TOXIC EMISSION CONTROL SYSTEMS FOR MIXED WASTE STORAGE TANKS

Greg E. Hansen
Engineering-Science, Inc.
1955 Jadwin Ave., Suite 470
Richland, WA 99352

ABSTRACT

The use of emission control systems on mixed waste storage tanks is a critical issue as characterization and remediation of tanks becomes a leading priority at DOE sites. The current tank ventilation systems, where installed, are designed primarily for the control of radionuclides with no treatment systems incorporated for toxic emissions. Many of the tanks also lack ammonia treatment systems, although ammonia, due to its noxious odor, is controlled in some applications. The need for emission control systems has become apparent by the numerous occurrences of occupational employee exposure and the buildup of toxic and/or flammable materials in the vapor space of tanks. This issue will become more critical as characterization and remediation programs are implemented which agitate the tank waste and generate aerosols and toxic vapors. Nuclear applications for exhaust systems are a complicated and controversial issue due to the inherent safety concerns, difficulties associated with characterizing the vapor space, and the magnitude of the problem caused by the number of tanks and the variety of waste types received. This paper will focus on two alternate systems for the control of toxic emissions, and will provide a discussion of the key issues which must be addressed for each system.

The contents of this paper are the results of two efforts being performed by Engineering-Science, Inc., under the contract to Battelle Environmental Management Operations (EMO), for the Westinghouse Hanford Company. These efforts are for the study, design, fabrication, installation, and testing of new modular exhaust units for the 241-C-103 Tank and for several tanks which are candidates for the Rotary Mode Core Sampling (RMCS) characterization. If one exhaust system can be used in several applications, during high activity and personnel exposure periods, then a tremendous savings to the capital investment needs, the annual operating budget, and decontamination and decommissioning costs can be realized.

The two systems which show the most promise for universal application, thereby allowing the design of a modular (semi-standardized) system, are a passive filtration system using activated/impregnated media and a fume incineration system. Each system has numerous advantages, and unfortunately, each system has inherent disadvantages. This paper will address the evaluation process performed for these systems. Treatment technologies which generate significant quantities of liquid waste, such as wet scrubbing systems, are not addressed due to the lack of waste water treatment facilities at DOE sites, the desire to discontinue discharges to the soil column, and the inability of tank farms to accommodate increased volumes of waste water from new sources.

CASE STUDIES

Tank 241-C-103

The 241-C-103 (C-103) tank at the Hanford site is a single shell tank which was used for the disposal of waste from chemical separation plants in the 200 Areas. This tank has a well defined organic layer and is considered the worst organic tank at the Hanford site. Over the last six years there have been several documented occurrences of employees smelling vapors and feeling nauseous. These occurrences have prompted all work in the area to be performed in OSHA Level B protection and initiated the development of an exhauster system.

The first step in developing a new exhauster was to adequately define the vapor space characteristics. A variety of information was provided including tank vapor temperatures, humidity, and the chemical and radiological composition. Immediately after initiating the project, there were numerous challenges to the validity of the vapor space data. The primary focus of these challenges was that the cryogenic vapor space sampling methods were incorrectly used. This issue was eventually proven, and the project has been on hold for approximately one year while a task team evaluates the appropriate methods for obtaining valid vapor space data.

Although the vapor space composition was being questioned, activities in developing the best available control technology (BACT) and a system conceptual design continued. The emphasis of the BACT was two-fold. The first priority was to determine the actual concentration of toxic materials in the airstream at steady state conditions. A model was developed using diffusion through a stagnant layer as shown in Fig. 1. The mass transfer equation used to model the rate of diffusion (Ref. 1) is :

$$P_{x,2} = \frac{P_{\text{total}} A_{\text{surface}} D_{x,air}}{Q(Z_2 - Z_1)} \ln \frac{(1 - P_{x,2})}{(1 - P_{x,1})}$$

Where:

$P_{x,2}$ = Concentration of contaminants at steady state
P_{total} = 1 Atmosphere
A_{surface} = Area of supernate surface
Q = Airflow rate through tank vapor
$Z_2 - Z_1$ = Thickness of stagnant layer
$P_{x,1}$ = Initial equilibrium concentration
$D_{x,\text{air}}$ = Diffusivity constant of contaminant

This equation was used for numerous contaminants, at airflow rates from 200 cfm through 700 cfm, and stagnant layer

