Hanford Tank BY-108 Thermal Oxidation System Performance Testing Methodology – 21055

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ABSTRACT

In 2014, the Tank Vapor Assessment Team identified the need to provide engineered controls to protect tank farm workers from toxic organic vapors emitted from Hanford high-level waste tanks. Toxic organic species found in the vapor phase are referred to as chemicals of potential concern (COPCs). In response to this need, NUCON International, Inc. (NUCON) presented a proposal to the 2016 U.S. Department of Energy Office of River Protection Grand Challenge competition for treating headspace COPCs using a novel thermal oxidation system (TOS). The TOS directs tank vapors to an internal combustion engine, where they are destroyed in-cylinder by the engine combustion and the engine's exhaust aftertreatment. NUCON developed a prototype of the proposed system and conducted proof-of-concept tests (Phase 1). Upon successful completion of NUCON's proof-of-concept testing, Washington River Protection Solutions (WRPS) partnered with Pacific Northwest National Laboratory (PNNL) to conduct an engineering-scale evaluation (i.e., Phase 2) using a modified version of the NUCON TOS.

The Phase 2 testing was conducted by selecting 11 COPC surrogates (out of 61 identified COPCs in total) and quantitatively measuring them at various points in the TOS. These measurements were performed using both online instruments and grab samples and were reported in 2019. The Phase 2 TOS testing concluded that 8 of the 11 COPCs were successfully removed to the target criterion (95% destruction) and all but one could be detected down to 10% of the occupational exposure limit. Though the testing was successful, Phase 2 testing was focused on 11 COPC compounds; consequently, testing was not performed with complex mixtures of COPCs (as would be found in Hanford tank headspaces) nor did it demonstrate successful operation of the MERSORB® bed (mercury-selective adsorption functionality). Therefore, to evaluate the full functionality of the TOS, WRPS decided to proceed with planning for a Phase 3 demonstration test to be performed in the Hanford tank farm.

After a site selection process, Hanford tank BY-108 was chosen as the candidate tank for the Phase 3 TOS testing. Currently, the design of the NUCON TOS planned for deployment at Hanford tank BY-108 is nearing completion. In parallel with the TOS design and fabrication process, PNNL developed a set of Phase 3 testing objectives and metrics to critically assess "real-world" performance of the TOS system. An important part of the testing methodology is to collect Phase 3 performance data using a sampling system that will be co-located with the TOS at BY-108. The sampling system is designed to collect a series of sorption tube, cartridge, and canister samples to measure COPC levels simultaneously at TOS inlet (BY-108 vapor stream) and outlet (exhaust) locations. The TOS methods, objectives, and metrics developed by PNNL to support Phase 3 testing were selected to define TOS operating effectiveness and potential for protecting Hanford workers from harmful vapor exposure.

INTRODUCTION

The possibility of chemical vapor exposure in the Hanford tank farms has been the subject of a series of assessments, reports, and recommendations over the past couple decades. The primary concern with chemical vapor exposure is the health of tank farm workers and both acute and potential chronic impacts. In 2014, Washington River Protection Solutions (WRPS) set out to identify and implement mitigations to reduce or remove the concern, beginning with the commissioning of an independent panel of experts known as the Hanford Tank Vapor Assessment Team. Their summary report was issued in 2014 [1], and among its recommendations [OR 7] is to “accelerate implementation of tailored engineering technologies to detect and control vapor emissions.” This recommendation is one of many; the tank vapors issue is complex and no one mitigation strategy is likely to completely alleviate the concerns.

One of the tailored engineering technologies under development arose from a 2016 proposal by NUCON International, Inc. NUCON proposed to use a novel thermal oxidation system (TOS) to directly treat tank headspace gas using internal combustion and exhaust aftertreatment. The TOS has progressed through prototype (Phase 1) and engineering-scale (Phase 2) test programs, and preparations are being made for an at-tank demonstration test in the Hanford tank farm, e.g., Phase 3. The rest of the paper discusses some relevant background information from previous test efforts and the planned approach for Phase 3 testing based on the expected TOS deployment.

BACKGROUND

Historically, the focus of tank vapor assessments has been a list of compounds known as chemicals of potential concern (COPCs). The current list for Hanford tank farms contains 61 compounds that include an array of species: inorganic compounds, hydrocarbons (primary olefinic species), alcohols, ketones, aldehydes, furans and substituted furans, phthalates, nitriles, amines, nitrosamines, organophosphates and organophosphonates, halogenated hydrocarbons, pyridines, organonitrites, organonitrates, and isocyanates. These compounds have been identified in varying amounts depending on the tank, its waste history, and the sampling/analysis tools available. An important benchmark is the occupational exposure limit (OEL) established by Hanford tank farms for each COPC.

