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Rev. 1

Technology Maturation Plan (TMP)

Wet Air Oxidation (WAO)

For Tank 48H Treatment Project (TTP)

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Westinghouse Savannah River Company LLC
Savannah River Site
Aiken, SC 29808

DISCLAIMER

APPROVAL PAGE

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ABBREVIATIONS AND ACRONYMS

CD	Critical Decision
CRESP	Consortium for Risk Evaluation with Stakeholder Participation
CTE	critical technology element
DoD	U.S. Department of Defense
DOE	U.S. Department of Energy
DOE-SR	U.S. Department of Energy-Savannah River Operations Office
DWPF	Defense Waste Processing Facility
EDTA	Ethylenediaminetetraacetic Acid
EM	Office of Environmental Management
FBSR	Fluidized Bed Steam Reforming
FY	Fiscal Year
HEPA	High-Efficiency Particulate Air
HLW	High-Level Waste
ITR	Independent Technical Review
LFL	Lower Flammability Limit
LWO	Liquid Waste Organization
MOC	Materials-of-Construction
NASA	National Aeronautics and Space Administration
PNNL	Pacific Northwest National Laboratory
R&D	Research and Development
RFP	Request for Proposal
SRS	Savannah River Site
SRNL	Savannah River National Laboratory
THC	Total Hydrocarbon
TMP	Technology Maturation Plan
TRA	Technical Readiness Assessment
TRL	Technology Readiness Level
TTP	Tank 48H Treatment Project
VOC	Volatile Organic Carbon
WAC	Waste Acceptance Criteria
WAO	Wet Air Oxidation
WSRC	Washington Savannah River Company
lb	Pound
m	Meter
M	Molar
mg/L	milligrams per liter
ppm	parts per million

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1.0 INTRODUCTION

1.1 Purpose of the Tank 48H Waste Treatment Project

Tank 48H is a 1.3 million gallon Type IIIA tank, one of 49 tanks at the Savannah River Site (SRS) still containing High Level Waste (HLW). The tank has been isolated from the system and unavailable for use since 1983, because its contents – approximately 250,000 gallons of radioactive salt solution with significant quantities of organic tetraphenylborate (TPB), a material not compatible with the Tank Farm operation. It is therefore an important element of the U.S. Department of Energy-Savannah River Operations Office (DOE-SR) mission to remove, process and dispose of the contents of Tank 48H, both to eliminate the flammability hazard it presents to the SRS H-Tank Farm and return the tank to Tank Farm service to support ongoing HLW SRS processing and orderly tank closures.

The Washington Savannah River Company (WSRC), the SRS prime contractor, has evaluated alternatives and selected two processes, Wet Air Oxidation (WAO) and Fluidized Steam Bed Reforming (FBSR) as candidates for Tank 48H treatment. Over the past year WSRC has been sponsoring and reviewing the results of testing of these two technologies to support DOE in making the final technology selection.

1.2 Purpose of the Technology Maturation Plan

The purpose of this Technology Maturation Plan (TMP) is to describe the:

- Activities and schedules to resolve the WAO maturity issues.
- Relationship of the Technology Readiness Assessments (TRA), The Consortium for Risk Evaluation with Stakeholder Participation (CRESP), and Independent Technical Review (ITR) issues.
- Plan to manage the closure of the Wet Air Oxidation technology issues.

This plan was modeled after the Technology Maturation Plan for the Hanford Waste Treatment and Immobilization Plant.[1]

The proposed testing, costs and schedule are preliminary information based on the current maturity of this project and should only be used as general guidelines. This plan is a living document and will be reviewed to refine the testing, costs and schedule as the program develops.

[1] DOE/ORP-2007-02 – *Technology Maturation Plan for the Waste Treatment and Immobilization Plant*, Volume I, U.S. Department of Energy, Office of River Protection, August 2007.

2.0 TECHNOLOGY ASSESSMENTS OF THE TANK 48H WASTE TREATMENT PROCESSES

2.1 *Tank 48H Independent Technical Review*

On June 6th 2006, an ITR Team convened at the SRS to assess the technical viability of the current WSRC path forward for resolution of the long-standing problems posed by the TPB contamination in SRS HLW Tank 48H. The DOE-approved Charter outlined the objectives of the Tank 48H ITR, the requisite size and composite capabilities of the ITR Team, the methods to be employed, and the evaluation time frame. Included in the Charter were nine lines of inquiry, addressing specific issues to be addressed by the ITR Team[2]

In summary the ITR Team concluded the two TPB processing methods chosen by WSRC as lead candidates (FBSR and WAO) are technically sound, likely viable methods, and offer the best prospects for success among the approximately 80 alternatives considered.

However, the ITR Team also identified several areas in which the previous evaluations have not been sufficiently complete. As examples, heel management (removal of residual material and tank cleanup after removal of the bulk of the material currently in the tank), consideration of parallel-path options as outlined below, and understanding of the form, quantities, concentrations and implications of TPB processing by-products are all topics very important to success that received relatively superficial treatment in the alternative evaluations. These require further consideration, as delineated in the report.

The ITR Team found the WAO technology option a strong candidate, but less developed than the primary FBSR option for this application and is lacking demonstrated performance in radioactive material processing. Its very high pressure operating regimen also poses a challenge. None of these obstacles was considered by the ITR Team to be insurmountable, but it was the Team's judgment that it would take longer (in comparison to FBSR), by a year or more, to achieve WAO operational status at SRS. However, WAO's anticipated shorter processing or treatment time will most likely offset this time lag because WAO proposed feed rate (3 – 5 gpm) is about 12 – 20 times that of FBSR (0.25 gpm).

2.2 *CRESP Review of Alternatives for Treatment of Waste in SRS Tank 48H*

DOE requested that an independent review of the testing programs for FBSR and WAO in support of treatment of Tank 48H waste be conducted by CRESP under the leadership of Prof. David Kosson (Vanderbilt University and CRESP). The following presents their findings and recommendations resulting from review of the testing program in support of design of the FBSR process and WAO. Other findings and recommendations on schedule, compatibility of process with Building 241-96H, and safety evaluation are

[2] ITR-T48-2006-001 - DeVine, J.C. et al., *Independent Technical Review (ITR) of the Path Forward for Savannah River Site (SRS) Tank 48*, Revision 0, August 2006.

discussed in the CRESP report, but are less pertinent to the technology maturation of FBSR and WAO.[3]

Specific to WAO technology, the CRESP review noted that batch bench-scale autoclave testing had been carried out on WAO to provide preliminary evaluation of process conditions necessary for achieving acceptable destruction of organic constituents in Tank 48H wastes. CRESP recommended pilot-scale testing for WAO to (1) establish operating conditions necessary to reliably achieve process objectives, (2) demonstrate stable, continuous operations at design conditions for periods long enough to achieve steady-state (e.g., approximately three times the reactor mean residence time for liquid waste feed), and (3) verify recommended materials of construction. CRESP estimated that approximately 6 - 12 months would be required to schedule and complete the required testing based on discussions with the technology vendor and review participants. This effort should be carried out in parallel with other program activities so that it does not adversely impact overall program schedule.

2.3 *Wet Air Oxidation (WAO) Technology Readiness Assessment*

The purpose of this assessment was to determine the technology maturity level of the candidate Tank 48H treatment technologies that are being considered for implementation at DOE's SRS. DOE convened a team of independent qualified experts (the Assessment Team) to conduct this Technology Readiness Assessment (TRA).[4]

The methodology used for the TRA was based on detailed guidance for conducting TRAs contained in the Department of Defense (DoD), *Technology Readiness Assessment Deskbook*.[5] The assessment utilized a slightly modified version of the Technology Readiness Level (TRL) Calculator[6] originally developed by Nolte et al. to determine the TRL for the Critical Technology Elements (CTE). CTEs are those elements (such as subsystems) of an overall process that are essential to its success, are new, or are being applied in new or novel ways or in new environments. The calculator was adapted for DOE assessments by adding to and modifying the existing questions to make them more

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[3] CRESP 2007 - Kosson, D.S., Case, J.T., Garrick, B.J., Mathis, J.F., Matthews, R.B., and Sandler, S., *Factual Accuracy Review (FAR) Report: CRESP Review of Alternatives for Treatment of Wastes in SRS Tank 48*, Consortium for Risk Evaluation with Stakeholder Participation, July 2007.

