THE DESIGN AND MANAGEMENT OF SYSTEM COMPONENTS FOR IN SITU METHANOTROPHIC BIOREMEDIATION OF CHLORINATED HYDROCARBONS AT THE SAVANNAH RIVER SITE

K. H. Lombard, J. W. Borthen, and T. C. Hazen

ABSTRACT

The successful operation of an in situ bioremediation system is inherent within its design. Well-organized system components enable ease of maintenance, limited down time, and relatively rapid data acquisition. The design effort in this project focused on injection of a low-pressure air/methane mixture into a horizontal well below the water table, a methane-blending system that provided control of the injected mixture, redundant safety interlocks, vapor-phase extraction from a second horizontal well, and an off-gas treatment system that provided efficient thermal catalytic oxidation of the extracted contaminant vapors. The control instrumentation provided sufficient redundancies to allow the system to remain in operation in the event of a component failure, and equally important, the safe shutdown of the system should any designed safety parameters be exceeded (i.e., high methane concentration). Final design approval took into consideration the reliability of the equipment and the components specified. Product knowledge and proper application limited the risk of a component or system failure while providing a safe, efficient, and cost-effective remediation system. Microprocessor data acquisition and system control were integrated with an autodialer to provide 24-hour emergency response and operation without on-site supervision. This integrated system also insured accurate data analysis and minimum downtime. Since operations commenced, the system has operated a total of 7,760 hours out

1-56670-084-1/94/$0.00 + $.50

of the possible 8,837 hours available. This equates to an operating efficiency of 87.8%.

PURPOSE

A recent search of the literature regarding in situ bioremediation revealed only limited sources of information associated with the design and engineering of the surface supply and support systems. A successful biostimulation of the indigenous microbial community in a subsurface environment depends on effective delivery of key components (i.e., nutrients and electron acceptors) and proper monitoring to ensure safe and consistent delivery.

It is the intent of this paper to provide the reader with additional insight through lessons learned and, to provide the knowledge necessary to aid in the design and construction of an effective in situ methanotrophic bioremediation system. It is our objective to provide continued research and development of new and innovative engineering concepts so that safe, efficient, and cost-effective systems can be realized.

INTRODUCTION

Site History

Contamination of the Savannah River Site's M-Area ground (vadose zone) and groundwater by chlorinated solvents from M-Area degreasing facilities evolved over a 35-year period. It is estimated that from 1952 to 1982, M-Area used approximately 13,000,000 lb (5,900,000 kg) of trichloroethylene (TCE) and tetrachloroethylene (PCE) as degreasing solvents. The degreasing processes resulted in the evaporation of 50 to 95% of the solvents. An estimated 2,000,000 lb (947,200 kg) of TCE and PCE may have been released to the M-Area process sewer system leading to the M-Area settling basin and some 1,500,000 lb (710,400 kg) to the A-014 outfall (Marine & Bledsoe 1984).

The following abbreviated history of the site's construction efforts and solvent usage is adapted from Marine and Bledsoe (1984) and recast by Looney and Rossabi (1992). This information will help the reader understand the magnitude of the problem that exists, and the engineering challenges faced today, in the research and development of new technologies for cleanup operations of hazardous waste sites.

To support the degreasing operations, a terra-cotta process sewer line and an 8,000,000-gal (30,280,000-L) unlined surface impoundment, used for a settling basin, were constructed. Effluent disposal to seepage or settling basins was standard industrial practice during the 1950s through the 1970s.

Dissolved solvents were identified in the groundwater beneath the settling basin in 1981. A subsequent investigation of the process sewer line revealed cracks and plant roots penetrating the terra-cotta pipe. In 1984 the pipeline to the basin was relined and by 1985, the process wastes from M-Area were diverted to the Liquid Effluent Treatment Facility, and settling basin use was discontinued.

