Off-Gas Mercury Control Using Sulfur-Impregnated Activated Carbon – Test Results

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Nick Soelberg
Arlin Olson
Richard Boardman
Kevin Ryan
Brad Mason

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Idaho National Laboratory

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Nick Soelberg, Arlin Olson, and Richard Boardman, Idaho National Laboratory

Kevin Ryan and Brad Mason, THOR Treatment Technologies, LLC

ABSTRACT

Several laboratory and pilot-scale tests since the year 2000 have included demonstrations of off-gas mercury control using fixed bed, sulfur-impregnated activated carbon. These demonstrations have included operation of carbon beds with gas streams containing a wide range of mercury and other gas species concentrations representing off-gas from several U.S. Department of Energy (DOE) mixed waste treatment processes, including electrical resistance heated (joule-heated) glass melters, fluidized bed calciners, and fluidized bed steam reformers. Surrogates of various DOE mixed waste streams (and surrogates of off-gas from DOE mixed waste streams) including liquid "sodium bearing waste" (SBW) located at the Idaho National Laboratory (INL), liquid "low activity waste" (LAW) from the Hanford Site, and liquid waste from Savannah River Site ("Tank 48H waste") have been tested.

Test results demonstrate mercury control efficiencies up to 99.999%, high enough to comply with the Hazardous Waste Combustor (HWC) Maximum Achievable Control Technology (MACT) standards even when the waste feed mercury content would have introduced uncontrolled off-gas mercury concentrations exceeding 400,000 µg/dscm (at 7% O_2) if unmitigated, and confirm carbon bed design parameters for such high efficiencies. Results of several different pilot-scale and engineering-scale test programs performed over several years are presented and compared.

INTRODUCTION

Low concentrations of mercury are found in many materials, and are emitted to the atmosphere from many industrial processes. Studies in the past decades have evaluated anthropogenic emissions of mercury to the environment, and environmental mercury levels and effects on ecology and human health. The United States Environmental Protection Agency (U.S. EPA) has reported that coal-fired utility boilers are the largest source of anthropogenic Hg emissions in the U.S., followed by waste incinerators and other thermal processes (most notably chloro-alkali plants, Portland cement kilns, pulp and paper manufacturing, and geothermal power plants) (1).

The EPA has promulgated the Hazardous Waste Combustor (HWC) Maximum Achieveable Control Technology (MACT) standards to reduce emissions of various pollutants including mercury from hazardous waste combustors. The EPA has included incinerators that treat mixed (both radioactive and hazardous) waste in facilities that are regulated under the HWC MACT standards. These standards can also be applied by regulators to facilities that are not considered "incinerators."

At this time, most mixed waste thermal treatment processes including incinerators, calciners, vitrification plants, and steam reformers are likely to be regulated under the HWC MACT standards. Some mixed waste treatment facilities including the New Waste Calcining Facility (NWCF) and the Waste Experimental Reduction Facility (WERF) incinerator at the Idaho National Laboratory (INL), and the Consolidated Incineration Facility (CIF) at the Savannah River Site (SRS) have been closed, in part due to cost to retrofit those existing facilities (or impose restrictive feed limits) to comply with the HWC MACT standards.

Most new facilities under construction or being planned for treating mixed wastes are being designed to comply with the HWC MACT standards (2). Following closure of the NWCF after emissions inventory testing was completed in the year 2000, the U.S. Department of Energy (DOE) and subcontractors and the INL have studied various options to treat the remaining ~3.8 million L (~1 million gallons) of remaining "sodium bearing waste" (SBW) stored in 3 tanks. The sodium bearing waste is an aqueous nitric acid waste containing 1.1-2.9 gmole/L H^+, 5.6-7.5 gmole/L NO_3^-, and dissolved and undissolved radioactive and hazardous waste residues (3). This liquid

waste must be removed from storage tanks and solidified by December 31, 2012 to comply with a Settlement Agreement between the DOE and the State of Idaho. Treatment options that were evaluated included calcination in the existing NWCF (following a retrofit to comply with the HWC MACT standards), vitrification, steam reforming, aqueous separations and grouting, and evaporation (4).

The DOE has selected fluidized bed steam reforming (FBSR) for treating the SBW. Like calcination in the NWCF, FBSR evaporates and calcines liquid SBW that is injected into a fluidized bed, producing a solid granular product. Unlike calcination in the NWCF, the FBSR process is performed in a steam (instead of air) fluidized bed, using a reductant that produces stoichiometrically reducing conditions that efficiently convert the nitrates directly to N_2, with little NO_x formation. The reducing environment in the steam reformer can also result other reduced gas species such as CO, H_2, hydrocarbons, and reduced sulfur species, and reduced (elemental) Hg. When the CO, H_2, and other reduced gas species are oxidized in the Carbon Reduction Reformer (CRR), the high temperature of the CRR still thermodynamically favors elemental rather than oxidized Hg species.

The SBW FBSR process can be configured to produce either a carbonate-based product that is mostly Na_2CO_3, or a product that is similar to sodium aluminosilicate minerals. The mineralized product requires the addition of clay (aluminosilicate) to combine with the predominant Na in the waste, and can be highly leach-resistant. The current design of the SBW FBSR process, in a new facility called the Integrated Waste Treatment Unit (IWTU), is based on the carbonate product. If DOE determines that a leach-resistant waste form is required, then the process could be converted to produce the mineralized product (5).

Compliance of the IWTU to the HWC MACT standards is expected to be required, and will be achieved as follows (6):

- Chlorides are efficiently retained in the solid product, enabling off-gas HCl/Cl_2 emissions to meet the MACT standard

- Particulate matter (PM) and hazardous metals are partitioned to the solid product under the relatively moderate FBSR temperatures, and efficiently filtered from the off-gas at various locations at temperatures low enough to re-condense and capture even the most volatile (non-mercury) metals

- Stoichiometry and temperature control efficiently destroy CO and hydrocarbons and prevent the formation of dioxins and furans

- Mercury volatilizes in the FBSR process and is efficiently captured in a fixed bed of sulfur-impregnated activated carbon.