In order to focus the scope of initial testing of the TOS, the full suite of 61 COPCs was not considered. Rather, a target list was developed based on a series of considerations, including (1) identifying COPCs that could be a surrogate for classes of compounds (e.g., 1,3-butadiene for hydrocarbon species, benzene for aromatic species, etc.), (2) selecting those compounds that would have the potential to survive combustion chemistry, (3) filling in uncertainties in combustion chemistry, and (4) availability of the compound for use in testing (as well as detection methods to measure it). A target list of 11 COPCs was developed and then cross-referenced against the maximum measured concentrations of those compounds in the Hanford single-shell tanks (SSTs) (see [2] for more information). The target list was used for testing in Phase 2.

The Phase 1 NUCON TOS proof-of-concept testing was based on a stoichiometric (i.e., spark ignition) propane engine and an 11.4-kVA generator. Due to potential nuclear safety and operational issues identified for the use of a propane-based system, the decision was made to terminate further testing with propane and proceed with a diesel-based system. For the Phase 2 evaluation, the TOS was modified by replacing the stoichiometric propane generator and three-way catalyst aftertreatment with a 15-kVA diesel generator plus aftertreatment (i.e., a diesel oxidation catalyst and a diesel particulate filter). The Phase 2 TOS is pictured in Fig. 1. The Phase 2 testing was conducted at Pacific Northwest National Laboratory (PNNL) by injecting the 11 COPC target compounds (for reference, test concentrations are shown in TABLE I) and quantitatively measuring them at various points in the TOS. These measurements were performed using both online instruments and grab samples.

A key element of the NUCON TOS is a mercury-selective absorption bed (the MERSORB® bed) which is intended to remove mercury from the vapor stream. This technology was not tested in Phase 2 and instead was deferred to subsequent testing. The Phase 2 testing program and results are described in detail in [3].

Fig. 1. Engineering-Scale Configuration of the TOS used in Phase 2 Testing at PNNL.

The Phase 2 TOS testing concluded that 8 of the 11 COPCs were successfully removed to the target criterion of 95% destruction (refer to TABLE I). All but one of the tested COPCs were demonstrated to be detectable at ≤10% of their OELs. The exception was NDMA, which had a very low concentration at 10% OEL – 0.03 ppb. However, the testing did not involve complex mixtures of COPCs (as would be found in Hanford tank headspaces) or attempt to demonstrate successful operation of the MERSORB® bed [3]. Based on that information, WRPS decided to proceed with planning for a Phase 3 test to be performed in the Hanford tank farm. It is anticipated that an at-tank deployment of the system would address the remaining technical uncertainties regarding TOS performance and serve as a demonstration of the mitigation approach for SSTs.

TABLE I. Selected COPCs Tested in Phase 2 at PNNL. The COPCs were tested at 200% of the OEL and, as appropriate, at a higher concentration (see comparison with maximum concentration values). Values that are highlighted did not achieve a > 95% destruction of the COPC.

CAS	Name	Maximum Concentration (COPC or surrogate)	200% OEL[a] Test	High Concentration Test	Analytical Method
75-07-0	Acetaldehyde	39 ppm	50 ppm	– [b]	PTR-MS
75-05-8	Acetonitrile	18.8 ppm	40 ppm	– [b]	PTR-MS
71-43-2	Benzene	0.189 ppm	1 ppm	– [b]	PTR-MS
107-12-0	Propanenitrile	0.78 ppm	12 ppm	– [b]	PTR-MS
106-99-0	1,3-Butadiene	3.38 ppm	3.4 ppm[c]	– [c]	PTR-MS
50-00-0	Formaldehyde	0.157 ppm	0.6 ppm	– [b]	PTR-MS
108-47-4	2,4-Dimethylpyridine	0.147 ppm	1 ppm	– [b]	PTR-MS
62-75-9	N-Nitrosodimethylamine	0.0621 ppm	0.0006 ppm	0.062 ppm	PTR-MS
110-00-9	Furan	0.721 ppm[c]	0.002 ppm	0.017 ppm	PTR-MS
7664-41-7	Ammonia	2,502 ppm[d]	50 ppm	630 ppm	FTIR
10024-97-2	Nitrous Oxide	831 ppm	100 ppm	831 ppm	FTIR

[a] Hanford tank farm OEL.
[b] No maximum concentration test required since the testing conditions at 200% OEL already bounded the high concentration test conditions.
[c] Due to comparatively similar values for 1,3-butadiene for 200% OEL concentration and the maximum applicable observed concentration, it was decided to increase the concentration of 1,3-butadiene employed in the 200% OEL to be inclusive of both values.
PTR-MS = proton transfer reaction mass spectrometer instrument; FTIR = Fourier-transform infrared spectroscopy instrument.

METHODS

The design of the TOS unit and supporting equipment for the demonstration testing on Hanford tank BY-108 remains ongoing at the time of this writing; once completed, the system will be fabricated, assembled, and shook down in preparation for the testing phase. The methods discussed in this section focus on the technical basis for the planned testing and a discussion of the sampling approach that will be used to assess performance.[1]

Selection of BY-108 for Demonstration

Selection of a good candidate tank for the at-tank deployment of the NUCON TOS was based on historical COPC data as well as site access, available utilities, and presence of an available riser. The site selection process is discussed in [4]. BY-108 was chosen based on having the greatest weighted score when evaluated against a matrix of criteria, which was heavily influenced by it having sixteen COPCs detected at greater than 10% OEL according to the Site-Wide Industrial Hygiene Database (SWIHD, publicly available at www.tankvaporsexplorer.com). This assessment was also supported by recent cartridge testing analysis of BY-108 reported by PNNL [5].