The Savannah River Site (SRS) voluntarily commenced groundwater remediation with a full-scale pump-and-treat system in April of 1985. In the operating permit from the South Carolina Department of Health and Environmental Control (SCDHEC), the SRS made a series of commitments, one of which was to develop and evaluate new technologies to improve system performance. To date, several innovative projects have successfully demonstrated the SRS's commitment to the environmental restoration of the M-Area settling basin system. As the host site for the U.S. Department of Energy's Integrated Demonstration Program, the SRS is conducting a multiphased experiment, implemented to test new remediation and monitoring technologies and innovative engineering concepts along the abandoned process sewer line. Part of this integrated demonstration includes the In Situ Bioremediation Demonstration as part of the cleanup of organics from sediments and groundwater at non-arid sites.

THE IN SITU BIOREMEDIATION DEMONSTRATION

Phase I In Situ Air Stripping and Geophysical Monitoring

Phase I of the project included extensive site characterization. The geology of the site consists predominantly of unconsolidated sands and clayey sands with interbedded clay horizons. These tertiary sediments were deposited in shallow marine, lagoonal, and fluvial environments (Eddy et al. 1991). Many geophysical devices were deployed, and water table monitoring wells were installed to provide data to help determine the effectiveness of using air stripping in horizontal wells to remediate a contaminated site.

In 1989, two horizontal wells were installed along the abandoned sewer, in what was considered to be a hot spot, an area of high concentrations of contaminants (TCE and PCE). During the experiment, air was injected into the horizontal well below the water table, at varying rates of 65, 170, and 270 scfm (31, 80, and 127 L/sec) and extracted from the upper horizontal well located in the vadose zone, at a constant rate of 580 scfm (274 L/sec). During the 139-day test, nearly 16,000 lb (7,258 kg) of volatile organic compounds were removed from the subsurface (Looney et al. 1991).

The information from this experiment established the baseline data for the Phase II Methane Injection Campaign, which is intended to stimulate the methanotrophic bioremediation of the volatile organic contaminants.

Phase II Methane Injection Campaign

The goals of the In Situ Bioremediation Demonstration and design criteria for the Methane Injection Campaign were established by an expert panel of scientists and engineers using Phase I data retrieved during the in situ air stripping operations. A detailed description of the project is documented in the Test Plan (Hazen 1991). The air/methane injection rate was set at 200 scfm (94 L/sec). In order to provide the required air flow, a compressor capable of delivering 300 scfm (142 L/sec) at 100 psig (45 kg/cm^2) was specified.

An extraction rate of 20% greater than the injection rate was established. This strategy was adapted to prevent plume expansion while stimulating the bacteria in the saturated sediments and vadose zone, and to prevent the methane from reaching a potentially explosive concentration of 5%, the lower explosive limit (LEL). To provide the necessary vapor extraction rate, a vacuum-blower unit capable of generating 500 scfm (236 L/sec) at 10 in. (25.4 cm) Hg (inlet), was specified.

The final design parameter for the extracted gases, was to reduce the total organic contaminants in the off-gas to a concentration of less than 5 ppm (vol/vol). To facilitate this an Allied Signal Halocarbon Destructive Catalytic (HDC) oxidation system, Air Resources Inc. (ARI), fluidized-bed catalytic oxidation system or approved equal was specified. The system configuration is shown in Figure 1.

Since operations commenced, the system has operated a total of 7,760 hours out of a possible 8,837 hours. This is equal to an operating efficiency of 87.8%. The system's downtime was attributed to maintenance, testing, system modifications, repairs, and experiments for a total of 1,077 hours. It should be noted that maintenance of the system attributed to only 3.8% of the total downtime, equaling approximately 5.8 h/wk.

