

## A NEW METHOD FOR DETECTING, LOCATING, AND QUANTIFYING RESIDUAL CONTAMINATION IN PIPES AND DUCTS IN SUPPORT OF D&D ACTIVITIES

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### ABSTRACT

Vista Engineering Technologies, L.L.C., has developed a new, minimally invasive technology called PCUT<sup>2</sup> for *detection, location, and quantification* of residual contamination in pipes and ducts using gaseous tracers. PCUT (Pipeline Characterization Using Tracers) can be used in support of deactivation and decommissioning (D&D) of piping and ducts that may have been contaminated with hazardous chemicals such as chlorinated solvents, petroleum products, radioactive materials, or heavy metals. The PCUT approach operates by advecting two or more tracers along a pipe or duct section and then monitoring the temporal characteristics of the tracers at the other end of the pipe section. One of the tracers is a conservative tracer, i.e., it will not dissolve, adhere, or interact with the contaminant of interest. The other tracer (or tracers) is an interactive tracer, which is selected so it will partition or react with the contaminant of interest. The *presence* of the contaminant is determined from the shape or amplitude of the measured concentration curve. The *amount* of contaminant within the pipe or duct is determined by measuring the difference in the arrival times between the conservative and the other tracers at the extraction point in the pipe. The *location* of the contamination is determined by introducing a perturbation to the advection flow field after the interactive tracer (or tracers) has reached the contamination. This paper will describe the capability of PCUT and present the results of experimental tests performed in the laboratory on a test section of pipe.

### INTRODUCTION

During the course of weapons and nuclear fuel production, fuel reprocessing, and waste disposal, the U.S. Department of Energy (DOE) and its predecessor agencies, have constructed over 20,000 facilities at more than 10 sites across the United States [1]. These facilities include buildings, structures, tanks, pipelines, ductwork, etc. Many of these facilities are contaminated with hazardous chemicals, such as chlorinated solvents, radioactive materials such as plutonium and tritium, heavy metals like mercury and lead, or mixtures of the above and more. With the shift in DOE's mission from production to environmental management, several of the facilities are no longer being used, and many have exceeded their design life. The contaminants in these facilities can pose a serious threat to human health and the environment if left unmitigated. DOE plans to deactivate and decommission (D&D) most of these facilities in order (1) to reduce the costs associated with monitoring and maintaining them and (2) to decrease the potential for release of radioactive, hazardous, or mixed waste to the environment. It is estimated that the total cost to stabilize, deactivate, and decommission these facilities and structures is on the order of \$21 billion dollars [1].

A similar problem exists in industrial and chemical/petroleum facilities that are taken out of service for closure or for maintenance and cleaning. Chlorinated solvents, such as trichlorethylene (TCE) and carbon tetrachloride (CCl<sub>4</sub>), which were used as degreasers within DOE and Department of Defense (DOD) facilities, are examples. Petroleum fuels are another example of a common hazardous substance.

Contaminated pipelines and ductwork within the DOE facilities are a significant component of the D&D plans. Pipelines were used to transport various types of contaminated fluid (liquids and gases) from one location to another. Ductwork was used to move air, such as fume hood effluent, for radiological work. It is estimated that there are several thousand miles of pipelines and ductwork awaiting D&D. Based on their usage and lifespan, it is likely they contain significant quantities of hazardous, radiological, and mixed wastes, and in multiple forms (liquids, sludge, salt cake, crystallized solids, etc.). Before D&D operations commence, characterization of the pipelines and duct systems is required to make this operation more cost effective and to appropriately protect workers performing the D&D activities.

Many of the piping and duct systems and/or portions of these systems are inaccessible and external inspection techniques that require access or safe access to the outside wall of the pipe or duct cannot be used. For example, many of the pipes are buried underground, or are located beneath the floor of a building or a paved area. Because direct access to the external wall of a pipe or duct is frequently not possible, whether for safety or physical reasons, methods that involve internal inspection of the pipe or duct need to be used. In general, these methods generally require that any liquid in the pipe be removed, and some physical device needs to be inserted into the pipe or duct to perform the characterization.

A common measurement approach for determining whether or not a pipe or duct is contaminated is to use a camera or sensors to inspect the inside of the pipe. For short sections of pipe, a small camera or sensor can be inserted into the pipe on a cable. For radioactive sampling, sensors and cameras can be inserted into a pipe using an inverting membrane instrument deployment system (PipeExplorer<sup>®</sup>) comprised of a tubular polyethylene membrane [2]. This system can be used for pipes with lengths of 300 to 400 ft and diameters as small as 2 in. and as large as 36 in. Such methods, however, have a limited working range of only several hundred feet. Another pipe inspection approach is to mount a camera or sensor on a robotic vehicle, which is inserted into the pipe or duct and allowed to move down the pipe. Many of these robotic systems are limited for use in piping or ducts with diameters of 3- to 4-in., or larger. This approach is acceptable for larger diameter piping, but for small piping, the robotic vehicle may be too large to be used or not be able to move past bends and constrictions in the pipe.