MERCURY EMISSIONS CONTROL FOR MIXED WASTE TREATMENT

Mercury emissions control for mixed waste thermal treatment processes, and especially for SBW treatment, has been of particular interest the past decade since the HWC MACT standards were first proposed (7, 8, 9). Mercury has had various uses in nuclear fuel reprocessing and other nuclear processes, and so is often present in legacy mixed wastes. Mercury was used as a catalyst for dissolving aluminum cladding, aluminum containers, and uranium during nuclear fuel reprocessing (10, 11, 12). Mercury was also used to produce enriched lithium-6, used in nuclear weapons. New spent fuel reprocessing technologies that do not require mercury are now being developed, but legacy wastes from past nuclear operations normally contain mercury.

The HWC MACT standards allow compliance using feed limits. But levels of mercury in some legacy mixed waste streams are too high for feed mercury limits to be practical. Levels of mercury in the SBW range between 2.1 to 7.1 x 10^{-3} gmole/L (340 to 1,100 ppmw) (3). Figure 1 compares the maximum theoretical Hg concentrations in process gas, and Hg control efficiencies that would be needed to comply with the HWC MACT standard, to mercury concentrations in the surrogate waste feeds for the various mixed waste steam reforming and calcination tests that have been performed. For the different tests, one ppmw of Hg in the feed resulted in 40-400 ug/dscm Hg in the off-gas (dry, @ 7% O_2), depending on the scale of the process (small pilot scale, engineering scale, or full scale) and the amounts of other process flows. These data are from the different pilot and engineering scale steam reformer tests, one calcination pilot test, and NWCF calciner operations. For the conditions of these tests, the mercury in the surrogate waste feed would have to be below 0.02-0.2 ppmw to comply with the HWC MACT standards without at least some degree of mercury control. Reducing the Hg feedrate by reducing the waste treatment rate or by removing the mercury prior to thermal treatment to comply with the HWC MACT standard of 8.1 μg/dscm (@ 7% O_2) for new facilities are not practical options when the mercury levels must be reduced by as much as 99.999%.
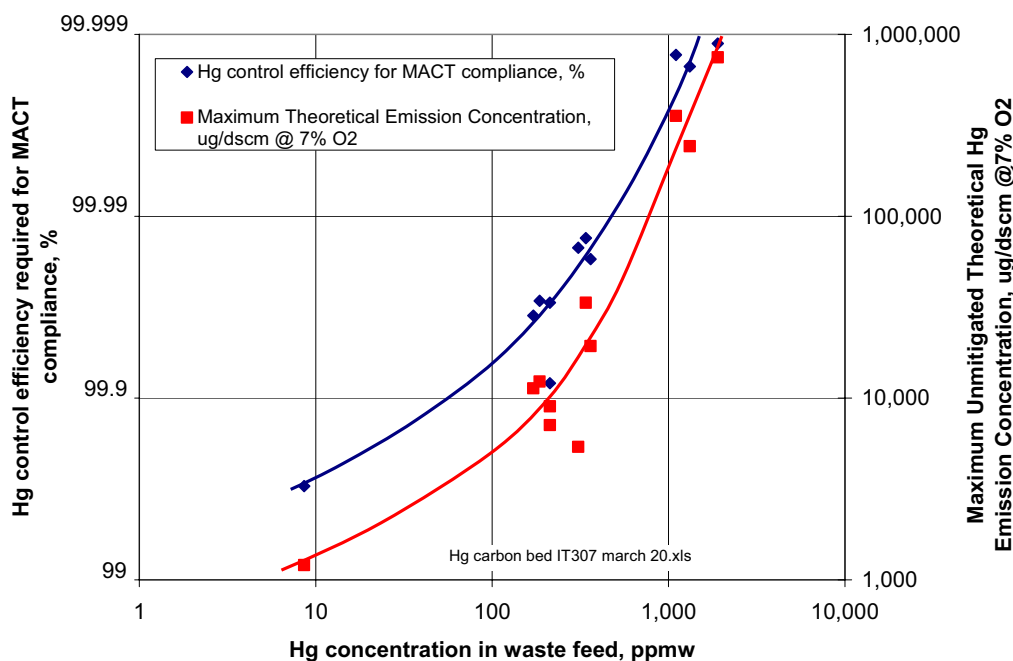
Figure 1. Off-gas Hg levels and Hg control efficiencies needed for MACT compliance.

PILOT AND ENGINEERING SCALE TEST FACILITIES

Ten different pilot and engineering-scale fluidized bed steam reformer and calciner tests have been performed since 2002. Mercury was included in the simulant feed, a sulfur-impregnated activated carbon bed was used for evaluating mercury control, and feed, solid product, scrubber, off-gas, and spent carbon sample analyses were performed to determine the fate of mercury during these tests. The tests were performed in two different test facilities – the Idaho National Laboratory (INL) pilot-scale fluidized bed test facility, and the Engineering Scale Test Demonstration (ESTD) facility.

Idaho National Laboratory Pilot-Scale Fluidized Bed Test Facility

The pilot-scale tests were performed using the INL pilot-scale fluidized bed test facility located at the Science Applications International Corporation (SAIC) Science and Technology Applications Research (STAR) Center in Idaho Falls, Idaho. This test facility includes a 15-cm (6-inch) diameter fluidized bed sized for a simulant waste feedrate of up to about 10 L/hr, but was more typically operated with a feedrate of about 3-5 L/hr. This facility (Figure 2) includes a surrogate waste feed preparation and supply system, a fluidizing gas supply system, the fluidized bed, that can be operated as a calciner or a steam reformer, a cyclone for collecting and recycling the coarser fines that normally elutriate from the fluidized bed during operation, a high-temperature heated filter vessel for more efficient fines control, a thermal oxidizer for secondary oxidation of off-gas species, an optional wet scrubber, a 3-stage carbon bed, and an air eductor for system vacuum control.