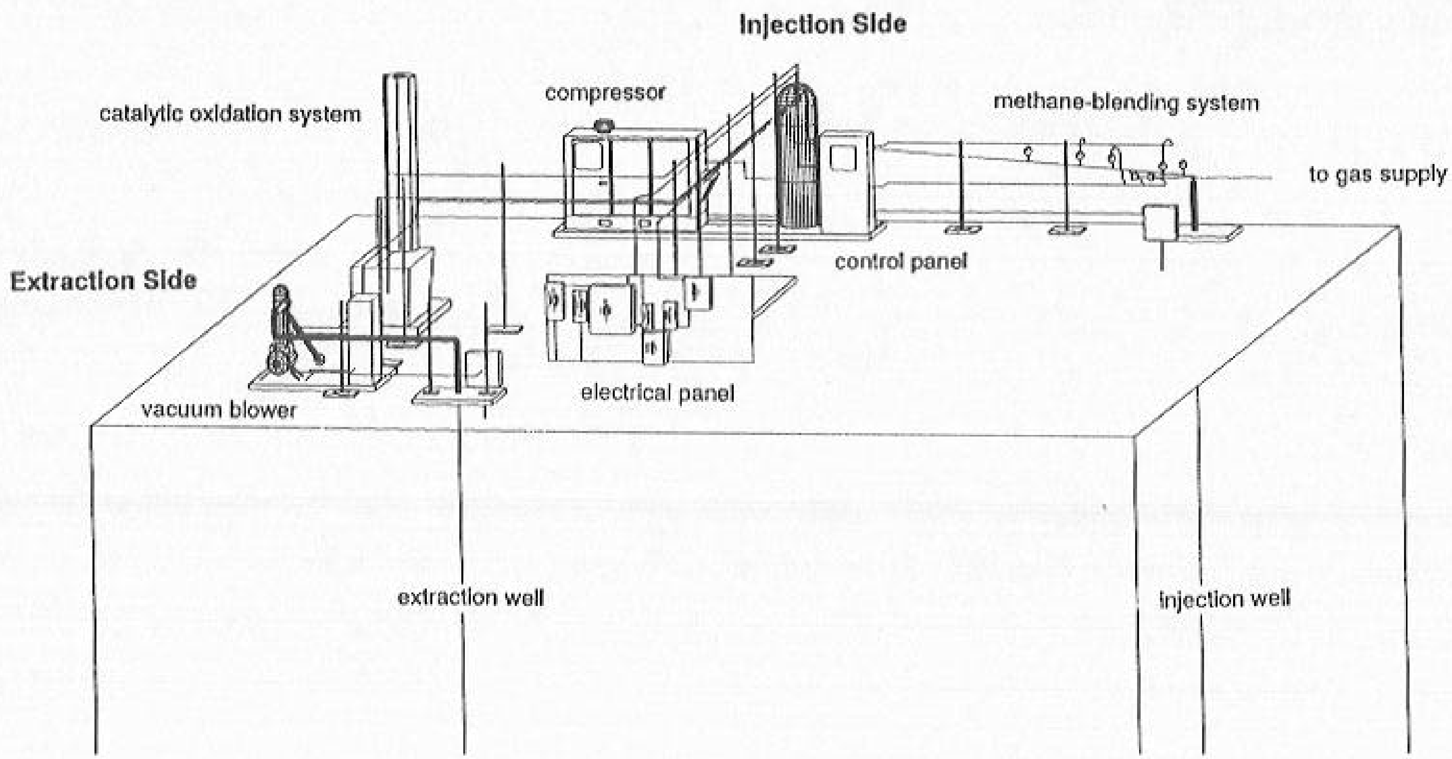

FIGURE 1. Isometric configuration of surface-mounted equipment for the in situ methanotrophic bioremediation demonstration.

SYSTEM COMPONENT DESCRIPTION

Methane-Blending System

The heart of the surface-mounted equipment supporting the methanotrophic bioremediation process is the methane-blending system (Figure 2). The system is designed to inject and blend a controlled flow of methane (natural gas) with the airstream, which is introduced into the lower horizontal injection well. The system's principal components are comprised of a Foxboro controller, Horiba gas analyzer, Foxboro/Jordan rotary actuator, and flow control valve, as described below.

Methane Gas Analyzer. The analyzer used for this project was an Horiba model PIR-2000 general purpose gas analyzer. It is a "precision gas analyzer based on nondispersive infrared ray absorption for continuously determining the concentration of a given component in a gaseous stream" (Horiba literature). It operates on an airstream of approximately 2 scfh (0.9 L/min) at a pressure less than 1 psig. For purposes of this