[4] SPD-07-195 – Harmon, H.D., Berkowitz, J.B., DeVine, Jr., J.C., Sutter, H.G., and Young, J.K., *Savannah River Site Tank 48H Waste Treatment Project Technology Readiness Assessment*, July 31, 2007, U.S. Department of Energy, Savannah River Operations Office.

[5] Department of Defense, *Technology Readiness Assessment (TRA) Deskbook*, prepared by the Deputy Undersecretary of Defense for Science and Technology, May 2005.

[6] Nolte 2003 - Nolte, W.L., et al., *Technology Readiness Level Calculator*, Air Force Research Laboratory, presented at the National Defense Industrial Association Systems Engineering Conference, October 20, 2003.

applicable to DOE waste treatment equipment and processes. The TRL scale used in this assessment is shown in Table 1.

The TRA consists of three parts:

- Determination of the CTEs for each candidate process.
- Evaluation of the TRLs of each CTE for each process using the Technical Readiness Level Calculator
- Defining of the technology testing or engineering work necessary to bring immature technologies to the appropriate maturity levels.

The TRA methodology assigns a TRL to a technology based on the lowest TRL assigned to any CTE of that technology. Specific to WAO technology, the Assessment Team identified the following CTEs. Figure 1 identifies these CTEs with their assigned TRL

- Reactor System
- Offgas Treatment System

The Feed Receipt, Preparation, and Feed System, and the Product Handling systems were not considered CTEs because they are not new, novel, or repackaged. The WAO Reactor (TRL-3) and offgas system (TRL-2) technologies used for WAO were determined to be relatively immature due to the lack of testing using actual Tank 48H waste, no pilot-scale simulant testing, and limited development of the continuous design concepts and project requirements for implementation of these technologies. However, based on previous testing of these technologies with Tank 48H simulant and multiple commercial applications, the Assessment Team considers that the reactor technology can be brought to an appropriate level of maturity through pilot-scale testing with simulants, laboratory batch bench-scale autoclave testing with actual wastes, and concept development to support design implementation.

Although desirable from a standpoint of demonstrating technology maturity, laboratory and batch bench-scale autoclave testing with actual wastes for the offgas system may not be feasible. If it is not practical to conduct laboratory offgas testing with actual wastes, conducting offgas testing using tracers at hot commissioning should be considered.

In conclusion, the TRA determined that WAO technology appear to be viable. As would be anticipated for a radioactive treatment process, WAO does not meet the TRL 6 level usually considered by DoD and National Aeronautics and Space Administration (NASA) to be prerequisite to final design. However, since the Tank 48H Waste Treatment Project is approaching Critical Decision (CD) 1 (*Approve Alternative Selection and Cost Range*), a lower technology readiness level score was considered by the Assessment Team to be an adequate basis for moving forward.

Table 1

Technology Readiness Levels Used in Tank 48H TRA

Relative Level of Technology Development	Technology Readiness Level	TRL Definition	Description
System Operations	**TRL 9**	Actual system operated over the full range of expected conditions.	The technology is in its final form and operated under the full range of operating conditions. Examples include using the actual system with the full range of wastes.
System Commissioning	**TRL 8**	Actual system completed and qualified through test and demonstration.	The technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental testing and evaluation of the system with actual waste in hot commissioning.
	TRL 7	Full-scale, similar (prototypical) system demonstrated in relevant environment	This represents a major step up from TRL 6, requiring demonstration of an actual system prototype in a relevant environment. Examples include testing the prototype in the field with a range of simulants and/or actual waste and cold commissioning.
Technology Demonstration	**TRL 6**	Engineering/pilot-scale, similar (prototypical) system validation in relevant environment	Engineering-scale models or prototypes are tested in a relevant environment. This represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype with actual waste and a range of simulants.
Technology Development	**TRL 5**	Laboratory scale, similar system validation in relevant environment	The basic technological components are integrated so that the system configuration is similar to (matches) the final application in almost all respects. Examples include testing a high-fidelity system in a simulated environment and/or with a range of actual waste and simulants.
	TRL 4	Component and/or system validation in laboratory environment	The basic technological components are integrated to establish that the pieces will work together. This is relatively "low fidelity" compared with the eventual system. Examples include integration of ad hoc hardware in a laboratory and testing with a range of simulants.
Research to Prove Feasibility	**TRL 3**	Analytical and experimental critical function and/or characteristic proof of concept	Active research and development (R&D) is initiated. This includes analytical studies and laboratory-scale studies to physically validate the analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative. Components may be tested with simulants.
Basic Technology Research	**TRL 2**	Technology concept and/or application formulated	Once basic principles are observed, practical applications can be invented. Applications are speculative, and there may be no proof or detailed analysis to support the assumptions. Examples are still limited to analytic studies.
	TRL 1	Basic principles observed and reported	This is the lowest level of technology readiness. Scientific research begins to be translated into applied R&D. Examples might include paper studies of a technology's basic properties.

2.4 *Technology Heritage*

WAO Reactor System

The Zimpro WAO process has been used commercially for over 50 years to treat a variety of waste streams, including sludges from municipal and industrial wastewater treatment, pulp and paper wastes, and spent caustics from ethylene process facilities, oil refineries and other industries. The process is operating successfully in more than 150 full-scale commercial applications. Siemens is the leading vendor for the process. Systems have operated as long as 30 years with minimal maintenance.

In January 2007, Siemens began operation of a 27-gpm (1,620-gallons per hour) WAO plant for destruction of hydrolysate from prior treatment of non-stockpile binary weapon components. The plant is located at the Texas Molecular facility in Deer Park, Texas.[7, 8] The work is being done under contract for U.S. Department of Defense (DoD). The system was tested in a 9-gallon reactor (at a flow rate of 5 gallons per hour) pilot plant unit and scaled up to a 6,200-gallon (two 3,100-gallon reactors in series) full scale reactor – a scale up factor of approximately 700

Batch bench-scale autoclave WAO testing was successfully tested at the Hanford Site in the 1990s to destroy organic complexing agents in actual radioactive waste.[9],[10] At 280^{o}C and 1 hour, organics destruction based on total organic carbons for both simulant and radioactive actual waste was > 98.

A two-stage Kenox-designed WAO system went into operation in 1993 at Ontario Hydro's Bruce Spent Solvent Treatment Facility. The waste feeds were spent aqueous solutions from cleaning of the secondary side of Ontario Hydro's nuclear steam generators. The principle solution components were ethylenediaminetetraacetic acid (EDTA), copper and iron, contaminated with low levels of radionuclides (Co-60, Cs-137, Sb-124, and tritium). Design flow rate was 12 gpm. The reactors were operated at

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[7] LWO-SPT-2007-00084 - Davis, N., et al, *Trip Report for April 12, 2007 Visit to Wet Air Oxidation (WAO) Plant at Texas Molecular Site*, Deerpark, TX, Revision 0, Washington Savannah River Company, April 2007.

[8] WSRC-STI-2007-00314 - Shah, S. and Adu-Wusu, K., *Siemens Wet Air Oxidation (WAO) Tank 48 Alternate Solution*, Revision 1, presented at Tank 48 Technology Readiness Assessment, June 13-14, 2007, Washington Savannah River Company.

[9] PNL-10108 - Orth, R.J., Schmidt, A.J., and Zacher, A.H., *Hydrothermal Processing of Hanford Tank Waste: Organic Destruction Technology Development Task Annual Report – FY 1993*, Pacific Northwest National Laboratory, September 1993.

[10] PNL-10765 - Orth, R.J., Schmidt, A.J., Elmore, M.R., et al., *Removal of Strontium and Transuranics from Hanford Waste Via Hydrothermal Processing – FY 1994/95 Test Results*, Pacific Northwest National Laboratory, September 1995.

temperatures of 200 - 250°C and a pressure of 50 atmospheres. Destruction of EDTA was greater than 99.5% and the dissolved iron virtually precipitated simultaneously as a mixture of hematite and magnetite. The Kenox technology operates at somewhat lower temperatures and pressures than the Zimpro process, but both are based on the same principles.[11]

Offgas and treated Tank 48H simulant compositions were analyzed in eleven screening, four optimization, and four confirmation batch bench-scale autoclave experiments. Offgas contained low molecular weight volatile organic compounds, including benzene. The total hydrocarbon (THC) concentration in the offgas ranged from 720 (0.07%) to 3,390 (0.34%) ppm by volume, reported as ethane. Over half of the offgas THC was benzene, but at levels less than 24% of its lower flammability limit (LFL - 1.4% at 25°C). The batch bench-scale autoclave tests also demonstrated 99.99% destruction of TPB (< 2 mg/L). Biphenyl was observed floating on the surface of the treated simulant. Supplemental treatment may be required to remove biphenyl.