The carbon bed system used in all but the earliest (Phase 1) INL pilot-scale tests is shown in Figure 3. Three separate stages accomplish multiple test objectives. The top stage is designed to be shallow [2.5 cm (1 inch)] so that it contained less carbon than the other stages, and could more quickly approach Hg saturation levels, depending on the amount of Hg exposure. The second and third stages are designed to (a) enable gas and spent carbon sample collection to evaluate Hg removal efficiency as a function of bed depth, and (b) provide sufficient gas superficial residence time and total bed depth to demonstrate efficient Hg control and enable the test facility to comply with State of Idaho air permit exemption requirements. The gas "superficial" residence time is calculated based on the empty volume of the bed. This 3-stage carbon bed is designed for test data generation and is not intended to emulate the geometry or configuration of a full-scale carbon bed.
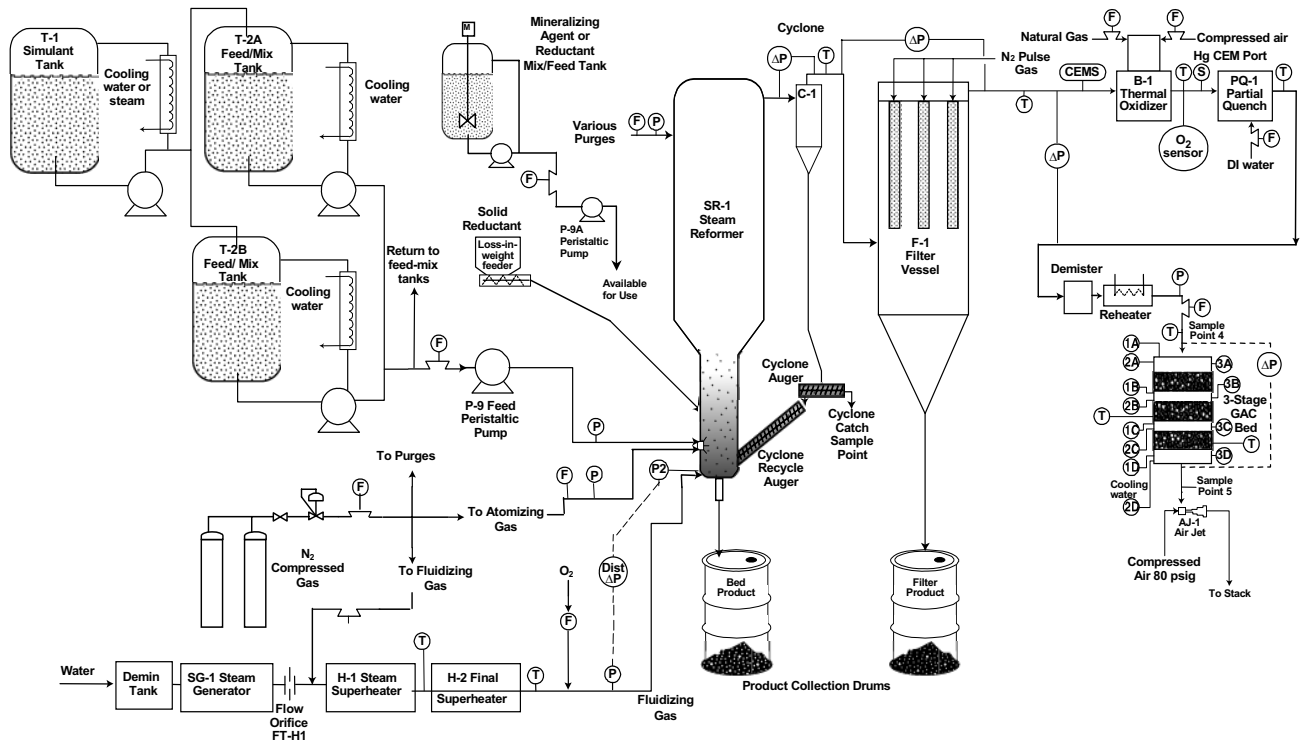
Figure 2. INL pilot-scale fluidized bed test system (the optional wet scrubber is not shown).
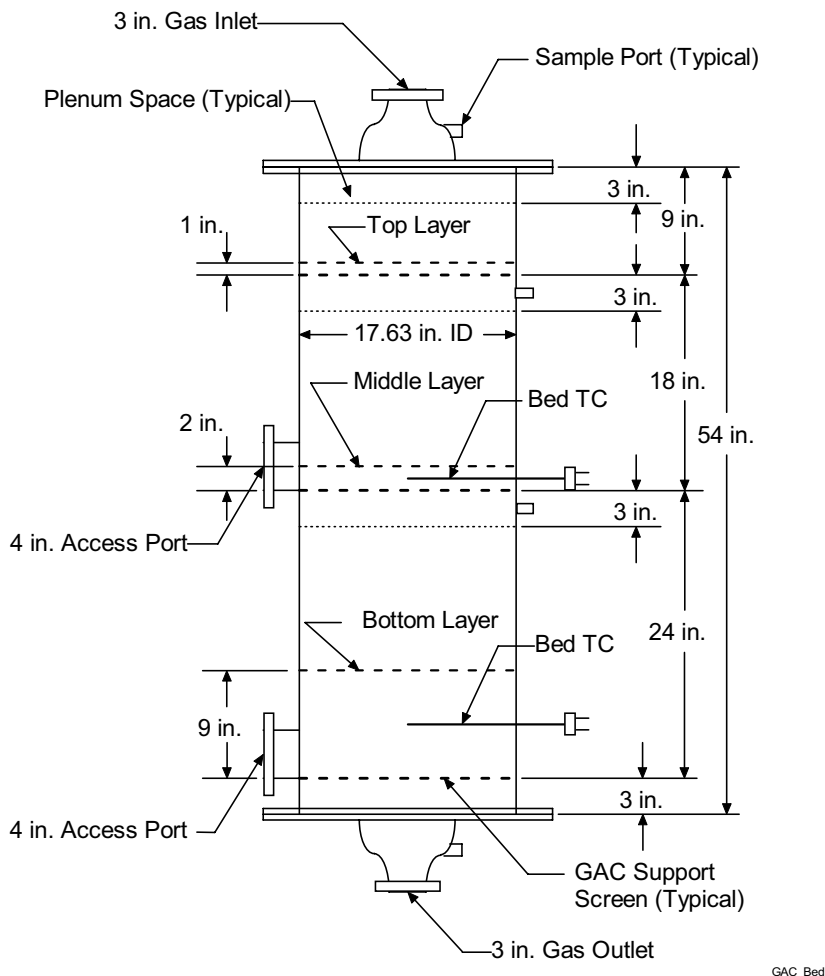
Figure 3. Three-stage carbon bed used in most of the INL pilot-scale fluidized bed tests.

