6.6×10^2 [laminar]	1.1×10^4 [fully turbulent]
Critical velocity ($U_{Crit,i}$) prediction method(s) used	Gillies et al. (2007)/Bbosa et al. (2017) with α = 60, 100	Thomas (1979) Wasp and Slater (2004) Poloski et al. (2009)
Ratio of $U_{i,PL}/U_{Crit,i}$	2.7 (α = 60) 4.6 (α = 100)	2.6 4.2 10.3
Stokes Number (recirculation line/process feed line tee)	1.3×10^{-2}	1.3×10^{-3}

3.5 System Overview, Equipment, and Instruments

This section summarizes the configuration of the test system and some of the key equipment that was used for the high-solids filtration and IX testing using waste simulants that had a range of solids concentrations. The general approach for the tests was to prepare a waste simulant with a target concentration of solids and then pump the simulant through a recirculation loop. A slip or sample stream from the recirculation loop, with the solid concentration nominally constant over the duration of the test, served as the feed to the separation technologies consisting of a filtration unit and a full-height CST column. The filtration step consisted of a pair of filters to allow prototypic switching, done manually by test operators, between individual filters and cleaning of the filter that is not currently in use (these processes are described in more detail in Section 5.2.3). The filters were instrumented with pressure transducers to monitor the pressure difference across the filter in use and to determine when to switch filters. The CST column also had pressure transducers to determine the pressure drop across both the overall column and the inlet section of the column. The system was operated at a fixed flow rate via a flow controller after the column, so any increase in filtration resistance or deposition of solids in the IX column was exhibited as increased local measured pressure drops.

The separation technologies in the system were designed to be examined between tests if needed. The filter assemblies could be taken apart to examine the porous media (see Figure 3.9) and to thoroughly clean the filters between tests. The full-height IX column was assembled from multiple sections of 2-inch outer diameter SS sanitary tubing with tri-clamp/O-ring connections. The individual sections could be taken apart at the conclusion of a test for collection of post-test samples or observation as required; this also facilitated the removal of used CST after the test so it could be replaced with fresh CST for the next test. If CST bed plugging was indicated by an increase in pressure drop along the column, or if visual inspection of the top of the CST bed after testing showed a layer of fines, samples of the fines and CST were collected from the individual column sections for characterization. In these tests, the only characterization that was performed was visual observation of CST particles under an optical microscope.

3.5.1 System Components and Configuration

Figure 3.12 shows the key components and flow configuration of the test system. All the major equipment and valves are shown in the schematic; note that this is the system as it was at the end of testing.[30] Nearly all the tubing used, except where indicated in Figure 3.12, was SS. Polymer lines (polytetrafluoroethylene) were only used at the short discharge sections to TK-03 and TK-04 and for the suction line to PMP-01. All valves and fittings were also constructed of SS. Table 3.4 lists all the various component and instruments shown in Figure 3.12 with some accompanying description. During test operations, the elements in Table 3.4 were assigned unique identifiers for use in procedure development and refinement, i.e., safe operating procedure(s), Test Instructions, etc. These identifiers are used throughout the report when referring to equipment or valves for convenience.

Note that one concern during operations was potential line plugging, both at the inlet to the 1/8-in. tubing that is attached with a “T” to the recirculation line and in the tubing running to the filters. Components were available (but not permanently installed and thus not shown in Figure 3.12) to flush the 1/8-in. tubing from the “T” on the recirculation line to the filters. Flushing these lines could also be accomplished using PMP-02 by flowing backwards toward V-02 as warranted.

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[30] The system was modified slightly after Tests NB1 and HS2 for operational convenience. These changes, which are described in Section 5.3, were to minor functions of the system and did not impact the scaling or process functions of the system.

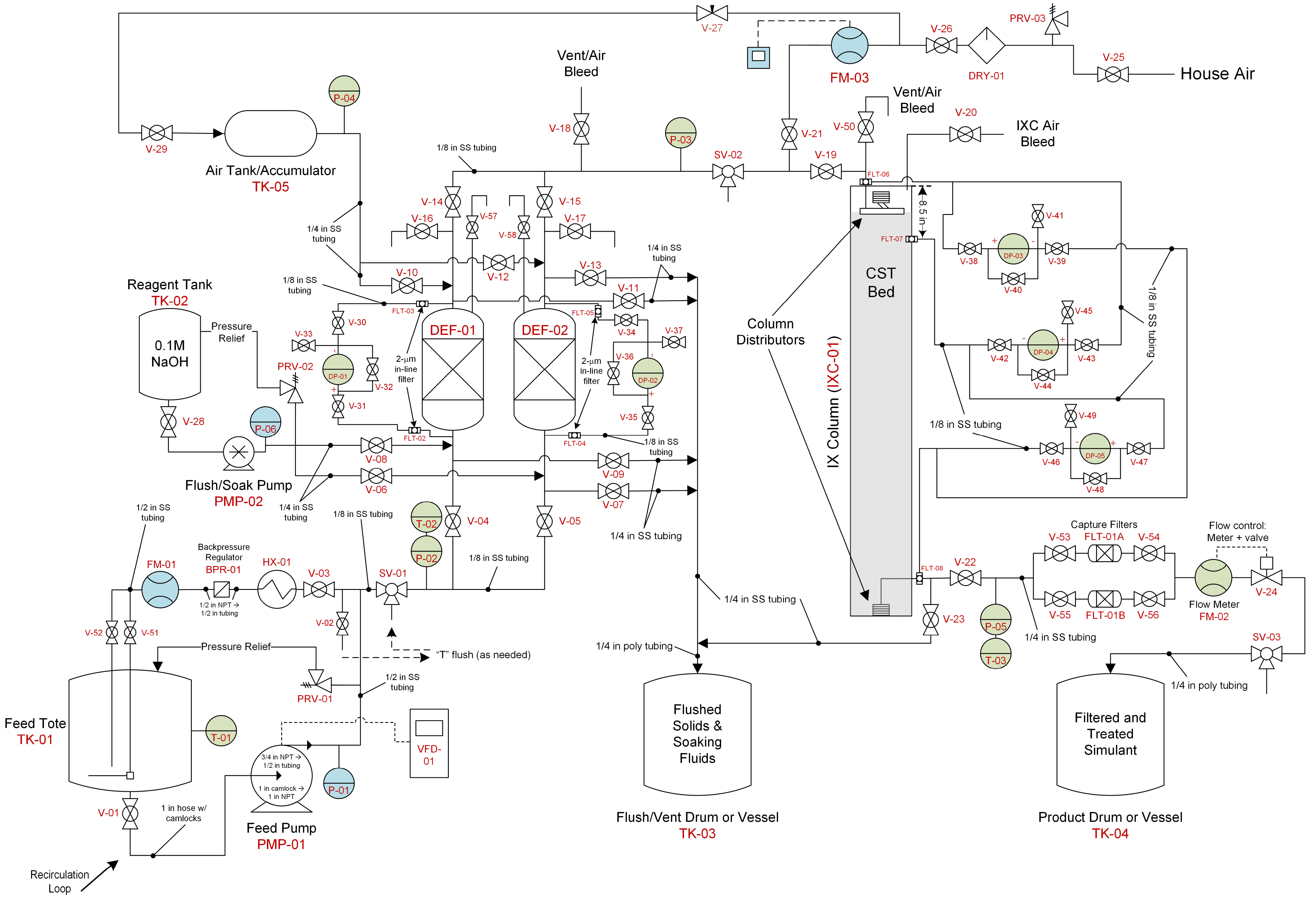

Figure 3.12. Test System and Instruments for Conducting the High-Solids Filtration and IX Tests as Configured at the End of Testing. Green color designates calibrated instruments and associated measurements, i.e., those that are quality-affecting; instruments/measurements colored in blue are "For Information Only" (FIO) and were present as operator aids.

Table 3.4. Components and Instruments for High-Solids Filtration and IX Test System (labels are used in Figure 3.12).

Instrument/Component	Label	Description / Location
Validyne P55 Differential Pressure Transducers	DP-01	Differential pressure across filter DEF-01
	DP-02	Differential pressure across filter DEF-02
	DP-03	Differential pressure from column inlet to exit
	DP-04	Differential pressure from column inlet to 6 in. from the top of the CST bed
	DP-05	Differential pressure from 6 in. from the top of the CST bed to the column exit
Hydra-Cell D10 Feed Pump	PMP-01	Pump for recirculating simulant with suspended solids and mixing and suspending solids in feed tote
Cole-Parmer 7521-70 Digital Gear Flush/Soak Pump	PMP-02	Pump for supplying 0.1 M NaOH to test system (up to ~300 mL min^{-1} based on installed gear drive)
Omega KHSS-316G-RSC-12 Thermocouples w/ Fluke 52II Digital Reader	T-01	Temperature in simulant feed tote
	T-02	Temperature of simulant in flow line upstream of filters
	T-03	Temperature of simulant in flow line downstream of column
Swagelok PGI-PG160 Pressure Gauge	P-01	Gauge pressure at discharge of feed pump PMP-01 (FIO/operator aid)
Ashcroft DG25 Pressure Transducers	P-02	Gauge pressure upstream of filters
	P-03	Gauge pressure downstream of filters/upstream of column
Swagelok PGI-63B-PG100 Pressure Gauge	P-04	Gauge pressure at air tank/accumulator
Ashcroft DG25 Pressure Transducer	P-05	Gauge pressure downstream of column
Swagelok PGI-PG100 Pressure Gauge	P-06	Gauge pressure at discharge of PMP-02 (FIO/operator aid)
Swagelok SS-4R3A Pressure Relief Valves	PRV-01, PRV-02	Simulant recirculation line and 0.1 M NaOH flush line over-pressure relief
ifm SM6001 Magnetic Flow Meter	FM-01	Flow meter on simulant recirculation line to TK-01 (FIO/operator aid)
Bronkhorst ES-FLOW Ultrasonic Liquid Flow Meter/Controller	FM-02 with V-24	Flow meter and actuated control valve for maintaining desired flow
Brooks SLAMF50S Mass Flow Controller	FM-03	Mass flow controller for supplying dry air to column inlet (FIO/operator aid)
PNNL-assembled Filter Assemblies using Mott Grade 5 Porous Tube	DEF-01, DEF-02	Duplicate dead-end filters that can be swapped between in-use and offline during processing
Swagelok SS-4F-2 2-μm Inline Filters	FLT-01A, FLT-01B	Inline guard filters (swappable) at column exit
PNNL-assembled Sanitary Tubing CST Column	IXC-01	Full-height IX column with CST bed within column; assembled out of sections of tri-clamped sanitary tubing
275-gal IBC Tote for Feed Tank/Vessel	TK-01	Large vessel tote for mixing and feeding simulant
5-gal Poly Reagent Tank/Vessel	TK-02	Tank for holding 0.1 M NaOH or other flush fluids, i.e., water
55-gal Poly Drum Flush Tank	TK-03	Tank for receiving flushed solids and other miscellaneous waste

Instrument/Component	Label	Description / Location
55-gal Poly Drum Product Tank	TK-04	Tank for receiving processed waste simulant (Cs-decontaminated)
Swagelok 316L-HDF4-500 Air Tank/Accumulator	TK-05	Scaled (0.5 L) volume tank with compressed air during filter cleaning
Swagelok BSN4-02-2-NNP Backpressure Regulator	BPR-01	Backpressure regulator to control pressure at inlet to filters and test system
Exergy AS-00528 Tube-in-Tube Heat Exchanger	HX-01	Heat exchanger to heat or cool simulant in recirculation line to maintain target temperature; plumbed to water bath (Fischer Scientific Isotemp® 4100)
Parker DAS 3NPT Air Dryer	DRY-01	Dryer to provide low-humidity air to IXC-01 to blow out moisture at test end
Honeywell NX20200A1002 Variable Frequency Drive	VFD-01	Variable frequency drive for controlling PMP-01 speed
Swagelok SS-42GXS4 Sample Ports	SV-01, SV-02, SV-03	Sampling locations at filter inlet, filter exit/column inlet, and column exit

Because the differential pressure (DP) instruments were critical for fulfilling the objectives of the testing, each of the pressure lines connected to the DP transducers for the flow system or column had inline filters to minimize any particles entering these lines. For DEF-01 and DEF-02, these filters (FLT-02, -03, -04, and -05) were Swagelok SS-2F-2 inline filters (1/8 in. tubing, 2-µm pore size) and were installed as provided by the manufacturer on the pressure lines as close to the measurement point as possible. For the DP lines at the inlet and exit of the column, a Mott porous frit (0.062 in. thick, 0.25 in. diameter, Grade 100, SS) was inserted into a Swagelok fitting (1/4-in. to 1/8-in. reducer, SS-400-R-2) as shown in Figure 3.13 (FLT-06 and -08). For the one pressure port on the column, a Mott porous frit (0.062 in. thick, 0.25 in. diameter, Grade 100, SS) was welded into a Swagelok pipe weld fitting (1/8 in. tube, 1/8 in. pipe weld, SS-200-1-2W) as show in Figure 3.14 (FLT-07). This fitting was welded to the column with the porous frit flush with the inside of the column wall.

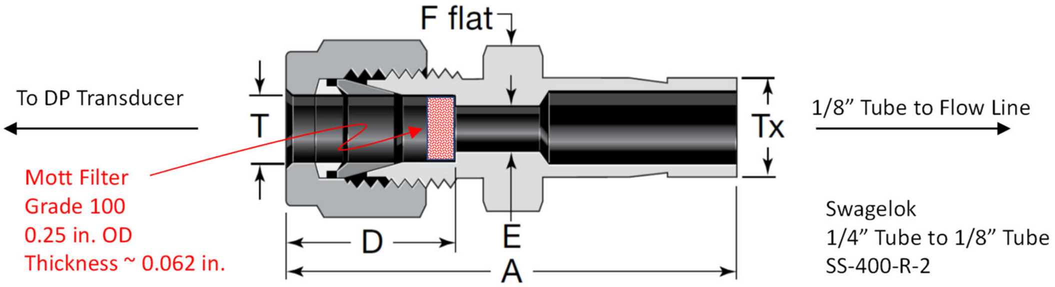

Figure 3.13. Fitting with Filter (FLT-06 and FLT-08) Connecting Flow Lines to Differential Pressure Transducer Lines (image does not show correct tube dimensions of 1/4 in. to 1/8 in.).

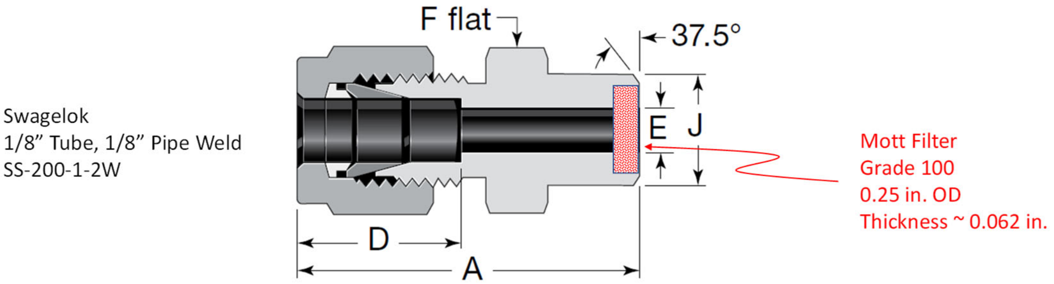

Figure 3.14. Fitting Welded to Column for Pressure Port to Differential Pressure Transducer Line (identified as FLT-07).

The DP instruments were mounted in such a way that the lines could be readily filled, flushed, isolated, or vented to remove any resident air. The local configuration of each of the DP instruments is illustrated in Figure 3.15. The ability to isolate a DP instrument was important for protecting DP-01 and DP-02 from pressurized air during filter backflushing and checking on instrument drift during test operations. When the transducer was isolated, the two isolation valves were closed and the bypass valve was open; when in operation, those same valves were in the opposite positions.

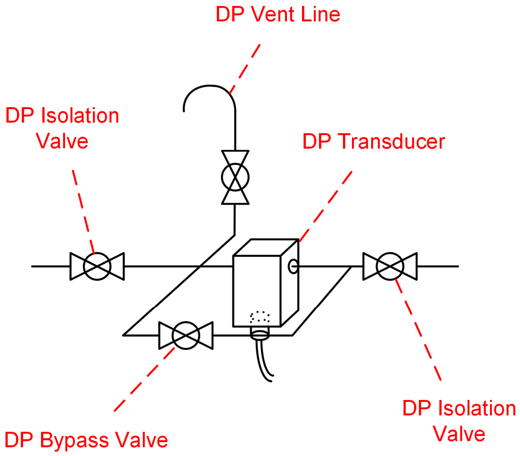

Figure 3.15. Schematic of the Differential Pressure Instrument Configuration Used for All Transducers.

3.5.2 As-Built Dimensions of PNNL-Assembled Components

Table 3.4 describes all the equipment that was used in the test system. All these components were used as provided by the listed manufacturer, except for the two PNNL-assembled components: the DEFs and IXC-01. In this section, the as-built dimensions of these components are provided for comparison with the target or design parameters discussed in Sections 3.3 and 3.4.

The DEF filters were constructed from two porous elements provided by Mott Corporation. They were custom-built to PNNL specifications one at a time and had different identifying numbers stamped on them as shown in Table 3.5. Each Mott porous element was welded to a 300# 1.5-in NPT flange with a 1/8-in fitting tapped into it (for all tests except NB1 the flange also had a shell-side vent line). The filter shell was constructed of a Schedule 80 1.5-in pipe cut to approximately 30 inches in length and threaded on both ends. One end was capped with a 1.5-in NPT pipe cap with a 1/8-in fitting tapped into it. On the other end, a threaded 300# 1.5-in NPT flange was added. The filter assembly was completed by bolting the two flanges together with a Teflon gasket between them. Figure 3.16 shows the two pieces of the filter assembly prior to bolting them together. Table 3.5 also provides the as-built dimensions of both filter assemblies; although they are nominally duplicate assemblies, there are small differences between the two units, with DEF-01 having a slightly larger surface area and shell volume than DEF-02.

Table 3.5. As-Built Elements of the Test System Filters DEF-01 and DEF-02.

Element Description (unit)	DEF-01 Value	DEF-02 Value
Mott Grade 5 Porous Element ID	PD0070994 01-5	PD0071739 01-5
Length of Mott Grade 5 Porous Section (in.)	24.38	24.31
Length of Non-Porous Section (in.)	4.06	4.13
Outer Diameter of Porous Element (in.)	1.0	1.0
Inner Diameter of Porous Element (in.)	0.88	0.88
Inner Diameter of Filter Shell (in.)	1.5	1.5
Distance Below End of Porous Element when Inserted into the Filter Shell (in.)	2.31	2.09
Filter Porous Surface Area (in^2 [m^2])	76.58 [0.0494]	76.38 [0.0492]
Filter Shell Volume (in^3 [gal])	32.19 [0.139]	31.77 [0.138]

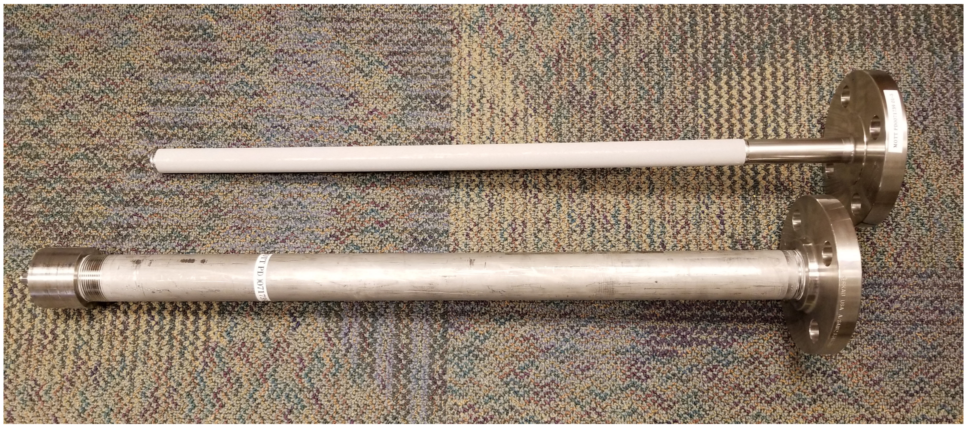

Figure 3.16. Image of Filter Assembly Pieces Side-by-Side before Bolting Together. In the image, the Mott porous element is on the top, and the filter shell is on the bottom.

Figure 3.17 shows the assembly and dimensions of the inlet and exit screens (Johnson VEE-WIRE® Screen, Aqseptence Group, #93 VEE-WIRE® [0.089 in. width] and #63 Rod with target dimensions of 0.005 in. slots, 0.8 in. OD, and 1/4 in. long screen interval). Table 3.6 gives the "as-built" top and bottom screen dimensions and Table 3.7 gives the "as-built" dimensions for the heights of the screens and column top, and CST bed. Although not quantitatively measured, the slot width visually varied within the screens (near closed at some locations with adjacent slots roughly 0.01 in., or twice the target width of 0.005 in.). Table 3.8 presents other "as-built" dimensions for the column: the internal diameter and the inlet/outlet tubing dimensions used in the test system.

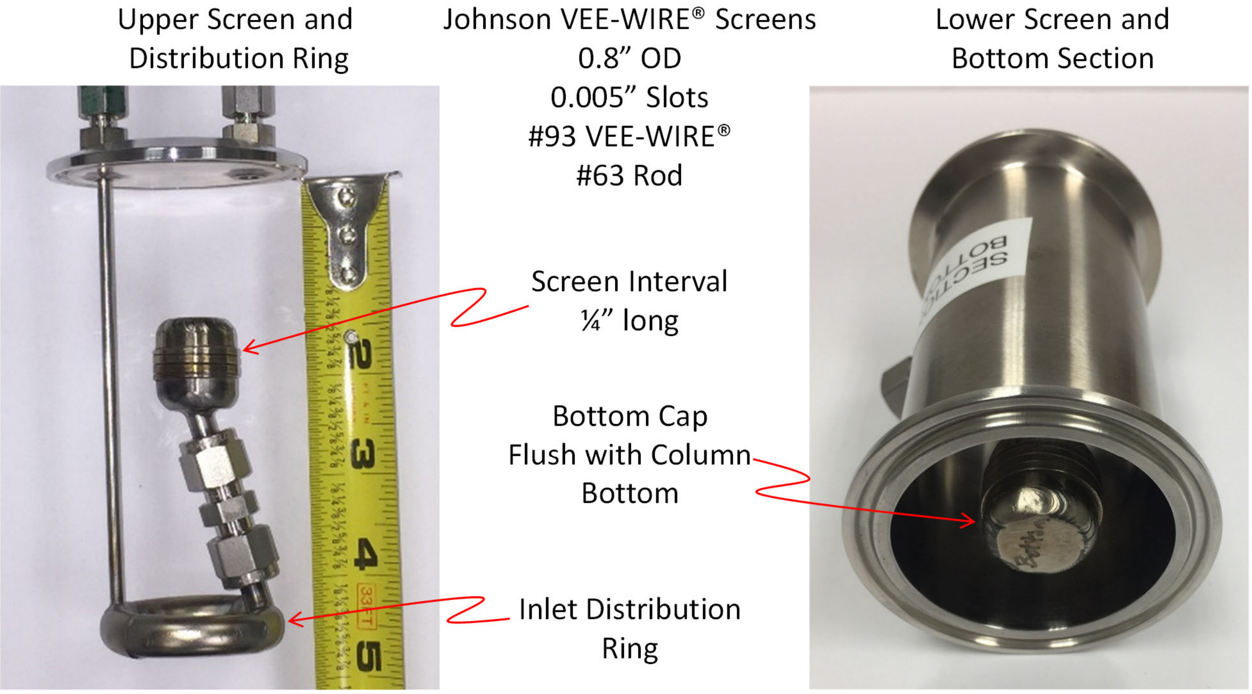

Figure 3.17. Upper (inlet) screen and distribution ring and lower (outlet) screen for CST column.

Table 3.6. As-Built Top and Bottom Screen Dimensions

Screen Component	Dimension (in.)
Bottom screen – screen height	0.25
Bottom screen – diameter	0.85
Bottom screen – bottom cap height	0.28
Upper screen – screen height	0.25
Upper screen – diameter	0.84

Table 3.7. As-Built Dimensions for the Heights of the Screens, Column Top, and CST Bed

Position	Height from Bottom of Column (in.)
Bottom screen – bottom of assembly	0.0 (flush with bottom flange)
Bottom screen – bottom of slots	0.3
Bottom screen – top of slots	0.6
Upper screen – bottom of slots	92.5
Upper screen – top of slots	92.75
Column top	94.5
Top of CST bed	NB1 – 92.5 HS1, HS2, HS3 – 92.0

Table 3.8. As-Built Dimensions for Column Components

Component	Dimension (in.)
Column Inner Diameter (full-scale column is an annulus)	1.87
ID of Inlet Distribution Ring Tubing (3/8 in. tubing)	0.305[a]
ID of Tubing Connecting Distribution Ring with Upper Screen (1/4 in. tubing, thickwall)	0.120[a]
ID of Inlet Tubing (1/8 in. tubing)	0.069[a]
OD of circular distribution ring (average of four measurements)	1.78
ID of Tubing Connecting Bottom Screen to Column Discharge (1/4 in. tubing, thickwall)	0.120[a]

(a) OD of tubing confirmed by measurement and ID determined from Swagelok tubing specifications

3.5.3 Test System As Assembled

The laboratory-scale test system for the high-solids testing was assembled from the components described in previous sections and configured as indicated in Figure 3.12. Most of the assembly required mounting elements on a frame (Bosch strut was used for this purpose) since many instruments, valves, and tubing runs needed to be at heights of more than 8 feet. The entire system was contained in a 10×10-ft collapsible secondary containment with an elevated work platform situated to provide access to valves and instruments that were at elevated heights. As-assembled images of the laboratory-scale high-solids test system, which is also referred to as the “test system” for the remainder of the report, are provided in Figure 3.18, Figure 3.19, and Figure 3.20.

The isometric view of the system in Figure 3.18 provides a sense of the test system’s scale and ambient location. Most of the equipment and instruments were on or near the Bosch strut frame seen in the left side of the image. Behind the frame is an elevated work platform used by operators to access valves and instruments, as well as load the IX column with CST. Behind the platform is the feed system, the flow controller FM-02/V-24, and the effluent collection tank TK-04. In the far right of the image a simulant tote from the vendor is staged along with other IBC totes for collecting material from testing.

Figure 3.18. Isometric View of the Laboratory-Scale High-Solids Test System. The elevated platform separates the recirculation loop (PMP-01, TK-01) and effluent collection vessel (TK-04) from the rest of the system (DEFs, IX column).

Figure 3.19. Front View of the Laboratory-Scale High-Solids Test System. The DEFs are on the left side of the Bosch frame and the IX column is on the right; outside the frame within the secondary containment is TK-03 (far left) and TK-02 with PMP-02 (far right).

Figure 3.19 shows a front view of the system, so-called because the DEFs, IX column, and most of the visible instrument readouts were located there. The DP readouts are in the front-center of the image, with the DEFs just to the left and the column to the right. Simulant was fed under the elevated platform and entered the active DEF from the bottom; filtrate exited out the top and traveled near the top of the frame until it went down through the IX column and then back under the platform to TK-04.

Figure 3.20 – a “side” view – shows the rest of the system: the feed system with its recirculation loop (TK-01, PMP-01, HX-01, BPR-01, and FM-01) and the effluent collection system (FM-02/V-24 flow controller, TK-04). The recirculation loop comes out of TK-01 (the upper IBC tote) into PMP-01 and flows through HX-01 and BPR-01 before traveling upward to return through the top of TK-01. Simulant is fed forward to the front-side at SV-01, which is visible in the image with a piece of orange tape attached. Effluent from the IX column returns in the foreground of the image via the flow controller just to the right of the platform as it is sent to TK-04.

Figure 3.20. Image Showing the Feed Vessel (TK-01) and Recirculation Loop of the Laboratory-Scale High-Solids Test System. On the ground in front of the stacked totes is PMP-01, with TK-01 being the upper tote (partially filled with simulant). The effluent collection vessel TK-04 is in the foreground.

3.6 Data Collection and Analysis

During testing, data was recorded manually from all system instruments on a periodic basis – nominally every 0.5 to 1 hour – as well as select other times at the operator’s discretion. Special attention (data at 2, 4, 6, 8, and 10 minutes) was paid to the initial increase in differential pressure when a previously inactive DEF was brought into service. The time stamps of each filter backflushing evolution step were also recorded as it was executed. As a backup, critical data was recorded via Brinno Inc. TLC200 time-lapse cameras every 10 seconds (the cameras recorded images of the instrument readouts). For these tests, the data considered critical were all the differential pressure instruments (DP-01 through DP-05) and the system flow rate (as measured and controlled by FM-02).

Samples were collected throughout each test, falling into one of four general categories:

1. Samples taken for analysis of the feed simulant. These were primarily taken after initial loading of the simulant into TK-01 from either SV-01 or V-02 and covered a comprehensive suite of analyses, including chemical composition, density, viscosity, particle size, and solids content. Samples of this type were occasionally taken later in the test if there was a change in the test simulant or the need to confirm a previous value.
2. Samples taken periodically for visual observation. An initial feed sample was collected as a visual reference and then post-DEF samples were taken from SV-02 approximately every 12 hours during testing.
3. Samples taken periodically from SV-03 for cesium analysis. Effluent samples were collected every 8 hours for the first 72-96 hours of operation and every 2 hours thereafter for the remainder of the test.
4. Samples taken at the end of test/post-test for observation. This catch-all category includes a final simulant archive sample, an end-of-test effluent sample, and post-test CST samples for visual observation. Most of these were taken directly from totes, tanks, or columns.

Samples that fall in the first category are described in more detail in Section 4.0 since they are relevant to the as-tested simulant properties. Samples in the second and fourth categories were not analyzed by any quantitative techniques; they were collected for the purpose of making visual observations and looking for anomalous system behavior. Samples in the third category were analyzed for cesium in solution by inductively coupled plasma mass spectrometry (ICP-MS).

3.6.1 General System Performance Analysis

The primary methods by which the scaled system performance was measured included:

- quantifying the control of system flow rate to its target value
- assessing the rate of increase in the pressure differential across DEFs when active
- observing the frequency of backflushing needed to maintain the target flow rate
- measuring filter recovery, e.g., the ΔP at $t = 10$ minutes on the active DEF after swapping filters
- monitoring pressure differentials measured across the IX column
- collecting effluent samples for cesium concentration
- examining post-DEF samples for evidence of solid particles

The methods listed above, except for the effluent sample analyses, were executed directly from the recorded data collected during the tests. Only simple post-test analyses, such as removing known low-quality data points and statistical calculations (averages, standard deviations) were performed. Specific performance analyses for each unit operation provides additional valuable information; methodologies used to conduct them are described in the next subsections.

3.6.2 Filtration Data Analysis

A common method used to analyze filtration data is to place it within the framework of Darcy's law (Darcy 1856), which is valid when the Reynolds number < 10 (Bear 1972). For the filters considered in the test system, the Reynolds number is defined as

$$Re_F = \frac{\rho_s \left(\frac{Q_o}{A_F}\right) d_F}{\mu_S} \tag{3.25}$$

where ρ_s is the simulant density, μ_s is the simulant viscosity, Q_o is the nominal flow rate, A_F is the surface area of the filter, and d_F is the characteristic length-scale. The length-scale d_F is usually defined as the mean grain size to represent the nominal pore size; in this case, it is approximated based on the grade of the Mott filter, i.e., $d_F = 5$ microns. The quantity (Q_o/A_F) is called the filter flux and has units of velocity.

The viscosity of the test simulants is a function of temperature which, following Daniel et al. (2018), is written as

$$\mu_S = \mu_{S,o} \exp\left[\lambda\left(\frac{1}{T} - \frac{1}{T_o}\right)\right] \tag{3.26}$$

where $\mu_{S,o}$ and λ are measured parameters, T is the temperature of interest (in Kelvins), and T_o is the reference temperature of 298.15 K (25 °C). Data for these parameters are given in Section 4.0 in Table 4.13. The density is also a weak function of temperature, but for the purposes of estimating the Reynolds number only the maximum density across all simulants was used ($\rho_s = 1275$ kg m^{-3}).

If Darcy's law is valid, the relationship between the pressure differential across a filter ΔP_F and the filter flux J_o is defined as

$$\left(\frac{Q_o}{A_F}\right) = J_o = \frac{\Delta P_F}{\mu_S R} \tag{3.27}$$

where R is the total resistance of the filter media. Dead-end filters of the type used in TSCR (and the test system) operate at constant flux (Q_o and J_o are target parameters to which the system is controlled) and allow the driving pressure to change, so performance is described in terms of changes in resistance over time. The resistance is often represented as

$$R = R_{m,o} + R^*(t) = \frac{\Delta P_F}{\mu_S J_o} \tag{3.28}$$

where $R_{m,o}$ is the initial resistance of the membrane only and $R^*(t)$ is the component that changes with time (for $t > 0$) which is some combination of membrane fouling, cake development, cake maturation, and other particle-filter attractive interactions. The initial resistance can be calculated from manufacturer's data but is best measured when the filter is "clean" in its operating configuration, which serves as a baseline for gauging performance. A baseline measurement was performed prior to each test with 0.1 M NaOH at flow rate Q_o for the purpose of determining $R_{m,o}$ using Eq. (3.27) and a few substitutions:

$$R_{m,o} = \frac{\Delta P_{F,o}}{\mu_o J_o} \tag{3.29}$$

where μ_o is the viscosity of 0.1 M NaOH and $\Delta P_{F,o}$ is the pressure drop across a filter measured with 0.1 M NaOH solution. Eq. (3.29) was generated assuming that the filter is a flat geometry, but the DEFs have a tubular geometry; thus, a curvature correction is employed to appropriately compare the resistance across geometries:

$$R_{m,o}^{+} = -\left(\frac{\Delta P_{F,o}}{\mu_o J_o}\right)\left[\frac{D_{F,o}}{2\theta_F}\ln\left(1-\frac{2\theta_F}{D_{F,o}}\right)\right] = \gamma_c\left(\frac{\Delta P_{F,o}}{\mu_o J_o}\right) \tag{3.30}$$

where θ_F is the filter tube thickness, $D_{F,o}$ is the outer diameter of the filter tube, and the correction factor is called γ_c for convenience. For the DEF geometry in the test system, γ_c is ~1.07. Finally, a simple normalization of Eq. (3.28) with $R^{+}_{m,o}$ (and using $R^{+}_{m,o}$ in place of $R_{m,o}$) yields

$$\omega = \frac{R}{R_{m,o}^{+}} = 1 + \frac{R^{*}(t)}{R_{m,o}^{+}} \tag{3.31}$$

where ω is the normalized resistance, which is equal to unity when the filter resistance is the same as the "clean" membrane and greater than unity when any resistance, i.e., fouling, above the baseline level is present. The normalized resistance is a useful comparison tool when the initial filter resistance $R_{m,o}$ (or $R^{+}_{m,o}$) is substantially different between data sets.

During testing, filter data was collected as a function of time, which for constant-flux filtration is identical to collecting data as a function of volume filtered. To facilitate comparison of the data across different scales, different process fluids, and different media grades, the specific volume filtered is used. The dimensionless specific volume filtered is defined as

$$v^{+} = \frac{\int_0^t Q\,dt}{l_c A_F} \tag{3.32}$$

where the integration of the measured flow rate Q was accomplished by discrete numerical integration of the measured values of flow rate (from FM-02) and associated time increments. The specific volume filtered is often made dimensionless by an appropriate length-scale (l_c), where a typical selection is an estimate of the cake thickness. For consistency with other work, the inner radius of the filter tube ($D_{F,i}/2$) was selected as the length-scale.

3.6.3 Ion Exchange Column Analysis

Darcy's law is also appropriate for assessing the CST bed in the IX column if the Reynolds number criterion is met. For the IX column, the Reynolds number is defined as

$$Re_{IX} = \frac{\rho_S\left(\frac{Q_o}{A_{IX}}\right)d_{CST}}{\mu_S} \tag{3.33}$$

where A_{IX} is the cross-sectional area of the ion exchange column and d_{CST} is the average grain diameter of the CST (taken to be 709 microns as reported by Gauglitz et al. 2019). Note that the ratio of the two Reynolds numbers (combining Eq. (3.25) and Eq. (3.33)) for the unit operations reduces to

$$\frac{Re_F}{Re_{IX}} = \left(\frac{d_F}{d_{CST}}\right)\left(\frac{A_{IX}}{A_F}\right) \tag{3.34}$$

because they share the same fluid and flow rate during operation. Using Eq. (3.34), the ratio for the test system is approximately 1×10^{-3}; the IX column Reynolds number is ~3 orders of magnitude greater than Re_F. During the baseline flow tests prior to operation, Re_{IX} was determined to be approximately 0.9 to 1.0. Because test operations utilized a more viscous fluid than 0.1 M NaOH, the baseline flow test value of Re_{IX} is bounding. Since, as Eq. (3.34) demonstrates, Re_F is orders of magnitude less, the proposed Darcy's law approximations are valid for both unit operations.

For the IX column, the pressure differential expression is constructed a bit differently than for the filters, but otherwise is functionally the same:

$$\left(\frac{Q_o}{A_{IX}}\right) = \beta \frac{\Delta P_{IX}}{\mu_S h_{bed}} \tag{3.35}$$

where β is called the permeability of the CST bed and h_{bed} is the bed height. To obtain reference values of permeability for the CST bed only, Eq.(3.35) can be rearranged as follows

$$\beta_{IX,o} = \left(\frac{Q_o}{A_{IX}}\right)\frac{\mu_o h_{bed}}{\Delta P^*_{IX,o}} \tag{3.36}$$

where $\beta_{IX,o}$ is the permeability of the CST bed only (a reference value) and $\Delta P^*_{IX,o}$ is the pressure drop defined by

$$\Delta P^*_{IX,o} = \Delta P_{IX,o} - \Delta P_{nb,w}. \tag{3.37}$$

The $\Delta P_{IX,o}$ term is the measured pressure drop with CST present and $\Delta P_{nb,w}$ is the measured pressure drop with no CST present (subtracts out the impact of column piping, fittings, and the inlet/outlet distributors). Note that a small error is introduced in $\beta_{IX,o}$ because the $\Delta P_{IX,o}$ measurement was collected with 0.1 M NaOH but $\Delta P_{nb,w}$ was measured with water. At the same temperature this error is approximately 2%. Similar to ω in Eq.(3.31), a normalized permeability β^* can be formulated as

$$\beta^* = \frac{\beta(t)}{\beta_{IX,o}} = \left(\frac{1}{\beta_{IX,o}}\right)\left(\frac{Q_o}{A_{IX}}\right)\frac{\mu_S h_{bed}}{\Delta P^*_{IX,S}} = K_o \frac{\mu_S}{\Delta P^*_{IX,S}} = \left(\frac{\mu_S}{\mu_o}\right)\left(\frac{\Delta P^*_{IX,o}}{\Delta P^*_{IX,S}}\right) \tag{3.38}$$

where $\beta(t)$ is the instantaneous permeability defined by the adjusted pressure differential $\Delta P^*_{IX,S}$ and the simulant viscosity μ_s as defined in Eq. (3.26). K_o is a constant that combines the constants Q_o, A_{IX}, h_{bed}, and $\beta_{IX,o}$. A value of $\beta^* > 1$ indicates an increase in permeability over the baseline measurement performed with 0.1 M NaOH. Note that $\Delta P^*_{IX,S}$ must be adjusted in a similar manner as in Eq. (3.37), i.e.,

$$\Delta P^*_{IX,S} = \Delta P_{IX,S} - \Delta P_{nb,w} \tag{3.39}$$

where $\Delta P_{IX,S}$ is the measured value and the prior water pressure drop is used to adjust for the presence of other impacts as before in Eq. (3.37). The use of Eq. (3.39) implicitly assigns all the pressure variation between the differential pressure measurement points to frictional loss and assumes laminar flow in the entire IX system (including fittings, smaller tubing, etc.). As such, it is an approximation.

Note that an analog to Eq. (3.36) can be generated from the filter data as well starting with Eqs. (3.29) and (3.30), which is

$$\beta_{F,o} = \frac{\theta_F}{R^{+}_{m,o}} = \left(\frac{Q_o}{A_F}\right)\frac{\mu_o\theta_F}{\gamma_c \Delta P_{F,o}} \tag{3.40}$$

Eq. (3.40) demonstrates mathematically that the permeability is the inverse of the resistance per unit thickness (or depth) of a porous media. Thus, an increase in resistance would manifest as a decrease in media permeability, and vice versa.

In addition to the hydraulic performance of the IX column, the cesium concentration was measured in the effluent to assess the progression of the cesium breakthrough curve. As discussed in Section 3.3.1, the tests were not run long enough to generate the entire breakthrough curve and were designed to observe only the initial detection of breakthrough in the system, which is defined here as > 0.1% C/C_o. For examining the initial breakthrough data, the approach made in this study was to perform a qualitative assessment of the cesium loading behavior using plots of C/C_o versus BV processed.

4.0 Simulant Selection and Development

A simulant development effort was undertaken to provide chemistries suitable for testing scaled TSCR unit operations, namely DEF and IX, at both nominal saltcake waste supernatant solids loadings (200 ppm) and at solids loadings approaching the TSCR specification limit (15,000 ppm) as described in Chamberlain and Eaton (2018) and Ard (2019). In particular, simulant development efforts involved design of simulant recipes for eventual procurement of at least four 300-gal batches from an external vendor. The specific targets for the four simulants were:

- a nominally solids-free supernatant simulant recipe based on the nominal 5.6 M Na simulant described in Russell et al. (2017) [hereafter referred to as the nominal batch (NB) simulant]
- a solids-bearing AP-tank farm representative simulant (hereafter referred to as the high solids (HS) simulant] with solids loading target of 0.3-wt% (3,000 ppm)
- an HS simulant with a solids loading target of 0.9-wt% (9,000 ppm), and
- an HS simulant with a solids loading target of 1.5-wt% (15,000 ppm).

The present section of the report provides the basis for baseline simulant recipe selection, specific modifications to those recipes to render them suitable for demonstration of DEF/IX unit operations, final simulant recipes for scaled 300-gal batches, and final produced simulant chemistries used for testing. In Section 4.1, the basis for simulant chemistry selection is reviewed and the methods used to quantify prepared simulants are outlined. As Section 4.1 focuses primarily on the basis for selecting the simulants and the analytical methods used to quantify their physical properties, specific recipes or physical properties are not given. Next, Section 4.2 discusses baseline simulant recipes and specific modifications made to those recipes for the current testing. Section 4.2 also briefly discusses the vendor selected to prepare large-scale batches and specific vendor instructions for simulant preparation. Finally, Section 4.3 discusses receipt of the prepared 300-gal batches of simulant (along with specific issues resulting from transport), test-specific modifications to the simulant chemistry in response to observed test behavior of the simulant, and the chemistry of the as-prepared batches across the various scaled tests.

4.1 Methods

4.1.1 Basis for Simulant Selection

Selection of simulants for scaled DEF/IX unit operations testing considered two basic low-activity waste chemistries: the nominal simulant chemistry as developed and specified by Russell et al. (2017) and an AP-105 simulant recipe recently developed and tested by Daniel et al. (2020a, 2020b) for the purpose of evaluating dilution-induced precipitation in high-sodium simulants. Use of the nominal simulant was directly requested by WRPS, as it is a nominally solids-free tank waste supernatant simulant (~200 ppm level solids) and has well-characterized ion exchange and dead-end filter performance profiles [see Daniel et al. (2018) and Wilson (2019b)]. The test designation of the nominal simulant, as noted above, was the "nominal batch" (NB).

No formal designation for the high-solids simulant chemistry was made; however, WRPS requested, in their SOW,[31] that:

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[31] Statement of Work Requisition #339013, Rev. 0. June 4, 2020. TSCR High Solids Filtration and Ion Exchange Testing. Washington River Protection Solutions, Richland, Washington

> [t]his simulant should be developed to be relevant to the expected TSCR feed and address the mid and upper range of the solids concentration identified in RPP-SPEC-61910, Rev 2, Table 3-4 (and associated footnotes). This simulant will be used to test the impact to the filtration and IX system as described in Section 3.2.

Section 3.2 of the SOW continues by specifying the targets solids loadings for the "new" simulant, namely 20%, 60%, and 100% of the 15,000-ppm maximum specified by RPP-SPEC-61910, Rev. 2. With respect to the requirement that the selected simulant be relevant to the expected TSCR feed, the AP-105 simulant developed by Daniel et al. (2020a) targets analyte contents matching that chemical data for Hanford tank AP-105 [Ferriter (2016) and Fiskum et al. (2018)] and is therefore chemically representative. Physical properties testing reported in Daniel et al. (2020a, 2020b) demonstrates that the physical properties align with the requirements of Table 3-4 of RPP-SPEC-61910, Rev 2.[32]

The baseline AP-105 recipe is an 8.53 M Na simulant that contains precipitated salt solids. The solids concentration of this "as-made" 8.53 M Na simulant has not been quantified, as the simulant is diluted to 5.6 M Na prior to testing. Dilution to 5.6 M Na generally dissolves most of the initially precipitated content present in the as-made simulant; however, the dilution process itself may yield additional precipitated solids, especially if the water used to dilute contains background ions common in process and tap water (such as Ca^{2+} and Mg^{2+}). Chemical analysis of the precipitated solids in Daniel et al. (2020b) found precipitation was a transient process, with initial solids forming immediately after dilution and additional solids forming for several months after dilution. Precipitation in the month immediately following dilution was most largely associated with Ca^{2+} and Mg^{2+} ions (common in process water), whereas precipitation in the two-to-three-month period after dilution was largely associated with analytes originating from the simulant itself (iron, aluminum, etc.). Estimates of the ultimate extent of dilution-induced precipitation suggested an upper-end solids content of 130 ppm (achievable only after several months).

While the 130-ppm ultimate solids content was lower than desired for the current testing, as noted [and has been historically recognized – see Fiskum et al. (2000)], the rapid first-month precipitation results from the instability of nominally water-soluble calcium in the highly caustic tank waste suspending phase. Specifically, simulant design efforts could take advantage of the tendency of calcium-bearing solids to precipitate from tank wastes by dilution with calcium chloride solutions. For the current program, the benefits of this approach are:

1. the calcium chloride content of the solution used to dilute the "as-made" AP-105 solution from 8.53 M Na to 5.6 M Na can be controlled to yield the desired solids content in the final diluted test simulant,
2. the fouling proclivity of the resulting precipitates has been evaluated in both Fiskum et al. (2000) and Daniel et al. (2020b) and found to be adverse to dead-end filter performance, and
3. the solids produced are believed to be representative of solids that will be generated by actual waste dilution with river water in the staging tank, which has been shown to adversely impact bench-scale dead-end-filtration of actual Hanford wastes from the AP Tank Farm [see Geeting et al. (2018a, 2018b, 2019)].

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[32] The surface tension of the AP-105 simulant has not been evaluated for compliance with the 70-100 mN m^{-1} range specified by Table 3-4 of RPP-SPEC-61910, Rev 2. For the present efforts, capillarity is not expected to impact DEF or IX performance of fully saturated filtration or ion exchange media. Likewise, the AP-105 simulant is a high-salt aqueous solution that does not include surface-active agents known to substantially lower surface tension. As such, its surface tension is expected to be compatible with the Table 3-4 requirements.

The primary drawback of using calcium addition (or any chemical addition to the simulant) to yield the target precipitated solids is that the quantity of calcium needed to yield the RPP-SPEC-61910, Rev 2, limit of 15,000 ppm is large, to the extent that it could not feasibly occur in any "typical" treatment or staging of tank wastes. Prototypic water additions [per Daniel et al. (2020a, 2020b)] involved adding 40 grams of process water (as a substitute for actual river water) with approximately 22,000 µg L^{-1} Ca^{2+} to every 100 grams of as-made simulant and yielded ~100-ppm level quantities of solids. As such, it was expected that the aqueous calcium content of the test diluent needed to reach target solids contents of 3,000 to 15,000 ppm would fall near saturation [~75 grams per 100 mL for anhydrous $CaCl_2$]. As suggested above, single-shot calcium additions at this concentration are not prototypic and are an artifact of the process needed to meet the current test targets, which are predicted on off-normal conditions or could arise from long-term accumulation of dilution-induced precipitates in the staging tank. It should be noted that the reasonableness of single-shot additions leading to solids contents on the order of 10,000 ppm is not just associated with Ca^{2+}-induced precipitates but is rather associated with any single- or multi-component addition [e.g., addition of $FePO_4$ to precipitate iron-bearing solids for crossflow filter testing in Daniel et al. (2018)] to a nominally solids-free LAW representative waste.

Thus, despite reservations about the representativeness of calcium additions needed to effect target solids contents, the AP-105 recipe developed in Daniel et al. (2020a) when coupled with calcium instability provides a demonstrated means of producing chemically representative solids through an actual (albeit highly exaggerated) tank treatment process. Simulant development efforts identified three target concentration $CaCl_2$ solutions by which to effect dilution of the as-made 8.53 M Na simulant to the 5.6 M Na target (comparable to the nominal simulant) while also effecting precipitation of insoluble solids at 3,000 (20% of maximum), 9,000 ppm (60% of maximum) and 15,000 ppm (100% of maximum). These simulants were designated, as noted earlier, as the high-solids simulant (individually referred to as the HS1, HS2, and HS3 simulants, respectively, or globally as the HSX simulants).

4.1.2 Analytical Methods

Testing and characterization efforts were undertaken to support simulant development and scaled testing. Here, brief descriptions of the target chemical and physical properties quantified, and the methods used to quantify those properties, are given in the descriptive list below.

Liquid Phase Chemistry: The liquid phase chemistry (namely the speciation of different analytes in solution) was quantified by a combination of inductively coupled plasma (ICP) optical emission spectroscopy (OES), ICP mass spectrometry (MS), ion chromatography (IC), total carbon (TC) and total organic carbon (TOC) analyses, and free OH^- analysis. Total inorganic carbon (TIC) is not directly provided by these analyses but may be calculated as the difference between TC and TOC (which are both reported in grams of carbon per unit mass/volume of sample). Unless otherwise noted, characterization was limited to the feed material (i.e., the material supplied to the DEF/IX operations) for each test; these samples were taken upstream of the filters at either SV-01 or V-02. Here, ICP-OES was used to quantify simulant loadings of Al, Fe, Ca, Si, Na, and K. ICP-MS was used to measure the Cs content of the simulant (both in the as-received and post-IX column effluent). Simulant anion loadings (Br^-, Cl^-, F^-, NO_3^-, NO_2^-, PO_4^{3-}, and SO_4^{2-}) were quantified by using IC. Organic carbon and inorganic carbon (presumed to be CO_3^{2-}) were quantified using TC/TOC. Here the inorganic carbon is determined as the difference between total carbon and total organic carbon. Finally, the free hydroxide was quantified by acid titration. The primary function of liquid phase chemistry testing was to validate simulant contents (e.g., Na content) and verify cesium breakthrough on the IX unit. All liquid phase chemical analyses were performed by PNNL's Environmental Sciences Laboratory (ESL), except for free OH analysis, which was done by the Analytical Support Operations laboratory operating out of PNNL's Radiochemical Processing Laboratory.

Solid Phase Chemistry: Simulant solid phase chemistry was determined by ICP-OES. Dissolution of solids was accomplished by nitric acid addition. As above, ICP-OES was used to identify the absolute abundance of primarily Al, Fe, Ca, Si, Na, and K. Characterization of solid anions (Br^-, Cl^-, F^-, NO_3^-, NO_2^-, PO_4^{3-}, and SO_4^{2-}) would nominally be done using IC; however, the target test solids are largely insoluble in neutral or caustic aqueous solutions compatible with the IC method. The primary function of solid phase chemistry was to evaluate the chemistry of precipitated, insoluble solids suspended in the simulant. Collection of simulant solids for analysis was accomplished by pressurized (using nitrogen gas at 20 to 30 psig) dead-end filtration onto a Mott 0.2 grade circular media disk. To avoid dissolution of potentially water-soluble solids that exist in the high-salt waste simulant suspending phase, the collected solids were not washed. Rather, dead-end filtration was allowed to continue until nitrogen breakthrough, at which point the filter was removed from its assembly and solids scraped off the surface using a flat-edge razor blade. In conjunction with solids content analysis, the solids were weighed, dried, and sampled before submission for chemical analysis. Solid phase chemical analysis was done by PNNL's ESL.

Mineral Phase Identification: Identification of crystalline mineral phases in the HSX solids precipitated by calcium addition was accomplished by x-ray diffraction (XRD). Solids were collected by dead-end filtration on to a Mott Grade 0.2 filter disk (with filtration driven by 20-30 psig N_2 overpressure), dried, and subsampled for analysis. The make-up chemistry of the HSX simulants was used to optimize software-assisted mineral phase identification by specifying key analytes expected to comprise the solids.

Total Solids Content: The total undissolved solids content in the nominal batch (NB) simulant and in the high-solids (HSX) simulants was characterized by dead-end filtration of 1-L make-up samples (during simulant development) and 1-L grab samples of simulants (taken from the feed vessel during full-scale testing). The dead-end-filter assembly used to separate precipitated simulant solids from the high-salt aqueous suspending phase consisted of a 1-L cylindrical suspension reservoir joined by C-clamps to a 70-mm Mott Grade 0.2 dead-end filter [and is similar to the assembly used for initial dead-filtration studies in Geeting et al. (2018a, 2018b)]. Liquid flow through the Mott disk is driven by 20-30 psig N_2 overpressure and continues until the entire contents of the suspension reservoir have been filtered and N_2 breakthrough through the filter is audibly noted. Immediately following breakthrough, the system is dissembled, and the "wet" solids scraped off the filter surface (to the best extent practicable) using a razor blade. This process removes the vast majority of solids collected [except for solids that may have penetrated the tortuous network formed of pores with a hydrodynamic diameter on the order of 1-3 µm – see Daniel et al. (2011)]. The collected solids are weighed, dried at 105 °C for at least 24 hours, and reweighed until a stable mass is reached. The final mass is then corrected to remove the mass of dried solids that derive from supernate hold-up in the solids (based on moisture loss during drying) and ratioed to the mass of the 1-L sample to determine total solids content.

Dissolved Solids Content: The dissolved solids content of nominally solids-free liquids (derived from dead-end filtration – see "Total Solids Content" method description above) is determined by placing a 5-to-15-gram sample of liquid into a pre-weighed dish and oven-drying at 105 °C until a stable mass is reached (after more than 24 hours of drying). The dissolved solids content of the liquid is determined as the ratio of the dried sample mass to original liquid sample mass.

Liquid Phase Density: Liquid phase density is determined at 15, 20, 25, and 30 °C by use of 25-to-50-mL glass pycnometers. First, the liquid and pycnometers are thermostatted to the target temperature by immersion in a recirculating water bath (whose temperature is verified using a calibrated thermocouple with ± 2.2 °C accuracy). Next, liquid is quickly added to a pre-weighed, certified pycnometer and the pycnometer capped, dried, and weighed. The net mass of liquid in the pycnometer is then divided by the certified pycnometer volume to determine liquid density. The nominally solids-free NB and HSX liquids provided for density measurement were derived from dead-end filtration of 1-L simulant batches or feed tote grab samples (see "Total Solids Content" method).

Liquid Phase Viscosity: Liquid phase viscosity is measured at 15, 20, 25, and 30 °C using a high-precision, air-bearing rheometer with a concentric cylinder single gap geometry. Temperature control was achieved by connection of the rheometer to a recirculating water bath whose temperature was verified by a calibrated thermocouple (accurate to ± 2.2 °C). The stress response of the relatively solid simulants (derived from bench-scale make-up) and feed tote grab samples (from scaled testing) were characterized as a function of shear rate (spanning 0 to 1,000 s^{-1}). The viscosity of the liquid was quantified by linear regression of the slope of the stress response against shear rate (in accordance with the Newtonian constitutive equation and with care taken to eliminate shear rate regions impacted by second flows such as Taylor vortices).

Particle Size Distribution: The particle size distribution of a representative sampling of the HSX simulant precipitates was measured using laser diffraction. To avoid any agglomerating and recrystallization effects from drying, all size measurements were made using solids that were sampled directly from the suspending phase and diluted (when necessary) using solids-free filtrates from the dead-end filter system (see "Total Solids Content" method). During size analysis, samples were mixed and dispersed using an in-cell recirculator and sonicator. Beyond continuous recirculation and periodic sonication during measurements, no additional means of dispersing the solids, such as the use of surface-active agents, were undertaken. The particle size measurements therefore reflect the state of solids agglomeration that occurs under conditions of active shear that can be measured with laser diffraction technology[33] rather than the true, primary particle size, of the solids themselves.

4.2 Simulant Development

4.2.1 Nominal Simulant Recipe and Development

The nominal simulant recipe used for the current test program was adapted, without substantial modification, from that provided by Russell et al. (2017). The only change to the recipe was to slightly lower the [Cs] content specified in Russell et al. (2017) from 104 µM to 100 µM.

Table 4.2 provides the nominal simulant salt basis recipe (note: Section 4.3 reformats this recipe into an expected per-analyte concentration basis). The general preparation steps followed to prepare bench-scale quantities are:

1. Select an appropriately sized vessel (1-L for simulant development) and add the required mass of (deionized [DI]) water to the vessel.
2. While mixing, add the required mass of each component listed in
3. Table 4.2 to the vessel, allowing each component to completely dissolve (heating may be required) into solution before adding the next [note: all chemicals should be added in the order they are presented in
4. Table 4.2].
5. Heat the resulting solutions to 60 ± 5 °C and hold at that temperature for 0.5 to 1.0 hour while continuing to mix.
6. Cool the solution to ambient temperature over approximately 8 hours and hold (while still mixing) for at least 16 additional hours.

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[33] The instrument used for the reported measurements (a Malvern Mastersizer 2000) has a lower limit of 20 nm under the best conditions. Measurement of typical tank waste simulant dispersions, which comprise broad mixtures of solids containing agglomerates > 1000 nm in size, is limited to sizes > 200 nm.

7. Add deionized water to return the final solution to its target mass / volume (e.g., to make-up water loss due to evaporation) if necessary.

As the nominal simulant recipe produces a 5.6 M Na simulant, no additional dilution is necessary to adjust the sodium content after make-up. Since the nominal simulant recipe was to be used "as-is" to baseline the performance of the scaled DEF/IX operations, no additional modifications to the underlying simulant chemistry or solids content were made after make-up.

4.2.2 High-Solids Simulant Development

The high-solids simulant recipe used for the current test program was based on the 8.53 M Na AP-105 simulant recipe developed by Daniel et al. (2020a) using AP-105 waste data provided by Ferriter (2016) and Fiskum et al. (2018). To provide parity with the [Cs] and [K] content of the nominal simulant, the contents of both [Cs] and [K] in the AP-105 simulant (at 8.53 M Na) were adjusted to 152 µM and 0.186 M, respectively (or 100 µM and 0.122 M for [Cs] and [K], respectively, after dilution of the simulant to 5.6 M Na). Table 4.3 provides the 8.53 M Na (baseline) salt basis recipe for the high-solids simulant (note: Section 4.3 reformats this recipe into an expected per-analyte concentration basis). The general preparation steps followed to prepare bench-scale quantities of this simulant are identical to those for the nominal simulant save for differences in the chemicals used. As before, the order in which chemicals are added to the solution being prepared corresponds to the order in which those chemicals are presented in Table 4.3.

As the baseline simulant recipe for the high-solids simulant was adapted from an existing recipe in Daniel et al. (2020a), the primary focus of high-solids simulant development efforts focused on controlled precipitation of solids during the dilution step needed to lower the [Na] from 8.53 to 5.6 M. As discussed above, the mechanism proposed to precipitate solids during dilution involved exploiting calcium instability in high-salt, caustic media [see Fiskum et al. (2000) and Daniel et al. (2020a)]. Here, precipitation of what were expected to be solids insoluble in the high-caustic simulant matrix was effected by diluting the as-made 8.53 M Na simulant with solutions of calcium chloride prepared by mixing calcium chloride dihydrate ($CaCl_2 \cdot 2H_2O$) with deionized water. The initial dilution scheme assumed calcium would fall out as a mixture of calcium hydroxyapatite [$Ca_5(PO_4)_3(OH)$], as limited by phosphate, and calcium hydroxide [$Ca(OH)_2$]. A single presumptive target $CaCl_2 \cdot 2H_2O$ solution that was expected to yield 1.5-wt% (15,000 ppm) mixed hydroxyapatite and hydroxide-bearing calcium solids was determined, prepared, and tested. Specifically, an aqueous solution of calcium chloride was prepared and added to an as-made 8.53 M AP-105 simulant in the proper ratio to reduce Na content to 5.6 M and the mass fraction of insoluble solids formed by dilution and calcium-induced precipitation was quantified. Precipitation resulting from targeted solution addition exceeded its expected 1.5-wt% target by a factor of approximately two, suggesting (as might be expected given the complex nature of the simulant) that calcium-induced precipitation yields a more diverse array of solid species and/or the formation of hydrates. Additional preparation of as-made AP-105 simulant and subsequent dilution using a broad array of calcium chloride concentrations were used to develop a precipitation quantification curve to directly target the actual loading of $CaCl_2$ leading to the precipitation of 0.3, 0.9, and 1.5-wt% solids when diluting the simulant from 8.53 M to 5.6 M Na.