Table 2 displays the optimum test conditions identified after the screening and optimization tests. Note that the four confirmation tests were run under the conditions shown in Table 2. An additional test identified the materials-of-construction (MOC). The data from the confirmation and MOC tests were used to design preliminary full-scale system parameters and evaluate process economics.

Table 2 WAO Confirmation Test Conditions

Temp (ºC)	300
Time (hour)	3
Baffles	Yes
Antifoam-IIT B52	2000
Cu Catalyst (mg/L)	500
Feed Slurry Dilution	1:1 (2 M NaOH)

Corrosion is not expected not be a problem. The MOC test mentioned above involved conducting a single 100-hour test of stressed coupons in the autoclave under slightly more severe conditions than the confirmation runs. Inconel 600, Inconel 690, Nickel 201, and Monel K-500 were found to be potentially suitable materials for a full-scale WAO reactor. Plugging could be a problem because of the formation of carbonate salts by reaction of CO_2 (reaction by-product) with caustic. It was a problem in pilot tests on H-neutralent. The problem was solved by using KOH as a diluent instead of NaOH. The solubility of K_2CO_3 is higher than that of Na_2CO_3, so that no solids were formed.

[11] ICOA 1995 - Evans, D.W., Soliamani, H.M., Garamszeghy, M., Stott, J.B., *Treatment of Steam Generator Chemical Cleaning Wastes: Development and Operation of the Bruce Spent Solvent Treatment Facility*, Chemical Oxidation Technology for the Nineties, Fifth International Symposium, International Chemical Oxidation Association, Nashville, Tennessee, February 15-17, 1995.

Pilot-scale continuous flow simulant testing at the selected vendor facility has been proposed to refine the optimum conditions and to determine offgas and product composition. Batch bench-scale autoclave testing of actual Tank 48H radioactive wastes at SRS has been proposed to confirm destruction efficiencies and rates.

The CRESP report also recommended pilot-scale testing on WAO to (1) establish operating conditions necessary to reliably achieve process objectives, (2) establish stable continuous operations at design conditions for periods long enough to achieve steady state, and (3) verify recommended materials of construction.

WAO Offgas Treatment System

WAO has had a successful bench test. It has not been tested in a continuous flow system for the Tank 48H application, and the offgas treatment system has not yet been defined. The conventional equipment includes a water scrubber to remove particulates and water soluble gases, generating an aqueous slurry. Thermal oxidizers or thermal catalytic oxidizers also have been used. For radioactive applications, the significant components would likely include particulate removal equipment (e.g., High Efficiency Particulate Air [HEPA] filters), fans and blowers.

2.5 *Tank 48H Waste Treatment Project Activities and Technology Maturation*

WSRC had performed four System Engineering Evaluations (SEE) in FY-02, FY-04, FY-05, and FY-06 to identify technologies that could treat and/or disposition the waste in Tank 48H and return the tank to service. The most recent SEE[12] narrowed the technology selection to two leading candidates, FBSR and WAO. After a number of independent reviews, DOE has selected FBSR as the primary or baseline technology and WAO as the backup technology.

The Tank 48H Treatment Process (TTP) project scope for the recommended alternative includes modifications to utilities, infrastructure, and waste transfer systems to support operation of the primary option, Fluidized Bed Steam Reformer technology in Building 241-96H. This building is an operating SRS facility which currently houses the Actinide Removal Process in the south section shielded cells. The project is planning to locate the FBSR process in the north section of the building. Meanwhile WAO will be developed as the backup technology until ongoing technology development on FBSR has proven that all technical issues have been resolved.

Technology risks identified by WSRC and independent reviews will be addressed in the Technology Maturation Plans for WAO as described in Section 3.0. Technology performance risks also may emerge during the cold and hot commissioning phases of the Tank 48H Waste Treatment Project. These risks will be identified and mitigated during

[12] G-ADS-H-00011 - Winship, G.C., *Liquid Waste Disposition Projects, Tank 48 Return to Service Systems Engineering Evaluation (SEE) Results Report*, Washington Savannah River Company, Revision 0, April 2006.

technology installation and acceptance, and cold and hot commissioning of the actual plant equipment systems.

2.6 *Management of Technology Maturity*

The Liquid Waste Organization (LWO) of WSRC and the Savannah River National Laboratory (SRNL) will provide management with oversight from DOE-SR Waste Disposition Programs Division, and DOE-Headquarters, Office of Environmental Management (EM-20), Engineering and Technology. Management of technology maturity for WAO will follow the guidance of this TMP and of detailed tests plans and test procedures that will follow. Detailed schedules will be prepared for each major activity in the TMP and the LWO will maintain schedule status based on weekly updates from SRNL and vendor(s) performing pilot-scale tests. Any changes in scope and schedule will require change control following established procedures.

3.0 TECHNOLOGY MATURATION PLAN

3.1 *Development of Technology Maturation Requirements*

Development of the maturation plan for the WAO CTEs involved an assessment of the functions and critical design requirements of the TTP and a review of the project risk assessment. However, most of the risks were not technology-specific. Thus, the development of the maturation plan for the WAO CTEs was based primarily on the recommendations from the three previous independent reviews discussed in Section 2.0, WSRC documents referenced in those reviews, and the requirements and criteria for achieving TRL 6 (see Appendix B). This approach ensured that:

- Maturation plans for the CTEs were developed using a systematic approach.
- Tank 48H WAO project-specific and life-cycle schedule implications of maturing the CTEs were recognized.
- Opportunities for improving operational performance, reducing cost, or simplifying the system were considered.

3.2 *Life-Cycle Benefit*

The use of the TRA approach to assess and plan technology maturation for the WAO results in:

- Methodical evaluation of all systems in the WAO process to ensure identification of all technology maturation needs.
- Reduced overall project costs by resolving technology maturity issues and avoiding engineering re-work and potential delays in WAO commissioning.
- Higher confidence that the WAO design will achieve program mission operating requirements by the assessment of technology readiness and the completion of required technology maturation activities.

Technology maturation costs are small compared to impacts from design re-work and potential delays in the WAO operating schedule. The TRA process is also designed to ensure that future performance issues associated with the technology systems are identified and resolved before operations.

3.3 *Specific Technology Maturation Plans*

3.3.1 Wet Air Oxidation Reactor System

3.3.1.1 Key Technology Addressed

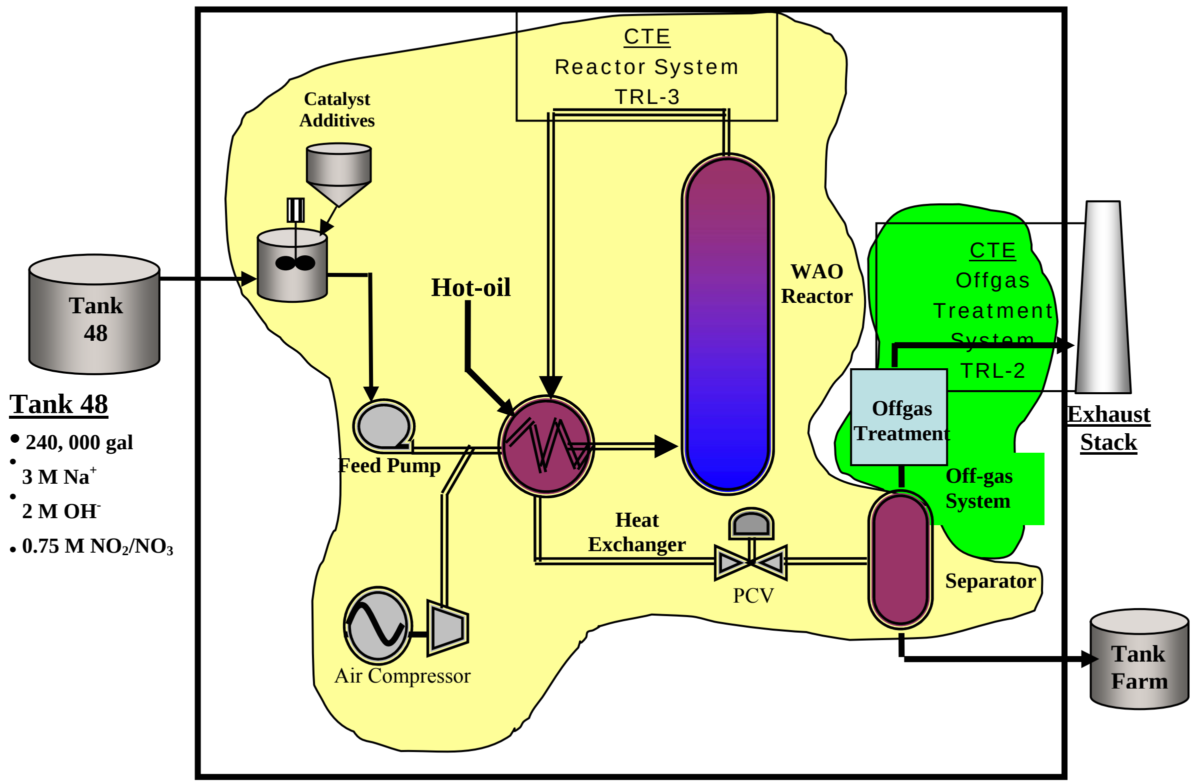
Destruction of organic components in Tank 48H waste.