[1] A thorough discussion of the test approach, configuration, and methods is presented in the current revision of the test plan for Phase 3 TOS testing: Rappe KG, "NUCON TOS BY-108 Demonstration Testing," TP-TOSP3-001, Rev. 0.0, Pacific Northwest National Laboratory, Richland, WA.

The PNNL cartridge testing analysis also summarizes BY-108 historical data; the tank has measurements for almost half of the 61 COPCs (29) at levels above 1% of the compound's OEL, which offers the potential for a representative complex mixture of COPCs in the headspace gas. These compounds, their OELs, and their maximum measured concentrations (as %OEL), are listed in TABLE II. For reference, the sorption tubes or canisters that would be used to analyze for each compound are also listed. The entire suite of 29 compounds can be measured by nine sorption tubes and a SUMMA® canister sample. This forms the basis for the sample collection approach discussed later in this section.

TABLE II. Maximum COPC Concentrations Measured in BY-108. The COPCs shown are above 1% of the OEL, which defines the set of analytes for the Phase 3 testing; also shown is the sample tube that will be used.

COPC/Compound Name	OEL Value	OEL Units	Maximum Value (Post-2005) Measured as %OEL	Required Sorption Tube or Canister
Ammonia	25	ppm	2576%	Anasorb 747 (sulfuric acid), SKC-226-29
NDMA	0.3	ppb	2063%	Thermosorb/N
Furan	1	ppb	1840%	Carbotrap 300 TDU VOA
1,3-Butadiene	1	ppm	338%	Charcoal SKC-226-37 (Parts A and B)
NMEA	0.3	ppb	251.9%	Thermosorb/N
Acetonitrile	20	ppm	94.0%	Charcoal Tube, SKC-226-09 and Carbotrap 300 TDU
2,3-Dihydrofuran	1	ppb	74.5%	TDU Tenax
Mercury	0.025	mg m^{-3}	68.0%	Anasorb C300, SKC-226-17-1A
2,5-Dihydrofuran	1	ppb	43.8%	TDU Tenax
NDEA	0.1	ppb	34.5%	Thermosorb/N
3-Buten-2-one	0.2	ppm	23.5%	Carbotrap 300 TDU VOA
1-Butanol	20	ppm	21.6%	Carbotrap 300 TDU VOA
N-Nitrosomorpholine	0.6	ppb	18.3%	Thermosorb/N
2-Methylfuran	1	ppb	12.3%	Carbotrap 300 TDU VOA
Acetaldehyde	25	ppm	11.3%	DNPH Treated Silica Gel, SKC-226-119
2-Propylfuran	1	ppb	11.1%	Carbotrap 300 TDU VOA
Formaldehyde	0.3	ppm	8.56%	DNPH Treated Silica Gel, SKC-226-119
Ethylamine	5	ppm	3.63%	XAD-7 (NBD) Chloride), SKC 226-96
Nitrous Oxide	50	ppm	3.60%	SUMMA® Canister
2-Pentylfuran	1	ppb	3.57%	TDU Tenax
Benzene	0.5	ppm	2.00%	Carbotrap 300 TDU VOA

Testing Performance Standards and Objectives

Phase 3 plans to adopt a similar set of performance standards as Phase 2 with modifications to reflect the composition of BY-108. The performance standards for Phase 3 testing are proposed as follows:

1. At the point of emissions from the NUCON TOS, the target COPCs will individually have a 95% destruction [as measured by destruction removal efficiency (DRE)]. DRE will be determined using inlet and exhaust sorbent tube or SUMMA® canister samples with approved analytical methods at certified laboratories.
2. At the point of emissions from the NUCON TOS, volatile organic compounds (VOCs) measured in aggregate will have a collective concentration of less than 500 ppm as determined using:
    a. Summation of analytical results from sorbent tube and SUMMA® canister samples for calibrated compounds and approved methods (VOCs, aldehydes, nitrosamines)
    b. A commercial photo-ionization detector
3. At the point of emissions from the NUCON TOS, select COPCs will have individual concentrations of ≤ 10% of their Hanford tank farm OELs.
    a. Whenever the detection method makes it possible, the concentration will be quantified and compared to the target level of 10% of the OEL concentration for that COPC. [2]
    b. For any offline analyses with a detection or reporting limit greater than 10% of the OEL, the concentration in the TOS exhaust will be quantified and reported as a percentage of OEL.[3]
4. The TOS is demonstrated to operate reliably and achieve a nominal steady-state while interacting with the BY-108 headspace vapors. Based on Phase 2 testing, the best real-time proxy for assessing steady state is a catalytic converter temperature of at least 660 °F that is not changing rapidly over a period of approximately 5 minutes.