The precipitation curve resulting from the development effort described in the preceding paragraph is shown in Figure 4.1. This figure differentiates results that include initial screening tests [where the dissolved solids content of the precipitated solids (collected via filtration) was not explicitly quantified] from those that include only results where the dissolved solids content of the filter cake was explicitly evaluated. The set including both initial screening and "explicit" data points is denoted in Figure 4.1 as the "all" data set (red circles). A second set denoted as the "explicit" set in Figure 4.1 (blue "x" symbols) contains only those "precipitation-calibration" tests where the dissolved solids content of the filter cake was measured explicitly. Both sets suggest a similar linear relationship (as expected) between the mass of calcium chloride solids added to the simulant and the quantity of solids precipitated by calcium addition. The lines shown in Figure 4.1 (red dashed corresponding to the "all" set of measurements and blue dashed-dotted corresponding to the "explicit" set of measurements) represent the result of linear regression analysis of the precipitation curves. It should be noted that the linear regression assumed a nonzero intercept, and in both cases, found an intercept that was not statistically significant (i.e., the p-value associated with the intercept was greater than 0.05). When all measurements were included, calcium addition generated 1.39 grams of precipitated solids per gram of calcium added to the simulant (referenced to the final diluted simulant). Similarly, using only the data wherein the dissolved solids content was explicitly measured, linear regression suggested 1.28 grams of solids were precipitated per gram of calcium added. Table 4.1 translates these two calcium sensitives into the mass of calcium chloride addition required per kilogram of final 5.6 M Na simulant for the target scaled test loadings of 0.3-wt% (3,000 ppm), 0.9-wt% (9,000 ppm), and 1.5-wt% (15,000 ppm). Note: all dilutions of the as-made 8.53 M Na to 5.6 M Na were accomplished by adding 36.5 grams of water to every 100 grams of as-made simulant (calculated based on expected densities of as-made and diluted AP-105 base simulant liquids), corrected for any waters of hydration associated with the added mass of $CaCl_2 \cdot 2H_2O$.

Table 4.1. Estimated masses of calcium chloride (expressed as grams $CaCl_2$ additional salt added to the simulant per kilogram of final 5.6 M Na AP-105 simulant) needed to effect final target solid loadings for full-scale testing.

Target		$CaCl_2$ Addition "All" Sensitivity[(a)]	$CaCl_2$ Addition "Explicit" Sensitivity[(b)]
[wt%]	[ppm]	[(g $CaCl_2$) (kg 5.6 M Na simulant)$^{-1}$]	[(g $CaCl_2$) (kg 5.6 M Na simulant)$^{-1}$]
0.3	3,000	2.14	2.21
0.9	9,000	6.46	6.90
1.5	15,000	10.77	11.59

(a) addition based on the "all" correlation in Figure 4.1 (1.39 grams of solids per gram of added $CaCl_2$)
(b) addition based on the "explicit" correlation in Figure 4.1 (1.28 grams of solids per gram of added $CaCl_2$)

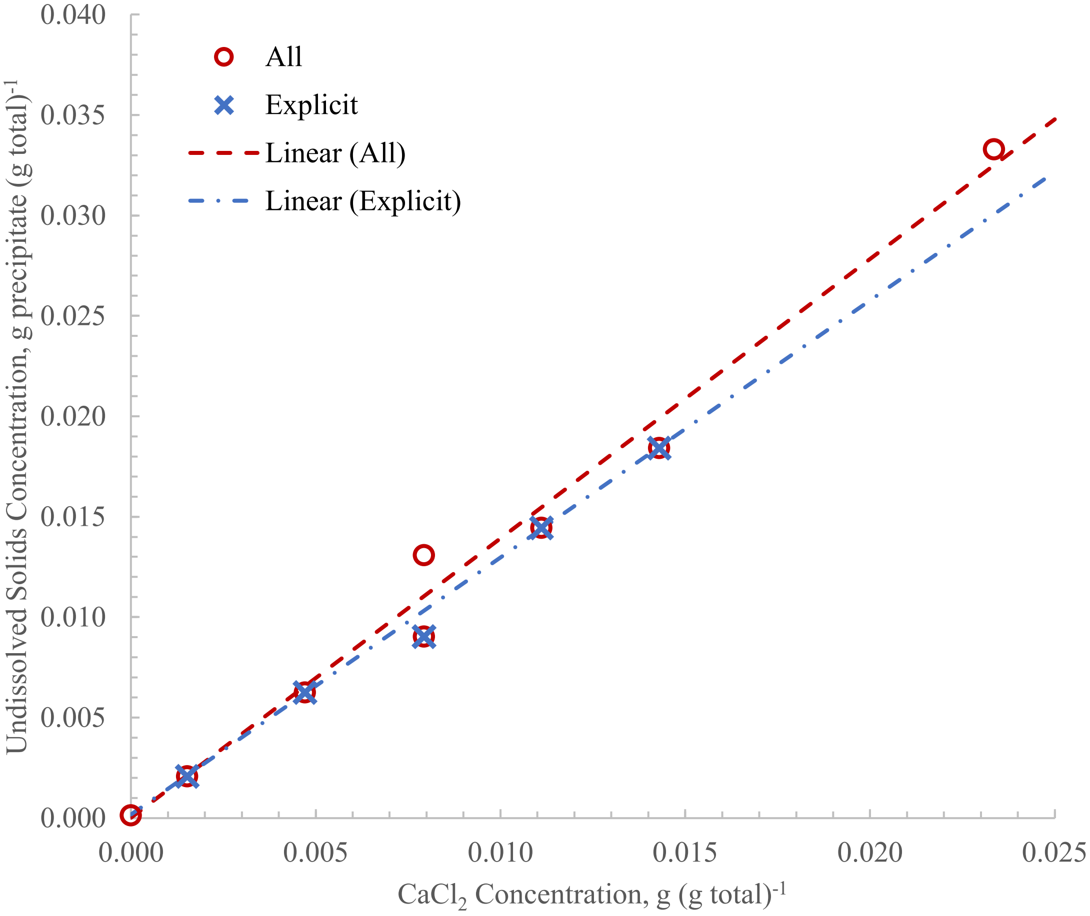

Figure 4.1. Precipitation curve relating the dilution-step added calcium chloride salt (as $CaCl_2$) concentration in the final simulant to the final undissolved content of the 5.6 M Na sodium high-solids test simulant (with both quantities expressed as grams solid per gram of 5.6 M Na simulant). The separate data sets shown in the graph differentiate data sets derived from using the full set of measurements ("all" – red circles), which includes measurements where the dissolved solids content of the supernatant was assumed (during undissolved solids content analysis), from a more limited set of measurements ("explicit" – blue "x" symbols) where the dissolved solids content of the supernatant was measured explicitly. The red dashed line and blue dashed-dotted line show the result of linear regression analysis (assuming a nonzero intercept) for the "all" and "explicit" data sets, respectively, and suggest anywhere between 1.28 and 1.39 grams of precipitate are formed per added mass of $CaCl_2$.

Table 4.2. Recipe for preparing the nominal simulant. This recipe assumes a density of 1250 kg m^{-3}.

Component Name	Component Formula	Formula Weight [g mol^{-1}]	Composition[a] [g kg^{-1}]	Composition[b] [g L^{-1}]
deionized water[c]	H_2O	18.02	598.36	747.95
aluminum nitrate nonahydrate	$Al(NO_3)_3 \cdot 9H_2O$	375.13	49.82	62.27
cesium nitrate	$CsNO_3$	194.91	0.0156	0.0195
50-wt% sodium hydroxide solution	NaOH (50wt%)	40.00	132.73	165.91
sodium phosphate dodecahydrate	$Na_3PO_4 \cdot 12H_2O$	380.12	13.14	16.42
potassium chloride	KCl	74.55	7.277	9.096
sodium sulfate	Na_2SO_4	142.04	7.511	9.389
sodium oxalate	$Na_2C_2O_4$	134.00	1.361	1.702
sodium nitrite	$NaNO_2$	69.00	56.30	70.38
sodium nitrate	$NaNO_3$	84.99	87.17	108.97
sodium carbonate monohydrate	$Na_2CO_3 \cdot H_2O$	124.00	46.33	57.91

(a) Represents the simulant composition in grams of component per kilogram of final as-prepared simulant [i.e., g component (kg simulant)$^{-1}$].

(b) Represents the simulant composition in grams of component per liter of final as-prepared simulant [i.e., g component (L simulant)$^{-1}$].

(c) Deionized water shall be used for simulant preparation.

Table 4.3. Recipe for preparing the undiluted (8.53 M Na) high-solids simulant base. This recipe assumes a density of 1405 kg m^{-3}.$^{-}$

Component Name	Component Formula	Formula Weight [g mol^{-1}]	Composition[a] [g kg^{-1}]	Composition[b] [g L^{-1}]
deionized water[c]	H_2O	18.02	330.55	464.42
aluminum nitrate nonahydrate	$Al(NO_3)_3 \cdot 9H_2O$	375.13	204.84	287.81
iron nitrate nonahydrate	$Fe(NO_3)_3 \cdot 9H_2O$	404.00	0.036	0.050
cesium nitrate	$CsNO_3$	194.91	0.0211	0.0297
50% sodium hydroxide solution	NaOH (50%)	40.00	273.85	384.76
sodium phosphate dodecahydrate	$Na_3PO_4 \cdot 12H_2O$	380.12	3.972	5.581
potassium chloride	KCl	74.55	8.74	12.28
calcium chloride dihydrate	$CaCl_2 \cdot 2H_2O$	147.02	0.247	0.347
sodium fluoride	NaF	41.99	0.387	0.544
sodium sulfate	Na_2SO_4	142.04	2.596	3.647
sodium formate	NaCOOH	68.01	7.032	9.879
sodium acetate	$NaCOOCH_3$	82.03	4.242	5.960
sodium oxalate	$Na_2C_2O_4$	134.00	0.289	0.406
sodium nitrite	$NaNO_2$	69.00	92.51	129.98
potassium nitrate	KNO_3	101.10	1.519	2.135
sodium nitrate	$NaNO_3$	84.99	10.07	14.15
sodium meta silicate nonahydrate	$Na_2SiO_3 \cdot 9H_2O$	284.20	0.461	0.648
sodium carbonate monohydrate	$Na_2CO_3 \cdot H_2O$	124.00	58.63	82.38

(a) Represents the simulant composition in grams of component per kilogram of final as-prepared simulant [i.e., g component (kg simulant)$^{-1}$].

(b) Represents the simulant composition in grams of component per liter of final as-prepared simulant [i.e., g component (L simulant)$^{-1}$].

(c) Deionized water shall be used for simulant preparation.

Table 4.4. Schedule for HSX 8.53 M Na as-made (baseline) simulant dilution to effect target solids loadings.

Batch	Target Solids Concentration [wt%]	Required Quantity of Baseline 8.56 M Na Simulant: Volume [gal]	Required Quantity of Baseline 8.56 M Na Simulant: Mass [kg]	Diluent Composition (Salt as $CaCl_2 \cdot 2H_2O$): Water [kg]	Diluent Composition (Salt as $CaCl_2 \cdot 2H_2O$): Salt [kg]	Final Simulant: Volume [gal]
HS1	0.3	200	1,050	382.85	4.15	300
HS2	0.9	200	1,050	380.73	12.77	300
HS3	1.5	200	1,050	378.60	21.48	300
HSC(a)	-- --	200	1,050	-- --	-- --	200

(a) HXC – is the high-solids “contingency” batch and is an as-made 8.53 M Na batch that can be diluted to suit the needs of potential high-solids recovery or follow-on tests.

4.3 Full Scale-Preparation and Simulant Properties

This section discusses the simulant preparation vendor and vendor-specific instructions for preparing the 300-gal batches of the single nominal simulant batch and the three HSX batches at 0.3-wt%, 0.9-wt%, and 1.5-wt% solids loadings. Likewise, it discusses issues with receipt of the as-received nominal simulant and HSX batches (and how those issues impacted the physical properties). Finally, chemical and physical properties of the tested simulants are discussed.

4.3.1 Simulant Batch Preparation Vendor and Vendor Instructions

The NOAH Technology Corporation (hereafter referred to as NOAH or NOAH Technologies) was selected by PNNL to produce the four 300-gal batches of simulant for scaled testing. Selection was predicated on NOAH’s previous experience in producing a 680-gal batch of complex Hanford waste simulant for PNNL’s Tall Column Testing program (Fiskum et al. 2019b), which tested a full-height IX column filled with CST.

The

Table 4.2 nominal simulant recipe and associated bench-scale preparation instructions (see Section 4.2.1) were provided to NOAH to effect make-up of a 300-gal batch. Additional vendor instructions were also provided to effect preparation of a scaled 300-gal nominal simulant batch (batch NB). These instructions were to:

1. Prepare one 300-gal batch (1136 L) of the nominal simulant [All preparation vessels should be rinsed with DI water and well-drained/dried prior to simulant make-up. Where possible, glass vessels shall be avoided during simulant preparation as the high pH of the simulant attacks and dissolves glass.]
2. Measure the prepared simulant density at 20 °C and verify that it falls within 1.23 to 1.27 kg L^{-1}.
3. Ship prepared simulant to PNNL in a new, clean, and dry 330-gallon IBC tote with bottom drain.
4. Deionized water (DI water) used as a simulant component shall have a resistivity greater than 18 MΩ·cm. [Water used as a rinse for equipment and transport containers (truck tanks and/or totes) need not meet this requirement.]
5. Use ACS reagent grade chemicals (or equivalent). [Note: DI water is exempted from this requirement.]

6. Provide a summary report of the production processes that includes:
    - reagent materials used, manufacturer, lot number, description (inclusive of impurities as listed by the manufacturer), and a Chemical Analytical Report (or Certificate of Analysis) for each of the chemicals used in preparing the simulant solution, containing the actual results of chemical analyses performed on the specific chemicals used
    - measured as-prepared simulant density
    - process steps applied and associated bench sheets
    - identification/description of equipment
    - observations and issues
    - dated signature (including typed or printed name) of the scientist in charge of the operation, with position title
    - dated signature (including typed or printed name) of the technical reviewer, including position title

To aid in preparation of the scaled 300-gal HSX batches, PNNL provided to NOAH the Table 4.3 recipe and the bench-scale-specific instructions for preparing the 8.53 M Na baseline AP-105 simulant (see Section 4.2.2). In addition to the make-up table and instructions, a dilution schedule (reproduced in Table 4.4) was provided. As well as the three primary HSX batches, a fourth 200-gallon batch of as-made 8.53 M Na AP-105 simulant was requested as a contingency to facilitate timely recovery from an event resulting in unexpected loss of one of the primary HSX batches or to allow rapid reformulation of the HSX simulant as dictated by preliminary scaled test results. It should be noted that Table 4.4 uses the average of the masses of calcium needed to reach the target contents of 0.3-wt%, 0.9-wt%, and 1.5-wt% calculated using the two simulant calcium sensitivities (namely 1.28 and 1.39 grams $CaCl_2$ per gram simulant – see Section 4.2.2) to estimate that needed for scaled (300-gal) batch production.

As with the 300-gal nominal simulant batch, PNNL provided NOAH a list of vendor-specific instructions for preparing the three HSX batches at scale. These instructions are similar to those provided above for batch NB preparation, but contain enough HSX-specific instructions to warrant full reproduction. These HSX-specific instructions were to:

1. Prepare the four following THSPT simulants:
    a. Batch #1: 300-gal batch of THSPT simulant with a solids-loading of 0.3 wt%
    b. Batch #2: 300-gal batch of THSPT simulant with a solids-loading of 0.9 wt%
    c. Batch #3: 300-gal batch of THSPT simulant with a solids-loading of 1.5 wt%
    d. Batch #4: 200-gal of the baseline 8.53 M Na simulant
2. Perform all preparation in vessels that have been rinsed with DI water and well-drained/dried prior to simulant make-up. [Where possible, glass vessels shall be avoided during simulant preparation as the high pH of the simulant attacks and dissolves glass.]
3. Measure the prepared simulant density at 20 °C and verify that it falls within 1.38 to 1.42 kg L^{-1} (for Batch #4) and 1.23 to 1.27 kg L^{-1} (for Batches #1 through #3).
4. Ship each batch of prepared simulant to PNNL in a new, clean, and dry 330-gal IBC tote with bottom drain.
5. Use deionized water (DI water) with a resistivity greater than 18 MΩ·cm for preparations. Water used as a rinse for equipment and transport containers (truck tanks and/or totes) need not meet this requirement.

6. Use ACS reagent grade chemicals (or equivalent) for preparations. Note: DI water is exempted from this requirement.
7. Provide a summary report of the production processes that includes:
    - reagent materials used, manufacturer, lot number, description (inclusive of impurities as listed by the manufacturer), and a Chemical Analytical Report (or Certificate of Analysis) for each of the chemicals used in preparing the simulant solution, containing the actual results of chemical analyses performed on the specific chemicals used
    - measured as-prepared simulant density
    - process steps applied and associated bench sheets
    - identification/description of equipment
    - observations and issues
    - dated signature (including typed or printed name) of the scientist in charge of the operation, with position title
    - dated signature (including typed or printed name) of the technical reviewer, with position title

In addition to those outlined above, vendor-specific instructions were given to effect dilution as governed by Table 4.4. These instructions were to:

1. Select an appropriately sized make-up vessel.
2. Add the required mass of water to the vessel (per Table 4.4). [Note: Deionized water should be used.]
3. Add the required mass of calcium chloride dihydrate ($CaCl_2 \cdot 2H_2O$) to the vessel (per Table 4.4).
4. Allow the salt to completely dissolve.
5. Combine the $CaCl_2$ solution prepared in above with the target mass of baseline 8.53 M Na simulant. The aqueous $CaCl_2$ solution should be slowly transferred into a vessel containing the baseline simulant, and the baseline simulant should be actively mixed during transfer and dilution.

4.3.2 Simulant Delivery, Receipt, and Handling Issues

As suggested by the structure of Section 4.3.1, simulant procurement for the nominal simulant (NB) and high-solids simulants (HSX) was done in two separate requests. The nominal simulant batch request was placed in early January 2021 and was due to be fulfilled (delivered to PNNL) in mid-February 2021. The 300-gallon batch was indeed prepared in early February in a Texas-based NOAH facility and readied for freight transport to PNNL's campus in Washington state. However, prior to shipment, a large portion of Texas-based industries, including NOAH and PNNL's bulk freight contractor, were impacted by historic snowfalls and low temperatures that resulted in widespread, prolonged (week-long) power outages that delayed transport of the nominal simulant until the weather improved in late February 2021.

Upon receipt of the simulant at the PNNL test facility in early March 2021, inspection found a significant quantity of precipitated solids (estimated at around 4- to 5-wt%) that appeared to be more than the expected 200 ppm (0.02-wt%) solids based on historical data and measured simulant development batches. It is suspected that the simulant was exposed to temperatures less than 20 °C during storage (possibly sub-freezing temperatures) while awaiting transport, resulting in substantive precipitation of otherwise-soluble solids. Careful examination of chemical characterization data such as the associated liquid phase composition and physical properties largely supports this assertion, as the dissolved solids content, liquid density, liquid viscosity, and sodium content were much lower than expected based on simulant chemical make-up [see Table 4.5].

Table 4.5. Discrepancies between the target nominal simulant properties and that received.

Parameter	Unit	Nominal Simulant Value Expected	Received
Undissolved Solids Content	ppm	214	40,000 to 50,000 (estimated)
Dissolved Solids Content	wt%	30.2	26.9
Liquid Density (at 20 °C)	kg m^{-3}	1250	1224
Liquid Viscosity (at 20 °C)	mPa s	3.83	3.10
Sodium Concentration	M	5.6	4.7

Inspection of the pre-delivery make-up documents provided by NOAH found no discrepancies between the requested and actual make-ups, and the pre-transport confirmation batch density of 1,240 kg m^{-3} fell within the range of "acceptable" densities specified in the vendor-specific instructions. Unfortunately, a full physical and analytical workup of the received nominal simulant batch was not feasible at the time of receipt. While the initial analytical results available suggested a [Cs] content of 11,100 µg L^{-1} (approximately 84% of its target value), a decision was made to decant as much of the solids-free liquid from the nominal batch receipt tote as possible for use in the first, reference scaled program test for baselining the DEF/IX performance, with the knowledge that the lowered [Cs] content would limit observance of IX breakthrough with the reduced (solids-free) batch volume and that potential entrainment of fine colloidal solids may impact DEF performance. And indeed, testing of the nominal batch 1) did not observe [Cs] breakthrough and 2) did observe unexpected fouling of the DEF system. However, with respect to the latter, it is not clear if the settle/decant operation inadvertently allowed solids to pass into the feed tank, as the dissolved solids content of the decanted nominal batch feed exhibited no observable/collectable quantities (indicating levels below 200 ppm). For this reason, the unexpected nominal batch filter behavior is not immediately traceable back to pre-test simulant handling. Finally, it should be noted that post-test assessment of grab samples of the nominal simulant receipt tote heel found the solids to be largely soluble in water (suggesting pre-receipt environmental conditions led to re-crystallization of the nominally soluble salts used to prepare the simulant).

The three 300-gallon HSX batches (and the single 200-gallon contingency batch) were ordered in late February 2021 and arrived at PNNL in early May 2021. Initial characterization of the HS1, HS2, and HS3 grab samples found [Cs] ranging from 13,500 to 14,000 µg L^{-1} for the three 5.6 M Na batches (expected ~13,000 µg L^{-1}) and at 19,500 µg L^{-1} for the 8.53 M Na contingency batch (expected 20,000 µg L^{-1}). Likewise, visual inspection of the simulant totes found the expected variation in simulant opacity (namely, increasing simulant opacity with increasing weight fraction of solids). As such, initial characterization of the simulants relative to expected properties, coupled with review of the make-up documents and as-prepared densities reported by NOAH for the HSX simulants, found no apparent discrepancies between the expected and as-received simulants. Later chemical and physical characterizations of the simulants, reported in Section 4.3.2, for samples collected before and during scaled PNNL testing, largely confirmed that the simulant properties fell at or near the expected values based on simulant development efforts.

The only difficulty encountered during the pre-test handling of the HSX simulants was related to sedimentation of simulant precipitated solids prior to simulant receipt and during pre-test storage. Here, initial samplings of the HS1 test simulant after dispersion and transfer of the initial ~205 gal from its receipt tote to the scaled-test stand feed tote suggested a substantially lower solids content of 670 ppm than the expected (3,000 ppm). During the second batch transfer of the remaining HS1 simulant from the receipt tote to the feed tote, substantive efforts were undertaken to mix the contents of the HS1 receipt tote, resulting in an increased feed tote solids content of 1,000 ppm (still lower than the expected 3,000 ppm). Visual inspection of the HS1 receipt tote heel found a substantial quantity of solids, of mixed crystalline and amorphous sludge-like phases, remained in the vessel after the final transfer.

It is suspected that solids cohesion, combined with the limited ability to effectively mix the receipt tote contents from its upper access point, prevented adequate dispersal of these solids. It should be noted that the solids formed during development of the HSX simulant did not show similar formation of mixed crystalline/amorphous solids and a did not settle to form a cohesive, difficult-to-redisperse bed in its native supernatant (although filtration and subsequent drying of the HSX solids did form a hard, porous puck). Thus, it was unclear whether the nature and accumulation of the solids in the HS1 tote resulted from an inherent problem with scaling 1-L bench-scale preparations to large 300-gal engineering-scale batches, environmental conditions during transport and pre-test storage, differences in mixing energy at scale, or some combination thereof.

It should be noted that, similar difficulties were encountered when attempting to fully disperse the HS2 tote. Here, specific efforts were made to maximize dispersion of the receipt tote contents prior to transfer into the test (feed) tote. Despite these efforts, the scaled test system feed tank contents only showed a concentration of 3,000 ppm (approximately one-third of the 9,000-ppm targeted). Thus, the phenomenon driving agglomeration/accumulation of solids appears to impact all HSX preparations at scale rather than being localized to just the HS1 simulant. Ultimately, inability to achieve the expected target test contents in the HSX simulants was offset by the significant fouling proclivity at the available, lowered solids contents in both the HS1 and HS2 scaled tests (1,000 ppm and 3,000 ppm, respectively). Specifically, frequent backflushing of the DEFs was required to maintain acceptable pressure, even at the lowered contents of 1,000 and 3,000 ppm, challenging the minimum filter operation times. For the HS2 test at 3,000 ppm in particular, rapid fouling required relaxing the 2-psid action limit (to a higher pressure) to initiate backflush operations to effect timely execution of the test. As a result, it was decided that operations at the full 15,000-ppm HS3 solids content would be infeasible with the current simulant and solids chemistry. Consequently, the solids content targeted for the HS3 test was lowered from 15,000 ppm to $\leq$ 1,000 ppm.

4.3.3 Tested Simulant Properties

The current section outlines the chemical and physical properties of the nominal (NB) and high-solids (HSX) simulants. Here, the properties are largely presented in the order introduced in Section 4.1.2. In particular, the physical properties presented below and on the pages that follow are ordered as:

- liquid and solid phase chemistry by ICP, IC, and TC/TOC (as applicable)
- precipitated solid mineral phase identification by XRD
- total solid and dissolved content by filtration-assisted gravimetric analysis
- liquid phase density by glass pycnometry
- liquid phase viscosity as measured by concentric cylinder rheometer
- particle size distribution by laser diffraction

4.3.3.1 Liquid and Solid Phase Simulant Chemistry

Table 4.6, Table 4.7, Table 4.8, and Table 4.9 present the liquid and solid phase chemistry of the nominal (NB) and HSX simulants, as quantified by combination of ICP-OES, ICP-MS, IC, and TC/TOC (as applicable). The tables itemize the as-made (i.e., the test feed) and expected (based on simulant make-up) analyte contents of the simulants. Table 4.7, Table 4.8, and Table 4.9 have separate entries for 1) the liquid, 2) the solid, and 3) the total analyte contents of the simulants. In all four tables, the "ratio" is the ratio of the as-made content to the expected content. Under-reported ("lean") and over-reported ("rich") feed components are highlighted in red text in the tables.

As discussed above, the nominal simulant receipt tote contained a substantive quantity of solids not expected by historical and current bench-scale preparations but presumed to have precipitated as a result of exposure to cold (possibly freezing) temperatures before and during transport from Texas (where the simulant was prepared) to PNNL's Washington campus (see Section 4.3.2 for details). To provide the nominally solids-free simulant anticipated and planned-for in nominal simulant testing, the solids-free supernatant from the recipe tote was decanted and pumped into the feed tank. Filtration of 1-L grab samples of the decanted nominal simulant from the feed tank found no measurable solids. As such, Table 4.6 presents only the liquid (and presumably whole simulant) analyte content. As expected from exposure to cold and subsequent analyte content loss to precipitated solids, the analyte content of the decanted nominal simulant generally falls (with exception of Al and TOC) below the target (expected) values based on simulant make-up. Analytes that are significantly impacted by precipitation loss appear to be Cs, Na, PO_4, and possibly CO_3 (based on lowered total carbon). Not shown in Table 4.6 is the free OH concentration, which was measured to be 1.32 M. The measured value compares well with its expected value of 1.41 M, especially when considered against the overall loss of dissolved solids that resulted from pre-test handling of the nominal simulant batch. As noted previously (and as shown in the physical property measurements provided below), the loss of analyte content manifests as lower dissolved solids content, liquid density, and viscosity.

With respect to Al, its as-made content is approximately 15% higher than its expected content. It is unclear why it would be larger than expected beyond potential system contaminants or analytical error. Of greater concern is the large excess of organic carbon suggested by the results. While organic contamination of the system was suspected based on poorer-than-anticipated filtration performance (see Section 6.2 for a full discussion) and based on recovery of some solids preferentially soluble in organic liquid during post-test cleaning of the scaled DEFs, all chemical analysis results seem to suggest higher-than-expected total organic carbon (see liquid phase results for HSX simulants in Table 4.7, Table 4.8, and Table 4.9) and correspondingly lean total inorganic carbon (TIC) results. The possibility of organic contamination in later tests is low, given the high throughput of caustic simulant and cleaning solutions through the system (which should flush out any residual organics in the system from fabrication of lines or servicing of pumps). The persistence of TOC at the expense of TIC (with nearly expected total carbon content for the HSX simulant in Table 4.7, Table 4.8, and Table 4.9) would suggest a potential issue with the analytical method that partitions total carbon into TOC and TIC.

Table 4.6. Nominal Simulant Liquid Composition. Note: analysis found no measurable solids in the nominal batch used for scaled testing (thus, the table below represents the liquid analyte content of the simulant). The as-made composition corresponds to the test feed material. The expected composition corresponds to that defined by the recipe. The ratio is the ratio of as-made to expected concentrations. Concentrations are in mg of analyte per liter of simulant. The ratios of under- or over-represented feed components have been highlighted in red. “-- --” denotes a concentration either not measured or below detection.

	Concentration, mg L^{-1}		
Analyte	As-Made	Expected	Ratio
Al	5,120	4,479	1.143
Fe	1.21	-- --	-- --
Ca	1.34	-- --	-- --
Si	5.62	-- --	-- --
Cs	11,100	13,284	0.836
Na	108,000	128,679	0.839
K	4,570	4,770	0.958
F	-- --	-- --	-- --
NO_3	105,000	110,378	0.951
NO_2	45,000	46,927	0.959
PO_4	2,010	4,103	0.490
SO_4	5,800	6,350	0.913
Cl	4,130	4,325	0.955
Total C	3,330	5,914	0.563
TOC	3,010	305	9.866
TIC	320	5,609	0.057

Table 4.7. High-Solids (HSX) Simulant Liquid Composition. The as-made composition corresponds to the test feed material. The expected composition corresponds to that defined by the recipe (including $CaCl_2$ additions to effect precipitation) and represents the full simulant composition (not just the fraction expected to remain in liquid). The ratio is the ratio of as-made to expected concentrations. Concentrations are in mg of analyte per liter of simulant. The ratios of under- (lean) or over-represented (rich) feed components have been highlighted in red. “-- --” denotes a concentration either not measured or below detection. Simulant make-up estimates include added calcium and chloride needed to effect solids precipitation.

	Expected Conc., mg L^{-1}			As-Made Conc., mg L^{-1}			Ratio		
Analyte	HS1	HS2	HS3	HS1	HS2	HS3	HS1	HS2	HS3
Al	13,600	12,100	11,900	13,683	13,568	13,485	0.994	0.892	0.882
Fe	5.00	4.64	1.48	4.60	4.56	4.53	1.087	1.018	0.327
Ca	229	1,000	238	1,062	3,116	5,165	0.216	0.321	0.046
Si	48.0	47.6	43.9	42.3	41.9	41.7	1.135	1.135	1.053
Cs	14,100	14,000	14,200	13,375	13,262	13,181	1.054	1.056	1.077
Na	125,000	118,000	118,000	129,560	128,468	127,684	0.965	0.919	0.924
K	6,350	5,770	5,990	4,803	4,762	4,733	1.322	1.212	1.265
F	-- --	-- --	-- --	163	161	160	-- --	-- --	-- --
NO_3	99,200	98,800	98,300	102,042	101,182	100,565	0.972	0.976	0.977
NO_2	55,500	54,500	53,600	57,290	56,808	56,461	0.969	0.959	0.949
PO_4	1,770	1,650	1,600	922	914	908	1.920	1.805	1.761
SO_4	2,680	2,140	2,130	1,631	1,617	1,607	1.644	1.324	1.326
Cl	5,630	8,960	11,600	5,740	9,340	12,942	0.981	0.959	0.896
Total C	7,930	7,600	7,470	7,629	7,565	7,519	1.039	1.005	0.994
TOC	6,040	4,720	4,780	2,355	2,335	2,321	2.565	2.021	2.060
TIC	1,890	2,880	2,690	5,274	5,230	5,198	0.358	0.551	0.518

Table 4.8. High-Solids (HSX) Simulant Solids Composition. See Table 4.7 text for additional details on table entry formatting and symbols. No highlighting of lean/rich component ratios is done for the current table.

	Expected Conc., mg L^{-1}			As-Made Conc., mg L^{-1}			Ratio		
Analyte	HS1	HS2	HS3	HS1	HS2	HS3	HS1	HS2	HS3
Al	252	1,017	1,496	13,683	13,568	13,485	0.018	0.075	0.111
Fe	8.69	8.00	9.78	4.60	4.56	4.53	1.890	1.754	2.159
Ca	805	2,267	3,034	1,062	3,116	5,165	0.757	0.728	0.587
Si	1.43	2.72	7.49	42.3	41.9	41.7	0.034	0.065	0.180
Cs	-- --	-- --	-- --	-- --	-- --	-- --	-- --	-- --	-- --
Na	307	1,025	1,705	129,560	128,468	127,684	0.002	0.008	0.013
K	16	54	88	4,803	4,762	4,733	0.003	0.011	0.019

Table 4.9. High-Solids (HSX) Simulant Composition (Comprising Solids plus Liquid Content). See Table 4.7 text for additional details on table entry formatting, symbols, and highlighting.

	Expected Conc., mg L^{-1}			As-Made Conc., mg L^{-1}			Ratio		
Analyte	HS1	HS2	HS3	HS1	HS2	HS3	HS1	HS2	HS3
Al	13,852	13,117	13,396	13,683	13,568	13,485	1.012	0.967	1.993
Fe	13.7	12.6	11.3	4.60	4.56	4.53	2.978	2.772	2.485
Ca	1,034	3,267	3,272	1,062	3,116	5,165	0.973	1.049	0.633
Si	49.4	50.3	51.4	42.3	41.9	41.7	1.168	1.200	1.233
Cs	-- --	-- --	-- --	-- --	-- --	-- --	-- --	-- --	-- --
Na	125,307	119,025	119,705	129,560	128,468	127,684	0.967	0.926	0.938
K	6,366	5,824	6,078	4,803	4,762	4,733	1.325	1.223	1.284

Table 4.7, Table 4.8, and Table 4.9 provide, respectively, the liquid, solid, and total (solid + liquid) phase analyte speciation for all three HSX simulants tested. Here, the expected values are based on the full simulant make-up (regardless of where the analytes actually end up) and are the same across all three phases. Thus, the ratio for the liquid (Table 4.7) and solids (Table 4.8) provides a rough means of estimating how a specific analyte partitions, whereas the total composition (Table 4.9) provides an estimate of total recovery. Unfortunately, the analyte content testable for the solid material is limited due to the insoluble nature of the solids precipitated in caustic or neutral media used to perform the IC analysis. As such, anion content for the solids table (and therefore the total simulant table) is missing.

Evaluation of the compositions in Table 4.7, Table 4.8, and Table 4.9 finds the contributions of major analytes and salt anions (Al, Cs, Ca, Si, Na, Cl, NO_2, and NO_3) to fall largely in line with expectations – all have ratios of nearly 1, where measurable, and their entries do not defy expectation when only assessable through liquid contents (e.g., Cs should be close to unity in the liquid phase, as should the relatively soluble nitrate and nitrite salt anions). Calcium (Ca) is measurable in the liquid in quantities greater than may be expected, given that it is relatively insoluble in high-caustic media. However, the content of Ca in the solids is greater than in liquid fraction, and nearly 100% of the added calcium being recovered in the HS1 and HS2 simulants seems reasonable.

The measured free OH contents of high-solids simulants HS1, HS2, and HS3, were 1.19, 1.10, and 1.06 M, respectively. These results compare favorably with the predicted values based on HSX simulant make-up, which were 1.15, 1.14, and 1.13 M for HS1, HS2, and HS3, respectively. The measured free OH results show greater decrease at increasing simulant solids loadings (i.e., as solids content increases from 0.3 to 1.5-wt%) than expected from the simulant make-up calculations. This increase likely reflects an increasing loss of OH content to the solid precipitates. As discussed in Section 4.3.3.2, many of the HSX precipitated solids identified in XRD analysis include OH bearing mineral phases likely supplied, in part, by free OH in the simulant liquid phase.

On the other hand, several analytes appear in the simulant at quantities much greater than expected based on their make-up contents. Iron (Fe) is found at or below expected values in the simulant (which is inconsistent with its presumed role in hydrolyzing to form iron hydroxide upon caustic addition to the simulant during preparation). Indeed, examination of the solids content finds greater-than-expected Fe content (at 2.5 to 3.0 times greater than expected for the simulant as a whole). While it was possible that Fe could have been slightly elevated due to a rounding error in the NOAH formulation documents provided at simulant receipt, that potential error would only account for, at most, a 30% increase in iron loading rather than a three-fold increase. Other components are similarly over-represented, including K, PO_4, and SO_4. All over-represented components are present at loadings less than 10,000 ppm, suggesting that potential interference from the high-salt matrix impacted the analysis.

Of final interest is the carbon chemistry of the HSX simulants. The total carbon measured for all HSX simulants (and accessible only through the liquid chemistry data) appears to fall in line with that expected from simulant make-up. However, evaluation of the TOC finds that organic carbon is over-represented by a factor of 2.0 to 2.5, which results in under-represented TIC (as TIC is calculated as the difference between TC and TOC). The over-representation of TOC in all HSX measurements mirrors that observed in the nominal simulant (NB) chemistry, albeit to a much lower extent than the NB simulant. As noted previously, this over-representation cannot be directly traced to any disparities between the requested and executed simulant make-up of the 300-gal HSX batches, or any obvious contamination events during pre-test handling of the HSX simulants, or from the scaled test system itself. Moreover, it is unlikely that any hold-up of organic contaminants (grease/soaps) inadvertently introduced during system assembly would persist across system shakedown, the nominal simulant test, and the three high-solids tests. As such, the specific TOC and corresponding TIC values for the simulant are anomalous and may be impacted by interference from the high-salt matrix. Regardless, the TC results appear consistent with the expected values and do not suggest loss of carbonate or organics to the solid precipitates.

4.3.3.2 Solid Phase Chemistry

Samples of precipitated solids in the HSX simulants were collected during solids content analysis and submitted for mineral phase characterization by XRD. The XRD characterization and resulting data should be considered FIO. Table 4.10 provides a summary of the mineral phases identified for the HS1, HS2, and HS3 simulants. As noted in previous sections, no solids were recovered from the grab samples of the decanted nominal simulant (NB) used in testing. Solid mineral phases identified across HS1, HS2, and HS3 are largely identical and comprise mixed calcium- and aluminum-bearing hydroxide components (katoite and hydrocalumite) and sodium nitrate/nitrate salts (which could possibly be liquid phase contaminants from the filtration processes). The only observed change in mineral phase with increasing simulant solids content is an apparent shift from portlandite [$Ca(OH)_2$ – observed in HS1 and HS2] to bayerite [$Al(OH)_3$ – observed in HS2 and HS3 (but not HS1)]. Regardless, all observed phases seem reasonable based on the means of producing precipitated solids in the simulant (namely calcium addition) and the existing composition of the simulant itself (which is rich in aluminum, hydroxide, and nitrate/nitrite). Quantitative XRD analysis was limited to the HS2 solids. It suggested that the HS2 solids were largely amorphous (~63-wt%). The remaining crystalline material was dominated by hydrocalumite (~20-wt% of the solids) and katoite (7.5-wt%). The remaining identified crystalline solids, bayerite, portlandite, and both nitrate/nitrite salts, were each present at ~2-wt%. The balance of crystalline solids identified were present in negligible amounts.

Table 4.10. Mineral phases identified in HSX simulant precipitated solids by XRD (FIO).

Simulant	Identified Phase	Phase Formula
HS1	Katoite	$Ca_3Al_2(OH)_{12}$
	Hydrocalumite	$Ca_2Al(OH)_6Cl(H_2O)_2$
	Portlandite	$Ca(OH)_2$
	Sodium Nitrate	$NaNO_2$
	Nitratine	$NaNO_3$
HS2	Katoite	$Ca_3Al_2(OH)_{12}$
	Hydrocalumite	$Ca_2Al(OH)_6Cl(H_2O)_2$
	Portlandite	$Ca(OH)_2$
	Bayerite	$Al(OH)_3$
	Sodium Nitrate	$NaNO_2$
	Nitratine	$NaNO_3$
HS3	Katoite	$Ca_3Al_2(OH)_{12}$
	Hydrocalumite	$Ca_2Al(OH)_6Cl(H_2O)_2$
	Bayerite	$Al(OH)_3$
	Sodium Nitrate	$NaNO_2$
	Nitratine	$NaNO_3$

4.3.3.3 Simulant Solids Content, Density, and Viscosity

Table 4.11 provides a summary of the solids content (both dissolved and undissolved) of tested simulants. The table also includes the expected values based on historic simulant make-up efforts and simulant development efforts. As discussed previously, the nominal simulant contained an unexpected quantity of precipitated solids upon receipt (because of suspected exposure to freezing temperatures due to abnormal weather that delayed transit to the testing facility). The solids-free liquid fraction of the nominal simulant receipt vessel was decanted. Sampling of the decanted nominal simulant found no measurable solids in a 1-L grab sample (suggesting contents below the 200-ppm value derived from simulant make-up). The loss of nominal simulant analytes to receipt tank precipitates is reflected in the lowered dissolved solids content of the feed (26.9-wt% measured versus 29.7-wt% expected based on make-up).

Similarly, suspected agglomeration and sampling issues from the receipt totes greatly lowered the available solids content for HS1 and HS2 testing. Best-efforts to redisperse settled solids in the receipt tank only achieved solids contents that were one-third the targeted value in HS1 and HS2. Post-test inspection of the HS1 receipt vessel confirmed that a substantial quantity of settled solids remained in the tank after transfer, suggesting that an inability to re-suspend those solids was the main contributor to lowered feed tank solids content (rather than underestimates of the calcium sensitivity of the simulant when produced at large scale). While the HS3 measured contents of 970 ppm (for the initial period of HS3 operations) and 500 ppm (for the later period of HS3 operation) were substantively lower than the 15,000 ppm originally targeted by the HS3 test, these lower 500-1,000 ppm test contents were planned (and achieved by strategic settle-decant operations of the HS3 receipt tote) to address difficulties encountered during scaled DEF testing at the HS2 loading of 3,000 ppm. For all HS3 testing, the dissolved solids content of the feed was largely consistent at just above 32-wt%. This content was slightly larger (and more consistent) than observed in the bulk of high-solids simulant development testing (an average of 31.3-wt% over eight simulant iterations with a standard deviation of ± 0.7-wt%). The higher dissolved solids content may explain some of the analyte over-representation in the HSX simulant seen in Table 4.7, Table 4.8, and Table 4.9; however, as noted before, this is not supported by any noted deviations in simulant make-up.

Table 4.12 provides a summary of the liquid phase density and viscosity measured (at four representative simulant temperature ranges spanning 15 to 30 °C). Both density and viscosity data sets are within expectations for the TSCR-relevant feeds and show the expected functional relationship with temperature (namely, both density and viscosity decrease with increasing temperature). Note that the measured viscosities at 20 °C are slightly higher than the simulant viscosities assumed in many of the scaling calculations in Section 3.0 (typically assumed to be 3 or 4 mPa s). The impact of the measured viscosities on those calculations is minimal and other quantities used in those calculations (the density of the solid particles, for example) are still bounding values for the test simulants. In Table 4.13, the parameters for the viscosity relationship described in Eq. (3.26) are given based on the data in Table 4.12.

Table 4.11. Solids content (dissolved and undissolved) of the nominal (NB) and HSX test simulants. The expected values are based on simulant make-up (or bench-scale measurements of prototype simulants in the case of HSX dissolved solids content).

	Undissolved Solids Content, ppm		Dissolved Solids Content, wt%	
Simulant	Measured	Expected	Measured	Expected
Nominal (NB)	n/m(a)	214	26.9	29.7
HS1-A(c)	670	3,000	32.3	31.3 ± 0.7(b)
HS1-B(d)	930	3,000	32.3	31.3 ± 0.7(b)
HS2	3,000	9,000	32.1	31.3 ± 0.7(b)
HS3-A(f)	970	15,000(e)	32.2	31.3 ± 0.7(b)
HS3-B(g)	500	15,000(e)	32.1	31.3 ± 0.7(b)

(a) No measurable quantity of solids could be recovered from a 1-L grab sample.
(b) Range based on variation seen in high-solids simulant precipitation quantification tests.
(c) -"A" corresponds to the HS1 feed batch of the initial 205 gal pumped from the receipt tote to the feed tote.
(d) -"B" corresponds to the HS1 feed batch after vigorous mixing and transfer of the remaining volume of receipt tote simulant during the second half of testing.
(e) The solids content of HS3, initially targeting 15,000 ppm, was deliberately lowered through settle-decant operations to provide a content around 500 ppm rather than the full target of 15,000 ppm.
(f) Test HS3 was operated at two solids loadings. The initial solids loading was 970 ppm (see Section 6.5)
(g) Test HS3 was operated at two solids loadings. The final solids loading was 500 ppm (see Section 6.5))

Table 4.12. Liquid phase density and viscosity of the as-tested nominal (NB) and high-solids (HSX) simulants.

Temperature	Density, kg m^{-3}			
[°C]	NB	HS1	HS2	HS3
15	1,227	1,273	1,269	1,267
20	1,224	1,271	1,266	1,264
25	1,222	1,268	1,263	1,262
30	1,220	1,265	1,261	1,258
	Viscosity, mPa s			
	NB	HS1	HS2	HS3
15	3.50	4.71	5.09	4.93
20	3.10	4.11	4.39	4.27
25	2.73	3.62	3.81	3.71
30	2.42	3.21	3.34	3.25

Table 4.13. Liquid viscosity parameters of the as-tested nominal (NB) and high-solids (HSX) simulants.

Simulant	Viscosity Parameter			
	$\mu_{S,o}$, mPa s	λ, K	T_o, K	R^2
NB	2.73	2156	298.15	0.9998
HS1	3.63	2230	298.15	0.9999
HS2	3.82	2460	298.15	0.9998
HS3	3.72	2433	298.15	1.0000

4.3.3.4 Precipitated Solids Particle Size Distribution

Figure 4.2 shows the particle size distribution (PSD) of a representative sampling of HSX precipitates derived from bench-scale testing. A similar size distribution for the nominal batch is not available, as no measurable solids appeared to be present in the as-tested nominal batch system. For the HSX simulant solids, efforts were made to maintain the as-precipitated state of agglomeration in the native, high-ionic-strength suspending phase. Namely, the HSX solids sampled for size analysis were taken directly from the prepared suspension itself (without assistance of forced separation by filtration or centrifugation) and diluted using filtered supernatant liquid from the same preparation. The data shown correspond to solids derived from an HSX dilution targeting 0.9-wt% solids. For reference, Figure 4.2 compares the HSX precipitate PSD to that of the iron phosphate simulant previously tested by Daniel et al. (2018) [albeit under crossflow conditions]. The HSX precipitate PSD shown in Figure 4.2 is taken after brief application of sonic energy and under continuous shear and should be representative of the size distribution under mixed conditions. However, it should be noted that the size distribution of the HSX simulant is sensitive to shear and sonication. Indeed, application of sonic energy greatly reduces the PSD of HSX precipitate (see Figure 4.3), suggesting the existence of weak agglomerates even in bench-scale preparation of the simulant. A strong tendency of the simulant solids to agglomerate is expected, given the high ionic strength of the 5.6 M Na suspending phase (which collapses any electrical double-layer that could prevent agglomeration under weak ionic conditions). Comparison of Figure 4.2 and Figure 4.3 suggests that the large 100- to 1000-µm particle populations correspond to weak to moderate-strength agglomerates. It is also possible that some of the largest particles (above 300 µm) are artifacts of the analysis itself, as this size typically exceeds the suspending capability of the flow cell used to effect suspension (a small-volume Malvern Mastersizer Hydro µP dispersion unit). Regardless, the Figure 4.3 result highlights the sensitivity of the solids to local shear and dispersion and their proclivity to agglomerate (a phenomenon relevant to the observed settling behavior in the HSX simulant receipt totes and possibly to the filter fouling proclivity of the HSX solids).

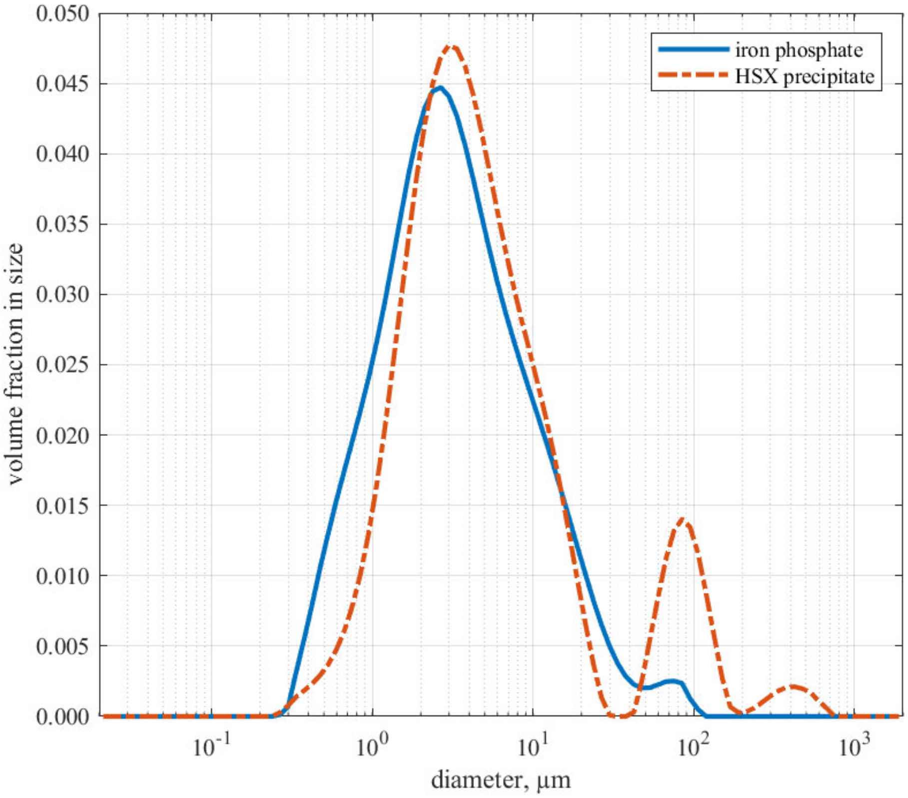

Figure 4.2. Representative particle size distribution (after brief sonication) of the HSX precipitate (red dotted-dashed curve). For comparison, an iron phosphate simulant tested in Daniel et al. (2018) and found to challenge previous LAW filtration operations is shown (blue solid curve).

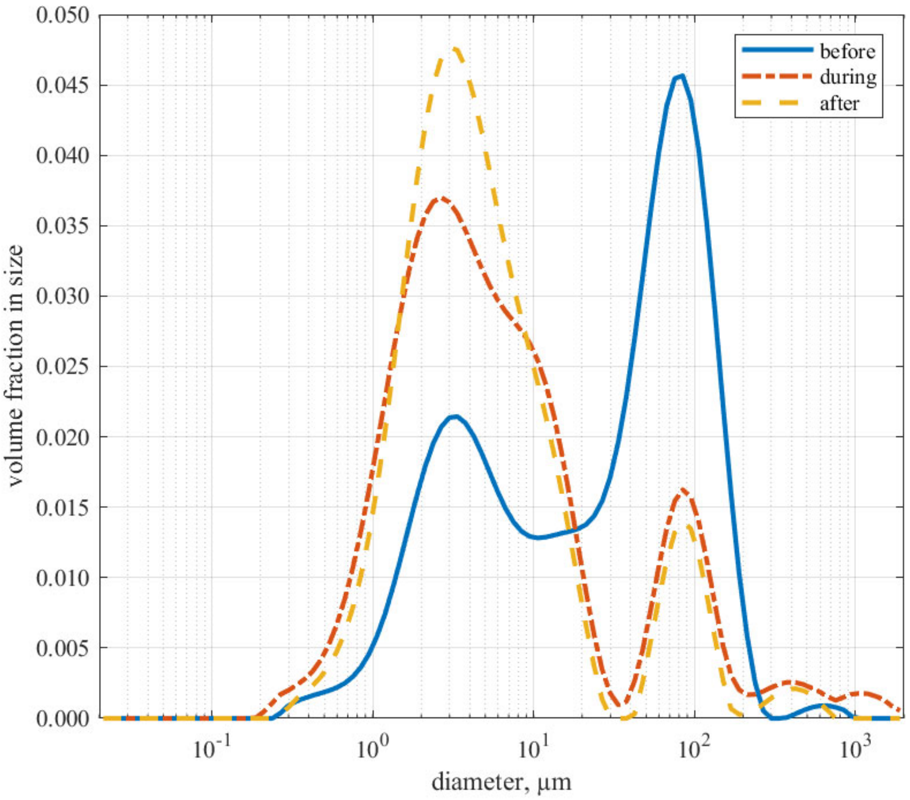

Figure 4.3. HSX simulant solids size distribution as a function of applied sonic energy. The distribution "before" (solid blue curve), "during" (dashed-dotted red curve), and "after" (dashed yellow curve) are shown. Sonication is accomplished using an in-cell sonicator. All curves correspond to the same solids aliquot.

4.4 Simulant Development Concluding Remarks

The preceding sections have discussed in detail the technical basis for nominal and high-solids simulant selection for scaled testing, the developmental efforts undertaken to render the solids content of the high-solids simulant suitable for testing, scaled production of 300-gal batches for testing, and the physical and chemical properties of those scaled test batches. For the single 300-gal batch of nominal simulant prepared, the as-tested composition of key analytes and key physical properties were lower than formulated and measured at bench-scale. The source of this disparity is most likely environmental exposure to sub-freezing (or low) temperatures while the simulant was staged for transport during the historic snowstorm of 2021 (which led to widespread industrial and residential power outages in Texas, where the simulant was prepared, and delayed transport of the simulant for two weeks). With respect to the HSX simulant, the analyte content and physical properties of the simulant were largely in line with expected values from simulant development. However, the precipitated HSX solids were more difficult to re-suspend in the receipt tote than simulant development efforts had indicated, leading to a lower pre-test recovery of solids from the receipt tote and ultimately lower-than-targeted test concentrations for the first two high-solids tests. As will be discussed in the next section, the inability to achieve the desired target test solids concentrations of 3,000 and 9,000 ppm in tests HS1 and HS2, respectively, suggested that operating at higher solids loadings would lead to a physically unimplementable backflush schedule.

5.0 Test Approach and Conditions

This section contains an overview of test operations used to collect the high-solids performance data. Included in the section is a discussion of the target and actual test conditions (Section 5.1), the general steps used to perform the testing (Section 5.2), and some notable differences between tests due to configuration changes in the system (Section 5.3).

5.1 Test Matrix

As described in Section 3.1, satisfying the test objectives required performing tests across a range of solids loading spanning the nominal value (~200 ppm) to 15,000 ppm (1.5 wt%). To meet this requirement, four tests were planned. The conditions of each test are summarized in this section; for context, the tests that were originally planned at the outset of the test program are discussed first. This is followed by the conditions of the tests as they were actually conducted.

5.1.1 Planned Test Matrix

The high-solids performance tests were planned to comprise a baseline test and three tests with increasingly higher solids loading as presented in Table 5.1. The baseline test, NB1, was designated to use the 5.6 M Na nominal simulant – a frequently-studied simulant in historical unit operations testing relevant to TSCR – that would serve as a measure of "nominal" TSCR performance in the scaled system. Each test identified as HS# would use the high-solids simulant described in Section 4.0 at different solids loadings selected to be at 20, 60, and 100% of the 15,000-ppm solids limit identified in the TSCR design basis (Ard 2019). All four tests had the same target values for simulant volume to process (300 gal) at a controlled flow rate of 130 mL min^{-1} and a feed temperature of 22 °C (± 3 °C). The simulant volume and flow rate arise from the scaling basis described in Section 3.2.

Table 5.1. Matrix of TSCR High-Solids Tests Planned to be Performed at the Outset of Testing

Test Identifier	Target Solids Loading (ppm)	Target Liquid Flow Rate (gpm [mL min^{-1}])	Target Simulant Feed Temperature (°C)	Target Simulant Volume to Process (gal [L])	Simulant for Use
NB1	200	~0.034 [130]	22 ± 3	300 [~1140]	5.6 M Nominal Simulant
HS1	3,000	~0.034 [130]	22 ± 3	300 [~1140]	High-Solids Simulant
HS2*	9,000*	~0.034* [130]	22 ± 3*	300 [~1140]	High-Solids Simulant
HS3*	15,000*	~0.034* [130]	22 ± 3*	300 [~1140]	High-Solids Simulant

* Conditions for HS2 and HS3 were intended to (potentially) be adjusted based on the outcome of HS1. For example, if the performance of HS1 was greatly impacted at 3,000 ppm solids loading, the HS2 solids loading could be reduced.

The performance of the system at the target solids loading for HS1, i.e., simulants with solids loadings greater than 1,000 ppm, was considered highly uncertain due to the absence of prior experimental data. Thus, the major reason the testing was performed in order of increasing solids loading was to enable adjustments to the conditions of HS2 and HS3 contingent on the results of HS1 (NB1 was expected to perform satisfactorily based on prior data). Adjustments could be made to the simulant (to manipulate the solids loading), the target flow rate (to manipulate the rate of change in the differential pressure across the system), or the system temperature (if of interest to observe the impact of temperature on solid precipitation dynamics, fluid viscosity, and ion exchange performance).

5.1.2 Executed Test Matrix

The four tests as they were executed are shown in Table 5.2. Compared to the planned conditions of the tests as given by Table 5.1, the tests mainly differed in the measured solids loading and the total amount of volume processed during the testing. Flow rate and temperature control to the target values was achieved readily in the test system and there were no significant deviations. The actual solids loading measured from feed samples collected from the test system were generally below the intended values by a significant amount (approximately a factor of three for HS1 and HS2). This is attributed primarily to the effect of exposure, during shipping and prolonged storage, to uncontrolled environmental conditions that complicated mobilization of the simulant into the feed tank; to a lesser extent, simulant make-up at larger scale could have also been a contributor (this cannot be assessed because the simulant was not assessed prior to being shipped). The solids concentration of Test HS3 was purposely adjusted to obtain additional relevant information from the test system.

Table 5.2. Matrix of TSCR High Solids Tests As Performed

Test Identifier	Actual Solids Loading in Feed (ppm)	Actual Mean Liquid Flow Rate (mL min^{-1}])[a]	Actual Mean Simulant Feed Temperature (°C)[a]	Simulant Volume Actually Processed (gal [L])	Simulant Used
NB1	Negligible[b]	130.0 ± 0.1	22.0 ± 0.2	~279 [1058]	5.6 M Nominal Simulant
HS1	670, 930[c]	130.0 ± 0.7	21.9 ± 0.2	~295 [1115]	High-Solids Simulant
HS2	3,000	129.3 ± 4.1	21.8 ± 0.4	~158 [598]	High-Solids Simulant
HS3[d]	970 / 500	129.9 ± 1.0	22.3 ± 0.2	~300 [1137]	High-Solids Simulant

(a) Based on an average of all measurements over the test operation; also shown is one standard deviation of the average.
(b) A small amount of solids was present in the sample, but not enough to quantify.
(c) In Test HS1, the solids loading was measured on two feed samples that were collected during the test – the first at the beginning of the test, and the second at approximately 50 hours. Shown in the table are both values from the solids analysis of the samples.
(d) Test HS3 modified the simulant in the feed tank approximately halfway through the test. The modification was an ~50% dilution with solids-free simulant supernatant. The values are the solids loadings for the two halves of the test.

The actual simulant volume processed in each test differs slightly from the target of 300 gal for Tests NB1 and HS1, but this was caused by the amount of volume that could be recovered from the totes in which the simulant batches were shipped. The significant reduction in Test HS2 resulted from an intentional truncation of test operations due to the system's degraded performance during the test. By the time Test HS2 was discontinued, the DEFs had exhibited a consistent and repeatable cycle for more than 72 hours but maintaining flow in the system was challenged by line plugging in multiple locations. These challenges are discussed in more detail in a later section.

5.2 Test Operations

This section outlines the typical steps performed in conducting the four tests described in Table 5.2. Each test contained four elements:

1. Preparation (as required) of the simulant and loading it into the test system.
2. Preparation of the test system and start-up activities.
3. Test operations at the target conditions.
4. Shutdown of operations and post-test observations.

Of these four elements, the first two preparation steps sometimes occurred simultaneously in practice, but both were complete before proceeding with testing. Additional details of these elements are provided in the subsections that follow; when applicable, operational steps specific to a subset of the four tests are described.

For convenience, most equipment and instruments are referred to by their identifiers as shown in Figure 3.12. Refer to Section 3.5 for additional information on the configuration of the test system.

5.2.1 Simulant Preparation and Loading

Before a test was started, the appropriate batch of simulant that was prepared by NOAH Technologies had to be received, sampled, and loaded into the test system. These steps often occurred at the same time as the CST washing and loading steps (Section 5.2.2) since different parts of the test system were involved; the simulant loading primarily involved the feed tank and recirculation loop. The general steps involved with simulant preparation and loading were:

- Receive the simulant batch from NOAH Technologies into the Applied Process Engineering Laboratory (APEL) high-bay and examine for abnormalities. The batches were shipped in intermediate bulk container (IBC) totes of 330-gallon maximum capacity.
- Collect as-received samples from the simulant tote and save for archive. An FIO analysis was performed on a liquid sample to confirm that the dissolved cesium concentration was as expected.
- Prepare the tote contents for transfer into TK-01; usually the tote was sparged with low-pressure air using a handheld 1/2-in. steel tube for 10-15 minutes to re-suspend the solids (they were often settled in a layer on the bottom). In the case of Test NB1, no sparging was performed because the tote was decanted to minimize the quantity of solids sent forward.
- TK-01 was a 275-gal IBC tote and could not accept the entire volume contained in the simulant totes (which were 330-gal IBC totes with 300 gallons of simulant). Once the shipped tote was ready for transfer, it was pumped into TK-01 using a 1-in. air-operated diaphragm pump. The inlet to the pump ended in a polyvinyl chloride lance that was used to extract simulant through the 6-in. port on the top of the tote. Pumping was performed from the top to avoid sending slugs of solids into TK-01 all at once (some of the solids were much larger and difficult to disturb off the bottom).
  - TK-01 was usually filled approximately 75% full initially (~205 to 210 gallons). The remainder of the simulant was added sometime during the third day of the test by the same method.
  - Once the pivot nozzle mixer was submerged under the simulant in TK-01, the recirculation loop was turned on to assist with mixing the contents and mobilizing the solids. This was done with the valve going to the DEF feed line closed (recirculation system was isolated).