Once D&D is underway, a common approach for determining whether or not contamination still exists is to sample the liquid that is being used to clean the pipe. However, this approach can miss low spots in the pipe containing contamination and may not accurately characterize the extent of the non-liquid residual contamination on the walls.

In general, other pipeline and ductwork characterization approaches are still needed to support the characterization needs of D&D, especially ones that can characterize the small diameter or inaccessible pipes and ones that are more economical and safe to use.

## **A NOVEL PIPELINE AND DUCTWORK CHARACTERIZATION TECHNOLOGY**

To address these pipeline and ductwork characterization needs, Vista Engineering Technologies, L.L.C., has undertaken a program to demonstrate and evaluate a novel characterization technique to determine the *presence, location, and amount* of a contaminant in a pipe or duct. The technique is

called PCUT, which is an acronym for *Pipeline Characterization Using Tracers*. This work was performed with Battelle's Pacific Northwest National Laboratory (PNNL) under a Small Business Technology Transfer (STTR)/Small Business Innovation Research (SBIR) program [3, 4]. The *detection, location, and quantification* aspects of the characterization technique, which were experimentally demonstrated in the laboratory, are described below for application to a contaminated pipe; however, the same technique can be used for ducts.

## OVERVIEW OF THE PCUT APPROACH

PCUT, which is illustrated in Fig. 1, uses conservative and interactive (partitioning and/or reactive) tracers to remotely determine the amount of contaminant within a run of piping or ductwork. The basic measurement approach is to inject a finite volume of a conservative tracer and one or more interactive (non-conservative) tracers at one end of the line, where the volume of the tracers is small compared to the pipe volume, and then to transport this slug or pulse of tracer along the line. Another gas, such as nitrogen, which does not interact with the contaminant or the tracers, is used to transport both the conservative and non-conservative tracers along the pipe. The conservative tracer does not interact with the contaminant of interest as it passes by the contaminant. The interactive tracer, however, interacts with the contaminant, but not the conservative tracer or the advection gas. The measured elution curves of concentration of the interactive tracer would be identical to the measured concentration curve of the conservative tracer if the line had no contamination. As illustrated in Fig. 1, if contamination is present, the concentration curves of the conservative tracer and interactive tracer will be different.

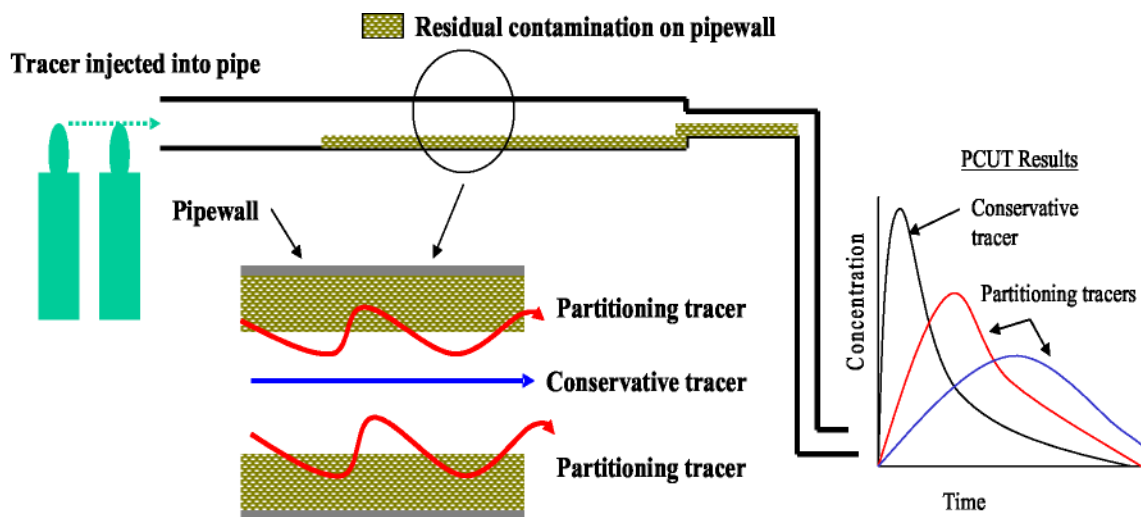


Fig. 1. Schematic of Partitioning Tracer Concept Deployed for Pipeline Characterization. The Elution Curves of Concentration for both the Conservative, and Partitioning Tracers are also Shown.

For many contaminants, there are a number of tracers available that can be used, especially for chlorinated solvents and petroleum fuels. Many of these tracers have been previously used for characterizing subsurface contamination that typically results from a release from a pipe or a tank [5-9]. For other pipeline contaminants such as heavy metals and radionuclides, new tracers will have to be developed and tested.