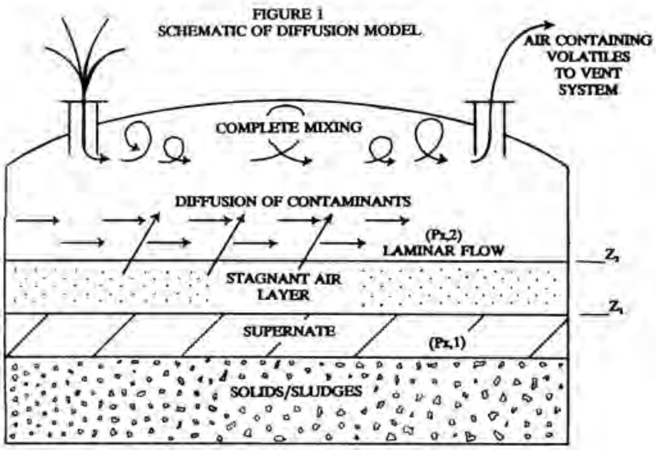

Fig. 1. Schematic of diffusion model.

thicknesses ranging from 10% to 75% of the tank vapor space volume. The resultant iterative calculations culminated in the development of maximum, minimum, and design basis values anticipated for each contaminant at steady state. Table I shows the resultant values.

The maximum concentration was calculated at a 700 cfm flow rate and a stagnant layer thickness of 10% of the vapor space height. The minimum concentration was calculated at a flow rate of 200 cfm and a stagnant layer thickness of 75% of the vapor space height. The design basis concentration assumed a flow rate of 300 cfm and a stagnant layer thickness of 50% of the vapor space height.

The second focus of activities for the C-103 tank was evaluating potential technologies to meet the requirements of the EPA's top-down BACT methodology. It was necessary to perform both a best available radionuclide control technology (BARCT) and a toxics best available control technology (T-BACT). The entire range of technologies for each class of contaminants was evaluated. Table II shows the technologies, and their relative technical feasibility, for each class of contaminants. From these technologies a detailed evaluation of the effectiveness, implementability, and cost was performed and process systems were developed.

Rotary Mode Core Sampling Exhauster

The RMCS system is an apparatus which uses a drill to penetrate the solids within single shell tanks to obtain core samples. A high pressure nitrogen purge is used to cool the drill bit and displace solids from the drill path. The use of a compressed gas causes solid and liquid aerosols to be introduced into the vapor space. The agitation of the waste matrix also creates a continual pathway for introduction of contaminants into the vapor space. Unlike the C-103 application, the vapor space cannot be modeled for steady state exhauster operation assuming only diffusion. In addition, 81 single shell tanks are scheduled for characterization using the RMCS apparatus. Thus, an exhauster must be developed which can accommodate a wide range of vapor space conditions, including a variety of temperatures, moisture levels, and chemical and radiological contaminants.

The exhauster being developed for the RMCS is progressing in a decidedly different manner than the C-103 project. The project team for this activity recognized the significant lack of vapor space data, and the difficulties in obtaining the composition of the vapor space for all 81 candidate tanks in a timely manner. A federal facility consent order, the Tri-Party Agreement, required that the RMCS activities begin in September 1993. Therefore, a project plan was developed which utilized two parallel paths of study, design, and fabrication of exhausters. Both paths were initiated with studies performed by WHC and/or their contractors and preparation of a sensitivity analysis. These studies evaluated the physical and chemical parameters of the tanks, and established a range of possible conditions for aerosols, temperature, humidity, radiological source and isotopic profile, and chemical contaminants. A variety of technologies were examined in the sensitivity analysis to see if the parameter ranges established would have significant impacts on the design or operation of an exhauster unit.

Following the preparation of the sensitivity analysis, the two parallel paths of project development began. The fast track project required obtaining concurrence from the Washington State Department of Ecology for operation of a "broad-brush" BACT unit. This concurrence was obtained for one year of operation. The "broad-brush" BACT unit consisted of HEPA filters, carbon adsorption units, and reactant media for ammonia removal. The final design for this effort is nearing completion and procurement of the adsorption system has begun.

The second path consists of a formal BACT development process. This process has begun, using lessons learned from the C-103 activities and design development on the first unit. The BACT will establish the regulatory requirements, define the design criteria and operating conditions, and fully evaluate all technologies for control of the contaminants. A preliminary design report (PDR) will follow with emphasis on reducing the size and increasing the portability from the first unit's design. The detailed design and fabrication activities will follow the approval of the PDR.