These performance standards will be accomplished via the following objectives for the Phase 3 testing:

1. Complete a performance test of the full NUCON TOS (including the MERSORB® bed) for destruction of COPCs from the BY-108 headspace.
2. Measure VOCs, in aggregate, at the TOS exhaust and determine if the system meets the performance standard.
3. Execute offline sampling methods for measuring select COPC concentrations in the diesel exhaust with ambient air intake to the TOS to establish the baseline emission profile for these COPCs.
4. Demonstrate proper operation of the TOS when connected to BY-108 headspace and characterize elements of its performance:
    a. Operate the NUCON MERSORB® bed, diesel engine, and catalytic converter to reach an operating steady state (this presumably has steady-state TOS exhaust vapors). Ideally, this would include saturating the MERSORB® bed with organic constituents so the true performance of the TOS will be measured.[4]

[2] It will be assumed during the comparison that the "10% of the OEL" criterion is met if the detection limit is below 10% of the OEL and the results are below the detection limit. Data that is below the analytical detection/reporting limits as established by the measuring laboratory will not be quantified.

[3] Based on Phase 2 data, this is anticipated to be only a small percentage of analytes. Of the 11 COPCs tested in Phase 2, 9 were detected at or below 10% of the OEL in the exhaust using offline sampling techniques [3].

[4] It is expected that the TOS will have a startup phase where the constituents in the vapor phase are equilibrating with the MERSORB® bed. During initial operation of the TOS, data will be collected to establish that bed equilibration has or has not occurred. However, even if it is determined that it has not (or the data are indeterminate),

   b. If test operation permits, estimate the operating volumetric flow rate of the NUCON TOS during steady-state operation.
5. Determine if the TOS maintains a negative pressure on the BY-108 headspace for a period of sustained operation. Furthermore, over this same period, perform measurements to determine if COPC TOS inlet concentrations are reduced over time.[5]
6. During steady periods of TOS operation:
   a. Execute the sampling methods that will collect the necessary data to determine the efficacy of the TOS MERSORB® bed, e.g., measure the mercury concentration before and after the bed.
   b. Execute the offline sampling methods to collect data for measuring the impact of TOS operation on select COPC concentrations via samples collected prior to the TOS and at selected points after the TOS (minimally the exhaust).
7. Calculate the DRE for each measured select COPC and mercury using the data generated from the relevant sampling methods. Estimate the approximate uncertainty in the DRE calculation based on known analytical uncertainties, if available.

Overview of the Phase 3 TOS Configuration

The NUCON TOS will be tested by physically linking the system to the BY-108 headspace through a riser pipe and drawing gas from the headspace through the system. The Phase 3 TOS design is in preparation (by NUCON and their subcontractors) and is not complete as of this writing. The design is modular with two skids (filtration and TOS) and is installed and removed with minimal construction. A general schematic reflecting the major system components is shown in Fig. 2. The design will include similar functionality to the TOS tested in Phase 2, with the addition of front-end equipment to remove radioactive particulate from the BY-108 tank vapor. The pretreatment equipment includes a demister, prefilter, heater, high-efficiency particulate air (HEPA) filters, and a continuous radiological monitoring system. The filtration skid is intended to mitigate radiological hazards, provide a vapor stream that has low relative humidity, and achieve a temperature that is conducive to the operation of the MERSORB® bed.

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samples will also be collected after the MERSORB® bed (prior to the engine) to establish the true abatement performance of the TOS. The MERSORB® bed can be bypassed but will not be unless dictated by test conditions.

[5] A sustained negative pressure on the tank headspace demonstrates the ability of the TOS to prevent headspace vapors from being released through the passive breather filter or other fugitive emission points during TOS operation, thus protecting workers and potentially eliminating the need for respiratory protection and personal/area monitoring for COPCs. The BY-108 TOS was sized for a single SST and not for a series of SSTs connected in a cascade as is believed to be the case for BY-108. The SST cascade introduces the possibility that this test will not be successful. However, it is important to know if the TOS will reduce headspace concentrations in SSTs over time (presumably to an equilibrium level) where the COPC generation rate is equal to the COPC TOS removal rate (flow rate × concentration).