There are two basic types of *interactive* tracers that might be used. One is a *partitioning* tracer, and the other is a *reactive* tracer. There are important differences between these two types of tracers. A reactive tracer, as the name implies, reacts with the contaminant as the tracer moves by the contaminant. This reaction may or may not change the chemical composition of the tracer. In general, the reaction will decrease the concentration or volume of the tracer being transported in the pipe. However, the reaction will not generally change the mean time of arrival of the reactive tracer at the outlet measurement point. This is illustrated in Fig. 2a, which graphically presents the difference in the concentration curves that might be measured at the outlet point in a pipe with contamination present for a conservative tracer and a reactive tracer. The peak of the curves and the centroid of the curves results in the same time of arrival for both the conservative and reactive tracers. The volume of the reactive tracer, as assessed from the magnitude or area under the concentration curve measured at the outlet section of the pipe, is less than the volume of tracer injected into the pipe at the inlet section.

A partitioning tracer, on the other hand, is temporarily “absorbed” by the contaminant as the tracer passes by the contaminant. After the partitioning tracer has passed the contaminant, the tracer that had partitioned into the contaminant will re-enter the flow stream of the pipe and be advected along the pipe to the extraction point. Figure 2b illustrates graphically the difference in the concentration curves that would be measured at the outlet point in the pipe for a conservative tracer and a partitioning tracer with the presence of contamination in a pipe. While the shape of the concentration curves of the conservative and partitioning tracers are different, unlike the reactive tracers, the total volume of the tracers injected is recovered at the outlet point. Also, unlike the reactive tracers, the mean time of arrival, as determined from the centroid of the concentration curves, is different for the conservative and partitioning tracers.

### **Advantages of the PCUT Approach**

There are a number of important advantages of the PCUT method over the physical delivery systems currently used for characterizing contamination in pipe and ductwork. The first advantage of the proposed method is that the same procedure will work on pipes (or ducts) of any size and nearly any length. Tracers are just as easily injected into a small diameter pipe (e.g., 0.5 in.) as they are into larger diameter pipe (e.g., 12 in.). Other remote pipe inspection equipment, which transport cameras and sensors by crawlers into a pipe, require pipe diameters of 3- to 4-in. or larger for entry and operation. Many of the pipelines within building systems are on the order of 0.5 to 2.0 inches, making inspection using cameras very difficult or nearly impossible.

The second advantage of PCUT is that the injected tracers can easily navigate pipe (or duct) bends and other pipe irregularities with ease compared to remotely operated inspection equipment. Tight bends and changes in diameter are not a problem for the tracer gases, yet represent major hurdles for other characterization techniques. Gas tracers also inspect the entire surface of the pipe, including any crevices or nooks that may be difficult to inspect using video approaches. This will result in a more complete and thorough inspection of the pipe (or duct).