3.3.1.2 Objective

The primary function of the WAO reactor system is to destroy organic constituents in the feed slurry through oxidation. The WAO reactor system includes feed heaters, reactor, and product coolers. The system also includes ancillary and support equipment, such as feed tanks, high pressure feed pumps and air compressors, gas-fired hot oil unit, product separator, and a cold chemical storage tank. The feed solution is delivered to the reactor through a high pressure pump. A schematic flow diagram is shown in Figure 1.

Based on recent batch bench-scale autoclave tests with Tank 48H simulants[13,14] and prior discussions with WAO vendor with pilot plant experience with other wastes, it is anticipated that the Tank 48H WAO reactor would have design features of 3 – 5 gpm feed rate, 3 hours reaction time, at operating temperature of 300°C. Air is injected to the process, resulting in three phases within the reactor: gas, solid (from insoluble components in the waste feed), and aqueous solution.

Figure 1 – Typical WAO Flow Diagram



3.3.1.3 <u>Approach</u>

The only testing that has been conducted to date on WAO is the batch bench-scale autoclave testing with Tank 48H simulant (includes 100-hour MOC testing). Even though the batch testing results indicate WAO is a feasible process for destroying TPB, the production-scale WAO system is continuous.

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[13] Siemens 03-09-2007 - *Evaluation of Wet Air Oxidation Treatment of Tank 48H Simulated Waste Slurry, Bench Scale Test Program Final Report*, Siemens Water Technology Corporation, March 2007.

[14] WSRC-STI-2007-00314 - Shah, S. and Adu-Wusu, K., *Siemens Wet Air Oxidation (WAO) Tank 48 Alternate Solution*, Revision 1, presented at Tank 48 Technology Readiness Assessment, June 13-14, 2007, Washington Savannah River Company.

The maturation approach for this CTE is divided into four activities. See Table 3 for the required testing, schedule, and TRL changes for the WAO Reactor System.

(1) Integrated continuous flow pilot scale testing (prototypical environment) of WAO technology using Tank 48H simulant at the vendor facility,
(2) 1000-hour MOC test using Tank 48H simulant at the vendor facility,
(3) Batch bench-scale autoclave validation of WAO technology using Tank 48H real waste at SRNL shielded cell, and
(4) Integrated continuous flow engineering scale testing using Tank 48H simulant at the vendor facility.

These activities are described as follows.

1. <u>Integrated Continuous Flow Pilot Scale Testing at Vendor Facility:</u>

This test will be carried out in two phases.

<u>Phase I:</u>

Phase I pilot scale unit will include a continuous flow integrated WAO reactor system, including feed heaters, reactor, and product coolers, ancillary and support equipment, and a cold chemical storage tank for Tank 48H simulant. The test will optimize processing and operating parameters established from prior batch bench-scale autoclave testing of Tank 48H simulant to achieve desired organic (including TPB and associated compounds) destruction efficiency in an integrated continuous flow operation mode.

The output from this test will be (1) optimized process conditions, (2) organic destruction efficiency including obtaining a better measure of the biphenyl destruction; (3) quantified secondary byproducts; (4) demonstration of a robust, continuous, and safe steady-state operations; (5) material balance closure for the major and minor constituents; (6) identifying and resolving any pertinent issues that may emerge, (e.g., biphenyl destruction and its residual levels in the treated effluent and offgas, generation of benzene and/or other flammable compounds and their residual levels in the treated effluent and offgas, efficacy of depressurization system, solids/scale formation, pumpability of feed slurry, etc.); and (7) design data for a full-scale system including the evaluation of process economics.

<u>Phase II:</u>

Phase II will include all integrated components of Phase I pilot scale unit, plus an offgas treatment system and associated equipment needed to comply with regulatory limits. This phase will allow further evaluation of process interfaces between the components and subsystems including the offgas treatment system, material balances, development of off-normal operating responses, etc. This phase will also confirm offgas treatment system performance to comply with regulatory limits which is included in Section 3.3.2 scope.

2. <u>1000-Hour MOC Test:</u>

This test will be carried out by the vendor, and will include include a 1000-hour (extended-duration) batch bench-scale autoclave MOC testing using Tank 48H simulated waste to confirm the high nickel content alloys (Nickel-201, Inconel 690, Inconel 600, and Monel K-500) identified in the prior 100-hour (short-duration) batch bench-scale autoclave MOC testing as potentially acceptable MOC candidates for a full-scale system.

3. Batch Bench-Scale Autoclave Testing at SRNL Shielded Cell:

This test will demonstrate and verify WAO technology efficiencies and rates for the destruction of organics, including TPB in Tank 48H real waste. Due to high radioactivity associated with Tank 48H real waste, this test will be carried out in SRNL shielded cell.

4. Engineering Scale Integrated Continuous Flow Test:

An integrated engineering scale continuous flow unit equipped with an offgas treatment system will be designed, fabricated and installed at the vendor facility. The unit will be tested in the prototypical environment to verify organic destruction efficiency, material balances, offgas compliances with regulatory limits, evaluate process interfaces between components/subsystems, develop off-normal operating responses, and Reliability, Availability, Maintainability, and Inspectability (RAMI) data.

NOTE:

The TRA criteria require a prototypical engineering-scale test to reach TRL 6. An ‘Engineering-scale’ unit must be greater than 1/10 of the size of the final application but can be less than the scale of final application. For a proposed 3 or 5-gpm WAO production unit, an engineering scale test unit requires a minimum pilot scale reactor volume of roughly 54 or 90 gallons respectively, based on the 3-hour reaction time obtained from the earlier batch bench-scale autoclave testing. The selected vendor will have to design, fabricate and install a new ‘engineering-scale’ integrated continuous flow test unit, equipped with offgas treatment and other supporting systems for a prototypical environment testing.

Discussions with a WAO vendor (Siemens) revealed scale ups of up to a factor of 2,300 are typical because reactor dynamics are well understood based on decades of experience. For example, as mentioned earlier in Section 2.4, Siemens recently used a 9-gallon (flow rate of about 5 gallons per hour) pilot scale test reactor to design and build a 6,200-gallon (flow rate of 27 gpm or 1,620 gallons per hour) full or commercial scale WAO plant for DoD for the destruction of chemical warfare materiel.[15]. This corresponds to a scale up factor of about 700.

[15] LWO-SPT-2007-00084 - Davis, N., et al, *Trip Report for April 12, 2007 Visit to Wet Air Oxidation (WAO) Plant at Texas Molecular Site*, Deerpark, TX, Revision 0, Washington Savannah River Company, April 2007.

3.3.1.4 Scope

(A) Integrated continuous flow Pilot Scale testing:

This includes following scope elements:

Phase I Pilot Scale:

- Develop Statement of Work (SOW) (for both Phases I and II), performance requirements, cost/schedule, Request for Proposal (RFP), and award of contract.
- Prepare Tank 48H simulant slurry and ship to vendor facility (Phases I and II).
- Vendor incorporates facility modifications and preparation for Phase I pilot scale testing (including regulatory operating permitting requirements).
- Perform Phase I test.
- Determine biphenyl and organic levels in effluent stream and volatile organic compounds (VOC) in offgas for regulatory compliances and Phase II pilot design input.
- Issue test report with recommendations.

Phase II Pilot Scale:

- Vendor designs, procures and retrofits an offgas treatment system to the pilot scale unit.
- Perform Phase II integrated continuous flow pilot scale test with offgas treatment system, and demonstrate offgas compliances with regulatory requirements.
- Issue test report with recommendations.