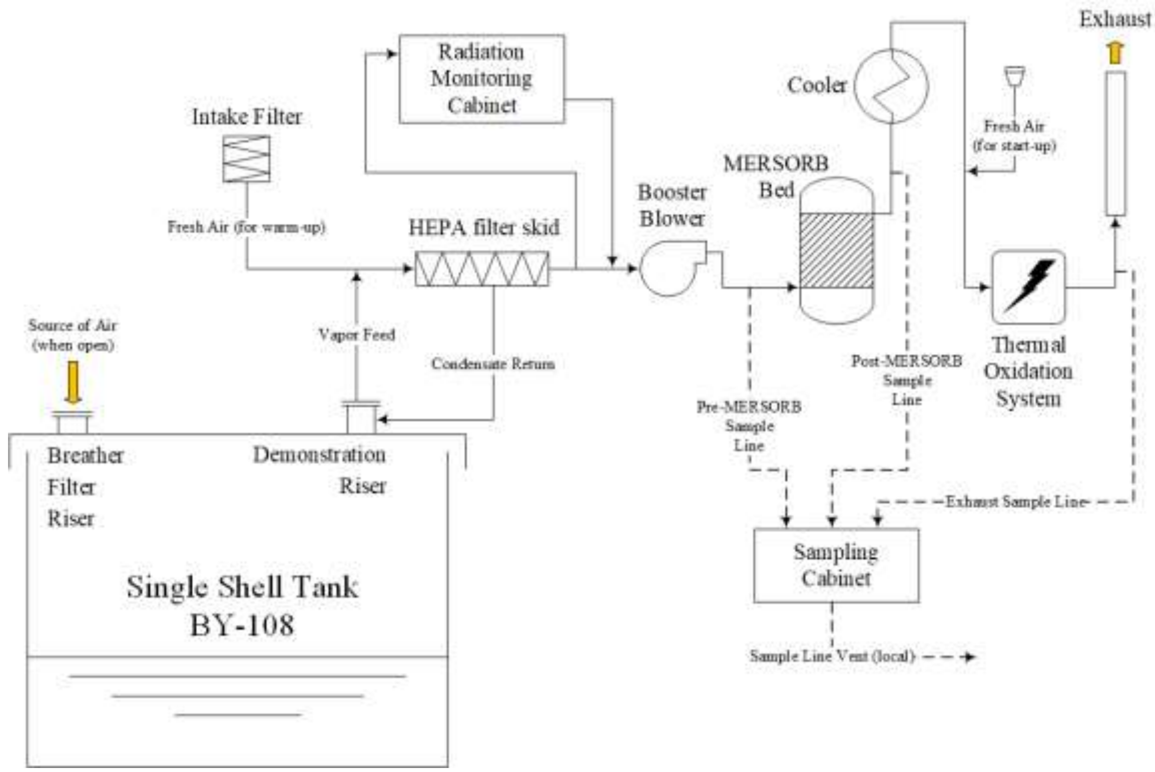

Fig. 2. General System Diagram of the NUCON TOS to be installed on Hanford Single-Shell Tank BY-108.

The vapor stream is drawn through the system using a booster blower operating at a nominal discharge flow rate of 0.0236 $m^3 s^{-1}$ (50 cubic feet per minute). The blower discharges the heated vapor stream [approximately 43 to 49 °C (110 to 120 °F)] into a packed vessel (i.e., the MERSORB® bed). The bed contains sulfur-impregnated carbon that is selective for mercury capture. Other organic species will also be adsorbed by the bed but are expected to quickly reach an equilibrium state where the incoming and outgoing organic concentrations are equal. Capture sites for mercury and organic species are different and mercury capture is not expected to be impacted by organic saturation in the MERSORB®. The organic species equilibrium is likely dynamic, and an examination of the equilibrium loading of organic compounds will need to be performed in the field. MERSORB® bed inlet and outlet concentrations during testing will be monitored at a frequency needed to establish the state of equilibrium. Downstream of the MERSORB® bed, the vapor stream is cooled (removing the heat of compression created by the blower) to bring the gas to an acceptable diesel engine inlet temperature. The stream then enters the TOS, which includes a diesel engine, generator with load bank, catalytic converter, and diesel particulate filter. The TOS itself is similar to the one specified in [3]. After the TOS, the treated vapor stream is vented to the atmosphere in a 20-foot-high exhaust stack.

Performance Assessment by Sample Collection

Assessment of TOS performance will be conducted primarily using gas stream samples that are collected while the system is actively operating on the BY-108 vapor stream. As shown in Fig. 2, the sample points are just prior to the MERSORB® bed (considered the inlet sample, or pre-MERSOB®), just after the MERSORB® bed (post-MERSORB®, needed for determining organic equilibrium of the bed and mercury removal performance), and near the muffler (the exhaust sample).

Samples will be drawn by vacuum pump (as necessary) to a climate-controlled cabinet [target temperature range of 18 to 32 °C (65 to 90 °F)] through a manifold of sorbent tubes chosen for specific COPCs. Each sorbent tube can be isolated and has a target flow rate that will be metered by a mass flow controller. The gas stream leaving the sorbent tube manifold will be vented or returned to the TOS. The pressure, temperature, and relative humidity of the sample streams will be monitored to guide the sample collection process. Refer to Fig. 3 for a general schematic of the sampling system for the inlet (pre- and post-MERSORB®), and Fig. 4 for the outlet (exhaust) sampling system. The systems have similar manifold configurations, but the exhaust gas is at temperatures > 315 °C (600 °F) and needs to be diluted with nitrogen gas to reduce temperature and moisture content in the sample stream. The dilution functionality adds some additional equipment to that system as shown in Fig. 4.