TABLE I

Contamination Concentration at Steady State

		Steady State		
Contaminants	Initial	Maximum	Minimum	Design Basis
Normal Paraffin Hydrocarbons	3450 ppm	293 ppm	18 ppm	64.6 ppm
Acetone	2290 ppm	398 ppm	28 ppm	97.4 ppm
Ammonia	370 ppm	114 ppm	10 ppm	32.8 ppm

TABLE II
Control Technologies

Radioactive Particles	Efficiency	Technically Feasible	Volatile Organic Compounds	Efficiency	Technically Feasible	Ammonia	Efficiency	Technically Feasible
HEPA Filters	99.97%	Yes	Thermal Incineration	99%	Yes	Thermal Incineration	99%	Yes
Mist Eliminator	<80%	No	Catalytic Incineration	99%	Yes	Catalytic Incineration	99%	Yes
HEME	98%	Yes	Flares	0-90%	No	Reactant Filter	95%	Yes
Baghouse/ Fabric Filter	95%	No	Boilers	0-80%	No	Absorber/ Scrubber	95%	No
Cyclone	<80%	No	Carbon Adsorption	95%-99%	Yes			
Glass/Sand Filters	99%	No	Absorber/ Scrubbing	85%-95%	No			
Electrostatic Precipitator	98%	No	Condensers	85%-95%	No			

SYSTEM DESCRIPTIONS

Two systems are technically feasible for implementation on mixed waste storage tanks. Systems using wet scrubbing technologies are not considered technically feasible due to the generation of radioactive and hazardous waste water. The two systems considered feasible, and implementable for mixed waste toxic emission control systems, are a passive filtration system and an incineration system. These two systems are discussed in a general sense only. The specific physical and chemical properties must be fully defined to properly size and evaluate the relative merits and disadvantages of each system.

Due to the high level of radiological particulates in the airstream, both systems require HEPA filters prior to treatment of organic and inorganic pollutants. The high relative humidity of Hanford's tanks requires dehumidification of the airstream using a condenser/heater configuration. Likewise, a high quantity of mists are known to be in Hanford's tanks and thus, a mist eliminator is used in both scenarios. Figures 2 and 3 reflect the two possible operating systems.

PASSIVE FILTRATION SYSTEM

The following are the control technologies and associated effectiveness for each component in the passive filtration alternative.

Condenser: The purpose of the condenser is to cool the airstream to 5°C (40°F). This will remove most of the moisture in the airstream and, due to contaminant solubilities, will remove significant quantities of contaminants. Preliminary calculations (outlined in Ref. 2) indicate that over 80% of the ammonia and acetone and 50% of the butanol will be removed from a saturated airstream entering the condenser at 60°C (140°F). At lower relative humidities and/or lower temperatures, the quantity of organics/ammonia which will be removed is dependent on temperatures and humidity. The design of the condenser is critical to the effective operation of the rest of the system. The ability to "wash" the airstream, without adding any new water, is highly desirable. The condenser recommended for the RMCS application is a straight pass through condenser with countercurrent heat transfer fluid flow. This eliminates the use of tubes and fins and minimizes the potential for a buildup of highly radioactive solids in a piece of equipment which must be readily decontaminated.

High Efficiency Mist Eliminator (HEME): The HEME is designed to remove entrained liquids from the airstream. The filter unit is made from either metal chevrons or plastic/glass fibers, dependent on the required efficiencies. Generally, the metal chevrons can remove over 95% of all liquid aerosols with a diameter of greater than 5 microns. Fiber HEMEs can remove up to 99% of all particles over 1 micron; however, have a much greater pressure drop and require more frequent washing to prevent plugging. The most significant concerns with the HEME unit are plugging and the need to keep the filter media wetted to allow capture of the particles. A high level of solid and liquid aerosols, a function of the vapor space characteristics and the airstream velocity, can plug the HEME, causing frequent high pressure water washing. If a relatively dry airstream is used, water must be added to the HEME media to allow removal of the contaminants. As with the condenser, some soluble contaminants (ammonia, acetone, and butanol) will be removed. Specific removal efficiencies of soluble vapors in the HEME unit have not been documented.

Heater: The purpose of the heater is to elevate the airstream temperature to 28°C (50°F) above the dewpoint of the airstream. Thus, the 5°C (40°F) airstream is heated to 33°C (90°F). This prevents problems caused by moisture or liquid droplets inherent with HEPA filters and activated carbon adsorbers downstream of the heater unit. An intrinsically safe (spark proof) heater is needed due to the potential for a high concentration of hydrogen, above the lower explosive limit