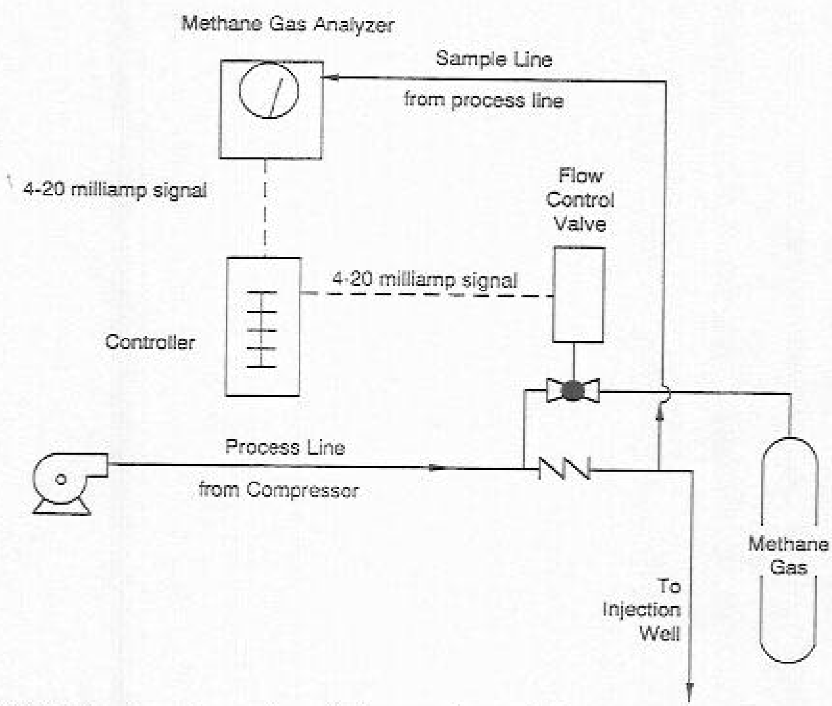

FIGURE 2. A schematic of the methane-blending system which is designed to inject and blend a controlled flow of methane (natural gas) with the airstream.

project, a small stream of gas was diverted from the process injection line to operate the gas analyzer.

The instrument initially was factory-calibrated for handling concentrations of methane between 0 and 100% of the LEL. The signal output from the analyzer is 4 to 20-milliamps, representing full span of the LEL. This signal is transmitted to the Foxboro controller.

The quality and performance of the Horiba Analyzer was very good, consistently producing precise and repeatable data. However, analyzers require factory recalibration on an annual basis and field calibration on a daily basis. The field calibration procedure requires two standard gases (zero and full span).

Foxboro Controller. The controller used for this project was a Foxboro 761C single station micro plus controller, which has a reputation for being a highly reliable controller. The Foxboro controller values for the proportional band, integral and derivative (PID) actions function by using a continuous monitoring adjustment process that measures the difference between an incoming signal and set point control variables (Foxboro literature). The real-time process dynamics vary the dampening and overshoot response effort based on controller-calculated parameters.

The controller reads the input signal from the analyzer and compares the indicated methane concentration with the set point concentration. The controller adjusts the concentration via the flow control valve to the indicated set point. This is done by sending a second 4 to 20-milliamp signal to the Foxboro/Jordan rotary actuator which positions the flow control valve to the required opening. If the indicated concentration is above or below the controllers' set point, the signal to the flow control valve is adjusted accordingly.

Foxboro/Jordan Rotary Actuator and Flow Control Valve. The Foxboro/Jordan rotary actuator receives the signal from the controller and mechanically adjusts the flow control valve. The valve, a segment style 1/4 turn ball valve, was selected because it has a fairly linear performance curve over the flow range anticipated.

All of the equipment and instrumentation devices in this control loop have operated well within the design parameters. Concentrations are controllable to a set point with a tolerance of ± 2% of the LEL (± 0.11% by volume). Nevertheless, although the system responded nicely to moderate changes, quick or sudden changes could push the system out of tolerance and trigger alarm conditions.

Oxidation of Contaminant Vapors

Treatment Options. Despite advances in environmental remediation technologies, there are still only two viable options available for treatment of off-gases from vapor extraction systems: (1) thermal type systems, comprised of catalytic oxidation or thermal catalytic oxidation; and (2) carbon absorption, which requires further treatment to destroy extracted contaminants. The larger share of this technology development has revolved around the improvement of catalytic materials, which now can handle a much greater variety of reaction-inhibiting compounds (Hardison & Dowd 1977).