  - In the unique case of Test HS3, the simulant tote was initially decanted to add ~150 gal of supernatant into TK-01, then the tote was sparged. A small amount of solids-laden simulant was then added (~30 gal) to dilute the solids content in the test. After a sample analysis determined that the solids content was higher than the target, an additional ~50 gal of decanted liquid was added from leftover Test HS2 simulant after ~10 gal of the TK-01 contents were removed via the bottom drain.
- Once TK-01 was loaded, the recirculation loop continued to run to bring the feed material to the target temperature of 22 °C using HX-01. This took up to a couple of hours depending on the starting temperature of the simulant.
- Feed verification samples were collected from the recirculation system, usually at V-02, after loading was completed and the contents had been recirculating for at least 15 minutes. These samples were used to estimate the solids loading, particle size distribution, density, and chemical composition of the simulant.

Once these steps were completed, the simulant in TK-01 was ready for testing. The recirculation loop was run continuously to agitate the contents and provide thermal control until the test system was ready to commence with normal operations.

5.2.2 System Preparation and Startup

The initial step in system preparation was to fill the test system with water, without CST in the column, and operate the system to evaluate system readiness (no leaks, instrumentation is working, target pressure can be achieved, etc.). After the system was evaluated with water, the water was drained from the system and then the system was filled and flushed with 0.1 M NaOH, including flushing the lines to the DP transducers. At this point, the system pressure was increased to the nominal operating pressure of 60 psig and the zeros on the DP transducers were checked and adjusted if needed. The next step was to conduct a flow test with 0.1 M NaOH at the target flow rate of 130 mL/min and record data from the test system. After conducting the baseline flow test with 0.1 M NaOH solution, the column was loaded with CST that had been conditioned with 0.1 M NaOH. Additional details on these preparation steps are provided in the remainder of this section.

Dry “as-received” CST media, IONSIV™ R9140-B (Material No. 8056202-999, Lot No. 2002009604), was provided by WRPS and is from the same CST lot used in the previous CST drying study (Gauglitz et al. 2019). For each test, the CST was conditioned and washed using 0.1 M NaOH solution prepared from 50 wt.% NaOH stock solution (LabChem, Certified Reagent Grade) and distilled water; conditioning was conducted to mimic the conditions expected for CST used in the planned full-scale column following the approach used by Gauglitz et al. (2019). For initial contacting, a volume of 0.1 M NaOH that was approximately twice the bulk volume of CST was added to a container with the CST. The slurry was gently mixed and then the supernatant liquid with suspended fines was removed by decanting. This washing and decanting was conducted three times, then the wet CST was soaked in 0.1 M NaOH for at least 24 h. For each test, the washed, wet CST was then slowly added to the column, which was filled with 0.1 M NaOH, using a small scoop. The CST particles were allowed to gravity-settle through the column of liquid to form a settled bed. This slow addition of small quantities of CST allowed any gas bubbles entrained in the CST to be released. Periodically, the column was tapped on the side with a rubber mallet to help settle the bed. Once the column was loaded with CST to a bed height a couple of inches less than the target height of 92 in., the inlet distribution ring and screen were inserted so the bottom of the VEE-WIRE® was at a target height of 92.5 in. Following this, CST was added to reach the target bed height of 92 in.[34]

After loading the column, the column was flushed with 0.1 M NaOH solution using PMP-02 with the column effluent directed to tank TK-03 for Tests HS1, HS2, and HS3. Flushing was conducted until the effluent was visually clear with no fines; the fines were likely from the CST bed. After flushing, flow was redirected through a capture filter (FLT-01A or FLT-01B) to the flow controller (FM-02/V-24). For Test NB1 (the first test) preliminary flushing was not conducted and the capture filter (a single filter) quickly plugged, which prompted the operational change to conduct the flushing in the subsequent tests and install two capture filters (FLT-01A and FLT-01B).

Following flushing, a preliminary flow test with 0.1 M NaOH solution was conducted at the target flow rate and system pressure using PMP-02 for each test. In addition to confirming that the system and instruments were functioning properly, differential pressure measurements for each DEF and the CST column were collected as baseline data, which were then used to confirm that the DEFs and CST column were behaving as expected and if there were any changes between tests. After completing this preliminary flow test, the system was configured to receive simulant feed from the feed tote with PMP-01 and to begin normal test operations.

5.2.3 Normal Test Operations

For each test, following the preliminary flow test, “normal” test operations involved processing simulant at the target flow rate through one of the DEFs and the ion exchange column IXC-01, monitoring their differential pressure response, and performing filter swaps/backflushes when the appropriate criteria were reached. The system was operated continuously at the target flow rate using a flow controller (FM-02/V-24, a flow meter paired with an actuated valve). While the system was in a normal operating mode, instruments were monitored for signs of instability or system upsets and data was periodically recorded by hand. During Test NB1, data recording was performed approximately hourly; for the other tests it was roughly every half-hour. Samples were collected periodically as outlined in Section 3.6 without interrupting normal operations.

The feed tank (TK-01) temperature was controlled by manually adjusting the set-point temperature on the HX-01 water bath as needed to maintain it at 22 °C. The feed pump PMP-01 was typically run at a fixed speed for the entire test period with only minor adjustments made to backpressure regulator BPR-01 to keep the pressure ≥ 60 psig and the recirculation flow rate of ≥ 4 gpm. For most of the test, the pivot nozzle mixer was in use (V-51 open, V-52 closed) until the level in feed tank TK-01 became low. At low level, the valves were reversed (V-51 closed, V-52 open) to avoid aspiration/air entrainment into the suction of PMP-01. Visual observations of the TK-01 contents were made periodically to observe mixing motion in the vessel and look for evidence of solids maldistribution, although this was not reliable due to the opacity of the simulant.

The filters were swapped based on criteria during each test’s operations. The original swap criterion (that mimics the TSCR approach) was only applied for Test NB1. Tests HS1 and HS3 were both conducted such that the 2-hour 0.1 M NaOH soak was preserved in its entirely, but in almost all cases the filters were then swapped shortly thereafter because the 2-psid limit had already been exceeded. In effect, this meant that the filters were swapped about every 2.5 hours. Test HS2 relaxed this still further because the entire 2-hour soak time could not be held before the differential pressure rose to approximately 25 psid. In

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[34] In test NB1, CST was added to the target height of 92 in. before inserting the inlet distribution ring and screen. Inserting the inlet distribution ring into the CST bed was difficult, so in the subsequent tests CST was added to a couple of inches less than 92 in. to make inserting the inlet distribution ring easier.

the TSCR system, a 25 psid pressure across a DEF would trigger an interlock that locks-out the slip stream and halts processing. Thus, it was not considered to be representative to operate the test system above that differential pressure, so filters were swapped when it was reached.

Once the filters were swapped, the filter that had just been active was backflushed using nominally 0.5 L (TK-05) of 80 psig air. Flushed simulant with solids was sent to TK-03 using the compressed air and then the filter was filled with 0.1 M NaOH using PMP-02 from TK-02. During the fill, fluid was confirmed to be present by collecting it out of the shell-side and tube-side vents. Once full, the filter was soaked for two hours (except for in Test HS2, where more frequent swapping decreased the soak times[35]) and backflushed again. After being refilled with 0.1 M NaOH a second time, the backflushed filter was ready to become the active filter again. In general, this sequence of operations was executed successfully on the first attempt, but occasionally the pressure would not fully decay during a backflush, which was indicative of an obstruction or partial plug. This was usually in the 1/8-in. lines on the filter outlet and would not be prototypic of the full-scale TSCR system.[36] These plugs were cleared out using flow from PMP-02 to displace the obstruction and the backflush was repeated.

Other routine activities during normal operations involved swapping the guard filter between FLT-01A and FLT-01B to maintain the target flow rate, measuring the ambient temperature of the high bay where the test system was located, checking tank levels, and repositioning T-01 (which measured feed tote temperature) in TK-01 as the level dropped. TK-02 was periodically refilled with pre-made batches of 0.1 M NaOH from 5-gal carboys as needed. TK-03 and TK-04 contents were occasionally transferred to other, larger holding vessels as they became full. Unusual activities that were conducted involved unplugging lines, typically between the slip stream point (SV-01) and the inlet to DEF-01 or DEF-02. This was frequently performed using PMP-02 and flushing back to V-02 or some other outlet, but in a few cases required disassembly and manual cleaning of the affected tubing section.[37] Whenever an unplugging activity was performed, the system was either in recirculation mode or briefly shut down; accordingly, in Tests HS1, HS2, and HS3 there were short periods where the system was not actively processing that are not obvious in the data due to the discretely collected data points.

The system was operated in this manner until the amount of simulant remaining in TK-01 was approaching the level of the PMP-01 suction line (for Tests NB1, HS1, and HS3) or the test was truncated early due to operating challenges (Test HS2). Once feed was no longer provided to the system, the normal operating mode was complete. Whichever filter was the last to be active was backflushed using the standard protocol to put the filters into the same state at the end of the test.

5.2.4 Test Shutdown and Post-Test Activities

Following simulant testing, the flow system and CST bed were flushed with 0.1 M NaOH solution followed by process water. After flushing was complete, air was injected into the column (blowdown) at a target of 5.8 standard liters per minute (FIO flow measurement by FM-03) for approximately 1 hour.

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[35] Tests HS1 and HS3 had a few cycles with soak times shorter than two hours, but nearly all had soak times of at least 2 hours.

[36] Plugging in this manner is not representative of the full-scale TSCR system because: (1) the test system piping layout included tees or elbows that are not present in the TSCR system, and (2) the test system had a sudden contraction at the filter flush outlet, which is also not present in the TSCR system.

[37] Plugs in the feed line are also not representative of the full-scale TSCR system because the ratio of particle size to line diameter cannot be scaled between the systems. The larger particle size/line diameter ratio, combined with the lower line velocity in the scaled test system, makes it far more susceptible to plugging.

After air blowdown, the top flange of the column was removed, and the top of the CST bed was visually assessed and photographed to see if there was any evidence of simulant particles collecting at the top of the CST bed that may be a cause of bed plugging. A small CST sample was then collected from the top of the bed in each test and observed under an optical microscope for any evidence of simulant particles. After the CST samples were collected, the inlet distribution ring and screen were removed, disassembled, and then flushed with water; the water was collected to observe whether there was any evidence of simulant particles collecting in the distribution ring and/or screen. The CST was then removed from the column, and the flow lines and the empty column were flushed with water.

Following the completion of simulant testing, liquid samples were collected from the combined effluent that was collected in a tote (samples were collected for Tests NB1, HS1, and HS2, but not Test HS3 because HS3 effluent was mixed with other used test material due to a lack of storage space).

Whenever test data indicated something unusual, test components were removed from the system for additional inspection. This was only performed after Test NB1.

5.3 Notable Changes to the Testing Configuration

During the testing, a few modifications were made to the test equipment or system to better facilitate operations or make minor improvements. These notable changes are described below. None of the changes resulted in any major impacts on test parameters or operations.

Three notable modifications were made following Test NB1:

1. Because plugging of the capture filter was observed in Test NB1 during initial flow testing with 0.1 M NaOH solution, the single capture filter used in Test NB1 was replaced with a pair of identical filters (FLT-01A and FLT-01B), together with valves that allowed switching between the capture filters. When one of the capture filters became plugged during testing, it was removed from the system, cleaned, and re-installed. This occurred most frequently at the beginning of a test and only rarely thereafter. New capture filters were installed prior to each subsequent test.

2. Also following Test NB1, shell-side vents with valves (V-57 and V-58 in Figure 3.12) were installed on the top flanges of DEF-01 and DEF-02. It was thought to be possible that air pockets remained in the tops of DEF-01 and DEF-02 after filling with 0.1 M NaOH solution during Test NB1 (though no particular adverse effects of this were observed) and venting through the filter effluent lines (V-16 and V-17 in Figure 3.12), so the shell-side vents were used for removing any air pockets in Tests HS1, HS2, and HS3. The installation of the shell-side vents also more properly mirrored the configuration of the full-scale TSCR filter elements.

3. During Test NB1, the pressure drops across DEF-01 and DEF-02 increased more rapidly with each successive filter swap, suggesting fouling of these filters (this is described in more detail in Section 6.2). These filters were disassembled following Test NB1 for inspection of the filter elements and for installing shell-side vent lines. As part of this activity, DEF-02 was rebuilt prior to conducting the subsequent tests (HS1, HS2, and HS3) because it could not be reassembled as it had been. As-built measurements of the new DEF-02 shell confirmed it was identical in all dimensions to the original DEF-02 shell.

The only other notable change occurred after Test HS2: the location of SV-03 was moved to be downstream of the flow controller FM-02/V-24 to reduce flow disturbances when collecting an effluent sample. The method of sample collection was not affected.

6.0 Test Data and Results

In this section, the data collected from each test is presented and discussed. First, the results from the baseline flow measurements for all tests are presented in Section 6.1. Then, each test is discussed separately in turn in the same order as presented in Table 5.2: NB1 (Section 6.2), HS1 (Section 6.3), HS2 (Section 6.4), and HS3 (Section 6.5). The last section (Section 6.6) makes comparisons across tests and summarizes the observed test performance.

Narratives of each test are not incorporated into the text in this section; however, Appendix A contains a timeline of events for each of the four tests. The timelines highlight the major activities, including sample collection, that occurred during each test evolution. Appendix B contains tables of the data collected manually by the test operators that are used to perform the assessments in this section. Appendix C includes time series of operating data that are not presented (or discussed) in the subsections below.

6.1 Baseline Flow Test Data

Prior to each test, a baseline flow measurement was collected before initiating feed of simulant to the system. The flow test occurred once the IX column had been loaded with CST, all differential pressure measurement lines had been filled with 0.1 M NaOH, all system lines downstream of SV-01 were filled with 0.1 M NaOH, and differential pressure instruments' zero points were checked and re-zeroed (as required). Before collecting data, flow of 0.1 M NaOH solution was established in the system and the CST bed was rinsed until visually clear of fines (with effluent leaving via V-23).

In each baseline flow test, flow was controlled to 130 mL min^{-1} and sent through each DEF in turn, with the pressure nominally near the 60-psig feed pressure typically targeted during test operations. The measured differential pressures, in combination with other physical parameters, were used in the expressions presented in Sections 3.6.2 and 3.6.3 to calculate $R^{+}_{m,o}$ and $\beta_{x,o}$. In Table 6.1, these results are summarized for all four tests. For reference, the underlying ΔP for the DEFs under the baseline flow measurement conditions was approximately 0.1 – 0.2 psid, and the column ΔP ranged from 1.27 to 1.50 psid (depending on the test).

Table 6.1. Summary of Baseline Flow Test Results with 0.1 M NaOH Solution.

	Initial membrane resistance ($R^{+}_{m,o}$)		Baseline permeability ($\beta_{x,o}$)			
Test	DEF-01 [m^{-1}]	DEF-02 [m^{-1}]	DEF-01 $\beta_{F,o}$ [m^2]	DEF-02 $\beta_{F,o}$ [m^2]	IXC-01 $\beta_{IX,o}$ [m^2]	IXC-01 $\beta_{IX,o}$ [Da]
NB1	2.03E+10	1.61E+10	7.83E-14	9.87E-14	2.73E-10	277.0
HS1	1.52E+10	1.52E+10	1.04E-13	1.05E-13	3.01E-10	304.7
HS2	2.33E+10	3.04E+10	6.81E-14	5.22E-14	2.92E-10	295.5
HS3	1.55E+10	4.46E+10	1.03E-13	3.56E-14	2.82E-10	286.1
Average	1.86E+10	2.66E+10	8.83E-14	7.28E-14	2.87E-10	290.8
Std Dev	3.92E+09	1.39E+10	1.80E-14	3.41E-14	1.18E-11	11.9

The initial membrane resistances vary over a reasonably compact range, with DEF-01 being considerably more tightly distributed than DEF-02. The measured $R_{m,o}$ values reflect, in part, the variability in the post-test "cleaning" process which usually involved a series of flushes and rinses (with the exception of Test NB1). Overall, these measured resistances agree with other quoted (2×10^{10} m^{-1}, see Allred et al. 2021) or measured (~6×10^9 m^{-1} in Allred et al. 2020 and ~2×10^9 m^{-1} in Daniel et al. 2020b) values. Considering the use of distinct cleaning protocols and different filter geometries (but the same media) across the cited references, an order of magnitude agreement is reasonable. The $R_{m,o}$ values returning to approximately the same value after each test is anecdotal evidence that the fairly simple cleaning procedures used during testing were effective enough; no chemical cleaning was used, and it does not appear to be necessary.

The values of $\beta_{IX,o}$ are in good agreement across all four tests and narrowly distributed. This result provides some confidence that the CST pretreatment and loading process was consistent in each test, since new material was used every time. For comparison, the filters have permeability that are three to four orders of magnitude smaller, i.e., similar to the relative difference in Re_F and Re_{IX}.

It is instructive to compare the CST bed permeability to an empirical prediction. Bear (1972) provides such an expression:

$$\beta_{emp} = 0.617\times10^{-11}\left(d_{gd}\right)^2 \tag{6.1}$$

where the β_{emp} result is in units of cm^2 and d_{gd} is the mean grain diameter (in microns). Using d_{CST} in Eq. (6.1) yields a value of 314.3 Da for β_{emp}, which is only about 8% different than the average value from Table 6.1.

The pressure drop of the bed that was measured during the flow test was compared to the Kozeny-Carman equation (Kozeny [1927]; Carman [1937, 1956]) prediction from the formula

$$\Delta P = \left[\frac{150\mu_o\left(\frac{Q_o}{A_{IX}}\right)h_{bed}}{d_{CST}^2}\right]\left[\frac{(1-\varepsilon)^2}{\varepsilon^3}\right] \tag{6.2}$$

where ε is the packed bed void fraction. There is significant uncertainty as to the value of ε; Hamm et al. (2002) suggest a value of 0.50, but recent measurements suggest something closer to 0.67 (Fiskum et al. 2019b). Eq.(6.2) is usually restricted for use at $\varepsilon \le 0.5$, but for estimation purposes, values of $\varepsilon = 0.5$ and $\varepsilon = 0.67$ were used in Eq. (6.2), resulting in ΔP values of 0.24 psid and 0.04 psid, respectively. The $\varepsilon = 0.5$ result, which is on the edge of applicability for the Kozeny-Carman formula, is almost an order of magnitude lower than the measured ΔP. These results suggest that the void fraction is smaller than the reported values, at least with respect to the IX column configuration used in these tests.

By rearrangement of Eq. (6.2), the permeability can be used to back-calculate the void fraction:

$$\beta = \frac{\mu_o\left(\frac{Q_o}{A_{IX}}\right)h_{bed}}{\Delta P} = \frac{d_{CST}^2}{150}\left(\frac{\varepsilon^3}{(1-\varepsilon)^2}\right) \tag{6.3}$$

The similarity of β_{emp} to $\beta_{IX,o}$ adds confidence to the validity of this approach for estimating the void fraction. The average value of $\beta_{IX,o}$ was used to perform this calculation by setting it equal to the right-hand side of Eq. (6.3) and solving for ε. This gives a void fraction of about 0.34.

Aside from the parameters derived from the baseline flow measurements, the measurements also served to establish that the system is in a similar initial state as it had been in prior tests; consequently, data comparisons across tests are meaningful because they are starting from the same base state.

6.2 Test NB1

Test NB1 was conducted using the "nominal" 5.6 M sodium simulant with a trace number of solids. The simulant arrived at PNNL after delays in shipping due to unusual winter weather in Texas (where the simulant was produced); the consequence was that the tote likely experienced freezing (or near-freezing) temperatures[38] and there was significant precipitation of solids. Redissolving the solids was not practical because there were no readily available methods to heat-up and recirculate the tote contents. Precipitation is frequently irreversible, so re-dissolving was not certain to succeed regardless. Instead, supernatant was decanted into TK-01 from the received tote to minimize the amount of the unexpected solids in the system. The decanted simulant was added in three increments: (1) an additional amount of ~210 gallons, (2) a second, smaller decant of ~60 gallons, and (3) a third, even smaller amount of liquid that was free drained from the tote (~16 L [~4 gal]). Decanting the simulant kept the solids very low as desired, but less than the 200-ppm target. Small amounts of particles were present, but not enough to quantify from 1-L samples. The other impact of decanting was the Test NB1 run time: the significant solids that were left behind in the shipped tote represented lost volume on the order of 20-30 gallons (see Figure 6.1 for a photo of the remaining tote contents after all decanting was complete).

Figure 6.1. Solids Remaining in the Shipping Tote after Decanting to TK-01 in Test NB1.

During Test NB1, the test system was operated continuously for approximately 136 hours (~279 gallons processed) with the flow rate tightly controlled to the target (130.0 ± 0.1 mL min^{-1}) and the average temperature in the system varying over a small range (22.0 ± 0.2 °C). For time traces of flow rate, temperature, and system pressures, see Appendix C, Figure C.1 through Figure C.4. The feed pressure to the system from the recirculation loop (P-02) was consistently greater than 55 psig. Flow was introduced

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[38] The simulant liquid had a measured temperature of ~16 °C after being pumped into TK-01 as part of the first decant; this suggests it experienced much colder temperatures prior to its arrival at PNNL.

to DEF-01 first (as in all subsequent tests) and the DEFs were alternated thereafter once either 24 hours had elapsed or the 2-psid trigger point was reached, whichever occurred first. Each operating period for DEF-01 and DEF-02 comprised a cycle.

Figure 6.2 shows the initial ΔP for each cycle of Test NB1. The trigger point for swapping was 2 psid more than these values for each DEF (~2.4 to 2.5 psid). Over the 136 hours of operation, each filter was used four times; Cycle #4 for DEF-02 was brief because the test was completed due to lack of simulant material remaining to process. Figure 6.3 shows the ΔP evolution for each cycle of DEF operation; the first cycle for both filters was able to run for a full 24-hr period, and each subsequent cycle saw a degradation in performance relative to the previous cycle. The increased rate of change in differential pressure was more pronounced for DEF-01 than DEF-02, and the 4th cycle for DEF-01 reached the ΔP trigger in approximately 11 hours. The normalized resistance data for the filters is shown in Figure 6.4. The resistance only increased modestly over the measured baseline resistance $R^{+}_{m,o}$ and did not exceed a factor of approximately 8. The data in Figure 6.2, Figure 6.3, and Figure 6.4 all demonstrate that the DEFs returned to their initial performance level (similar ΔP after 10 min and ω ~ 1) after each backflush and filter swap.

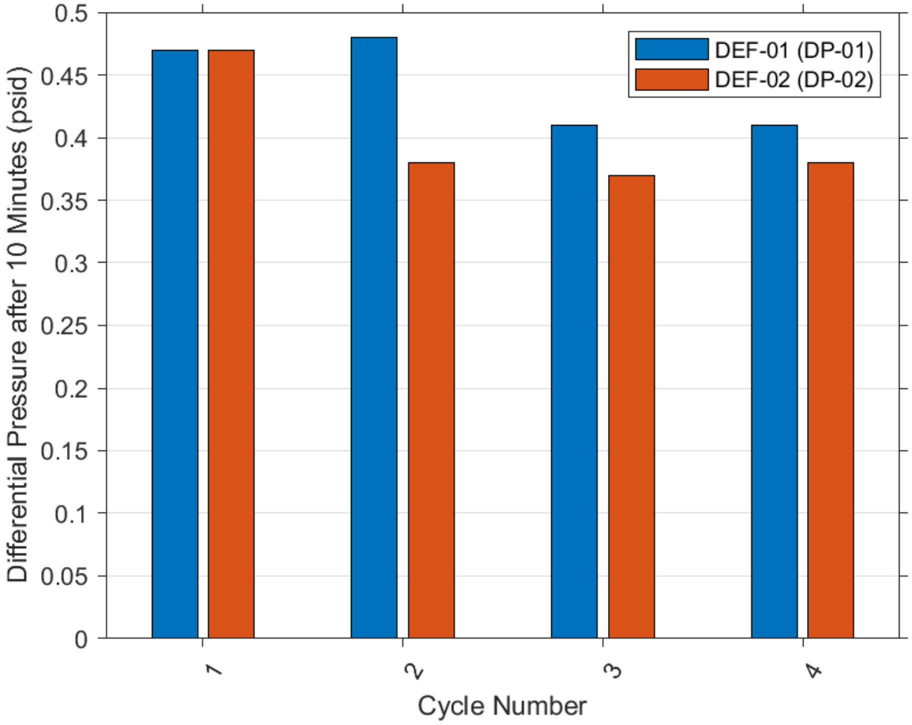
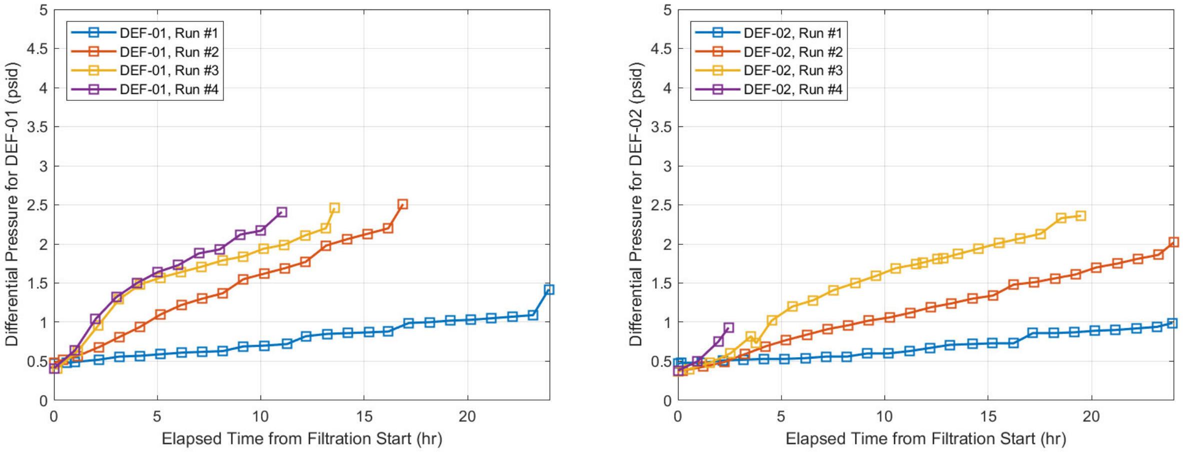


Figure 6.2. Differential Pressure Observed after 10 Minutes for DEF-01 (blue) and DEF-02 (orange) for Each Filter Cycle in Test NB1.



(a) Differential pressures for DEF-01

(b) Differential pressure for DEF-02

Figure 6.3. Differential Pressures for (a) DEF-01 and (b) DEF-02 for all Cycles (“Runs” in the plot legends) in Test NB1. The elapsed time has been adjusted to show all the filter evolutions starting from the same time, which is the point at which the initial ΔP (at t = 10 min) was recorded.

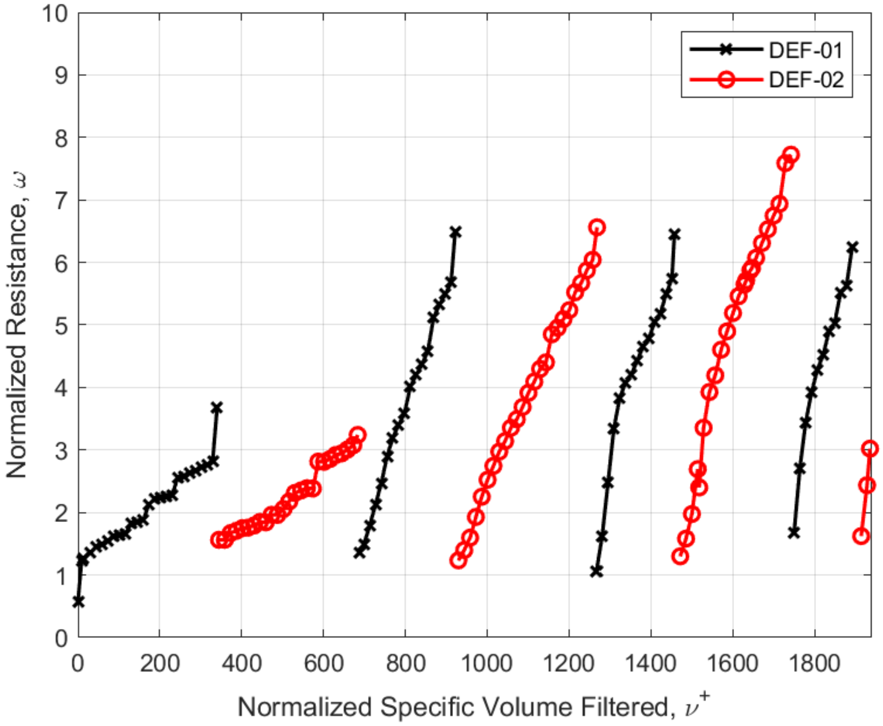


Figure 6.4. Evolution of DEF Normalized Resistance for Test NB1.

The differential pressures observed in the IX column (IXC-01) are shown in Figure 6.5. Recall that DP-03 is the pressure differential across the entire column, DP-04 is the inlet distributor and top 6 inches of the CST bed, and DP-05 is the bottom ~86 inches of the CST bed and the outlet distributor. The differential pressure increases only slightly over the entire test (no more than ~0.5 psid) and appears to be limited to the CST bed below the 6-inch level by comparison of the DP-04 and DP-05 traces. It is likely that this is related to consolidation of the CST bed itself in the presence of the constant flow rather than any significant particle deposition, which is expected mostly at or near the highest elevations of the bed. As discussed later in Section 6.6.3, there were no observable particle deposits seen at the top surface of the CST in IXC-01 after Test NB1.

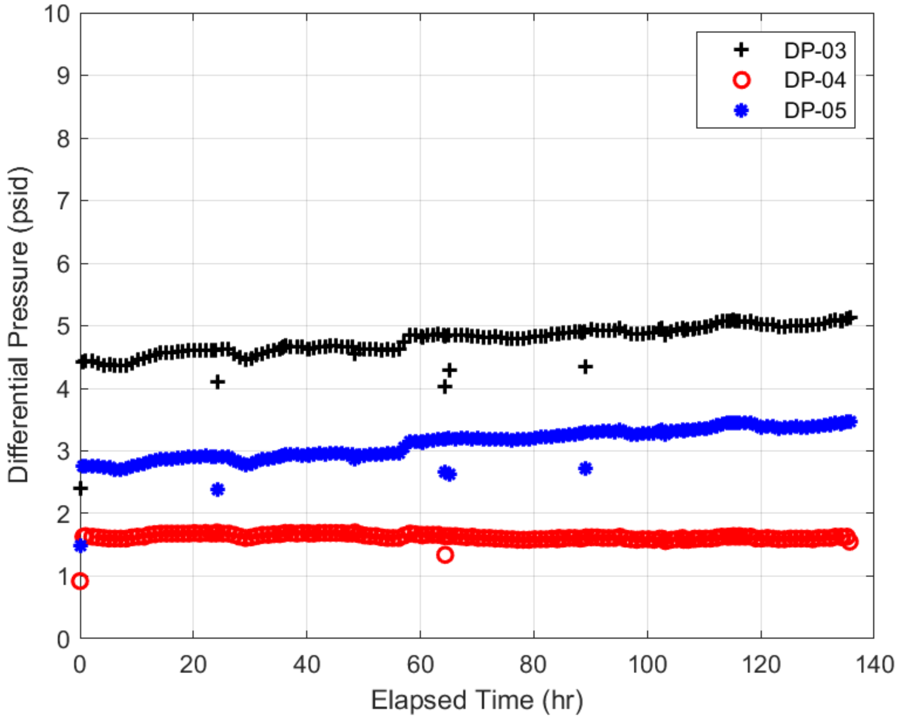


Figure 6.5. Differential Pressure Traces for IXC-01 During Test NB1.

The cesium concentrations measured in the IXC-01 effluent were below the ICP-MS estimated quantitation limit, or EQL, for all Test NB1 samples; based on the EQL of the analysis technique, the effluent concentration was < 0.18% C/C_o for the entire test. This was expected due to processing less than the target 300 gal in Test NB1 and the lower sodium concentration in the TK-01 feed due to the precipitation of solids described earlier in this section. The BVs processed were estimated to be 256 and there were no indications of unusual behavior for the CST in the IX column. The Test NB1 cesium data did not establish initial cesium breakthrough; for a comparison with other tests see Section 6.6.2.

During Test NB1, an acceleration in fouling with each cycle for both DEFs was observed (seen in Figure 6.3 and Figure 6.4). The cause of the acceleration was not immediately apparent. The simulant in TK-01 appeared unchanged during the testing, had only a trace amount of solids, and there were no major excursions from the well-controlled flow rate, pressures, and temperatures during operations. After the test was completed, the DP across the filters remained elevated (DP-01 = ~0.5 psid compared to ~0.1 psid, DP-02 = ~0.3 psid compared to ~0.1 psid) when operating the filters at the target flow rate with water. Because a filter shell vent line was going to be installed on both DEFs after Test NB1, it was decided to disassemble the DEFs and examine them. Upon examination, both DEFs were found to have solid deposits of a gray-brown color pictured in Figure 6.6. The deposits were not crystalline in appearance and were sludgy or slimly in nature. The deposits were mostly readily removed by application of ethanol (nitric acid was also used but was not as effective) and manually cleaned using a solution of ethanol and a fine brush.

Some of the solids were collected from the filters but were not able to be readily solubilized in water and appeared amorphous (not suitable for identification by XRD). Anecdotal information implies that the solids were, at least in part, comprised of organic species. It cannot be ruled out that the solids arose from some change in the simulant as it was tested, but it seems more likely that some unknown contamination entered the system (or was already resident) and slowly fouled the filters.[39] DEF-01 had noticeably more solids than DEF-02, which explains the higher value for DP-01. After the filters were manually cleaned and re-assembled, the DP across the filters was checked again with water and found to be as expected for a "clean" filter, i.e., DP-01 and DP-02 ~0.1 psid. This phenomenon occurred only in Test NB1.

Figure 6.6. Close-Up Image of As-Found Solid Deposits on DEF-01 and DEF-02 Following Test NB1.

6.3 Test HS1

Test HS1 was originally planned to be conducted using the high-solids 5.6 M sodium simulant with a target solids loading of 3,000 ppm. The simulants for Test HS1, HS2, and HS3 all arrived at PNNL together just before the start of Test HS1, each in separate 330-gal IBC totes. Solids loadings appeared proportionally correct based on the settled layer presence in the three totes (HS1 < HS2 < HS3). The HS1 simulant tote was sparged to mix and suspend the solids and then immediately transferred to TK-01 using an air-operated diaphragm pump and a lance that was held at various locations near the IBC tote bottom. TK-01 was filled about 75% full (nominally 205 gal), with a second volume added later in the test to transfer the remaining HS1 simulant. After the simulant tote was emptied out, some solids remained on

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[39] Possible sources include grease or oil from PMP-01, residues from pipefitting during system assembly, or caulking/sealant material found to be decomposing in TK-02 during Test NB1. The decomposing material in TK-02 was cleaned out approximately 30 hours into the test (15:55 03/05/2021).

the bottom that were generally quite large and difficult to mobilize. At that point, it was already known that the solids loading in TK-01 and the recirculation loop was less than the target (~700 to 900 ppm rather than 3,000 ppm) and this confirmed that a significant fraction of the solid phase in the simulant was challenging to keep suspended and load into TK-01. It was preferrable to test at a reduced solids loading rather than add in the additional solids because of their large size – it was expected that the solid particles left behind would only create operational challenges such as line plugging and feed inhomogeneity. Despite this limitation, almost the entire simulant volume was eventually processed during the test.

During Test HS1, the test system was operated continuously for approximately 143 hours (~295 gallons processed) with the flow rate tightly controlled to the target (130.0 ± 0.7 mL min^{-1}) and the average temperature in the system varying over a small range (21.9 ± 0.2 °C). For time traces of flow rate, temperature, and system pressures, see Appendix C, Figure C.5 through Figure C.8. The feed pressure to the system from the recirculation loop (P-02) was consistently greater than ~65 psig. Flow was introduced to DEF-01 first and the DEFs were alternated thereafter: in contrast to Test NB1, it quickly became apparent that neither the 24-h nor the 2-psid trigger point would be practical for test operations and an adjustment was made to the swap criterion. The adjustment was to continue using the active filter even after its ΔP exceeded 2 psid to permit the inactive filter to undergo the following recovery steps: (a) backflush with 80-psig air; (b) fill with 0.1 M NaOH and soak for 2 h; (c) backflush with 80-psig air; and (d) refill with 0.1 M NaOH. This evolution required approximately 2.25 to 2.5 h in most cases. The evolution was truncated (by reducing the 2-h soak time) if the ΔP approached 25 psid, which did happen for some of the evolutions (see Figure C.8). Each operating period for this adjusted approach with DEF-01 and DEF-02 comprised a cycle.

Figure 6.7 shows the initial ΔP measured for each cycle of Test HS1. Since the trigger point for swapping was based on prototypic operations and not a numerical target, the pressure at which the swap occurred varied. Over the 143 hours of operation, each filter was used 30 times; after the first several cycles, both DEFs reached a point where they consistently returned to roughly the same initial ΔP (DEF-01: ~1 to 1.5 psid and DEF-02: ~1.5 to 2 psid). There was no observable trend after approximately five cycles, suggesting that backflushing was consistently successful in restoring the DEFs to the same starting point.

Figure 6.8 shows the ΔP evolution for each cycle of DEF operation; the second and second-to-last cycles are shown in thicker black lines to illustrate that there is no increasing/decreasing trend in the evolution curves as a function of cycle. The data show that the 2-psid trigger was reached in ≤ 0.5 h (in most cases) for both DEFs and that the increase in pressure accelerates with time (the curves appear to be non-linear). Almost all the cycles on DEF-01 were able to incorporate the full 2-h soak time, with a handful of DEF-02 cycles shortened due to reaching 25 psid.

The normalized resistance data for the filters is shown in Figure 6.9. The resistance increased rapidly and significantly (factors of 40 to 70) across all regions of v^+ over the measured baseline resistance $R^+_{m,o}$ and achieved a maximum of > 90. The data in Figure 6.7, Figure 6.8, and Figure 6.9 all demonstrate that the DEFs returned to their initial performance level (similar ΔP after 10 min and $\omega \sim 1$) after each backflush and filter swap despite being allowed to operate well above the 2-psid trigger point. Note that the repeatable return to the same initial state was truer for DEF-01 than DEF-02 for Test HS1.

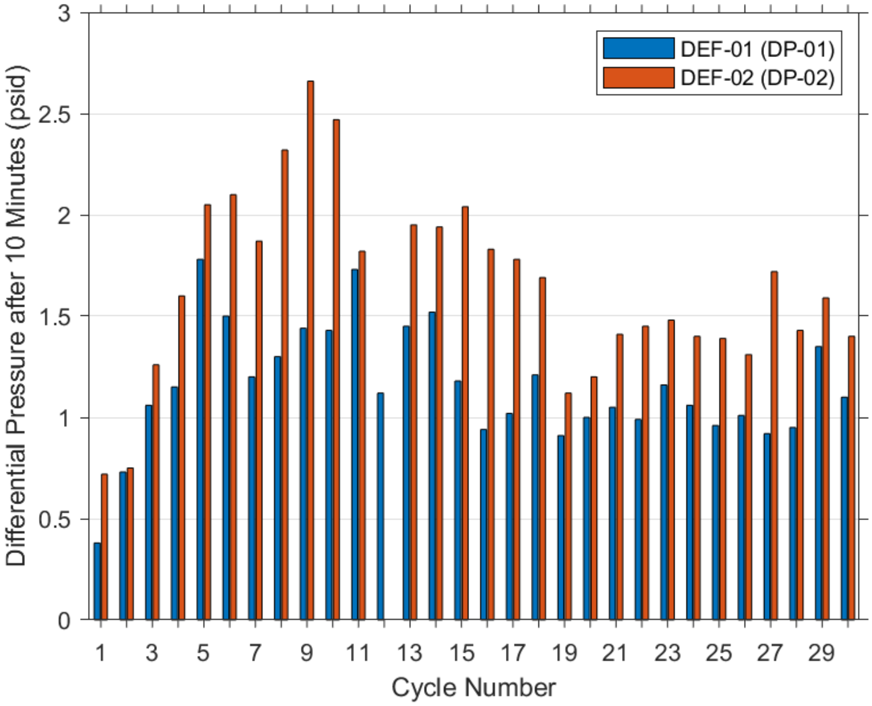
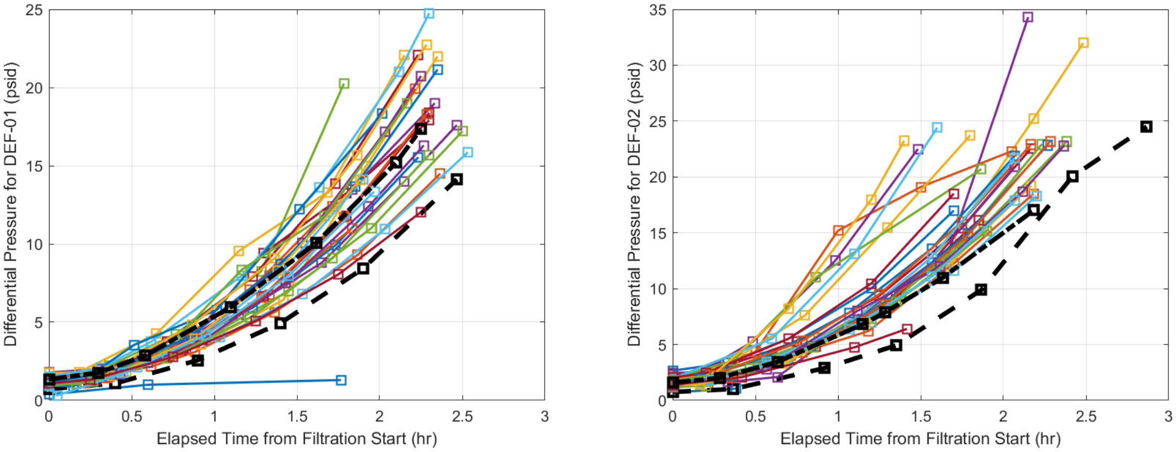


Figure 6.7. Differential Pressure Observed after 10 Minutes for DEF-01 (blue) and DEF-02 (orange) for Each Filter Cycle in Test HS1.



(a) Differential pressures for DEF-01

(b) Differential pressure for DEF-02

Figure 6.8. Differential Pressures for (a) DEF-01 and (b) DEF-02 for all Cycles in Test HS1. The elapsed time has been adjusted to show all the filter evolutions starting from the same time, which is the point at which the initial ΔP (at t = 10 min) was recorded. The thicker black dashed lines are provided to indicate the second and penultimate cycle for each DEF.

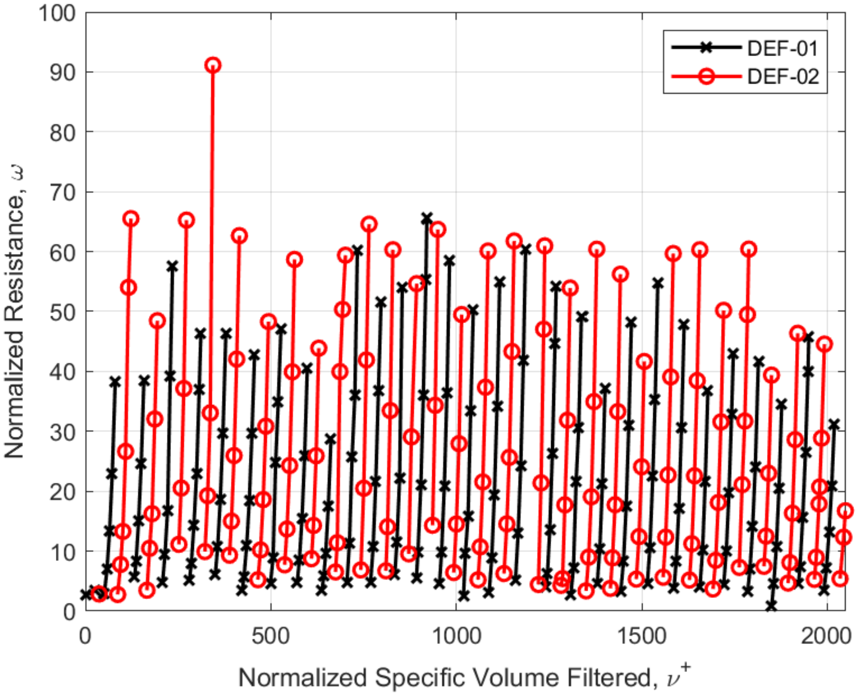


Figure 6.9. Evolution of DEF Normalized Resistance for Test HS1.

The differential pressures observed in IXC-01 are shown in Figure 6.10. The differential pressure oscillates more significantly than in Test NB1; these oscillations originate from the more frequent filter swaps that occurred during Test HS1 (each filter swap displaces some 0.1 M NaOH through the CST bed, which has a lower viscosity than the simulant). The DPs increase only slightly over the entire test (again, no more than ~0.5 psid) and the increase is primarily in the CST bed below the 6-inch level by comparison of the DP-04 and DP-05 traces. It is likely this is related to consolidation of the CST bed itself in the presence of the flow rather than any significant particle deposition, which is expected mostly at or near the highest elevations of the bed. As discussed later in Section 6.6.3, there were no observable particle deposits seen at the top surface of the CST in IXC-01 after Test HS1.

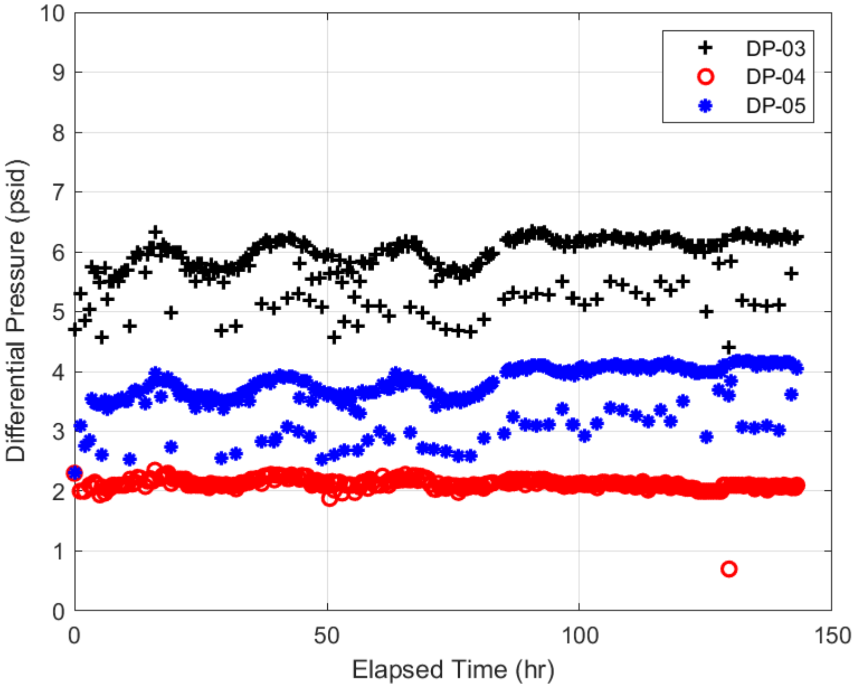


Figure 6.10. Differential Pressure Traces for IXC-01 During Test HS1.

The cesium concentrations measured in the IXC-01 effluent were below the ICP-MS EQL (equal to ~0.13% *C*/*C*_o) for all but the last four Test HS1 samples collected; the final measured effluent concentration was approximately 0.18% C/C_o. The first effluent sample above the EQL was collected at an elapsed time of 137.6 h, which is equivalent to about 260 BV. This was consistent with the target of reaching initial breakthrough (0.1% C/C_o) near the end of a test; since the EQL was slightly greater than the initial breakthrough level, the point at which 0.1% C/C_o was exceeded can only be estimated by extrapolating from the last few data points. The total BVs processed were estimated to be 271 and there were no indications of unusual behavior for the CST in the IX column. The Test HS1 cesium data suggests an initial cesium breakthrough at approximately 250 BV; for a comparison with other tests see Section 6.6.2.

There was no significant acceleration in fouling that was discernable in Test HS1, so the DEFs were not suspected of being progressively contaminated with subsequent filter evolutions as it appeared had been the case in Test NB1. This was confirmed by measuring the filter DPs using water (at the target flow rate and nominal feed pressure) after the test was completed and the DEFs had been backflushed and rinsed. The post-test DPs agreed with DPs measured under the same conditions before Test HS1 began. Data from the 0.1 M NaOH baseline flow measurement also supports this point (see Table 6.1).

6.4 Test HS2

Test HS2 was originally planned to be conducted using the high-solids 5.6 M sodium simulant with a target solids loading of 9,000 ppm. Based on experience with Test HS1, it was anticipated that the entire 9,000 ppm would not be transferred to TK-01; given the rapid fouling of the DEFs during Test HS1, it was likely that any increase in solids loading over the HS1 level would be even more challenging to operations. Thus, the same approach was used to load the HS2 simulant: the HS2 simulant tote was sparged to mix and suspend the solids and then immediately transferred to TK-01 using an air-operated diaphragm pump and a lance that was held at various locations near the IBC tote bottom. TK-01 was filled about 75% full (nominally 205 gal); due to the progression of test operations, a second volume was never added. Like Test HS1, the solids loading in TK-01 and the recirculation loop was less than the target by about a factor of three (~3,000 ppm rather than 9,000 ppm). At the HS2 solids loading, maintaining throughput required very onerous operations (rapid sequences of valve operations and frequent unplugging of process lines); as a result, only about half the simulant volume was processed during the test once sufficient data had been collected to repeatedly demonstrate system performance.

During Test HS2, the test system was operated continuously for approximately 77 hours (~158 gallons processed) with the flow rate more variable than in other tests compared to the target (129.3 ± 4.1 mL min^{-1}) and the average temperature in the system varying over a small range (21.8 ± 0.4 °C). The variation in the flow rate was caused by frequent line plugging (whether partial or full) that resulted in significant pressure drops in the system such that the target flow rate was unable to be maintained intermittently over short periods of time. For time traces of flow rate, temperature, and system pressures, see Appendix C, Figure C.9 through Figure C.12. The feed pressure to the system from the recirculation loop (P-02) was consistently ~70 psig or greater. Flow was introduced to DEF-01 first and the DEFs were alternated thereafter: as expected based on operations during Test HS1, it quickly became apparent that neither the 24-h nor the 2-psid trigger point would be practical for test operations and an adjustment was made to the swap criterion. Test HS2 required an even more aggressive adjustment to avoid exceeding a ΔP of > 25 psid across the active DEF. The adjustment was to continue using the active filter until its ΔP was approaching 25 psid; this was routinely accomplished by the following recovery steps: (a) backflush with 80-psig air; (b) fill with 0.1 M NaOH and soak until the active filter's ΔP was ~20 psid; (c) backflush with 80-psig air; and (d) refill with 0.1 M NaOH. This evolution required < 1 h in all cases where there was not a loss of system flow due to a line plugging. Each operating period defined by this adjusted approach for DEF-01 and DEF-02 comprised a cycle.

Figure 6.11 shows the initial ΔP measured for each cycle of Test HS2. Since the trigger point for swapping was based on attempting to not exceed 25 psid, the pressure at which the swap occurred was always ~25 psid. Over the 77 hours of operation, each filter was used 46 times; after the first several cycles, both DEFs reached a point where they consistently returned to roughly the same initial ΔP (~2 to 3 psid for both filters). There was no observable trend after approximately four cycles, suggesting that backflushing was consistently successful in restoring the DEFs to the same starting point.

Figure 6.12 shows the ΔP evolution for each cycle of DEF operation; the second and second-to-last cycles are shown in thicker black lines to illustrate that there was no increasing/decreasing trend in the evolution curves as a function of cycle. The "outlier" curves (or single data points) for both DEFs represent evolutions where filtration as interrupted by line plugging or other short process upsets. The data show that the 2-psid trigger was reached in ≤ 0.25 h (in most cases) for both DEFs and that the increase in pressure may accelerate with time (the curves appear to be non-linear but the number of data points per cycle is limited). Every cycle for both filters was shortened due to reaching 25 psid, with a nominal swap frequency of about 0.75 h (45 minutes).

The normalized resistance data for the filters is shown in Figure 6.13. The resistance increased so rapidly and significantly across all regions of v^+ over the measured baseline resistance $R^+_{m,o}$ that it could not be properly quantified by the recorded data collected during testing (many of the filter evolutions only had one or two data point before a swap occurred). However, the values of ω that were captured are on the same order as Test HS1 (maximum ω is ~40) which is expected because the similar ΔPs were reached in both cases (ΔP approached or was equal to 25 psid). The values of ω are somewhat lower than Test HS1 due to the higher value of $R^+_{m,o}$ for Test HS2. The data in Figure 6.11 and Figure 6.12 demonstrate that the DEFs returned to their initial performance level (similar ΔP after 10 min) following each backflush and filter swap despite being allowed to operate up to 25 psid. The data in Figure 6.13 is not as definitive on this point compared to the other tests because the initial value of ω is often ~5; this is almost certainly due to a temporal data collection rate that could not keep up with the rapid change in differential pressure during operations.

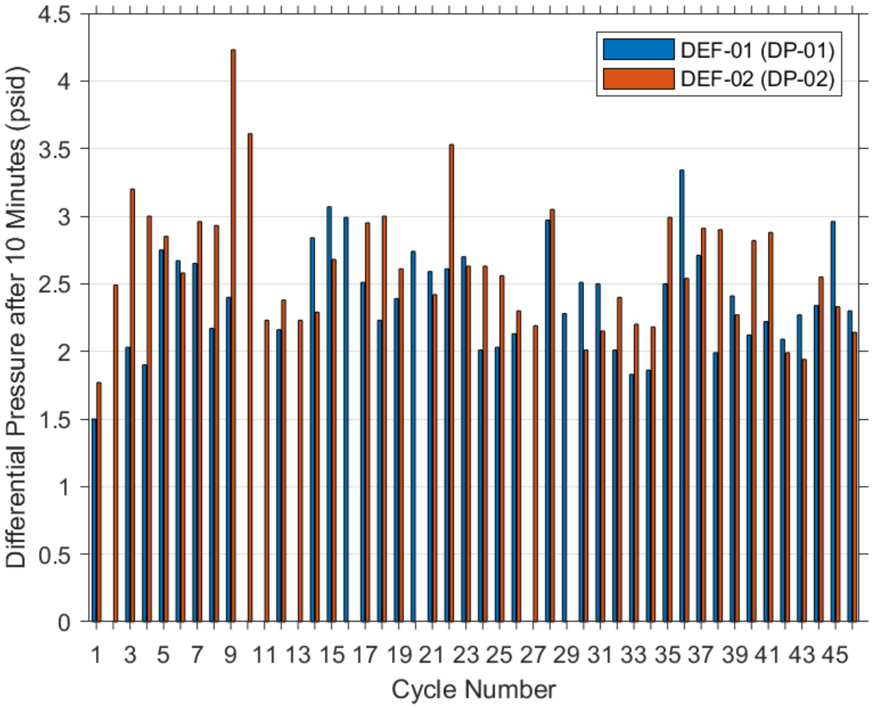
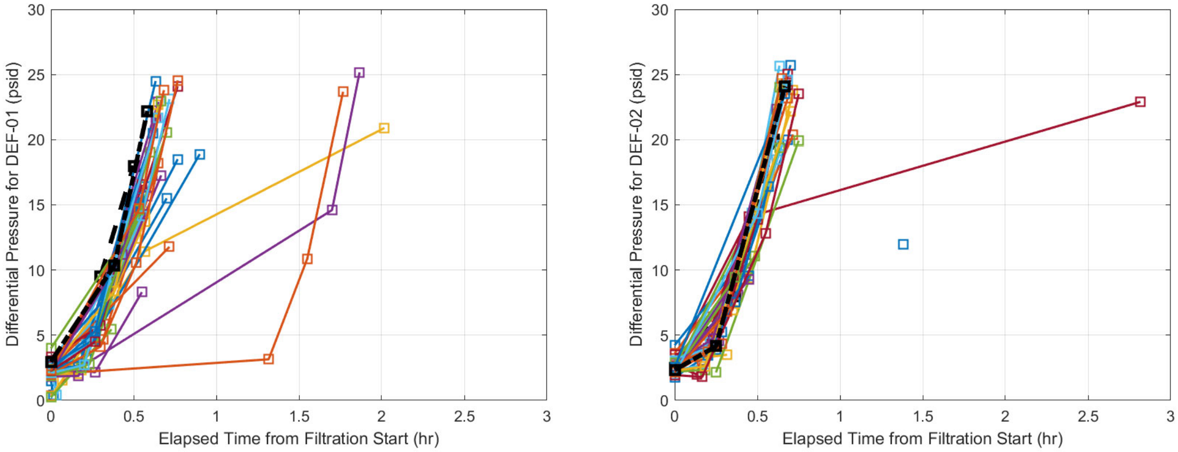


Figure 6.11. Differential Pressure Observed after 10 Minutes for DEF-01 (blue) and DEF-02 (orange) for Each Filter Cycle in Test HS2.



(a) Differential pressures for DEF-01 (b) Differential pressure for DEF-02

Figure 6.12. Differential Pressures for (a) DEF-01 and (b) DEF-02 for all Cycles in Test HS2. The elapsed time has been adjusted to show all the filter evolutions starting from the same time, which is the point at which the initial ΔP (at t = 10 min) was recorded. The thicker black dashed lines are provided to indicate the second and penultimate cycle for each DEF.

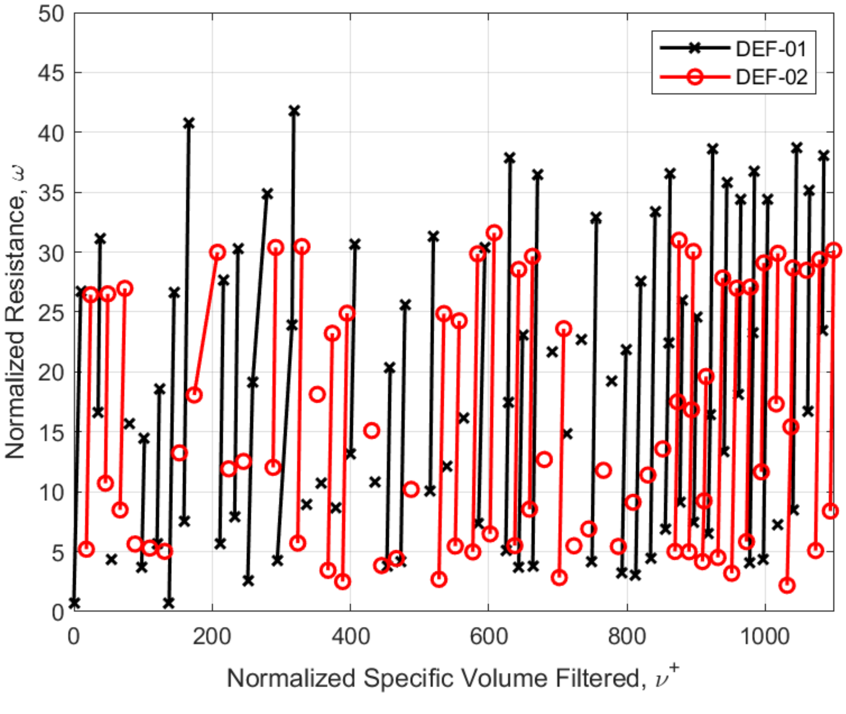


Figure 6.13. Evolution of DEF Normalized Resistance for Test HS2.

The differential pressures observed in IXC-01 are shown in Figure 6.14. The differential pressure oscillates even more significantly than in Test HS1; the oscillations originate from the very frequent filter swaps that occurred during Test HS2 (each filter swap displaces some 0.1 M NaOH through the CST bed, which has a lower viscosity than the simulant). The DPs increase only slightly over the entire test (at most, ~1.0 psid) and the increase is concentrated over the first ~40 h of operation. As in prior tests, the increase is focused in the CST bed below the 6-inch level by comparison of the DP-04 and DP-05 traces. For this reason, it is also likely in this test that the small increase is related to consolidation of the CST bed itself in the presence of the flow rather than any significant particle deposition, which is expected mostly at or near the highest elevations of the bed. As discussed later in Section 6.6.3, there were no observable particle deposits seen at the top surface of the CST in IXC-01 after Test HS2.