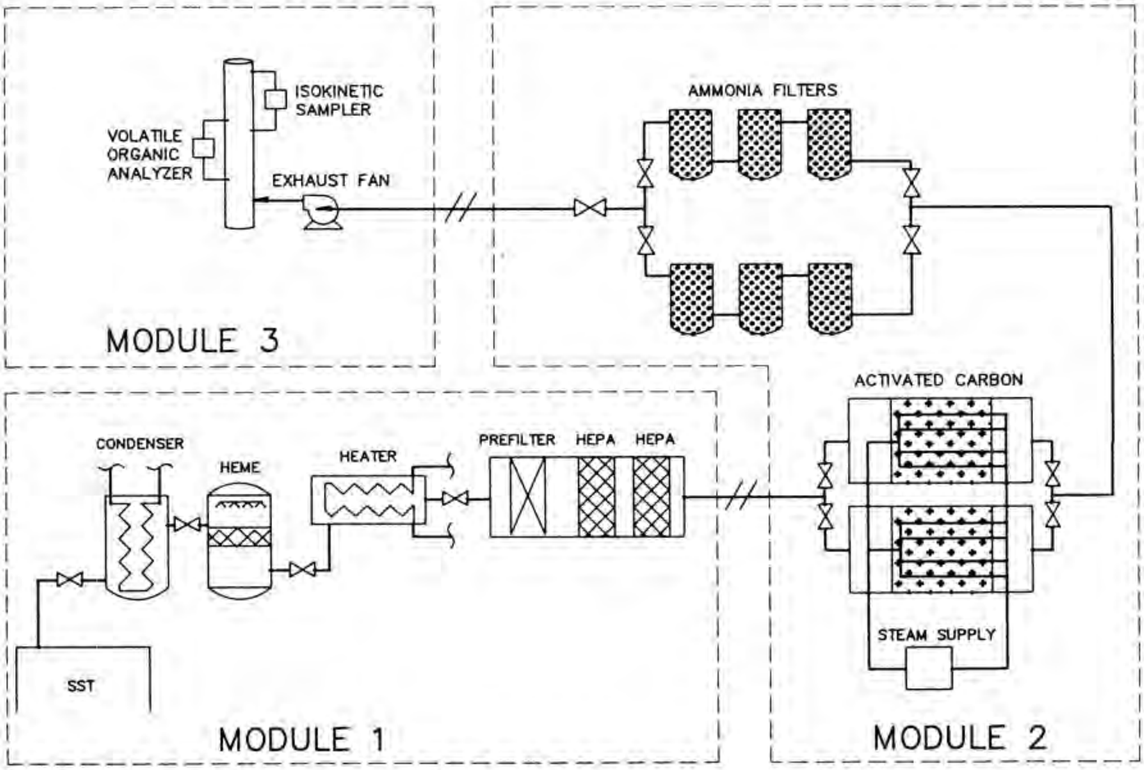

Fig. 2. Alternative 1 - passive filtration system.

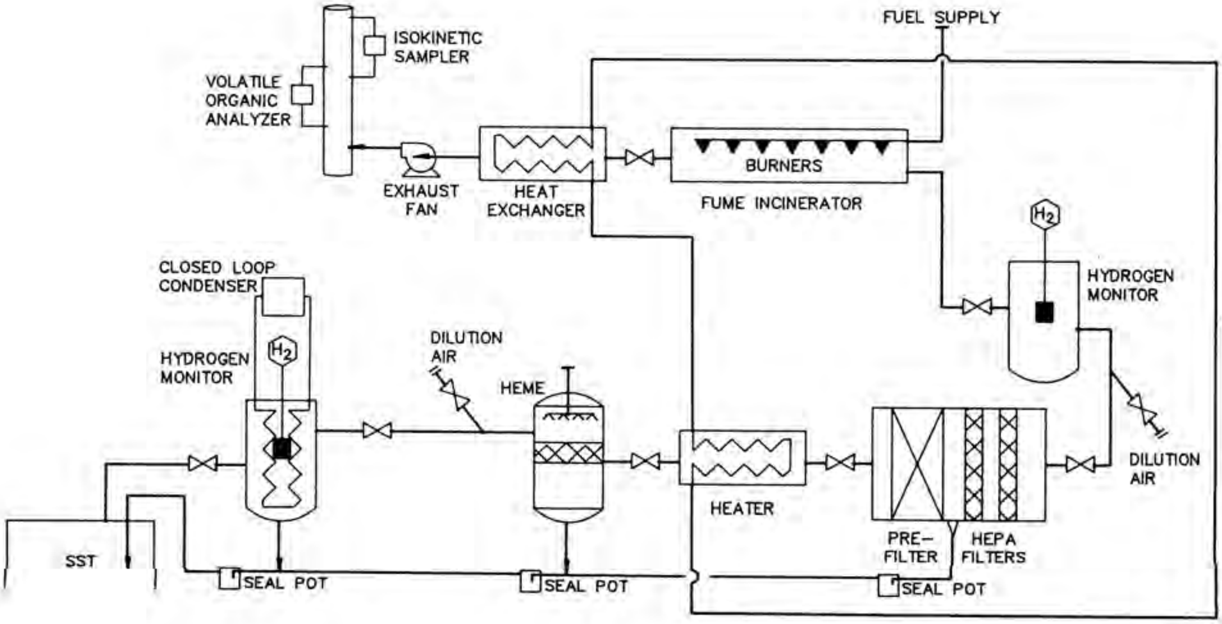

Fig. 3. Alternative 2 - fume incineration.