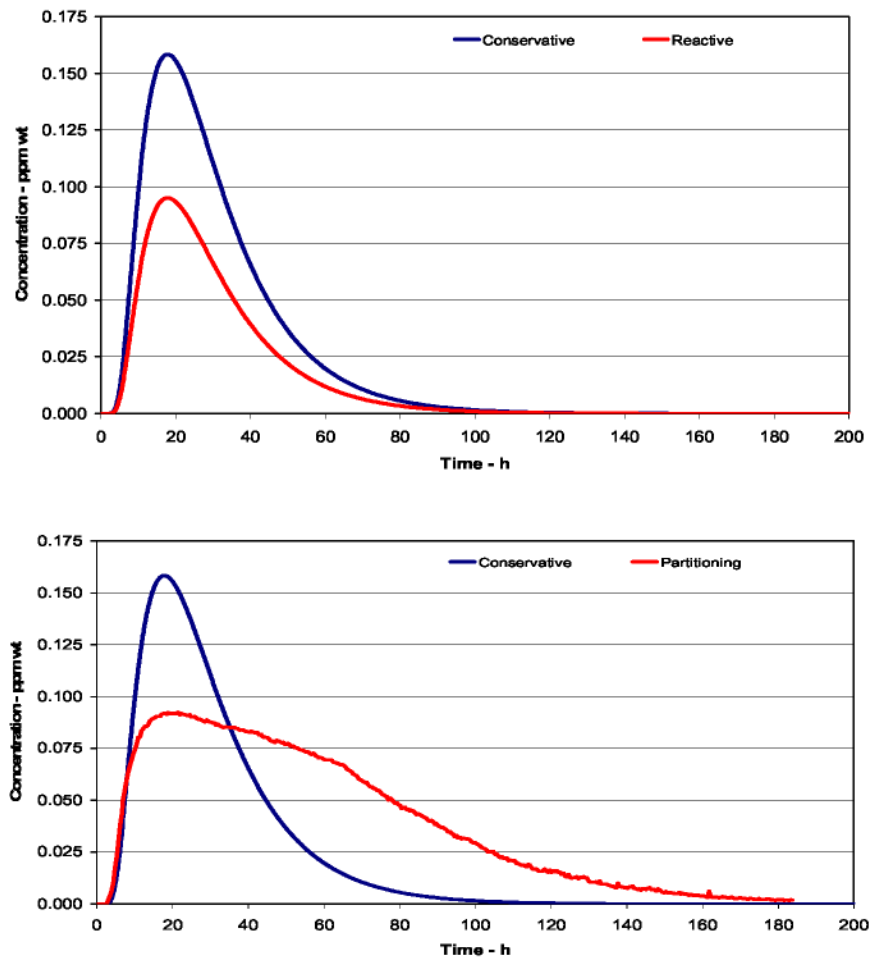


Fig. 2. (a) Illustration of the Elution Curves of Concentration for a Conservative Tracer, and a *Reactive* Tracer with the Presence of Contamination in a Pipe and (b) Illustration of the Elution Curves of Concentration for a Conservative Trace, and a *Partitioning* Tracer with the Presence of Contamination in a Pipe.

The third advantage of PCUT is that there are no moving parts or equipment that has to enter the pipe. For pipes or ducts that may contain explosive vapors or contaminants that could ignite, the partitioning tracer technique offers a characterization approach that remains safe. In addition, since no mechanical equipment enters the pipe, this eliminates the possibility of equipment malfunction or getting “stuck” and “plugging” the pipe (or duct).

The fourth advantage is that equipment contamination and de-contamination is avoided. This has both safety and cost implications. Because no equipment enters the pipe, there is no equipment that must be decontaminated when it exits the pipe. This reduces the amount of investigation-derived wastes that need to be disposed of properly.

The fifth advantage of PCUT is that it can be operated more cost effectively and more safely than other techniques without sacrificing performance. In fact, the performance of the PCUT method should be better than the more conventional methods.

PCUT can also be used in a variety of detection and measurement scenarios. The most common scenario is to characterize a pipe (or duct) system to determine if the pipe (or duct) has any residual contamination that must be removed before the system can be decommissioned or released. PCUT can also be used before and after a decontamination event to determine the amount of contamination that has been removed from or remains in the pipe (or duct). Finally, PCUT can be used to routinely monitor pipelines and ductwork for any residual buildup of contaminants that could reduce efficiency of the fluid flow system.

## DESCRIPTION OF THE PCUT METHODOLOGY FOR DETECTION AND QUANTIFICATION

The PCUT approach can be applied to both pipes and ductwork. As depicted in Fig. 1, conservative and interactive tracers are injected directly into the line. In general, measured volumes of the tracers to be used in a test are inserted into a gas bottle and pressurized. The gas bottle containing the tracers is connected to the line with a valve that can be used to isolate the gas tracers from the line. A regulator or flow meter is used to control the amount of tracer that is injected. A timer is used to determine the volume of tracer injected into the line. The tracers are advected down the pipe or duct using an inert gas such as nitrogen or compressed air at a fixed or known rate. Detection of a contaminant does not require a fixed or known flow rate; however, location and quantification does. A gas chromatograph (GC) is used at the extraction point to sample the tracers being removed from the pipe. All of the laboratory tests conducted to date have been conducted using *partitioning* tracers, and as a consequence, the PCUT methodology and the laboratory tests presented in this paper will be described for partitioning tracers.

The key feature of PCUT is that a suite of tracers are transported down a length of pipe and come in contact with any and all possible sources of contamination within the pipe. Because the conservative tracer will not interact with the contamination inside the pipe, it has a partition coefficient of zero relative to the contamination. The partitioning tracer (or tracers), on the other hand, will interact with the contamination, and therefore, have a non-zero partitioning coefficient. The partitioning coefficient ( $K_i$ ) is defined as

$$K_i = C_{i,D} / C_{i,M} \quad (\text{Eq. 1})$$

where  $C_{i,D}$  is the concentration of the "i"th tracer in the contamination, and  $C_{i,M}$  is the concentration of the "i"th tracer in the mobile phase, i.e. the nitrogen transporting the tracer. The retardation of the tracers by the contamination for flow through a porous media,  $R_f$ , is given by

$$R_f = \frac{\langle t_p \rangle}{\langle t_c \rangle} = 1 + \frac{K_i S_D}{(1 - S_D)} \quad (\text{Eq. 2})$$

where  $\langle t_p \rangle$  is the mean time of travel of the partitioning tracer,  $\langle t_c \rangle$  is the mean time of travel of the conservative (i.e., non-partitioning) tracer, and  $S_D$  is the average contamination saturation, i.e. the

fraction of the volume occupied by contamination in the total swept volume of the porous media. This porous media flow model can be adapted for flow in a pipe. The average contamination saturation for flow in a pipe or other fluid flow system,  $S_{Dpipe}$ , is related to  $S_D$ , by an empirical constant,  $\alpha$ , where  $\alpha$  should be approximately equal to 2 for flow in a pipe. In a pipe, only the top of the contaminant layer can interact with the tracer. In porous media, the tracer can interact with all sides of the contaminant. The values of  $\langle t_p \rangle$  and  $\langle t_c \rangle$  can be determined from the centroid of the elution curves of tracer concentration during a pipe test, and  $K_i$  can be determined in laboratory calibration tests.