These contaminant destruction methods are energy intensive and very expensive under the design requirements of today's vapor extraction projects (large volumes of air and concentrations of contaminants in the range of 0.5 to 1000 ppm). It could be argued that the energy consumed, associated resources used, and potential contamination produced may offset the environmental gains made by a vapor extraction project. Nevertheless, in most applications, the regulators (the U.S. Environmental Protection Agency [EPA] and the SCDHEC) require the contaminants to be removed from the airstream as directed by the Clean Air Act, 1991.

Thermal Catalytic Oxidation System Design

Site resources and design considerations for the vapor extraction dictated the use of a thermal catalytic oxidation system. Once the decision to use thermal catalytic oxidation had been made, several options required design engineering evaluation. Those included the power source (electric vs. propane/natural gas), air preheating, and the type of catalyst to use.

Power Source. Two options are available for heating: electricity and gas power. Given the choice, most engineers will agree that a gas-heated system is preferable from a safety and economic perspective. Oxidation systems require huge amounts of energy, as much as 200,000 BTUs per hour. For an electric system to produce these requirements, it is not unusual to operate a 480-V power system in excess of 250 amps. However, in some situations an electric system is the only option available.

Industrial settings, such as refineries, where the presence of an igniting flame is prohibited, rule out a gas-powered system. Electric systems, for these situations, can be made explosion proof and suitable to a Class I, Division 2 electrical areas. In some areas gas simply is not available, as was the case at SRS. Electric systems typically cost more. A more complex control system and a smaller market for these systems account for much of the price difference. Additionally, many of the manufacturers that make electric systems make them as a modification to a gas system, which further drives up the cost.

It is worth remembering that some of the power requirements can be reduced by the contaminant itself. BTU content of the contaminants can be used to provide some of the energy requirements. For this to be effective, the contaminant concentrations must be very large, certainly larger than the 200 to 400 ppm available on this project. Nevertheless, one should be careful in designing around this heat source, as concentrations usually fall off precipitously in the first weeks of extraction and continue to fall over the course of a successful project.

Air Preheating. Air preheating involves the use of a heat exchanger to heat the incoming extracted air using recovered hot exhaust gases. A heat exchanger can recover 40 to 50% of the waste heat, and will most certainly pay for itself in reduced energy costs. However, the increase in capital costs is significant and it should be carefully considered.

On projects where chlorinated contaminants are being destroyed there will be hydrochloric acid produced. The presence of the acid requires the use of materials that are more acid tolerant. These materials generally are very expensive and make the use of preheaters a more difficult decision to make. The duration of the project and the cost of energy will dictate the answer to this question. On the SRS project, preheating was not used. This decision was based in part on the short duration of the project (12 months) and the need to have the equipment fabricated and deployed quickly in the field.

Catalyst Selection. Treatment of contaminants containing halogens has been a dubious proposition at best, in recent years. Several elements can poison or inhibit the activity of the catalytic material. For example, halogens can quell the catalytic activity, but the effect can be reversed by removing the catalyst from the system and washing it to remove the contaminants. Nevertheless, when a halogen is absorbed to the catalyst surface it renders the material ineffective for the oxidation process. Halogen tolerance should be of primary concern in the selection of a catalytic material.

A second consideration for catalyst selection is whether to use a fixed catalyst bed or a fluidized bed. In a fixed catalyst bed, the material is attached to the surface of a substrate which has a high porosity. The contaminated air then passes through the substrate and comes in contact with the catalyst and reacts. In a fluidized bed, the catalyst is attached to small particles. A chamber is filled with particles and the contaminated air is passed through them. When a certain air velocity is attained, the particles become fluidized and begin to mix vigorously. This allows good contact between the contaminants and the catalyst material. One benefit of this method is that the catalyst material can easily be removed or added to the system for cleaning and replenishing purposes. Because all catalysts eventually loose their activity, this is a benefit for projects with long durations.

Several catalysts produced in recent years claim to be halogen tolerant, but their performance has not been firmly established. Toward that end, a second-generation, halogen-tolerant, fixed catalyst manufactured by Allied Signal Inc. was installed in the thermal oxidizer for testing its effectiveness in the destruction of chlorinated solvents. With the addition of the new catalyst, the operating temperature of the oxidizer was lowered to 825°F (441°C), resulting in an energy savings of more than 41%, while still maintaining a destructive efficiency of greater than 95%. A complete report of the results of this modification will be published at the completion of the project.