Sulfur-impregated granular activated carbon (MERSORB® HT-1.5, 1.5 mm High Temperature) provided by NUCON, International was used in all pilot-scale tests. This carbon is coal-based and activated by high temperature steam. It is provided in 1.5 mm diameter pellets that are typically under 2-3 mm long. MERSORB® contains up to 13 wt% sulfur. The sulfur provides the ability to chemically sorb ("chemisorb") volatile elemental mercury, by reacting with the mercury to form mercury sulfide, that is analogous to stable cinnabar (HgS, with a sublimation temperature of about 584°C) found in nature. Active sites on the carbon that are not occupied by sulfur sorb volatile Hg species such as $HgCl_2$.

Off-gas Hg measurements were made during all INL pilot-scale tests except the Phase 1 tests using a PSA Analytical Sir Galahad continuous mercury analyzer system. The analyzer detects mercury using atomic fluorescence.   This system included a single analyzer configured to speciate elemental and oxidized Hg, and used two separate sampling and conditioning systems to enably cyclic measurements at multiple sampling locations. The conditioning systems diluted Hg concentrations to within the instrument analytical range of up to 4,000 μg/dscm^3. Off-gas mercury measurements during the Phase 1 steam reforming tests were performed using the manual Ontario Hydro Sample Train.

Engineering Scale Test Demonstration

The ESTD facility is an approximately 1/10th scale test system for the IWTU fluidized bed steam reformer system, located at Hazen Research Incorporated (HRI) in Golden, CO. A schematic of this system is shown in Figure 4. This test facility includes a 38-cm (15-inch) diameter fluidized bed, over 6 times the cross-sectional area of the 15-cm INL fluidized bed test system, with about 1/10th the planned throughput of the IWTU. The ESTD facility is sized for a simulant waste feedrate of up to about 100 L/hr (0.44 gallon/min), but has been most typically operated with a feedrate of about 40-70 L/hr.

The ESTD facility includes a simulant feed preparation and supply system, a fluidizing gas supply system, the fluidized bed steam reformer, a cyclone for collecting and recycling the coarser fines that normally elutriate from the fluidized bed during operation, a high-temperature heated filter vessel for more efficient fines control, a second fluidized bed for oxidation of off-gas species from the first steam reformer, a pulse-jet baghouse filter, an optional wet scrubber, a 3-stage carbon bed, and three induced draft fans.

The ESTD carbon bed system is shown in Figure 5. Similar to the carbon bed in the INL test facility, this carbon bed system also includes three separate stages to accomplish multiple test objectives. The top stage is designed to be shallow [15 cm (5.9 inches)] and is also smaller in diameter [61 cm (2 feet)] than the other two stages, so that it contains less carbon than the other stages, and can more quickly approach Hg saturation levels, depending on the amount of Hg it is exposed to. The second and third stages are designed to (a) enable gas and spent carbon sample collection to evaluate Hg removal efficiency as a function of bed depth, and (b) provide sufficient total bed depth and gas superficial residence time to provide efficient Hg control so that the test facility can comply with State of Colorado emission limits for the test facility. This 3-stage carbon bed is designed for test data generation and is not intended to emulate the geometry or configuration of a full-scale carbon bed.

Sulfur-impregnated granular activated carbon (MERSORB®-3) provided by NUCON, International was used in all of the ESTD tests. This carbon is coal-based and activated by high temperature steam. It is provided in 3 mm diameter pellets that are typically under 4-5 mm long. The larger-sized carbon was selected for testing in the ESTD, instead of the smaller 1.5-mm carbon. The 3-mm carbon is planned for the full-scale IWTU carbon bed as the larger carbon particles provide less pressure drop for the same bed operating conditions than does the 1.5-mm carbon. The physical and chemical properties of the 3-mm carbon are similar to those of the 1.5-mm carbon.

Off-gas Hg measurements were made during the ESTD tests using the Ontario Hydro Sample Train at locations in-between and downstream of the carbon bed stages and using EPA Method 29 at the stack.

CARBON BED TEST RESULTS

Table I shows carbon bed performance data for eleven different sets of mercury control data (13-21). Seven different pilot-scale tests and three different engineering-scale tests are reported. One of the pilot-scale tests (the high temperature MACT compliant calcination test) was performed with the fluidized bed operating in a stoichiometrically oxidizing calcination mode, not a steam reforming mode. The mercury results of the full-scale NWCF calciner emissions inventory test are included for comparison to the 10 sets of pilot-scale and engineering-scale test data.