(B) 1000-Hour MOC Test:

- Vendor performs a 1,000-hour batch bench-scale autoclave MOC test using Tank 48H simulant with the optimum process parameters identified in Phase I pilot scale test.
- Issue test report with recommendations.

(C) SRNL Batch Bench-Scale Autoclave Real Waste Test:

- Design, procure and fabricate a bench bench-scale autoclave for Tank 48H real waste test. Verify DSA requirements for shielded cell for performing WAO test are met. Perform mock up test.
- Perform WAO batch bench-scale autoclave set up verification test using Tank 48H simulant, followed by Tank 48H real waste test in the shielded cell. Determine organic content of treated waste and destruction efficiency/rate.
- Issue test report with recommendations.

(D) Engineering Scale Integrated Continuous Flow Test:

- Develop SOW, performance requirements, cost/schedule, Request for Proposal (RFP), vendor selection, obtain DOE approval for contract award. and issue of Purchase Order.

- Vendor designs, fabricates and installs an integrated continuous flow ‘engineering scale WAO test unit’ equipped with an offgas treatment system. The MOC shall be based on the 1,000-hour MOC test results.
- Perform integrated continuous flow engineering scale test with Tank 48H simulant.
- Verify organic destruction efficiency, material balances, offgas compliances with regulatory limits, evaluate process interfaces between components/subsystems, develop off-normal operating responses, etc.
- Issue test report with recommendations.

3.3.1.5 Current State of Art – TRL 3

With only batch bench-scale autoclave testing with Tank 48H simulant, the WAO Reactor System was determined to be TRL 3. See Table 3 for the required testing, schedule, and TRL changes for WAO Reactor System.

Table 3

Wet Air Oxidation Reactor System

Year (**)	Milestones	Performance Target	TRL Achieved at Milestone[a]
3Q 2008	Continuous, integrated system testing at the Vendor pilot-scale facility (Phase I - without modification for offgas compliance performance)	• Demonstrate continuous integrated operations. • Determine organic destruction efficiency. • Characterize properties of treated effluent. • Demonstrate organic levels in effluent stream are compliant with Tank Farm/DWPF Waste Acceptance Criteria (WAC). • Develop optimum process flowsheet conditions for continuous flow operation including reaction temp, residence time, feed dilution, copper catalyst and antifoam concentration in feed to produce acceptable effluent quality. • Conduct longer term, 1,000-hour MOC test to confirm the MOCs identified in the prior batch bench-scale autoclave testing using Phase I pilot test optimum flowsheet conditions.	4
4Q 2008	Batch bench-scale autoclave testing with actual Tank 48H waste in SRNL shielded cells • Use batch autoclave equipment matching that used by Siemens for simulant testing as much as possible. • Use optimum conditions defined in Vendor Phase I pilot testing.	• Determine organic content of treated waste, destruction efficiency/rate and compare to the corresponding simulant test.	4
2Q 2009	Continuous, integrated system testing at the Vendor pilot-scale facility (Phase II - with modification for offgas compliance performance in place)	• Demonstrate organic levels in effluent stream are compliant with Tank Farm/DWPF Waste WAC. • Determine the flowsheet and operating conditions based on integrated pilot-scale testing including the offgas system.	5 Note: Prototypical engineering-scale testing is required to reach TRL 6. See comment at the end of section 3.3.1.3.

(**) Schedule is only an estimate based on current maturity of the project and should only be used as a guideline.

Table 3

Wet Air Oxidation Reactor System (Continued)

Year (**)	**Milestones**	**Performance Target**	**TRL Achieved at Milestone[a]**
4Q 2010 (****)	Continuous and fully integrated Engineering Scale testing with a prototypical unit, including offgas, treatment system. **<u>NOTE:</u>** Per TRA criterion, an 'Engineering Scale' unit must be greater than 1/10 of the size of the final application, but can be less than the scale of final application.	• Determine material balances based on integrated pilot-scale testing (including offgas system). • Allow process interfaces between components/subsystems to be more completely evaluated. • Determine off-normal operating responses.	6 Note: Prototypical engineering-scale testing is required to reach TRL 6. See comment at the end of section 3.3.1.3.
1Q 2011	Design Documentation required for TRL-6.(***) • Technology Development Program Plan, • Final Technical Report • Conceptual design report, • Risk Management Plan, • Configuration Management Plan, • Draft high level design drawings for final plant system, • Estimate cost of system design, and • Establish acquisition program milestones for start of final design.		6

[a]Major test activities required to reach the TRL are shown in this table. However, as presented in Appendix B, numerous other activities must be completed to fully satisfy the criteria for the TRLs listed above. It is assumed that the other activities can be completed by the dates shown in the first column above.
(**) Schedule is only an estimate based on current maturity of the project and should only be used as a guideline.
(***) During the maturation period Design documents will be revised and updated as the technology is achieved to higher TRL.

(****) Design, fabrication and installation of a 0.5 gpm integrated prototypical engineering test unit is based on recent preliminary planning discussion with WAO vendor (Siemens)

3.3.2 Wet Air Oxidation Offgas Treatment System

3.3.2.1 Key Technology Addressed

Treatment of WAO offgas to remove volatile organic products and radioactivity.

3.3.2.2 Objective

Offgas treatment may be required to comply with regulatory limits. The WAO Offgas System has not yet been defined. For non-radioactive air emission control, the conventional equipment includes a water scrubber to remove particulates and water soluble gases, a thermal oxidizer or thermal oxidizers/thermal catalytic oxidizers for fugitive organic air contaminants. For radioactive applications, the significant components would likely include particulate removal equipment (e.g., HEPA filters, fans, and blowers.

3.3.2.3 Approach

The maturation approach for this Critical Technology Element (CTE) is divided into two activities. See Table 4 for the required testing, schedule, and TRL changes for WAO Offgas Treatment System.

(1) Assessment of offgas data from Phase I integrated continuous flow pilot scale testing, followed by validation of an offgas treatment system during Phase II pilot scale testing using Tank 48H simulant at the vendor facility, and
(2) Characterization of offgas from SRNL batch bench-scale autoclave testing of Tank 48H real waste if feasible.

These activities are further described as follows.

(1) Assessment and Validation of an Offgas Treatment System at Pilot Scale:

During Phase I pilot scale testing (see Section 3.3.1), offgas data including NO_x, SO_x, particulates and other hazardous pollutants will be collected and assessed against the regulatory compliance limits. The data will be used as input for selection, design and procurement of an offgas treatment system. Phase II pilot scale testing with offgas treatment system installed (see Section 3.3.1) will demonstrate and validate offgas system performance and compliance with regulatory limits. The Phase II test will also evaluate and determine interaction/effects of offgas related equipment (HEPA filters, offgas treatment system, blowers, stack, etc.) on the remaining WAO components as a whole. It will also provide design data for a full-scale system especially the offgas system.

(2) SRNL Batch Bench-Scale Autoclave test:

SRNL batch bench-scale autoclave testing (see Section 3.3.1) will also characterize the offgas if feasible. The data will be used to make meaningful comparisons with corresponding simulant test data.

3.3.2.4 Scope

Integrated continuous flow testing at vendor facility will include following scope elements:

Phase I Pilot Scale:

(Following are additional scope to the Phase I scope in Section 3.3.1)

- Collect offgas data in accordance with the appropriate regulatory protocols.
- Analyze and evaluate offgas data for regulatory compliances, issue finding report with recommendations. The data will serve as design input for an offgas treatment system.
- Customer acceptance of recommendations and approval to proceed to Phase II if recommended.

Phase II Pilot Scale:

- Vendor to designs, procures and retrofits an offgas treatment system to the pilot scale unit.
- Demonstrate and validate offgas treatment system performance to comply with the regulatory limits.
- Issue a report with recommendations.

SRNL batch bench-scale autoclave testing with Tank 48H real waste:
(Following are additional scope to the SRNL real waste batch bench-scale autoclave test in Section 3.3.1)

- Analyze and make meaningful comparison of simulant offgas test information.
- Determine if it is necessary and feasible to design, procure and install necessary equipment to analyze offgas data from real waste batch bench-scale autoclave test.
- If determined to be needed, characterize offgas as practical as possible.
- Issue a report with recommendations.

3.3.2.5 Current State of Art – TRL 2

The offgas system technology is a TRL 2, because there has not been testing of the integrated, prototypical system. See Table 4 for the required testing, schedule, and TRL changes for WAO Offgas Treatment System.