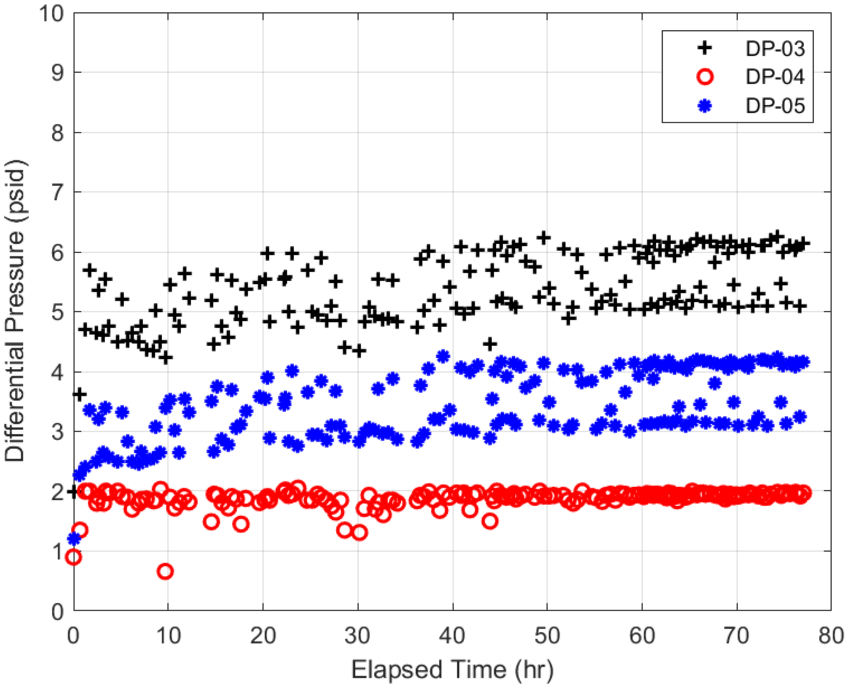


Figure 6.14. Differential Pressure Traces for IXC-01 During Test HS2.

The cesium concentrations measured in the IXC-01 effluent were below the ICP-MS detection limit for all Test HS2 samples; based on the EQL of the analysis technique, the effluent concentration was < 0.13% C/C_o for the entire test. Observing initial breakthrough was not expected due to the shortened processing time in Test HS2 (about 77 h, or only a total of ~145 BV). There were no indications of unusual behavior for the CST in the IX column. The Test HS2 cesium data did not provide information to support any additional performance assessment for the CST bed; for a comparison with other tests see Section 6.6.2.

There was no significant acceleration in fouling that was discernable (although it should be noted that in this particular test, acceleration would have been difficult to observe due to the rapid rate of change in DPs) in Test HS2, so the DEFs were not suspected of being gradually contaminated as it appeared had been the case in Test NB1. This was confirmed by measuring the filter DPs using water (at the target flow rate and nominal feed pressure) after the test was completed and the DEFs had been backflushed and rinsed. The post-test DPs agreed with DPs measured under the same conditions before Test HS2 began. Data from the 0.1 M NaOH baseline flow measurement also supports this point (see Table 6.1).

6.5 Test HS3

Test HS3 was conducted using the high solids 5.6 M sodium simulant with an adjusted target solids loading of < 1,000 ppm. The adjustment to the target was made after observing performance during Tests HS1 and HS2, which challenged the upper limit of 25 psid for the DEFs and challenged the system's ability to maintain flow due to line plugging. The goal was to introduce a significant number of the smallest particles in the simulant at a concentration at or below the level at which Test HS1 was conducted. The method by which this was performed involved some iteration to the simulant preparation and loading process.

First, the HS3 simulant tote was sparged to mix and suspend the solids and observe its settling behavior. Then, 150 gal of HS3 supernatant were decanted from the tote into TK-01 to serve as the dilutant for a more-concentrated solids-laden amount of HS3 simulant. The solids-laden volume was obtained by sparging the remaining 150 gal, letting it settle for 0.5 h, and then transferring ~30 gal into TK-01. The contents were then recirculated to mix and then sampled. The initial solids analysis was ~1,100 ppm, so a small adjustment was made by removing ~10 gal of the TK-01 contents and adding another ~50 gal of decanted supernatant from the HS2 simulant tote (volume leftover from truncating Test HS2). The HS2 simulant material was chemically identical, so this was using the same simulant. A second solids analysis indicated the solids content was about 970 ppm. At this point Test HS3 started (called Part 1); later, once the level in TK-01 had dropped to ~125 gal, an additional ~125 gal was decanted from the HS3 IBC tote to effectively dilute the solids concentration by approximately half. This operation was performed without interrupting processing through the system (the addition of this decanted liquid marks the start of Part 2). After the second addition, more than 300 gal of simulant were available for the test; when Test HS3 was stopped, some volume remained in TK-01.

During Test HS3, the test system was operated continuously for approximately 146 hours (~300 gallons processed) with the flow rate well-controlled to the target (129.9 ± 1.0 mL min^{-1}) and the average temperature in the system varying over a small range (22.3 ± 0.2 °C). For time traces of flow rate, temperature, and system pressures, see Appendix C, Figure C.13 through Figure C.16. The feed pressure to the system from the recirculation loop (P-02) was consistently greater than 60 psig. Flow was introduced to DEF-01 first and the DEFs were alternated thereafter: initially, it quickly became apparent that neither the 24-h nor the 2-psid trigger point would be practical, so the adjustment used in Test HS1 was adopted for HS3 (due to the similarity in solids loadings between the tests). For Part 1 of the test, this evolution required approximately 2.0 h in most cases because the ΔP approached 25 psid. For Part 2, the evolution was closer to 2.25 to 2.5 h and the 25-psid limit was not reached. Each operating period incorporating an active period with both DEF-01 and DEF-02 comprised a cycle.

Figure 6.15 shows the initial ΔP measured for each cycle of Test HS3. The trigger point for swapping was different depending on the cycle, but the pressure at which the swap occurred in Part 1 was usually 25 psid whereas for Part 2 the pressure was typically < 8 psid. Over the 146 hours of operation, each filter was used 35 times (Part 1: 15 cycles, Part 2: 20 cycles); after the first couple of cycles, both DEFs reached a point where they consistently returned to roughly the same initial ΔP (Part 1: ~1 to 1.4 psid and Part 2: ~0.7 to 0.9 psid). There was no observable trend after approximately three cycles[40], suggesting that backflushing was consistently successful in restoring the DEFs to the same starting point.

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[40] This ignores the small decrease in initial ΔP for both filters that occurred around cycle number 15 when the solids concentration was reduced by approximately a factor of two (at the transition from Part 1 to Part 2 of Test HS3). A couple of cycles after that occurs, there is again no trend in the initial ΔP. Since this is a known cause, it is not considered indicative of a change in filter performance.

Figure 6.16 shows the ΔP evolution for each cycle of DEF operation; the second and second-to-last cycles are shown in thicker black lines; in this case, they do not clearly show the lack of trend because they occur in separate parts of the test.[41] Data in Figure 6.16 is bifurcated due to the change in solids concentration during Test HS3. The ΔP curves that increase more rapidly are from Part 1 (970 ppm solids), and the other curves are from Part 2 (500 ppm solids). The data show that the 2-psid trigger was reached in ≤ 0.5 h (in most cases) for both DEFs during Part 1 but closer to ~1.5 h in Part 2. There still appears to be an increase in pressure that accelerates with time (the curves appear to be non-linear) but it is much less pronounced, especially for the Part 2 data. All the cycles during Part 2 were able to incorporate the full 2-h soak time, with a relatively modest increase in pressure compared to Tests HS1, HS2, and HS3 Part 1.

The normalized data for the filters is shown in Figure 6.17. The resistance increased rapidly and significantly (factors of 20 to 60) across all regions of v^+ over the measured baseline resistance $R^+_{m,o}$ during Part 1 of Test HS3. The impact of reduced solids concentration is starkly evident in the drop in ω values that occurred in Part 2 – at $v^+ \geq 750$, ω is only 5 to 20, or roughly a factor of three less than Part 1. The data in Figure 6.15, Figure 6.16, and Figure 6.17 all demonstrate that the DEFs returned to their initial performance level (similar ΔP after 10 min and $\omega \sim 1$) after each backflush and filter swap despite being allowed to operate well above the 2-psid trigger point. The data also indicate that performance can be shifted sharply by diluting the solids concentration of the same simulant material while keeping all other operations the same in the system.

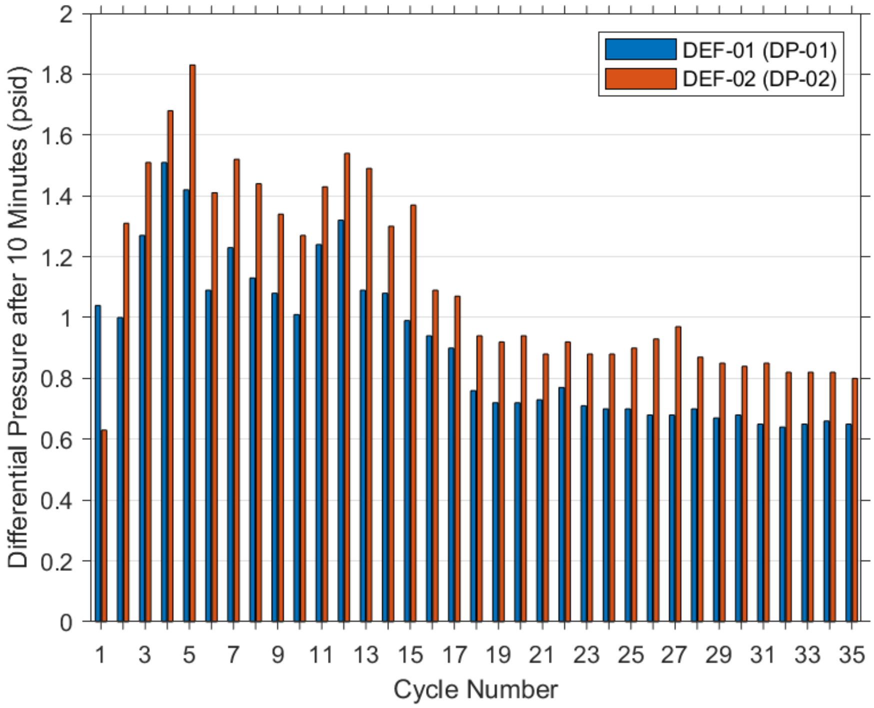

Figure 6.15. Differential Pressure Observed after 10 Minutes for DEF-01 (blue) and DEF-02 (orange) for Each Filter Cycle in Test HS3.

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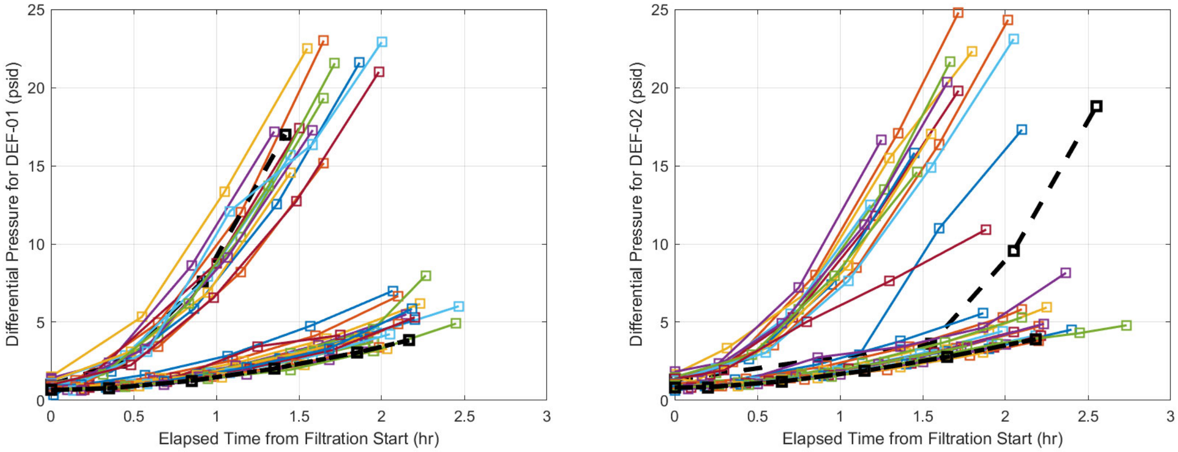
[41] Note that the second cycle shown in black in Figure 6.16(b) is not similar to the other cycles from Part 1 of the test; this is due to a plugging event that occurred during that cycle.



(a) Differential pressures for DEF-01 (b) Differential pressure for DEF-02

Figure 6.16. Differential Pressures for (a) DEF-01 and (b) DEF-02 for all Cycles in Test HS3. The elapsed time has been adjusted to show all the filter evolutions starting from the same time, which is the point at which the initial ΔP (at t = 10 min) was recorded. The thicker black dashed lines are provided to indicate the second and penultimate cycle for each DEF. Test HS3 has two discrete sets of differential pressure curves due to the change in simulant solids concentration during the test.

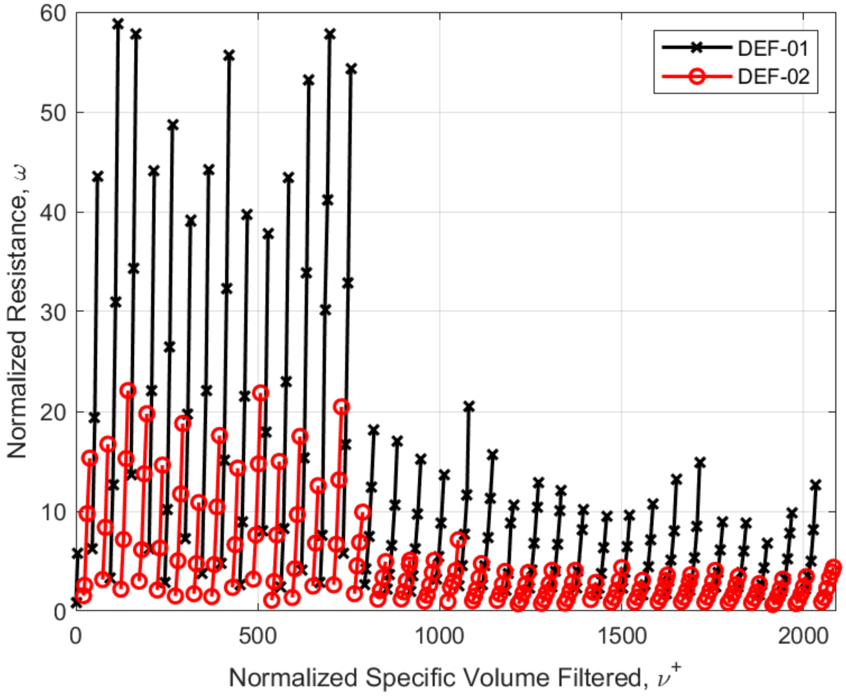


Figure 6.17. Evolution of DEF Normalized Resistance for Test HS3.

The differential pressures observed in IXC-01 are shown in Figure 6.18. The differential pressure oscillation is similar to what was observed in Test HS1; the oscillations originate from the filter swaps that occurred during Test HS3 (each filter swap displaces some 0.1 M NaOH through the CST bed, which has a lower viscosity than the simulant). Test HS3 had the most pronounced, longer-duration fluctuations in the DP data (seen as "humps" in Figure 6.18 that have a length of ~18 to 24 h), which is probably reflecting the higher variation in system temperatures during the test. The DPs increase only slightly over the entire test (as in Test HS1, no more than ~0.5 psid) and the increase is primarily in the CST bed below the 6-inch level by comparison of the DP-04 and DP-05 traces. It is likely this is related to consolidation of the CST bed itself in the presence of the flow rather than any significant particle deposition, which is expected mostly at or near the highest elevations of the bed. As discussed later in Section 6.6.3, there were no observable particle deposits seen at the top surface of the CST in IXC-01 after Test HS3.

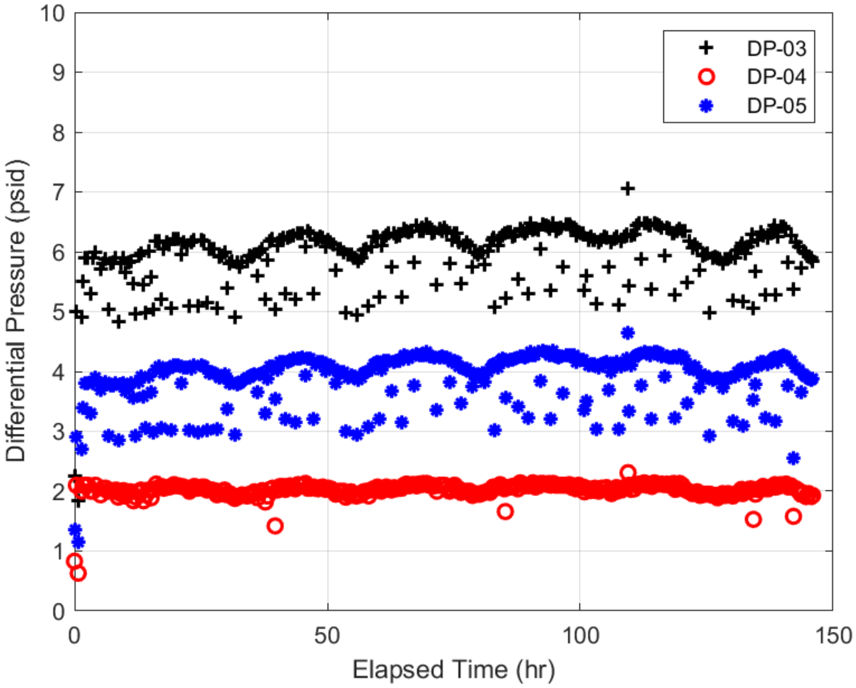


Figure 6.18. Differential Pressure Traces for IXC-01 During Test HS3.

The cesium concentrations measured in the IXC-01 effluent were below the ICP-MS EQL (equal to ~0.13% C/C_o) for all but the last two Test HS3 samples collected; the final measured effluent concentration was approximately 0.15% C/C_o. The first effluent sample above the EQL was collected at an elapsed time of 143.2 h, which is equivalent to about 270 BV. This was consistent with the target of reaching initial breakthrough (0.1% C/C_o) near the end of a test; since the EQL was slightly greater than the initial breakthrough level, the point at which 0.1% C/C_o was exceeded can only be estimated by extrapolating from the last couple of data points. The total BVs processed were estimated to be 275 and there were no indications of unusual behavior for the CST in the IX column. The Test HS3 cesium data suggests an initial cesium breakthrough at approximately 260 BV; for a comparison with other tests see Section 6.6.2.

No significant acceleration in fouling was observed in Test HS3, so the DEFs were not suspected of being progressively contaminated with each filter evolution as it appeared had been the case in Test NB1. This was confirmed by measuring the filter DPs using water (at the target flow rate and nominal feed pressure) after the test was completed and the DEFs had been backflushed and rinsed. The post-test DPs agreed with DPs measured under the same conditions before Test HS3 began. Data from the 0.1 M NaOH baseline flow measurement also supports this point (see Table 6.1).

6.6 Comparisons Between Tests

There are limitations with comparing test data across the four tests conducted in the laboratory-scale system because they were appreciably different in their filtration behavior. The tests with higher solids loadings – particularly Test HS2 – also experienced a higher frequency of plugging events in the 1/8-in. feed line (which interrupted normal processing operations), pressure fluctuations (due to variations in the feed pressure that were passed on to the DP instruments), and had less data collected per cycle (because the filter swapping occurred more frequently). Despite the limitations, there are a few important inferences that can be drawn by comparing data across the tests.

6.6.1 Comparison of DEF Data

Table 6.2 compares the slopes and intercepts from DEF data sets for the four tests. The slopes and intercepts were computed using linear regression for each individual cycle and then averaged together over all filter cycles. If a data set contained fewer than three data points for any cycle, a linear regression was not performed for that cycle. The regression analysis was used for both the "initial" period where differential pressure was recorded at t = 2, 4, 6, 8, and 10 minutes and for the entire cycle that a filter was active. Active filter data was combined for DEF-01 and DEF-02. The 10-minute initial period is largely comprised of the displacement of the 0.1 M NaOH resident in the DEF and thus is not directly comparable to the overall active period when the only simulant was being filtered.

Table 6.2. Summary of Average Slopes and Intercepts from Linear Regression Analysis of DEF Data from All Tests. The data shown are the mean of all the data and the uncertainty is represented by the standard deviation of the mean.

Test	DEF-01 Initial Slope (psid/h)	DEF-01 Initial Intercept (psid)	DEF-02 Initial Slope (psid/h)	DEF-02 Initial Intercept (psid)	Active Filter Slope (psid/h)	Active Filter Intercept (psid)
NB1	1.70 ± 0.44	0.19 ± 0.07	1.83 ± 0.13	0.13 ± 0.04	0.11 ± 0.07	0.48 ± 0.11
HS1	5.83 ± 1.76	0.27 ± 0.16	8.55 ± 2.78	0.38 ± 0.27	8.41 ± 2.54	-0.56 ± 0.91
HS2	14.2 ± 5.1	-0.02 ± 0.28	15.5 ± 2.6	0.03 ± 0.17	27.0 ± 7.0	0.68 ± 1.15
HS3[(a)]	5.88 ± 0.60 3.47 ± 0.41	0.24 ± 0.10 0.19 ± 0.11	6.56 ± 1.40 3.90 ± 0.40	0.39 ± 0.11 0.32 ± 0.04	10.4 ± 2.2 1.86 ± 0.47	-0.52 ± 0.71 0.39 ± 0.19

(a) Since Test HS3 had two distinct periods of operation, the filtration data was separated for the statistical summary in this table. The upper value is from the first half of the test (Part 1, where the solids loading was approximately double the second half of the test). The second half of the test (Part 2) is the lower value.

The statistical summary in Table 6.2 illustrates the impact of solids loading on the slope both initially and over the entire cycle. Higher solids loadings greatly increased both slopes (and led to a much more uncertain measurement); the hierarchy in solids goes as Test HS2 > Test HS1 ~ Test HS3 (Part 1) > Test HS3 (Part 2) > Test NB1. The differences in active slopes between tests appear to be (approximately) directly proportional to the changes in solids loading. For instance, HS2 had about three times the solids loading as HS1, and the average active filter slope increases in HS2 by approximately that amount over HS1.

The time (in hours) between swapping DEFs compared to the filter cycle number is presented in Figure 6.19. Although there was some variability in the calculated slopes for the filter cycles as discussed previously, the amount of time that transpired between filter swaps was steady for all the tests with appreciable solids (HS1, HS2, and HS3). The reduction in swap time for Test NB1 was likely due to the suspected contamination described in Section 6.2. Figure 6.19 supports the conclusion that the fouling of both DEFs did not accelerate over the operating time of the test, and filter recovery (via backflushing) was successful over many repeated uses.

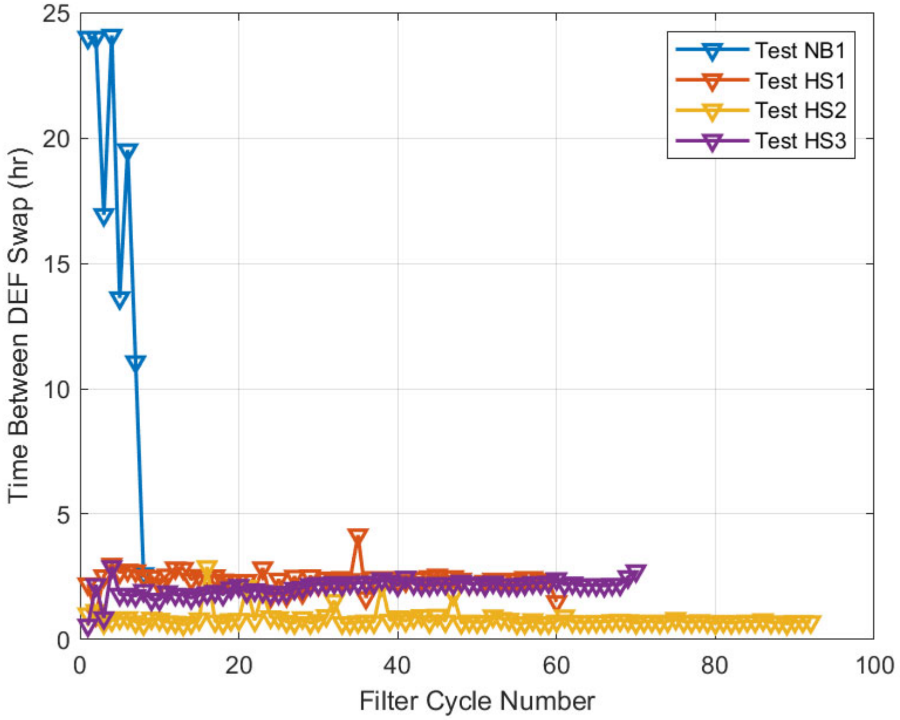


Figure 6.19. Time Between DEF Swaps as a Function of Cycle Number for All Tests.

6.6.2 Comparison of IX Column Data

The average differential pressure data from three periods of operation (early – 12 to 24 h elapsed time; middle – 60 to 72 h elapsed time, and late – 120 to 132 h elapsed time) are compared in Table 6.3. Examination of the mean pressure data collected from the IX column does not suggest any significant trend with operating time during the tests. There is an increase in the DP-03 average for three of the tests between the early and middle periods; however, only one test (NB1) increased between all three periods (note that Test HS2 was not operated long enough to reach the late period). The DP-05 average is also shown for comparison because it does not include the inlet screen and top 6 inches of the CST bed (which were significant contributors to the overall column pressure drop). The DP-05 average generally increases slightly over the three periods for all tests except HS3. This is probably indicative of bed consolidation in the presence of flow; no evidence was found of any breakthrough from the filters or other solids deposition. The average values from these periods are also arbitrarily selected and may include stoppages in flow, differences in temperature (viscosity of the simulant), or different numbers of 0.1 M NaOH displacement events that impact the average value.

Table 6.3. Summary of Average Differential Pressures Measured at the Beginning (12 to 24 h), Middle (60 to 72 h), and End (120 to 132 h) of Testing. The data are the mean of all the data in the stated time period and the uncertainty is represented by the standard deviation of the mean.

	Average DP-03 Measurement (psid)			Average DP-05 Measurement (psid)		
Test	12 – 24 h	60 – 72 h	120 – 132 h	12 – 24 h	60 – 72 h	120 – 132 h
NB1	4.58 ± 0.03	4.76 ± 0.24	5.01 ± 0.01	2.88 ± 0.03	3.12 ± 0.18	3.38 ± 0.02
HS1	5.90 ± 0.26	5.79 ± 0.46	5.96 ± 0.43	3.66 ± 0.25	3.58 ± 0.41	3.93 ± 0.27
HS2	5.22 ± 0.45	5.70 ± 0.46	n/a	3.29 ± 0.42	3.73 ± 0.46	n/a
HS3	5.80 ± 0.48	6.16 ± 0.36	5.90 ± 0.31	3.73 ± 0.45	4.06 ± 0.35	3.86 ± 0.29

Figure 6.20 shows the normalized permeability β^* for all four tests as calculated using Eq. (3.38). For presentation purposes, the data shown in the figure were smoothed using a 9-point moving average. In all the tests, after the displacement of 0.1 M NaOH that occurs at the test start, the permeability is within 50% of a value of unity (and in three of the tests, much less than 50%), e.g., close to the baseline measured permeability for the length of the test. There are no appreciable trends in β^* over time: if there were significant changes in solids entrainment in the bed, the permeability should decrease with time. The normalized permeability incorporates both differences in baseline permeability $\beta_{IX,o}$ for the CST beds in each test and any variation in simulant viscosity, which makes it a better comparison than the measured differential pressure data. The data suggests that the CST beds in all four tests had very similar hydraulic performance and did not become significantly more resistive to flow over the test operating period.

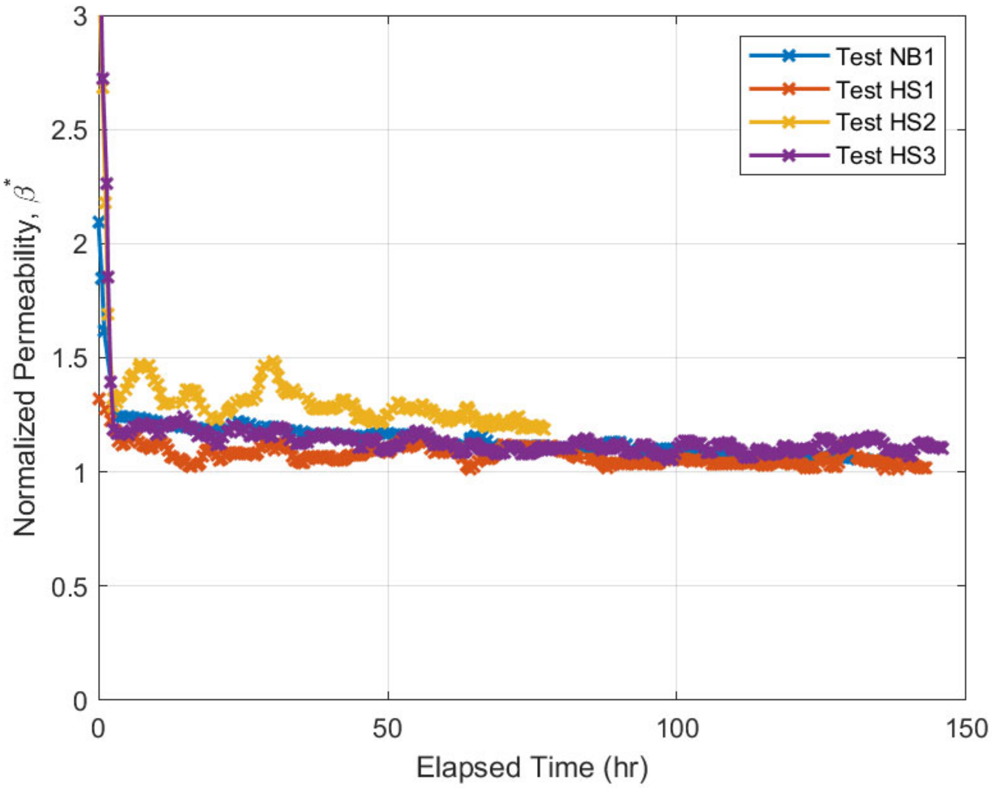


Figure 6.20. Normalized Permeability for the CST Bed in the IX Column for All Tests.

Finally, Figure 6.21 compares the effluent data collected to assess cesium removal performance for all four tests. Only two tests (HS1 and HS3) had effluent samples that exceeded the EQL of the analysis method used to detect cesium. This was not surprising, since Test NB1 had a much lower [Na] than planned and Test HS2 was truncated. Since the EQL is greater than the 0.1% C/C_o level, the precise time when cesium started initial breakthrough can only be estimated by extrapolation. Based on visual extrapolation as shown in the Figure 6.21, it appears that C/C_o exceeded 0.1% at approximately 250 to 260 BVs for both Tests HS1 and HS3, which is consistent with expectation and previously collected data (see the discussion in Section 3.3.1). The effluent data from the testing suggests that the IX process was performing as expected and it did not appear to experience any impacts from higher solids loading in the feed. This is further supported by the evidence provided in the next section.

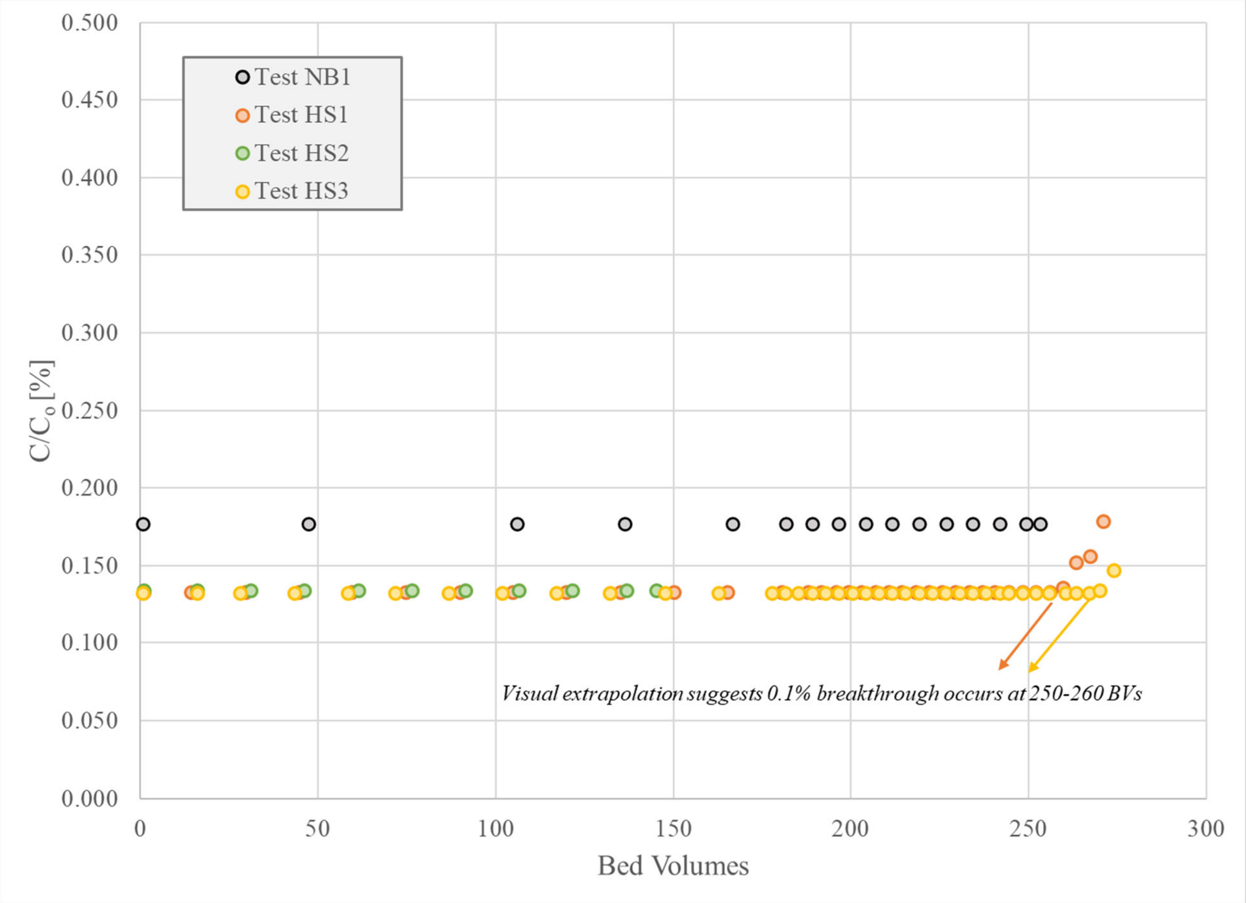
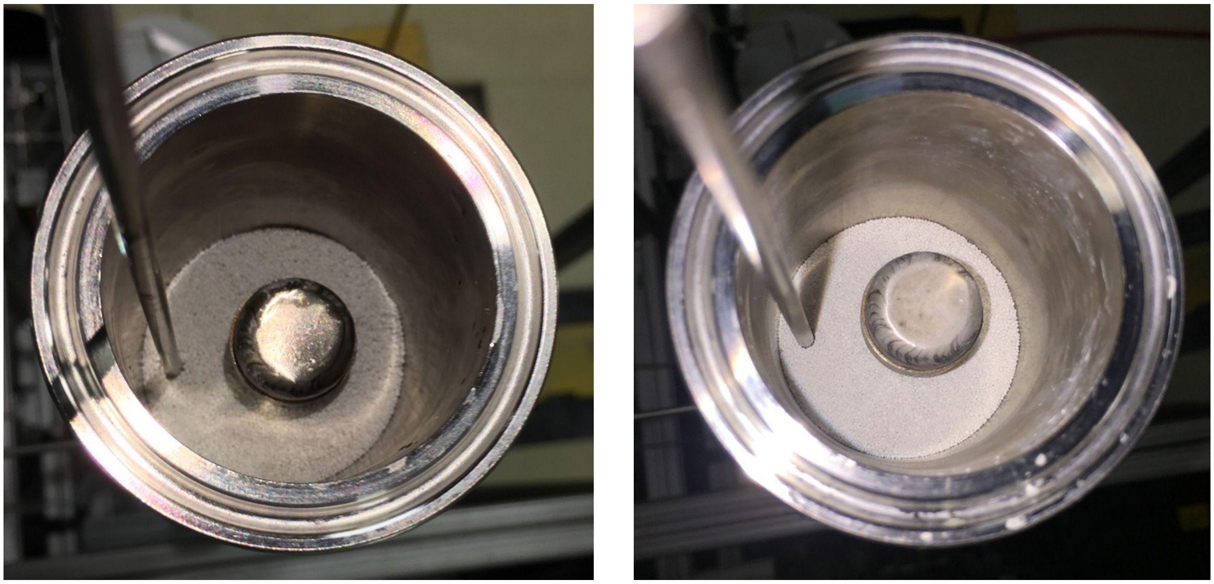


Figure 6.21. Comparison of the Effluent Concentration Ratio (C/C_o) with BV Processed for All Tests.

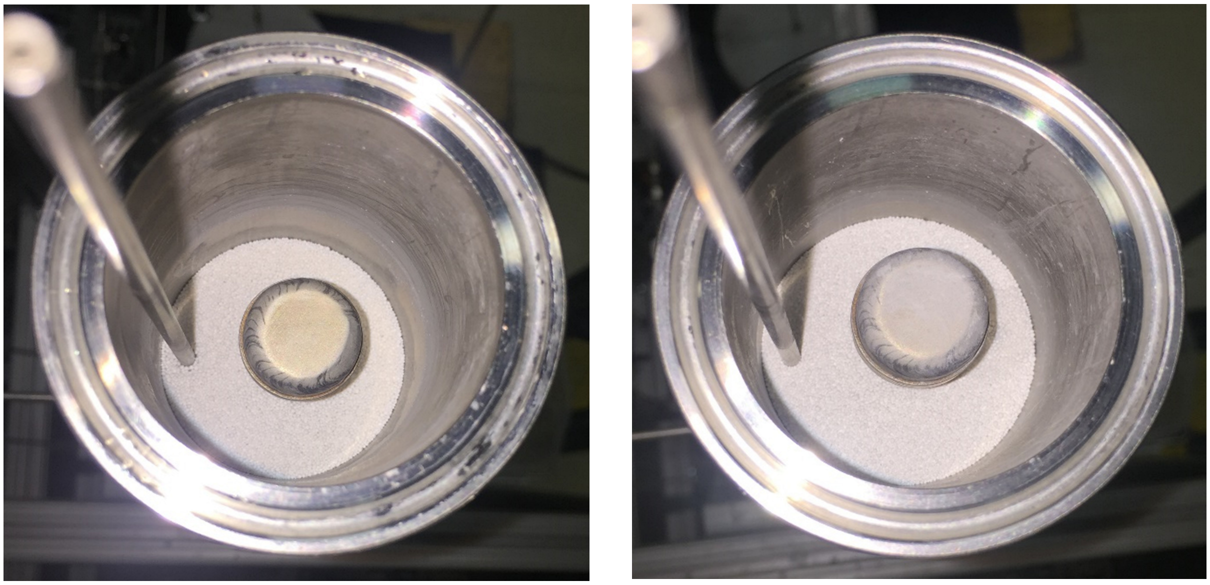
6.6.3 Post-Test Observations of CST at the Top of the Bed

Figure 6.22 shows images of the CST bed at the column top after test completion and air blowdown for each of the four tests. Although these images do not have enough magnification to see individual CST particles, there was no visual indication of particle accumulation. Note that the pressure drop data for each test only showed a very minor increase over the duration of each test (see, for example, the summary data in Table 6.3 and Figure 6.20), so any particle collection within the CST bed was not appreciable enough to affect the pressure drop through the bed. Small samples of CST were collected from the top of the CST beds from each test and observed under an optical microscope. These observations also showed no fine particles that might have caused bed plugging and these observations are consistent with the minor increase in pressure drop in the CST bed over the duration of each test.



Test NB1

Test HS1



Test HS2

Test HS3

Figure 6.22. Images of the IX Column Top after Testing and Air Blowdown.

7.0 Summary and Conclusions

A series of four tests were conducted using a scaled test system prototypic of the full-size TSCR system to assess filtration and ion exchange performance at higher-than-nominal solids loading. The testing used waste simulants with representative chemical constituents and solids generated by a dilution-precipitation process using dissolved $CaCl_2$. A baseline performance test was performed first using a 5.6 M Na simulant with a chemical composition that is, approximately, an average of projected DFLAW feeds and contained only a trace amount of suspended solids. This was followed by three tests with suspended solids loadings ranging from ~500 ppm to 3,000 ppm; the solids included a fraction of particles that were below the manufacturer's rating of the dead-end filters (< 5 microns). Ultimately, while the solids loadings tested were higher than in prior scaled testing, they were still substantially below the maximum allowable TSCR value of 15,000 ppm, primarily due to limitations of operability expected at solids loading levels > 3,000 ppm.

All the test operations were similar: the flow rate was well-controlled at the target of 130 mL min^{-1} at a feed temperature of 22 ± 1 °C. The dead-end filters retained the solid particles—no breakthrough or accumulation of particles downstream of the filters was observed—and backflushing was effective at restoring filter performance. The ion exchange column performed as expected and no significant change in hydraulic resistance was observed. Post-test observations did not uncover any unusual deposition of solids in the CST bed or inlet distributor; aside from an unexplained contamination event in the first test, the filters were successfully "cleaned" in place between tests.

Based on analysis of data and operational observations, the important conclusions drawn from the testing are the following:

- The dead-end filters successfully performed their primary function of protecting the IX column at all tested solids loadings. This was supported by several pieces of evidence collected during the testing:
  - Based on differential pressure drop measurements along the column, where only a negligible increase in pressure drop was measured over the duration of each test, there was no observable plugging of the column during each test.
  - Visual observations of the top of the CST bed after each test showed no evidence of particle accumulation.
  - Particles were not visually observed in the effluent collection tank.
  - There was an absence of visually observed solids in post-DEF samples collected periodically during operation.
  - Solids deposition was not observed in post-test examination of the post-DEF process lines.
  - The initial cesium loading behavior onto the CST was not discernably impacted by higher solids loadings.
- The filters exhibited a rapid rate of change in pressure differential even at modest solids loadings, i.e., ~1,000 ppm and greater. Though the target throughput of the system was maintained, the observed system performance challenges the planned operational approach for TSCR because:
  - The ΔP across each DEF increased above the 2-psid target in as little as ~10 to 15 minutes for the highest solids loading tested (~3,000 ppm). Swapping between filters when the 2-psid pressure target is reached demands rapid response by operators, requires operational vigilance, and generates an appreciable amount of flushed waste (which would ultimately collect in tank AP-108).

  - Above the 2-psid target, the rate of change in ΔP usually accelerated, especially above ~10 psid. This introduces a risk that the pressure could suddenly increase beyond the maximum allowed pressure differential of 25 psid and an interlock could be activated in the TSCR facility.
  - Rapid swapping would greatly reduce the duration of the 2-hr 0.1 M NaOH soak time that is planned for TSCR. While there was not a noticeable impact on backflush efficacy when the soak time was shortened during the scaled testing, it is not certain that this would also be the case for full-scale radioactive operations.
  - The filter swapping frequency may significantly reduce the amount of "net" treated waste since every backflush evolution sends the equivalent of two DEF volumes to tank AP-108. The DEF shell volume was not scaled to the full-scale TSCR shell volume, so the breakeven point cannot be projected directly from the test data.
- Despite pressure differentials that increased up to 25 psid over time periods of less than an hour, the DEFs were backflushed repeatedly and reliably during test operations. Backflushing and a 0.1 M NaOH soak (even if the soak period was truncated) consistently returned the DEF to its baseline ΔP. DEF performance, as observed during these tests, is well-described by the term "cyclic."
- Following the completion of a test run, the system was readily returned to its baseline performance level (as determined by a 0.1 M NaOH flow measurement conducted before each test) without any significant interventions. The only "cleaning" conducted between tests involved flushing out simulant material with 0.1 M NaOH, water rinsing the pH down to ~7 or 8, and a handful of backflushes on each DEF.
- The scaled system tests were conducted in such a way as to be faithful to the planned TSCR configuration and procedural steps as possible. No significant issues were identified with the operational configuration during testing. One minor observation was that when the CST was contacted initially with simulant after being loaded with 0.1 M NaOH, a significant number of fines were released and flowed downstream. A similar effect would be anticipated when first contacting CST with actual waste feed.

Overall, the scaled TSCR testing demonstrated that the full-scale unit operations can succeed in fulfilling their processing objectives in the presence of solids up to 3,000 ppm, but there are potential performance challenges to filtration operations at solids loadings as low as ~500 ppm. The severity of the challenge is likely to be dependent on the type and size distribution of solids, of which the current testing only examined a single type and size distribution. To provide some flexibility for future full-scale operations, the results of the testing suggest two possible risk-reduction strategies that can be implemented without any changes in TSCR design or configuration. One option would be to enact an administrative limit on the solids loading to protect TSCR from feeds that are likely to require an unacceptable DEF swap frequency; however, a quantitative measurement of solids content at the $10^2 – 10^3$ ppm level requires a large sample (~1 L was used in this work). Another option is to permit operation of the DEFs at differential pressures greater than 2 psid before swapping filters. The selection of a higher differential pressure target is not anticipated to adversely impact DEF backflushing efficacy and would reduce both swap frequency and the amount of waste sent to tank AP-108.

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Appendix A – Test Timelines

In this appendix, timelines of major events during the scaled system tests are summarized. Each test timeline contains activities that were conducted as part of the test preparation in one table, followed by a second table with the events that occurred during normal test operation. Note that post-test activities are not described in these test timelines unless they were important to performing the subsequent test.

A.1 Timelines of Test NB1

Table A.1. Test NB1 Preparation Timeline

Date	Time (24h)	Description
2/19/2021	11:15	Water flow test
2/18/2021	N/A	Caustic preparation
2/18/2021	N/A	Balance check
2/19/2021	11:30	DP zero check and adjustment
2/22/2021	N/A	Caustic preparation
2/22/2021	N/A	Balance check
2/25/2021	N/A	CST preparation
2/26/2021	N/A	System pressure verification
2/26/2021	10:50	DP zero check and adjustment
2/26/2021	N/A	CST loaded into IXC-01
2/26/2021	N/A	0.1 M NaOH flow test
3/1/2021	N/A	FLT-01 plugging and V-24 not properly controlling; both cleaned and proper operation restored. As described in Section 5.3, the single filter FLT-01 was replaced by a pair of filters (FLT-01A and FLT-01B) for subsequent tests.
3/3/2021	N/A	Received simulant batch for NB1
3/3/2021	14:37	Decanted simulant from as-received tote to TK-01 via diaphragm pump. New FLT-01 installed. As described in Section 5.3, the single filter FLT-01 was replaced by a pair of filters (FLT-01A and FLT-01B) for subsequent tests.
3/3/2021	N/A	Pre-test acceptance of simulant
3/3/2021	10:25	Sample NB1-O1
3/3/2021	10:26	Sample NB1-CS1
3/4/2021	09:05	Sample NB1-O2
3/4/2021	09:06	Sample NB1-O3
3/4/2021	09:12	Sample NB1-O4
3/4/2021	09:13	Sample NB1-O5

Table A.2. Test NB1 Operations Timeline

Date	Time (24h)	Description
3/4/2021	06:18	Started recirculation loop to heat TK-01 to target temperature
3/4/2021	09:38	Verified DP zero readings
3/4/2021	09:50	Test start
3/4/2021	09:50	Filter period 1 start
3/4/2021	10:20	Sample NB1-CS2
3/4/2021	18:10	Sample NB1-CS3
3/4/2021	21:37	Sample NB1-O6
3/5/2021	02:10	Sample NB1-CS4
3/5/2021	02:40	Transferred contents from TK-04 to holding tote
3/5/2021	09:37	Sample NB1-O7
3/5/2021	09:50	Filter period 2 start
3/5/2021	10:58	Sample NB1-CS5
3/5/2021	15:55	TK-02 cleaned to remove deposit of white solids near pump intake
3/5/2021	18:12	Sample NB1-CS6
3/5/2021	21:34	Sample NB1-O8
3/6/2021	02:12	Sample NB1-CS7
3/6/2021	09:02	Sample NB1-O10
3/6/2021	09:03	Sample NB1-O11
3/6/2021	09:37	Sample NB1-O9
3/6/2021	09:50	Filter period 3 start
3/6/2021	11:00	Sample NB1-CS8
3/6/2021	18:08	Sample NB1-CS9
3/6/2021	18:40	Transferred contents from TK-04 to holding tote
3/6/2021	19:25	Sample NB1-O12
3/6/2021	19:30	Decanted remaining simulant volume from as-received tote to TK-01
3/6/2021	19:40	Sample NB1-O13
3/6/2021	N/A	Determined that total simulant processed during NB1 will be less than target 300 gal
3/6/2021	22:06	Sample NB1-O14
3/7/2021	02:10	Sample NB1-CS10
3/7/2021	02:21	FLT-01 plugged, was replaced and cleaned
3/7/2021	02:46	Filter period 4 start
3/7/2021	06:57	Two leak locations identified, cleaned, and checked for tightness
3/7/2021	10:06	Sample NB1-O15
3/7/2021	10:10	Sample NB1-CS11
3/7/2021	18:10	Sample NB1-CS12
3/7/2021	18:10	Transferred contents from TK-04 to holding tote
3/7/2021	22:09	Sample NB1-O16
3/8/2021	02:10	Sample NB1-CS13
3/8/2021	02:51	Filter period 5 start
3/8/2021	10:09	Sample NB1-O17
3/8/2021	10:12	Sample NB1-CS14

Date	Time (24h)	Description
3/8/2021	12:04	Sample NB1-CS15
3/8/2021	14:03	Sample NB1-CS16
3/8/2021	14:35	Extracted ~10 L from as-received tote and added to TK-01
3/8/2021	16:04	FLT-01 plugged, was replaced and cleaned
3/8/2021	16:05	Sample NB1-CS17
3/8/2021	16:28	Filter period 6 start
3/8/2021	18:05	Sample NB1-CS18
3/8/2021	19:10	Transferred contents from TK-04 to holding tote
3/8/2021	19:20	Extracted ~6 L from as-received tote and added to TK-01
3/8/2021	20:05	Sample NB1-CS19
3/8/2021	22:05	Sample NB1-CS20
3/8/2021	22:07	Sample NB1-O18
3/9/2021	00:03	Sample NB1-CS21
3/9/2021	02:03	Sample NB1-CS22
3/9/2021	04:03	Sample NB1-CS23
3/9/2021	04:18	Adjusted V-51, V-52, and VFD to maintain system pressure while slowing whirly bird
3/9/2021	06:03	Sample NB1-CS24
3/9/2021	06:18	Adjusted V-51, V-52, and VFD to maintain system pressure while slowing whirly bird
3/9/2021	08:03	Sample NB1-CS25
3/9/2021	10:03	Sample NB1-O19
3/9/2021	10:05	Sample NB1-CS26
3/9/2021	11:59	Filter period 7 start
3/9/2021	12:24	Closed V-51, opened V-52, and adjusted BPR-01 to maintain system pressure and stop whirly bird
3/9/2021	12:30	Sample NB1-CS27
3/9/2021	14:05	Sample NB1-CS28
3/9/2021	16:06	Sample NB1-CS29
3/9/2021	16:10	Transferred contents from TK-04 to holding tote
3/9/2021	18:05	Sample NB1-CS30
3/9/2021	20:05	Sample NB1-CS31
3/9/2021	22:03	Sample NB1-CS32
3/9/2021	22:05	Sample NB1-O20
3/9/2021	23:03	Filter period 8 start
3/9/2021	23:30	Sample NB1-CS33
3/10/2021	00:04	Sample NB1-CS34
3/10/2021	01:30	Sample NB1-O21
3/10/2021	01:40	Test end

A.2 Timelines of Test HS1

Table A.3. Test HS1 Preparation Timeline

Date	Time (24h)	Description
3/31/2021	13:40 – 15:00	Caustic preparation
4/20 – 4/21/2021	N/A	CST Preparation
4/21/2021	N/A	System check and verification
4/21/2021	N/A	IXC-01 loading
4/21/2021	11:40 – 12:05	Flushing IXC-01 to remove CST fines
4/30/2021	14:00	Sample HS1 – CS1
4/30/2021	14:00	Sample HS1 – O1
4/30/2021	16:00	Feedstock received from vendor
5/3/2021	09:15	Transferred feedstock from as-received tote to feed tote
5/3/2021	09:45	Flushed IXC-01 until clear
5/3/2021	10:15	DP zero check
5/3/2021	10:28 – 11:49	Pre-test conditions and 0.1 M NaOH flow test
5/3/2021	11:20	Accidental excessive drainage of IXC-01
5/3/2021	11:58	Sample HS1 – O2
5/3/2021	11:59	Sample HS1 – O3
5/3/2021	12:01	Sample HS1 – S1
5/3/2021	12:02	Sample HS1 – S2
5/3/2021	12:03	Sample HS1 – O4
5/3/2021	12:05	Sample HS1 – O5

Table A.4. Test HS1 Operations Timeline

Date	Time (24h)	Description
5/3/2021	12:24	HS1 test start
5/3/2021	12:24	Filter period 1 start
5/3/2021	12:55	Sample HS1 – CS2
5/3/2021	13:14	Feedline plugged
5/3/2021	14:08	Flow from TK-01 to system restored
5/3/2021	14:37	Filter period 2 start
5/3/2021	14:47	Switched from FLT-01A to FLT-01B
5/3/2021	15:36	Filter period 3 start
5/3/2021	18:08	Filter period 4 start
5/3/2021	19:29	Switched from FLT-01B to FLT-01A
5/3/2021	20:05	Sample HS1 – CS3
5/3/2021	21:08	Filter period 5 start
5/3/2021	23:49	Filter period 6 start
5/4/2021	00:25	Sample HS1 – other 6
5/4/2021	02:35	Filter period 7 start
5/4/2021	04:05	Sample HS1 – CS4

Date	Time (24h)	Description
5/4/2021	04:30	Switched from FLT-01A to FLT-01B
5/4/2021	05:19	Filter period 8 start
5/4/2021	06:04	Backflush plug
5/4/2021	07:51	Filter period 9 start
5/4/2021	10:21	Filter period 10 start
5/4/2021	12:05	Sample HS1 – CS5
5/4/2021	12:25	Sample HS1 – O6
5/4/2021	12:33	Filter period 11 start
5/4/2021	15:07	Filter period 12 start
5/4/2021	17:58	Filter period 13 start
5/4/2021	18:08	Feedline plug
5/4/2021	18:30	Backflush plug
5/4/2021	20:00	Sample HS1 – CS6
5/4/2021	20:48	Filter period 14 start
5/4/2021	23:12	Filter period 15 start
5/5/2021	00:25	Sample HS1 – O7
5/5/2021	00:45	Sample HS1 – O8
5/5/2021	01:45	Filter period 16 start
5/5/2021	04:05	Sample HS1 – CS7
5/5/2021	04:16	Filter period 17 start
5/5/2021	06:48	Filter period 18 start
5/5/2021	09:10	Filter period 19 start
5/5/2021	11:30	Filter period 20 start
5/5/2021	12:08	Sample HS1 – CS8
5/5/2021	12:25	Sample HS1 – O9
5/5/2021	13:00	Feedline plug
5/5/2021	13:51	Filter period 21 start
5/5/2021	13:51	Pumped remainder of HS1 simulant into feed tote
5/5/2021	15:00	Feedline plugged twice in succession
5/5/2021	16:12	Filter period 22 start
5/5/2021	16:32	Sample HS1 – S3
5/5/2021	18:10	Filter period 23 start
5/5/2021	20:02	Sample HS1 – CS9
5/5/2021	20:30	Switched from FLT-01A to FLT-01B
5/5/2021	21:01	Filter period 24 start
5/5/2021	22:44	Filter period 25 start
5/6/2021	00:25	Sample HS1 – O10
5/6/2021	01:08	Filter period 26 start
5/6/2021	02:53	Filter period 27 start
5/6/2021	04:01	Sample HS1 – CS10
5/6/2021	05:24	Filter period 28 start
5/6/2021	07:17	Filter period 29 start
5/6/2021	09:48	Filter period 30 start

Date	Time (24h)	Description
5/6/2021	11:59	Filter period 31 start
5/6/2021	12:05	Sample HS1 – CS11
5/6/2021	12:25	Sample HS1 – O11
5/6/2021	13:03	Sample HS1 – O12
5/6/2021	14:26	Filter period 32 start
5/6/2021	16:47	Filter period 33 start
5/6/2021	19:15	Filter period 34 start
5/6/2021	20:00	Sample HS1 – CS12
5/6/2021	21:38	Filter period 35 start
5/7/2021	01:48	Filter period 36 start
5/7/2021	02:03	Sample HS1 – O13
5/7/2021	03:28	Filter period 37 start
5/7/2021	04:03	Sample HS1 – CS13
5/7/2021	05:56	Filter period 38 start
5/7/2021	08:20	Filter period 39 start
5/7/2021	10:48	Filter period 40 start
5/7/2021	12:05	Sample HS1 – CS14
5/7/2021	13:05	Sample HS1 – O14
5/7/2021	13:06	Filter period 41 start
5/7/2021	15:05	Sample HS1 – S4
5/7/2021	15:06	Sample HS1 – S5
5/7/2021	15:26	Filter period 42 start
5/7/2021	15:50	Sample HS1 – O15
5/7/2021	16:03	Sample HS1 – CS15
5/7/2021	17:42	Filter period 43 start
5/7/2021	18:01	Sample HS1 – CS16
5/7/2021	20:09	Filter period 44 start
5/7/2021	20:10	Sample HS1 – CS17
5/7/2021	22:00	Sample HS1 – CS18
5/7/2021	22:39	Filter period 45 start
5/7/2021	00:00	Sample HS1 – CS19
5/8/2021	01:03	Sample HS1 – O16
5/8/2021	01:13	Filter period 46 start
5/8/2021	02:06	Sample HS1 – CS20
5/8/2021	03:43	Filter period 47 start
5/8/2021	03:50	Sample HS1 – O17
5/8/2021	04:03	Sample HS1 – CS21
5/8/2021	06:13	Filter period 48 start
5/8/2021	06:03	Sample HS1 – CS22
5/8/2021	08:05	Sample HS1 – CS23
5/8/2021	08:37	Filter period 49 start
5/8/2021	10:01	Sample HS1 – CS24
5/8/2021	10:50	Filter period 50 start

Date	Time (24h)	Description
5/8/2021	11:59	Sample HS1 – CS25
5/8/2021	13:04	Filter period 51 start
5/8/2021	13:57	Sample HS1 – CS26
5/8/2021	15:23	Filter period 52 start
5/8/2021	16:01	Sample HS1 – O18
5/8/2021	16:05	Sample HS1 – CS27
5/8/2021	17:47	Filter period 53 start
5/8/2021	18:00	Sample HS1 – CS28
5/8/2021	19:53	Sample HS1 – CS29
5/8/2021	20:09	Filter period 54 start
5/8/2021	22:00	Sample HS1 – CS30
5/8/2021	22:33	Filter period 55 start
5/9/2021	00:02	Sample HS1 – CS31
5/9/2021	00:56	Filter period 56 start
5/9/2021	02:03	Sample HS1 – CS32
5/9/2021	03:24	Filter period 57 start
5/9/2021	04:05	Sample HS1 – O19
5/9/2021	04:07	Sample HS1 – CS33
5/9/2021	05:01	Fully opened V-52 and closed V-51
5/9/2021	05:52	Filter period 58 start
5/9/2021	06:00	Sample HS1 – CS34
5/9/2021	08:01	Sample HS1 – CS35
5/9/2021	08:15	Filter period 59 start
5/9/2021	09:11	Sample HS1 – CS36
5/9/2021	10:04	Sample HS1 – CS37
5/9/2021	10:35	Filter period 60 start
5/9/2021	11:33	Sample HS1 – CS38
5/9/2021	12:04	Sample HS1 – CS39
5/9/2021	12:05	Air in feedline indicated test must end

A.3 Timelines of Test HS2

Table A.5. Test HS2 Preparation Timeline

Date	Time (24h)	Description
4/30/2021	15:42	Sample HS2-CS1
5/10 – 5/19/2021	N/A	Caustic preparation and makeup
5/11 – 5/12/2021	N/A	CST Preparation
5/12/2021	13:55	Sample HS2-O1
5/12/2021	N/A	System check and verification
5/12/2021	N/A	IXC-01 Loading
5/14/2021	11:10 – 11:35	Flushing IXC-01 column to remove CST fines
5/14/2021	11:35	DP zero check
5/14/2021	12:45 – 12:55	0.1 M NaOH flow test
5/14/2021	N/A	Transferred simulant to feed tote
5/14/2021	14:52	Sample HS2-S1
5/14/2021	14:53	Sample HS2-S2
5/14/2021	14:55	Sample HS2-O2
5/14/2021	14:56	Sample HS2-O3

Table A.6. Test HS2 Operations Timeline

Date	Time (24h)	Description
5/17/2021	08:44	Sample HS2-O4
5/17/2021	08:44	Sample HS2-O5
5/17/2021	08:48	Start of HS2 test
5/17/2021	08:48	Start of filter period 1 (DEF-01)
5/17/2021	09:21	Sample HS2-CS2
5/17/2021	09:40	System plug
5/17/2021	09:49	Start of filter period 2
5/17/2021	10:42	System plugged and PMP-01 stopped
5/17/2021	10:58	Start of filter period 3
5/17/2021	11:38	Start of filter period 4
5/17/2021	12:24	Start of filter period 5
5/17/2021	13:15	Start of filter period 6
5/17/2021	14:07	Start of filter period 7
5/17/2021	14:49	Start of filter period 8
5/17/2021	15:26	Start of filter period 9
5/17/2021	16:17	Start of filter period 10
5/17/2021	16:51-17:05	System plugged
5/17/2021	17:05	Start of filter period 11
5/17/2021	17:10	Backflush plugged DEF-02
5/17/2021	17:20	Sample HS2-CS3
5/17/2021	17:47	Start of filter period 12