(LEL) of 4% by volume. Electrical heaters, or heaters which use heat transfer fluids such as hot oils, should be considered.

High Efficiency Particulate Air (HEPA) Filter Assembly: A standard HEPA filter assembly will be used with two 60 cm (24 in) x 60 cm (24 in) x 30 cm (12 in) deep HEPA filters. A paper prefilter is provided for the removal of 60% of all particles over 5 microns. HEPA filters have a rated efficiency of 99.97% of all particles over 0.3 microns. HEPA filters are the standard BARCT for radiological particulates.

Activated Carbon VOC Adsorber: The VOCs are adsorbed on activated sites of the carbon media. The affinity of contaminants to the carbon is dependent on the properties of the carbon and the molecular weight and bonding properties of the contaminants. These affinities are called adsorption isotherms and are stated in kilograms of contaminant per kilogram of carbon. The following are representative isotherms which are common to the activated carbon industry:

Acetone:	0.05 kg Acetone/kg Carbon
Butanol:	0.15 kg Butanol/kg Carbon
NPH:	0.30 kg NPH/kg Carbon

From these isotherms, the quantity of carbon required, assuming no regeneration, was calculated to be very high. For the RMCS Exhauster, it was calculated that 34 canisters, each containing 200 kg of carbon, would be required for one month of continuous operation. For the C-103 application, it was determined that over 25,000 kg of carbon would be required for one month of continuous operation. The use of this quantity of carbon causes significant concerns with waste disposal and exhauster size. To alleviate these concerns, several options should be considered, including:

1. Installation of an on-site regeneration unit (rotary kiln and off gas treatment unit);
2. Use of on-line regenerative activated carbon systems (hot gas or steam); or,
3. Use of on-line regenerative polymers/resins for adsorption of VOCs (new technology).

These three options are still being evaluated in the BACT process for the two case studies. For the fast track RMCS Exhauster a regenerative activated carbon unit was recommended following an engineering analysis of alternatives. It was determined that this provided the best technical approach to the problem and was the most cost effective option on life cycle cost basis. The use of activated carbon for the adsorption of volatile organics is a common T-BACT approach.

Ammonia Reactant Filters: The normal T-BACT for ammonia is a liquid scrubbing/absorption system, due to the high solubility of ammonia in water. For mixed waste storage tanks the generation of waste water is highly unfavorable. This system alternative uses activated carbon impregnated with reactant coating for the removal of ammonia. The actual reactant materials are proprietary information amongst the various vendors; however, the resultant product is an ammonia salt and a metal cation. The efficiencies of these units have been documented at close to 95% with an adsorption/reactant isotherm of approximately 20%. For an airstream containing 200 ppm ammonia, it was calculated that 600 kg (3-200 kg canisters) would provide adequate removal efficiencies.

Exhaust Fan, Stack, Monitoring, and Control System:. The "non-treatment" portions of the exhaust unit include a high pressure-low volume exhaust fan; a stack; and a monitoring system consisting of continuous air monitors for alpha and beta/gamma emitters, an isokinetic record sampler, an on-line VOC analyzer such as a photo ionization detector, and an on-line ammonia detector. The entire exhauster unit is controlled using a programmable logic controller (PLC).

THERMAL INCINERATION

The thermal incineration system uses the same control technologies for radiological particulates as the passive filtration system. The airstream is cooled to condense water vapor, mists are removed using a HEME, the airstream is reheated, and radioactive particles are removed using HEPA filters. The primary difference in the equipment used for radiological control is that the airstream velocity must be sufficiently lowered to allow monitoring of hydrogen gas concentration in the airstream. The system shown in Fig. 3 uses redundant monitoring locations and dilution air inlets to keep the airstream hydrogen composition below acceptable levels. Standard incineration guidelines require that the hydrogen concentration (or other flammable gases) be maintained below 25% of the LEL (Ref. 2). The quantity of dilution air required is calculated using the following equations (Ref. 2):

$$Q_d = [(h_e/h_d) - 1]Q_e$$

and

$$Q_{e,d} = Q_e(h_e/h_d)$$

where:

