Survey Of Technologies Available To Detect Small Leaks On The Trans Alaska Pipeline

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Abstract

The Alyeska Pipeline Service Company (Alyeska) operates the 1290 kilometer-long Trans Alaska Pipeline System (TAPS). Alyeska engaged Caltech's Jet Propulsion Laboratory (JPL), NASA's Center for Exploration of the Solar System Beyond Earth Orbit, to see whether it would be practical to use sensor technologies developed for space exploration to detect any small leaks which might occur along the pipeline. Migration of technology to practical application is important for TAPS to ensure a high level of system integrity.

JPL examined the following major technology areas: remote chemical and thermal sensors, both active and passive; airborne LIDAR (light detection and ranging); ground penetrating radar; *in situ* chemical sensing; and others. Space-based remote sensing does not provide adequate resolution to detect leaks of the small size desired. Similar issues also arose for aircraft-based sensors including ground-penetrating radar.

A simple *in situ* system consisting of mass-produced, single-chip, or very small sensors capable of one-time or multi-use detection of hydrocarbons may be the best future option for a retrofitted leak detection system for TAPS if the technical and economic hurdles can be overcome.

1.0 Introduction

Alyeska Pipeline Service Company (Alyeska) operates a 1290 kilometer pipeline that moves oil from the North Slope of Alaska to a tanker port in Valdez. The pipeline traverses difficult terrain with weather extremes. In addition, the pipeline is located in an environmentally sensitive area. As a result, Alyeska has always been concerned with leak detection

Some facts about the pipeline will help characterize the dimension of the problem facing Alyeska. Of the 1290 kilometer of pipeline, 675 kilometers is above ground while the remainder is below ground at depths of 1-14 meters in soil of varying degrees of natural stability. There are 6 operating pump stations, 151 valves and 36 above ground major stream crossings. Temperature extremes range from 40 °C to -50 °C with snow cover part of the year. Much of the pipeline has reduced sunlight during the year while part of it is in darkness half of the year; this limits any sort of visual inspection or optical remote-sensing.

Alyeska currently relies primarily on the "Transient Line Volume Balance" system to detect any major leak in the pipeline. This system, under stable operating conditions with no "slack" (vapor pockets) in the line, can detect as little as a 100 barrel per hour spill in about 10 minutes or more, which is considered state of the art for volume balance technology.

In addition, for external leak detection, Alyeska relies on trained observers who monitor the line by helicopter. These flights are made about twice per week.

This twice weekly visual surveillance sets the bench mark for any other type of external detection that might be considered. That is, any other system must be more sensitive, more reliable, cost effective, and generally more effective than the trained observer in a helicopter at approximately 500' altitude.

As a back up Alyeska has infrared camera equipment. This equipment is more suited to mapping of verified spills than detection of small leaks, the focus of the current search for new technology.

At time, the US Government has notified Alyeska of anomalous heat patterns near the pipeline without revealing how they were detected, indicating some form of surveillance by someone other than Alyeska. These notifications have been in the spring and when checked, have been water seeps at about the same location caused by melting from the warm pipeline. These incidents have prompted speculation that there may be other technology suitable for Alyeska to use. Alyeska generated a set of leak detection requirements and published a request for proposals (RFP) to commercial vendors and federal government agencies. The requirement advertised was for "off the shelf" (proven) technology that will improve remote sensing crude oil leak detection along the line. Advertised requirements were for leak detection ranges from the surface to 12 meters below the surface, over a variety of terrain and climactic conditions along the entire pipeline corridor. Advertised requirements were that the proposed system(s) be able to detect a 38 liter oil leak and locate it within 90 meters under the following conditions or a combination of these conditions: darkness, on water, in/on/under ice, on/under land, cloud cover, below snow.

We think that the responses are interesting for this conference and will give some general breakdown of the replies that illustrate the difficulties of the desired requirements. Twenty four responses were received, proposing a range of concepts including: ground based sensors, development of sensors incorporating fiber optics as part of the sensor, arrays of conventional single sensors, in pipe sensors using sonic detection principles, aircraft mounted sensors, improvements in sensors (IR, UV, radar, laser fluorosensing) singularly or using enhanced combined imaging in manned aircraft including helicopters, airborne sensors in an unmanned airborne vehicle (UAV) applying recent advances in unmanned aircraft technology, satellite mounted sensors, developments in trace gas sensing.

