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INFORMAL REPORT

DETECTION OF INTERSTATE LIQUIDS PIPELINE LEAKS: FEASIBILITY EVALUATION

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DETECTION OF INTERSTATE LIQUIDS PIPELINE LEAKS: FEASIBILITY EVALUATION

A Concept Paper

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ABSTRACT

The approximately 200,000-mile fuel pipeline system in the U.S. operates at flow rates up to 2.5×10^6 gallons per hour (GPH). Most commercial technologies only provide on-line leak detection at about 0.3% of flow rate, i.e., about 7,500 GPH or larger. Detection of leaks at about 1 GPH or so is desirable both from a regulatory and leak-prevention standpoint.

Brookhaven's commercially-accepted perfluorocarbon tracer (PFT) technology for underground leak detection of utility industry dielectric fluids at leak rates less than 0.1 GPH, with new enhancements, will be able to cost-effectively detect fuel pipeline system leaks to about 1 GPH—3 orders-of-magnitude better than any on-line system. The magnitude of detected leaks would be calculable as well. Proposed mobile surveys (such as those used periodically in the gas pipeline industry) at about 110 to 120 miles per day would allow such small leaks to be detected at 10-ppb tagging levels (less than $1,500 of PFT for a 48-hour tag at the maximum transport rate) under worst-case meteorological dispersion conditions. Smaller leaks could be detected by proportionately larger tagging concentrations. Leaks would be pinpointed by subsequent conventional barholing and vapor analyses.

There are no health nor safety issues associated with the use of the proposed technological approach nor any consequential environmental impacts associated with the proposed magnitudes of PFT tagging.

Introduction

Some 200,000 miles of oil pipelines carry nearly half of the crude oil and petroleum products (gasoline, kerosene, home heating oils, diesel fuels, and national defense fuels) consumed in the United States. This system is vital to our nation, its economy, and its national security.[1]

Recently, the frequency and magnitude of fluid spills from these systems has come under more intensive federal and state scrutiny. One possible active countermeasure that could be employed by pipeline companies would be the early detection of leaks while they are still small, that is, about 0.5 to 5 GPH. This likely would significantly reduce the number of major spills induced from small-leak erosion of the pipe-wall integrity.

This brief note summarizes how the Brookhaven perfluorocarbon tracer (PFT) technology can be applied to detecting and pinpointing these small (< 1 GPH) weepage leaks. Discussion will focus around the Colonial Pipeline Company system, the company with the largest trunkline traffic (710 billion barrel-miles in 1996) and one which is actively considering new leak-prevention strategies.

Transport versus Spill Magnitudes and Frequency of Leaks

Each day the Colonial Pipeline system of 5349 miles (about 2.7% of the nationwide pipeline lengths) delivers about 80 million gallons of fuels. At peak, the main trunkline from Houston to New York Harbor transports about 2.5 million GPH of liquid fuels through a 4-foot diameter pipeline at about 4.8 mph (~115 miles per day). Their total annual product shipments constitute about 17% of nationwide pipeline deliveries, about twice that of the next largest transporter.

In the 29-year period from 1968 to 1997, a total of 194 spills were reported to the Federal Office of Pipeline Safety (OPS) for an average of 6.7 per year or 1 every year per 800 miles. As a percentage of Colonial's annual delivery, however, total annual leaked product is significantly less than 0.001%. The problem is that the magnitude of annual delivery is huge!

In a recent 5-year period (1991-1995), the 64 recorded Colonial spills were equivalent to 12.8 per year or 1 every year per 400 miles. Thus, the number of incidents, although small on a per-mile basis, appears to be escalating. In that last reported 5-year period, the cost to Colonial in environmental damages was $22.5 million, not including the value of lost product and downtime.

Finally, in November 1997, Colonial agreed to pay $4 million in damages for a single spill on March 28, 1993. Although more than 91% of the product was recovered, Colonial had to bear those costs plus the legal expenses during the more than 4-year settlement study.

Thus, the environmental and consequential financial incentive is in place to promote the evaluation of new, promising, leak detection and pinpointing processes.