An estimate of the mean travel time of the partitioning or conservative tracers,  $\langle t_p \rangle$  and  $\langle t_c \rangle$ , can be computed from the centroid of the elution curves of tracer concentration using the following equation.

$$\langle t_{p\_or\_c} \rangle = \frac{\int tC(t)dt}{\frac{C_i}{\int C(t)dt}} \quad (\text{Eq. 3})$$

An estimate of the volume of the contamination can be estimated by solving Eqs. (1) and (2) for  $S_{Dpipe}$ , assuming  $S_{Dpipe} = \alpha S_D$ ,

$$S_{Dpipe} = \alpha \frac{R_f - 1}{K_i + (R_f - 1)} = \alpha \frac{\frac{\langle t_p \rangle}{\langle t_c \rangle} - 1}{K_i + \left( \frac{\langle t_p \rangle}{\langle t_c \rangle} \right) - 1}, \quad (\text{Eq. 4})$$

where  $\alpha$  is theoretically equal to 2 for a thin layer of contamination at the bottom of a pipe.

Partitioning tracers undergo retardation due to their partitioning into and then out of the contamination, while conservative tracers are unaffected by the presence of the contamination. Figure 3a illustrates the difference in the measured concentration curves between a partitioning tracer that was injected into a pipe section free of contamination and the same pipe section when it contained a thin layer of diesel fuel contamination. The difference between tracer concentration curves with contamination and without contamination is clearly evident in Fig. 3a. Figure 3a shows both a reduction in concentration and a difference in the mean time of arrival of the partitioning tracer due to the presence of a contaminant in the pipe. If a conservative tracer was also injected into the pipe section when the contamination was present, its concentration curve would be similar to the one measured without the contamination present. This is shown in Fig. 3b. If a conservative tracer was also injected into the pipe section when the contamination was present, its concentration curve would be similar to the one measured without the contamination, since it does not interact with the contaminant.