Date	Time (24h)	Description
5/17/2021	17:50	Backflush plug DEF-01
5/17/2021	18:28	Start of filter period 13
5/17/2021	19:04	Start of filter period 14
5/17/2021	19:44	Start of filter period 15
5/17/2021	20:10-20:15	System plugged
5/17/2021	20:33	Start of filter period 16
5/17/2021	20:52	Sample HS2-O6
5/17/2021	23:27	Start of filter period 17
5/18/2021	00:11	Start of filter period 18
5/18/2021	01:22	Sample HS2-CS4
5/18/2021	00:51	Start of filter period 19
5/18/2021	01:01-01:09	System lost flow
5/18/2021	01:38	Start of filter period 20
5/18/2021	02:15	DEF-02 plugged
5/18/2021	02:26	Start of filter period 21
5/18/2021	03:03-04:25	System set to standby to clear plug below DEF-02
5/18/2021	04:33	Start of filter period 22
5/18/2021	05:19	Start of filter period 23
5/18/2021	05:44-06:50	System set to standby to clear plug below DEF-01
5/18/2021	07:14	Start of filter period 24
5/18/2021	08:08	Start of filter period 25
5/18/2021	08:50	Sample HS2-O7
5/18/2021	09:00	Start of filter period 26
5/18/2021	09:22	Sample HS2-CS5
5/18/2021	09:43	Start of filter period 27
5/18/2021	10:23	Start of filter period 28
5/18/2021	11:15	Start of filter period 29
5/18/2021	11:55	Start of filter period 30
5/18/2021	12:40	Start of filter period 31
5/18/2021	13:37	Start of filter period 32
5/18/2021	15:00	Switched to FLT-01A
5/18/2021	15:10	Start of filter period 33
5/18/2021	15:50	Start of filter period 34
5/18/2021	16:29	Start of filter period 35
5/18/2021	17:11	Start of filter period 36
5/18/2021	17:24	Sample HS2-CS6
5/18/2021	17:55	Start of filter period 37
5/18/2021	18:37	Start of filter period 38
5/18/2021	18:53-18:58	Pump off
5/18/2021	19:03	Pump off
5/18/2021	20:48	Start of filter period 39
5/18/2021	21:13	System lost flow
5/18/2021	21:32-23:37	System switched off for maintenance to clear plugs

Date	Time (24h)	Description
5/18/2021	21:00	Sample HS2-O9
5/18/2021	21:03	Sample HS2-O8
5/18/2021	21:34	Start of filter period 40
5/18/2021	22:38	Start of filter period 41
5/18/2021	23:13	Start of filter period 42
5/18/2021	23:56	Lost flow
5/19/2021	00:06	Start of filter period 43
5/19/2021	00:39	Lost flow
5/19/2021	00:52	Lost flow
5/19/2021	01:03	Start of filter period 44
5/19/2021	01:20	Sample HS2-CS7
5/19/2021	01:45	Start of filter period 45
5/19/2021	02:19-02:38	Lost flow
5/19/2021	02:43	Start of filter period 46
5/19/2021	03:27	Start of filter period 47
5/19/2021	03:35-03:56	Feed line plugged
5/19/2021	03:56-04:42	System switched off for maintenance to clear plugs
5/19/2021	05:15	Start of filter period 48
5/19/2021	05:55	Start of filter period 49
5/19/2021	06:39	Start of filter period 50
5/19/2021	07:21	Start of filter period 51
5/19/2021	08:04	Start of filter period 52
5/19/2021	09:00	Start of filter period 53
5/19/2021	09:06	Sample HS2-O10
5/19/2021	09:50	Start of filter period 54
5/19/2021	09:20	Sample HS2-CS8
5/19/2021	10:38	Start of filter period 55
5/19/2021	11:17	Start of filter period 56
5/19/2021	11:57	Start of filter period 57
5/19/2021	12:44	Start of filter period 58
5/19/2021	13:23	Start of filter period 59
5/19/2021	14:03	Start of filter period 60
5/19/2021	14:47	Start of filter period 61
5/19/2021	15:43	Start of filter period 62
5/19/2021	16:26	Start of filter period 63
5/19/2021	17:08	Start of filter period 64
5/19/2021	17:20	Sample HS2-CS9
5/19/2021	17:50	Start of filter period 65
5/19/2021	18:33	Start of filter period 66
5/19/2021	19:16	Start of filter period 67
5/19/2021	20:01	Start of filter period 68
5/19/2021	20:47	Start of filter period 69
5/19/2021	21:00	Sample HS2-O11

Date	Time (24h)	Description
5/19/2021	21:32	Start of filter period 70
5/19/2021	22:12	Start of filter period 71
5/19/2021	22:55	Start of filter period 72
5/19/2021	23:39	Start of filter period 73
5/20/2021	00:20	Start of filter period 74
5/20/2021	01:04	Start of filter period 75
5/20/2021	01:20	Sample HS2-CS10
5/20/2021	01:54	Start of filter period 76
5/20/2021	02:37	Start of filter period 77
5/20/2021	03:19	Start of filter period 78
5/20/2021	04:04	Start of filter period 79
5/20/2021	04:46	Start of filter period 80
5/20/2021	05:25	Start of filter period 81
5/20/2021	06:48	Start of filter period 82
5/20/2021	07:30	Start of filter period 83
5/20/2021	08:14	Start of filter period 84
5/20/2021	08:50	Sample HS2-O12
5/20/2021	08:57	Start of filter period 85
5/20/2021	09:09	Sample HS2-O13
5/20/2021	09:20	Sample HS2-CS11
5/20/2021	09:44	Start of filter period 86
5/20/2021	10:25	Start of filter period 87
5/20/2021	11:07	Start of filter period 88
5/20/2021	11:45	Start of filter period 89
5/20/2021	12:28	Start of filter period 90
5/20/2021	13:11	Start of filter period 91
5/20/2021	13:47	Sample HS2-CS12
5/20/2021	13:53	Test end

A.4 Timelines of Test HS3

Table A.7. Test HS3 Preparation Timeline

Date	Time (24h)	Description
4/30/2021	15:44	Sample HS3-CS1
5/26/2021	N/A	Caustic preparation and makeup
5/27/2021	N/A	CST Preparation
6/1/2021	N/A	System check and verification
6/1/2021	N/A	Final CST preparation
6/1/2021	N/A	IXC-01 Loading
6/1/2021	14:05	DP zero check
6/1/2021	16:02-16:30	Flushing IXC-01 column to remove CST fines
6/2/2021	10:45-10:53	Flushing IXC-01 column to remove CST fines
6/2/2021	11:18-11:26	0.1 M NaOH flow test
6/4/2021	08:04	Sample HS3-O1
6/4/2021	08:25-10:05	Transferred simulant to feed tote
6/4/2021	09:50	Sample HS3-O3
6/4/2021	09:52	Sample HS3-O2
6/4/2021	09:53	Sample HS3-S1
6/4/2021	09:54	Sample HS3-S2
6/7/2021	09:15	Sample HS3-S3
6/7/2021	09:16	Sample HS3-O4
6/7/2021	10:10	Sample HS3-O5
6/7/2021	10:11	Sample HS3-O6
6/9/2021	N/A	Caustic preparation and makeup

Table A.8. Test HS3 Operations Timeline

Date	Time (24h)	Description
6/7/2021	10:20	Test start
6/7/2021	10:20	Start of filter period 1 (DEF-01)
6/7/2021	10:51	Sample HS3-CS2
6/7/2021	10:54	Start of filter period 2
6/7/2021	11:10	System paused because both FLT-01A and FLT-01B plugged
6/7/2021	13:05	Start of filter period 3
6/7/2021	13:57	Start of filter period 4
6/7/2021	16:51	Start of filter period 5
6/7/2021	18:39	Start of filter period 6
6/7/2021	18:51	Sample HS3-CS3
6/7/2021	20:27	Start of filter period 7
6/7/2021	22:12	Start of filter period 8
6/7/2021	22:30	Sample HS3-O7
6/8/2021	00:09	Start of filter period 9

Date	Time (24h)	Description
6/8/2021	01:21	Sample HS3-CS4
6/8/2021	01:45	Start of filter period 10
6/8/2021	03:21	Start of filter period 11
6/8/2021	05:15	Start of filter period 12
6/8/2021	07:03	Start of filter period 13
6/8/2021	08:50	Start of filter period 14
6/8/2021	09:22	Sample HS3-CS5
6/8/2021	10:21	Sample HS3-O8
6/8/2021	10:30	Start of filter period 15
6/8/2021	12:17	Start of filter period 16
6/8/2021	14:08	Start of filter period 17
6/8/2021	16:30	Start of filter period 18
6/8/2021	17:22	Sample HS3-CS6
6/8/2021	17:51	Start of filter period 19
6/8/2021	19:54	Start of filter period 20
6/8/2021	22:03	Start of filter period 21
6/8/2021	22:24	Sample HS3-O9
6/8/2021	23:48	Sample HS3-O10
6/8/2021	23:57	Start of filter period 22
6/9/2021	00:24	Sample HS3-CS7
6/9/2021	01:56	Start of filter period 23
6/9/2021	03:51	Start of filter period 24
6/9/2021	05:41	Start of filter period 25
6/9/2021	07:32	Start of filter period 26
6/9/2021	08:22	Sample HS3-CS8
6/9/2021	09:25	Start of filter period 27
6/9/2021	10:21	Sample HS3-O11
6/9/2021	11:27	Start of filter period 28
6/9/2021	13:31	Start of filter period 29
6/9/2021	15:42	Start of filter period 30
6/9/2021	16:25	Sample HS3-CS9
6/9/2021	16:30	Mid-test addition of solids -free simulant to feed tote
6/9/2021	17:56	Start of filter period 31
6/9/2021	20:08	Start of filter period 32
6/9/2021	22:17	Sample HS3-O12
6/9/2021	22:24	Start of filter period 33
6/10/2021	00:27	Sample HS3-CS10
6/10/2021	00:35	Start of filter period 34
6/10/2021	02:50	Start of filter period 35
6/10/2021	05:06	Start of filter period 36
6/10/2021	07:23	Start of filter period 37
6/10/2021	08:27	Sample HS3-CS11
6/10/2021	09:38	Start of filter period 38

Date	Time (24h)	Description
6/10/2021	10:21	Sample HS3-O13
6/10/2021	11:48	Sample HS3-O14
6/10/2021	11:55	Sample HS3-O15
6/10/2021	11:57	Sample HS3-S4
6/10/2021	12:03	Start of filter period 39
6/10/2021	14:22	Start of filter period 40
6/10/2021	16:32	Start of filter period 41
6/10/2021	16:38	Sample HS3-CS12
6/10/2021	19:01	Start of filter period 42
6/10/2021	21:15	Start of filter period 43
6/10/2021	22:25	Sample HS3-O16
6/10/2021	23:26	Start of filter period 44
6/11/2021	00:37	Sample HS3-CS13
6/11/2021	01:37	Start of filter period 45
6/11/2021	03:51	Start of filter period 46
6/11/2021	06:05	Start of filter period 47
6/11/2021	08:18	Start of filter period 48
6/11/2021	08:37	Sample HS3-CS14
6/11/2021	10:32	Sample HS3-O17
6/11/2021	10:34	Sample HS3-CS15
6/11/2021	10:37	Start of filter period 49
6/11/2021	12:32	Sample HS3-CS16
6/11/2021	12:51	Start of filter period 50
6/11/2021	14:34	Sample HS3-CS17
6/11/2021	15:06	Start of filter period 51
6/11/2021	16:34	Sample HS3-CS18
6/11/2021	17:16	Start of filter period 52
6/11/2021	18:34	Sample HS3-CS19
6/11/2021	19:33	Start of filter period 53
6/11/2021	20:35	Sample HS3-CS20
6/11/2021	21:44	Start of filter period 54
6/11/2021	22:32	Sample HS3-O18
6/11/2021	22:33	Sample HS3-CS21
6/11/2021	23:48	Sample HS3-O19
6/11/2021	23:55	Start of filter period 55
6/12/2021	00:33	Sample HS3-CS22
6/12/2021	02:05	Start of filter period 56
6/12/2021	02:32	Sample HS3-CS23
6/12/2021	04:18	Start of filter period 57
6/12/2021	04:32	Sample HS3-CS24
6/12/2021	06:32	Sample HS3-CS25
6/12/2021	06:34	Start of filter period 58
6/12/2021	08:32	Sample HS3-CS26

Date	Time (24h)	Description
6/12/2021	08:49	Start of filter period 59
6/12/2021	10:32	Sample HS3-CS27
6/12/2021	10:35	Sample HS3-O20
6/12/2021	11:06	Start of filter period 60
6/12/2021	11:30	Possible partial plug on in feed line
6/12/2021	11:44	Increased BPR-01 so P-01 increased by ~3 psig
6/12/2021	11:58	Problem resolved, decreased BPR-01 and P-01 to initial settings
6/12/2021	12:32	Sample HS3-CS28
6/12/2021	13:31	Start of filter period 61
6/12/2021	14:34	Sample HS3-CS29
6/12/2021	15:43	Start of filter period 62
6/12/2021	16:34	Sample HS3-CS30
6/12/2021	17:58	Start of filter period 63
6/12/2021	18:34	Sample HS3-CS31
6/12/2021	19:56	Sample HS3-CS32
6/12/2021	20:08	Start of filter period 64
6/12/2021	22:34	Sample HS3-O21
6/12/2021	21:56	Sample HS3-CS33
6/12/2021	22:19	Start of filter period 65
6/12/2021	23:55	Sample HS3-CS34
6/13/2021	00:30	Start of filter period 66
6/13/2021	01:55	Sample HS3-CS35
6/13/2021	02:39	Start of filter period 67
6/13/2021	04:15	Start of filter period 68
6/13/2021	04:22	Sample HS3-CS36
6/13/2021	05:55	Sample HS3-CS37
6/13/2021	07:03	Start of filter period 69
6/13/2021	07:55	Sample HS3-CS38
6/13/2021	08:30-08:37	Feedline plugged
6/13/2021	09:32	Sample HS3-CS39
6/13/2021	09:33	Start of filter period 70
6/13/2021	10:32	Sample HS3-O22
6/13/2021	11:32	Sample HS3-CS40
6/13/2021	12:05	Sample HS3-O23
6/13/2021	12:13	Sample HS3-CS41
6/13/2021	13:00	Test end

Appendix B – Tabulated Recorded Test Data

In this appendix, the manually recorded data from each test is tabulated. Each test contains two data sets that are tabulated in each section. The first data set is the data from all the system instruments recorded periodically throughout test operation. The second data set is the initial differential pressure data collected each time a filter swap was conducted and includes only the differential pressure measured for the active filter as it came on-line. Note that two instruments (indicated by [FM-01] and [P-01] in the appropriate columns) were not calibrated and the data is For Information Only (FIO); FIO values are shown in *italic text*. When instrument data was not recorded, it is indicated by “n/m” for “not measured”. This is typical for the DP instrument on the non-active DEF and T-REF (which was recorded only occasionally).

B.1 Test NB1 Tabulated Data

Table B.1. Periodically Recorded Data from Test NB1.

Values shown in *italic text* are associated with uncalibrated instruments and are For Information Only (FIO).

DEF Segment	Date	Time	*[FM-01]* (gpm)	FM-02 (mL min^{-1})	DP-01 (psid)	DP-02 (psid)	DP-03 (psid)	DP-04 (psid)	DP-05 (psid)	*[P-01]* (psig)	P-02 (psig)	P-03 (psig)	P-05 (psig)	T-01 (°C)	T-02 (°C)	T-03 (°C)	T-REF (°C)
1	3/4/2021	09:50	*4.03*	128.8	0.23	n/m	2.40	0.92	1.49	*60*	57.9	50.9	48.2	21.1	20.8	19.5	n/m
1	3/4/2021	10:27	*4.00*	130.0	0.48	n/m	4.42	1.63	2.75	*61*	58.3	49.4	42.9	21.8	21.7	19.6	n/m
1	3/4/2021	10:50	*3.99*	130.0	0.49	n/m	4.44	1.64	2.76	*61*	58.5	49.6	43.0	21.9	21.8	20.8	n/m
1	3/4/2021	12:00	*4.00*	129.9	0.52	n/m	4.44	1.63	2.76	*61*	58.4	49.5	42.8	22.0	21.9	21.0	20.9
1	3/4/2021	13:00	*4.00*	130.0	0.56	n/m	4.40	1.62	2.75	*61*	58.5	49.5	42.9	21.9	21.6	21.3	n/m
1	3/4/2021	14:00	*3.99*	130.1	0.57	n/m	4.37	1.61	2.74	*60*	58.3	49.4	42.8	22.0	22.0	21.5	n/m
1	3/4/2021	15:00	*3.99*	130.0	0.59	n/m	4.38	1.60	2.73	*60*	58.3	49.4	42.8	22.2	22.1	21.6	n/m
1	3/4/2021	16:00	*3.99*	130.0	0.61	n/m	4.37	1.60	2.71	*60*	58.2	49.3	42.8	22.2	22.2	22.2	n/m
1	3/4/2021	17:00	*3.99*	130.0	0.62	n/m	4.37	1.60	2.71	*60*	58.3	49.3	42.8	22.2	22.2	21.8	21.2
1	3/4/2021	18:00	*3.99*	130.0	0.63	n/m	4.37	1.60	2.72	*60*	58.2	49.3	42.7	22.3	22.2	21.7	n/m
1	3/4/2021	19:00	*3.99*	130.0	0.69	n/m	4.41	1.62	2.76	*60*	58.3	49.2	42.6	22.2	22.2	22.2	n/m
1	3/4/2021	20:00	*3.99*	130.0	0.70	n/m	4.45	1.63	2.78	*60*	58.3	49.1	42.5	22.1	22.1	21.5	n/m
1	3/4/2021	21:06	*3.99*	129.9	0.72	n/m	4.47	1.63	2.80	*60*	58.3	49.1	42.5	22.0	21.9	21.3	20.8
1	3/4/2021	22:01	*3.99*	130.0	0.82	n/m	4.52	1.66	2.83	*60*	58.2	49.0	42.3	22.0	21.8	21.1	n/m
1	3/4/2021	23:03	*3.99*	130.0	0.85	n/m	4.54	1.67	2.85	*60*	58.2	48.9	42.2	21.9	21.8	21.1	n/m
1	3/5/2021	00:02	*3.99*	130.0	0.86	n/m	4.57	1.68	2.87	*60*	58.1	48.8	42.1	22.0	21.9	20.8	n/m
1	3/5/2021	01:04	*3.99*	130.0	0.87	n/m	4.57	1.68	2.86	*60*	58.1	48.8	42.1	22.0	21.9	20.8	n/m
1	3/5/2021	02:00	*3.99*	130.0	0.88	n/m	4.57	1.68	2.87	*60*	58.1	48.8	42.1	22.0	21.8	20.7	n/m
1	3/5/2021	03:00	*3.99*	130.0	0.99	n/m	4.59	1.68	2.89	*60*	58.1	48.1	42.0	22.0	21.9	20.6	n/m
1	3/5/2021	04:00	*4.00*	130.0	1.00	n/m	4.59	1.68	2.89	*60*	58.1	48.7	42.0	22.0	21.8	20.5	n/m
1	3/5/2021	05:00	*3.99*	129.9	1.02	n/m	4.60	1.68	2.90	*60*	58.1	48.7	41.9	22.0	21.9	20.6	19.5
1	3/5/2021	06:00	*3.99*	130.0	1.03	n/m	4.60	1.69	2.90	*60*	58.1	48.6	41.9	22.0	21.9	20.6	n/m
1	3/5/2021	07:00	*3.99*	130.0	1.05	n/m	4.61	1.68	2.91	*60*	58.1	48.6	41.8	22.0	21.9	20.6	n/m
1	3/5/2021	08:00	*3.99*	130.0	1.07	n/m	4.61	1.69	2.92	*60*	58.2	48.6	41.8	22.0	21.9	20.5	n/m
1	3/5/2021	09:00	*3.99*	130.0	1.09	n/m	4.60	1.68	2.90	*60*	58.1	48.5	41.8	22.1	21.9	20.5	n/m
1	3/5/2021	09:46	*3.99*	130.0	1.42	n/m	4.61	1.68	2.91	*60*	58.1	48.2	41.5	22.1	22.0	20.6	n/m
2	3/5/2021	10:00	*3.99*	130.0	n/m	0.48	4.11	1.70	2.38	*60*	58.1	50.9	44.6	22.1	21.9	20.8	n/m
2	3/5/2021	11:00	*3.99*	130.1	n/m	0.48	4.62	1.68	2.91	*60*	58.0	50.9	44.1	22.1	21.9	20.8	n/m
2	3/5/2021	12:00	*3.99*	130.0	n/m	0.51	4.62	1.68	2.90	*60*	58.0	50.9	44.1	22.1	22.0	21.2	n/m

Values shown in *italic text* are associated with uncalibrated instruments and are For Information Only (FIO).

DEF Segment	Date	Time	*[FM-01]*	FM-02	DP-01	DP-02	DP-03	DP-04	DP-05	*[P-01]*	P-02	P-03	P-05	T-01	T-02	T-03	T-REF
			(gpm)	(mL min^{-1})	(psid)	(psid)	(psid)	(psid)	(psid)	(psig)	(psig)	(psig)	(psig)	(°C)	(°C)	(°C)	(°C)
2	3/5/2021	13:00	*3.99*	130.0	n/m	0.52	4.56	1.66	2.85	*60*	58.0	50.8	44.2	22.2	22.1	21.3	21.4
2	3/5/2021	14:00	*3.99*	130.0	n/m	0.53	4.50	1.63	2.81	*60*	58.1	50.8	44.3	22.1	22.0	21.8	n/m
2	3/5/2021	15:00	*3.99*	130.0	n/m	0.53	4.45	1.61	2.77	*60*	58.2	50.9	44.4	22.1	22.0	22.2	n/m
2	3/5/2021	16:00	*3.99*	130.0	n/m	0.54	4.48	1.62	2.79	*60*	58.1	50.9	44.3	21.9	21.9	22.3	21.8
2	3/5/2021	17:00	*3.99*	130.0	n/m	0.56	4.54	1.64	2.84	*60*	58.0	50.8	44.2	21.8	21.8	22.0	n/m
2	3/5/2021	18:00	*3.99*	130.0	n/m	0.56	4.56	1.66	2.86	*60*	58.1	50.8	44.0	21.6	21.6	21.9	n/m
2	3/5/2021	19:00	*3.99*	130.0	n/m	0.60	4.58	1.66	2.87	*60*	58.0	50.7	44.0	21.5	21.5	21.6	n/m
2	3/5/2021	20:00	*3.99*	130.0	n/m	0.60	4.61	1.67	2.89	*60*	57.9	50.6	43.9	21.5	21.5	21.5	n/m
2	3/5/2021	21:02	*3.98*	129.9	n/m	0.63	4.62	1.67	2.90	*60*	58.0	50.6	43.9	21.5	21.5	21.4	21.2
2	3/5/2021	21:32	*n/m*	n/m	n/m	0.64	4.65	1.68	2.92	*n/m*	n/m	n/m	n/m	n/m	n/m	n/m	n/m
2	3/5/2021	21:36	*n/m*	n/m	n/m	0.57	4.66	1.68	2.93	*n/m*	n/m	n/m	n/m	n/m	n/m	n/m	n/m
2	3/5/2021	22:01	*3.99*	130.0	n/m	0.67	4.68	1.69	2.94	*60*	57.9	50.5	43.7	21.5	21.4	21.1	n/m
2	3/5/2021	22:59	*3.99*	130.0	n/m	0.71	4.67	1.69	2.94	*60*	57.9	50.4	43.6	21.6	21.6	21.1	n/m
2	3/6/2021	00:04	*3.99*	130.1	n/m	0.72	4.66	1.68	2.94	*60*	57.8	50.4	43.7	21.8	21.8	21.2	n/m
2	3/6/2021	01:03	*3.98*	130.0	n/m	0.73	4.66	1.69	2.92	*60*	57.9	50.4	43.6	21.9	21.9	21.2	n/m
2	3/6/2021	02:04	*3.98*	130.0	n/m	0.73	4.63	1.69	2.94	*60*	57.7	50.3	43.5	22.0	21.9	21.0	n/m
2	3/6/2021	02:13	*n/m*	n/m	n/m	0.75	4.62	1.68	2.92	*n/m*	n/m	n/m	n/m	n/m	n/m	n/m	n/m
2	3/6/2021	03:00	*3.99*	130.0	n/m	0.86	4.65	1.68	2.94	*60*	57.7	50.1	43.3	22.1	22.0	21.1	n/m
2	3/6/2021	04:00	*3.99*	130.0	n/m	0.86	4.66	1.69	2.96	*60*	57.7	50.1	43.4	22.1	21.9	21.1	n/m
2	3/6/2021	05:00	*3.99*	130.0	n/m	0.87	4.67	1.69	2.95	*60*	57.7	50.0	43.3	22.1	22.0	21.3	20.4
2	3/6/2021	06:00	*3.99*	130.0	n/m	0.89	4.68	1.69	2.96	*60*	57.6	50.0	43.2	22.2	22.2	21.1	n/m
2	3/6/2021	07:00	*3.99*	130.0	n/m	0.90	4.69	1.69	2.97	*60*	57.7	50.0	43.2	22.2	22.0	21.1	n/m
2	3/6/2021	08:00	*3.98*	130.0	n/m	0.92	4.67	1.69	2.96	*60*	57.7	50.0	43.2	22.2	22.0	21.0	n/m
2	3/6/2021	09:00	*3.98*	130.0	n/m	0.94	4.66	1.68	2.95	*60*	57.6	50.0	43.3	22.2	22.0	21.1	n/m
2	3/6/2021	09:45	*3.99*	130.0	n/m	0.99	4.66	1.68	2.95	*60*	57.6	50.0	43.2	22.2	22.0	21.1	n/m
3	3/6/2021	10:17	*3.98*	129.8	0.52	n/m	4.56	1.70	2.87	*60*	57.5	48.5	42.0	22.2	22.1	21.4	n/m
3	3/6/2021	11:00	*3.99*	130.0	0.57	n/m	4.63	1.67	2.92	*60*	57.6	48.7	41.9	22.2	22.1	21.3	n/m
3	3/6/2021	12:00	*3.99*	130.0	0.68	n/m	4.62	1.65	2.93	*60*	57.6	48.5	41.8	22.2	22.2	21.4	21.3
3	3/6/2021	13:00	*3.99*	130.1	0.81	n/m	4.62	1.64	2.94	*60*	57.6	48.4	41.7	22.3	22.2	21.5	n/m
3	3/6/2021	14:00	*3.99*	130.0	0.94	n/m	4.62	1.64	2.95	*60*	57.6	48.2	41.5	22.2	22.1	21.5	n/m
3	3/6/2021	15:00	*3.99*	130.0	1.10	n/m	4.60	1.62	2.95	*60*	57.5	48.0	41.4	22.1	22.0	22.0	n/m
3	3/6/2021	16:00	*3.99*	130.0	1.22	n/m	4.62	1.61	2.96	*60*	57.5	47.9	41.3	22.0	22.0	21.6	n/m
3	3/6/2021	17:00	*3.99*	130.0	1.30	n/m	4.61	1.61	2.96	*60*	57.5	47.8	41.2	22.0	22.0	21.5	n/m
3	3/6/2021	18:00	*3.99*	130.0	1.37	n/m	4.62	1.61	2.97	*60*	57.6	47.8	41.1	22.0	21.9	21.6	n/m
3	3/6/2021	19:00	*3.99*	129.4	1.55	n/m	4.73	1.65	3.06	*60*	58.1	48.0	41.1	21.3	21.3	21.2	n/m

Values shown in *italic text* are associated with uncalibrated instruments and are For Information Only (FIO).

DEF Segment	Date	Time	*[FM-01]* (gpm)	FM-02 (mL min^{-1})	DP-01 (psid)	DP-02 (psid)	DP-03 (psid)	DP-04 (psid)	DP-05 (psid)	*[P-01]* (psig)	P-02 (psig)	P-03 (psig)	P-05 (psig)	T-01 (°C)	T-02 (°C)	T-03 (°C)	T-REF (°C)
3	3/6/2021	20:00	*3.99*	130.0	1.62	n/m	4.85	1.68	3.15	*60*	58.1	47.8	40.7	21.5	21.5	21.1	n/m
3	3/6/2021	21:00	*3.99*	130.0	1.69	n/m	4.85	1.67	3.15	*60*	58.0	47.7	40.7	21.6	21.5	21.0	20.7
3	3/6/2021	22:00	*3.99*	129.9	1.77	n/m	4.84	1.66	3.15	*60*	58.0	47.6	40.6	21.6	21.5	21.0	n/m
3	3/6/2021	22:09	*n/m*	n/m	1.20	n/m	4.82	1.65	3.14	*n/m*	n/m	n/m	n/m	n/m	n/m	n/m	n/m
3	3/6/2021	23:00	*3.99*	129.9	1.98	n/m	4.85	1.66	3.17	*60*	58.0	47.4	40.4	21.7	21.5	20.9	n/m
3	3/7/2021	00:00	*3.99*	130.1	2.06	n/m	4.85	1.66	3.17	*60*	57.9	47.3	40.3	21.7	21.6	20.8	n/m
3	3/7/2021	01:00	*3.99*	130.0	2.13	n/m	4.86	1.66	3.19	*60*	58.0	47.3	40.3	21.7	21.5	20.7	n/m
3	3/7/2021	02:00	*3.99*	129.4	2.20	n/m	4.85	1.64	3.18	*60*	57.9	47.2	40.2	22.0	21.8	20.5	n/m
3	3/7/2021	02:09	*n/m*	n/m	2.21	n/m	4.84	1.64	3.18	*n/m*	n/m	n/m	n/m	n/m	n/m	n/m	n/m
3	3/7/2021	02:12	*n/m*	n/m	1.65	n/m	4.03	1.34	2.67	*n/m*	n/m	n/m	n/m	n/m	n/m	n/m	n/m
3	3/7/2021	02:43	*3.99*	130.0	2.51	n/m	4.85	1.64	3.20	*60*	58.0	46.8	39.9	22.1	21.9	20.6	n/m
4	3/7/2021	03:00	*3.99*	130.3	n/m	0.38	4.29	1.64	2.63	*60*	58.0	50.7	44.3	22.2	21.9	20.6	n/m
4	3/7/2021	04:00	*3.99*	130.0	n/m	0.43	4.85	1.64	3.19	*60*	57.8	50.6	43.7	22.2	22.0	20.6	n/m
4	3/7/2021	05:00	*3.99*	130.0	n/m	0.49	4.85	1.63	3.20	*60*	57.8	50.6	43.6	22.3	22.1	20.7	19.9
4	3/7/2021	06:00	*3.99*	130.0	n/m	0.59	4.85	1.62	3.20	*60*	57.8	50.5	43.5	22.4	22.2	20.8	n/m
4	3/7/2021	07:00	*3.99*	130.0	n/m	0.69	4.84	1.63	3.19	*60*	57.8	50.3	43.3	22.4	22.2	20.7	n/m
4	3/7/2021	08:00	*3.99*	130.0	n/m	0.77	4.84	1.61	3.20	*60*	57.8	50.2	43.3	22.5	22.3	20.9	n/m
4	3/7/2021	09:00	*3.98*	130.0	n/m	0.84	4.82	1.61	3.18	*60*	57.8	50.2	43.3	22.3	22.1	20.9	n/m
4	3/7/2021	10:00	*3.99*	130.0	n/m	0.91	4.82	1.61	3.18	*60*	57.8	50.1	43.2	22.1	22.0	21.0	n/m
4	3/7/2021	11:00	*3.98*	130.1	n/m	0.96	4.83	1.60	3.19	*60*	57.7	50.0	43.0	22.0	21.9	21.2	n/m
4	3/7/2021	12:00	*3.99*	130.0	n/m	1.02	4.81	1.60	3.18	*60*	57.8	49.9	43.0	22.3	22.2	21.3	20.9
4	3/7/2021	13:00	*3.99*	130.0	n/m	1.06	4.80	1.59	3.18	*60*	57.6	49.8	42.9	22.3	22.2	21.4	n/m
4	3/7/2021	14:00	*3.99*	130.0	n/m	1.12	4.80	1.59	3.17	*60*	57.8	49.8	43.0	22.2	22.1	21.5	n/m
4	3/7/2021	15:00	*3.99*	130.0	n/m	1.19	4.80	1.58	3.18	*60*	57.7	49.7	42.9	22.0	22.0	21.5	n/m
4	3/7/2021	16:00	*3.99*	130.0	n/m	1.24	4.80	1.58	3.18	*60*	57.7	49.7	42.8	22.0	22.0	21.8	n/m
4	3/7/2021	17:00	*3.99*	130.0	n/m	1.30	4.81	1.58	3.19	*60*	57.7	49.6	42.7	22.0	22.1	21.8	n/m
4	3/7/2021	18:00	*3.99*	130.0	n/m	1.34	4.84	1.59	3.21	*60*	57.7	49.5	42.6	21.9	22.0	21.4	20.3
4	3/7/2021	19:00	*3.99*	130.0	n/m	1.48	4.84	1.59	3.22	*60*	57.7	49.4	42.4	21.9	21.9	21.3	n/m
4	3/7/2021	20:00	*3.99*	130.0	n/m	1.51	4.84	1.59	3.22	*60*	57.7	49.4	42.4	21.9	21.9	21.4	n/m
4	3/7/2021	21:00	*3.99*	130.0	n/m	1.56	4.86	1.60	3.23	*60*	57.7	49.3	42.3	21.8	21.7	21.2	20.6
4	3/7/2021	22:00	*3.99*	130.0	n/m	1.61	4.86	1.59	3.24	*60*	57.6	49.2	42.2	21.8	21.6	21.0	n/m
4	3/7/2021	22:14	*n/m*	n/m	n/m	1.27	4.87	1.61	3.25	*n/m*	n/m	n/m	n/m	n/m	n/m	n/m	n/m
4	3/7/2021	23:00	*3.99*	130.0	n/m	1.70	4.88	1.60	3.25	*60*	57.6	49.2	42.1	21.8	21.6	20.9	n/m
4	3/8/2021	00:02	*3.99*	130.0	n/m	1.75	4.89	1.61	3.27	*60*	57.6	49.0	42.0	21.8	21.6	20.7	20.3
4	3/8/2021	01:00	*3.99*	130.0	n/m	1.81	4.90	1.61	3.27	*60*	57.5	49.0	42.0	21.9	21.8	20.6	n/m

Values shown in *italic text* are associated with uncalibrated instruments and are For Information Only (FIO).

DEF Segment	Date	Time	*[FM-01]*	FM-02	DP-01	DP-02	DP-03	DP-04	DP-05	*[P-01]*	P-02	P-03	P-05	T-01	T-02	T-03	T-REF
			(gpm)	(mL min^{-1})	(psid)	(psid)	(psid)	(psid)	(psid)	(psig)	(psig)	(psig)	(psig)	(°C)	(°C)	(°C)	(°C)
4	3/8/2021	02:00	*3.99*	130.1	n/m	1.86	4.91	1.60	3.28	*60*	57.5	48.9	41.9	22.0	21.9	20.6	n/m
4	3/8/2021	02:14	*n/m*	n/m	n/m	1.69	4.89	1.60	3.28	*n/m*	n/m	n/m	n/m	n/m	n/m	n/m	n/m
4	3/8/2021	02:45	*3.98*	130.1	n/m	2.02	4.90	1.61	3.30	*60*	57.5	48.7	41.7	22.0	21.9	20.6	n/m
5	3/8/2021	03:01	*3.98*	130.0	0.41	n/m	4.35	1.62	2.72	*60*	57.5	48.5	42.1	22.0	21.9	20.6	n/m
5	3/8/2021	04:00	*3.99*	130.0	0.63	n/m	4.94	1.62	3.30	*60*	57.5	48.2	41.2	22.0	21.9	20.5	n/m
5	3/8/2021	05:00	*3.98*	130.0	0.96	n/m	4.92	1.62	3.30	*60*	57.5	47.9	40.9	22.0	21.8	20.5	20.0
5	3/8/2021	06:00	*3.98*	130.0	1.29	n/m	4.92	1.61	3.31	*60*	57.5	47.6	40.6	22.1	21.9	20.6	n/m
5	3/8/2021	07:00	*3.98*	130.0	1.48	n/m	4.92	1.61	3.31	*60*	57.4	47.4	40.4	22.1	21.9	20.6	n/m
5	3/8/2021	08:00	*3.98*	130.0	1.57	n/m	4.93	1.61	3.30	*60*	57.4	47.3	40.2	22.1	22.0	20.8	n/m
5	3/8/2021	09:00	*3.99*	130.0	1.64	n/m	4.97	1.63	3.34	*60*	57.4	47.2	40.1	22.0	21.8	20.0	n/m
5	3/8/2021	10:00	*3.99*	130.0	1.71	n/m	4.90	1.60	3.30	*60*	57.4	47.1	40.1	22.0	21.9	20.6	n/m
5	3/8/2021	11:00	*3.98*	129.9	1.79	n/m	4.87	1.59	3.27	*60*	57.4	47.1	40.1	22.1	22.0	20.8	n/m
5	3/8/2021	12:00	*3.98*	130.0	1.84	n/m	4.87	1.58	3.27	*60*	57.4	47.0	40.1	22.2	21.9	20.9	n/m
5	3/8/2021	13:00	*3.98*	130.0	1.94	n/m	4.87	1.59	3.28	*60*	57.4	46.9	40.0	22.0	21.8	21.0	20.8
5	3/8/2021	14:00	*3.99*	130.0	1.99	n/m	4.88	1.59	3.28	*60*	57.4	46.8	39.8	21.9	21.8	21.2	n/m
5	3/8/2021	15:00	*3.99*	130.0	2.11	n/m	4.88	1.58	3.28	*60*	57.3	46.6	39.7	22.1	22.0	21.1	n/m
5	3/8/2021	16:00	*3.99*	130.0	2.20	n/m	4.95	1.60	3.32	*60*	57.5	46.7	39.6	22.1	22.0	21.2	n/m
5	3/8/2021	16:25	*3.99*	130.0	2.46	n/m	4.96	1.60	3.33	*60*	57.4	46.3	39.2	22.2	22.3	21.3	n/m
6	3/8/2021	17:00	*3.99*	130.4	n/m	0.40	4.85	1.56	3.27	*60*	57.6	50.4	43.6	22.2	22.3	20.2	n/m
6	3/8/2021	18:00	*3.99*	130.0	n/m	0.48	4.91	1.58	3.31	*60*	57.5	50.2	43.2	22.2	22.2	21.5	n/m
6	3/8/2021	19:00	*3.99*	130.0	n/m	0.60	4.94	1.59	3.32	*60*	57.5	50.1	43.0	22.3	22.2	21.4	21.0
6	3/8/2021	20:00	*3.99*	130.0	n/m	0.82	4.96	1.61	3.34	*60*	57.5	49.9	42.9	22.2	22.3	21.1	n/m
6	3/8/2021	20:15	*3.98*	130.0	n/m	0.73	4.92	1.58	3.31	*60*	57.7	50.1	43.2	22.2	22.2	21.3	n/m
6	3/8/2021	21:00	*3.98*	130.0	n/m	1.02	4.95	1.58	3.34	*60*	57.7	49.8	42.8	22.2	22.2	21.3	20.9
6	3/8/2021	22:00	*3.98*	130.0	n/m	1.20	4.95	1.59	3.34	*60*	57.8	49.6	42.6	22.0	22.0	21.1	n/m
6	3/8/2021	22:11	*n/m*	n/m	n/m	0.70	4.96	1.60	3.34	*n/m*	n/m	n/m	n/m	n/m	n/m	n/m	n/m
6	3/8/2021	23:00	*3.98*	130.0	n/m	1.28	4.97	1.60	3.35	*60*	57.7	49.6	42.5	22.2	22.1	21.1	n/m
6	3/9/2021	00:00	*3.98*	130.0	n/m	1.41	4.98	1.60	3.36	*60*	57.6	49.4	42.4	22.2	22.0	20.9	n/m
6	3/9/2021	00:09	*n/m*	n/m	n/m	1.23	4.99	1.60	3.36	*n/m*	n/m	n/m	n/m	n/m	n/m	n/m	n/m
6	3/9/2021	01:02	*3.98*	130.0	n/m	1.50	5.00	1.60	3.38	*60*	57.6	49.3	42.2	22.2	22.0	20.9	n/m
6	3/9/2021	02:02	*3.98*	130.0	n/m	1.59	5.04	1.61	3.40	*60*	57.7	49.1	42.0	22.2	22.0	20.9	n/m
6	3/9/2021	02:06	*n/m*	n/m	n/m	1.29	5.06	1.62	3.41	*n/m*	n/m	n/m	n/m	n/m	n/m	n/m	n/m
6	3/9/2021	03:00	*3.98*	130.0	n/m	1.69	5.07	1.63	3.43	*60*	57.5	48.9	41.8	22.2	22.0	20.1	n/m
6	3/9/2021	04:00	*3.98*	130.0	n/m	1.74	5.07	1.63	3.44	*55*	51.0	42.5	35.3	22.1	21.9	20.5	n/m
6	3/9/2021	04:09	*n/m*	n/m	n/m	1.74	5.07	1.63	3.44	*n/m*	n/m	n/m	n/m	n/m	n/m	n/m	n/m

Values shown in *italic text* are associated with uncalibrated instruments and are For Information Only (FIO).

DEF Segment	Date	Time	*[FM-01]*	FM-02	DP-01	DP-02	DP-03	DP-04	DP-05	*[P-01]*	P-02	P-03	P-05	T-01	T-02	T-03	T-REF
			(gpm)	(mL min^{-1})	(psid)	(psid)	(psid)	(psid)	(psid)	(psig)	(psig)	(psig)	(psig)	(°C)	(°C)	(°C)	(°C)
6	3/9/2021	04:18	*4.20*	130.0	n/m	1.76	5.08	1.63	3.44	*60*	56.9	48.3	41.1	22.1	21.9	20.5	n/m
6	3/9/2021	05:00	*4.20*	130.0	n/m	1.81	5.09	1.64	3.44	*60*	56.8	48.1	41.0	22.1	21.9	20.5	19.6
6	3/9/2021	05:18	*4.40*	130.0	n/m	1.82	5.07	1.63	3.44	*60*	57.2	48.5	41.3	22.1	22.0	20.5	n/m
6	3/9/2021	06:00	*4.40*	130.0	n/m	1.87	5.08	1.63	3.44	*60*	57.1	48.4	41.3	22.2	22.0	20.5	n/m
6	3/9/2021	06:05	*n/m*	n/m	n/m	1.87	5.08	1.64	3.44	*n/m*	n/m	n/m	n/m	n/m	n/m	n/m	n/m
6	3/9/2021	07:00	*4.40*	130.0	n/m	1.94	5.06	1.63	3.44	*60*	57.1	48.4	41.1	22.2	22.0	20.6	n/m
6	3/9/2021	08:00	*4.41*	130.0	n/m	2.01	5.06	1.63	3.44	*60*	57.1	48.5	41.2	22.2	22.0	20.5	n/m
6	3/9/2021	08:05	*n/m*	n/m	n/m	2.01	5.07	1.63	3.44	*n/m*	n/m	n/m	n/m	n/m	n/m	n/m	n/m
6	3/9/2021	09:00	*4.41*	130.1	n/m	2.07	5.03	1.60	3.41	*60*	57.4	48.4	41.3	22.2	22.0	20.8	n/m
6	3/9/2021	10:00	*4.41*	130.2	n/m	2.13	5.02	1.60	3.38	*60*	57.5	48.4	41.3	22.0	21.8	20.9	n/m
6	3/9/2021	11:00	*4.41*	130.0	n/m	2.33	5.02	1.61	3.40	*60*	57.5	48.1	41.1	21.9	21.8	20.9	n/m
6	3/9/2021	11:58	*4.41*	130.1	n/m	2.36	5.01	1.60	3.40	*60*	57.4	48.0	41.0	22.2	22.1	21.0	n/m
7	3/9/2021	13:00	*4.41*	130.0	0.64	n/m	4.98	1.59	3.35	*61*	59.1	49.7	42.8	22.1	22.0	21.2	20.8
7	3/9/2021	14:00	*4.41*	130.1	1.04	n/m	4.99	1.59	3.37	*64*	59.8	50.0	42.9	22.0	21.9	21.3	n/m
7	3/9/2021	15:00	*4.41*	130.0	1.32	n/m	5.00	1.60	3.37	*64*	59.7	50.0	42.8	22.0	21.9	21.3	n/m
7	3/9/2021	16:00	*4.41*	130.0	1.50	n/m	5.00	1.60	3.39	*64*	60.0	49.9	42.8	22.0	22.0	21.2	n/m
7	3/9/2021	17:00	*4.41*	130.0	1.64	n/m	5.00	1.60	3.38	*64*	60.2	49.9	42.9	22.0	22.0	21.3	n/m
7	3/9/2021	18:00	*4.41*	130.0	1.73	n/m	5.00	1.60	3.38	*64*	60.3	49.8	42.8	22.0	22.0	21.3	n/m
7	3/9/2021	19:00	*4.41*	130.0	1.88	n/m	5.01	1.59	3.39	*64*	60.3	49.9	42.7	22.0	21.9	21.2	n/m
7	3/9/2021	20:00	*4.41*	130.0	1.93	n/m	5.02	1.61	3.40	*64*	60.3	49.8	42.7	22.0	22.0	21.2	n/m
7	3/9/2021	21:00	*4.41*	130.0	2.12	n/m	5.03	1.61	3.41	*64*	60.6	49.7	42.5	22.0	21.9	21.1	n/m
7	3/9/2021	22:00	*4.41*	130.0	2.17	n/m	5.07	1.61	3.43	*64*	60.4	49.5	42.5	21.9	21.7	20.9	n/m
7	3/9/2021	22:10	*n/m*	n/m	1.93	n/m	5.07	1.61	3.42	*n/m*	n/m	n/m	n/m	n/m	n/m	n/m	n/m
7	3/9/2021	23:00	*4.41*	130.0	2.41	n/m	5.09	1.63	3.45	*64*	60.4	49.4	42.2	21.9	21.8	20.9	n/m
8	3/10/2021	00:00	*4.41*	130.0	n/m	0.50	5.07	1.63	3.43	*64*	60.5	53.2	46.0	21.9	21.8	20.6	n/m
8	3/10/2021	00:10	*n/m*	n/m	n/m	0.47	5.08	1.62	3.45	*n/m*	n/m	n/m	n/m	n/m	n/m	n/m	n/m
8	3/10/2021	01:00	*4.41*	130.0	n/m	0.75	5.12	1.63	3.46	*64*	60.6	53.0	45.6	21.9	21.8	20.7	n/m
8	3/10/2021	01:30	*4.41*	130.1	n/m	0.93	5.14	1.55	3.47	*65*	59.9	50.2	45.3	21.9	21.7	20.8	n/m

Table B.2. Initial Differential Pressure Data for DEFs from Test NB1.

DEF Segment	Date	Start Time	ΔP (psid) at t = 2 min	ΔP (psid) at t = 4 min	ΔP (psid) at t = 6 min	ΔP (psid) at t = 8 min	ΔP (psid) at t = 10 min
1	3/4/2021	09:50	0.27	0.38	0.45	0.47	0.47
2	3/5/2021	09:50	0.22	0.31	0.42	0.46	0.47
3	3/6/2021	09:50	0.21	0.31	0.42	0.47	0.48
4	3/7/2021	02:46	0.15	0.25	0.34	0.38	0.38
5	3/8/2021	02:51	0.24	0.35	0.39	0.41	0.41
6	3/8/2021	16:28	0.14	0.26	0.34	0.36	0.37
7	3/9/2021	11:59	0.15	0.23	0.36	0.39	0.41
8	3/9/2021	23:03	0.13	0.22	0.33	0.36	0.38
End of Test	3/10/2021	01:40	n/m	n/m	n/m	n/m	n/m

B.2 Test HS1 Tabulated Data

Table B.3. Periodically Recorded Data from Test HS1

Values shown in *italic text* are associated with uncalibrated instruments and are For Information Only (FIO).

DEF Segment	Date	Time	*[FM-01]* (gpm)	FM-02 (mL min^{-1})	DP-01 (psid)	DP-02 (psid)	DP-03 (psid)	DP-04 (psid)	DP-05 (psid)	*[P-01]* (psig)	P-02 (psig)	P-03 (psig)	P-05 (psig)	T-01 (°C)	T-02 (°C)	T-03 (°C)	T-REF (°C)
1	5/3/2021	13:00	*3.98*	131.0	1.00	n/m	4.70	2.30	2.30	*70*	65.0	50.1	44.0	22.1	22.5	22.4	n/m
1	5/3/2021	14:10	*4.02*	129.0	1.30	n/m	5.30	2.00	3.10	*70*	64.8	52.5	44.4	22.0	22.3	21.9	n/m
2	5/3/2021	15:00	*4.00*	130.0	n/m	1.05	4.85	2.00	2.75	*65*	63.2	55.4	47.3	22.0	22.7	23.9	n/m
3	5/3/2021	16:00	*3.99*	132.0	1.08	n/m	5.03	2.10	2.85	*65*	64.6	53.1	45.3	22.0	22.5	23.8	n/m
3	5/3/2021	16:30	*3.99*	129.6	2.57	n/m	5.75	2.06	3.55	*65*	64.2	51.7	42.4	22.1	22.7	23.1	n/m
3	5/3/2021	17:00	*4.00*	130.0	4.94	n/m	5.65	2.15	3.47	*65*	64.8	49.4	39.5	22.1	22.9	23.4	23.7
3	5/3/2021	17:30	*4.00*	131.5	8.43	n/m	5.66	2.11	3.45	*65*	64.3	45.5	36.5	22.1	22.9	23.5	n/m
3	5/3/2021	18:04	*4.03*	130.0	14.13	n/m	5.49	1.94	3.44	*65*	65.2	41.4	31.6	22.1	22.8	23.4	n/m
4	5/3/2021	18:30	*4.01*	130.0	n/m	1.02	4.57	2.07	2.60	*65*	63.6	55.5	40.7	22.2	22.8	23.9	n/m
4	5/3/2021	19:03	*4.01*	129.0	n/m	2.88	5.72	1.97	3.52	*65*	65.5	54.5	44.9	22.2	22.8	23.3	n/m
4	5/3/2021	19:29	*4.01*	125.5	n/m	4.91	5.21	2.04	3.38	*65*	65.3	52.9	44.0	22.2	22.9	23.4	n/m
4	5/3/2021	20:00	*4.01*	130.0	n/m	9.88	5.51	2.05	3.43	*65*	64.2	47.5	38.2	22.2	22.7	23.3	n/m
4	5/3/2021	20:33	*4.03*	130.0	n/m	20.03	5.50	2.10	3.45	*70*	65.7	37.5	28.2	22.2	22.7	23.3	23.4
4	5/3/2021	21:00	*4.03*	130.0	n/m	24.50	5.60	2.10	3.50	*70*	65.5	32.5	23.5	22.1	22.3	23.0	n/m
5	5/3/2021	21:45	*4.01*	130.9	2.15	n/m	5.50	2.10	3.50	*70*	65.7	52.7	43.5	22.1	22.3	22.5	n/m
5	5/3/2021	22:01	*4.01*	130.0	3.10	n/m	5.60	2.10	3.50	*70*	64.0	52.0	42.5	22.1	22.3	22.6	n/m
5	5/3/2021	22:30	*4.01*	130.0	5.65	n/m	5.65	2.10	3.56	*70*	65.0	49.5	40.3	22.0	22.1	22.6	n/m
5	5/3/2021	23:00	*4.01*	130.0	9.30	n/m	5.70	2.10	3.50	*70*	65.0	45.0	36.0	22.0	22.0	22.5	n/m
5	5/3/2021	23:30	*4.01*	130.0	14.50	n/m	5.70	2.12	3.50	*70*	65.5	40.0	30.5	22.0	22.0	22.3	n/m
6	5/4/2021	00:02	*4.01*	131.0	n/m	1.32	4.75	2.20	2.54	*70*	65.1	56.5	48.5	22.0	21.8	22.3	n/m
6	5/4/2021	00:32	*4.01*	130.2	n/m	4.00	5.90	2.12	3.65	*70*	65.5	53.0	43.5	21.9	21.8	21.9	n/m
6	5/4/2021	01:00	*4.02*	130.3	n/m	6.20	5.90	2.15	3.70	*70*	65.0	51.0	41.3	21.9	21.8	22.0	n/m
6	5/4/2021	01:31	*4.02*	130.0	n/m	12.25	6.00	2.23	3.68	*70*	65.5	45.0	35.0	21.9	21.7	21.9	n/m
6	5/4/2021	02:00	*4.01*	130.1	n/m	18.50	5.95	2.22	3.65	*70*	65.5	38.5	28.9	21.9	21.8	21.9	n/m
7	5/4/2021	03:03	*4.02*	129.6	1.83	n/m	5.65	2.08	3.46	*71*	66.5	53.8	44.6	21.8	21.7	20.9	n/m
7	5/4/2021	03:30	*4.02*	129.3	3.58	n/m	5.95	2.17	3.73	*71*	65.9	51.4	41.9	21.8	21.8	22.0	n/m
7	5/4/2021	04:00	*4.02*	130.2	6.42	n/m	6.07	2.21	3.79	*71*	65.2	48.3	39.8	21.7	21.6	21.9	n/m
7	5/4/2021	04:30	*4.01*	130.4	14.96	n/m	6.06	2.17	3.83	*71*	66.1	40.2	30.3	21.7	21.6	21.8	n/m
7	5/4/2021	04:56	*4.03*	129.8	21.98	n/m	6.32	2.35	3.98	*71*	65.4	31.8	21.4	21.7	21.7	21.6	n/m
8	5/4/2021	06:04	*4.03*	129.8	n/m	4.30	5.93	2.22	3.58	*71*	66.3	52.9	43.7	21.6	21.3	21.5	n/m

Values shown in *italic text* are associated with uncalibrated instruments and are For Information Only (FIO).

DEF Segment	Date	Time	*[FM-01]* (gpm)	FM-02 (mL min^{-1})	DP-01 (psid)	DP-02 (psid)	DP-03 (psid)	DP-04 (psid)	DP-05 (psid)	*[P-01]* (psig)	P-02 (psig)	P-03 (psig)	P-05 (psig)	T-01 (°C)	T-02 (°C)	T-03 (°C)	T-REF (°C)
8	5/4/2021	06:30	*4.04*	130.4	n/m	7.92	6.12	2.26	3.85	*70*	65.7	49.2	39.3	21.6	21.4	21.5	n/m
8	5/4/2021	07:00	*4.03*	130.2	n/m	14.38	6.06	2.28	3.85	*71*	65.5	43.1	32.4	21.6	21.3	21.3	n/m
8	5/4/2021	07:30	*4.04*	129.5	n/m	25.20	6.01	2.30	3.89	*71*	65.3	32.3	22.2	21.7	21.5	21.3	n/m
8	5/4/2021	07:48	*n/m*	130.3	n/m	32.00	n/m	n/m	n/m	*n/m*	n/m	n/m	n/m	n/m	n/m	n/m	n/m
9	5/4/2021	08:09	*4.05*	128.5	2.00	n/m	4.98	2.13	2.74	*71*	65.2	53.4	45.0	21.9	21.6	21.5	n/m
9	5/4/2021	08:30	*4.05*	128.5	3.10	n/m	6.00	2.21	3.80	*72*	65.5	51.6	42.1	21.9	21.6	20.3	n/m
9	5/4/2021	09:00	*4.03*	130.2	5.50	n/m	6.00	2.20	3.80	*71*	65.3	49.4	40.4	22.0	21.9	21.4	n/m
9	5/4/2021	09:30	*4.04*	130.1	8.80	n/m	6.00	2.20	3.70	*71*	65.7	45.9	36.9	22.0	21.7	21.6	n/m
9	5/4/2021	10:00	*4.04*	130.3	14.00	n/m	6.00	2.20	3.60	*71*	65.3	41.3	31.2	22.0	21.9	22.0	n/m
9	5/4/2021	10:19	*4.03*	130.2	17.60	n/m	5.90	2.20	3.70	*71*	66.2	37.9	28.5	22.0	21.9	22.0	n/m
10	5/4/2021	11:00	*4.04*	130.4	n/m	3.80	5.70	2.20	3.60	*71*	65.7	53.4	44.6	22.0	22.2	21.3	n/m
10	5/4/2021	11:30	*4.05*	130.2	n/m	7.30	5.80	2.10	3.60	*71*	65.6	50.2	40.8	22.1	22.0	22.3	n/m
10	5/4/2021	12:00	*4.03*	130.2	n/m	12.50	5.70	2.10	3.60	*71*	65.7	44.9	35.4	22.0	22.0	22.5	n/m
10	5/4/2021	12:30	*4.04*	130.2	n/m	34.30	5.74	2.13	3.50	*71*	65.7	23.3	14.1	22.0	22.2	22.6	n/m
11	5/4/2021	13:03	*4.03*	131.0	2.30	n/m	5.50	2.10	3.40	*71*	65.4	52.2	44.4	22.0	21.9	22.3	n/m
11	5/4/2021	13:30	*4.04*	130.1	4.00	n/m	5.80	2.10	3.60	*71*	65.5	51.3	42.0	22.0	22.3	22.8	n/m
11	5/4/2021	14:00	*4.02*	130.5	7.00	n/m	5.80	2.10	3.60	*71*	65.6	48.4	39.3	22.0	22.0	22.9	n/m
11	5/4/2021	14:30	*4.05*	130.1	11.02	n/m	5.66	2.10	3.55	*65*	66.2	44.3	34.9	22.0	22.5	23.0	n/m
11	5/4/2021	15:03	*4.05*	130.4	17.20	n/m	5.70	2.10	3.58	*70*	65.5	37.9	28.5	22.0	22.4	23.1	n/m
12	5/4/2021	15:38	*4.04*	130.1	n/m	3.50	5.55	2.06	3.43	*70*	65.7	54.4	46.3	22.0	22.4	22.7	n/m
12	5/4/2021	16:00	*4.02*	130.5	n/m	5.58	5.78	2.13	3.60	*70*	65.0	51.2	42.6	22.0	22.5	23.3	n/m
12	5/4/2021	16:30	*4.05*	129.8	n/m	9.67	5.68	2.11	3.54	*70*	65.4	48.1	39.2	22.0	22.3	23.3	n/m
12	5/4/2021	17:00	*4.05*	129.9	n/m	15.63	5.73	2.11	3.52	*70*	66.6	41.9	33.3	22.0	22.5	23.3	24.1
12	5/4/2021	17:30	*4.05*	130.2	n/m	23.20	5.68	2.11	3.55	*70*	66.3	34.3	25.4	22.1	22.6	23.5	n/m
13	5/4/2021	18:08	*4.05*	130.4	1.24	n/m	4.68	2.09	2.55	*70*	66.4	54.2	46.8	22.1	22.6	23.8	n/m
13	5/4/2021	18:30	*4.05*	129.5	2.14	n/m	5.48	2.10	3.37	*70*	66.2	53.5	44.8	22.1	22.5	23.0	n/m
13	5/4/2021	19:00	*4.04*	130.2	4.02	n/m	5.75	2.11	3.51	*70*	65.6	50.6	42.3	22.1	22.5	23.6	n/m
13	5/4/2021	19:30	*4.04*	130.3	6.78	n/m	5.70	2.10	3.53	*70*	65.5	48.6	39.4	22.1	22.5	23.6	n/m
13	5/4/2021	20:00	*4.04*	130.4	10.97	n/m	5.72	2.08	3.52	*70*	65.5	44.4	35.1	22.1	22.2	23.5	n/m
13	5/4/2021	20:30	*4.05*	129.9	15.86	n/m	5.71	2.10	3.54	*70*	66.3	39.1	30.3	22.1	22.2	23.4	n/m
14	5/4/2021	21:00	*4.05*	130.0	n/m	1.95	4.75	2.04	2.62	*70*	66.0	55.5	47.8	22.1	22.3	23.3	n/m
14	5/4/2021	21:30	*4.03*	130.1	n/m	3.82	5.70	2.10	3.50	*70*	65.5	54.0	44.3	22.0	22.2	23.0	n/m
14	5/4/2021	22:00	*4.05*	130.0	n/m	7.00	5.80	2.14	3.63	*70*	65.5	50.8	41.7	22.0	22.1	22.8	n/m
14	5/4/2021	22:30	*4.05*	130.1	n/m	11.60	5.85	2.13	3.66	*70*	66.0	45.8	36.7	22.0	22.2	22.7	n/m
14	5/4/2021	23:00	*4.06*	130.0	n/m	18.30	5.90	2.15	3.67	*70*	66.0	38.5	30.0	21.9	21.8	22.5	22.6

Values shown in *italic text* are associated with uncalibrated instruments and are For Information Only (FIO).