Commercial Pipeline Leak Detection versus PFT Technology

To be responsive to both the environment and the customers' transported product, the pipeline should have a real-time on-line leak detection/alarming system. Unfortunately, a recent review of such technologies[2] revealed that the best on-line systems are good to no better than ±0.2

to 0.4% of total flow under ideal conditions. On the main Colonial pipeline, 0.3% of 2.5×10^6 GPH is a 7,500-GPH leak detection threshold—much too large except for major pipeline failures.

Table 1 gives examples of the three primary, commercially-available technological approaches. APS/EFA offer the flow-totalizng mass-balance approach which may be cost effective for quick response to major failures. ASI offers an acoustic-based technique based on pressure-wave propagation from a sudden pressure loss; on a 4-ft diameter hydraulic pipeline system, a major leak will be required to initiate a significant-enough pressure loss. Again, this system may also be cost-effective for alarming of major leaks.

The third technique, a tracer vapor-based approach, is available from two sources. From TRC, below-ground soil air is analyzed for the presence of tracer vapors escaping from the leaking fuel. It would **not** be cost-effective to use their soil-air vapor extraction approach along thousands of miles of pipeline, but very small leaks would be detectable. Brookhaven's tracer vapor approach, however, would be cost effective.

This last approach, based on Brookhaven's PFT technology, is a commercially-accepted system for pinpointing underground dielectric fluid leaks of less than 0.1 GPH from such circulating (up to 25,000 GPH), but not consumed, fluids in pipelines.(3) In Table 1, it is estimated that based on even further improvements in this technology, supported both by the Consolidated Edison Company of New York, Inc.(4) and several federal agencies, mobile leak surveys by driving along the pipeline at about 15 to 20 mph will be able to detect Colonial pipeline leaks of as little as 1GPH—that is, less than 0.0001% of flow rate or more than 3 orders-of-magnitude better than any on-line system.

The next section provides some details of the proposed PFT approach and some technical description of the envisioned process.

Detection Surveying for Oil Pipeline Weepage

The proposed approach for small-leak detection is based on the cost-effective PFT tagging of a batch of gasoline for about 2 days, followed by a continuous leakmobile surveying (i.e., driving) of the pipeline route using a new-generation quasi-real time analyzer, looking for the presence of a subsurface gasoline leak as indicated by the emission of vapors from the PFT tag, in this case, a PFT that has never previously been manufactured and which should have a background concentration comparable to the new instrument's detection limit.

Tagging, emission rates, and peak above-ground air concentration. The assumed specifications of the pipeline are given in Table 2. A 2.9 million barrel batch of gasoline, tagged for 48 hours (2 days) at 10 ppb by wt of PFT, will be transported about 115 miles per day. The total of 3.5 kg of PFT would only cost $1400 for the 2 days of tagging. If a 55-gallon drum of tagging fluid is prepared at 10% by weight of octane (gasoline), then a 10^{-7} dynamic dilution of that solution would establish the desired final 10 ppb concentration. As shown in Table 2, the metering rate of only 15.8 mL/min would, in 48 hours, consume less than 1/4 of the drum's contents; a single drum could thus be used to perform up to 4 separate surveys of the total pipeline system traversed by the tagged batch of gasoline.

The leak rate emissions of both PFT vapors and gasoline vapors into the air at steady state (about 24 to 48 hours after the arrival of tagged gasoline) would, for a 1-GPH leak occurring 6 feet below the surface, give estimated emissions of 1.5 nanoliters per minute (nL/min or 10^{-9} L/min) and 510 mL/min, respectively. Assuming unstable daytime meteorology with winds at 5.6 mph and the van 8-m downwind in the plume centerline, the narrow plume(σ_y = 2.15 m) would produce a peak PFT concentration of 0.73 parts per quadrillion (ppq) or parts per 10^{15} and 260 ppb of gasoline. How would these compare to estimated backgrounds of both vapors?