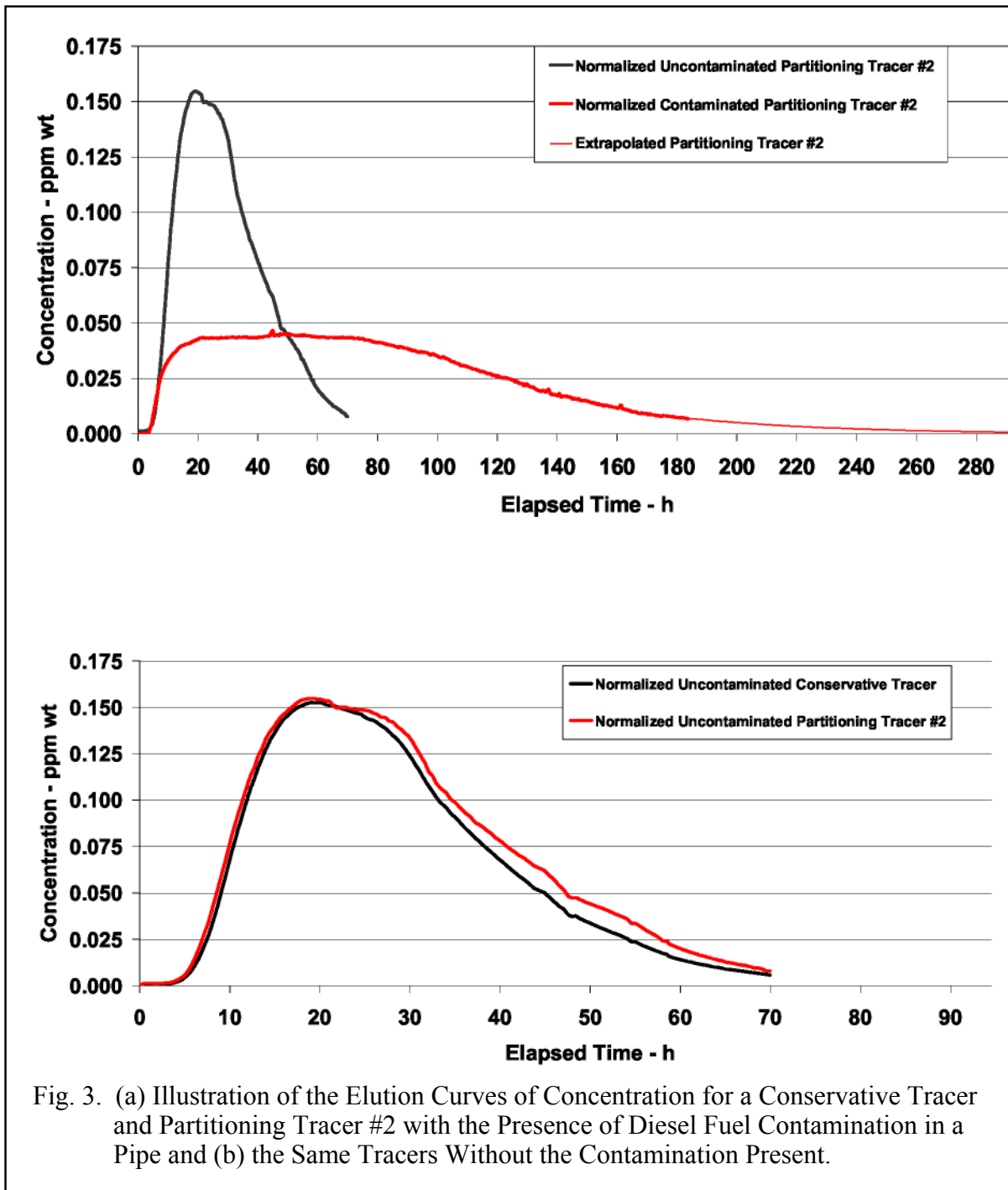


Fig. 3. (a) Illustration of the Elution Curves of Concentration for a Conservative Tracer and Partitioning Tracer #2 with the Presence of Diesel Fuel Contamination in a Pipe and (b) the Same Tracers Without the Contamination Present.

The partitioning process is caused by the mass transfer of the partitioning tracers into the contaminant until equilibrium partitioning has been reached. For this reason, the flow rate of the tracers must be designed so that sufficient time exists to allow the partitioning tracers to interact with the contaminant. Once the tracer slug has passed the contamination, the partitioning tracer elutes



back into the flow field as dictated by the partitioning coefficient. Therefore, the net flux of the partitioning tracers will be from the contaminant back into the flow field to preserve the equilibrium partitioning dictated by the particular coefficient for the tracer. Thus, recovery of the partitioning tracers at the extraction point is delayed (i.e. retarded) relative to the recovery of the conservative tracer.

### Detection and Quantification Demonstration Tests

The PCUT technology was experimentally demonstrated in the laboratory using partitioning tracers in a 23-ft section of 2-in.-diameter PVC pipe contaminated with diesel fuel. The middle section of the pipe was a 10-ft long, 3-in.-diameter section of PVC pipe that held a 0.5-in. layer of diesel fuel. An inert gas was selected as the conservative tracer ( $\text{SF}_6$ ), and two fluorocarbons (Partitioning Tracer #1 =  $\text{C}_7\text{F}_{14}$ , Partitioning Tracer #2 =  $\text{C}_8\text{F}_{16}$ ) were selected as the partitioning tracers; nitrogen was used to transport all of the tracers from the inlet to the outlet of the pipe.

### Detection and Quantification Demonstration Test Results

The results of the technology demonstration tests are presented below. Two sets of tests were conducted, (1) one set with contamination and (2) one set without contamination. Figure 3a shows the elution curve of tracer concentration for one of the partitioning tracers (Partitioning Tracer #2) with and without the presence of the diesel contamination. There is a clear and unambiguous difference between the two curves in terms of magnitude, shape, and time of arrival of the center of mass. Since the conservative tracer is not affected by the presence of contamination, it can be used to replicate the response of the partitioning tracer that would have been obtained if no contamination were present in the pipe (see Fig. 3b). The conservative tracer response is then compared to the response of the various partitioning tracers in an actual pipe measurement when contamination is present as the fundamental part of the detection algorithm.

Figure 4 superimposes the concentration curves of the conservative tracer and the two partitioning tracers measured during one of the contamination tests. The presence of contamination can be determined as soon as the peak of the conservative tracer curve arrives. Detection is accomplished by comparing the peak amplitudes of the conservative and partitioning tracer concentrations. Quantification is accomplished once the exponential tail of the partitioning tracer is measured. The most rapid and most accurate estimates of the contaminant volume are obtained by mathematical extrapolation of the exponential tails of the partitioning tracers. Table 1 summarizes the results. The most accurate results are within 6% of the 1.5 L of diesel used to contaminate the 3-in.-diameter pipe section.

A number of observations are noteworthy concerning the shape and temporal response of the conservative and partitioning tracers presented in Fig. 4. The observations are made with respect to the partitioning tracer #1, but are equally valid for partitioning tracer #2.

- First, the initial arrival time of both the conservative tracer and the partitioning tracer #1, as illustrated by the leading edge of the concentration curve, is approximately the same.
- Second, the peak of partitioning tracer #1 is significantly lower than the conservative tracer. It is clear that partitioning tracer #1 has an affinity for the diesel fuel, and the partitioning into

the diesel occurs very quickly. The difference in the peak amplitudes between the conservative and partitioning tracers can be exploited in the development of a real-time detection algorithm.