DEF Segment	Date	Time	*[FM-01]* (gpm)	FM-02 (mL min^{-1})	DP-01 (psid)	DP-02 (psid)	DP-03 (psid)	DP-04 (psid)	DP-05 (psid)	*[P-01]* (psig)	P-02 (psig)	P-03 (psig)	P-05 (psig)	T-01 (°C)	T-02 (°C)	T-03 (°C)	T-REF (°C)
15	5/4/2021	23:31	*4.05*	130.5	1.76	n/m	5.76	2.15	3.50	*70*	66.0	53.7	44.4	21.9	21.9	22.6	n/m
15	5/5/2021	00:01	*4.05*	130.0	3.36	n/m	5.95	2.20	3.70	*70*	65.5	51.8	42.0	21.9	21.9	22.4	n/m
15	5/5/2021	00:30	*4.05*	130.0	9.40	n/m	6.05	2.19	3.78	*70*	66.0	45.8	36.3	21.9	21.9	22.3	n/m
15	5/5/2021	01:00	*4.05*	130.0	13.25	n/m	6.05	2.21	3.75	*70*	66.4	41.9	32.2	21.8	21.9	22.0	n/m
15	5/5/2021	01:30	*4.05*	130.0	17.90	n/m	6.07	2.20	3.83	*70*	66.0	37.3	27.5	21.8	21.8	21.8	n/m
16	5/5/2021	02:03	*4.06*	129.2	n/m	2.95	5.13	2.13	2.84	*72*	66.3	55.2	47.8	21.7	21.7	22.0	n/m
16	5/5/2021	02:30	*4.06*	129.8	n/m	5.27	6.14	2.25	3.86	*72*	66.5	52.5	43.0	21.7	21.6	21.5	n/m
16	5/5/2021	03:00	*4.06*	130.2	n/m	9.37	6.19	2.26	3.85	*72*	66.3	48.2	37.4	21.6	21.6	21.3	n/m
16	5/5/2021	03:30	*4.06*	129.3	n/m	15.42	6.16	2.26	3.88	*71*	66.3	42.3	32.2	21.6	21.5	21.3	n/m
16	5/5/2021	03:55	*4.06*	130.2	n/m	22.55	6.09	2.28	3.81	*72*	66.4	34.6	25.1	21.6	21.6	21.6	n/m
17	5/5/2021	04:35	*4.06*	129.1	1.81	n/m	5.06	2.19	2.83	*71*	65.8	53.8	44.9	21.6	21.5	21.8	n/m
17	5/5/2021	05:00	*4.05*	130.3	3.27	n/m	6.16	2.27	2.88	*71*	66.4	52.1	42.4	21.5	21.4	21.2	n/m
17	5/5/2021	05:30	*4.05*	129.9	5.93	n/m	6.20	2.27	3.93	*71*	66.1	49.1	39.3	21.5	21.6	21.4	n/m
17	5/5/2021	06:00	*4.06*	130.2	9.92	n/m	6.20	2.26	3.91	*71*	65.8	45.1	35.3	21.5	21.5	21.6	n/m
17	5/5/2021	06:30	*4.06*	130.1	15.54	n/m	6.17	2.25	3.89	*71*	65.8	39.1	29.3	21.5	21.5	21.5	n/m
18	5/5/2021	07:08	*4.06*	131.7	n/m	3.35	5.22	2.21	3.08	*71*	66.1	54.2	46.1	21.5	21.4	22.0	n/m
18	5/5/2021	07:30	*4.06*	130.1	n/m	5.52	6.24	2.21	3.92	*71*	65.9	51.9	42.1	21.5	21.5	21.3	n/m
18	5/5/2021	08:00	*4.06*	129.9	n/m	10.01	6.21	2.27	3.92	*71*	65.3	47.4	37.7	21.5	21.5	21.3	n/m
18	5/5/2021	08:30	*4.04*	129.9	n/m	16.99	6.20	2.25	3.90	*71*	66.2	40.5	30.8	21.5	21.4	21.2	n/m
19	5/5/2021	09:18	*4.07*	129.8	1.34	n/m	5.29	2.22	3.00	*72*	66.3	53.9	45.3	21.5	21.5	21.3	n/m
19	5/5/2021	09:37	*4.06*	130.1	2.25	n/m	5.80	2.20	3.57	*71*	66.4	53.2	44.1	21.5	21.3	21.0	n/m
19	5/5/2021	10:00	*4.05*	130.0	3.75	n/m	6.08	2.26	3.85	*72*	65.5	51.6	42.0	21.5	21.5	21.1	n/m
19	5/5/2021	10:30	*4.07*	130.2	6.75	n/m	6.15	2.24	3.85	*71*	66.5	48.6	39.1	21.5	21.5	21.4	n/m
19	5/5/2021	11:00	*4.06*	129.9	11.00	n/m	6.10	2.25	3.85	*71*	66.1	43.8	34.6	21.5	21.6	21.6	n/m
20	5/5/2021	11:40	*4.06*	130.0	n/m	2.50	5.18	2.15	2.91	*71*	65.8	55.1	46.1	21.6	21.6	21.9	n/m
20	5/5/2021	12:00	*4.06*	130.0	n/m	4.35	5.55	2.10	3.51	*71*	66.2	53.8	45.0	21.6	21.9	21.9	n/m
20	5/5/2021	12:30	*4.06*	130.0	n/m	15.20	6.00	2.15	3.71	*71*	66.5	42.6	33.4	21.6	21.8	22.2	n/m
20	5/5/2021	13:00	*4.07*	129.9	n/m	19.10	5.95	2.18	3.73	*70*	66.5	38.9	29.6	21.7	21.8	22.4	n/m
20	5/5/2021	13:33	*3.99*	130.0	n/m	22.30	5.56	2.16	3.65	*70*	63.5	32.0	22.9	21.7	22.3	22.7	n/m
21	5/5/2021	14:02	*3.92*	130.0	1.81	n/m	5.08	2.10	2.53	*70*	61.2	51.2	42.7	21.7	22.2	22.9	n/m
21	5/5/2021	14:30	*3.98*	130.0	4.26	n/m	5.91	2.13	3.65	*70*	62.9	49.5	39.4	21.8	22.3	22.6	n/m
21	5/5/2021	15:00	*4.00*	130.0	9.56	n/m	5.96	2.15	3.60	*70*	63.1	44.0	35.4	21.8	22.4	23.0	n/m
21	5/5/2021	15:32	*4.00*	131.1	13.30	n/m	5.64	1.88	3.64	*70*	64.7	40.7	31.9	21.9	22.7	23.5	n/m
21	5/5/2021	16:00	*4.01*	128.7	22.06	n/m	5.94	2.16	3.61	*70*	57.8	32.1	22.7	21.9	22.6	23.9	n/m
22	5/5/2021	16:27	*3.98*	131.1	n/m	2.54	4.57	2.02	2.61	*70*	64.0	53.8	46.2	21.9	22.5	23.7	n/m

Values shown in *italic text* are associated with uncalibrated instruments and are For Information Only (FIO).

DEF Segment	Date	Time	*[FM-01]* (gpm)	FM-02 (mL min^{-1})	DP-01 (psid)	DP-02 (psid)	DP-03 (psid)	DP-04 (psid)	DP-05 (psid)	*[P-01]* (psig)	P-02 (psig)	P-03 (psig)	P-05 (psig)	T-01 (°C)	T-02 (°C)	T-03 (°C)	T-REF (°C)
22	5/5/2021	17:00	*3.99*	129.9	n/m	7.60	5.65	2.13	3.54	*70*	65.2	48.7	40.2	22.0	22.4	23.6	n/m
22	5/5/2021	17:30	*4.00*	130.0	n/m	15.50	5.86	2.15	3.61	*70*	64.3	41.6	32.5	22.0	22.6	23.6	24.8
22	5/5/2021	18:00	*4.00*	124.7	n/m	23.73	5.48	1.97	3.45	*70*	65.6	34.6	25.4	22.2	22.8	23.9	n/m
23	5/5/2021	18:30	*3.99*	130.0	1.72	n/m	4.84	2.11	2.69	*70*	66.2	52.9	44.8	22.1	22.6	24.2	n/m
23	5/5/2021	19:00	*4.00*	130.0	3.94	n/m	5.70	2.10	3.63	*70*	65.2	51.1	41.3	22.1	22.6	23.8	n/m
23	5/5/2021	19:30	*4.01*	130.0	7.96	n/m	5.82	2.11	3.51	*70*	65.3	46.2	37.4	22.2	22.7	23.8	n/m
23	5/5/2021	20:00	*4.00*	129.9	13.50	n/m	5.66	2.10	3.62	*70*	65.8	40.3	31.8	22.2	22.7	23.9	n/m
23	5/5/2021	20:30	*4.01*	124.5	19.00	n/m	5.25	1.98	3.35	*70*	66.0	36.0	28.5	22.2	22.5	23.7	n/m
24	5/5/2021	21:11	*4.01*	130.0	n/m	2.50	4.75	2.10	2.68	*70*	65.5	53.5	46.5	22.2	22.3	23.5	n/m
24	5/5/2021	21:30	*4.01*	130.0	n/m	5.25	5.50	2.07	3.30	*70*	65.0	52.0	43.5	22.2	22.3	23.2	n/m
24	5/5/2021	22:00	*4.01*	130.0	n/m	12.50	5.85	2.15	3.67	*70*	65.0	44.0	34.8	22.1	22.1	23.3	n/m
24	5/5/2021	22:30	*4.02*	130.0	n/m	22.50	5.80	2.16	3.61	*70*	65.0	34.8	25.3	22.1	22.2	23.3	n/m
25	5/5/2021	23:06	*4.01*	130.0	2.22	n/m	5.10	2.05	2.85	*70*	65.5	52.0	44.8	22.1	22.2	24.0	23.9
25	5/5/2021	23:30	*4.04*	130.0	4.25	n/m	5.80	2.20	3.65	*70*	65.0	50.5	38.5	22.1	22.2	23.3	n/m
25	5/6/2021	00:01	*4.03*	130.0	8.25	n/m	5.80	2.15	3.65	*70*	65.0	46.5	37.8	22.1	22.3	23.0	n/m
25	5/6/2021	00:31	*4.01*	130.0	20.25	n/m	5.96	2.10	3.65	*70*	65.0	34.5	24.8	22.0	22.0	22.9	n/m
26	5/6/2021	01:30	*4.03*	130.0	n/m	3.58	5.10	2.10	3.00	*70*	65.0	53.0	45.5	22.0	21.9	23.2	n/m
26	5/6/2021	02:00	*4.02*	130.0	n/m	11.00	6.05	2.25	3.79	*70*	65.0	45.5	36.0	22.0	21.9	22.5	n/m
26	5/6/2021	03:00	*4.04*	129.3	n/m	20.70	6.03	2.16	3.71	*70*	55.4	34.5	25.4	21.9	21.9	22.4	n/m
27	5/6/2021	03:12	*4.01*	130.6	2.08	n/m	4.93	2.10	2.87	*70*	65.8	53.2	44.6	21.9	21.9	23.0	n/m
27	5/6/2021	03:30	*4.03*	130.2	3.74	n/m	6.04	2.19	3.71	*70*	64.9	51.1	41.9	21.9	22.0	22.3	n/m
27	5/6/2021	04:03	*4.03*	129.7	7.97	n/m	5.95	2.17	3.84	*70*	65.6	46.7	36.9	21.9	21.9	22.3	n/m
27	5/6/2021	04:31	*4.02*	129.7	13.62	n/m	6.01	2.22	3.97	*70*	65.5	40.3	30.7	21.8	21.9	22.1	n/m
27	5/6/2021	05:00	*4.04*	129.6	21.00	n/m	6.13	2.18	3.86	*70*	65.3	33.3	23.9	21.8	21.8	22.0	n/m
27	5/6/2021	05:11	*4.03*	130.1	24.75	n/m	6.14	2.24	3.90	*70*	65.6	29.7	20.2	21.8	22.2	22.2	n/m
28	5/6/2021	06:00	*4.03*	130.3	n/m	5.51	6.08	2.19	3.76	*70*	65.6	52.8	43.6	21.8	21.7	21.4	n/m
28	5/6/2021	06:30	*4.03*	130.4	n/m	13.13	6.18	2.28	3.89	*71*	65.4	44.5	34.4	21.7	21.8	21.8	n/m
28	5/6/2021	07:00	*4.03*	130.6	n/m	24.41	6.08	2.19	3.92	*70*	65.6	27.9	18.7	21.7	21.6	21.8	n/m
29	5/6/2021	07:35	*4.04*	131.5	1.75	n/m	5.08	2.19	2.98	*70*	66.4	52.9	45.4	21.7	21.6	22.8	n/m
29	5/6/2021	07:59	*4.04*	130.1	3.74	n/m	6.15	2.26	3.83	*70*	55.6	51.2	41.9	21.7	21.8	22.2	n/m
29	5/6/2021	08:30	*4.05*	130.9	7.91	n/m	6.16	2.26	3.83	*72*	66.1	47.5	37.8	21.7	21.8	22.0	n/m
29	5/6/2021	09:00	*4.04*	129.0	13.86	n/m	6.05	2.18	3.82	*71*	66.5	41.5	31.2	21.7	21.9	21.9	n/m
29	5/6/2021	09:30	*4.00*	130.7	22.10	n/m	6.03	2.25	3.84	*72*	66.0	32.7	23.3	21.8	22.0	22.3	n/m
30	5/6/2021	10:00	*4.05*	130.2	n/m	2.44	4.98	2.19	2.72	*71*	65.9	55.5	46.5	21.8	22.0	22.3	n/m
30	5/6/2021	10:30	*4.04*	129.9	n/m	5.51	5.90	2.22	3.73	*71*	65.9	52.1	42.8	21.8	21.9	22.3	n/m

Values shown in *italic text* are associated with uncalibrated instruments and are For Information Only (FIO).

DEF Segment	Date	Time	*[FM-01]* (gpm)	FM-02 (mL min^{-1})	DP-01 (psid)	DP-02 (psid)	DP-03 (psid)	DP-04 (psid)	DP-05 (psid)	*[P-01]* (psig)	P-02 (psig)	P-03 (psig)	P-05 (psig)	T-01 (°C)	T-02 (°C)	T-03 (°C)	T-REF (°C)
30	5/6/2021	11:00	*4.03*	129.7	n/m	10.45	5.87	2.20	3.70	*72*	66.6	47.6	38.4	21.8	22.3	23.0	n/m
30	5/6/2021	11:30	*4.04*	130.0	n/m	18.51	5.82	2.11	3.64	*71*	66.6	40.8	31.1	21.9	22.4	22.9	n/m
31	5/6/2021	12:08	*4.04*	130.3	0.90	n/m	4.82	2.04	2.70	*71*	66.6	55.3	47.4	21.9	22.6	23.3	n/m
31	5/6/2021	12:30	*4.05*	130.5	3.55	n/m	5.51	2.03	3.41	*71*	66.2	52.5	43.7	22.0	22.9	23.3	n/m
31	5/6/2021	13:00	*4.05*	130.2	5.79	n/m	5.80	2.13	3.64	*71*	66.5	49.9	40.5	22.0	22.8	23.6	n/m
31	5/6/2021	13:30	*4.04*	130.4	12.24	n/m	5.70	2.06	3.58	*70*	66.3	43.5	34.6	22.0	22.9	23.7	n/m
31	5/6/2021	14:00	*4.05*	130.3	18.36	n/m	5.62	2.06	3.53	*71*	66.1	37.2	28.3	22.1	23.0	23.9	n/m
32	5/6/2021	14:36	*4.05*	130.0	n/m	1.90	4.71	2.05	2.67	*70*	66.5	56.4	48.7	22.2	23.1	24.4	n/m
32	5/6/2021	15:00	*4.05*	130.0	n/m	3.92	5.68	2.11	3.46	*70*	66.5	53.4	45.5	22.2	23.0	24.0	n/m
32	5/6/2021	15:30	*4.03*	130.0	n/m	7.85	5.68	2.09	3.55	*70*	66.2	50.3	41.5	22.2	23.0	24.4	n/m
32	5/6/2021	16:00	*4.03*	130.0	n/m	13.59	5.73	2.09	3.54	*70*	66.4	44.4	35.6	22.3	23.0	24.5	n/m
32	5/6/2021	16:30	*4.05*	130.0	n/m	21.86	5.69	2.09	3.56	*70*	66.3	36.2	27.5	22.3	23.0	24.5	n/m
33	5/6/2021	17:00	*4.05*	130.0	1.11	n/m	4.68	1.98	2.58	*70*	66.2	55.1	47.3	22.3	23.2	24.5	25.8
33	5/6/2021	17:30	*4.04*	130.0	3.22	n/m	5.57	2.05	3.48	*70*	66.4	53.2	44.3	22.3	23.1	24.5	n/m
33	5/6/2021	18:00	*4.04*	130.0	7.06	n/m	5.68	2.09	3.56	*70*	66.2	48.6	39.2	22.3	23.0	24.4	n/m
33	5/6/2021	18:30	*4.05*	130.0	12.42	n/m	5.66	2.06	3.53	*70*	66.3	43.2	34.4	22.3	22.9	24.3	n/m
33	5/6/2021	19:00	*4.05*	130.0	19.91	n/m	5.62	2.07	3.56	*70*	66.1	35.8	26.7	22.3	23.1	24.4	n/m
34	5/6/2021	19:30	*4.06*	130.0	n/m	2.28	4.67	2.09	2.58	*70*	66.5	55.8	48.2	22.3	22.9	24.5	n/m
34	5/6/2021	20:02	*4.04*	130.0	n/m	5.32	5.67	2.11	3.58	*70*	66.4	52.8	44.1	22.3	22.8	24.3	n/m
34	5/6/2021	20:30	*4.06*	130.0	n/m	9.50	5.77	2.08	3.63	*70*	66.3	48.3	39.3	22.2	22.3	23.8	n/m
34	5/6/2021	21:00	*4.05*	130.0	n/m	16.00	5.80	2.10	3.60	*70*	66.5	42.3	32.8	22.2	22.7	23.6	n/m
34	5/6/2021	21:25	*4.05*	130.0	n/m	22.90	5.80	2.08	3.67	*70*	66.5	34.8	26.0	22.2	22.5	23.5	n/m
35	5/6/2021	22:00	*4.05*	130.0	1.90	n/m	4.87	2.05	2.89	*70*	66.5	53.8	46.0	22.1	22.5	23.8	n/m
35	5/6/2021	22:30	*4.05*	130.0	4.82	n/m	5.97	2.12	3.74	*70*	66.0	50.8	41.6	22.1	22.3	23.1	n/m
35	5/6/2021	23:00	*4.06*	130.0	9.10	n/m	5.92	2.11	3.73	*70*	66.5	46.8	37.3	22.0	22.2	22.8	n/m
35	5/6/2021	23:30	*4.05*	130.5	15.70	n/m	5.95	2.14	3.79	*70*	66.5	40.2	30.7	22.0	22.0	22.6	23.0
35	5/6/2021	23:55	*4.05*	130.0	22.75	n/m	5.97	2.14	3.83	*70*	66.3	32.8	23.4	21.9	21.9	22.4	n/m
36	5/7/2021	02:00	*4.06*	130.0	n/m	1.69	5.21	2.15	2.97	*70*	66.3	54.8	48.3	21.8	21.7	22.1	n/m
36	5/7/2021	02:30	*4.04*	130.5	n/m	8.19	6.19	2.17	3.99	*71*	66.2	49.1	39.3	21.7	21.5	22.0	n/m
36	5/7/2021	03:00	*4.05*	130.2	n/m	17.96	6.24	2.13	4.02	*71*	66.5	39.2	29.3	21.7	21.7	22.0	n/m
36	5/7/2021	03:12	*4.05*	129.6	n/m	23.24	6.17	2.20	4.04	*71*	66.4	34.1	24.2	21.7	21.8	22.0	n/m
37	5/7/2021	03:50	*4.06*	130.1	1.51	n/m	5.32	2.15	3.24	*71*	63.9	52.2	44.6	21.6	21.6	22.0	n/m
37	5/7/2021	04:04	*4.06*	129.7	2.41	n/m	6.16	2.14	3.99	*71*	66.0	52.7	43.5	21.6	21.7	20.9	n/m
37	5/7/2021	04:30	*4.06*	129.8	5.19	n/m	6.21	2.20	4.03	*71*	65.5	49.3	39.7	21.6	21.6	21.4	n/m
37	5/7/2021	05:00	*4.07*	129.9	10.09	n/m	6.27	2.19	4.07	*71*	65.5	44.5	34.8	21.6	21.8	21.4	n/m

Values shown in *italic text* are associated with uncalibrated instruments and are For Information Only (FIO).

DEF Segment	Date	Time	*[FM-01]* (gpm)	FM-02 (mL min^{-1})	DP-01 (psid)	DP-02 (psid)	DP-03 (psid)	DP-04 (psid)	DP-05 (psid)	*[P-01]* (psig)	P-02 (psig)	P-03 (psig)	P-05 (psig)	T-01 (°C)	T-02 (°C)	T-03 (°C)	T-REF (°C)
37	5/7/2021	05:30	*4.06*	130.8	17.18	n/m	6.29	2.20	4.06	*71*	66.0	37.8	28.1	21.6	21.5	21.4	n/m
37	5/7/2021	05:43	*4.06*	130.1	20.74	n/m	6.25	2.19	4.08	*71*	65.8	33.6	24.0	21.6	21.7	21.5	n/m
38	5/7/2021	06:16	*4.06*	129.9	n/m	1.65	5.24	2.11	3.12	*71*	66.3	56.5	47.8	21.6	21.5	21.8	n/m
38	5/7/2021	06:34	*4.06*	130.0	n/m	2.09	6.24	2.20	4.02	*71*	66.3	54.5	44.8	21.6	21.6	21.3	n/m
38	5/7/2021	07:00	*4.06*	130.1	n/m	6.85	6.27	2.18	4.07	*71*	65.9	50.5	40.8	21.6	21.5	21.3	n/m
38	5/7/2021	07:30	*4.06*	130.1	n/m	12.32	6.34	2.19	4.11	*71*	66.1	45.2	35.4	21.5	21.4	21.3	n/m
38	5/7/2021	08:00	*4.06*	130.1	n/m	20.93	6.31	2.19	4.10	*71*	66.3	36.7	26.9	21.5	21.3	21.1	n/m
39	5/7/2021	08:30	*4.06*	130.0	1.04	n/m	5.30	2.13	3.10	*70*	66.3	54.3	45.3	21.5	21.5	21.0	n/m
39	5/7/2021	09:00	*4.06*	129.8	2.81	n/m	6.31	2.20	4.11	*71*	66.1	52.5	42.9	21.5	21.5	20.5	n/m
39	5/7/2021	09:30	*4.06*	130.0	8.36	n/m	6.30	2.17	4.11	*69*	66.3	46.8	37.2	21.5	21.4	20.9	n/m
39	5/7/2021	10:00	*4.05*	129.9	11.80	n/m	6.32	2.20	4.10	*71*	66.5	43.3	33.7	21.5	21.5	21.1	n/m
39	5/7/2021	10:30	*4.05*	130.1	18.99	n/m	6.27	2.18	4.07	*72*	66.4	36.3	26.4	21.5	21.4	21.2	n/m
40	5/7/2021	11:00	*4.07*	130.2	n/m	1.30	5.28	2.16	3.12	*71*	66.3	56.5	47.3	21.5	21.6	21.4	n/m
40	5/7/2021	11:30	*4.07*	130.0	n/m	3.49	6.20	2.13	4.02	*70*	65.3	54.2	44.4	21.6	21.6	20.9	n/m
40	5/7/2021	12:00	*4.06*	129.9	n/m	7.31	6.14	2.15	4.01	*69*	66.2	50.5	41.0	21.6	21.8	21.6	n/m
40	5/7/2021	12:30	*4.06*	130.2	n/m	13.40	6.19	2.13	4.00	*70*	66.2	44.1	34.4	21.6	21.8	21.6	n/m
40	5/7/2021	13:02	*4.06*	129.8	n/m	22.94	6.15	2.13	4.01	*70*	66.4	34.5	24.9	21.6	21.9	22.2	n/m
41	5/7/2021	13:30	*4.06*	130.1	1.70	n/m	5.51	2.10	3.37	*72*	65.6	53.2	44.2	21.6	21.8	22.4	n/m
41	5/7/2021	14:00	*4.06*	130.1	3.94	n/m	6.08	2.08	3.95	*70*	66.2	51.4	41.9	21.7	21.9	22.2	n/m
41	5/7/2021	14:30	*4.06*	130.0	8.08	n/m	6.17	2.11	3.99	*70*	65.6	47.2	37.7	21.7	21.8	22.0	n/m
41	5/7/2021	15:00	*4.06*	130.0	14.13	n/m	6.16	2.12	4.01	*70*	66.1	41.1	31.4	21.7	21.8	22.0	n/m
42	5/7/2021	15:36	*4.06*	130.0	n/m	1.45	5.22	2.09	3.11	*70*	66.3	56.4	47.6	21.7	21.7	21.9	n/m
42	5/7/2021	16:00	*4.06*	129.5	n/m	3.45	6.09	2.12	3.93	*70*	66.4	54.3	45.0	21.7	21.6	20.8	n/m
42	5/7/2021	16:30	*4.06*	130.0	n/m	6.82	6.18	2.13	4.03	*70*	66.3	50.7	41.1	21.7	21.6	21.6	n/m
42	5/7/2021	17:00	*4.06*	130.0	n/m	12.81	6.23	2.12	4.06	*70*	66.2	44.8	35.3	21.6	21.6	21.5	21.8
42	5/7/2021	17:30	*4.06*	130.0	n/m	21.66	6.17	2.14	4.08	*70*	66.2	36.1	26.3	21.6	21.5	21.5	n/m
43	5/7/2021	17:59	*4.07*	130.0	1.28	n/m	5.12	2.11	2.93	*70*	66.1	54.2	45.9	21.7	21.6	21.7	n/m
43	5/7/2021	18:30	*4.07*	130.0	3.19	n/m	6.15	2.11	3.97	*70*	66.3	52.5	42.8	21.8	21.7	21.5	n/m
43	5/7/2021	19:00	*4.06*	130.0	6.64	n/m	6.19	2.11	4.01	*70*	65.9	48.7	39.2	21.9	21.9	21.8	n/m
43	5/7/2021	19:30	*4.06*	130.0	11.82	n/m	6.18	2.12	4.04	*70*	66.0	43.4	33.8	21.9	21.8	21.7	n/m
43	5/7/2021	20:00	*4.06*	130.0	18.38	n/m	6.19	2.12	4.05	*70*	66.2	36.8	27.2	21.9	21.8	21.7	n/m
44	5/7/2021	20:30	*4.06*	130.0	n/m	2.04	5.20	2.06	3.13	*70*	66.2	55.6	46.9	21.9	21.5	22.0	n/m
44	5/7/2021	21:01	*4.07*	130.0	n/m	4.80	6.20	2.12	4.06	*70*	65.2	51.9	42.2	21.9	21.5	21.2	n/m
44	5/7/2021	21:30	*4.06*	130.0	n/m	9.30	6.28	2.15	4.10	*70*	64.3	46.5	36.8	21.9	21.6	21.2	n/m
44	5/7/2021	22:00	*4.07*	130.1	n/m	16.11	6.26	2.15	4.11	*70*	65.8	41.2	31.5	21.9	21.6	21.1	n/m

Values shown in *italic text* are associated with uncalibrated instruments and are For Information Only (FIO).

DEF Segment	Date	Time	*[FM-01]* (gpm)	FM-02 (mL min^{-1})	DP-01 (psid)	DP-02 (psid)	DP-03 (psid)	DP-04 (psid)	DP-05 (psid)	*[P-01]* (psig)	P-02 (psig)	P-03 (psig)	P-05 (psig)	T-01 (°C)	T-02 (°C)	T-03 (°C)	T-REF (°C)
45	5/7/2021	23:01	*4.07*	130.5	1.79	n/m	5.50	2.13	3.40	*70*	66.3	53.8	45.0	21.9	21.4	21.3	n/m
45	5/7/2021	23:30	*4.06*	130.0	4.08	n/m	6.22	2.13	4.09	*70*	66.0	51.2	41.4	21.9	21.5	20.9	n/m
45	5/8/2021	00:03	*4.07*	130.0	8.70	n/m	6.28	2.15	4.13	*70*	66.0	46.4	36.7	21.9	21.4	21.0	n/m
45	5/8/2021	00:30	*4.07*	130.0	13.65	n/m	6.26	2.13	4.12	*70*	66.0	41.4	31.7	21.9	21.3	21.1	n/m
45	5/8/2021	01:00	*4.07*	130.0	21.15	n/m	6.23	2.13	4.10	*70*	66.5	33.8	24.1	21.9	21.3	21.2	n/m
46	5/8/2021	01:34	*4.07*	130.0	n/m	2.17	5.44	2.11	3.36	*70*	66.2	55.6	47.0	21.9	21.4	21.8	n/m
46	5/8/2021	02:03	*4.07*	130.0	n/m	4.79	6.16	2.09	4.04	*70*	66.0	53.0	43.4	21.9	21.3	21.1	n/m
46	5/8/2021	02:30	*4.07*	130.1	n/m	8.76	6.22	2.12	4.08	*71*	66.1	48.7	39.1	21.9	21.6	21.3	n/m
46	5/8/2021	03:00	*4.07*	130.0	n/m	14.98	6.22	2.13	4.10	*71*	65.0	42.5	32.7	21.9	21.9	21.5	n/m
46	5/8/2021	03:29	*4.07*	130.1	n/m	22.84	6.20	2.10	4.09	*71*	66.1	34.5	24.9	22.0	21.9	21.6	n/m
47	5/8/2021	04:04	*4.07*	130.5	1.44	n/m	5.32	2.07	3.26	*71*	66.0	53.9	45.4	22.0	21.9	22.1	n/m
47	5/8/2021	04:30	*4.07*	130.1	3.19	n/m	6.15	2.08	4.03	*71*	66.0	52.1	42.7	22.0	22.0	21.4	n/m
47	5/8/2021	05:00	*4.07*	130.0	6.56	n/m	6.23	2.11	4.10	*71*	66.0	48.5	38.9	22.0	21.8	21.7	n/m
47	5/8/2021	05:30	*4.07*	130.0	11.71	n/m	6.22	2.16	4.10	*71*	66.1	43.4	33.7	22.0	21.8	21.6	n/m
47	5/8/2021	06:00	*4.07*	130.0	18.30	n/m	6.19	2.10	4.09	*71*	66.0	36.9	27.2	22.0	21.7	21.6	n/m
48	5/8/2021	06:33	*4.07*	130.1	n/m	1.97	5.21	2.02	3.16	*71*	66.2	55.9	27.2	22.0	21.8	22.2	n/m
48	5/8/2021	07:00	*4.07*	130.1	n/m	4.29	6.14	2.07	4.02	*71*	66.1	53.5	34.1	22.0	21.9	21.8	n/m
48	5/8/2021	07:30	*4.07*	130.0	n/m	8.63	6.22	2.10	4.07	*71*	66.0	48.9	39.3	22.0	21.9	21.7	n/m
48	5/8/2021	08:00	*4.07*	129.9	n/m	14.76	6.23	2.11	4.10	*71*	65.9	42.6	33.0	22.0	21.7	21.6	n/m
48	5/8/2021	08:30	*4.06*	130.0	n/m	23.20	6.26	2.11	4.13	*70*	66.2	34.4	24.7	22.0	21.7	21.4	n/m
49	5/8/2021	09:00	*4.07*	130.0	1.56	n/m	5.50	2.09	3.35	*70*	66.1	53.9	45.4	22.0	21.5	21.6	n/m
49	5/8/2021	09:30	*4.07*	130.0	3.95	n/m	6.23	2.12	4.11	*70*	66.0	51.2	41.7	21.9	21.5	20.9	n/m
49	5/8/2021	10:00	*4.07*	130.0	8.30	n/m	6.26	2.14	4.14	*70*	66.1	46.9	37.2	21.9	21.7	21.1	n/m
49	5/8/2021	10:30	*4.06*	130.0	14.09	n/m	6.26	2.10	4.15	*70*	66.1	41.2	31.4	21.9	21.8	21.2	n/m
50	5/8/2021	11:00	*4.07*	130.0	n/m	1.42	5.36	2.06	3.17	*70*	66.0	56.3	47.5	22.0	21.7	21.3	n/m
50	5/8/2021	11:30	*4.07*	130.0	n/m	3.30	6.17	2.08	4.06	*70*	66.1	54.4	44.8	22.0	21.7	20.4	n/m
50	5/8/2021	12:00	*4.07*	130.0	n/m	6.98	6.20	2.11	4.08	*71*	66.1	50.7	41.0	22.0	21.7	21.3	n/m
50	5/8/2021	12:30	*4.07*	130.0	n/m	12.10	6.21	2.12	4.10	*70*	65.9	45.4	35.8	22.0	21.9	21.5	n/m
50	5/8/2021	13:00	*4.07*	130.0	n/m	19.21	6.15	2.07	4.08	*70*	65.8	38.5	28.9	22.0	22.0	21.5	n/m
51	5/8/2021	13:30	*4.07*	130.0	1.65	n/m	5.50	2.07	3.51	*70*	65.9	53.4	44.5	22.0	21.7	22.2	n/m
51	5/8/2021	14:00	*4.07*	129.9	3.84	n/m	6.08	2.05	4.01	*71*	66.0	51.4	42.0	22.0	21.9	21.6	n/m
51	5/8/2021	14:30	*4.07*	130.0	7.50	n/m	6.10	2.05	4.05	*71*	66.1	47.8	38.3	22.1	21.7	21.8	n/m
51	5/8/2021	15:00	*4.07*	130.0	12.40	n/m	6.10	2.05	4.04	*71*	65.8	42.8	33.3	22.1	22.0	22.1	n/m
51	5/8/2021	15:20	*4.07*	130.0	16.30	n/m	6.10	2.05	4.04	*71*	65.9	38.7	29.2	22.1	22.0	22.0	n/m
52	5/8/2021	15:57	*4.07*	130.2	n/m	2.80	6.00	2.04	3.97	*71*	65.9	54.9	45.7	22.1	22.2	21.0	n/m

Values shown in *italic text* are associated with uncalibrated instruments and are For Information Only (FIO).

DEF Segment	Date	Time	*[FM-01]* (gpm)	FM-02 (mL min^{-1})	DP-01 (psid)	DP-02 (psid)	DP-03 (psid)	DP-04 (psid)	DP-05 (psid)	*[P-01]* (psig)	P-02 (psig)	P-03 (psig)	P-05 (psig)	T-01 (°C)	T-02 (°C)	T-03 (°C)	T-REF (°C)
52	5/8/2021	16:30	*4.07*	130.0	n/m	8.00	6.10	2.00	3.97	*71*	65.8	49.5	40.2	22.2	22.1	22.2	n/m
52	5/8/2021	17:00	*4.07*	130.0	n/m	12.00	6.10	2.00	4.00	*71*	65.8	45.5	36.1	22.2	22.2	22.2	n/m
52	5/8/2021	17:30	*4.07*	130.0	n/m	18.70	6.10	2.00	4.00	*71*	65.8	38.9	29.5	22.2	22.2	22.3	n/m
52	5/8/2021	17:45	*4.07*	129.9	n/m	22.80	6.00	2.00	4.00	*70*	65.8	34.9	25.5	22.2	22.2	22.4	n/m
53	5/8/2021	18:03	*4.07*	130.1	1.21	n/m	5.00	2.00	2.90	*71*	65.9	53.9	45.9	22.2	22.2	22.5	n/m
53	5/8/2021	18:30	*4.07*	130.0	2.67	n/m	6.10	2.00	4.00	*71*	65.9	52.5	43.2	22.2	22.3	22.0	n/m
53	5/8/2021	19:00	*4.07*	130.0	5.30	n/m	6.10	2.00	4.00	*71*	65.9	50.0	40.8	22.2	22.2	22.3	n/m
53	5/8/2021	19:30	*4.07*	130.0	9.10	n/m	6.10	2.00	4.00	*71*	65.9	46.2	36.8	22.2	22.2	22.2	n/m
53	5/8/2021	20:05	*4.07*	130.0	15.70	n/m	6.10	2.00	4.00	*70*	65.8	39.6	30.1	22.2	22.1	22.2	n/m
54	5/8/2021	20:37	*4.07*	130.0	n/m	2.85	5.80	2.00	3.70	*70*	66.0	54.8	46.0	22.2	21.8	21.9	21.7
54	5/8/2021	21:00	*4.07*	130.0	n/m	4.77	6.10	2.00	4.00	*70*	66.0	52.8	43.5	22.1	21.9	21.9	n/m
54	5/8/2021	21:30	*4.07*	130.0	n/m	8.79	6.20	2.10	4.10	*70*	65.9	48.7	39.1	22.1	21.8	21.8	n/m
54	5/8/2021	22:03	*4.07*	130.0	n/m	15.15	6.20	2.10	4.10	*70*	65.8	42.1	32.4	22.0	21.5	21.6	n/m
55	5/8/2021	22:36	*4.07*	130.0	0.31	n/m	4.40	0.70	3.60	*70*	65.7	56.5	49.9	22.0	21.5	21.3	n/m
55	5/8/2021	23:00	*4.07*	130.0	1.73	n/m	5.85	2.10	3.85	*70*	66.0	53.3	44.1	22.0	21.5	21.3	n/m
55	5/8/2021	23:30	*4.07*	130.0	4.18	n/m	6.27	2.10	4.15	*70*	65.8	53.8	41.1	21.9	21.5	21.1	n/m
55	5/9/2021	00:00	*4.07*	130.0	7.95	n/m	6.29	2.10	4.18	*70*	65.8	47.0	37.3	21.9	21.5	21.0	n/m
55	5/9/2021	00:31	*4.07*	130.0	13.35	n/m	6.30	2.10	4.17	*70*	65.8	41.5	31.8	21.9	21.4	21.0	n/m
56	5/9/2021	01:10	*4.07*	130.0	n/m	1.81	5.18	2.10	3.08	*70*	65.8	55.7	47.2	21.9	21.4	21.1	n/m
56	5/9/2021	01:31	*4.07*	130.5	n/m	3.19	6.23	2.09	4.15	*70*	65.9	54.5	45.0	21.9	21.3	19.9	n/m
56	5/9/2021	02:00	*4.07*	130.0	n/m	6.35	6.30	2.10	4.17	*70*	65.8	51.0	41.3	21.9	21.3	21.0	n/m
56	5/9/2021	02:30	*4.06*	130.1	n/m	11.08	6.29	2.11	4.17	*70*	65.7	46.2	36.4	21.9	21.4	21.2	n/m
56	5/9/2021	03:00	*4.07*	130.0	n/m	17.86	6.25	2.10	4.16	*70*	65.8	39.4	29.7	21.9	21.7	21.3	n/m
57	5/9/2021	03:42	*4.07*	129.9	1.77	n/m	5.11	2.04	3.06	*70*	66.1	53.6	45.2	21.9	21.7	22.2	n/m
57	5/9/2021	03:59	*4.07*	129.5	2.87	n/m	6.22	2.06	4.09	*70*	65.9	52.4	42.8	21.9	21.9	20.9	n/m
57	5/9/2021	04:30	*4.07*	130.0	5.96	n/m	6.27	2.09	4.15	*70*	65.9	49.0	39.3	22.0	21.8	21.8	n/m
57	5/9/2021	05:01	*4.07*	129.9	10.07	n/m	6.27	2.09	4.16	*70*	65.8	44.6	35.0	22.0	21.9	21.8	n/m
57	5/9/2021	05:30	*4.07*	129.9	15.20	n/m	6.22	2.09	4.15	*70*	53.3	27.2	17.5	22.0	21.9	21.9	n/m
57	5/9/2021	05:39	*4.07*	129.8	17.35	n/m	6.21	2.08	4.14	*70*	53.6	25.4	15.7	21.9	22.0	21.9	n/m
58	5/9/2021	06:09	*4.07*	129.4	n/m	2.01	5.09	2.02	3.09	*70*	54.2	44.0	35.8	21.9	21.8	22.3	n/m
58	5/9/2021	06:30	*4.07*	129.9	n/m	3.44	6.18	2.06	4.10	*70*	54.2	42.4	32.4	21.9	21.9	21.5	n/m
58	5/9/2021	07:01	*4.07*	130.0	n/m	6.82	6.24	2.08	4.15	*60*	54.3	39.0	29.3	21.9	21.9	21.9	n/m
58	5/9/2021	07:09	*4.42*	129.9	n/m	7.87	6.26	2.08	4.15	*70*	61.8	45.5	35.8	21.9	21.9	22.2	n/m
58	5/9/2021	07:30	*4.41*	130.0	n/m	10.99	6.25	2.08	4.15	*70*	61.7	42.1	32.4	22.0	21.9	22.0	n/m
58	5/9/2021	08:03	*4.41*	129.9	n/m	17.01	6.24	2.09	4.16	*69*	61.6	35.9	26.3	22.0	21.8	21.9	n/m

Values shown in *italic text* are associated with uncalibrated instruments and are For Information Only (FIO).

DEF Segment	Date	Time	*[FM-01]* (gpm)	FM-02 (mL min^{-1})	DP-01 (psid)	DP-02 (psid)	DP-03 (psid)	DP-04 (psid)	DP-05 (psid)	*[P-01]* (psig)	P-02 (psig)	P-03 (psig)	P-05 (psig)	T-01 (°C)	T-02 (°C)	T-03 (°C)	T-REF (°C)
59	5/9/2021	08:30	*4.41*	130.8	1.31	n/m	5.12	2.07	3.01	*70*	61.6	49.6	41.0	22.0	21.6	21.3	n/m
59	5/9/2021	09:00	*4.41*	130.1	2.77	n/m	6.20	2.07	4.12	*69*	61.8	48.5	38.9	22.0	21.7	20.8	n/m
59	5/9/2021	09:30	*4.41*	130.0	5.08	n/m	6.29	2.10	4.16	*69*	61.7	45.9	36.3	22.0	21.7	21.2	n/m
59	5/9/2021	10:00	*4.41*	130.1	8.05	n/m	6.26	2.08	4.16	*69*	61.6	42.9	33.3	22.0	21.5	21.2	n/m
59	5/9/2021	10:30	*4.41*	129.9	12.04	n/m	6.23	2.08	4.15	*69*	61.7	39.0	29.4	22.0	21.4	21.3	n/m
60	5/9/2021	11:00	*4.41*	129.9	n/m	2.06	5.64	2.06	3.61	*69*	61.9	51.7	42.8	22.1	21.9	22.0	n/m
60	5/9/2021	11:41	*4.39*	129.9	n/m	4.75	6.21	2.06	4.10	*69*	61.9	48.4	39.2	22.1	21.4	21.6	n/m
60	5/9/2021	12:00	*4.24*	131.2	n/m	6.40	6.26	2.10	4.04	*68*	59.7	46.3	34.5	22.1	n/m	21.8	n/m

Table B.4. Initial Differential Pressure Data for DEFs from Test HS1

DEF Segment	Date	Start Time	ΔP (psid) at t = 2 min	ΔP (psid) at t = 4 min	ΔP (psid) at t = 6 min	ΔP (psid) at t = 8 min	ΔP (psid) at t = 10 min
1	5/3/2021	12:24	0.23	0.25	0.28	0.32	0.38
2	5/3/2021	14:37	0.31	0.42	0.62	0.68	0.72
3	5/3/2021	15:36	0.25	0.36	0.58	0.69	0.73
4	5/3/2021	18:08	0.28	0.40	0.62	0.71	0.75
5	5/3/2021	21:08	0.40	0.79	0.90	1.00	1.06
6	5/3/2021	23:49	0.69	1.00	1.11	1.20	1.26
7	5/4/2021	02:35	0.43	0.72	1.02	1.08	1.15
8	5/4/2021	05:19	0.55	1.02	1.33	1.50	1.60
9	5/4/2021	07:51	0.54	1.07	1.50	1.67	1.78
10	5/4/2021	10:21	0.50	1.20	1.71	1.90	2.05
11	5/4/2021	12:33	0.33	0.75	1.21	1.40	1.50
12	5/4/2021	15:07	0.35	1.35	1.72	1.95	2.10
13	5/4/2021	17:58	0.28	0.58	0.96	1.10	1.20
14	5/4/2021	20:48	0.37	1.22	1.55	1.73	1.87
15	5/4/2021	23:12	0.94	1.07	1.15	1.21	1.30
16	5/5/2021	01:45	0.77	1.73	2.00	2.18	2.32
17	5/5/2021	04:16	0.49	1.05	1.27	1.36	1.44
18	5/5/2021	06:48	1.52	2.14	2.38	2.56	2.66
19	5/5/2021	09:10	0.46	0.88	1.19	1.33	1.43
20	5/5/2021	11:30	0.52	1.45	2.00	2.26	2.47
21	5/5/2021	13:51	0.53	1.05	1.56	1.62	1.73
22	5/5/2021	16:12	0.36	0.98	1.28	1.57	1.82
23	5/5/2021	18:10	0.30	0.56	0.85	1.00	1.12
24	5/5/2021	21:01	0.90	1.45	1.89	2.82	2.43
25	5/5/2021	22:44	0.45	0.99	1.22	1.30	1.45
26	5/6/2021	01:08	0.38	1.16	1.42	1.75	1.95
27	5/6/2021	02:53	0.41	0.97	1.25	1.40	1.52
28	5/6/2021	05:24	0.77	1.22	1.57	1.72	1.94
29	5/6/2021	07:16	0.47	0.84	0.99	1.10	1.18
30	5/6/2021	09:48	0.34	1.45	1.70	1.90	2.04
31	5/6/2021	11:59	0.30	0.55	0.75	0.85	0.94

DEF Segment	Date	Start Time	ΔP (psid) at t = 2 min	ΔP (psid) at t = 4 min	ΔP (psid) at t = 6 min	ΔP (psid) at t = 8 min	ΔP (psid) at t = 10 min
32	5/6/2021	14:26	0.30	1.05	1.42	1.65	1.83
33	5/6/2021	16:47	0.32	0.62	0.81	0.92	1.02
34	5/6/2021	19:15	0.29	1.05	1.40	1.61	1.78
35	5/6/2021	21:38	0.41	0.71	0.92	1.08	1.21
36	5/7/2021	01:48	0.92	1.30	1.42	1.56	1.69
37	5/7/2021	03:28	0.30	0.57	0.73	0.83	0.91
38	5/7/2021	05:56	0.40	0.71	0.93	1.03	1.12
39	5/7/2021	08:20	0.31	0.62	0.80	0.91	1.00
40	5/7/2021	10:48	0.29	0.69	0.95	1.12	1.20
41	5/7/2021	13:06	0.30	0.58	0.83	0.95	1.05
42	5/7/2021	15:26	0.34	0.73	1.11	1.28	1.41
43	5/7/2021	17:42	0.27	0.52	0.78	0.90	0.99
44	5/7/2021	20:09	0.34	0.85	1.18	1.33	1.45
45	5/7/2021	22:39	0.34	0.70	0.93	1.06	1.16
46	5/8/2021	01:13	0.50	0.85	1.20	1.35	1.48
47	5/8/2021	03:43	0.33	0.63	0.82	0.94	1.06
48	5/8/2021	06:13	0.42	0.90	1.12	1.31	1.40
49	5/8/2021	08:37	0.26	0.50	0.75	0.86	0.96
50	5/8/2021	10:50	0.35	0.85	1.14	1.30	1.39
51	5/8/2021	13:04	0.27	0.51	0.80	0.91	1.01
52	5/8/2021	15:23	0.30	0.78	1.03	1.18	1.31
53	5/8/2021	17:47	0.20	0.40	0.71	0.83	0.92
54	5/8/2021	20:09	0.43	1.08	1.43	1.61	1.72
55	5/8/2021	22:33	0.30	n/m	n/m	0.90	0.95
56	5/9/2021	00:56	0.41	0.98	1.25	1.33	1.43
57	5/9/2021	03:24	0.35	0.90	1.15	1.26	1.35
58	5/9/2021	05:52	0.69	1.11	1.35	1.51	1.59
59	5/9/2021	08:15	0.28	0.55	0.88	1.01	1.10
60	5/9/2021	10:35	0.27	0.90	1.14	1.30	1.40
End of Test	5/9/2021	12:05	n/m	n/m	n/m	n/m	n/m

B.3 Test HS2 Tabulated Data

Table B.5. Periodically Recorded Data from Test HS2

Values shown in *italic text* are associated with uncalibrated instruments and are For Information Only (FIO).

DEF Segment	Date	Time	*[FM-01]* (gpm)	FM-02 (mL min^{-1})	DP-01 (psid)	DP-02 (psid)	DP-03 (psid)	DP-04 (psid)	DP-05 (psid)	*[P-01]* (psig)	P-02 (psig)	P-03 (psig)	P-05 (psig)	T-01 (°C)	T-02 (°C)	T-03 (°C)	T-REF (°C)
1	5/17/2021	08:49	*4.00*	130.0	0.40	n/m	2.00	0.90	1.20	*70*	63.0	55.9	56.5	23.5	24.1	23.8	24.6
1	5/17/2021	09:30	*4.11*	98.5	15.50	n/m	3.62	1.35	2.28	*71*	68.6	47.7	41.6	23.2	24.1	24.3	n/m
2	5/17/2021	10:04	*4.00*	130.0	n/m	3.90	4.70	2.00	2.40	*70*	67.5	56.0	46.5	23.0	23.9	25.4	n/m
2	5/17/2021	10:30	*4.00*	130.0	n/m	20.00	5.70	2.00	3.35	*70*	68.5	37.5	27.0	22.9	23.5	25.1	n/m
3	5/17/2021	11:16	*4.00*	130.0	9.50	n/m	4.65	1.80	2.50	*70*	69.5	48.5	38.9	22.7	23.8	25.7	n/m
3	5/17/2021	11:28	*4.05*	130.0	18.00	n/m	5.35	1.90	3.20	*70*	68.5	37.5	29.2	22.6	24.0	24.5	n/m
4	5/17/2021	12:00	*4.10*	130.0	n/m	8.00	4.60	1.80	2.65	*70*	67.5	52.5	44.5	22.5	23.9	25.6	n/m
4	5/17/2021	12:14	*4.10*	130.0	n/m	20.00	5.55	2.00	3.40	*70*	68.0	40.0	30.7	22.4	24.0	24.8	n/m
5	5/17/2021	12:35	*4.08*	130.0	2.51	n/m	4.76	1.97	2.57	*70*	68.5	54.5	44.5	22.3	23.6	24.9	n/m
6	5/17/2021	13:29	*4.15*	130.0	n/m	6.40	4.50	2.00	2.50	*70*	68.5	54.5	47.0	22.2	23.7	25.1	n/m
6	5/17/2021	13:58	*4.18*	129.9	n/m	20.40	5.20	1.91	3.32	*70*	69.0	39.0	30.5	22.0	23.7	24.9	n/m
7	5/17/2021	14:30	*4.16*	130.0	9.03	n/m	4.52	1.90	2.83	*70*	69.0	51.0	42.5	21.9	23.2	25.6	26.6
8	5/17/2021	15:00	*4.19*	130.0	n/m	4.30	4.65	1.70	2.50	*70*	67.0	56.0	48.0	21.8	23.2	24.8	n/m
9	5/17/2021	15:42	*4.20*	130.0	2.15	n/m	4.50	1.80	2.45	*70*	68.0	57.0	48.0	21.7	23.4	25.0	n/m
9	5/17/2021	15:59	*4.20*	130.0	8.30	n/m	4.76	1.86	2.67	*70*	69.0	50.5	42.8	21.7	23.4	25.5	n/m
10	5/17/2021	16:30	*4.20*	130.0	n/m	4.03	4.36	1.87	2.52	*70*	69.0	57.0	49.0	21.6	23.1	25.1	n/m
11	5/17/2021	17:16	*4.20*	130.0	3.28	n/m	4.35	1.84	2.56	*70*	70.5	56.8	49.5	21.6	23.1	25.2	n/m
11	5/17/2021	17:30	*4.20*	130.0	10.67	n/m	5.01	1.85	3.07	*70*	70.0	48.8	40.0	21.5	23.2	25.8	n/m
12	5/17/2021	18:00	*4.20*	130.0	n/m	3.83	4.50	2.03	2.65	*70*	66.0	54.5	48.0	21.5	23.2	24.9	n/m
13	5/17/2021	18:30	*4.20*	130.0	0.42	n/m	4.23	0.66	3.39	*70*	69.5	63.4	56.9	21.4	24.3	24.9	n/m
13	5/17/2021	19:00	*4.15*	129.5	15.60	n/m	5.45	1.90	3.52	*70*	71.9	45.2	35.8	21.4	23.0	24.5	n/m
14	5/17/2021	19:30	*4.20*	130.0	n/m	10.10	4.95	1.72	3.02	*70*	71.0	53.0	45.0	21.3	22.8	25.2	n/m
15	5/17/2021	20:00	*4.20*	130.0	4.50	n/m	4.76	1.81	2.65	*70*	70.0	56.0	48.0	21.3	21.9	24.5	n/m
15	5/17/2021	20:30	*4.22*	131.0	24.10	n/m	5.64	1.91	3.55	*71*	68.9	35.1	25.7	21.2	22.2	24.7	n/m
16	5/17/2021	21:00	*4.21*	130.0	n/m	14.08	5.23	1.82	3.32	*70*	70.3	47.9	37.9	21.2	21.8	24.7	n/m
16	5/17/2021	23:22	*4.22*	130.2	n/m	22.90	5.18	1.49	3.50	*72*	70.1	37.7	29.9	21.8	22.9	25.0	24.8
17	5/17/2021	23:40	*4.09*	131.2	3.33	n/m	4.46	1.95	2.66	*72*	70.4	56.8	48.3	21.8	22.7	24.8	n/m
17	5/18/2021	00:01	*4.20*	130.0	16.38	n/m	5.61	1.93	3.75	*70*	71.0	42.4	33.6	21.8	22.6	24.2	n/m
18	5/18/2021	00:30	*4.25*	130.3	n/m	9.25	4.75	1.81	2.86	*70*	71.0	52.7	44.8	21.8	22.6	24.1	n/m
19	5/18/2021	01:10	*4.19*	129.6	4.71	n/m	4.57	1.72	2.77	*72*	71.4	56.2	48.7	21.8	22.9	23.8	n/m

Values shown in *italic text* are associated with uncalibrated instruments and are For Information Only (FIO).