Table 4

Wet Air Oxidation Offgas Treatment System

Year (**)	Milestones	Performance Target	TRL Achieved at Milestone[a]
3Q 2008	Continuous, integrated system testing at the Vendor pilot-scale facility (Phase I - without offgas treatment system)	• Assess and characterize offgas stream for compliance with regulatory limits and as Phase II testing design input.	4
3Q 2008	Batch bench-scale autoclave testing with actual Tank 48H waste in SRNL shielded cells • Use batch autoclave equipment matching that used by Siemens for simulant testing as much as possible. • Use optimum conditions defined in Vendor Phase I pilot testing.	• If feasible, capture and characterize offgas when the autoclave is vented, and compare with corresponding simulant test data.	4
2Q 2009	Continuous, integrated system testing at the Vendor pilot-scale facility (Phase II - with offgas treatment system installed).	• Demonstrate offgas compliance with regulatory limits.	5 Note: Prototypical engineering-scale testing is required to reach TRL 6. See comment at the end of section 3.3.1.3.
4Q 2010 (****)	Continuous and fully integrated Engineering Scale testing with a prototypical unit, including offgas, treatment system.	• Demonstrate offgas compliance with regulatory limits.	6 See comment at the end of section 3.3.1.3 to achieve TRL 6.
1Q 2011	Design Documentation required for TRL-6 (***). • Technology Development Program Plan, • Final Technical Report • Conceptual design report, • Risk Management Plan, • Configuration Management Plan, • Draft high level design drawings for final plant system, • Estimate cost of system design, and • Establish acquisition program milestones for start of final design.		6

[a]Major test activities required to reach the TRL are shown in this table. However, as presented in Appendix B, numerous other activities must be completed to fully satisfy the criteria for the TRLs listed above. It is assumed that the other activities can be completed by the dates shown in the first column above.
(**) Schedule is only an estimate based on current maturity of the project and should only be used as a guideline.

(***) During the maturation period Design documents will be revised and updated as the technology is achieved to higher TRL.

(****) Design, fabrication and installation of a 0.5 gpm integrated prototypical engineering test unit is based on recent preliminary planning discussion with WAO vendor (Siemens)

4.0 TECHNOLOGY MATURITY SCHEDULE

Figure 2 shows the DOE O 413.3[16] project management process, as applied to the Tank 48H Waste Treatment Project. This figure shows the critical decision process with major project activities (e.g., design construction, commissioning, and operations).

Figure 3 shows the technology maturity schedule for WAO testing activities. This figure also shows the relationship of the critical decision process and the maturity level of WAO CTEs. The figure illustrates the TRLs for WAO at CD-0 (approximate) and at CD-1 based on the TRA[17]. It is desirable to reach TRL 5 or 6 by CD-2 or early in final design. Based on precedents set by NASA and DoD, a TRL level of 6 indicates that a technology is sufficiently mature for incorporation into final design.

Start of testing activities is shown in January 2008 based on the assumption that EM-21 funding will not be available until then. The maturation schedule is an aggressive one based on the assumption that program will not have funding or programmatic constraints to achieve TRL 6. This aggressive maturation schedule allows achieving TRL 5, after completion of Phase II pilot-scale testing with prototypical integrated offgas system, about the same time when Tank 48H project milestone of CD-2/3B is scheduled for September 1, 2009. It is expected that TRL-6 will require additional 25 months to achieve after completion of Engineering Scale testing with prototypical integrated offgas system and completion of the Final Technical Report.

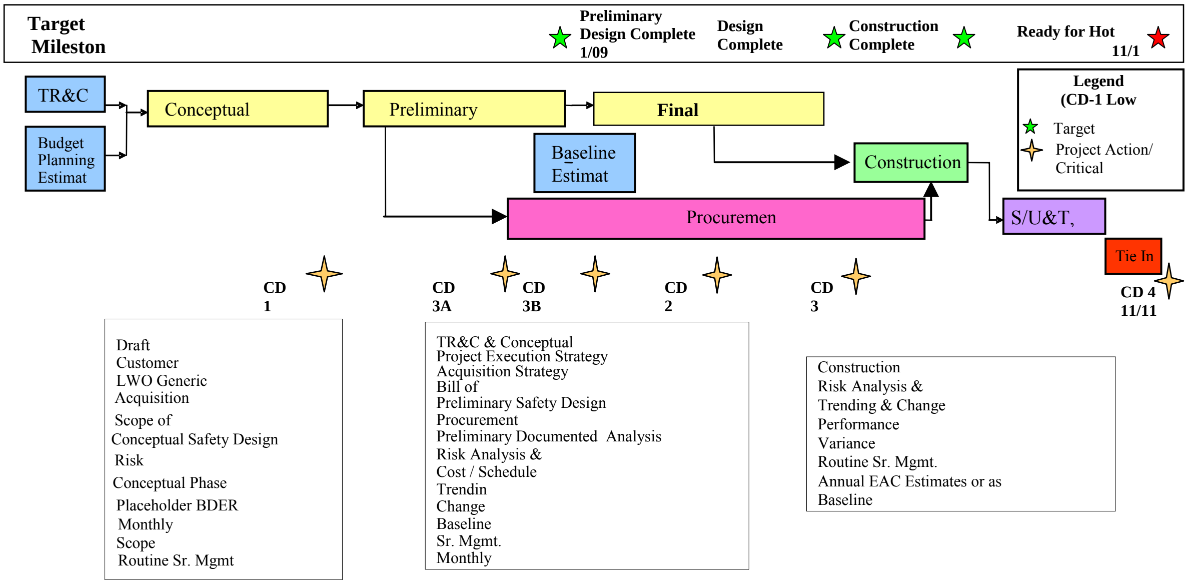
Figure 2 also shows the TRL status of the Fluidized Bed Steam Reforming Technology (FBSR- primary technology) as the WAO is progressing through the maturation plan.

The proposed testing, costs and schedule are preliminary information based on the current maturity of this project and should only be used as general guidelines. This plan is a living document and will be reviewed to refine the testing, costs and schedule as the program develops.

[16] DOE O 413.3 – *Program Management and Project Management for the Acquisition of Capital Assets,* January 3, 2006, U.S. Department of Energy, Washington, DC.

[17] SPD-07-195 - Harmon, H.D., Berkowitz, J.B., DeVine, Jr., J.C., Sutter, H.G., and Young, J.K., *Savannah River Site Tank 48H Waste Treatment Project Technology Readiness Assessment*, July 31, 2007, U.S. Department of Energy, Savannah River Operations Office.

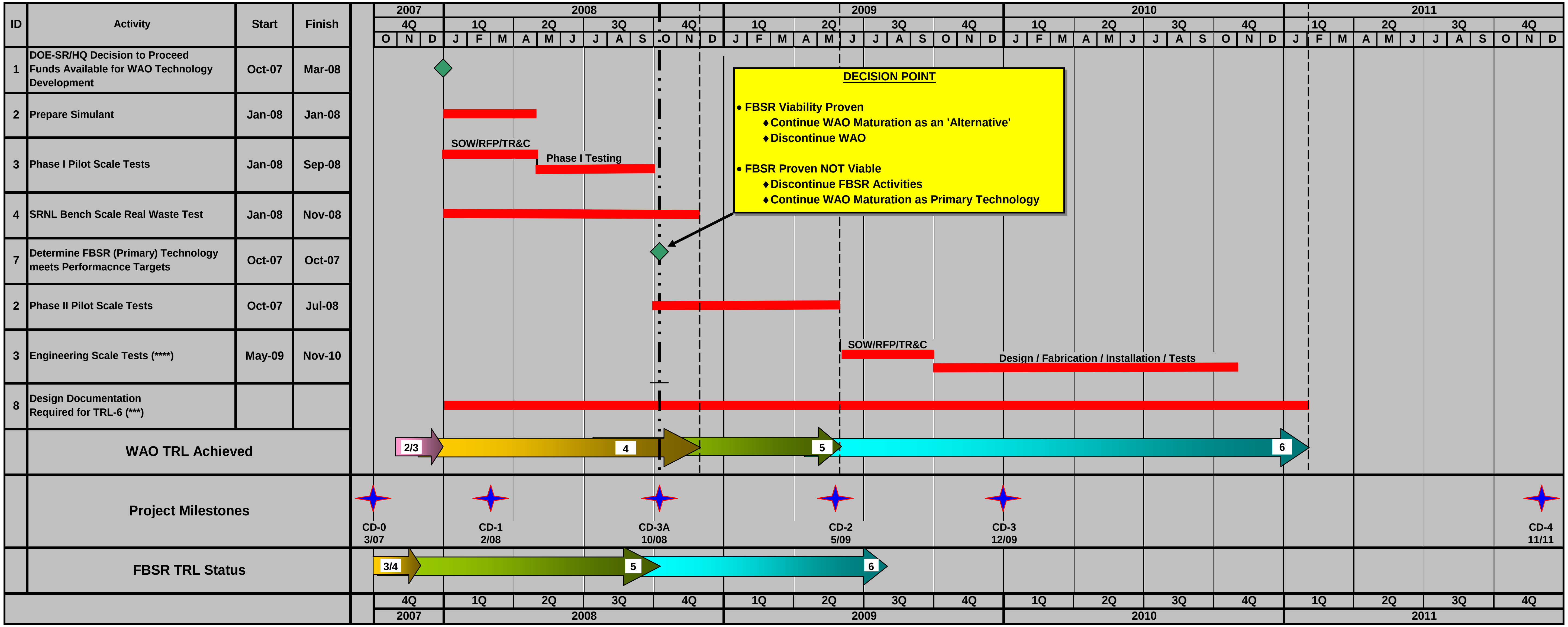
Figure 2 - Tank 48 Project Execution Strategy