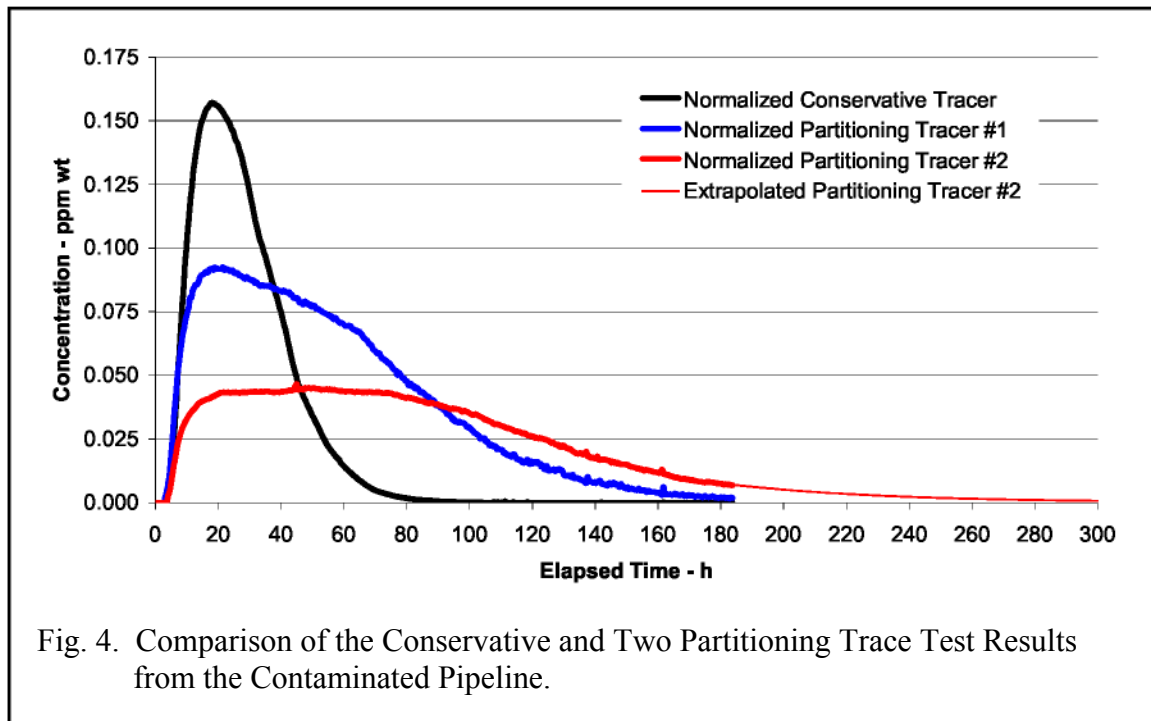


Table I. PCUT Estimation of the Volume of the 1.5 L of Diesel Fuel Contamination

| Tracer Gas             | PCUT Volume Measurement | Error (%) |
|------------------------|-------------------------|-----------|
|                        | (L)                     |           |
| Partitioning Tracer #1 | 1.40                    | 6.4%      |
| Partitioning Tracer #2 | 1.29                    | 13.7%     |

- Third, the conservative tracer indicates the travel time of the initial slug of tracers injected into the pipe. After 70 hr, all of the initial tracer material (both conservative and partitioning tracers) should have traveled the entire length of the pipe. Any tracer concentration being measured after this time is an indication that tracer is still being released from the diesel fuel.
- Fourth, the peak of the partitioning tracer is much broader than the peak of the conservative tracer. The conservative tracer is affected only by dispersion as it is advected along the pipe. The partitioning tracer also includes this affect, but is dominated by the partitioning of the

tracer into and out of the diesel fuel. The partitioning tracer remains approximately constant for many hours and then falls off exponentially. These same observations are true of the other partitioning tracer.

- Fifth, as exhibited by the exponential tail of the concentration curve, the partitioning of the tracers from the diesel back into the flow field occurs slowly.

While the time required to make the measurements in the laboratory tests described above took 200 hr, this would not be the case for an operational deployment of the technology. Such measurements of detection can be made in less than 24 hr.

## **DESCRIPTION OF THE PCUT METHODOLOGY FOR LOCATION**

The location of the contaminant can be determined by introducing a perturbation to the advection flow field or flushing the conservative and partitioning tracers in the line and then measuring the mean time of arrival of the partitioning tracers that are still being eluted from the contamination in the system.

A perturbation in the partitioning tracer flow field must be induced to locate the position of the contaminant in the pipe. This flow field variation can be introduced any time after the partitioning tracer has reached and begun partitioning into the contamination. This can be determined from the time history of the normalized concentration curves. As illustrated in Fig. 4, for partitioning tracer #1, this can occur any time after 20 to 24 hr such that the peak of the normalized concentration of the partitioning tracers have become a fraction of the conservative tracer. The flow field perturbation can be introduced during the peak portion of the curve or the exponential region of the concentration curve. If location is to be effectively combined with detection and quantification, then the flow field variation is best done when the concentration is changing exponentially and when sufficient data have been collected to accurately extrapolate the exponential portion of the curve to zero.