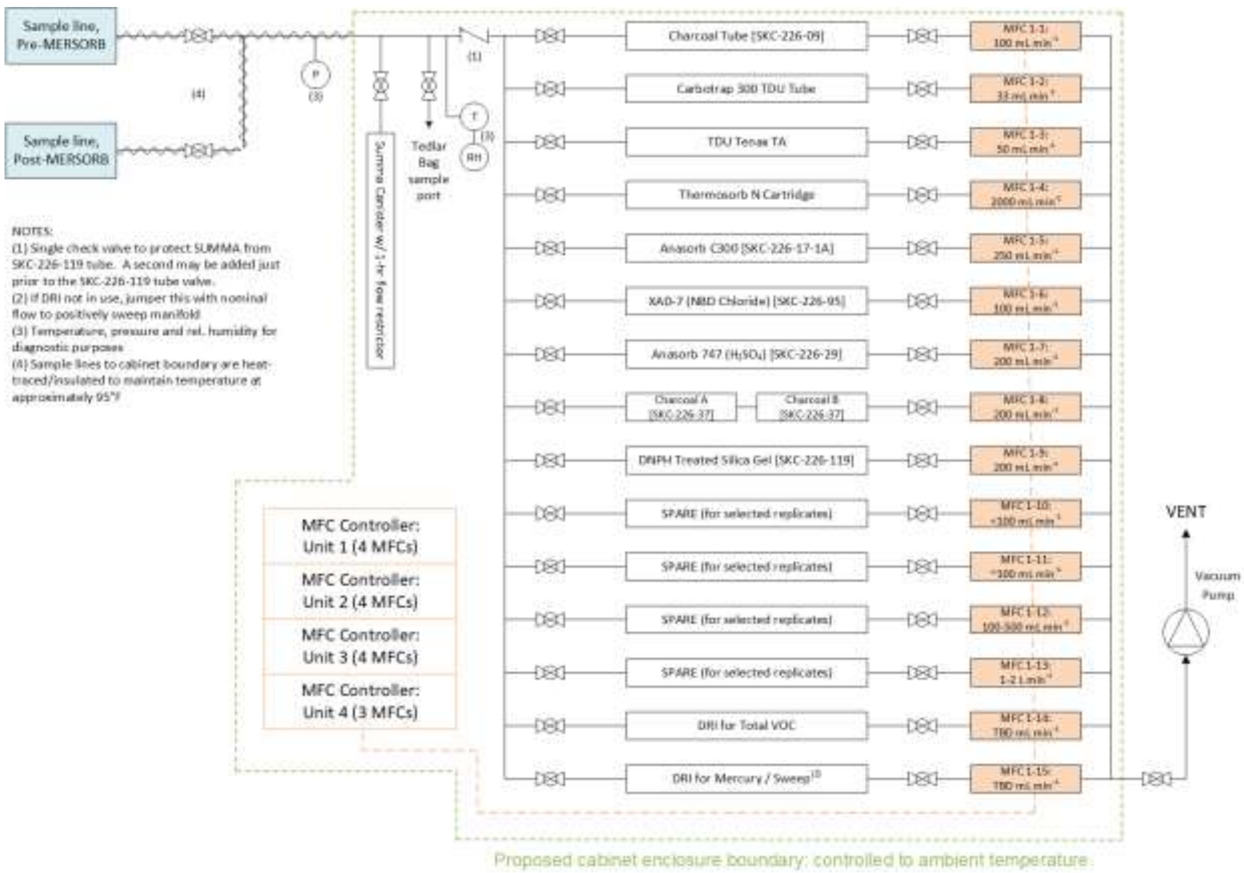

Fig. 3. Sample Manifold Schematic for Pre- and Post-MERSORB® Sample Locations.

The inlet (pre-MERSORB® and post-MERSORB®) sample lines may need insulation or heat trace to maintain the temperature near approximately 38°C (100 °F) for moisture control before they enter the manifold. The exhaust sample line will need heat trace and insulation to maintain the sample temperature above ~200 °C (392 °F), which is a best practice based on Phase 2 testing experience. Prior to sample collection, the exhaust gas in the sample line will be diluted with nitrogen gas at nominally a 3:1 (nitrogen to exhaust gas) ratio to reduce moisture. Because of the dilution, the exhaust sample collection time will be approximately four times the inlet sample collection time for sorbent tubes.

In addition to sorbent tubes, the sampling system will permit collection of SUMMA® canister and Tedlar® bag samples. Direct-reading instruments will be used for the measurement of mercury and total VOCs from the sample stream.

As an option, other analytical instruments can be interfaced with the sample manifold (as available). Spare sorbent tube locations (four in each manifold) will allow for the collection of duplicate samples for selected analytes, or several replicates of a single sorbent tube as data needs require.