The measured Hg control efficiencies are compared to the gas residence times in Figure 6. The control efficiency trend for each set of tests shows that as the gas residence time increases, the Hg control efficiency increases. The highest and lowest efficiencies relative to gas residence time were observed for the INL pilot-tests. The lowest efficiencies relative to the residence time occurred for the Phase 1 steam reformer tests, when there was no final oxidation of the process gas. The carbon bed was exposed to process gas that contained levels of incompletely oxidized hydrocarbons, that probably adsorbed on the carbon, competing with the Hg for active sites on the carbon. Excluding the Phase 1 steam reformer tests that did not include process gas oxidation, all of the Hg control trends show that high control efficiencies, up to 99.999%, are achievable based on the gas residence time. Of course, gas velocity can also impact the control efficiency, but the gas velocities for these tests were all below the general NUCON maximum velocity recommendations of about 0.5 m/s (100 ft/min, or 1.7 ft/s).
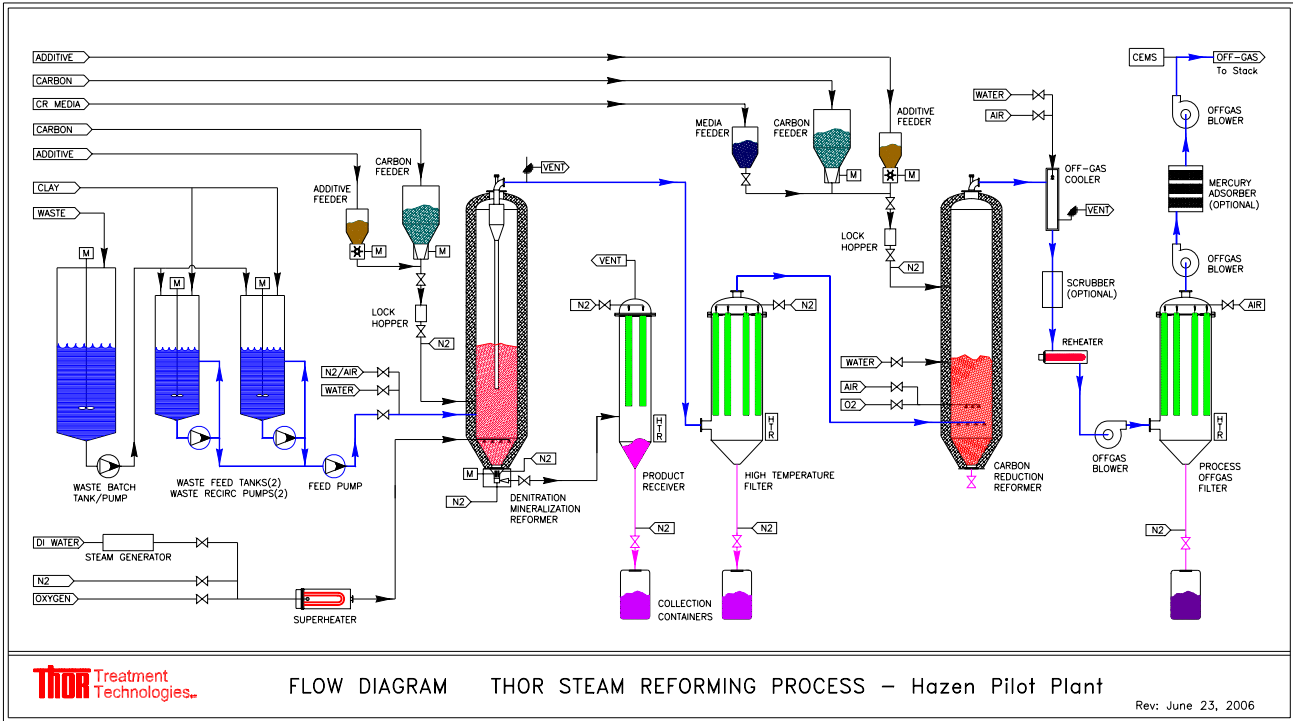
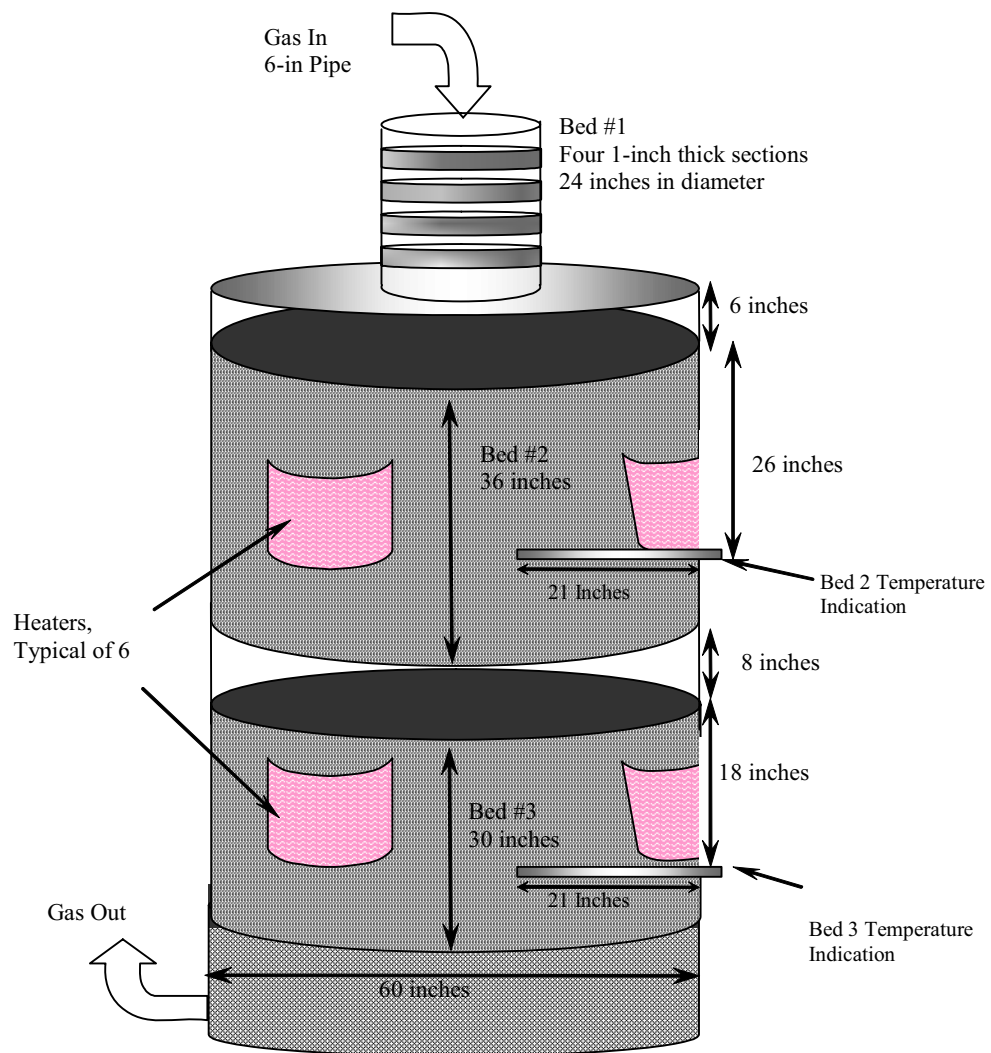Figure 4. Engineering Scale Test Demonstration system.

Figure 5. Three-stage carbon bed used in the ESTD facility.

Table I. Carbon bed test performance data.