The flow-field perturbation is produced by suddenly increasing the flow rate (i.e., velocity) of the nitrogen gas used to advect the tracers along the pipe. The purpose of this increase is to flush the partitioning tracers in the flow field. Once this is accomplished, the flow field can be returned to its original flow rate. The tracers present in the contamination will continue to come out of the contamination and be advected along the pipe. However, the leading edge of the partitioning tracers re-entering the nitrogen flow field will be clearly identifiable and distinguishable from the original concentration data. The distance between the contamination and the GC can be estimated by a measurement of the time of arrival of the partitioning tracer and the flow rate. The advection velocity does not have to be the same before and after the flushing, but it does have to be known.

### **Location Demonstration Test**

The location capability of the PCUT technology was experimentally demonstrated two partitioning tracers in a 116-ft section of 2-in.-diameter PVC pipe. A 3-ft by 1-5/8-in. rectangular tray was inserted into a 4-ft section of 3-in.-diameter PVC pipe whose center position was located 47.5 ft from the end of the pipe where the GC measurements were being made. The tray was used to contain 300 ml of aged diesel fuel. The same two tracers and the same advection gas as used in the detection and quantification tests were used in the location test. However, unlike the detection and quantification

tests described above, the volume and cross-section area of the diesel fuel was significantly less (five times less). Also, the flow rate of 14 to 19 ml/min was higher than the 11 ml/min flow rates used previously, but was not optimized for the shortest test period.

### Location Demonstration Test Results

Once the conservative tracer concentration started to reduce in the time history plot, such as the one shown in Fig. 4 at 40 hours, the advective airflow was increased to 350 ml/min. This swept all the remaining tracers out of the pipe and caused the concentrations to return to zero. After approximately one and half hours, the flow rate was returned to 15 ml/min. With a low flow rate re-established, the partitioning tracers in the diesel fuel re-enter the flow stream and are advected to the end of the line at a known flow rate. The location of the contamination is then determined from the advection velocity and the arrival time of the tracers. Both of the partitioning tracers were detected at the GC after about 19 hours.

Table 2 summarizes the location results. Two methods were used to locate the contamination. Both methods used the time of arrival of the leading edge of the tracer concentrations. The first method, which does not require a priori information about the diameter or geometry of the pipe, takes the ratio of the time of arrival of the leading edge of the first tracer pulse, which traveled over the full length of the pipe (i.e., 116 ft) and the time of arrival of the second tracer pulse, which traveled only the distance from the contamination to the end of the pipe, after weighting the arrival times by the mean of the measured flow rates. The second method uses the maximum velocity of travel for the second pulse, which for laminar flow in a pipe is computed from the average velocity of the advection and multiplying by two. The average velocity is computed by dividing the average of the measured flow rate by the diameter of the pipe.

Table II PCUT Estimation of the Location of the 300 ml of Diesel Fuel Contamination

| Location Method | PCUT Location Measurement (ft) | Error (%) |
|-----------------|--------------------------------|-----------|
| Method 1        | 53.2                           | 12.0 %    |
| Method 2        | 51.3                           | 8.0 %     |

\* The actual location of the contamination is centered 47.5 ft from the outlet end of the 116-ft pipe.

### CONCLUSIONS AND RECOMMENDATIONS

*PCUT (Pipeline Characterization Using Tracers)* is a new, minimally invasive technology for remote detection, location, and quantification of residual contamination in pipes and ducts using gaseous tracers. PCUT can be used in support of deactivation and decommissioning of piping and ducts that may have been contaminated with hazardous chemicals such as chlorinated solvents, petroleum products, radioactive materials, or heavy metals. Other than the gaseous tracers, no sensors or mechanical systems need to be inserted into the pipe or duct to use PCUT.

The laboratory experiments conducted to date have successfully showed that PCUT can readily detect the presence of the diesel fuel, accurately quantify the volume of the thin layer of fuel located

on the bottom of the pipe, and locate the contaminant along the pipeline. If appropriate tracers are available or can be developed for the contaminants of interest, the demonstration tests conducted to date indicate that this remote sensing technique will work and will be very accurate. Currently the PCUT approach is ready for application in pipes contaminated with petroleum products and chlorinated solvents such as TCE, PCE, and CCl<sub>4</sub>. Additional tracers are under development for heavy metals, explosives and radionuclides of interest.

## ACKNOWLEDGMENTS

The laboratory tests were funded under DOE's STTR/SBIR program. Our special thanks is extended to Battelle's Pacific Northwest National Laboratory (PNNL) for their technical support and for the use of their GC. We especially want to acknowledge and thank Dr. Lirong Zhong, Mr. Terry Liikala and Mr. R. Cameron, of PNNL, and Ms. D. Faultersack and Ms. C. Haas of Vista Engineering, for their participation in the experimental work.

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## FOOTNOTES

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