Vacuum-Blower and Compressor

The vacuum-blower and the compressor are the workhorses of the remediation system, operating continuously 24 hours a day. Both units turned out to be slightly overdesigned for the project and could be replaced with smaller units on a second generation system.

Vacuum-Blower. The vacuum-blower is a rotary positive-displacement Roots, Model URAI-56, and is powered by a direct-drive 20-HP electric motor. The vacuum-blower can pull a vacuum up to 10 in. (25.4 cm) Hg while producing a volume of 300 scfm (142 L/sec) of air. It is controlled by a Reliance Electric GP-2000 A-C VS controller, which allows for variable speed control of the 480-V motor. With this controller, the volume of air and the vacuum drawn on the extraction system can be regulated to meet the needs of the demonstration. For example, additional alternative off-gas treatment technologies can be tested simultaneously without reducing the primary project needs. The total cost of the vacuum-blower and control system is approximately $16,000.00. Although this is very expensive, the equipment has worked flawlessly since the project started.

Compressor. The compressor is a Quincy rotary screw assembly Model QNW-360-1, with an air-cooled oil cooler and a 75-HP, 480-V motor. The unit can supply 361 scfm (170 L/sec) of compressed air at 110 psig (50 kg/cm^2). The airstream goes to a 240-gal (908-L) air receiver tank that provides a reservoir of compressed air for the system to draw from, then through a regulator where the pressure and flowrate are adjusted to the injection well conditions. The injection flowrate of 200 scfm (94 L/sec) is manually controlled to ± 2%.

The injection well back pressure fluctuates between 20 to 30 psig (9 to 14 kg/cm^2), depending primarily on the soil moisture conditions at any particular time. Rainfall events are the major variable affecting the well back pressure. Other applications and soil types may have different back pressures, but this amount has proven to be in the range of typical values. This is unfortunate, for it is at a pressure range that borders on the lower efficiency range of the compressor. Compressors become less efficient and more costly to run at pressures and volumes such as this unit is experiencing. However, the compressor, like the blower, has performed consistently over the course of the project.

DISCUSSION

Instrumentation

For some engineers, there can never be enough instrumentation, and to some extent there may be strength to this argument. Inexpensive local reading gauges are readily available and can be incorporated into the design with a minimum of effort.

The thermal catalytic oxidation system used on the project was modified to correct instrumentation inadequacies. It was noted during start-up and testing that temperature gauges were not present at critical monitoring points: for example, areas where electrical power cables entered hot compartments, power feed attachments to heating electrodes, and the process airstream in front and behind the catalytic material.

By adding instrumentation to critical detection points, system deficiencies were detected and corrected prior to full-scale operation. Other problems associated with the system have been in the controls and power supply electronics. As mentioned earlier, natural gas was not available at the site, and an electric unit was required.

Electric units have a fairly complex control system which adjusts the 480-V, 3-phase current to keep the temperature within the specified limits. The Omron HL 2000 temperature controller, Model No. F5AX-A, was able to keep the temperature within 1 degree of the required set point. The temperature signal to the Omron controller, was from a type K thermocouple inserted in the combustion chamber of the oxidizer. A 4- to 20-milliamp control signal through a silicon-controlled rectifier (SCR) was used to power the silicon carbide resistance heaters. The heater unit also was equipped with a multiple-tap transformer control center to reduce the 480, 3-phase voltage as the heater elements aged. This action helps extend the life of the unit.

The area where the methane is blended is a Class I, Division 2 electrical zone, and equipment in that area must be intrinsically safe or explosion proof. To avoid having to supply equipment to meet those rigid specifications, the gas analyzer(s), controllers, and monitoring devices were placed outside of the area in a common enclosure (panel). The consolidation of the instrumentation with the high-voltage equipment proved to be an engineering challenge.