Low & High Schedule Ranges (Low Shown Above)

	CD-1	CD-2	CD-3	CD-4
Low BDER	**2/08**	**5/09**	**12/09**	**11/11**
High BDER	**2/08**	**8/09**	**03/10**	**08/12**

Figure 3 - WAO Technology Maturity Schedule to Achieve TRL 6



(***) During the maturation period Design documents will be revised and updated as the technology is achieved to higher TRL.

(****) Design, fabrication and installation of a 0.5 gpm integrated prototypical engineering test unit is based on recent preliminary planning discussion with WAO vendor (Siemens)

5.0 TECHNOLOGY MATURITY COST

The technology maturity budget for the activities described in this TMP is shown below for WAO. This funding must be available in early FY-08 to achieve the technology maturity schedule shown in Section 4.0 above.

Table 5

Technology Maturity Budget for WAO

Required Testing	**Technology Development Cost ($K) (**)**
Prepare Tank 48H simulant (2,500 gallons)	$500 [a]
Autoclave testing with actual Tank 48H waste in SRNL shielded cells	$1,000
Continuous, integrated system testing at the selected vendor pilot-scale facility (Phase I)	$1,300
Pilot-scale testing with prototypical, integrated offgas system (Phase II)	$3,000
Engineering-scale testing with prototypical, integrated offgas system	$6,000 – 9,000[b]
Design Documentation required for TRL-6.	$2,000 – 4,000
Total	**$13,750 – 17,750**

a Includes procuring 2,500 gallons Tank 48H simulant for both Phases I and II pilot-scale testing

[b] Includes design, fabrication, installation, and operation of a 0.5–0.6 gpm Integrated Engineering-scale unit with an offgas system, and simulant procurement, testing, vendor facility and support service fees.

(**) Cost is only an estimate based on current maturity of the project and should only be used as a guideline.

APPENDIX A

WAO TECHNOLOGY DEVELOPMENT RECOMMENDATIONS
CROSSWALK OF TANK 48 H INDEPENDENT TECHNICAL REVIEW, CRESP REVIEW, AND TANK 48H TECHNOLOGY READINESS ASSESSMENT

Major Tests	ITR	CRESP	TRA
Bench-scale Autoclave WAO tests with Tank 48H simulant	X	N/A	X
Autoclave testing with actual Tank 48 waste in SRNL shielded cells	X		X
Continuous, integrated system testing at the selected vendor's pilot-scale facility (Phase I)		X	X
Pilot-scale testing with prototypical, integrated offgas system (Phase II)			X
Project documentation required for CD-2			X

APPENDIX B

TECHNOLOGY READINESS LEVEL CALCULATOR AS MODIFIED FOR DOE OFFICE OF ENVIRONMENTAL MANAGEMENT

Appendix B presents the questions used for assessing the technology maturity of the U.S. Department of Energy, Office of Environmental Management waste processing and treatment technologies using a modified version of the Air Force Research Laboratory Technology Readiness Level (TRL) Calculator. The following TRL questions were used in Technology Readiness Assessments (TRA) conducted at Hanford and the Savannah River Site.

- Table B.1 for TRL 1
- Table B.2 for TRL 2
- Table B.3 for TRL 3
- Table B.4 for TRL 4
- Table B.5 for TRL 5
- Table B.6 for TRL 6

The TRL Calculator was used to assess the TRL of the Tank 48H waste treatment critical technology elements (CTE). The assessment begins by using the top-level questions listed in Figure B.1 to determine the anticipated TRL that would result from the detailed questions. The anticipated TRL was determined from the question with the first "yes" answer from the list in Figure B.1. Evaluation of the detailed questions was started one level below the anticipated TRL. If it was determined from the detailed questions that the technology had not attained the maturity of the starting level, the next levels down were evaluated in turn until the maturity level could be determined.

The TRL Calculator provides a standardized, repeatable process for evaluating the maturity of the hardware or software technology under development. The first column in Tables B-1 to B-6 identify the areas of readiness being evaluated: technical (T), programmatic (P), and manufacturing/quality requirements (M). A technology is determined to have reached a given TRL if column 3 is judged to be 100% complete for all questions.

If Yes, Then Logic		Top-Level Question
TRL 9	→	Has the actual equipment/process successfully operated in the full operational environment (hot operations)?
TRL 8	→	Has the actual equipment/process successfully operated in a limited operational environment (hot commissioning)?
TRL 7	→	Has the actual equipment/process successfully operated in the relevant operational environment (cold commissioning)?
TRL 6	→	Has prototypical engineering scale equipment/process testing been demonstrated in a relevant environment?
TRL 5	→	Has bench-scale equipment/process testing been demonstrated in a relevant environment?
TRL 4	→	Has laboratory-scale testing of similar equipment systems been completed in a simulated environment?
TRL 3	→	Has equipment and process analysis and proof of concept been demonstrated in a simulated environment?
TRL 2	→	Has an equipment and process concept been formulated?
TRL 1	→	Have the basic process technology process principles been observed and reported?

Figure B.1. Top-Level Questions Establish Expected Technology Readiness Level

Table B.1

TRL 1 Questions for Critical Technical Element

T/P /M	Y /N	Criteria	Documentation
T		"Back of envelope" environment	
T		Physical laws and assumptions used in new technologies defined	
T		Paper studies confirm basic principles	
P		Initial scientific observations reported in journals/conference proceedings/technical reports.	
T		Basic scientific principles observed and understood.	
P		Know who cares about the technology, e.g., sponsor, money source	
T		Research hypothesis formulated	
T		Basic characterization data exists	
P		Know who would perform research and where it would be done	

T-Technology, technical aspects; M-Manufacturing and quality; P-Programmatic, customer focus, documentation

Table B.2

TRL 2 Questions for Critical Technical Elements

T/P /M	Y /N	Criteria	Documentation
P		Customer identified	
T		Potential system or components have been identified	
T		Paper studies show that application is feasible	
P		Know what program the technology would support	
T		An apparent theoretical or empirical design solution identified	
T		Basic elements of technology have been identified	
T		Desktop environment (paper studies)	
T		Components of technology have been partially characterized	
T		Performance predictions made for each element	
P		Customer expresses interest in the application	
T		Initial analysis shows what major functions need to be done	
T		Modeling & Simulation only used to verify physical principles	
P		System architecture defined in terms of major functions to be performed	
P		Requirements tracking system defined to manage requirements creep	
T		Rigorous analytical studies confirm basic principles	
P		Analytical studies reported in scientific journals/conference proceedings/technical reports.	
T		Individual parts of the technology work (No real attempt at integration)	
T		Know what output devices are available	
P		Preliminary strategy to obtain TRL Level 6 developed (e.g. scope, schedule, cost)	
P		Know capabilities and limitations of researchers and research facilities	
T		The scope and scale of the waste problem has been determined	
T		Know what experiments are required (research approach)	
P		Qualitative idea of risk areas (cost, schedule, performance)	

T-Technology, technical aspects; M-Manufacturing and quality; P-Programmatic, customer focus, documentation