Background PFT and gasoline concentrations and their ambient air analyses. Up to 3 or 4 PFTs are uniquely identified down to their ambient backgrounds within the 30-second analysis time of the PFT analyzer. The present commercialized version, the Sentex dual-trap analyzer (SDTA),[3] based on the original Brookhaven DTA,[5] has a 2-min cycle time and can "see" a signal of 25% above the background of one PFT, ortho-perfluorodimethylcyclohexane (oPDCH), which is at 0.71 ppq (parts per 10^{15})—improved by a factor of 4 from the BNL/DTA detectability and a required 4-min cycle time. The new CDTA[4] will be available next summer and will have the requisite cycle time (30 seconds) and detectability (about 15% above the background of a new PFT with a background of 0.1 ppq). Brookhaven is soon to receive commercial samples of 3 new PFTs with the requisite low ambient background.[6]

Thus, the 0.73 ppq plume centerline peak PFT concentration at 8 m downwind of the pipeline would be 8.3 times the expected background of the new PFTs for a 1-GPH leak and significantly above the new CDTA limit-of-detection (LOD) of 1.15 x background.

Gasoline, on the other hand, is not a single unique compound; it is comprised of over 12 dominant compounds and over 40 to 45 components total. Fugitive gasoline emissions and incomplete combustion are major contributors to the ambient background of total volatile organic compounds (VOCs). Very comprehensive and time-consuming analysis schemes (whole air sampling, cryotrapping and cryofocussing techniques) allow detection down to ambient backgrounds of the first three most significant and volatile compounds (n-butane, isopentane, and n-pentane) in about a 30-min cycle time.[7] This alone is much too long for leak detection purposes. The average ambient air background concentration of these compounds (i.e., away from any urban plume) is equivalent to about 3.2 ppb per 1 mole % in gasoline (i.e., 320 ppb of the total gasoline vapors).

Thus, in the same sampling location with the PFT, while it would be at 8.3 x background (measurable in 30 seconds), the gasoline vapor concentration would be, at best, about 1.8 times background—i.e., (260 + 320)/320, and measurable in only 30-min intervals! In urban situations or near gasoline stations, the ambient background could be an order-of-magnitude higher. This means that a signal 10 times background might be a leak of about 11 GPH or it just might be a local source!

No further real consideration can be given to the direct sampling and analysis of air for gasoline vapors as a means to detect pipeline gasoline leaks in a mobile survey. Both the relatively high and variable background and the long analysis time preclude its acceptability. PFTs have already proven themselves in small leak detection and in the presence of a complex atmosphere as exists in the middle of New York City!

Anticipated pipeline mobile surveying leak-detection signals. For a van instrumented with a new-generation CDTA (CLOT column dual-trap analyzer) traveling at 18 mph (115 miles in ~ 6 1/2 hours keeps up with the tagged pipeline batch), an analysis result every 30 seconds represents an integrated distance of 0.15 miles (241 meters). Fourteen days would be needed to survey from Houston to New York.

The worst-case situation for detection is with the wind direction normal to the pipeline; this creates a narrow plume for the van to see. Table 3 provides the equation for estimating the expected measured average trap concentration from the peak centerline maximum concentration (about 2.2% of C_{max}); in this case the signal would be about 2 times the LOD of the CDTA in its 30-second analyses. For gasoline vapors directly, the signal would only be 1.02 times background and therefore not discernible even in 30-min analyses.

For a given PFT signal detected by the van and using estimates of pertinent parameters (e.g., meteorological conditions, tagging level, van speed and location relative to the pipeline, etc.), the relative magnitude of the leak associated with the signal can be estimated.

Once a leak of 1 GPH or larger is detected with the PFTs, the accepted barholing strategy would be implemented for pinpointing the leak location for excavation and repair. Likely, even a simple PID could be used for pinpointing on the gasoline vapors alone; the PFTs were needed strictly for the mobile survey portion.

It should be noted that using similar meteorological dispersion considerations, helicopter leak surveying is not feasible because the plume will not have diffused vertically to any extent at short distances from the pipeline right of way.

PFT Health and Environmental Safety Issues

Issues regarding the safe use of PFTs in atmospheric tracing and commercial leak detection applications have been addressed; a memorandum from 24 November 1992 is available. There are no known biological impacts.