All of the concepts proposed had limitations and possibilities. None of them would meet the published requirements with proven technology. Some of the responses were basically solicitation for development funding. Alyeska maintains a position as a fast follower of technology, but is not in the business of developing new technologies.

It is also worth noting that none of the responses offered technological breakthroughs; rather the responses were evolution or improvements in existing technologies. For example, fiber-optic based sensors have developed considerably and may be promising for new pipeline installations. UAV aircraft look interesting as sensor platforms. All of the remote sensing solutions were relatively expensive, going up to $18 million net present value (NPV) without providing improvement in sensitivity over present methods, at about $2.4 NPV.

There are some general strategies for leak detection, which can provide a useful technology guide. They are (1) detect the oil itself directly by imaging or visual inspection. (2) detect some physical effect of the oil on the surrounding soil such as heating, detected with thermal imaging or changes in ground penetrating radar reflection coefficients and (3) detect hydrocarbon vapors from the oil leak. For leaks deep underground or under snow cover, detecting hydrocarbon vapors appears to be the only strategy that can hope to detect small leaks. Relevant technologies here are remote techniques such as LIDAR, DIAL (Differential Absorption LIDAR) and spectral imaging or *in situ* sensors and sensor networks.

This breakdown suggested we looked at two major detection approaches- remote sensing and *in situ* instruments. Remote sensing detection would include thermal imaging, active spectral techniques such as LIDAR and DIAL and passive spectral imaging in the thermal infrared (IR) or in the 3-5 μm water window. The spectral technologies will detect the hydrocarbon vapor plume from oil leaks. *In situ* instruments involve sensors that detect hydrocarbon vapors.

2.0 Remote Sensing Detection

Remote sensing instruments are generally of one of two types, active or passive. Passive sensors include thermal IR imaging and some spectral sensors or imagers. Spectral sensors can detect hydrocarbon absorption bands using the sun as an illumination source in the 1-5 μm region and radiation emitted by the target in the 8-14 μm region. Active instruments, such as LIDAR and DIAL, use appropriate wavelength laser sources.

Remote sensing instruments can operate from satellite or airborne platforms. Satellite platforms for a dedicated system would be rather expensive. In addition, satellites may not provide coverage on a timely basis. Depending on the wavelength, cloud cover can affect operation. More importantly, real-time downlink of data is an extra expense for satellite sensors. Fixed wing aircraft or helicopters are most likely a better choice for a sensor platform, with the caveat that a helicopter offers a severe vibration and acoustic environment in which to operate sensors. On the other hand, aircraft are limited by weather, as is the current visual inspection program. This depends on the degree of foul weather and the technique or sensor involved, sensors operating in the microwave (radar) region of the spectral region can "see through" clouds and rain. Maintenance of sophisticated optical or microwave sensors in a remote environment is a significant cost and reliability issue. Either of these approaches offers substantial recurring operational and maintenance costs for the sensor and platform that *in situ* sensors do not.

2.1 Passive Remote-Sensing

Passive thermal imaging from either a satellite or airborne platform would not detect a small leak of the size of the current requirements and also not detect leaks deep underground unless they were very large. As mentioned previously, Alyeska has experience with thermal imaging but it is more useful for mapping verified spills than detecting spills.

Passive spectral detection or imaging is one approach to detection of the hydrocarbon plume released by a leak. Using the sun as an illumination source, a spectral sensor would observe the mid-wave infrared absorption bands of hydrocarbons, the same band used by LIDAR. One could also look in the thermal infrared at a different set of signatures. One advantage of spectral sensors is that they are very specific and relatively immune to background. The detection limits on these is estimated to be ~10-100 PPM/column meter for BTEX. During the Arctic winter, a leak may not generate sufficient vapor pressure to be detected at those limits, so they are not good choices in this setting.

2.2 Active Remote-Sensing

2.2.1 LIDAR

Active spectral detection systems such as LIDAR have been suggested for some time as detectors for oil spills. LIDAR is another spectral technique with high specificity. If one thinks of this as only a spill detector rather than mapper, range gating can be ignored to increase the signal. However, plume dispersion from the weather, and diffusion into a wide area from a point source below-ground, will effect sensitivity. There is no commercial-off-the-shelf (COTS) system available for Alyeska so there are significant development costs and risks that the system, when developed, will not produce the anticipated results. As mentioned previously, this sort of sensor has appreciable operation and maintenance costs.