Q_d = dilution air flow rate, scfm
h_e = emission stream heat content before dilution, BTU/scf
h_d = emission stream heat content after dilution, BTU/scf
Q_e = emission stream flowrate before dilution
$Q_{e,d}$ = $Q_d + Q_e$ = total flowrate after dilution

For the RMCS Exhauster, it was assumed that the worst case hydrogen concentration was 8% by volume. The calculated dilution air required, assuming a nominal flowrate of 1200 cfm from the tank dome, was 7700 scfm with a total system flowrate of 8900 scfm. The system would be designed to introduce the dilution air downstream of the condenser, HEME, and HEPA filters to minimize the size and maximize the effectiveness of these units.

The fume incinerator proposed for this alternative is a natural gas fired, 1000 °C (1832 °F), refractory lined unit. The size, residence time, and heat content of the airstream are the driving factors for sizing the fume incinerator and determining the fuel requirements. An incinerator is usually rated at 99% removal efficiency for VOCs and Ammonia. The VOCs would be reduced to carbon dioxide, carbon monoxide, and water. The ammonia would be reduced to nitrogen, water, and some NO_x compounds. The quantity of ammonia, the amount of excess air in the combustion chamber, and the regulatory requirements for a particular area determine the need for an NO_x treatment system.

SYSTEM EVALUATION

The two system alternatives presented in the previous section are evaluated based on effectiveness, implementability, and cost. These are the three EPA required criteria for determination of BACT. The following is a brief definition of each of these criteria:

Effectiveness: The ability of the control technology (system) to eliminate the contaminants of concern without significant effects on the environment. For this application, effectiveness is evaluated both from an industrial hygiene and an environmental compliance perspective.

Implementability: The technical feasibility of operating the control technology (system) under the constraints of the facility. This criterion requires an evaluation of safety consequences, permitting requirements, and operating and maintenance constraints.

Cost: This criterion includes capital cost, life cycle cost, and cost per unit of contaminant removed.

The two systems are evaluated assuming a chemical composition similar to that of a "typical" Hanford single shell tank, with contaminants including: NPH (kerosene, C_9, and C_{10}) Butanol, and Acetone; all at levels of several hundred ppm; Benzene, Carbon Tetrachloride, and Methyl Amine - all at levels of approximately 10 ppm; and Ammonia at 200 ppm. A detailed evaluation requires knowledge of the radioactive source term, isotopic profile, radioactive gases, airstream temperature and flowrate, airstream particulate levels and size distribution, and moisture levels. Likewise, inleakage and tank differential pressure limitations must be considered. These parameters are generally evaluated for technology specific evaluations prior to performing the system evaluation. The system evaluation below considers only the general chemical parameters of the airstream and does not provide specific design information for a detailed evaluation.

Effectiveness

Passive Filtration: The effectiveness of a VOC adsorption system and ammonia reactant filter system is sufficient to remove the organics and ammonia from the airstream to below industrial hygiene and environmental compliance levels. The use of a regeneration system would result in the collection of the condensed VOCs; however, this condensate could be returned to the tank. There are several issues concerning the effectiveness of this option:

1. The activated carbon loses a portion of its efficiency at each regeneration. After some set time, assumed to be every six months, the carbon must be replaced. Likewise, the ammonia reactant filters must be replaced on a monthly basis if the contaminant levels remain steady at 200 ppm. Therefore, the waste is not destroyed - it is simply transferred to another media which must be disposed of or treated.
2. The condensed VOCs will be returned to the tank where they will re-volatilize and be captured in the airstream. Collection of the wastes, without return to the tank, would be preferred if this waste could be appropriately treated.
3. The removal efficiency of both units decreases with time of operation. After some set period of time the efficiency will be sufficiently reduced to allow emissions close to, although still below, industrial hygiene and environmental compliance levels.

Thermal Incineration: The fume incineration system provides the greatest degree of efficiency with 99% removal. Only trace amounts of contaminants, well below the personal exposure limits, will be exhausted. The primary concern with the incinerator is the generation of NO_x. Since Hanford is not in a non-attainment area, it is assumed that the levels of NO_x will be below any regulatory guidelines. If there were concentrations significant enough to warrant regulatory concerns, then a catalytic reactor would be installed to destroy the NO_x. This is a common practice throughout industry.

Based on the criteria of effectiveness, the fume incineration system is considered the best technology. The other two criteria, implementability and cost, must be evaluated to determine if there are overriding factors to eliminate this technology.