Facility	Measurement program	Reference	Feed material	Hg measurements performed	Wet scrubber configuration
INL NWCF mixed waste calciner	Phase IV emissions inventory testing	Boardman 2001 (13)	SBW blended with recycled scrub solution and calcining additives	Feed and scrub Hg concentrations, off-gas Hg train sampling downstream of the scrubber	Quench, venturi scrubber, condenser, mist eliminator, packed silica gel beds, mist eliminator, reheater, 3-stage HEPAs
MACT-compliant calciner pilot plant	High temperature MACT compliant calcination	Boardman 2004 (14)	Non-radioactive simulant of SBW blended with calcining additives	Feed and scrub Hg concentrations, speciating Hg continuous emissions monitor (CEM) before and after scrubber and after selected carbon bed depths, spent carbon Hg	Quench, venturi scrubber
Pilot-scale fluidized bed steam reformer	Phase 1 Thermochem Waste Remediation (TWR) steam reformer tests	Marshall 2003 (15)	Non-radioactive simulant of SBW	Feed and scrub Hg concentrations, Hg train sampling upstream of the scrubber and downstream of the carbon bed	Quench, venturi scrubber
	Phase 1 THOR steam reformer tests	Marshall 2003 (16)	Non-radioactive simulant of SBW	Feed and scrub Hgconcentrations, Hg train sampling upstream of the scrubber and downstream of the carbon bed	Quench, venturi scrubber
	Phase 2 TWR steam reforming tests	Soelberg 2004 (17)	Non-radioactive simulant of SBW	Feed and scrub Hg concentrations, speciating Hg CEM before and after scrubber and after selected carbon bed depths	Quench, venturi scrubber
	Phase 2 THOR carbonate steam reforming tests	Soelberg 2004 (18)	Non-radioactive simulant of SBW	Feed and scrub Hg concentrations, speciating Hg CEM before and after scrubber and after selected carbon bed depths	Quench, venturi scrubber
	Phase 2 THOR mineralizing steam reforming tests	Soelberg 2004 (18)	Non-radioactive simulant of SBW blended with clay	Feed and scrub Hg concentrations, speciating Hg CEM before and after scrubber and after selected carbon bed depths	Quench, venturi scrubber
	INL/SRNL THOR mineralizing steam reforming tests	Olson 2004 (19)	Non-radioactive simulant of SBW blended with clay	Feed Hg concentration, spent carbon Hg concentration and toxicity characteristic leachability procedure (TCLP) test	None
Engineering - scale Test Demon-stration	SBW Carbonate Production Test 1 (CP1)	THOR Treatment Technologies 2006 (20)	Non-radioactive simulant of SBW	Feed Hg concentration, off-gas Hg train sampling at selected carbon bed depths and at stack, spent carbon Hg concentration and TCLP	None
	SBW Carbonate Production Test 2 (CP2)	THOR Treatment Technologies 2006	Non-radioactive simulant of SBW	Feed Hg concentration, off-gas Hg train sampling at selected carbon bed depths and at stack, spent carbon Hg concentration and TCLP	None
	SRS Tank 48H	THOR Treatment Technologies 2007 (21)	Non-radioactive simulant of Tank 48H waste	Feed Hg concentration, off-gas Hg train sampling at the carbon outlet and at stack, spent carbon Hg concentration and TCLP	None

Notes:
1. Mersorb carbon size used in the SAIC pilot-scale fluidized bed tests: 1.5 mm. Mersorb carbon size used in the Hazen ESTD tests: 3 mm.
2. Bed diameter used in the SAIC pilot-scale fluidized bed tests: 20.3 cm for the Phase 1 TWR and THOR tests; 44.8 cm for all other tests.
3. Bed diameter used in the Hazen ESTD fluidized bed tests: 2 ft (61 cm) for Stage 1, and 5 ft (152 cm) for Beds 2 and 3.
4. Nominal bed operating temperature used in the SAIC pilot-scale fluidized bed tests: 120-125°C.

Table I. Carbon bed test performance data (continued).

Facility	Measurement program	Hg concentration in the feed, ppmw	Hg MTEC, ug/dscm (dry, 7% O_2, normalized to stack gas flowrate)	Wet scrubber Hg removal efficiency, %	Hg at carbon bed outlet (or NWCF stack), ug/dscm (dry, 7% O_2)			Total system removal efficiency, %
					Speciation between elemental and oxidized Hg, % of total Hg		Total Hg concentration, ug/dscm (dry, 7% O_2)	
					Elemental Hg	Oxidized Hg		
INL NWCF mixed waste calciner	Phase IV emissions inventory testing	1,900	748,197	99.5	0.1	99.9	4,500	99.5
MACT-compliant calciner pilot plant	High temperature MACT compliant calcination	308	24,616	78.1	60	40	0.8	99.997
Pilot-scale fluidized bed steam reformer	Phase 1 TWR steam reformer tests	362	19,314	0.007	---	---	---	13.7
	Phase 1 THOR steam reformer tests	340	33,434	0.001	98	2	11,100	---
	Phase 2 TWR steam reforming tests	213	12,178	41.7	100	0	12	99.8
	Phase 2 THOR carbonate steam reforming tests	213	9,212	2.3	75	25	6	99.9
	Phase 2 THOR mineralizing steam reforming tests	171	11,311	0.1	88	12	12	99.8
	INL/SRNL THOR mineralizing steam reforming tests	186	12,325	---	---	---	---	---
Engineering -scale Test Demon-stration	SBW CP1	1,321	243,000	---	---	---	---	---
	SBW CP2	1,102	356,000	---	39	61	5.3	---
	SRS Tank 48H	8.6	1,205	---	62	38	2.2	99.8

Notes:
1. MTEC = Maximum theoretical emission concentration.
2. A "---" indicates measurements that were not made, or cells in the table that are not applicable for that test.

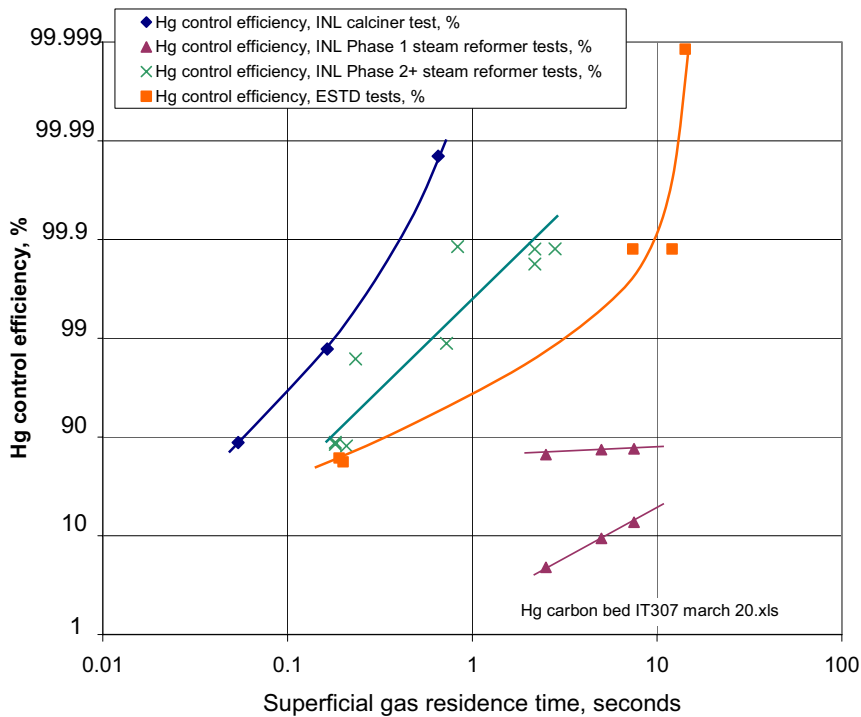[Hg carbon bed IT307 apr 6.xls]Hg summary presentation 2

Figure 6. Hg control efficiency measurements from the INL pilot-scale and the ESTD steam reforming and calcination tests.