2.2.2 Ground Penetrating Radar

Ground penetrating radar (GPR) is another remote sensing technology that may be able to detect oil leaks, particularly underground although surface scatter may also be detected. GPR would detect oil by the changes in the backscattered radiation caused by absorption What you are detecting is the change in the amount of backscattered radiation, this can be caused by a variety of circumstances. The technique is not specific to leaking oil, but can alert an observer to a change in the environment near the pipeline. Regardless of the presence of oil, the penetration depth depends very much on the soil moisture content and thus the weather and season; for wet soil, GPR penetration depth is ~ 1 m while for dry clays and sands it can be as large as 30 m. GPR would require frequent over-flights to develop a seasonal scene history to monitor subsequent changes. In addition, it also is a sophisticated instrument requiring high-level maintenance and calibration in the field.

This is not now available with resolution suited for detection of small spills. JPL investigated the possibility of developing a helicopter-mounted unit, but it would require permanent installation in a dedicated aircraft and a development program for the equipment. The practical disadvantage is that a large data gathering effort would be continually necessary with trained experts examining anomalies to interpret the significance. It is anticipated that small leaks may be overlooked, especially in damp soil and that a high incidence of false indications would be encountered. It is anticipated that practical application of this method would be similar to the LIDAR, that is, no significant improvement in precision over the current method of observers with an additional cost of about $12 million NPV.

3.0 *In Situ* Sensors for Detection of Hydrocarbon Plumes

Wherever there is a pipeline leak, there will be hydrocarbon vapors that may be detected. For the pipeline, the *in situ* detection of hydrocarbon plumes from leaks involves a variety of environments and combinations of techniques; hydrocarbons can be detected in the air, the soil, and water. Above ground vapor detection can be used for both leaks in pipes above ground, as well as below ground leaks that have migrated to the surface; this would involve detection of hydrocarbon vapors. Underground detection can involve the monitoring of hydrocarbon vapors in soil, and hydrocarbons in water. Hydrocarbon detection in water can also be used in rivers and streams.

Sensor systems should have low power needs for long-term remote operation. Since the pipeline itself is hot, thermoelectric power generating is a strong possibility. Thermoelectric or solar power can be coupled with trickle charged batteries for power management. Adjusting the sensor read frequency could also reduce power requirements.

Monitoring, using *in situ* sensors, will require some form of communications to transmit sensor data: to track housekeeping data or to alert people in the event of a leak. A spatially distributed set of sensors can be designed to communicate with each other and with central points (e.g. pumping stations). There are several ways that a web of sensors can be integrated. Using advances in RF broadcasting technology, a sensor web can be distributed, with network nodes consisting of sensors and communication chips (Delin and Jackson, 2000). Existing pipeline communication systems that run the length of the pipeline can also support the communications needs of a sensor web and transmit data from the distributed sensors.

A sensor web along the pipeline, continually monitoring for leaks, will provide additional environmental data on the pipeline that didn't exist before. The sensor web provides a synergistic interaction among many separate sensors, which greatly increases the value of the collected data. Besides hydrocarbon sensors, additional sensors can be added to profile local temperature, humidity, and soil conductivity. As a database of environmental information on the pipeline is collected, neural nets can be used to analyze the data The data is first analyzed and then used to teach the neural net, "learn" normal operating conditions, and it may become possible to detect changes in the pipeline before they become major problems.

3.1 Challenges of Vapor Pressure Detection

The environmental monitoring of the pipeline poses several challenges for sensor detection. There are four primary hydrocarbons to monitor for while looking for a leak: benzene, toluene, ethylbenzene, and xylenes (BTEX). For both above and below ground leaks, low Alaskan temperatures and the dispersion/dilution of the hydrocarbons into the environment pose the main challenges.

3.1.1 Above Ground Leaks

In order to detect a leak, there must be a high enough concentration of the vapor to be seen by the sensor. The concentration of hydrocarbon vapors above ground will drop as one moves away from the source of the vapor (above ground leak, seepage from below ground). The farther a sensor is from the leak, the more difficult the leak is to detect. This problem can be made more difficult if the vapors are further diluted by winds. In addition, the vapor pressure of any hydrocarbon drops as the temperature drops (see Table 1).