Implementability

As previously noted, there are several factors associated with this criterion. The primary implementability factors are listed below, and the relative merits and disadvantages of each system are provided.

Safety: The fume incineration system has numerous safety concerns associated with the operation of *high temperature* equipment including explosion, fire, personnel burns, and process control/uncontrolled releases. The only safety concern with the passive filtration system is the handling of bulk quantities of carbon media in the loading and unloading of the filter vessels.

Permitting Requirements: The use of a fume incineration system would have significant hurdles due to the radiological nature of the airstream. the problems associated with permitting would likely not be technical, rather political and public perception. The idea of installing a fume incinerator on a high hydrogen concentration airstream may be difficult to sell. The permitting of a passive filtration system has been successfully performed in several locations, and from preliminary discussion with the permitting group for the RMCS Exhauster, no significant obstacles are expected in the permitting process for the activated carbon/ammonia reactant units currently being designed and procured.

Operating and Maintenance Constraints: The fume incinerator requires a fuel source, such as a natural gas that may not be readily available. If natural gas is not available the use of portable fuel systems is required. The presence of Hydrogen gas causes the system to run at higher flowrates. The higher flowrate and/or significant variations in the flowrate may cause maintenance problems with dampers and other stationary and moving equipment. The use of a regenerative adsorption system/fixed ammonia reactant does present significant operational or maintenance concerns. The operation of heat exchangers and dangerous waste handling systems requires frequent operator interface; however, the requirements are less than those for the incineration system. The use of a passive filtration is highly favored when considering the implementability criterion.

The passive filtration system, based on the implementability criteria discussed above, is preferred over the fume incineration alternative.

Cost

Capital cost, life cycle cost, and cost per kg of contaminant removed were calculated for both the C-103 BACT evaluation and the RMCS Exhauster. The following presents a summary of the "estimated" costs for each system as calculated for the two technologies.

The annual operating cost of the incinerator assumed a portable propane fuel source.

For each cost category the passive filtration alternative is considered the most cost effective. The availability of natural gas would reduce the annual operating cost of the incinerator and more frequent carbon replacements would significantly increase the cost of the passive filtration system. Although this particular evaluation found the passive filtration option to be the more cost effective, the airstream characteristics will have a significant impact on these costs and each system must be fully evaluated to ascertain actual costs.

	Passive Filtration	Thermal Incineration
Capital Cost	$1,800,000	$2,500,000
Annual O & M Cost	$120,000	$270,000
Total Life Cycle Cost	$3,400,000	$4,800,000
Cost/KG Removed	$100/KG	$220/KG

RESULTS AND CONCLUSIONS

The activities planned for characterization, retrieval, and remediation will require the use of toxic and radiological emission control systems. The time required to determine the BACT, perform necessary studies, analysis, design, fabricate, and test the systems requires that the implementation of an exhauster program be initiated at an early stage. Vapor space data should be obtained early in the process or, if unavailable, a sound, conservative, estimate should be developed by the project team using past inventories and vapor samples from similar tanks.

Only two types of systems show significant promise for application on high level mixed waste storage tanks. These two systems are passive filtration (adsorption and reactant) and thermal incineration. The sizing, effectiveness, and operating parameters of these systems are easily calculated using standard chemical engineering principles and EPA prepared handbooks. Conformance to the Top-Down BACT process ensures that a sound engineering approach is taken and that all potential technologies are evaluated. For VOCs it has now been determined that the BACT is carbon adsorption for the two specific applications at Hanford. Significant technological advancements in the adsorption industry are making the removal of contaminants more efficient and cost effective. Previous to the advancements in the adsorption industry, if high efficiencies were required for removal of organics, the only technology capable of meeting these efficiencies was incineration. Incineration is still considered the most effective technology; however, implementability and/or cost concerns do not make this technology the "Best Available" for high level mixed waste tanks.

The "broad brush" BACT exhauster for the RMCS Exhauster is in the final design stages. Figure 4 shows a graphic representation of this design. The unit has been designed to