The highest Hg control efficiency was observed for the ESTD tests, which also had the highest Hg source term of Hg in the feed and the longest gas residence time. The high Hg control efficiency for this test may have been due to the high inlet Hg concentration, the practical Hg measurement capabilities at the outlet of the carbon bed, and the capability of the carbon bed to drive the off-gas concentrations to near zero at the outlet, regardless of the inlet Hg concentration, as long at the bed conforms with appropriate design criteria, bed depth, and bed residence time.

The trends also show that Hg removal efficiencies as high as 99% are achieved with gas residence times of about 0.5-1 second. This shows that the Hg sorption "mass transfer zone" (MTZ) is not deeper than the bed depths that provides this range of residence times. The "mass transfer zone" is the zone of active Hg sorption as the Hg-laden gas enters the carbon bed. When mass transfer is fast, the mass transfer zone is shallow. Over time, the carbon where the gas enters the mass transfer zone approaches saturation, Hg mass transfer to the carbon decreases, and the mass transfer zone migrates in the same direction of the gas flow through the bed. The speed at which the mass transfer zone progresses through the bed depends on the concenration of Hg in the incoming gas and the saturation concentration of Hg on the carbon.

The bed depth that corresponds to about 0.5-1 second residence time in both the INL pilot tests and the ESTD tests was about 15-30 cm (6-12 inches), suggesting that the Hg mass transfer zone was not greater than 15-30 cm for the operating conditions of these tests.

Concentrations of Hg and other species on the spent carbon were measured in several of the tests. Figure 7 shows the most recently obtained spent carbon Hg concentrations, which are from the ESTD Carbonate Production 1 (CP1) and Carbonate Production 2 (CP2) tests. The highest observed Hg concentrations, measured in the first bed that was designed to achieve Hg saturation depending on test operating time and feed Hg concentrations, averaged up to 19 wt% of the virgin carbon mass. This value confirms NUCON's expectation that the MERSORB® carbon can sorb Hg up to 20 wt% of the carbon mass.

The spent carbon analyses confirm the mass transfer zone estimates obtained from the Hg control efficiency data. The MTZ depth can be estimated by drawing the lines shown in Figure 7 through the measured concentrations in Bed 1 down to the "baseline" levels represented by the relatively flat concentrations in Beds 2 and 3. (These lines extrapolate the slope of the concentration data early in the bed, down to the Hg levels in the rest of the carbon bed. If we had been able to take more spent carbon samples at more discrete bed depths to measure the Hg concentrations at residence times between 0.5 – 4 seconds, then we could have used that data rather than extrapolations. Evenso, these extrapolation data represent estimates of the MTZs and are consistent with MTZs determined using the off-gas concentrations.) The MTZ for CP1 corresponded to about a 1 second residence time, or about 13 cm (5 inches). The MTZ for CP2 corresponded to about a 2 second residence time, or about 25 cm (10 inches).
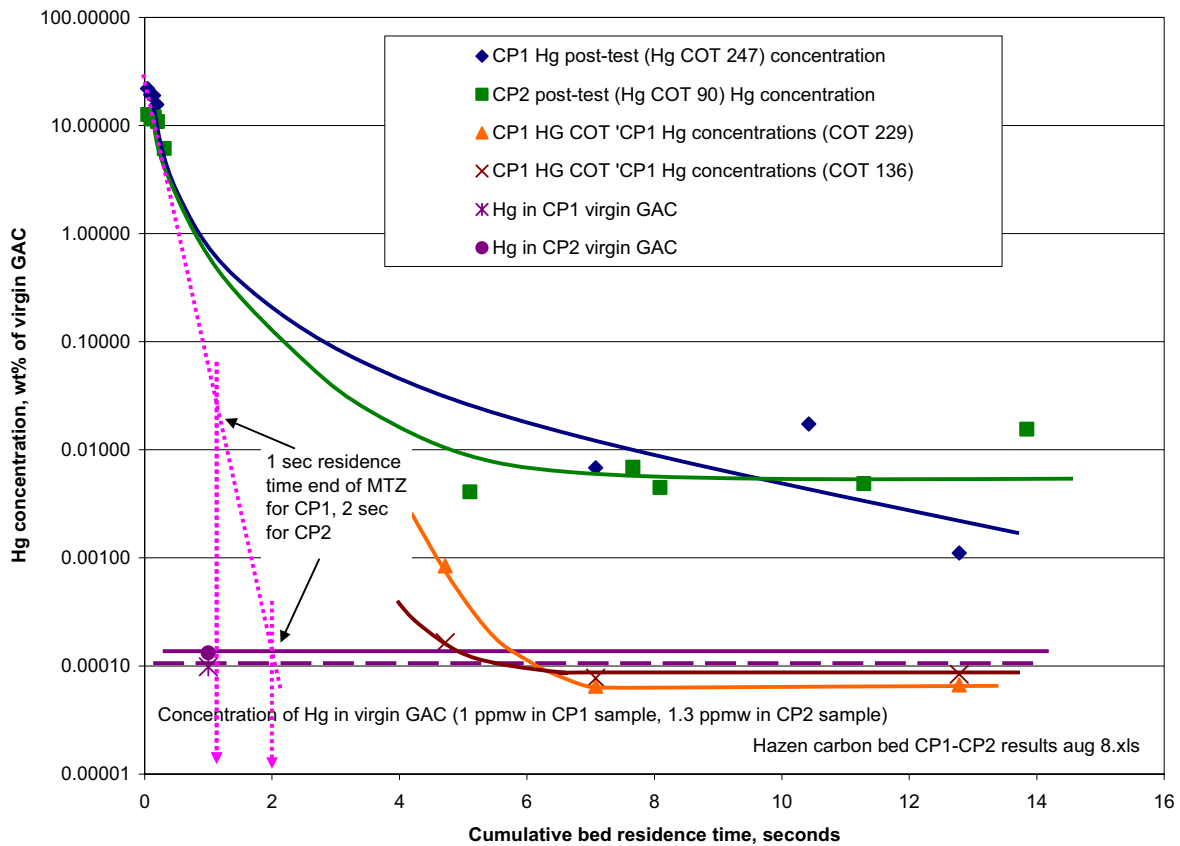

Figure 7. Hg concentrations in carbon bed samples from the ESTD CP1 and CP2 steam reformer tests (COT is continuous operating time, and GAC is granular activated carbon).