Table 1. Concentrations of BTEX Vapors in ppm (saturation vapor pressure at 1 atm)

Temp °C	Benzene	Toluene	Ethylbenzene	4-Xylene
35	175,000	21,000	57,900	19,100
10	45,800	5120	1560	4600
0	7560	780	2700	700
-46	800	74.8	310	65.7
-62	160	13.6	62.6	11.8

3.1.2 Below Ground Leaks

Vapor detection of below ground leaks faces additional problems. Until the leak seeps to the surface, the vapor won't be detected. In seeping to the surface, the leak will be dispersed through the ground and snow; this dispersion will increase the area over which vapor could be detected (this could be seen as an advantage if the vapor concentrations are high enough to be detected). When the vapor does reach the surface, it faces the same difficulties of dilution and low temperatures as an above ground leak.

3.2 Facilitating *in situ* BTEX Vapor Detection

It is possible to make a vapor easier to detect, one can either use sensors with increased sensitivity (can also increase path length for optical sensors) or find a way to concentrate the analyte near the detector. Finding more sensitive detectors will only solve half of the problem for the pipeline. Out in an open field, the dilution factors for the vapor from a leak may be so large that unless the leak is right next to the sensor, it will never be detected. It is also possible that even in close proximity, the wind will blow the vapors away from the sensor and the leak will be missed. The closer a sensor can be placed to the leak source, the easier it becomes to detect the vapors. This will be true both above and below ground.

Currently, some of the pipeline above ground is wrapped with insulation and surrounded by a metal sheath. *In situ* detection of pipeline leaks offers many advantages: detection of smaller leaks and containment of small leaks. The air space between the pipeline and the sheath would be protected from the winds, and would be at an ambient temperature much closer to the pipeline temperature. A higher temperature assures that saturated vapor pressures for any leaking hydrocarbons will be 100-1000 times greater than the detection limit for commercially available BTEX sensors, enabling detection of small leaks. This would allow for detection of small leaks. In addition, the operating environment for the detection sensors is a less harsh environment. The value of this advantage is limited, since small leaks in the above ground pipeline are readily observed.

Below-ground placement of sensors, within 1.2 meters of the pipeline, will put the sensors in a less harsh environment, closer to the leak source, and at warmer temperatures. Currently, there is a commercially available sensor with a sensitivity down to 100 ppm for benzene. There are also sensors available for ground water and running water. A below ground sensor array, using fiber optic sensors which are being developed, could be installed for about $70 million or more, assuming power and communications requirements can be furnished by existing facilities. Other sensor arrays would be more expensive because of power and communications requirements for remote installations. There is a risk of damaging the pipe with the extended excavation required to install 611 km of sensor array on both sides of the pipe while the line is pressurized. Additional cost and special arrangements would be required for detection in or under running water. It is not considered practical to retrofit the pipeline with an array of existing or nearly developed buried sensors.

3.3 Available Hydrocarbon Sensors

There are several options for detecting leaks using *in situ* hydrocarbon sensors. There are COTS sensors available for vapor monitoring above ground that have sensitivities to benzene down to 50 ppm, and will operate from –40 °C to +30 °C. Some of these may be functional below ground, with modifications. For underground leak detection, the closer sensors can be placed to the pipeline, the better the chances for early detection will be. These require individual power and communication support, a significant problem in remote sections.

There are also many technologies under development or prototyped that may soon become commercially viable options for implementation into a pipeline sensor web. These include (but are not limited to) an Electronic Nose for monitoring enclosed environments (10 ppm benzene, 15 ppm toluene) (Ryan, et al., 1999), ground water detection of BTEX using fiber optics and evanescent-wave absorption (200 μg/L) (Bürck et al., 1998), chemical indicators on long period gratings (90 ppm toluene) (Goswami et al., 1998), BTEX detection in contaminated soils using LIF and fiber optics (10 μg/L xylene) (Marowsky, 1998). These are not currently available and proven for widespread reliable application for retrofit on existing pipelines. The actual costs for an industrial installation for these technologies cannot be established at this time.

4.0 Conclusion

There is no current and technology that consistently performs better than the existing system of line volume balance combined with human observers. The best potential future option for a retrofitted leak detection system for the pipeline that would provide practical/effective detection of small external leaks is a robust, cost-effective, sensor web. The web would integrates a variety of *in situ* sensors (above-ground, below-ground, in-water) to monitor for BTEX vapors. Such a system is not now available to industry.

5.0 References

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