DEF Segment	Date	Time	*[FM-01]* (gpm)	FM-02 (mL min^{-1})	DP-01 (psid)	DP-02 (psid)	DP-03 (psid)	DP-04 (psid)	DP-05 (psid)	*[P-01]* (psig)	P-02 (psig)	P-03 (psig)	P-05 (psig)	T-01 (°C)	T-02 (°C)	T-03 (°C)	T-REF (°C)
19	5/18/2021	01:30	*4.23*	129.9	18.20	n/m	5.52	1.91	3.70	*73*	70.2	39.3	30.2	21.8	22.4	23.3	n/m
20	5/18/2021	02:00	*4.20*	129.7	n/m	9.80	4.99	1.87	3.05	*71*	69.8	51.6	43.3	21.8	22.3	23.9	n/m
21	5/18/2021	02:30	*4.20*	130.1	1.53	n/m	4.86	1.45	3.11	*72*	70.9	59.6	49.6	21.8	22.3	23.8	n/m
21	5/18/2021	03:00	*4.23*	130.5	11.43	n/m	5.37	1.88	3.34	*71*	72.2	48.7	48.3	21.8	22.5	23.8	n/m
21	5/18/2021	04:27	*4.24*	130.6	20.90	n/m	5.48	1.81	3.58	*74*	71.1	39.1	30.3	21.8	22.3	23.7	n/m
22	5/18/2021	05:00	*4.23*	130.1	n/m	9.40	5.55	1.86	3.54	*74*	71.4	52.3	43.4	21.8	22.3	24.0	n/m
22	5/18/2021	05:16	*4.22*	129.6	n/m	23.80	5.97	1.91	3.89	*74*	71.8	38.5	28.5	21.9	22.6	23.5	n/m
23	5/18/2021	05:30	*4.26*	129.6	2.57	n/m	4.83	1.85	2.89	*74*	69.8	57.5	49.7	21.8	22.2	23.5	23.5
23	5/18/2021	07:01	*4.26*	129.3	14.60	n/m	5.54	1.99	3.44	*78*	72.1	46.2	37.2	21.6	21.8	22.9	n/m
23	5/18/2021	07:11	*4.27*	130.1	25.16	n/m	5.58	2.02	3.56	*78*	72.6	33.4	23.5	21.7	22.0	23.6	n/m
24	5/18/2021	07:30	*4.26*	129.4	n/m	4.56	5.00	1.93	2.84	*78*	71.5	59.1	49.9	21.7	22.0	22.8	n/m
24	5/18/2021	07:55	*4.24*	129.1	n/m	24.54	5.97	1.95	4.01	*78*	71.6	37.7	27.9	21.7	21.6	22.5	n/m
25	5/18/2021	08:30	*4.24*	130.5	5.45	n/m	4.74	2.05	2.75	*80*	71.8	56.0	47.5	21.7	21.7	22.9	n/m
26	5/18/2021	09:29	*4.27*	130.5	n/m	14.50	5.70	1.85	3.65	*80*	72.0	49.8	41.4	21.6	22.1	22.5	n/m
27	5/18/2021	10:00	*4.27*	130.0	6.50	n/m	5.00	1.85	2.95	*80*	73.0	53.5	45.5	21.6	22.0	22.8	n/m
28	5/18/2021	10:34	*4.25*	130.0	n/m	2.75	4.95	1.95	2.95	*80*	72.0	60.5	50.5	21.6	22.1	22.7	n/m
28	5/18/2021	11:00	*4.27*	130.0	n/m	18.50	5.90	1.90	3.85	*80*	72.5	45.5	35.3	21.6	22.3	22.6	n/m
29	5/18/2021	11:30	*4.27*	130.0	5.25	n/m	4.85	1.85	2.85	*80*	72.0	53.5	46.5	21.6	22.2	23.0	n/m
30	5/18/2021	12:03	*4.27*	130.0	n/m	2.00	5.10	1.75	3.10	*80*	73.0	62.5	53.0	21.6	22.0	22.8	n/m
30	5/18/2021	12:30	*4.27*	125.0	n/m	20.00	5.50	1.65	3.67	*80*	72.5	45.0	36.5	21.6	21.9	22.4	n/m
31	5/18/2021	13:00	*4.27*	130.0	7.90	n/m	4.85	1.85	3.10	*80*	71.5	53.0	44.5	21.6	22.2	23.5	n/m
31	5/18/2021	13:26	*4.27*	100.0	18.50	n/m	4.40	1.35	2.90	*80*	74.5	47.5	41.3	21.7	22.2	23.2	n/m
32	5/18/2021	15:00	*4.27*	100.5	n/m	12.00	4.34	1.31	2.84	*80*	72.5	41.5	31.5	21.8	22.0	23.1	n/m
33	5/18/2021	15:30	*4.30*	131.0	6.53	n/m	4.83	1.71	2.98	*80*	71.1	54.8	47.8	21.8	21.8	23.5	n/m
34	5/18/2021	16:00	*4.22*	130.0	n/m	3.05	5.07	1.93	3.06	*80*	71.7	60.3	52.6	21.8	21.9	23.3	n/m
35	5/18/2021	16:40	*4.27*	130.0	2.35	n/m	4.92	1.70	3.02	*80*	72.2	59.8	51.0	21.8	20.5	23.4	n/m
35	5/18/2021	17:00	*4.30*	130.0	12.40	n/m	5.55	1.81	3.71	*80*	72.5	50.3	41.0	21.8	21.6	23.1	n/m
36	5/18/2021	17:30	*4.26*	130.0	n/m	3.50	4.87	1.61	2.97	*80*	72.0	61.0	51.0	21.8	22.2	23.3	n/m
37	5/18/2021	18:05	*4.30*	130.0	2.54	n/m	4.88	1.85	2.98	*80*	71.0	58.8	50.5	21.8	21.9	23.3	n/m
37	5/18/2021	18:30	*4.30*	130.0	15.70	n/m	5.53	1.85	3.88	*80*	73.2	46.0	36.5	21.9	21.3	23.0	n/m
38	5/18/2021	19:00	*4.30*	130.0	n/m	8.10	4.84	1.80	2.87	*80*	73.3	56.4	48.6	21.8	21.6	23.5	n/m
39	5/18/2021	21:05	*4.21*	131.1	6.05	n/m	4.73	1.84	2.84	*75*	71.3	54.7	46.5	21.8	21.9	23.9	23.5
39	5/18/2021	21:24	*4.19*	130.2	19.02	n/m	5.88	1.93	3.76	*75*	72.1	40.9	31.5	21.8	22.3	22.7	n/m
40	5/18/2021	21:49	*4.24*	130.2	n/m	2.14	5.01	1.91	2.96	*74*	70.5	60.3	52.1	21.8	22.2	22.9	n/m
40	5/18/2021	22:19	*4.25*	129.9	n/m	19.92	6.01	1.99	4.04	*75*	71.6	43.1	32.9	21.8	21.9	22.6	n/m

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DEF Segment	Date	Time	*[FM-01]* (gpm)	FM-02 (mL min^{-1})	DP-01 (psid)	DP-02 (psid)	DP-03 (psid)	DP-04 (psid)	DP-05 (psid)	*[P-01]* (psig)	P-02 (psig)	P-03 (psig)	P-05 (psig)	T-01 (°C)	T-02 (°C)	T-03 (°C)	T-REF (°C)
41	5/18/2021	22:49	*4.23*	129.7	7.36	n/m	5.19	1.86	3.21	*75*	71.0	53.3	44.7	21.7	21.8	23.0	n/m
42	5/18/2021	23:28	*4.24*	130.4	n/m	4.33	4.77	1.68	3.20	*74*	70.9	58.4	49.4	21.7	21.9	23.4	n/m
42	5/18/2021	23:52	*4.27*	129.9	n/m	19.60	5.85	1.97	4.26	*75*	70.4	38.2	26.6	21.6	21.7	22.2	n/m
43	5/19/2021	00:29	*4.25*	129.6	9.86	n/m	5.41	1.90	3.35	*75*	71.2	51.3	42.4	21.6	21.8	22.7	n/m
43	5/19/2021	00:52	*n/m*	n/m	25.70	n/m	n/m	n/m	n/m	*n/m*	71.8	34.9	25.0	21.6	21.8	n/m	n/m
44	5/19/2021	01:15	*4.26*	130.1	n/m	4.02	5.05	1.97	3.03	*76*	70.8	59.1	50.1	21.6	21.7	22.3	n/m
44	5/19/2021	01:44	*4.21*	129.8	n/m	24.22	6.08	1.93	4.06	*75*	69.5	36.8	26.4	21.6	21.8	21.8	n/m
45	5/19/2021	02:00	*4.26*	130.4	4.54	n/m	4.96	1.97	3.02	*76*	71.4	55.9	46.9	21.6	21.6	22.0	n/m
45	5/19/2021	02:39	*4.23*	130.1	18.89	n/m	5.68	1.69	4.00	*78*	70.3	41.8	32.9	21.5	21.8	21.6	n/m
46	5/19/2021	03:00	*4.27*	130.2	n/m	5.23	5.05	1.94	2.99	*78*	72.4	58.5	49.9	21.5	21.5	22.5	n/m
46	5/19/2021	03:25	*4.26*	129.3	n/m	25.72	6.03	1.97	4.10	*78*	70.8	37.9	28.1	21.5	21.6	21.8	n/m
47	5/19/2021	04:46	*4.25*	130.3	3.15	n/m	4.45	1.50	2.88	*78*	72.1	59.2	49.6	21.5	21.3	22.2	n/m
47	5/19/2021	05:00	*4.23*	131.2	10.86	n/m	5.69	1.92	3.55	*78*	71.5	49.1	39.1	21.5	21.5	21.8	n/m
47	5/19/2021	05:13	*4.28*	129.7	23.68	n/m	6.02	1.84	4.01	*78*	71.2	31.4	27.3	21.5	21.5	21.5	n/m
48	5/19/2021	05:30	*4.26*	130.5	n/m	4.46	5.17	2.00	3.12	*78*	71.4	57.6	48.9	21.5	21.4	22.3	21.8
48	5/19/2021	05:54	*4.25*	128.9	n/m	23.59	6.16	1.93	4.16	*78*	70.4	37.8	27.9	21.5	21.3	21.0	n/m
49	5/19/2021	06:05	*4.26*	129.8	2.31	n/m	5.23	1.92	3.20	*78*	69.9	56.8	48.7	21.5	21.3	22.2	n/m
49	5/19/2021	06:29	*4.27*	130.7	14.48	n/m	5.94	1.90	3.92	*78*	71.7	46.0	36.7	21.5	21.2	21.6	n/m
50	5/19/2021	07:00	*4.27*	129.9	n/m	6.95	5.13	1.92	3.21	*78*	71.2	55.4	47.1	21.4	21.4	22.0	n/m
50	5/19/2021	07:18	*4.26*	129.3	n/m	24.29	6.08	1.96	4.14	*78*	71.8	38.4	28.3	21.4	21.6	21.3	n/m
51	5/19/2021	07:31	*4.28*	130.5	2.34	n/m	5.08	1.87	3.11	*78*	71.1	58.6	49.7	21.4	21.5	21.8	n/m
51	5/19/2021	08:00	*4.24*	129.0	22.90	n/m	6.12	1.92	4.09	*78*	71.4	37.7	27.3	21.4	21.5	21.2	n/m
52	5/19/2021	08:30	*4.27*	130.0	n/m	10.50	5.85	1.95	3.73	*80*	71.5	52.0	43.0	21.4	21.0	21.2	n/m
53	5/19/2021	09:30	*4.27*	130.0	13.50	n/m	5.75	1.90	3.85	*80*	71.8	46.3	37.3	21.4	21.8	21.5	n/m
54	5/19/2021	10:01	*4.27*	130.0	n/m	2.35	5.25	2.00	3.18	*80*	71.5	61.0	51.5	21.3	21.0	21.2	n/m
54	5/19/2021	10:28	*4.27*	130.0	n/m	19.37	6.23	1.92	4.14	*80*	71.8	43.5	33.3	21.3	21.5	21.3	n/m
55	5/19/2021	11:00	*4.28*	130.1	9.22	n/m	5.39	1.92	3.48	*80*	71.9	50.9	41.5	21.3	21.5	21.9	n/m
56	5/19/2021	11:30	*4.27*	130.0	n/m	4.48	5.14	1.93	3.09	*80*	72.2	58.4	49.3	21.3	21.6	21.6	22.0
57	5/19/2021	12:30	*4.28*	130.0	14.25	n/m	6.05	1.93	4.02	*80*	71.8	46.8	36.5	21.3	21.4	21.2	n/m
58	5/19/2021	13:00	*4.28*	130.0	n/m	5.57	4.89	1.85	3.04	*80*	71.6	57.5	50.2	21.4	21.6	22.3	n/m
59	5/19/2021	13:33	*4.28*	130.0	2.58	n/m	5.07	1.80	3.12	*80*	71.0	58.3	49.5	21.5	21.0	22.3	n/m
59	5/19/2021	14:00	*4.28*	129.0	20.50	n/m	5.95	1.86	4.02	*80*	72.3	40.6	30.8	21.5	21.2	22.0	n/m
60	5/19/2021	14:30	*4.28*	130.0	n/m	9.55	5.65	2.00	3.83	*80*	72.2	54.1	44.8	21.5	21.2	22.5	n/m
61	5/19/2021	15:30	*4.29*	130.0	11.78	n/m	5.38	1.91	3.85	*80*	67.0	47.8	39.3	21.5	22.0	22.5	n/m
62	5/19/2021	16:00	*4.29*	130.0	n/m	4.36	5.05	1.89	3.03	*80*	71.5	59.5	50.5	21.6	21.6	22.8	n/m

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DEF Segment	Date	Time	*[FM-01]*	FM-02	DP-01	DP-02	DP-03	DP-04	DP-05	*[P-01]*	P-02	P-03	P-05	T-01	T-02	T-03	T-REF
			(gpm)	(mL min^{-1})	(psid)	(psid)	(psid)	(psid)	(psid)	(psig)	(psig)	(psig)	(psig)	(°C)	(°C)	(°C)	(°C)
63	5/19/2021	16:36	*4.29*	130.0	2.02	n/m	5.16	1.83	3.13	*80*	71.5	59.6	50.2	21.6	21.5	22.3	n/m
63	5/19/2021	17:00	*4.29*	130.0	13.70	n/m	5.95	1.93	3.99	*80*	72.3	47.5	37.0	21.6	21.1	21.8	n/m
64	5/19/2021	17:30	*4.30*	130.0	n/m	7.42	5.28	1.95	3.36	*80*	72.3	56.0	46.3	21.6	20.7	22.7	n/m
65	5/19/2021	18:00	*4.30*	130.0	1.88	n/m	5.12	1.85	3.10	*80*	71.7	54.5	50.5	21.6	20.7	22.3	n/m
65	5/19/2021	18:30	*4.30*	129.5	17.26	n/m	6.07	1.96	4.13	*80*	71.3	43.4	33.6	21.5	21.0	21.9	n/m
66	5/19/2021	19:00	*4.29*	130.0	n/m	9.30	5.50	1.95	3.66	*80*	71.5	54.1	45.0	21.6	20.7	22.5	n/m
67	5/19/2021	19:30	*4.30*	130.0	2.77	n/m	5.03	1.90	3.00	*80*	71.4	57.8	49.3	21.6	21.6	22.0	n/m
67	5/19/2021	19:58	*4.30*	129.4	20.55	n/m	6.10	1.93	4.14	*80*	72.1	40.5	30.3	21.6	22.3	21.7	n/m
68	5/19/2021	20:30	*4.29*	130.1	n/m	11.06	5.89	1.94	3.94	*78*	72.3	52.2	43.2	21.5	21.8	21.5	21.6
69	5/19/2021	21:00	*4.30*	130.0	4.30	n/m	5.04	1.91	3.11	*78*	71.9	57.4	48.6	21.6	21.5	21.4	n/m
69	5/19/2021	21:20	*4.30*	129.2	14.14	n/m	5.98	1.96	4.08	*78*	72.4	47.1	37.1	21.6	21.5	20.8	n/m
69	5/19/2021	21:30	*4.29*	129.3	23.11	n/m	6.08	1.95	4.13	*78*	71.8	35.5	25.8	21.7	21.2	20.9	n/m
70	5/19/2021	21:45	*4.30*	130.4	n/m	4.13	5.14	1.95	3.14	*79*	72.4	59.2	50.5	21.7	21.4	21.2	n/m
70	5/19/2021	22:00	*4.28*	128.8	n/m	14.41	5.82	1.93	3.88	*78*	71.9	49.2	39.8	21.8	21.3	21.3	n/m
70	5/19/2021	22:10	*4.30*	129.1	n/m	25.68	6.17	1.95	4.18	*79*	72.1	38.0	27.9	21.8	21.7	20.4	n/m
71	5/19/2021	22:30	*4.30*	130.1	5.73	n/m	5.07	1.95	3.14	*79*	75.5	55.9	47.0	21.8	21.4	21.5	n/m
71	5/19/2021	22:45	*4.30*	129.9	16.55	n/m	6.03	1.93	4.09	*79*	71.9	44.4	34.7	21.9	21.3	20.3	n/m
72	5/19/2021	23:10	*4.30*	129.8	n/m	4.11	5.21	1.93	3.16	*79*	71.9	59.4	50.2	21.9	21.5	21.1	n/m
72	5/19/2021	23:25	*4.30*	129.4	n/m	13.90	6.03	1.89	4.10	*79*	72.3	49.8	40.0	21.9	21.6	20.8	n/m
72	5/19/2021	23:36	*4.30*	129.9	n/m	25.01	6.15	1.97	4.18	*79*	72.6	38.4	28.4	21.9	21.2	20.6	n/m
73	5/19/2021	23:55	*4.30*	129.5	4.70	n/m	5.13	1.96	3.14	*79*	71.9	56.3	48.1	21.9	21.4	21.0	n/m
73	5/20/2021	00:11	*4.30*	129.5	15.55	n/m	5.93	1.91	4.07	*79*	72.3	45.6	35.8	21.9	21.8	20.2	n/m
74	5/20/2021	00:32	*4.31*	130.0	n/m	3.44	5.16	1.84	3.18	*79*	72.4	61.1	51.9	21.9	21.6	20.9	n/m
74	5/20/2021	00:42	*4.30*	130.3	n/m	7.56	5.34	1.93	3.41	*79*	72.5	56.1	46.8	21.9	21.5	21.5	n/m
74	5/20/2021	00:54	*4.30*	130.3	n/m	16.40	6.08	1.93	4.09	*79*	72.6	47.2	37.1	21.9	21.5	20.0	n/m
75	5/20/2021	01:22	*4.31*	130.1	4.13	n/m	5.05	1.90	3.10	*79*	71.3	57.5	48.7	22.0	21.1	21.2	n/m
75	5/20/2021	01:35	*4.31*	131.2	10.55	n/m	6.04	1.91	4.02	*79*	72.3	50.8	40.9	22.0	21.0	20.1	n/m
75	5/20/2021	01:50	*4.30*	129.5	24.55	n/m	6.10	1.93	4.14	*79*	72.7	37.1	27.2	22.0	21.0	20.7	n/m
76	5/20/2021	02:06	*4.32*	130.0	n/m	3.71	5.19	2.00	3.17	*80*	72.2	60.1	51.3	22.0	21.7	21.0	n/m
76	5/20/2021	02:35	*4.31*	130.0	n/m	23.17	6.21	1.94	4.19	*80*	72.2	40.3	30.2	22.0	21.7	20.1	n/m
77	5/20/2021	03:00	*4.30*	129.9	8.39	n/m	5.42	1.97	3.45	*78*	72.1	52.8	44.2	22.0	21.2	21.5	n/m
77	5/20/2021	03:16	*4.31*	128.9	22.68	n/m	6.16	1.97	4.18	*79*	72.1	38.4	28.2	22.0	21.6	20.4	n/m
78	5/20/2021	03:30	*4.30*	129.8	n/m	2.61	5.17	1.95	3.15	*79*	72.2	61.3	52.5	22.0	22.0	21.2	n/m
78	5/20/2021	04:01	*4.31*	129.5	n/m	22.18	6.17	1.96	4.16	*79*	72.2	41.4	31.2	22.0	21.9	20.8	n/m
79	5/20/2021	04:30	*4.30*	129.6	11.21	n/m	5.82	1.94	3.81	*79*	71.9	50.3	40.8	22.0	21.6	21.9	n/m

Values shown in *italic text* are associated with uncalibrated instruments and are For Information Only (FIO).

DEF Segment	Date	Time	*[FM-01]* (gpm)	FM-02 (mL min^{-1})	DP-01 (psid)	DP-02 (psid)	DP-03 (psid)	DP-04 (psid)	DP-05 (psid)	*[P-01]* (psig)	P-02 (psig)	P-03 (psig)	P-05 (psig)	T-01 (°C)	T-02 (°C)	T-03 (°C)	T-REF (°C)
79	5/20/2021	04:42	*4.30*	129.7	21.69	n/m	6.09	1.93	4.12	*79*	72.1	40.0	30.0	22.1	21.8	20.5	n/m
80	5/20/2021	05:00	*4.31*	129.7	n/m	4.75	5.10	1.92	3.14	*79*	72.1	59.0	49.9	22.1	22.0	21.4	21.3
80	5/20/2021	05:23	*4.30*	129.6	n/m	22.32	6.15	1.96	4.12	*79*	72.6	41.5	31.4	22.1	22.0	20.5	n/m
81	5/20/2021	05:36	*4.30*	130.1	2.51	n/m	5.13	1.87	3.14	*79*	72.3	59.2	50.4	22.1	21.9	21.3	n/m
81	5/20/2021	05:57	*4.30*	129.9	14.61	n/m	5.97	1.91	4.05	*79*	72.1	47.3	37.5	22.1	22.0	20.6	n/m
81	5/20/2021	06:05	*4.30*	128.8	22.99	n/m	6.18	1.95	4.17	*79*	72.4	38.5	28.4	22.1	22.1	20.7	n/m
82	5/20/2021	06:30	*4.31*	130.0	n/m	9.46	5.44	1.91	3.48	*79*	71.9	54.1	45.3	22.1	21.9	21.7	n/m
82	5/20/2021	06:46	*4.31*	129.6	n/m	24.01	6.09	1.94	4.13	*79*	72.3	39.6	29.7	22.1	21.9	20.5	n/m
83	5/20/2021	07:00	*4.31*	129.9	2.71	n/m	5.08	1.92	3.10	*79*	72.2	59.2	50.2	22.1	21.9	21.3	n/m
83	5/20/2021	07:27	*4.31*	129.1	21.66	n/m	6.10	1.94	4.13	*79*	72.2	39.5	29.5	22.1	21.8	20.6	n/m
84	5/20/2021	08:00	*4.31*	129.6	n/m	14.30	6.00	1.94	4.06	*79*	72.5	50.6	41.2	22.2	21.6	20.8	n/m
84	5/20/2021	08:11	*4.31*	129.5	n/m	24.60	6.12	1.97	4.18	*79*	72.4	39.8	29.7	22.1	21.8	20.8	n/m
85	5/20/2021	08:30	*4.30*	130.0	4.50	n/m	5.10	1.95	3.12	*79*	72.2	57.1	48.2	22.1	21.8	21.3	n/m
86	5/20/2021	09:07	*4.30*	130.0	n/m	1.80	5.30	1.92	3.25	*79*	72.3	62.4	53.3	22.1	21.7	21.0	n/m
86	5/20/2021	09:30	*4.30*	130.0	n/m	12.80	6.10	1.97	4.20	*79*	72.2	50.4	40.9	22.1	21.9	20.1	n/m
86	5/20/2021	09:42	*4.31*	129.5	n/m	23.50	6.10	1.90	4.20	*79*	72.3	40.2	30.5	22.1	22.0	20.9	n/m
87	5/20/2021	10:00	*4.31*	130.0	5.30	n/m	5.10	1.90	3.10	*79*	71.9	56.2	47.3	22.1	21.9	21.2	20.6
87	5/20/2021	10:22	*4.31*	129.5	24.50	n/m	6.20	1.95	4.15	*79*	72.3	36.4	26.4	22.0	21.8	20.3	n/m
88	5/20/2021	11:05	*4.30*	130.0	n/m	23.50	6.25	1.98	4.23	*79*	72.3	40.1	29.9	22.0	21.8	20.6	n/m
89	5/20/2021	11:30	*4.31*	130.0	10.35	n/m	5.47	1.93	3.49	*79*	72.2	50.5	41.5	22.1	21.7	21.8	n/m
89	5/20/2021	11:42	*4.31*	130.0	22.20	n/m	6.00	1.95	4.10	*79*	72.2	38.4	28.7	22.1	22.0	20.2	n/m
90	5/20/2021	12:00	*4.31*	130.0	n/m	4.15	5.15	1.98	3.13	*79*	71.5	59.2	50.6	22.1	21.9	21.4	n/m
90	5/20/2021	12:25	*4.31*	129.7	n/m	24.10	6.10	1.96	4.14	*79*	71.7	40.5	30.5	22.1	22.0	20.8	n/m
91	5/20/2021	13:00	*4.31*	130.0	14.70	n/m	6.03	1.98	4.08	*79*	71.9	43.5	35.2	22.1	21.9	20.9	n/m
91	5/20/2021	13:09	*4.31*	130.0	23.80	n/m	6.09	1.97	4.15	*79*	72.2	38.7	28.6	22.1	22.0	20.9	n/m
92	5/20/2021	13:30	*4.31*	130.0	n/m	6.80	5.10	1.92	3.25	*79*	72.2	56.5	48.8	22.1	21.9	21.8	n/m
92	5/20/2021	13:50	*4.31*	130.0	n/m	24.70	6.14	1.97	4.15	*79*	72.0	39.4	29.6	22.1	21.9	21.0	n/m

Table B.6. Initial Differential Pressure Data for DEFs from Test HS2

DEF Segment	Date	Start Time	ΔP (psid) at t = 2 min	ΔP (psid) at t = 4 min	ΔP (psid) at t = 6 min	ΔP (psid) at t = 8 min	ΔP (psid) at t = 10 min
1	5/17/2021	08:48	0.39	0.42	0.86	1.10	1.50
2	5/17/2021	09:49	0.55	0.76	1.04	1.43	1.77
3	5/17/2021	10:58	n/m	n/m	n/m	n/m	n/m
4	5/17/2021	11:38	0.50	1.11	1.35	2.23	2.49
5	5/17/2021	12:24	0.42	0.52	0.95	1.55	2.03
6	5/17/2021	13:15	0.55	1.17	1.85	2.29	3.20
7	5/17/2021	14:07	0.40	0.54	1.01	1.35	1.90
8	5/17/2021	14:49	0.55	1.25	2.00	2.75	3.00
9	5/17/2021	15:26	0.50	0.98	1.55	1.95	2.75
10	5/17/2021	16:17	0.45	1.15	1.83	2.30	2.85
11	5/17/2021	17:05	0.50	0.85	1.23	1.62	2.67
12	5/17/2021	17:47	0.44	1.13	1.95	2.10	2.58
13	5/17/2021	18:28	0.48	1.03	1.45	1.91	2.65
14	5/17/2021	19:04	0.55	1.29	1.85	2.38	2.96
15	5/17/2021	19:44	0.41	0.66	1.15	1.65	2.17
16	5/17/2021	20:33	0.61	1.43	2.07	2.36	2.93
17	5/17/2021	23:27	0.34	0.92	1.20	1.63	2.40
18	5/18/2021	00:11	1.68	2.11	2.55	3.46	4.23
19	5/18/2021	00:51	0.47	0.96	1.41	2.10	0.39
20	5/18/2021	01:38	0.61	1.60	2.22	2.84	3.61
21	5/18/2021	02:26	0.46	1.12	1.63	2.13	0.29
22	5/18/2021	04:33	0.39	0.85	1.22	1.68	2.23
23	5/18/2021	05:19	0.35	0.79	1.16	1.62	2.16
24	5/18/2021	07:14	0.41	0.83	1.37	1.88	2.38
25	5/18/2021	08:08	0.35	0.92	1.39	1.87	0.24
26	5/18/2021	09:00	0.39	0.87	1.27	1.69	2.23
27	5/18/2021	09:43	0.49	1.16	1.73	2.20	2.84
28	5/18/2021	10:23	0.36	0.97	1.45	1.97	2.29
29	5/18/2021	11:15	0.51	1.19	2.01	2.61	3.07
30	5/18/2021	11:55	0.39	0.92	1.51	1.95	2.68
31	5/18/2021	12:40	0.56	1.40	1.79	2.31	2.99

DEF Segment	Date	Start Time	ΔP (psid) at t = 2 min	ΔP (psid) at t = 4 min	ΔP (psid) at t = 6 min	ΔP (psid) at t = 8 min	ΔP (psid) at t = 10 min
32	5/18/2021	13:37	0.46	1.07	n/m	2.00	n/m
33	5/18/2021	15:10	0.40	0.93	1.50	1.95	2.51
34	5/18/2021	15:50	0.45	1.15	1.71	2.33	2.95
35	5/18/2021	16:29	0.33	0.77	1.39	1.65	2.23
36	5/18/2021	17:11	0.54	1.54	n/m	n/m	3.00
37	5/18/2021	17:55	0.41	0.86	1.58	1.85	2.39
38	5/18/2021	18:37	0.42	0.96	1.49	2.01	2.61
39	5/18/2021	20:48	0.43	1.08	1.57	2.16	2.74
40	5/18/2021	21:34	0.45	1.01	n/m	n/m	n/m
41	5/18/2021	22:28	0.51	1.09	1.40	2.03	2.59
42	5/18/2021	23:13	0.41	1.11	1.67	2.00	2.42
43	5/19/2021	00:06	0.46	1.07	1.52	2.11	2.61
44	5/19/2021	01:03	0.70	1.40	1.96	2.44	3.53
45	5/19/2021	01:45	0.52	1.11	1.57	1.97	2.70
46	5/19/2021	02:43	0.48	1.21	1.62	2.15	2.63
47	5/19/2021	03:27	0.37	0.89	1.38	0.22	2.01
48	5/19/2021	05:15	0.48	1.16	1.62	2.16	2.63
49	5/19/2021	05:55	0.29	0.57	1.17	1.61	2.03
50	5/19/2021	06:39	0.39	1.01	1.53	2.04	2.56
51	5/19/2021	07:21	0.37	0.78	1.21	1.66	2.13
52	5/19/2021	08:04	0.38	0.93	1.36	1.79	2.30
53	5/19/2021	09:00	0.40	1.10	1.70	4.99	3.99
54	5/19/2021	09:50	0.45	0.90	1.41	1.83	2.19
55	5/19/2021	10:38	0.49	1.17	1.74	n/m	2.97
56	5/19/2021	11:17	0.73	1.26	1.85	2.46	3.05
57	5/19/2021	11:57	0.43	0.90	1.37	1.81	2.28
58	5/19/2021	12:44	0.48	1.16	1.44	1.72	n/m
59	5/19/2021	13:23	0.44	1.00	1.47	2.10	2.51
60	5/19/2021	14:03	0.33	0.75	1.18	1.60	2.01
61	5/19/2021	14:47	0.26	1.07	1.57	2.00	2.50
62	5/19/2021	15:43	0.42	0.95	1.45	1.75	2.15
63	5/19/2021	16:26	0.40	1.17	1.17	1.56	2.01
64	5/19/2021	17:08	0.43	1.00	1.54	1.92	2.40

DEF Segment	Date	Start Time	ΔP (psid) at t = 2 min	ΔP (psid) at t = 4 min	ΔP (psid) at t = 6 min	ΔP (psid) at t = 8 min	ΔP (psid) at t = 10 min
65	5/19/2021	17:50	0.49	0.72	1.08	1.47	1.83
66	5/19/2021	18:33	0.41	0.94	1.37	1.74	2.20
67	5/19/2021	19:16	0.40	0.78	1.10	1.43	1.86
68	5/19/2021	20:01	0.41	0.94	1.35	1.75	2.18
69	5/19/2021	20:47	0.48	1.44	1.68	2.00	2.50
70	5/19/2021	21:32	0.75	1.60	2.22	2.56	2.99
71	5/19/2021	22:12	0.53	1.09	1.50	2.58	3.34
72	5/19/2021	22:55	0.64	1.10	1.55	2.02	2.54
73	5/19/2021	23:39	0.49	1.24	1.70	2.19	2.71
74	5/20/2021	00:20	0.60	1.32	1.80	2.35	2.91
75	5/20/2021	01:04	0.40	0.85	1.26	1.63	1.99
76	5/20/2021	01:54	0.57	1.38	1.84	2.33	2.90
77	5/20/2021	02:37	0.44	1.02	1.45	1.84	2.41
78	5/20/2021	03:19	0.38	1.03	1.42	1.87	2.27
79	5/20/2021	04:04	0.37	0.77	1.22	1.65	2.12
80	5/20/2021	04:46	0.42	1.20	1.70	2.24	2.82
81	5/20/2021	05:25	0.42	0.79	1.31	1.77	2.22
82	5/20/2021	06:08	0.43	1.25	1.77	2.31	2.88
83	5/20/2021	06:48	0.38	0.83	1.20	1.61	2.09
84	5/20/2021	07:30	0.24	0.77	1.12	1.49	1.99
85	5/20/2021	08:14	0.40	0.89	1.32	1.72	2.27
86	5/20/2021	08:57	0.31	0.70	1.20	1.53	1.94
87	5/20/2021	09:44	0.40	0.84	1.30	1.81	2.34
88	5/20/2021	10:25	0.40	1.10	1.58	2.03	2.55
89	5/20/2021	11:07	0.50	1.17	1.73	2.30	2.96
90	5/20/2021	11:45	0.40	0.98	1.41	1.80	2.33
91	5/20/2021	12:28	0.45	0.97	1.46	1.83	2.30
92	5/20/2021	13:11	0.40	0.97	1.44	1.72	2.14
End of Test	5/20/2021	13:53	n/m	n/m	n/m	n/m	n/m

B.4 Test HS3 Tabulated Data

Table B.7. Periodically Recorded Data from Test HS3

Values shown in *italic text* are associated with uncalibrated instruments and are For Information Only (FIO).

DEF Segment	Date	Time	*[FM-01]* (gpm)	FM-02 (mL min^{-1})	DP-01 (psid)	DP-02 (psid)	DP-03 (psid)	DP-04 (psid)	DP-05 (psid)	*[P-01]* (psig)	P-02 (psig)	P-03 (psig)	P-05 (psig)	T-01 (°C)	T-02 (°C)	T-03 (°C)	T-REF (°C)
1	6/7/2021	10:21	*4.04*	130.0	0.34	n/m	2.25	0.83	1.35	*70*	63.0	55.1	52.3	22.2	22.5	22.0	n/m
1	6/7/2021	10:43	*4.05*	130.0	2.31	n/m	5.00	2.10	2.90	*69*	62.0	49.5	41.2	22.2	22.3	22.2	n/m
2	6/7/2021	11:05	*4.06*	n/m	n/m	0.64	1.85	0.63	1.15	*70*	62.9	54.1	45.9	22.2	22.5	22.2	n/m
2	6/7/2021	11:48	*4.05*	130.0	n/m	1.74	4.90	2.00	2.70	*70*	62.0	52.3	43.5	22.2	22.6	22.7	n/m
2	6/7/2021	12:01	*4.05*	130.0	n/m	2.90	5.50	2.10	3.40	*70*	63.0	52.0	43.2	22.2	22.6	23.2	23.0
2	6/7/2021	12:30	*4.05*	129.9	n/m	11.00	5.90	2.10	3.80	*70*	63.5	44.8	34.9	22.3	22.5	23.0	n/m
2	6/7/2021	13:00	*4.05*	129.5	n/m	17.30	5.90	2.10	3.80	*70*	62.9	37.9	27.9	22.3	22.6	22.8	n/m
3	6/7/2021	13:30	*4.05*	130.0	2.40	n/m	5.30	2.00	3.30	*69*	61.9	49.0	40.0	22.3	22.5	23.4	n/m
3	6/7/2021	14:00	*4.05*	130.0	7.60	n/m	5.90	2.00	3.80	*70*	63.0	45.0	35.3	22.3	22.4	22.9	n/m
3	6/7/2021	14:30	*4.05*	130.0	17.00	n/m	6.00	2.10	3.90	*70*	62.5	34.8	24.6	22.3	22.6	22.9	n/m
4	6/7/2021	15:30	*4.05*	130.0	n/m	3.61	5.71	1.94	3.70	*70*	63.0	51.3	41.6	22.3	22.3	22.2	n/m
4	6/7/2021	16:00	*4.05*	130.0	n/m	9.55	5.81	2.05	3.78	*70*	62.8	44.8	34.9	22.3	22.0	22.8	n/m
4	6/7/2021	16:30	*4.05*	130.0	n/m	18.80	5.88	2.05	3.83	*70*	62.9	35.9	26.0	22.3	22.7	23.0	n/m
5	6/7/2021	17:00	*4.05*	130.0	1.29	n/m	5.04	2.00	2.93	*70*	62.2	50.4	41.6	22.3	23.0	23.1	n/m
5	6/7/2021	17:30	*4.05*	130.0	4.97	n/m	5.81	2.00	3.76	*70*	62.3	47.0	37.4	22.4	22.5	22.7	n/m
5	6/7/2021	18:00	*4.05*	130.0	12.01	n/m	5.82	2.00	3.77	*70*	62.5	39.8	30.0	22.4	22.6	23.2	n/m
5	6/7/2021	18:30	*4.05*	130.0	23.00	n/m	5.89	2.02	3.81	*70*	62.0	27.5	17.9	22.4	22.2	23.2	n/m
6	6/7/2021	19:00	*4.05*	130.0	n/m	2.44	4.83	1.90	2.85	*70*	62.9	52.3	43.8	22.4	22.8	23.7	n/m
6	6/7/2021	19:30	*4.05*	130.0	n/m	8.03	5.80	1.96	3.79	*70*	62.5	46.3	36.5	22.5	22.8	23.2	24.0
6	6/7/2021	20:00	*4.05*	130.0	n/m	17.10	5.90	2.01	3.81	*70*	61.3	36.0	26.3	22.4	22.8	23.2	n/m
6	6/7/2021	20:22	*4.05*	126.4	n/m	24.80	5.66	1.92	3.68	*69*	61.2	29.0	19.7	22.5	22.8	23.0	n/m
7	6/7/2021	21:00	*4.05*	129.9	5.34	n/m	5.83	1.99	3.76	*69*	58.7	43.3	33.7	22.5	22.8	22.6	n/m
7	6/7/2021	21:30	*4.05*	129.4	13.34	n/m	5.84	1.99	3.81	*69*	61.1	36.5	26.8	22.5	22.6	23.1	n/m
7	6/7/2021	22:00	*4.05*	122.0	22.50	n/m	5.47	1.84	3.56	*69*	63.2	29.8	20.9	22.5	22.5	23.2	n/m
8	6/7/2021	22:31	*4.04*	130.2	n/m	3.33	4.97	1.90	2.92	*69*	62.9	51.9	43.5	22.5	23.0	23.6	n/m
8	6/7/2021	23:00	*4.05*	129.9	n/m	6.89	5.93	1.98	3.82	*69*	62.9	47.9	38.2	22.5	22.9	23.1	23.3
8	6/7/2021	23:30	*4.04*	129.5	n/m	15.49	5.98	2.02	3.92	*69*	62.5	39.0	28.9	22.5	22.8	22.8	n/m
8	6/8/2021	00:00	*4.04*	119.1	n/m	22.32	5.44	1.84	3.58	*69*	63.5	33.3	24.5	22.5	22.5	22.9	n/m
9	6/8/2021	00:30	*4.05*	129.2	2.42	n/m	4.98	1.94	3.05	*69*	63.1	50.2	41.4	22.4	22.6	23.3	n/m
9	6/8/2021	01:00	*4.04*	129.8	8.61	n/m	6.01	2.02	3.92	*69*	62.5	43.4	33.5	22.4	22.6	22.8	n/m

Values shown in *italic text* are associated with uncalibrated instruments and are For Information Only (FIO).

DEF Segment	Date	Time	*[FM-01]* (gpm)	FM-02 (mL min^{-1})	DP-01 (psid)	DP-02 (psid)	DP-03 (psid)	DP-04 (psid)	DP-05 (psid)	*[P-01]* (psig)	P-02 (psig)	P-03 (psig)	P-05 (psig)	T-01 (°C)	T-02 (°C)	T-03 (°C)	T-REF (°C)
9	6/8/2021	01:30	*4.05*	120.7	17.19	n/m	5.58	1.89	3.66	*69*	63.3	36.1	26.7	22.4	22.6	22.9	n/m
10	6/8/2021	02:01	*4.04*	130.9	n/m	2.38	5.04	2.03	2.98	*69*	62.6	52.2	43.2	22.4	22.5	23.0	n/m
10	6/8/2021	02:30	*4.04*	130.0	n/m	7.20	6.17	2.12	4.02	*68*	62.3	46.7	36.4	22.4	22.3	22.5	n/m
10	6/8/2021	03:00	*4.04*	129.9	n/m	16.65	6.17	2.06	4.08	*68*	60.4	36.3	25.0	22.3	22.3	22.5	n/m
11	6/8/2021	03:32	*4.04*	129.6	1.13	n/m	5.20	2.08	3.06	*68*	62.6	50.8	41.8	22.3	22.5	22.2	n/m
11	6/8/2021	04:00	*4.04*	129.9	4.03	n/m	6.04	2.05	3.97	*68*	62.8	48.4	38.6	22.3	22.6	21.6	n/m
11	6/8/2021	04:30	*4.04*	130.1	10.45	n/m	6.15	2.06	4.05	*68*	62.6	41.9	31.7	22.3	22.5	22.0	n/m
11	6/8/2021	05:00	*4.04*	130.2	19.31	n/m	6.13	2.07	4.04	*68*	62.6	32.9	22.6	22.3	22.4	21.9	21.8
12	6/8/2021	05:30	*4.04*	130.1	n/m	1.74	5.05	2.08	3.02	*68*	60.4	50.8	41.6	22.3	22.4	21.9	n/m
12	6/8/2021	06:00	*4.04*	129.9	n/m	5.81	6.22	2.11	4.10	*68*	62.3	48.4	38.1	22.3	22.3	21.6	n/m
12	6/8/2021	06:31	*4.04*	130.1	n/m	13.49	6.22	2.09	4.11	*68*	61.9	40.3	30.0	22.2	22.3	21.8	n/m
12	6/8/2021	06:55	*4.04*	129.8	n/m	21.64	6.21	2.09	4.11	*68*	62.0	32.3	21.9	22.2	22.2	21.8	n/m
13	6/8/2021	07:30	*4.04*	130.1	2.89	n/m	5.96	2.08	3.81	*68*	62.3	48.9	39.4	22.2	22.0	22.3	n/m
13	6/8/2021	08:00	*4.04*	130.0	7.90	n/m	6.15	2.07	4.07	*68*	62.5	44.2	34.1	22.2	22.0	21.5	n/m
13	6/8/2021	08:30	*4.05*	130.0	15.70	n/m	6.10	2.05	4.07	*69*	62.8	36.5	26.4	22.1	21.9	21.6	n/m
14	6/8/2021	09:05	*4.05*	130.0	n/m	2.01	5.10	2.00	3.01	*69*	62.3	52.4	43.4	22.1	21.9	21.6	n/m
14	6/8/2021	09:32	*4.05*	130.0	n/m	5.52	6.15	2.05	4.05	*69*	62.6	48.9	39.0	22.1	22.1	21.2	21.7
14	6/8/2021	10:01	*4.05*	130.0	n/m	12.50	6.20	2.08	4.10	*69*	62.2	41.5	31.3	22.1	22.3	21.8	n/m
15	6/8/2021	10:44	*4.05*	130.0	1.50	n/m	5.10	2.05	2.99	*69*	62.1	50.4	41.4	22.1	22.2	21.9	n/m
15	6/8/2021	11:30	*4.04*	130.0	8.75	n/m	6.19	2.07	4.10	*69*	60.2	41.0	30.7	22.1	22.2	22.2	n/m
15	6/8/2021	12:00	*4.04*	130.0	17.40	n/m	6.17	2.07	4.08	*69*	62.2	34.5	24.4	22.1	22.4	22.5	n/m
16	6/8/2021	12:30	*4.04*	130.0	n/m	1.65	5.15	2.02	3.01	*69*	62.2	52.5	43.4	22.2	22.5	22.7	n/m
16	6/8/2021	13:00	*4.04*	130.0	n/m	5.30	6.05	2.03	3.98	*69*	62.5	49.0	39.1	22.2	22.5	22.5	n/m
16	6/8/2021	13:30	*4.04*	130.0	n/m	11.80	6.05	2.02	3.99	*69*	62.5	42.5	32.6	22.2	22.3	23.0	n/m
16	6/8/2021	14:00	*4.05*	130.0	n/m	19.80	6.05	2.01	3.98	*69*	62.3	34.3	24.4	22.2	22.5	23.1	n/m
17	6/8/2021	14:30	*4.04*	130.0	1.83	n/m	5.06	1.94	3.04	*69*	62.3	50.1	41.8	22.3	22.5	23.5	n/m
17	6/8/2021	15:00	*4.04*	130.0	5.86	n/m	5.92	1.95	3.90	*69*	62.4	46.4	36.6	22.3	22.6	23.3	n/m
17	6/8/2021	15:30	*4.04*	130.0	12.53	n/m	5.93	2.00	3.91	*69*	62.2	39.5	29.7	22.4	22.6	23.4	n/m
17	6/8/2021	16:00	*4.04*	129.9	21.59	n/m	6.00	2.02	3.95	*68*	62.5	30.9	21.2	22.4	22.3	23.6	n/m
18	6/8/2021	16:30	*4.04*	130.0	n/m	2.63	5.40	1.94	3.38	*69*	62.5	52.0	43.2	22.4	22.5	24.3	n/m
18	6/8/2021	17:00	*4.04*	130.0	n/m	7.40	5.80	1.96	3.80	*69*	62.5	47.1	37.6	22.5	22.8	23.8	n/m
18	6/8/2021	17:30	*4.04*	130.0	n/m	15.83	5.85	1.91	3.82	*68*	62.3	38.4	28.9	22.5	22.9	24.0	n/m
19	6/8/2021	18:02	*4.04*	130.0	1.02	n/m	4.91	1.88	2.94	*66*	62.0	51.0	42.6	22.5	22.9	24.0	n/m
19	6/8/2021	18:30	*4.04*	130.0	3.42	n/m	5.82	1.90	3.79	*66*	62.1	48.5	39.2	22.5	22.8	23.7	n/m
19	6/8/2021	19:00	*4.04*	130.0	8.21	n/m	5.75	1.92	3.80	*66*	62.0	43.7	34.3	22.6	22.9	24.1	n/m

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DEF Segment	Date	Time	*[FM-01]* (gpm)	FM-02 (mL min^{-1})	DP-01 (psid)	DP-02 (psid)	DP-03 (psid)	DP-04 (psid)	DP-05 (psid)	*[P-01]* (psig)	P-02 (psig)	P-03 (psig)	P-05 (psig)	T-01 (°C)	T-02 (°C)	T-03 (°C)	T-REF (°C)
19	6/8/2021	19:30	*4.04*	130.0	15.18	n/m	5.82	1.94	3.84	*66*	62.3	36.8	27.5	22.6	23.0	24.0	n/m
20	6/8/2021	20:30	*4.04*	130.1	n/m	3.55	5.84	1.92	3.89	*68*	62.2	50.9	41.5	22.6	23.0	23.6	n/m
20	6/8/2021	21:00	*4.01*	130.0	n/m	8.48	5.93	1.95	3.90	*68*	62.3	45.7	36.0	22.6	22.6	23.9	n/m
20	6/8/2021	21:30	*4.04*	129.9	n/m	16.40	5.92	1.95	3.93	*68*	61.3	37.8	28.1	22.6	22.8	23.7	n/m
20	6/8/2021	21:55	*4.04*	129.80	n/m	24.33	5.95	1.99	3.95	*68*	61.9	29.8	20.3	22.6	22.6	23.8	n/m
21	6/8/2021	22:32	*4.04*	131.4	3.13	n/m	5.59	1.89	3.66	*68*	62.5	29.3	40.3	22.6	22.8	23.3	n/m
21	6/8/2021	23:00	*4.04*	130.0	6.89	n/m	5.99	1.99	3.95	*68*	62.4	45.1	35.5	22.6	22.8	23.6	n/m
21	6/8/2021	23:30	*4.04*	130.0	14.57	n/m	6.05	2.01	3.98	*68*	62.2	37.1	27.4	22.6	22.8	23.6	23.7
22	6/9/2021	00:04	*4.04*	130.1	n/m	1.22	5.21	1.82	3.29	*68*	62.0	53.2	44.4	22.5	22.6	23.3	n/m
22	6/9/2021	00:30	*4.04*	130.0	n/m	3.33	5.86	1.92	3.87	*68*	62.3	50.9	41.2	22.5	22.8	22.7	n/m
22	6/9/2021	01:00	*4.04*	130.0	n/m	8.61	6.18	2.03	4.08	*68*	61.9	44.9	34.8	22.5	22.6	22.8	n/m
22	6/9/2021	01:30	*4.04*	129.8	n/m	17.04	6.21	2.05	4.09	*68*	61.8	36.6	26.6	22.5	22.4	22.5	n/m
23	6/9/2021	02:01	*4.04*	129.9	0.95	n/m	5.03	1.42	3.55	*68*	61.6	51.3	43.3	22.4	22.5	22.6	n/m
23	6/9/2021	02:30	*4.04*	131.3	3.29	n/m	6.10	2.02	4.03	*68*	62.1	48.2	38.5	22.4	22.3	21.6	n/m
23	6/9/2021	03:00	*4.04*	129.9	9.12	n/m	6.20	2.08	4.15	*68*	61.8	42.2	32.2	22.3	22.3	22.0	n/m
23	6/9/2021	03:31	*4.04*	129.9	17.28	n/m	6.23	2.08	4.15	*68*	62.3	34.5	24.3	22.3	22.3	21.9	n/m
24	6/9/2021	04:01	*4.04*	129.9	n/m	1.56	5.29	2.03	3.20	*68*	62.1	52.5	43.5	22.2	22.3	21.8	n/m
24	6/9/2021	04:30	*4.04*	130.0	n/m	4.93	6.24	2.08	4.16	*68*	62.0	49.2	38.9	22.2	22.3	21.0	n/m
24	6/9/2021	05:00	*4.04*	130.0	n/m	11.23	6.25	2.09	4.18	*68*	61.8	42.6	32.4	22.2	22.0	21.4	20.8
24	6/9/2021	05:30	*4.04*	130.0	n/m	20.34	6.28	2.07	4.21	*68*	62.1	33.7	23.5	22.1	22.0	21.3	n/m
25	6/9/2021	06:00	*4.04*	129.9	1.65	n/m	5.21	2.04	3.15	*68*	61.8	50.0	40.9	22.1	22.0	21.4	n/m
25	6/9/2021	06:31	*4.04*	130.0	6.20	n/m	6.31	2.11	4.22	*68*	61.8	45.0	34.6	22.1	21.9	21.0	n/m
25	6/9/2021	07:00	*4.04*	130.0	13.73	n/m	6.30	2.10	4.22	*68*	61.7	37.5	27.4	22.0	21.7	21.1	n/m
25	6/9/2021	07:24	*4.04*	129.8	21.55	n/m	6.31	2.11	4.23	*68*	62.0	30.1	19.8	22.0	21.8	21.1	n/m
26	6/9/2021	08:00	*4.04*	129.8	n/m	2.92	6.08	2.13	3.94	*68*	61.8	50.8	40.8	22.0	21.8	21.4	n/m
26	6/9/2021	08:30	*4.04*	129.9	n/m	7.95	6.35	2.05	4.21	*68*	62.0	45.9	35.8	22.0	21.8	21.2	n/m
26	6/9/2021	09:00	*4.04*	129.9	n/m	14.60	6.30	2.05	4.21	*68*	62.1	39.0	28.8	22.0	21.9	21.4	n/m
27	6/9/2021	09:36	*4.04*	129.9	1.16	n/m	5.30	2.07	3.20	*69*	61.4	50.0	40.8	22.0	21.9	21.8	n/m
27	6/9/2021	10:00	*4.04*	130.5	3.10	n/m	6.20	2.05	4.13	*69*	61.7	48.4	38.5	22.0	21.8	20.6	n/m
27	6/9/2021	10:30	*4.04*	130.0	12.10	n/m	6.22	2.04	4.15	*69*	61.8	39.4	29.3	22.0	21.6	21.9	n/m
27	6/9/2021	11:00	*4.04*	129.9	16.40	n/m	6.26	2.06	4.15	*69*	61.5	34.7	24.5	22.2	21.9	22.1	22.3
27	6/9/2021	11:25	*4.04*	129.9	22.90	n/m	6.23	2.07	4.16	*69*	61.8	28.6	18.4	22.1	22.1	22.3	n/m
28	6/9/2021	12:00	*4.04*	130.0	n/m	3.04	6.09	2.03	4.01	*69*	62.0	51.2	41.3	22.2	22.0	21.7	n/m
28	6/9/2021	12:30	*4.04*	130.0	n/m	7.63	6.20	2.05	4.11	*68*	62.0	46.1	36.2	22.2	22.1	22.6	n/m
28	6/9/2021	13:00	*4.04*	130.0	n/m	14.90	6.15	2.04	4.10	*69*	61.5	39.1	29.1	22.2	22.2	22.9	n/m

Values shown in *italic text* are associated with uncalibrated instruments and are For Information Only (FIO).

DEF Segment	Date	Time	*[FM-01]* (gpm)	FM-02 (mL min^{-1})	DP-01 (psid)	DP-02 (psid)	DP-03 (psid)	DP-04 (psid)	DP-05 (psid)	*[P-01]* (psig)	P-02 (psig)	P-03 (psig)	P-05 (psig)	T-01 (°C)	T-02 (°C)	T-03 (°C)	T-REF (°C)
28	6/9/2021	13:30	*4.04*	129.9	n/m	23.10	6.12	2.01	4.05	*68*	61.7	30.9	21.0	22.2	22.4	23.0	n/m
29	6/9/2021	14:00	*4.04*	129.9	2.25	n/m	5.70	1.95	3.81	*68*	62.0	49.7	41.0	22.3	22.0	23.3	n/m
29	6/9/2021	14:30	*4.04*	130.0	6.55	n/m	6.05	2.00	4.00	*66*	61.5	44.7	35.0	22.3	22.0	23.2	n/m
29	6/9/2021	15:00	*4.04*	130.0	12.72	n/m	6.04	2.00	4.00	*66*	61.5	38.6	28.8	22.3	22.7	23.4	n/m
29	6/9/2021	15:30	*4.04*	130.0	21.00	n/m	6.00	2.00	4.00	*66*	62.1	30.6	20.8	22.4	22.7	23.5	n/m
30	6/9/2021	16:00	*4.04*	130.0	n/m	1.93	4.99	1.90	3.00	*66*	62.4	52.3	44.0	22.4	22.8	23.8	n/m
30	6/9/2021	16:30	*4.04*	130.0	n/m	5.03	5.95	1.95	3.90	*66*	62.5	49.4	39.9	n/m	22.9	23.7	n/m
30	6/9/2021	17:00	*4.04*	130.0	n/m	7.62	5.95	1.99	3.93	*66*	62.5	47.0	37.5	22.6	23.0	23.8	n/m
30	6/9/2021	17:35	*4.04*	130.0	n/m	10.92	5.90	1.93	3.90	*66*	62.6	43.7	34.3	22.6	23.3	23.9	n/m
30	6/9/2021	17:47	*n/m*	n/m	n/m	12.20	5.90	1.95	3.92	*n/m*	n/m	n/m	n/m	n/m	n/m	n/m	n/m
31	6/9/2021	18:07	*4.04*	130.0	1.00	n/m	4.95	1.92	2.95	*66*	61.0	50.0	41.5	22.7	23.0	24.0	n/m
31	6/9/2021	18:30	*4.04*	130.0	1.63	n/m	5.85	1.95	3.86	*66*	62.2	50.2	40.9	22.7	23.3	23.5	n/m
31	6/9/2021	19:00	*4.04*	130.0	2.85	n/m	5.90	1.94	3.90	*66*	62.2	49.0	39.0	22.7	23.0	23.9	n/m
31	6/9/2021	19:30	*4.04*	130.0	4.75	n/m	6.02	1.99	3.98	*66*	62.1	46.3	36.7	22.7	23.0	23.8	n/m
31	6/9/2021	20:00	*4.04*	130.0	7.00	n/m	6.04	2.00	4.00	*66*	62.7	45.4	35.7	22.7	22.8	23.7	n/m
32	6/9/2021	20:30	*4.04*	129.7	n/m	1.32	5.10	1.92	3.07	*68*	62.9	53.9	45.5	22.7	22.9	24.1	n/m
32	6/9/2021	21:00	*4.04*	130.0	n/m	2.30	6.09	2.02	4.03	*68*	62.6	52.5	42.7	22.6	23.2	23.5	n/m
32	6/9/2021	21:30	*4.04*	130.0	n/m	3.79	6.25	2.04	4.12	*68*	62.5	50.7	40.6	22.6	22.8	23.0	n/m
32	6/9/2021	22:00	*4.04*	129.9	n/m	5.57	6.25	2.05	4.14	*68*	62.5	48.9	38.8	22.6	22.6	23.1	n/m
32	6/9/2021	22:16	*n/m*	n/m	n/m	6.83	6.23	2.07	4.15	*n/m*	n/m	n/m	n/m	n/m	n/m	n/m	n/m
33	6/9/2021	22:33	*4.04*	129.9	0.87	n/m	5.25	2.03	3.20	*68*	62.7	51.2	42.1	22.5	22.6	22.9	n/m
33	6/9/2021	23:00	*4.04*	130.1	1.45	n/m	6.10	2.00	4.03	*68*	60.6	48.7	38.9	22.5	22.3	22.2	23.0
33	6/9/2021	23:30	*4.04*	129.9	2.56	n/m	6.23	2.05	4.17	*68*	60.4	47.2	37.2	22.5	22.5	22.7	n/m
33	6/10/2021	00:00	*4.04*	130.0	4.14	n/m	6.28	2.07	4.17	*68*	62.4	47.9	37.8	22.5	22.7	22.8	n/m
33	6/10/2021	00:30	*4.04*	130.0	6.67	n/m	6.31	2.03	4.18	*68*	62.6	45.5	35.3	22.5	22.5	22.5	n/m
34	6/10/2021	01:01	*4.05*	129.9	n/m	1.37	5.75	2.02	3.68	*68*	62.7	53.4	44.1	22.4	22.5	23.0	n/m
34	6/10/2021	01:30	*4.04*	130.0	n/m	2.20	6.30	2.06	4.16	*68*	62.5	52.3	42.0	22.4	22.3	22.3	n/m
34	6/10/2021	02:00	*4.04*	130.0	n/m	3.44	6.26	2.04	4.17	*68*	62.4	51.1	41.0	22.3	22.5	22.3	n/m
34	6/10/2021	02:34	*4.04*	129.8	n/m	5.31	6.27	2.05	4.19	*66*	60.3	47.0	36.9	22.3	22.3	22.0	n/m
34	6/10/2021	02:41	*4.04*	130.0	n/m	5.82	6.29	2.05	4.18	*69*	62.5	48.7	38.7	22.3	22.5	22.0	n/m
35	6/10/2021	03:01	*4.04*	129.9	0.77	n/m	5.25	2.05	3.15	*69*	62.3	51.2	42.2	22.3	22.6	21.9	n/m
35	6/10/2021	03:30	*4.04*	130.0	1.41	n/m	6.38	2.10	4.27	*69*	62.3	50.4	40.0	22.2	22.3	21.0	n/m
35	6/10/2021	04:00	*4.04*	130.0	2.52	n/m	6.34	2.12	4.25	*69*	62.2	49.3	39.2	22.2	22.1	21.5	n/m
35	6/10/2021	04:30	*4.04*	130.0	3.93	n/m	6.32	2.09	4.22	*69*	62.5	48.3	38.2	22.2	22.0	21.3	n/m
35	6/10/2021	05:04	*4.04*	130.0	6.17	n/m	6.35	2.11	4.26	*69*	62.5	45.9	35.9	22.2	21.8	21.2	n/m

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DEF Segment	Date	Time	*[FM-01]* (gpm)	FM-02 (mL min^{-1})	DP-01 (psid)	DP-02 (psid)	DP-03 (psid)	DP-04 (psid)	DP-05 (psid)	*[P-01]* (psig)	P-02 (psig)	P-03 (psig)	P-05 (psig)	T-01 (°C)	T-02 (°C)	T-03 (°C)	T-REF (°C)
36	6/10/2021	05:30	*4.04*	130.0	n/m	1.15	5.82	2.11	3.77	*69*	62.2	53.0	43.3	22.2	22.0	21.7	20.7
36	6/10/2021	06:00	*4.04*	130.0	n/m	1.87	6.43	2.09	4.29	*66*	60.3	50.4	40.2	22.1	21.9	21.0	n/m
36	6/10/2021	06:30	*4.04*	130.0	n/m	3.03	6.34	2.12	4.28	*70*	62.3	51.4	41.1	22.1	21.9	21.1	n/m
36	6/10/2021	07:00	*4.04*	129.9	n/m	4.51	6.40	2.11	4.29	*69*	62.2	49.8	39.5	22.0	21.8	21.1	n/m
36	6/10/2021	07:21	*4.04*	130.0	n/m	5.94	6.34	2.13	4.27	*65*	62.3	48.2	38.0	22.0	21.8	21.1	n/m
37	6/10/2021	08:00	*4.04*	130.2	1.30	n/m	6.45	2.13	4.33	*69*	62.5	50.6	40.4	22.0	21.6	20.0	n/m
37	6/10/2021	08:30	*4.04*	130.0	2.20	n/m	6.40	2.10	4.25	*70*	62.6	50.0	39.7	22.0	21.7	21.1	n/m
37	6/10/2021	09:00	*4.04*	130.0	3.55	n/m	6.30	2.10	4.25	*70*	62.5	48.8	38.6	22.0	21.8	21.4	n/m
37	6/10/2021	09:32	*4.04*	130.0	5.50	n/m	6.32	2.09	4.23	*70*	62.3	46.3	36.1	22.0	21.8	21.7	n/m
38	6/10/2021	10:00	*4.04*	130.0	n/m	1.10	5.45	2.00	3.35	*69*	62.5	53.5	44.3	22.0	21.8	22.1	n/m
38	6/10/2021	10:30	*4.04*	130.0	n/m	2.75	6.38	2.10	4.23	*69*	62.4	51.6	41.3	22.1	22.0	21.9	22.0
38	6/10/2021	11:00	*4.04*	130.0	n/m	3.42	6.35	2.10	4.25	*69*	62.2	50.6	40.5	22.1	22.0	22.0	n/m
38	6/10/2021	11:30	*4.04*	130.0	n/m	4.65	6.40	2.10	4.23	*69*	62.0	49.2	39.1	22.1	22.2	22.2	n/m
38	6/10/2021	12:00	*4.04*	130.0	n/m	8.15	6.35	2.05	4.23	*66*	60.3	44.0	33.8	22.1	22.2	22.4	n/m
39	6/10/2021	12:30	*4.04*	130.0	1.00	n/m	5.80	2.00	3.83	*66*	60.2	48.9	39.6	22.1	22.3	23.0	n/m
39	6/10/2021	13:00	*4.04*	130.0	1.80	n/m	6.20	2.04	4.15	*68*	60.2	47.8	37.7	22.2	22.4	22.7	n/m
39	6/10/2021	13:30	*4.04*	130.0	3.00	n/m	6.30	2.10	4.18	*68*	62.4	48.9	38.7	22.2	22.5	22.9	n/m
39	6/10/2021	14:00	*4.04*	130.0	4.55	n/m	6.30	2.05	4.15	*68*	62.3	47.5	37.3	22.2	22.5	22.9	n/m
39	6/10/2021	14:19	*4.04*	130.0	7.99	n/m	6.15	2.04	4.08	*68*	62.2	43.7	33.7	22.2	22.6	23.2	n/m
40	6/10/2021	14:45	*4.04*	129.8	n/m	1.15	5.46	1.98	3.46	*68*	62.4	53.4	44.7	22.3	22.6	23.4	n/m
40	6/10/2021	15:08	*4.04*	130.0	n/m	1.70	6.10	2.00	4.05	*68*	62.2	52.8	42.9	22.3	22.2	23.2	n/m
40	6/10/2021	15:30	*4.04*	130.0	n/m	2.40	6.10	2.00	4.04	*68*	62.3	52.0	42.1	22.3	22.8	23.4	n/m
40	6/10/2021	16:00	*4.04*	130.0	n/m	3.72	6.15	2.00	4.05	*68*	62.2	50.5	40.6	22.3	22.7	23.6	n/m
40	6/10/2021	16:28	*4.04*	130.0	n/m	5.30	6.10	2.00	4.00	*68*	62.3	49.0	39.1	22.4	22.8	23.6	n/m
41	6/10/2021	17:01	*4.04*	130.0	1.03	n/m	5.75	1.93	3.75	*66*	62.6	51.1	42.3	22.4	22.8	23.4	25.4
41	6/10/2021	17:30	*4.04*	130.0	1.75	n/m	5.99	1.96	3.93	*66*	62.2	50.3	40.9	22.4	22.9	23.8	n/m
41	6/10/2021	18:00	*4.04*	129.8	2.80	n/m	5.95	1.95	3.95	*68*	61.9	49.1	39.5	22.5	23.1	24.0	n/m
41	6/10/2021	18:30	*4.04*	130.0	4.32	n/m	5.99	1.95	3.94	*67*	62.5	47.7	38.1	22.5	22.6	24.0	n/m
41	6/10/2021	19:00	*4.04*	130.0	6.02	n/m	6.00	1.97	3.98	*67*	62.3	46.0	36.2	22.5	22.7	23.9	n/m
42	6/10/2021	19:30	*4.04*	130.0	n/m	1.20	5.78	1.98	3.83	*68*	62.6	53.7	44.4	22.6	23.0	23.4	n/m
42	6/10/2021	20:00	*4.04*	130.0	n/m	1.90	6.01	2.00	4.00	*68*	62.3	52.4	42.7	22.6	22.9	23.8	n/m
42	6/10/2021	20:30	*4.04*	130.0	n/m	2.99	6.10	1.98	4.04	*68*	62.5	51.5	41.5	22.6	22.3	23.7	n/m
42	6/10/2021	21:00	*4.04*	129.9	n/m	4.43	6.19	2.04	4.11	*68*	62.1	49.7	39.9	22.6	22.7	23.6	n/m
42	6/10/2021	21:08	*n/m*	n/m	n/m	4.91	6.23	2.07	4.12	*n/m*	n/m	n/m	n/m	n/m	n/m	n/m	n/m
43	6/10/2021	21:29	*4.04*	130.2	0.80	n/m	5.08	2.06	3.02	*68*	62.5	53.1	42.4	22.6	22.2	23.6	n/m

Values shown in *italic text* are associated with uncalibrated instruments and are For Information Only (FIO).