CONCLUSIONS

A body of test data has been generated using larger scale test beds than has been previously reported in the public domain. These data show that while Hg control efficiencies up to 99.999% may be required for mixed waste thermal treatment, such high control efficiencies are achievable using fixed beds of granular activated carbon impregnated with sulfur. This performance has been achieved at bed operating tempeatures of typically $120^{o}C$ to $125^{o}C$. The measured Hg sorption capacities confirm expected levels of up to 20 wt% of the virgin carbon. The maximum Hg sorption mass transfer zone depths ranged between about 15-30 cm for the test conditions.

REFERENCES

1. EPA, "Mercury Study Report to Congress," EPA-452/R-97-003, December 1997.

2. Soelberg, Nick, "Advanced Off-Gas Control System Design for Radioactive and Mixed Waste Treatment," proceedings of the 10th International Conference on Environmental Remediation and Radioactive Waste Management, Glasgow, Scotland, September 4-8, 2005.

3. Barnes, Charles, Clark Millet, and V. Johnson, "Feed Composition for the Sodium-Bearing Waste Treatment Process," Idaho National Laboratory, INEEL/EXT-2000-01378, Revision 4, June 2004.

4. Barnes, Charles, Arlin Olson, and Dean Taylor, "Sodium-Bearing Waste Treatment Technology Evaluation Report," Idaho National Laboratory, INEEL/EXT-04-01692, Revision 1, May 2004.

5. Mason, J. B., K. Wolf, K. Ryan, S. Roesener, M. Cowan, D. Schmoker, P. Bacala, and B. Landman, "Steam Reforming Application for Treatment of DOE Sodium Bearing Tank Wastes at Idaho National Laboratory for Idaho Cleanup Project," WM'06 Conference, February 26 – March 2, 2006, Tucson, AZ.

6. THOR Treatment Technologies, LLC, and Washington Group International, Pilot Plant Report for Treating Sodium-Bearing Waste Surrogates, Carbonate Flowsheet," Revision 1, RT-ESTD-002, Project Number 28276, August 2006.

7. Chambers, A., M. Knecht, N. Soelberg, D. Eaton, D. Roberts, and T. Broderick, "Mercury Emissions Control for Mixed Waste Thermal Treatment," 1998 International Conference on Incineration and Thermal Treatment Technologies, Salt Lake City, UT, May 12-16, 1998.

8. "Hazardous and Radioactive Waste Treatment Technologies Handbook," edited by Chang Ho Oh, Chapter 7, "Off-gas Control for Mixed Waste Thermal Treatment Systems," by N. R. Soelberg, CRC Press, Washington, D.C., May 2001.

9. Soelberg, Nick, "Off-gas Mercury Control for the Idaho Tank Farm Project – Calcination with MACT Upgrade SBW Treatment Alternative," Idaho National Laboratory, Engineering Design File EDF-3292, January 2003.

10. Holton, L. K., "Behavior of Mercury and Iodine During Vitrification of Simulated Alkaline Purex Waste," Pacific Northwest National Laboratory, PNL-3964, UC-70, September 1981.

11. Collier, C. W., "Overview of Selective Aspects of Mercury Problems within DOE Relevant to Thermal Processes," BDM Federal, February 12, 1994.

12. Wilmarth, W. R. and S. W. Rosencrance, "Studies of Mercury in High Level Waste Systems," Westinghouse Savannah River Company, WSRC-TR-2003-00238, June 6, 2003.

13. Boardman, R. D., L. J. Young, N. R. Soelberg, and L. A. Matejka, "NWCF Calciner Emissions Inventory – Final Report for Phase IV Testing," INEEL/EXT/01-00260, February 2001.

14. Boardman, R.D., B.H. O'Brien, N.R. Soelberg, S.O. Bates, C. P. St Michel, R. A. Wood, and B. J. Ward, "High Temperature MACT Calcination Test," INEEL/EXT-04-01625, February 2004.

15. Marshall, D. W. and N. R. Soelberg, "TWR Bench-Scale Steam Reforming Demonstration," INEEL/EXT-03-00436, May 2003.

16. Marshall, D. W., N. R. Soelberg, and K. M. Shaber, "THOR[sm] Bench-Scale Steam Reforming Demonstration," INEEL/EXT-03-00437, May 2003.

17. Soelberg, N. R., D. W. Marshall, S. O. Bates, and D. D. Taylor, "Phase 2 THOR Steam Reforming Tests for Sodium-Bearing Waste Treatment," INEEL/EXT-04-01493, January 30, 2004.

18. Soelberg, N. R., D. W. Marshall, D. D. Taylor, and S. O. Bates, "Phase 2 TWR Steam Reforming Tests for Sodium-Bearing Waste Treatment," INEEL/EXT-04-01494, January 30, 2004.

19. Olson, A. L., N. R. Soelberg, D. W. Marshall, and G. L. Anderson, "Fluidizing Bed Steam Reforming of INEEL SBW Using THOR[sm], Mineralizing Technology," INEEL/EXT-04-02564, December 2004.

20. THOR Treatment Technologies, LLC, and Washington Group International, Pilot Plant Report for Treating Tank 48H Simulants, Carbonate Flowsheet," Doc. No. 28927-WEC-RPT-0001, Revision 1, Project Number 28927, February 2007.

21. THOR Treatment Technologies, LLC, and Washington Group International, Pilot Plant Report for Treating Sodium-Bearing Waste Surrogates, Carbonate Flowsheet," Revision 1, RT-ESTD-002, Project Number 28276, August 2006.