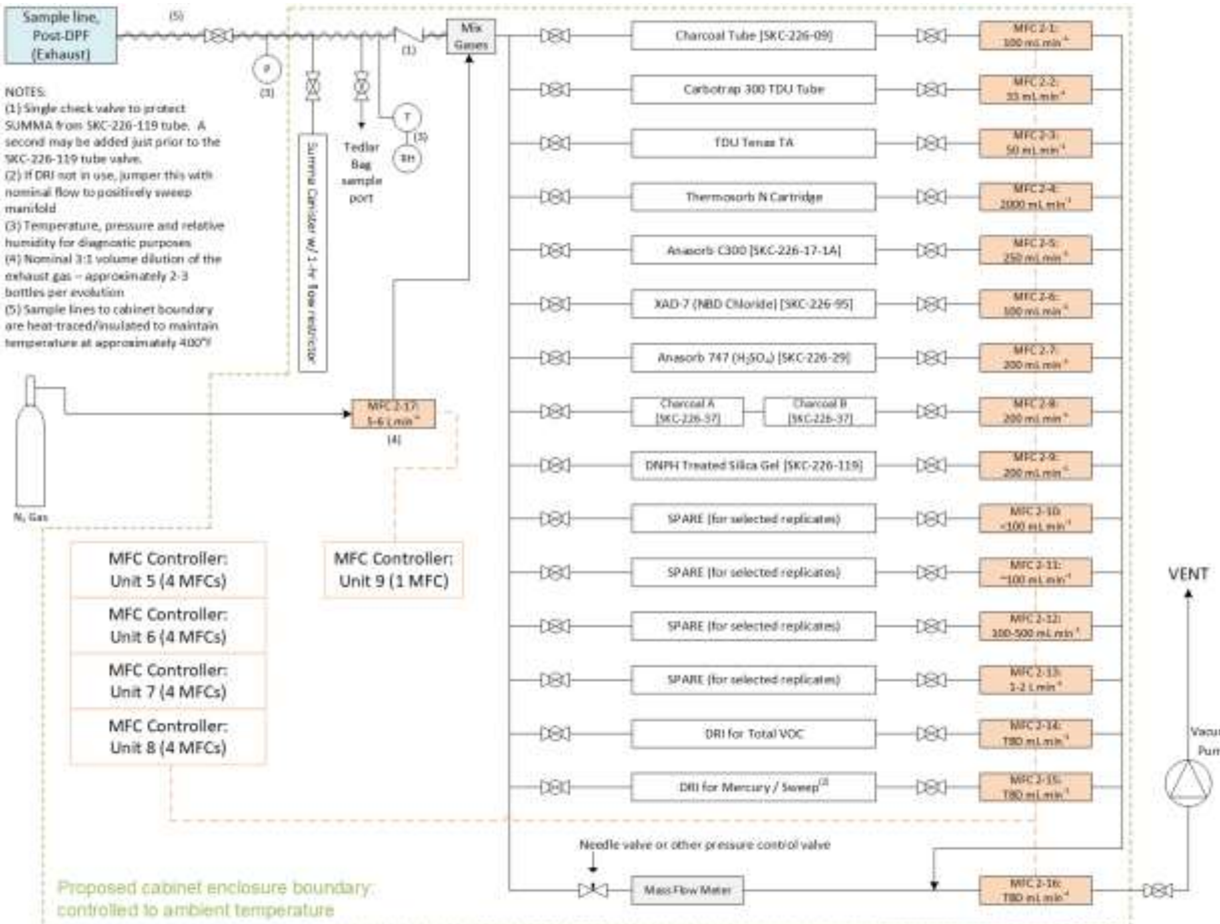

Fig. 4. Sample Manifold Schematic for Exhaust Sample Location.

The general schematics shown in Fig. 3 and Fig. 4 were used to create a proposed sample collection and sorbent tube manifold unit composed of a series of climate-controlled cabinets that will be integrated into the NUCON TOS skid design. An isometric drawing of the cabinets is shown in Fig. 5. The sample system is housed within five steel cabinets mounted adjacent to one another other on the NUCON filter skid. A single "intake" cabinet contains the inlets for the MERSORB®, exhaust, and nitrogen lines as well as ports for the discrete sample containers. From the intake cabinet, the inlet and exhaust lines are each plumbed to separate sets of two cabinets. Each set of two cabinets consists of a "manifold" cabinet and a "control" cabinet. The manifold cabinets contain 15 sample tubes or direct-reading instrument interfaces plumbed in parallel. The sample tubes are installed with sanitary fittings to allow for easy installation and removal by operators. The control cabinets contain the power outlets, the power supplies, and mass flow controllers.