Mass flow of air and methane were attained by using two calibrated Kurz in-line mass flowmeters, Model Nos. 505 and 455. The explosion-proof flow sensors were positioned for in-line detection, transmitting flow data to the data logger and digital display located in the common control panel. When properly calibrated, the flowmeters gave extremely accurate readings. The readings were verified by gas chromatography.

Materials and Spare Parts

Construction codes and standards for systems carrying potentially hazardous materials are significantly more restrictive than for ambient air systems. Hydrochloric acid is created by the oxidation of chlorinated solvents. Although the site is well within the limits imposed by the air permit, acid is created and the materials used must be corrosion resistant in order to survive the project. Another consideration is to use materials that will not generate an additional wastestream by becoming a hazardous waste when the project is complete.

Systems for scrubbing out the acid and neutralizing it are available but can be costly. Additional permitting may be required, and possibilities exist for additional wastes to be generated. During the course of this project, several components were taken out of service or failed, for various reasons. A contingency of spare parts and key components is essential for a successful project.

Equipment Configuration

The main emphasis was placed on the relationship between the methane-blending system (Figure 2), the gas delivery system, and the gas analyzer, monitoring devices, and the electrical supply to the thermal catalytic oxidizer. In order to get the blended air/methane sample to the gas analyzer, a 20 ft (6 m) length of tubing had to be run from the blender mixing point to the common control panel. This put a lag of about 15 seconds between the time in which the gas concentration was adjusted by the flow control valve and the altered gas mixture reached the analyzer.

This delay forced the controller to use a rather slow-response algorithm for adjusting the loop to fluctuations in the gas concentrations. For that reason, it would have been desirable to shorten the length of the sample line, or in the absence of that possibility, use a larger diameter sample line, increasing the flowrate to the analyzer. During cold weather operations this delay in signal response resulted in frequent alarm conditions. Significant efforts to fine-tune the system were required.

Another relationship, that presented interface problems, was the housing of low-voltage, heat sensitive instrumentation and high-voltage, heat generating power supplies in the same control panel. Calibration or adjustment of the monitoring equipment required working in very close proximity to live 480-V power. In fact, the safe operating range (120°F [49°C]) of some devices, was pushed to its limit during hot weather. To eliminate potential safety hazards and component failures, separate control panels should be specified for low- and high-voltage components.

Weather Conditions

The Savannah River Site, located in South Carolina, gets frequent and sometimes severe thunderstorms during the summer months with numerous lightning strikes. In areas such as this, lightning protection is a cheap form of insurance and is easy to install. There were several failures in the power control system and instruments, many due to lightning. In fact, lightning strikes contributed to over 80 hours of the system's downtime. It is relatively inexpensive to obtain the services of a local electrical engineer, familiar with the area, to design lightning protection into the system controls and obtain the necessary site-specific equipment. Designing lightning protection by surveying the literature and trying to make an educated purchasing decision may give the designing engineer a false sense of security. It is best to consult with local professionals in this case and remember, the small amount of effort just described will, and has on this project, provided sufficient protection for most situations.

Heat and high humidity placed unnecessary stress on the sensitive equipment in the control panel. This was alleviated by installing an air-conditioning unit in the panel. Although simple, the field modification required additional power revisions. Cold weather also provided some challenging conditions. As stated, the SRS does not have a direct supply line for natural gas. To support the project with methane gas, two compressed natural gas (CNG) tube trailers were manufactured. Each trailer has a capacity of approximately 12,500 scf (354 m^3), at 3,000 psig (1,361 kg/cm^2).

To meet the injection pressure at the wellhead, the trailers were equipped with a multistage regulator system, capable of reducing the pressure from 3,000 to 40 psig (18 kg/cm^2). A general rule of thumb for CNG is, for every 100 psig (45 kg/cm^2) reduction in pressure, the temperature of the flowing gas is reduced by 70°F (21°C). The trailers came equipped with an ambient loop between the second and third or final-stage regulator. The loop is designed to prevent freezing in the final-stage regulator. The loop worked well during warm weather, but when outside air temperatures dropped below 40°F (4.5°C), the system failed due to frozen regulators and supply lines. An erratic gas flow resulted, triggering high methane concentrations and system shutdown. As of this date, this condition has not yet been resolved. Several proposals are under consideration. It would be a great advantage if a low-pressure CNG source were available at the site.