The PFT compounds are fully fluorinated organic alkyl cycloalkanes. They contain only carbon and fluorine atoms, and thus are chemically very stable and biologically extremely inert. They do not affect the stratospheric ozone layer because they do not contain any chlorine atoms. Because the PFTs are so stable, other interfering constituents in air during analyses (for example, freons, oxides of nitrogen, etc., which are present at orders-of-magnitude higher concentrations) are destroyed by a reducing catalyst bed in the presence of hydrogen; only the PFTs survive for subsequent detection.

The pure PFT compounds are clear, slightly viscous (1.5 to 2cP), dense (~1.8g/mL) liquids at room temperature, boiling between 45° to 115°C. The liquids can be ingested with no demonstrated health consequence, and the vapors can be breathed indefinitely at concentrations in the percent range. The pure liquids, continuously purged with air or oxygen, have been used in lung ventilation studies using animals for more than two decades; ultimately, they will provide a better transition from the womb to the outside world for premature babies having difficulty breathing air directly (*New York Times,* Aug. 29, 1989). Since the liquid PFTs have a high solubility for O_2 and CO_2, the fluid can be "breathed" as long as the liquid is purged with air or oxygen. In emulsion form, they have served as blood substitutes in sensitive eye surgery; unlike natural blood, the emulsions cannot clot (New York Times, July 8, 1992). These demonstrations of the use of PFTs as substitute fluids for breathing and as blood substitutes attest to their accepted safety.

Similarly, there are essentially no environmental consequences of PFTs. Their global warming impact is trivial compared to other components currently being emitted commercially. A recent memorandum (13 October 1998) putting these in perspective is available.

Conclusions

Mobile surveying of fuel transport pipeline systems can be performed at about 100 to 120 miles per day using cost-effective and commercially-proven tracer technology.

The cost for tracer material would be less than $1,500 per survey.

A new-generation mobile analyzer will allow leaks of tracer-tagged gasoline to be detected during the surveying. Based on proposed tagging rates, expected subsurface evaporation rates, and usual meteorological conditions, leaks as small as 1 GPH should be seen.

Finally, the description of a proof-of-concept experiment, which would provide the following:

1. Demonstrate the practicality of the approach to Colonial Pipeline Company, and
2. Quantify the magnitude of the tracer emission rate enhancement due to co-evaporation of the leaking gasoline

can be prepared as a draft pre-proposal.

References

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(2) Purnhagen, D., Underground Systems, Inc.—personal communication.

(3) Ghafurian, R., Dietz, R. N., Rodenbaugh, T., Dominguez, J., and Tai, N., Leak Location in Fluid Filled Cables using the PFT Method, IEEE PE-314-PWRD-0-04-1998.

(4) Dietz, R. N. "Equipment for Rapid Cable-Leak Locating and Detecting Capabilities", a proposal, May 1998.

(5) D'Ottavio, T. W., Goodrich, R. W., and Dietz, R. N. Perfluorocarbon measurement using an automated dual-trap analyzer. Environ. Sci. Tech. 20, 100-104, (1986).

(6) Dietz, R. N., "Tracer study of long-range transport in support of the Big Bend National Park regional aerosol and visibility observational study", a proposal, April 1998.

(7) Bernardo-Bricker, et al. Validation of speciated nonmethane hydrocarbon compound data collected during the 1992 Atlanta intensive as part of the Southern Oxidants Study. JAWMA, 45, 591-603 (1995).