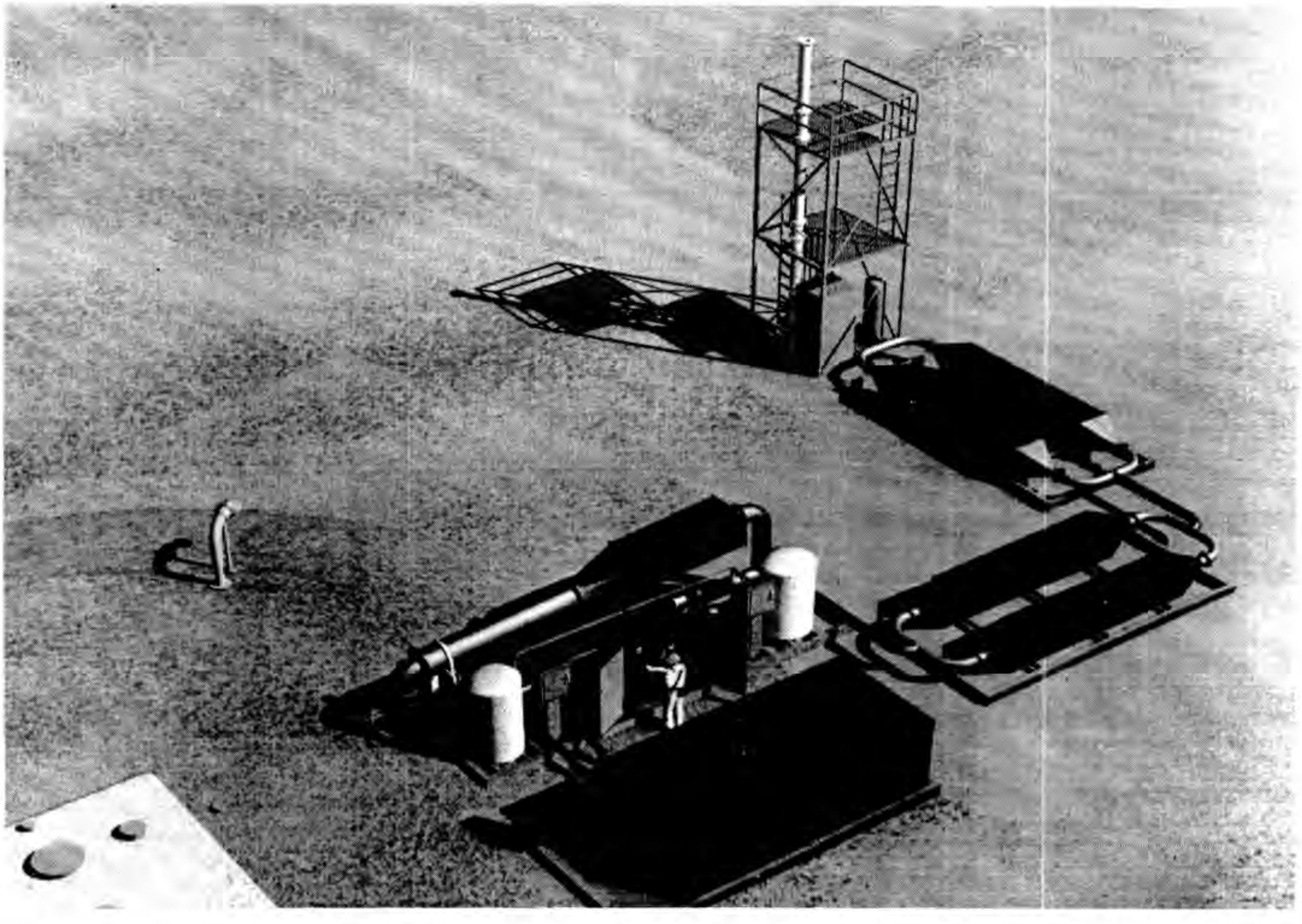

Fig. 4. RMCS exhauster.

handle a high level of radioactive aerosols, airstream temperatures of 60 °C (140 °F), a relative humidity of 100%, moderate levels of heavy and light molecular weight organic, high levels of hydrogen gas, and high concentrations of ammonia. The unit has been designed for the highly transient conditions caused by the rotary mode sampling techniques and the large number of tanks to be sampled. The one-year operation of this system will provide significant data on the effectiveness of this type of unit.

The public perception and safety concerns associated with fume incineration causes the focus of air treatment systems on mixed waste storage tanks to be on alternate technologies. The vendors of adsorption systems are making significant progress towards recovery of the wastes through regeneration, thereby minimizing the concerns over generating large quantities of mixed waste captured in the activated carbon matrix. The progress made, and lessons learned, on the two Hanford applications discussed herein can be a valuable tool towards expediting future exhauster evaluation and development.

REFERENCES

1. "Transport Phenomena," Bird, Stuart and Lightfoot, Department of Chemical Engineering, University of Wisconsin, John Wiley and Sons, 1960.
2. "Handbook: Control Technologies for Hazardous Air Pollutants," EPA/625/6-91/014, Environmental Protection Agency, June 1991.