Table B.3

TRL 3 Questions for Critical Technical Elements

T/P /M	Y /N	Criteria	Documentation
T		Academic (basic science) environment	
P		Some key process requirements are identified	
T		Predictions of elements of technology capability validated by analytical studies	
P		The basic science has been validated at the laboratory scale	
T		Science known to extent that mathematical and/or computer models and simulations are possible	
P		Preliminary system performance characteristics and measures have been identified and estimated	
T		Predictions of elements of technology capability validated by Modeling and Simulation (M&S)	
M		No system components, just basic laboratory research equipment to verify physical principles	
T		Laboratory experiments verify feasibility of application	
T		Predictions of elements of technology capability validated by laboratory experiments	
P		Customer representative identified to work with development team	
P		Customer participates in requirements generation	
T		Key process parameters/variables have begun to be identified.	
M		Design techniques have been identified/developed	
T		Paper studies indicate that system components ought to work together	
P		Customer identifies transition window(s) of opportunity (When technology is needed)	
T		Performance metrics for the system are established (What must it do)	
P		Scaling studies have been started	
M		Current manufacturability concepts assessed	
M		Sources of key components for laboratory testing identified	
T		Scientific feasibility fully demonstrated	
T		Analysis of present state of the art shows that technology fills a need	
P		Risk areas identified in general terms	
P		Risk mitigation strategies identified	

Table B.3

TRL 3 Questions for Critical Technical Elements (Continued)

T/P /M	Y /N	Criteria	Documentation
P		Rudimentary best value analysis performed for operations	
T		Key physical and chemical properties have been characterized for a number of waste samples	
T		A simulant has been developed that approximates key waste properties	
T		Laboratory scale tests on a simulant have been completed	
T		Specific waste(s) and waste site(s) has (have) been defined	
T		The individual system components have been tested at the laboratory scale	

T-Technology, technical aspects; M-Manufacturing and quality; P-Programmatic, customer focus, documentation

Table B.4

TRL 4 Questions for Critical Technical Elements

T/P /M	Y /N	Criteria	Documentation
T		Key process variables/parameters have been fully identified.	
M		Laboratory components tested are surrogates for system components	
T		Individual components tested in laboratory/ or by supplier	
T		Subsystems composed of multiple components tested at lab scale using simulants	
T		Modeling & Simulation used to simulate some components and interfaces between components	
P		Overall system requirements for end user's application are <u>known</u>	
T		Overall system requirements for end user's application are <u>documented</u>	
P		System performance metrics measuring requirements have been established	
P		Laboratory testing requirements derived from system requirements are established	
M		Available components assembled into laboratory scale system	
T		Laboratory experiments with available components show that they work together (lab kludge)	
T		Analysis completed to establish component compatibility (Do components work together)	

Table B.4 (Continued)

TRL 4 Questions for Critical Technical Elements

T/P /M	Y /N	Criteria	Documentation
P		Science and Technology exit criteria established (S&T targets understood, documented, and agreed to by sponsor)	
T		Technology demonstrates basic functionality in simulated environment	
M		Scalable technology prototypes have been produced (Can components be made bigger than lab scale)	
P		Draft conceptual designs have been documented	
M		Equipment scaleup relationships are understood/accounted for in technology development program	
T		Controlled laboratory environment used in testing	
P		Initial cost drivers identified	
M		Integration studies have been started	
P		Formal risk management program initiated	
M		Key manufacturing processes for equipment systems identified	
P		Scaling documents and designs of technology have been completed	
M		Key manufacturing processes assessed in laboratory	
P/T		Functional process description developed. (Systems/subsystems identified)	
T		Low fidelity technology “system” integration and engineering completed in a lab environment	
M		Mitigation strategies identified to address manufacturability/producibility shortfalls	
T		Key physical and chemical properties have been characterized for a range of wastes	
T		A limited number of simulants have been developed that approximate the range of waste properties	
T		Laboratory scale tests on a limited range of simulants and real waste have been completed	
T		Process/parameter limits are being explored	
T		Test plan documents for prototypical lab scale tests completed	
P		Technology availability dates established	

T-Technology, technical aspects; M-Manufacturing and quality; P-Programmatic, customer focus, documentation

Table B.5

TRL 5 Questions for Critical Technical Elements

T/P /M	Y /N	Criteria	Documentation
T		The relationships between major system and sub-system parameters are understood on a laboratory scale.	
T		Plant size components available for testing	
T		System interface requirements known (How would system be integrated into the plant?)	
P		Preliminary design engineering begins	
T		Requirements for technology verification established	
T		Interfaces between components/subsystems in testing are realistic (benchtop with realistic interfaces)	
M		Significant engineering and design changes	
M		Prototypes of equipment system components have been created (know how to make equipment)	
M		Tooling and machines demonstrated in lab for new manufacturing processes to make component	
T		High fidelity lab integration of system completed, ready for test in relevant environments	
M		Manufacturing techniques have been defined to the point where largest problems defined	
T		Lab scale similar system tested with range of simulants	
T		Fidelity of system mock-up improves from laboratory to benchscale testing	
M		Availability and reliability (RAMI) target levels identified	
M		Some special purpose components combined with available laboratory components for testing	
P		Three dimensional drawings and P&IDs for the prototypical engineering scale test facility have been prepared	
T		Laboratory environment for testing modified to approximate operational environment	
T		Component integration issues and requirements identified	
P		Detailed design drawings have been completed to support specification of engineering scale testing system	

Table B.5 (Continued)

TRL 5 Questions for Critical Technical Elements

T/P /M	Y /N	Criteria	Documentation
T		Requirements definition with performance thresholds and objectives established for final plant design	
P		Preliminary technology feasibility engineering report completed	
T		Integration of modules/functions demonstrated in a laboratory/batch bench-scale autoclave environment	
T		Formal control of all components to be used in final prototypical test system	
P		Configuration management plan in place	
T		The range of all relevant physical and chemical properties has been determined (to the extent possible)	
T		Simulants have been developed that cover the full range of waste properties	
T		Testing has verified that the properties/performance of the simulants match the properties/performance of the actual wastes	
T		Laboratory scale tests on the full range of simulants using a prototypical system have been completed	
T		Laboratory scale tests on a limited range of real wastes using a prototypical system have been completed	
T		Test results for simulants and real waste are consistent	
T		Laboratory to engineering scale scale-up issues are understood and resolved	
T		Limits for all process variables/parameters are being refined	
P		Test plan for prototypical lab scale tests executed – results validate design	
P		Test plan documents for prototypical engineering scale tests completed	
P		Risk management plan documented	

T-Technology, technical aspects; M-Manufacturing and quality; P-Programmatic, customer focus, documentation

Table B.6

<u>TRL 6 Questions for Critical Technical Elements</u>

T/P /M	Y /N	Criteria	Documentation
T		The relationships between system and sub-system parameters are understood at engineering scale allowing process/design variations and tradeoffs to be evaluated.	
M		Availability and reliability (RAMI) levels established	
M		Frequent design changes occur	
P		Draft high level design drawings for final plant system are nearly complete	
T		Operating environment for final system known	
P		Collection of actual maintainability, reliability, and supportability data has been started	
P		Estimated cost of the system design is identified	
T		Operating limits for components determined (from design, safety and environmental compliance)	
P		Operational requirements document available	
P		Off-normal operating responses determined for engineering scale system	
T		System technical interfaces defined	
T		Component integration demonstrated at an engineering scale	
P		Scaling issues that remain are identified and understood. Supporting analysis is complete	
P		Analysis of project timing ensures technology would be available when required	
P		Have begun to establish an interface control process	
P		Acquisition program milestones established for start of final design (CD-2)	
M		Critical manufacturing processes prototyped	
M		Most pre-production hardware is available to support fabrication of the system	
T		Engineering feasibility fully demonstrated (e.g. would it work)	
M		Materials, process, design, and integration methods have been employed (e.g. can design be produced?)	
P		Technology ”system” design specification complete and ready for detailed design	

Table B.6 (Continued)

TRL 6 Questions for Critical Technical Elements

T/P /M	Y /N	Criteria	Documentation
M		Components are functionally compatible with operational system	
T		Engineering scale system is high-fidelity functional prototype of operational system	
P		Formal configuration management program defined to control change process	
M		Integration demonstrations have been completed (e.g. construction of testing system)	
P		Final Technical Report on Technology completed	
M		Process and tooling are mature to support fabrication of components/system	
T		Engineering scale tests on the full range of simulants using a prototypical system have been completed	
T		Engineering to full scale scale-up issues are understood and resolved	
T		Laboratory and engineering scale experiments are consistent	
T		Limits for all process variables/parameters are defined	
T		Plan for engineering scale testing executed - results validate design	
M		Production demonstrations are complete (at least one time)	

T-Technology, technical aspects; M-Manufacturing and quality; P-Programmatic, customer focus, documentation