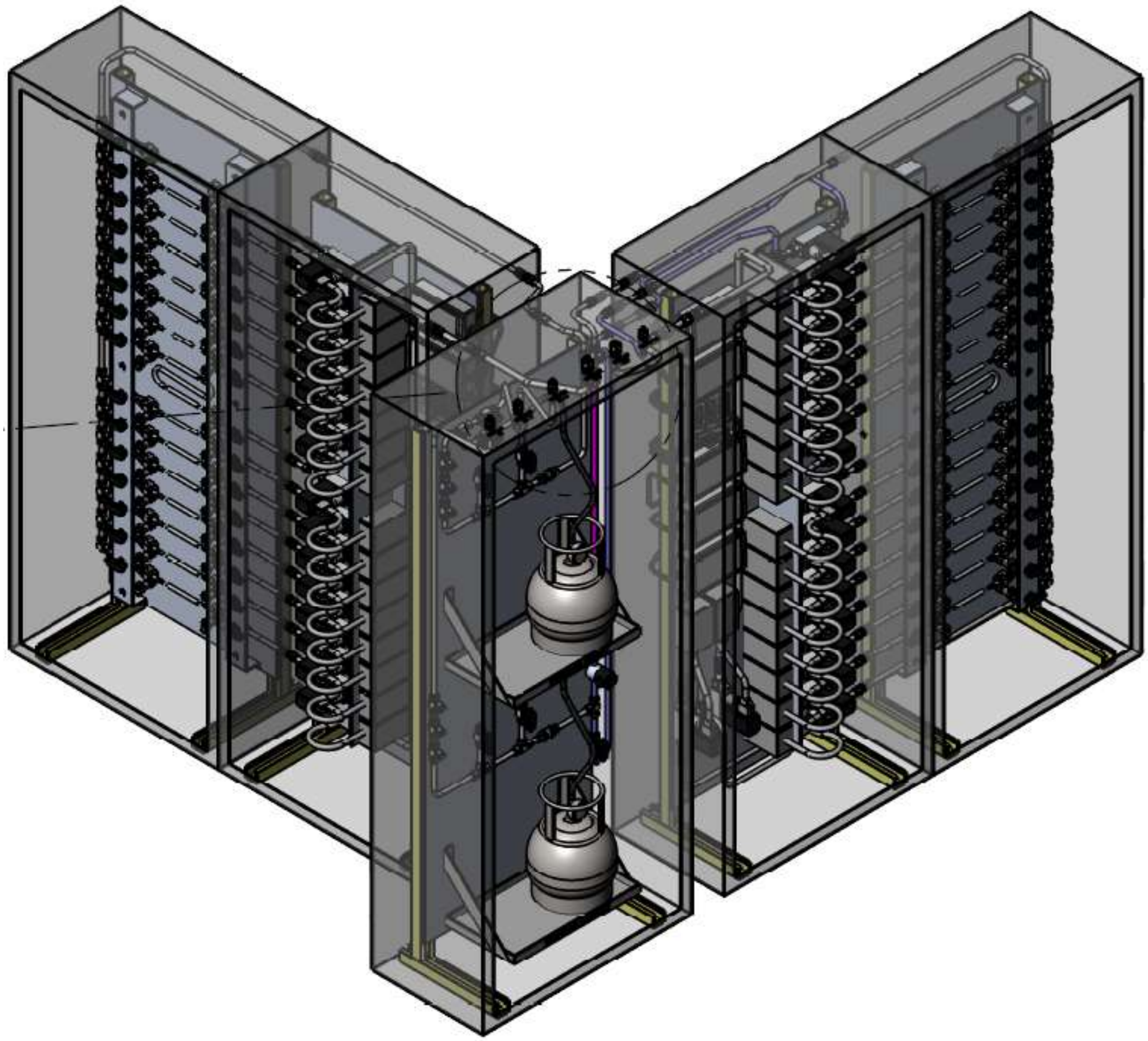

Fig. 5. Isometric of Sampling System Intake (center cabinet), Inlet Manifold (far left), Inlet Control (center-left), Exhaust Control (center-right), and Exhaust Manifold (far right) Cabinets.

A sample evolution will generally require more than 8 hours of continuous operation of the TOS at steady-state. The pre- and post-MERSORB® sorbent tubes each require a 2-hour sampling duration based on the selected flow rates for each tube (flow rates were used in prior BY-108 vapor sampling work – see [5]). Diluting the exhaust sample 3:1 with nitrogen increases the sample time for those tubes to 8 hours. Each sample evolution will also have a traveler and blank tube for quality control purposes. The demonstration effort is planned to have a duration of approximately 8 weeks, which should allow several sample sets to be collected and analyzed to obtain a comprehensive assessment of TOS performance.

CONCLUSIONS

A thermal oxidation system designed by NUCON is a potential mitigation technology for abating Hanford tank chemical vapor and reducing worker exposure risk. An at-tank demonstration test (Phase 3) of the NUCON TOS on SST BY-108 is in the planning stages. The testing is needed to further mature the technology after successful testing during Phase 2. Phase 2 tested single compounds in the vapor stream for only a limited number of COPCs (11 of 61) and did not assess the performance of the mercury-abatement technology (MERSORB® bed). Phase 3 testing will assess the performance of the TOS (including the MERSORB® bed) with a real, complex mixture of COPCs (29 greater than 1% OEL) in a tank headspace vapor stream. Analysis of the performance will be performed using a sample system conceived by PNNL to continuously draw the gas streams through appropriate sample media during steady-state operation. The performance data will be used to make recommendations, if warranted, on additional technical maturation needs for use of the NUCON technology.

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