DEF Segment	Date	Time	*[FM-01]* (gpm)	FM-02 (mL min^{-1})	DP-01 (psid)	DP-02 (psid)	DP-03 (psid)	DP-04 (psid)	DP-05 (psid)	*[P-01]* (psig)	P-02 (psig)	P-03 (psig)	P-05 (psig)	T-01 (°C)	T-02 (°C)	T-03 (°C)	T-REF (°C)
43	6/10/2021	22:00	*4.04*	129.9	1.45	n/m	6.11	2.06	4.06	*68*	62.5	50.8	40.8	22.5	22.8	23.2	n/m
43	6/10/2021	22:30	*4.04*	130.0	3.45	n/m	6.23	2.11	4.18	*68*	62.4	48.4	38.2	22.5	22.5	23.1	n/m
43	6/10/2021	23:00	*4.04*	130.0	4.16	n/m	6.28	2.08	4.22	*68*	62.5	47.6	37.3	22.5	22.3	22.8	n/m
43	6/10/2021	23:19	*n/m*	n/m	5.25	n/m	6.30	2.04	4.20	*n/m*	n/m	n/m	n/m	n/m	n/m	n/m	n/m
44	6/10/2021	23:32	*4.04*	129.9	n/m	0.82	5.22	1.66	3.56	*68*	62.4	54.0	44.9	22.5	22.4	22.7	n/m
44	6/11/2021	00:00	*4.04*	130.1	n/m	1.23	6.32	2.06	4.17	*68*	62.3	53.1	43.2	22.4	22.5	21.8	22.6
44	6/11/2021	00:29	*4.04*	130.1	n/m	2.03	6.32	2.07	4.20	*68*	62.3	52.1	42.0	22.4	22.5	22.5	n/m
44	6/11/2021	01:00	*4.04*	130.0	n/m	3.07	6.26	2.08	4.19	*68*	62.4	51.2	40.9	22.4	22.6	22.3	n/m
44	6/11/2021	01:29	*4.04*	129.9	n/m	4.39	6.27	2.09	4.22	*68*	59.8	47.6	37.5	22.3	22.8	22.2	n/m
45	6/11/2021	02:00	*4.04*	129.2	0.91	n/m	5.54	2.04	3.42	*68*	62.3	51.1	42.4	22.3	22.2	22.4	n/m
45	6/11/2021	02:30	*4.04*	130.0	1.64	n/m	6.38	2.14	4.26	*68*	62.1	50.1	39.9	22.3	22.3	21.8	n/m
45	6/11/2021	03:00	*4.04*	129.9	2.69	n/m	6.34	2.11	4.25	*69*	62.3	49.1	38.9	22.2	22.3	21.7	n/m
45	6/11/2021	03:30	*4.04*	130.0	4.14	n/m	6.30	2.09	4.24	*69*	62.1	47.3	37.6	22.2	22.1	21.6	n/m
45	6/11/2021	03:49	*4.04*	129.9	5.15	n/m	6.34	2.10	4.25	*69*	62.1	46.7	36.6	22.2	21.9	21.6	n/m
46	6/11/2021	04:02	*4.04*	130.0	n/m	0.89	5.30	2.09	3.23	*69*	62.3	53.4	44.4	22.2	22.1	21.5	n/m
46	6/11/2021	04:30	*4.04*	129.6	n/m	1.37	6.47	2.11	4.32	*69*	62.1	52.8	42.3	22.2	22.0	20.7	n/m
46	6/11/2021	05:00	*4.04*	130.0	n/m	2.13	6.37	2.14	4.27	*69*	62.4	52.2	42.1	22.1	22.0	21.4	n/m
46	6/11/2021	05:30	*4.04*	130.0	n/m	3.15	6.38	2.07	4.28	*69*	62.3	51.2	41.0	22.1	22.0	21.3	20.9
46	6/11/2021	06:03	*4.04*	130.0	n/m	4.76	6.37	2.09	4.32	*69*	62.2	49.4	39.1	22.1	21.9	21.2	n/m
47	6/11/2021	06:30	*4.04*	129.7	0.95	n/m	6.04	2.13	3.85	*69*	62.1	50.5	41.2	22.0	21.9	21.5	n/m
47	6/11/2021	07:00	*4.04*	130.0	1.63	n/m	6.45	2.13	4.34	*69*	62.2	50.1	39.8	22.0	21.8	20.9	n/m
47	6/11/2021	07:30	*4.04*	130.0	2.71	n/m	6.44	2.12	4.32	*69*	62.0	49.1	38.7	22.0	21.9	21.0	n/m
47	6/11/2021	08:00	*4.04*	130.0	4.06	n/m	6.42	2.11	4.31	*69*	62.1	47.7	37.5	22.0	21.8	21.1	n/m
47	6/11/2021	08:11	*4.04*	130.0	4.88	n/m	6.38	2.13	4.28	*69*	62.3	47.2	37.0	22.0	21.9	21.1	n/m
48	6/11/2021	08:32	*4.04*	130.0	n/m	0.93	5.35	2.10	3.20	*69*	62.4	53.2	44.0	22.0	21.6	21.3	n/m
48	6/11/2021	09:00	*4.04*	130.0	n/m	1.43	6.47	2.13	4.34	*69*	62.0	52.5	42.2	22.0	21.8	21.0	n/m
48	6/11/2021	09:32	*4.04*	130.0	n/m	2.30	6.35	2.10	4.26	*69*	62.1	52.0	41.8	22.0	21.9	21.6	21.6
48	6/11/2021	10:00	*4.04*	130.0	n/m	3.32	6.38	2.10	4.24	*68*	62.2	50.7	40.6	22.0	22.0	21.7	n/m
48	6/11/2021	10:30	*4.04*	130.0	n/m	4.72	6.40	2.10	4.25	*69*	62.2	49.3	39.2	22.0	21.9	21.7	n/m
48	6/11/2021	11:00	*4.04*	130.0	0.90	n/m	5.75	2.10	3.63	*68*	62.2	50.6	41.4	22.0	22.0	22.4	n/m
49	6/11/2021	11:30	*4.04*	130.0	1.60	n/m	6.45	2.10	4.28	*68*	62.1	50.0	39.7	22.0	22.0	22.0	n/m
49	6/11/2021	12:12	*4.04*	130.0	3.24	n/m	6.45	2.11	4.28	*68*	62.0	48.2	37.9	22.1	22.2	22.4	n/m
49	6/11/2021	12:29	*4.04*	130.0	4.00	n/m	6.42	2.10	4.25	*68*	62.0	47.5	37.0	22.1	22.2	22.5	n/m
49	6/11/2021	12:50	*n/m*	n/m	5.23	n/m	6.41	2.06	4.28	*n/m*	n/m	n/m	n/m	n/m	n/m	n/m	n/m
50	6/11/2021	13:30	*4.04*	130.0	n/m	1.32	6.28	2.04	4.15	*68*	62.0	52.5	42.3	22.2	22.3	22.2	n/m

Values shown in *italic text* are associated with uncalibrated instruments and are For Information Only (FIO).

DEF Segment	Date	Time	*[FM-01]* (gpm)	FM-02 (mL min^{-1})	DP-01 (psid)	DP-02 (psid)	DP-03 (psid)	DP-04 (psid)	DP-05 (psid)	*[P-01]* (psig)	P-02 (psig)	P-03 (psig)	P-05 (psig)	T-01 (°C)	T-02 (°C)	T-03 (°C)	T-REF (°C)
50	6/11/2021	14:00	*4.04*	130.0	n/m	2.12	6.32	2.10	4.20	*68*	61.8	51.3	41.3	22.2	22.6	22.9	n/m
50	6/11/2021	14:30	*4.04*	130.0	n/m	3.23	6.30	2.07	4.20	*67*	61.6	50.2	40.1	22.2	22.6	23.2	n/m
50	6/11/2021	14:56	*n/m*	n/m	n/m	4.40	6.30	2.07	4.20	*n/m*	n/m	n/m	n/m	n/m	n/m	n/m	n/m
51	6/11/2021	15:12	*4.04*	129.9	0.66	n/m	5.35	1.99	3.35	*68*	61.8	51.0	41.9	22.3	22.4	23.1	24.3
51	6/11/2021	15:30	*4.04*	130.0	0.87	n/m	5.60	2.05	3.50	*68*	61.9	50.8	42.1	22.3	22.8	23.8	n/m
51	6/11/2021	16:00	*4.04*	130.0	1.50	n/m	6.20	2.04	4.10	*68*	62.0	50.1	40.2	22.3	21.6	23.2	n/m
51	6/11/2021	16:30	*4.04*	130.0	2.47	n/m	6.25	2.01	4.12	*68*	62.0	49.1	39.0	22.3	22.4	23.3	n/m
51	6/11/2021	17:00	*4.04*	130.1	3.69	n/m	6.20	2.02	4.11	*67*	62.2	47.9	38.0	22.4	22.4	23.3	n/m
51	6/11/2021	17:13	*n/m*	n/m	4.40	n/m	6.20	2.05	4.13	*n/m*	n/m	n/m	n/m	n/m	n/m	n/m	n/m
52	6/11/2021	17:30	*4.04*	130.1	n/m	0.99	5.13	2.01	3.04	*67*	62.1	52.9	44.1	22.4	22.6	23.3	n/m
52	6/11/2021	18:00	*4.04*	130.0	n/m	1.50	6.15	2.00	4.07	*67*	61.9	52.4	42.7	22.4	22.8	23.2	n/m
52	6/11/2021	18:30	*4.04*	130.0	n/m	2.33	6.20	2.05	4.12	*68*	62.0	51.5	41.6	22.4	22.4	23.2	n/m
52	6/11/2021	19:00	*4.04*	130.0	n/m	3.45	6.25	2.04	4.14	*67*	62.0	50.3	40.3	22.4	22.2	23.2	n/m
52	6/11/2021	19:30	*4.04*	130.0	n/m	4.90	6.23	2.06	4.15	*67*	61.7	48.9	38.8	22.4	22.5	23.3	n/m
53	6/11/2021	20:00	*4.04*	130.0	0.91	n/m	5.75	2.00	3.69	*67*	62.0	50.9	41.9	22.5	22.3	23.5	n/m
53	6/11/2021	20:30	*4.04*	130.0	1.52	n/m	6.15	1.96	4.00	*68*	62.2	50.2	40.3	22.5	22.3	23.2	n/m
53	6/11/2021	21:00	*4.04*	130.0	2.51	n/m	6.21	2.02	4.13	*68*	62.2	49.1	39.1	22.5	22.8	23.3	n/m
53	6/11/2021	21:30	*4.04*	130.0	3.73	n/m	6.24	2.06	4.16	*68*	61.9	47.5	37.6	22.5	22.8	23.2	n/m
53	6/11/2021	21:37	*n/m*	n/m	4.07	n/m	6.26	2.00	4.16	*n/m*	n/m	n/m	n/m	n/m	n/m	n/m	n/m
54	6/11/2021	22:00	*4.04*	130.2	n/m	0.99	5.12	2.04	3.04	*68*	61.9	52.8	44.2	22.5	22.5	23.2	n/m
54	6/11/2021	22:30	*4.04*	129.8	n/m	1.55	6.17	2.02	4.08	*68*	61.9	52.3	42.4	22.4	22.5	23.2	n/m
54	6/11/2021	23:00	*4.04*	129.9	n/m	2.44	6.26	2.06	4.13	*68*	61.7	51.4	41.4	22.4	22.5	23.1	n/m
54	6/11/2021	23:30	*4.04*	129.9	n/m	3.48	6.29	2.07	4.21	*68*	61.9	50.1	39.9	22.4	22.6	23.0	n/m
54	6/11/2021	23:48	*n/m*	n/m	n/m	4.97	7.05	2.31	4.65	*n/m*	n/m	n/m	n/m	n/m	n/m	n/m	n/m
55	6/12/2021	00:03	*4.04*	130.0	0.65	n/m	5.43	2.10	3.33	*68*	61.4	50.5	41.1	22.4	22.6	22.9	23.3
55	6/12/2021	00:30	*4.04*	129.8	1.04	n/m	6.27	2.03	4.11	*68*	61.8	50.2	40.5	22.4	22.6	22.0	n/m
55	6/12/2021	01:00	*4.04*	129.8	1.76	n/m	6.29	2.04	4.23	*68*	61.5	49.4	39.3	22.4	22.4	22.5	n/m
55	6/12/2021	01:30	*4.04*	130.0	2.84	n/m	6.43	2.10	4.28	*68*	61.7	48.2	38.1	22.3	22.1	22.3	n/m
55	6/12/2021	01:58	*4.04*	129.9	4.23	n/m	6.47	2.12	4.29	*68*	61.4	46.9	36.7	22.3	22.4	22.2	n/m
56	6/12/2021	02:30	*4.04*	130.4	n/m	1.07	5.88	2.11	3.76	*68*	61.7	52.5	43.4	22.3	22.3	22.5	n/m
56	6/12/2021	03:00	*4.04*	129.9	n/m	1.63	6.47	2.14	4.33	*69*	61.7	51.9	41.5	22.2	22.2	21.8	n/m
56	6/12/2021	03:30	*4.04*	130.0	n/m	2.45	6.48	2.10	4.30	*68*	61.7	51.1	40.8	22.2	22.3	21.8	n/m
56	6/12/2021	04:00	*4.04*	130.0	n/m	3.52	6.43	2.12	4.30	*68*	61.6	50.1	39.9	22.2	22.2	21.8	n/m
56	6/12/2021	04:16	*4.04*	129.8	n/m	4.15	6.44	2.11	4.28	*68*	61.5	49.4	39.2	22.2	22.2	21.8	n/m
57	6/12/2021	04:30	*4.04*	129.7	0.70	n/m	5.38	2.08	3.20	*68*	61.9	50.5	41.4	22.2	22.3	21.8	n/m

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DEF Segment	Date	Time	*[FM-01]* (gpm)	FM-02 (mL min^{-1})	DP-01 (psid)	DP-02 (psid)	DP-03 (psid)	DP-04 (psid)	DP-05 (psid)	*[P-01]* (psig)	P-02 (psig)	P-03 (psig)	P-05 (psig)	T-01 (°C)	T-02 (°C)	T-03 (°C)	T-REF (°C)
57	6/12/2021	05:00	*4.04*	130.2	1.21	n/m	6.48	2.14	4.33	*67*	61.6	49.8	39.6	22.2	22.2	21.2	21.3
57	6/12/2021	05:30	*4.04*	129.9	2.05	n/m	6.46	2.12	4.32	*67*	61.7	49.2	38.9	22.2	22.2	21.5	n/m
57	6/12/2021	06:00	*4.04*	129.9	3.21	n/m	6.44	2.12	4.30	*68*	61.7	48.1	37.9	22.1	22.0	21.5	n/m
57	6/12/2021	06:30	*4.04*	130.0	5.31	n/m	6.41	2.12	4.25	*68*	61.8	46.2	36.0	22.1	21.7	21.5	n/m
58	6/12/2021	07:00	*4.04*	130.0	n/m	1.08	5.93	2.11	3.92	*68*	61.6	52.7	43.2	22.1	22.1	22.0	n/m
58	6/12/2021	07:30	*4.04*	130.0	n/m	1.59	6.41	2.12	4.26	*67*	61.7	52.1	41.9	22.1	22.1	21.6	n/m
58	6/12/2021	08:00	*4.04*	130.0	n/m	2.38	6.38	2.10	4.24	*68*	61.9	51.3	41.4	22.1	22.2	21.8	n/m
58	6/12/2021	08:30	*4.04*	130.1	n/m	3.37	6.31	2.10	4.24	*68*	61.6	50.3	40.3	22.1	22.3	22.1	n/m
58	6/12/2021	08:47	*4.04*	130.0	n/m	4.15	6.31	2.13	4.25	*68*	61.4	49.3	39.2	22.1	22.4	22.2	n/m
59	6/12/2021	09:09	*4.04*	129.8	0.80	n/m	5.28	2.03	3.22	*68*	61.9	50.8	42.4	22.1	22.0	22.6	n/m
59	6/12/2021	09:30	*4.04*	130.1	1.23	n/m	6.35	2.08	4.23	*68*	61.6	50.0	39.7	22.2	22.0	22.0	n/m
59	6/12/2021	10:00	*4.04*	130.0	2.11	n/m	6.38	2.13	4.28	*68*	61.6	48.9	38.5	22.2	22.2	22.6	n/m
59	6/12/2021	10:30	*4.04*	129.9	3.31	n/m	6.35	2.10	4.25	*67*	61.7	47.8	37.5	22.2	22.6	22.8	23.3
59	6/12/2021	11:00	*4.04*	131.5	5.85	n/m	6.34	2.03	4.20	*68*	57.1	40.6	30.5	22.2	22.2	23.0	n/m
60	6/12/2021	11:30	*4.04*	129.7	n/m	1.00	5.49	2.01	3.46	*67*	53.1	43.9	35.0	22.3	22.8	23.7	n/m
60	6/12/2021	12:00	*4.03*	130.0	n/m	1.57	6.18	1.99	4.04	*72*	69.4	59.9	49.9	22.3	22.5	23.3	n/m
60	6/12/2021	12:30	*4.04*	130.1	n/m	2.31	6.06	1.96	4.06	*68*	63.8	53.7	43.7	22.4	22.6	23.6	n/m
60	6/12/2021	13:00	*4.04*	130.0	n/m	3.31	6.13	1.98	4.08	*68*	63.8	52.7	42.6	22.4	22.6	23.7	n/m
60	6/12/2021	13:30	*4.03*	129.9	n/m	4.52	6.07	1.99	4.01	*68*	64.0	51.3	41.7	22.5	22.8	23.9	n/m
61	6/12/2021	14:00	*4.04*	129.9	0.93	n/m	5.70	1.93	3.72	*68*	64.1	53.0	43.8	22.5	22.7	24.0	n/m
61	6/12/2021	14:30	*4.04*	130.3	1.50	n/m	5.93	1.94	3.90	*68*	64.0	52.4	42.9	22.5	22.3	24.2	n/m
61	6/12/2021	15:00	*4.04*	130.0	2.32	n/m	5.95	1.95	3.94	*68*	64.0	51.5	41.9	22.6	23.1	24.2	n/m
61	6/12/2021	15:30	*4.04*	130.0	3.41	n/m	5.98	1.95	3.90	*68*	64.0	50.2	40.8	22.5	23.0	24.4	n/m
62	6/12/2021	16:00	*4.04*	130.0	n/m	0.92	4.98	1.95	2.92	*68*	64.0	55.1	46.5	22.5	23.3	24.7	n/m
62	6/12/2021	16:30	*4.04*	130.0	n/m	1.35	5.90	1.93	3.86	*68*	64.0	54.7	45.4	22.5	23.3	24.8	n/m
62	6/12/2021	17:00	*4.04*	130.0	n/m	1.96	5.91	1.93	3.87	*68*	64.0	54.2	44.7	22.5	22.9	24.6	n/m
62	6/12/2021	17:30	*4.04*	130.0	n/m	2.87	5.90	1.89	3.90	*68*	63.8	53.0	43.6	22.4	23.6	24.8	n/m
62	6/12/2021	17:55	*4.04*	130.0	n/m	3.80	5.88	1.94	3.88	*68*	63.5	51.9	42.6	22.4	22.8	24.7	n/m
63	6/12/2021	18:30	*4.04*	130.0	0.93	n/m	5.81	1.96	3.73	*68*	63.8	52.5	43.1	22.4	23.1	24.4	n/m
63	6/12/2021	19:00	*4.04*	130.0	1.48	n/m	5.87	1.93	3.87	*68*	63.5	51.9	42.6	22.4	23.0	24.8	26.3
63	6/12/2021	19:30	*4.04*	130.0	2.26	n/m	5.87	1.96	3.87	*68*	63.7	51.2	41.9	22.4	23.3	24.8	n/m
63	6/12/2021	20:00	*4.04*	130.0	3.30	n/m	5.91	1.95	3.90	*68*	63.5	50.0	40.6	22.4	23.5	24.6	n/m
64	6/12/2021	20:31	*4.04*	129.1	n/m	0.93	5.18	1.92	3.16	*68*	63.8	54.7	45.9	22.4	22.9	24.9	n/m
64	6/12/2021	21:00	*4.04*	130.0	n/m	1.43	5.90	1.95	3.92	*68*	63.6	54.1	44.7	22.4	22.9	24.4	n/m
64	6/12/2021	21:30	*4.04*	130.0	n/m	2.11	6.02	1.97	4.00	*69*	63.3	53.3	43.8	22.4	23.0	24.2	n/m

Values shown in *italic text* are associated with uncalibrated instruments and are For Information Only (FIO).

DEF Segment	Date	Time	*[FM-01]* (gpm)	FM-02 (mL min^{-1})	DP-01 (psid)	DP-02 (psid)	DP-03 (psid)	DP-04 (psid)	DP-05 (psid)	*[P-01]* (psig)	P-02 (psig)	P-03 (psig)	P-05 (psig)	T-01 (°C)	T-02 (°C)	T-03 (°C)	T-REF (°C)
64	6/12/2021	22:00	*4.04*	130.0	n/m	3.04	6.08	2.00	4.02	*69*	63.8	52.8	42.8	22.3	22.9	24.1	n/m
64	6/12/2021	22:13	*n/m*	n/m	n/m	3.59	6.14	2.03	4.04	*n/m*	n/m	n/m	n/m	n/m	n/m	n/m	n/m
65	6/12/2021	22:30	*4.03*	130.0	0.64	n/m	5.16	1.96	3.10	*69*	63.9	52.7	44.0	22.3	22.7	24.0	n/m
65	6/12/2021	23:00	*4.03*	129.8	1.01	n/m	5.97	1.99	3.97	*69*	63.8	51.4	41.8	22.3	23.0	24.0	n/m
65	6/12/2021	23:30	*4.04*	130.0	1.65	n/m	6.08	2.02	4.03	*69*	64.2	46.7	37.6	22.3	22.4	23.9	n/m
65	6/13/2021	00:00	*4.04*	129.9	2.61	n/m	6.16	2.04	4.07	*69*	63.4	48.4	38.6	22.3	22.6	23.8	n/m
65	6/13/2021	00:24	*n/m*	n/m	3.52	n/m	6.29	2.03	n/m	*n/m*	n/m	n/m	n/m	n/m	n/m	n/m	n/m
66	6/13/2021	00:35	*4.03*	129.9	n/m	0.73	5.05	1.53	3.52	*69*	64.1	55.8	47.2	22.2	22.6	23.6	25.2
66	6/13/2021	01:00	*4.04*	130.1	n/m	1.03	5.68	1.95	3.78	*69*	64.3	55.3	46.1	22.2	22.9	23.8	n/m
66	6/13/2021	01:30	*4.04*	130.0	n/m	1.64	6.19	2.03	4.09	*69*	63.7	54.3	44.3	22.2	22.8	23.8	n/m
66	6/13/2021	02:00	*4.04*	130.0	n/m	2.45	6.32	2.05	4.15	*69*	63.5	53.2	43.2	22.2	22.6	23.7	n/m
66	6/13/2021	02:30	*4.04*	130.0	n/m	3.58	6.28	2.08	4.16	*68*	63.8	52.0	42.0	22.2	22.5	23.5	n/m
67	6/13/2021	03:00	*4.04*	130.0	0.77	n/m	5.28	2.04	3.22	*69*	64.0	52.8	44.7	22.2	22.4	23.6	n/m
67	6/13/2021	03:30	*4.04*	130.0	1.25	n/m	6.23	2.04	4.13	*69*	62.6	50.9	40.8	22.2	22.7	23.3	n/m
67	6/13/2021	04:00	*4.04*	130.0	2.03	n/m	6.31	2.06	4.18	*69*	63.6	51.0	40.8	22.1	22.6	23.1	n/m
67	6/13/2021	04:30	*4.04*	130.0	3.05	n/m	6.37	2.07	4.22	*69*	63.4	49.8	39.6	22.1	22.7	23.0	n/m
67	6/13/2021	04:49	*4.04*	130.0	3.85	n/m	6.43	2.11	4.24	*69*	63.5	49.1	39.0	22.1	22.6	23.0	n/m
68	6/13/2021	05:03	*4.04*	130.1	n/m	0.84	5.28	2.07	3.17	*69*	63.3	52.3	42.2	22.1	22.5	23.0	23.4
68	6/13/2021	05:30	*4.04*	129.9	n/m	1.21	6.25	2.08	4.16	*69*	62.9	53.3	43.6	22.1	22.5	22.5	n/m
68	6/13/2021	06:00	*4.04*	130.0	n/m	1.89	6.42	2.11	4.25	*70*	63.7	53.6	43.4	22.0	22.5	22.8	n/m
68	6/13/2021	06:30	*4.04*	130.0	n/m	2.78	6.42	2.11	4.27	*69*	63.3	52.2	42.0	22.0	22.3	22.8	n/m
68	6/13/2021	07:02	*4.04*	130.0	n/m	3.91	6.39	2.12	4.26	*69*	63.9	51.5	41.5	22.0	22.4	22.8	n/m
69	6/13/2021	07:30	*4.04*	129.9	0.86	n/m	5.82	2.07	3.77	*70*	63.3	52.0	42.6	22.0	22.2	23.3	n/m
69	6/13/2021	08:00	*4.04*	130.1	1.39	n/m	6.27	2.09	4.18	*70*	62.9	51.0	41.0	22.0	22.5	23.0	24.2
69	6/13/2021	08:30	*4.04*	126.0	1.96	n/m	5.38	1.58	2.56	*68*	20.7	10.1	5.5	22.0	22.6	23.2	n/m
69	6/13/2021	09:00	*4.04*	129.8	3.16	n/m	6.15	2.04	4.06	*68*	61.5	47.9	38.0	22.1	22.6	23.6	n/m
69	6/13/2021	09:30	*4.03*	129.7	4.91	n/m	6.08	2.01	4.03	*70*	64.6	49.3	39.4	22.1	22.3	23.8	n/m
70	6/13/2021	10:00	*4.04*	130.5	n/m	1.01	5.72	1.95	3.65	*70*	65.0	56.1	46.8	22.1	22.3	24.2	n/m
70	6/13/2021	10:30	*4.04*	130.0	n/m	1.50	6.01	1.97	3.96	*70*	65.3	55.5	46.0	22.2	22.5	24.1	n/m
70	6/13/2021	11:00	*4.03*	129.9	n/m	2.52	5.98	1.91	3.92	*70*	65.3	52.2	40.5	22.2	22.4	24.3	n/m
70	6/13/2021	11:30	*4.04*	130.0	n/m	3.63	5.92	1.96	3.87	*70*	64.9	53.1	43.8	22.2	22.7	24.6	26.5
70	6/13/2021	12:00	*4.04*	130.1	n/m	4.30	5.89	1.91	3.86	*70*	65.2	53.1	43.8	22.2	22.8	24.8	n/m
70	6/13/2021	12:17	*4.03*	130.0	n/m	4.80	5.85	1.93	3.87	*69*	65.2	52.4	43.1	22.3	22.8	24.8	n/m

Table B.8. Initial Differential Pressure Data for DEFs from Test HS3

DEF Segment	Date	Start Time	ΔP (psid) at t = 2 min	ΔP (psid) at t = 4 min	ΔP (psid) at t = 6 min	ΔP (psid) at t = 8 min	ΔP (psid) at t = 10 min
1	6/7/2021	10:20	0.34	0.52	0.78	0.92	1.04
2	6/7/2021	10:54	0.38	0.41	0.52	0.59	0.63
3	6/7/2021	13:05	0.30	0.45	0.76	0.90	1.00
4	6/7/2021	13:57	0.44	0.77	1.01	1.18	1.31
5	6/7/2021	16:51	0.39	0.73	0.95	1.11	1.27
6	6/7/2021	18:39	0.49	0.81	1.22	1.35	1.51
7	6/7/2021	20:27	0.52	0.92	1.16	1.32	1.51
8	6/7/2021	22:12	0.78	1.14	1.32	1.53	1.68
9	6/8/2021	00:09	0.50	0.91	1.10	1.25	1.42
10	6/8/2021	01:45	0.75	1.23	1.43	1.63	1.83
11	6/8/2021	03:21	0.31	0.57	0.82	0.96	1.09
12	6/8/2021	05:15	0.48	0.83	1.10	1.29	1.41
13	6/8/2021	07:03	0.36	0.69	0.97	1.11	1.23
14	6/8/2021	08:50	0.47	0.92	1.21	1.39	1.52
15	6/8/2021	10:30	0.38	0.71	0.87	1.00	1.13
16	6/8/2021	12:17	0.50	0.91	1.16	1.33	1.44
17	6/8/2021	14:08	0.31	0.59	0.82	0.98	1.08
18	6/8/2021	16:03	0.43	0.83	1.09	1.24	1.34
19	6/8/2021	17:51	0.35	0.55	0.78	0.91	1.01
20	6/8/2021	19:54	0.42	0.77	1.01	1.21	1.27
21	6/8/2021	22:03	0.49	0.89	1.01	1.14	1.24
22	6/8/2021	23:57	0.51	0.92	1.17	1.33	1.43
23	6/9/2021	01:56	0.44	0.86	1.05	1.16	1.32
24	6/9/2021	03:51	0.47	0.94	1.22	1.39	1.54
25	6/9/2021	05:41	0.33	0.63	0.83	0.98	1.09
26	6/9/2021	07:32	0.50	0.97	1.21	1.36	1.49
27	6/9/2021	09:25	0.26	0.51	0.83	0.97	1.08
28	6/9/2021	11:27	0.50	0.81	1.06	1.21	1.30
29	6/9/2021	13:31	0.29	0.52	0.77	0.89	0.99
30	6/9/2021	15:42	0.58	0.94	1.13	1.25	1.37
31	6/9/2021	17:56	0.42	0.70	0.82	0.90	0.94

DEF Segment	Date	Start Time	ΔP (psid) at t = 2 min	ΔP (psid) at t = 4 min	ΔP (psid) at t = 6 min	ΔP (psid) at t = 8 min	ΔP (psid) at t = 10 min
32	6/9/2021	20:08	0.41	0.74	0.94	1.03	1.09
33	6/9/2021	22:24	0.46	0.73	0.81	0.87	0.90
34	6/10/2021	00:35	0.47	0.75	0.93	1.04	1.07
35	6/10/2021	02:50	0.25	0.48	0.65	0.72	0.76
36	6/10/2021	05:06	0.39	0.68	0.84	0.90	0.94
37	6/10/2021	07:23	0.24	0.38	0.63	0.68	0.72
38	6/10/2021	09:38	n/m	n/m	0.80	0.87	0.92
39	6/10/2021	12:03	0.20	0.35	0.61	0.67	0.72
40	6/10/2021	14:22	n/m	n/m	0.89	0.91	0.94
41	6/10/2021	16:32	0.27	0.47	0.64	0.70	0.73
42	6/10/2021	19:01	0.32	0.55	0.75	0.85	0.88
43	6/10/2021	21:15	0.47	0.66	0.70	0.74	0.77
44	6/10/2021	23:26	0.37	0.63	0.82	0.90	0.92
45	6/11/2021	01:37	0.26	0.45	0.62	0.68	0.71
46	6/11/2021	03:51	0.36	0.59	0.77	0.84	0.88
47	6/11/2021	06:05	0.25	0.42	0.61	0.67	0.70
48	6/11/2021	08:18	0.36	0.61	0.81	0.86	0.88
49	6/11/2021	10:37	0.23	0.42	0.59	0.66	0.70
50	6/11/2021	12:51	0.36	0.64	0.77	0.85	0.90
51	6/11/2021	15:06	0.21	0.36	0.58	0.65	0.68
52	6/11/2021	17:16	0.39	0.65	0.81	0.89	0.93
53	6/11/2021	19:33	0.22	0.41	0.59	0.63	0.68
54	6/11/2021	21:44	0.40	0.70	0.83	0.91	0.97
55	6/11/2021	23:55	0.23	0.48	0.60	0.64	0.70
56	6/12/2021	02:05	0.37	0.66	0.81	0.85	0.87
57	6/12/2021	04:18	0.21	0.36	0.57	0.64	0.67
58	6/12/2021	06:34	0.34	0.56	0.75	0.82	0.85
59	6/12/2021	08:49	0.20	0.34	0.56	0.63	0.68
60	6/12/2021	11:06	0.36	0.58	0.75	0.80	0.84
61	6/12/2021	13:31	0.19	0.32	0.55	0.62	0.65
62	6/12/2021	15:43	0.36	0.59	0.76	0.82	0.85
63	6/12/2021	17:58	0.22	0.35	0.55	0.62	0.64
64	6/12/2021	20:08	0.30	0.57	0.72	0.80	0.82

DEF Segment	Date	Start Time	ΔP (psid) at t = 2 min	ΔP (psid) at t = 4 min	ΔP (psid) at t = 6 min	ΔP (psid) at t = 8 min	ΔP (psid) at t = 10 min
65	6/12/2021	22:19	0.18	0.32	0.55	0.60	0.65
66	6/13/2021	00:30	0.35	0.63	0.73	0.76	0.82
67	6/13/2021	02:39	0.23	0.37	0.57	0.62	0.66
68	6/13/2021	04:51	0.38	0.58	0.75	0.81	0.82
69	6/13/2021	07:03	0.21	0.36	0.57	0.61	0.65
70	6/13/2021	09:33	0.31	0.47	0.69	0.77	0.80
End of Test	6/13/2021	12:17	n/m	n/m	n/m	n/m	n/m

Appendix C – Time Series of Test Data

In this appendix, time traces of data collected during the scaled system testing are presented for the four tests that were conducted (NB1, HS1, HS2, and HS3). Each test has the same four time series plots presented in the same order: (1) system temperatures versus elapsed time, (2) flow rate versus elapsed time, (3) system pressures versus elapsed time, and (4) filter differential pressures versus elapsed time. The plots capture manually recorded data which is also presented in tabular form in Appendix B; therefore, the time series data are presented in the remainder of this appendix without any additional description.

C.1 Time Traces for Test NB1

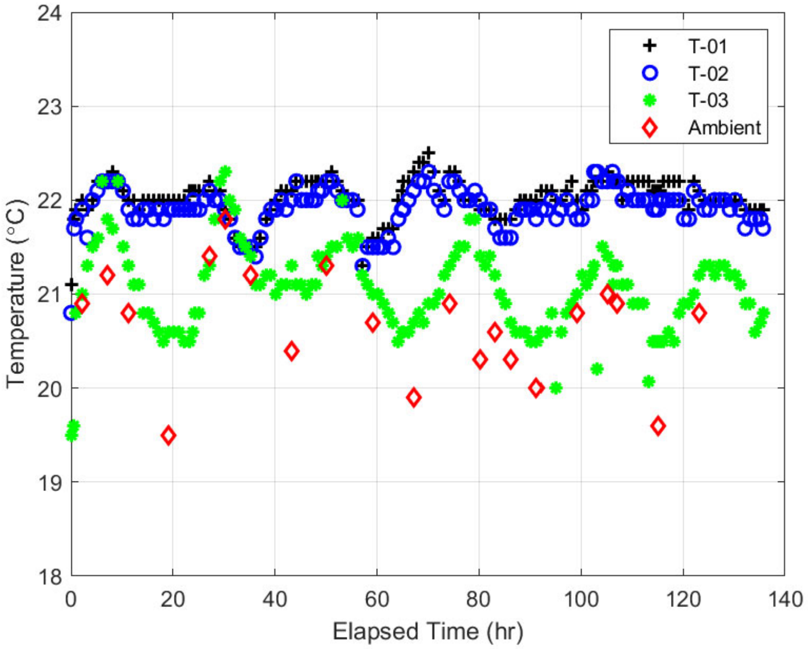

Figure C.1. Time Series of System Temperatures for Test NB1: T-01 (TK-01 temperature, black crosses); T-02 (feed line temperature, blue open circles); T-03 (effluent temperature, green closed circles), and Ambient (ambient measurements, red diamonds).

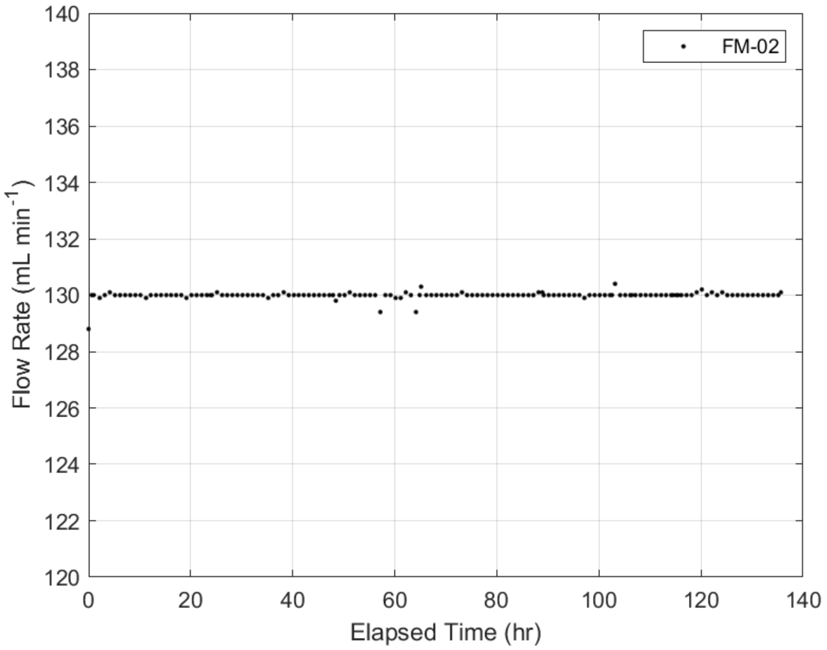

Figure C.2. Time Series of Flow Rate (FM-02) for Test NB1.

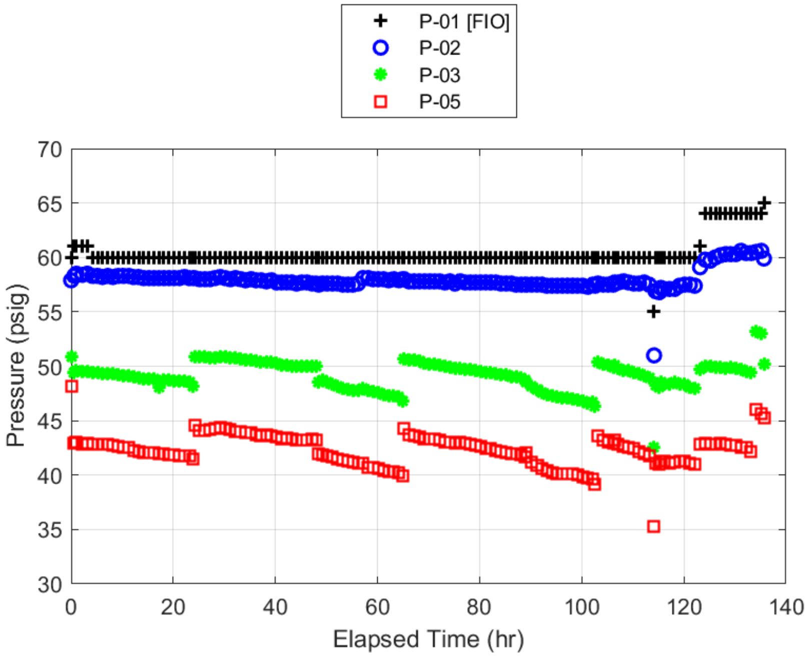

Figure C.3. Time Series of System Pressures for Test NB1: P-01 (FIO recirculation loop pressure, black crosses); P-02 (feed line pressure, blue open circles); P-03 (column entrance pressure, green closed circles); and P-05 (column exit pressure, red squares).

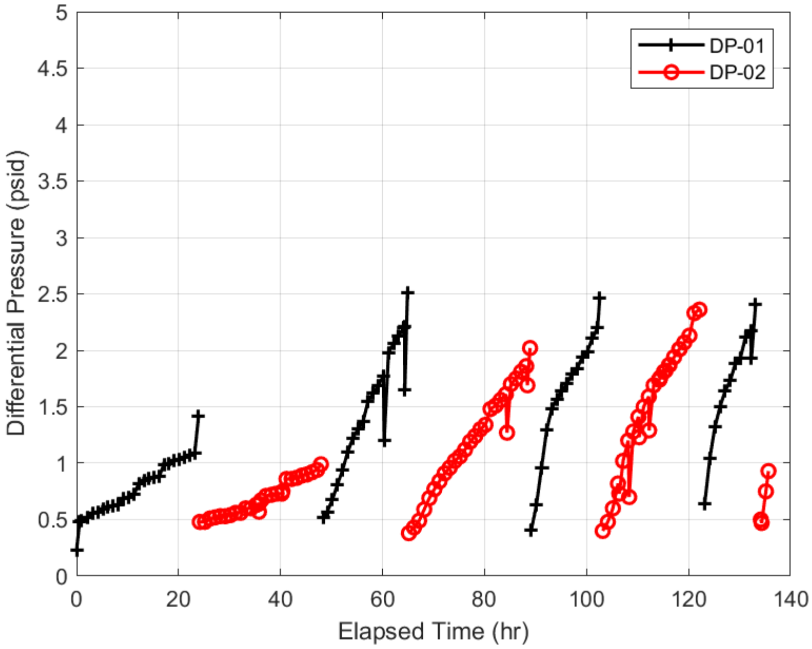

Figure C.4. Time Series of Differential Pressures for DEF-01 (instrument DP-01, black lines with crosses) and DEF-02 (instrument DP-02, red lines with circles) Recorded during Test NB1.

C.2 Time Traces for Test HS1

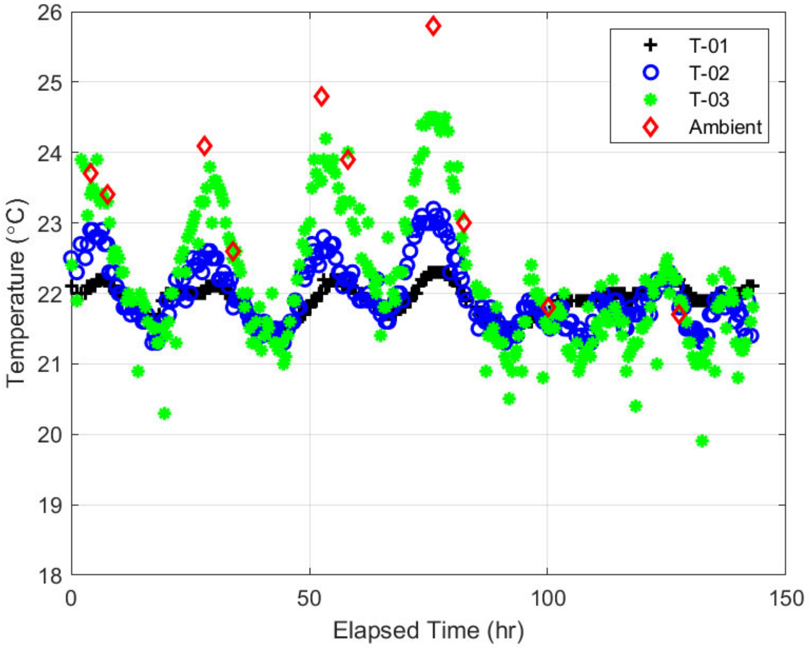

Figure C.5. Time Series of System Temperatures for Test HS1: T-01 (TK-01 temperature, black crosses); T-02 (feed line temperature, blue open circles); T-03 (effluent temperature, green closed circles), and Ambient (ambient measurements, red diamonds).

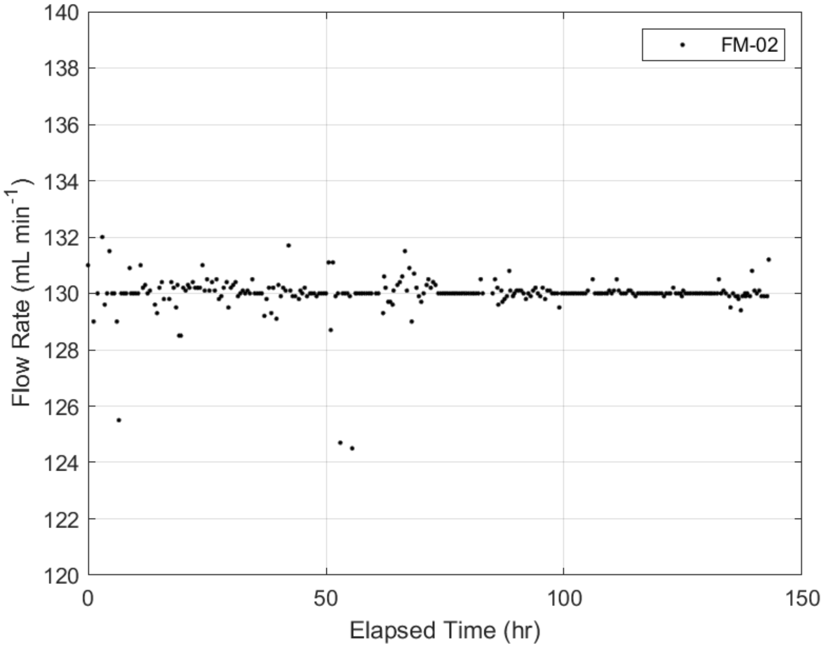

Figure C.6. Time Series of Flow Rate (FM-02) for Test HS1.

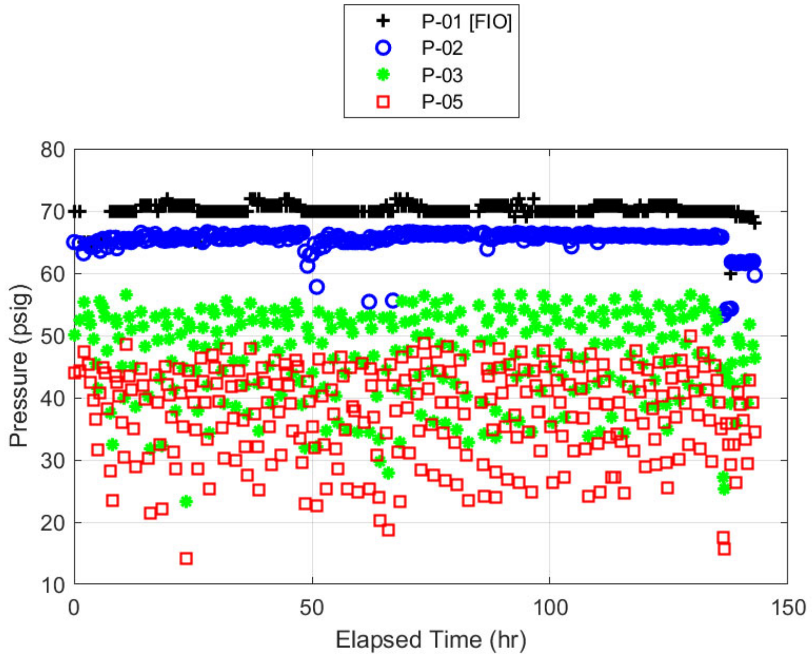

Figure C.7. Time Series of System Pressures for Test HS1: P-01 (FIO recirculation loop pressure, black crosses); P-02 (feed line pressure, blue open circles); P-03 (column entrance pressure, green closed circles); and P-05 (column exit pressure, red squares).

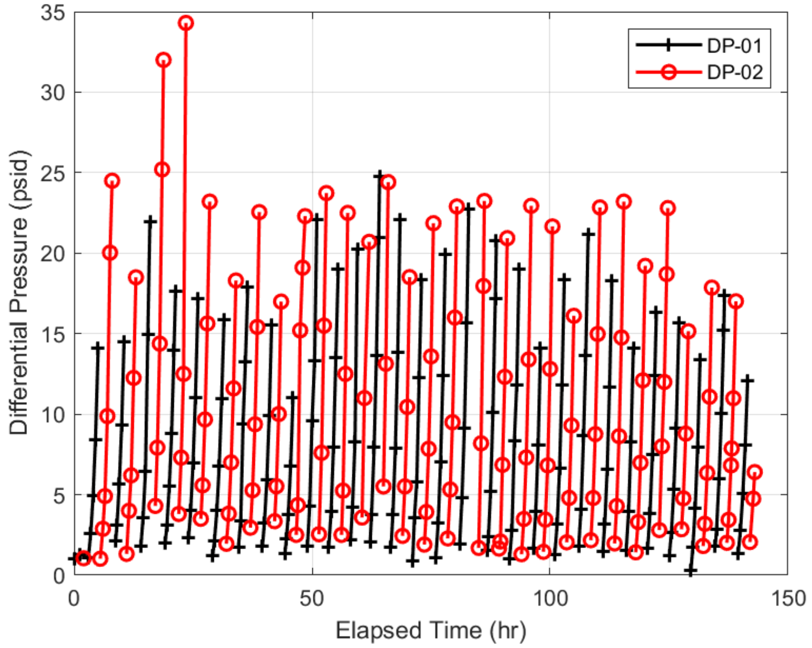

Figure C.8. Time Series of Differential Pressures for DEF-01 (instrument DP-01, black lines with crosses) and DEF-02 (instrument DP-02, red lines with circles) Recorded during Test HS1.

C.3 Time Traces for Test HS2

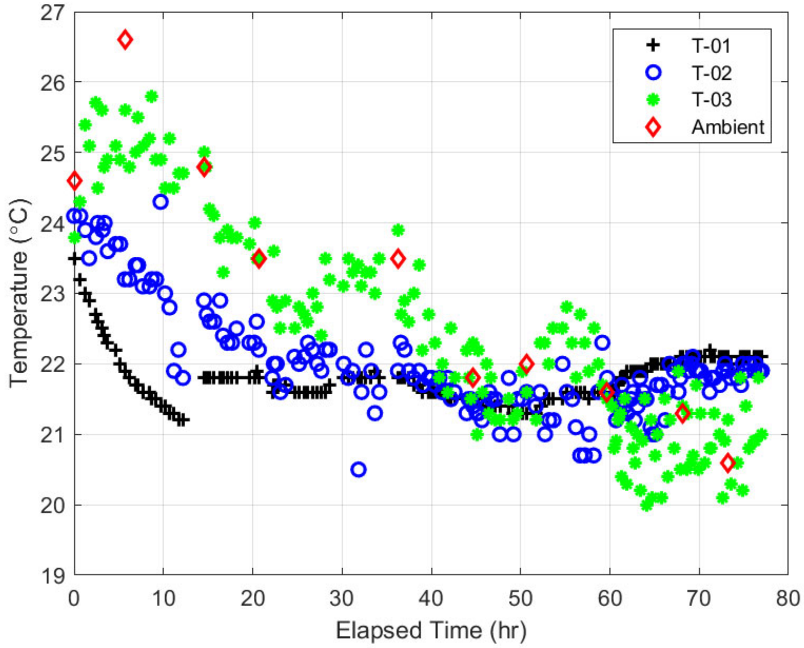

Figure C.9. Time Series of System Temperatures for Test HS2: T-01 (TK-01 temperature, black crosses); T-02 (feed line temperature, blue open circles); T-03 (effluent temperature, green closed circles), and Ambient (ambient measurements, red diamonds).

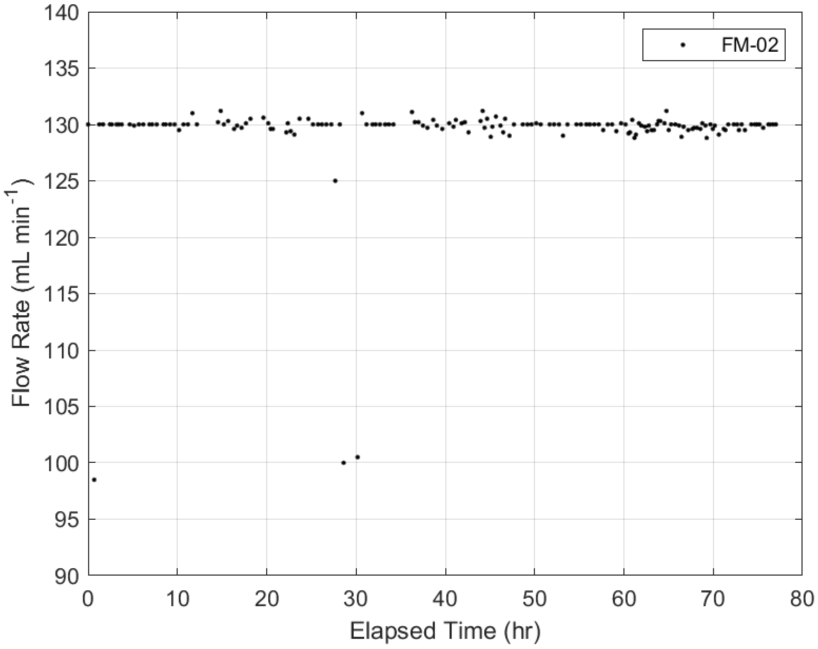

Figure C.10. Time Series of Flow Rate (FM-02) for Test HS2.

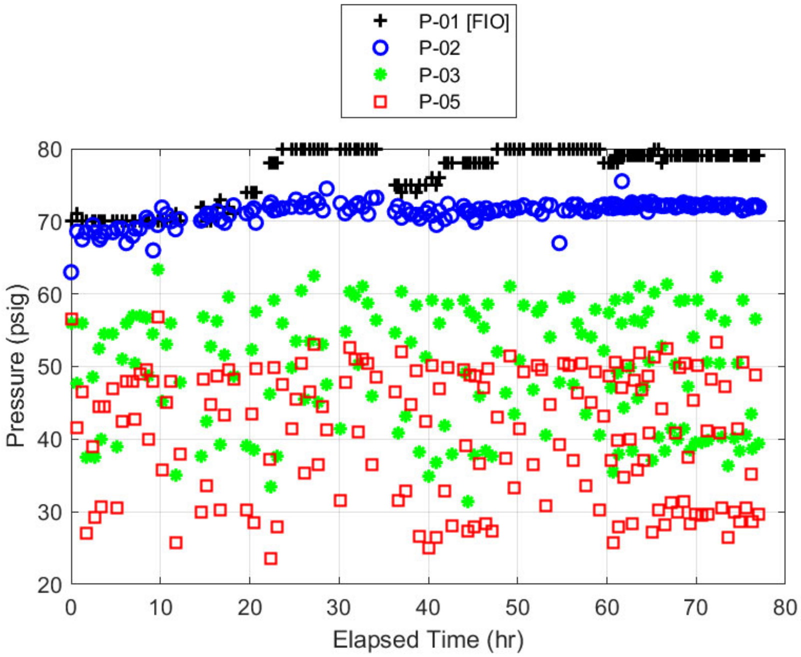

Figure C.11. Time Series of System Pressures for Test HS2: P-01 (FIO recirculation loop pressure, black crosses); P-02 (feed line pressure, blue open circles); P-03 (column entrance pressure, green closed circles); and P-05 (column exit pressure, red squares).

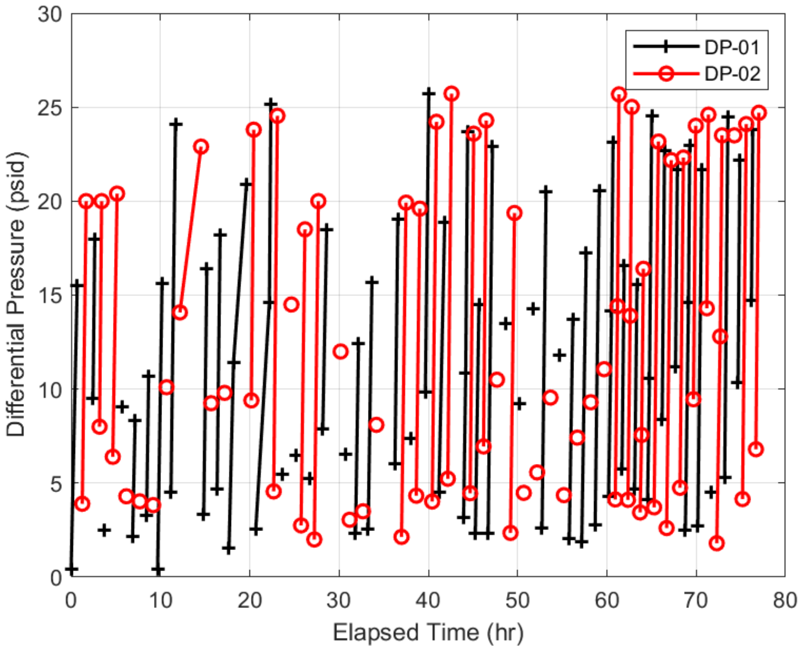

Figure C.12. Time Series of Differential Pressures for DEF-01 (instrument DP-01, black lines with crosses) and DEF-02 (instrument DP-02, red lines with circles) Recorded during Test HS2.

C.4 Time Traces for Test HS3

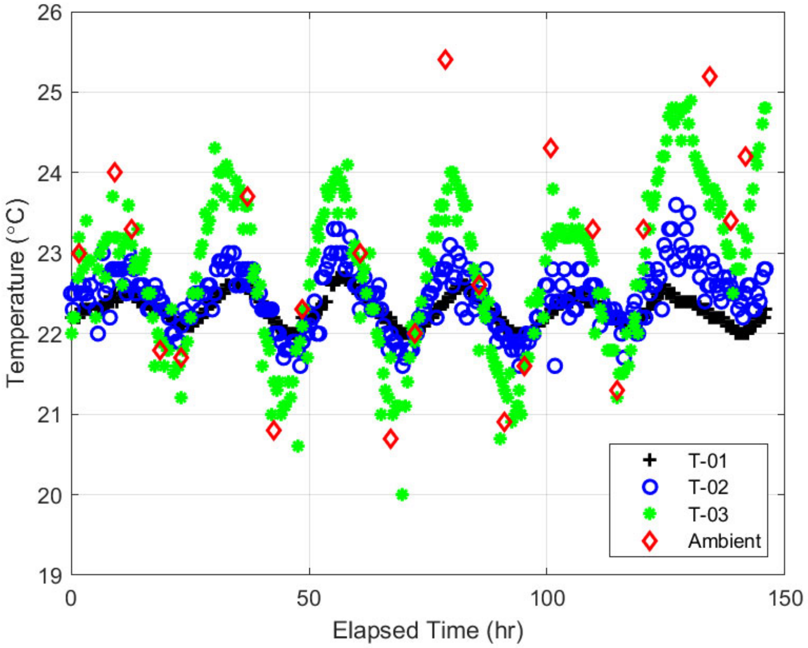

Figure C.13. Time Series of System Temperatures for Test HS3: T-01 (TK-01 temperature, black crosses); T-02 (feed line temperature, blue open circles); T-03 (effluent temperature, green closed circles), and Ambient (ambient measurements, red diamonds).

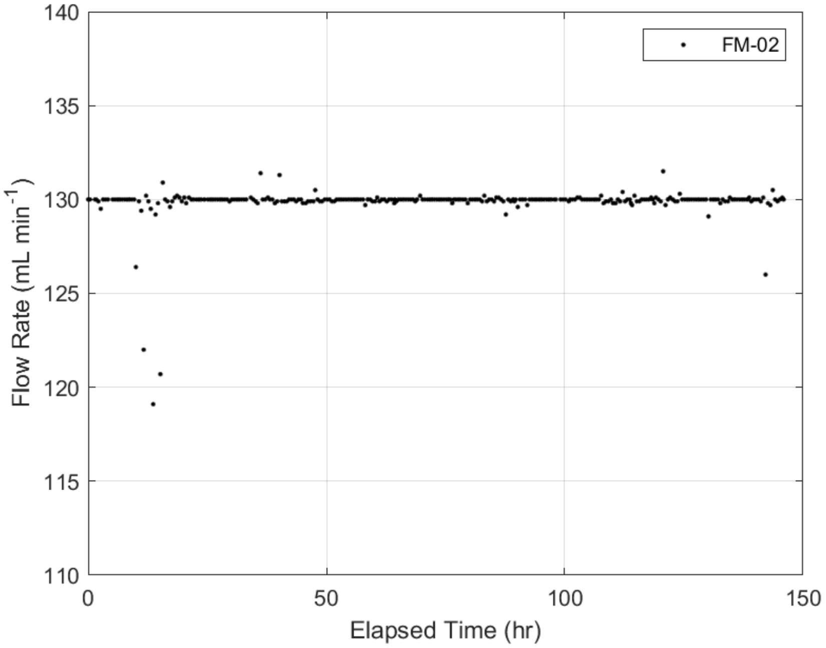

Figure C.14. Time Series of Flow Rate (FM-02) for Test HS3.

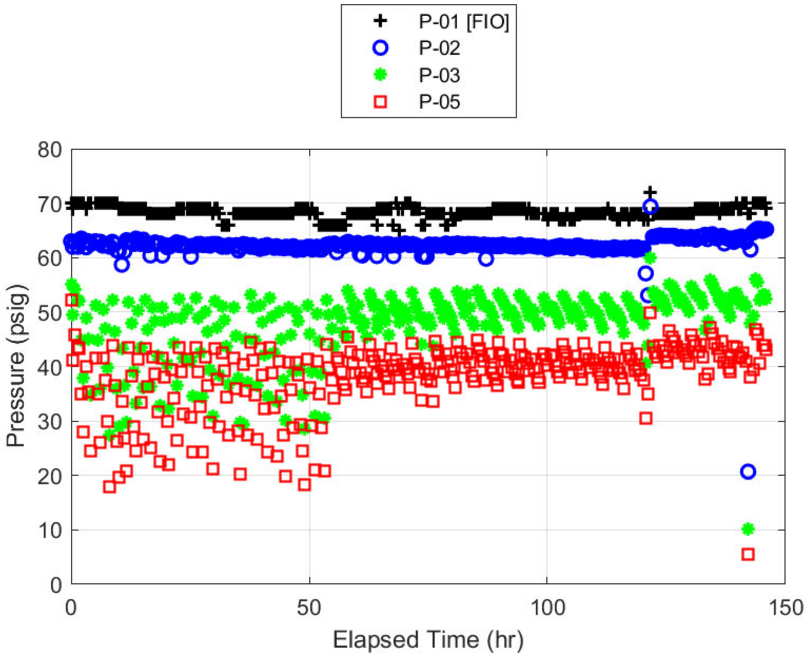

Figure C.15. Time Series of System Pressures for Test HS3: P-01 (FIO recirculation loop pressure, black crosses); P-02 (feed line pressure, blue open circles); P-03 (column entrance pressure, green closed circle); and P-05 (column exit pressure, red squares).

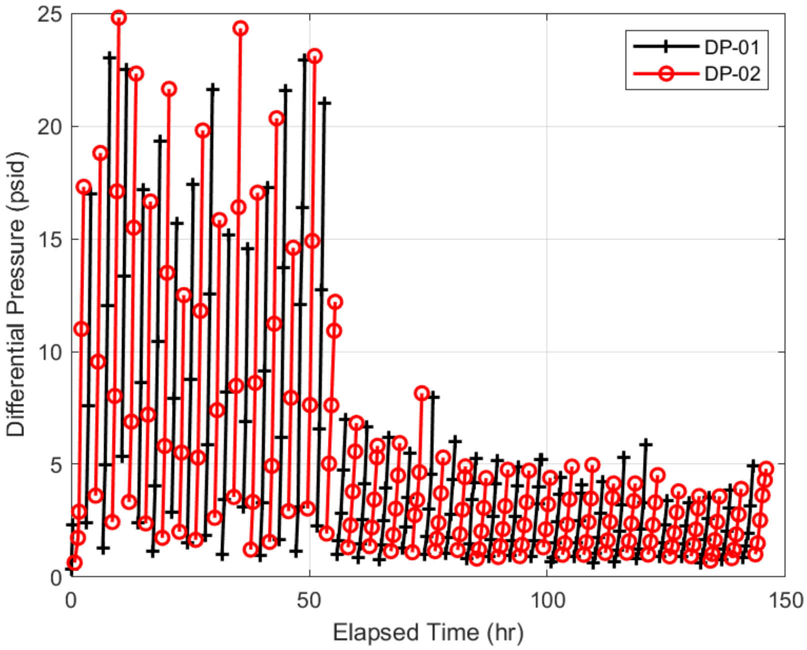

Figure C.16. Time Series of Differential Pressures for DEF-01 (instrument DP-01, black lines with crosses) and DEF-02 (instrument DP-02, red lines with circles) Recorded During Test HS3.

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