Table 1

Example Pipeline Leak Detection Technologies

Who	APS/EFA[1]	ASI[2]	TRC[3]	Brookhaven
Technology:				
Primary	Pressure	Acoustic	Tracer	PFTs
Secondary	Flow rate	Pressure wave	In-ground probes	Van GC
Leak Magnitudes:				
Remote on-line	~0.3% of flow	?	?	na
Above-ground vapor	na[4]	na	?	1 GPH
In-ground vapor	na	na	< 0.1 GPH	« 0.01 GPH
Leak Location	0.5% of length	± 500 ft	± 3 ft	± 3 ft
On-Line	Yes	Yes	No	No
In-Service	Yes	Yes	Yes	Yes

[1] Automation and Pipeline Systems Ltd., Stirlingshire, UK
[2] Acoustic Systems, Inc.
[3] Tracer Research Corp. (http://www.tracerresearch.com/)
[4] na—not applicable

Table 2

PFT-Tagged Vapor Emissions from a Colonial Main Pipeline Leak

Pipeline: Diameter, 4 ft.; Flow Rate, 2.5 x 10^6 GPH; Velocity, 4.8 mph

PFT Tag:
1. Gasoline mainline batch of 29.9 million barrels for 48 hours
   -- travels at 115 miles per day
2. Tag gasoline to 10 ppb by weight
   -- 0.072kg/h @ $400/kg = $29/h
   -- 2-day PFT cost = $1400 for 3.5 kg
3 Tagging fluid (10% PFT in Octane)
   -- 10^{-7} dilution
   -- one 55-gallon drum can tag 550 x 10^6 gallons
   -- 2.5 x 10^6 GPH times 48 h ≡ 120 x 10^6 gallons
   -- one drum would tag 4 batches (4 leak surveys)
   -- metering rate = 0.25 GPH (15.8 mL/min)
   ...against pipeline high pressure head

Leak Rate Emissions
1. Baseline: a 1-GPH leak at a depth of 6 ft to be detectable by van
2. PFT emissions reach steady state in 24 to 36 hours
   -- evaporation of PFT from non-volatile fuel leak
   ...dielectric fluid model estimate of ~ 0.1 nL/min
   -- co-evaporation of 5% of fuel from leak and its PFT
   ...emits PFT at 1.5 nL/min
   ...emits gasoline vapors at 510 mL/min

Maximum Air Conc.:
1. Assume co-evaporation of 5% of leaked gasoline/PFT
   -- to be determined in a proof-of-concept experiment
2. Daytime meteorology: unstable with winds at 5.6 mph
3. Distance from vapor emission location: 8-m downwind
   -- narrow plume (one std dev: $\sigma_y = 2.15$ m)
   -- centerline concentrations (C_{max}):
   ...PFT: 0.73 ppq (≡ 8.3 x background)
   ...Gasoline: 260 ppb (≡ ~1.1 to 2 x background—see text)

Note: ppq: parts per quadrillion or parts per 10^{15}
ppb: parts per billion or parts per 10^9

Table 3

PFT Above-Ground and In-Ground Measured Concentrations
(Baseline: 1 GPH Leak of 10-ppb PFT-tagged gasoline)

Mobile Survey:

1. Van travels at 18 mph
   - -- covers 115 miles in < 6 1/2 hours
   - -- equivalent to 0.15 miles/30 seconds
     - ... $\Delta y = 241$ m per 30-s CDTA analysis
   - -- about 14 days to cover 1600 miles from Houston to New York

2. Worst-case situation: winds normal to pipeline
   - -- $C_{meas} = (2\pi)^{1/2} \sigma_y C_{max}/\Delta_y = 0.0224\ C_{max}$
     - ...C_{meas} (PFT) = 0.016 fL/L
       - ≡ 1.16 x background of 0.1-ppq PFT
       - ≡ ~ 2 x LOD of 30-s CDTA
     - ...C_{meas} (gasoline) = 5.8 ppb
       - ≡ 1.02 x background of 320 ppb
       - (not detectable even in a 30-min analysis scheme)

Pinpoint Barholes:

1. Specifications
   - -- 1-ft deep barhole
     - ... 3-L soil air purge
     - ... 1-L bag filled for analysis
   - -- leak assumed at 6-foot depth

2. Estimated barhole conc. (w/5% gasoline evaporation)
   - -- C_{BH}(PFT) = 1.47 ppb (10^8 x LOD of CDTA)
   - -- C_{BH}(gasoline) = 51% (10^5 x LOD of PID)

Note:

CDTA	--	new generation CLOT dual-trap analyzer
CLOT	--	carbon-layer open-tubular capillary column
PID	--	photoionization detector