Safety Controls and Interlocks

The safe operation of the system must be paramount in the mind of the designer. Significant redundancies and safety interlocks must be designed into the system to prevent any unforeseen hazardous conditions from existing undetected. The SRS system includes audio and visual alarms, safety interlocks between major components (i.e., the methane injection system cannot function if the extraction system is not operational). There are overtemperature controls to prevent excessive heat buildup in the oxidizer and provide for unit shutdown in the event of a thermocouple burnout and mechanically operated solenoid valves that are normally closed if a power failure occurs.

Additional safety devices include off-gas low/high-pressure alarm switches, methane gas detection that shuts down the system if concentrations greater than the LEL are detected, and overcurrent protection with alarm and system shutdown capabilities. In the event of any malfunction, an emergency response telephone autodialing system, tied to the pager network of management, engineering, and operations staff, is activated.

SUMMARY

The events and conditions described in this paper are important to a successful project. Remember how important even the smallest missed detail can be in today's competitive economic climate. Small errors or inadvertent deletions can be very problematic and sometimes extremely costly.

The project was, without a doubt, a success from an engineering standpoint. The flexibility of the design to accommodate field modifications and the quick response to initial component and system failures made the endeavor successful. The total system downtime from field modifications and repairs, including the catalytic oxidizer modification, was only 214 hours of the total possible operating time. This represents only 19.8% of the total downtime. Significant knowledge has been gained about the reliability, compatibility, and performance of the system components in a unique environmental remediation application.

Elements of the system have been stressed to their limits, some to the point of failure. This action, although not intentional, provided data to design and build superior second-generation systems. The lessons learned from the research and development of this innovative technology should help to develop more efficient, cost-effective, and environmentally sound remediation programs. Future exploitation of these successfully tested technologies will provide information applicable to more difficult remediation problems where no proven methods exist.

ACKNOWLEDGMENTS

The information contained in this article was developed under the course of work under contract No.DE-AC09-89SR180035 with the U.S. Department of Energy. In addition, portions of this information were developed by Bechtel Savannah River Inc. and ECOVA Corporation as part of a subcontract with Westinghouse Savannah River Company.

REFERENCES

Eddy, C. A., B. B. Looney, J. M. Dougherty, T. C. Hazen, and D. S. Kaback. 1991. *Characterization of the Geology, Geochemistry, Hydrology and Microbiology of the In-Situ Air Stripping Demonstration Site at the Savannah River Site.* WSRC-RD-91-21. Westinghouse Savannah River Company, Savannah River Site, Aiken, SC.

Foxboro Company. 1985. *Exact Tuning with 760 Series Controllers*, Technical Information Publication, Bulletin No. TI 039-200.

Hardison, L. C., and E. J. Dowd. 1977. "Air Pollution Control: Emission Via Fluidized Bed Oxidation." *Chemical Engineering Progress*, Air Resources, Inc.

Hazen, T. C. 1991. *Test Plan for In Situ Bioremediation Demonstration of the Savannah River Integrated Demonstration Project.* DOE/OTD TTP No. SR

0566-01 (U). Westinghouse Savannah River Company, Savannah River Site, Aiken, SC.

Horiba Instruments Inc. 1987. Instrument Manual for Horiba Model PIR-2000. "General Purpose Infrared Gas Analyzer." Horiba Manual No. 090652, 4-87A.

Looney, B. B., T. C. Hazen, D. S. Kaback, and C. A. Eddy. 1991. *Full Scale Field Test of the In-Situ Air Stripping Process at the Savannah River Integrated Demonstration Test Site*. WSRC-91-22. Westinghouse Savannah River Company, Aiken, SC.

Looney B. B., and J. Rossabi. 1992. *Assessing DNAPL Contamination A/M Area, SRS: Phase I Results (U)*. WSRC-RP-92-1302. Westinghouse Savannah River Company, Savannah River Site, Aiken, SC.

Marine, I. W., and H. W. Bledsoe. 1984. *M-Area Groundwater Investigation (Supplemental Data Summary)*. Savannah River Laboratory Report DPSTD-84-112, Savannah River Plant, Aiken, SC.