A Comprehensive Re-evaluation of the Benefits of Pipeline Cover Depth

Michael Rosenfeld[1], Richard Gailing[2], Benjamin Zand[1], Joel Anderson[1]
[1]RSI Pipeline Solutions, [2]Retired

Pipeline Pigging and Integrity Management Conference

February 12-16, 2024

Organized by
Clarion Technical Conferences

https://doi.org/10.52202/072781-0060

https://doi.org/10.52202/072781-0060

Abstract

To reconcile differing requirements for pipeline cover in various standards and regulations, an evaluation was performed of the effect of cover depth and consistency on susceptibility to damage, other threats, risk, cost-benefit, and construction, with some surprising results. Current and historical US and foreign gas and liquids standards and regulations were compared. US and international incident data were analysed to determine the relationship between cover depth and mileage-normalized risk of damage, and risk of other integrity threats such as geohazards and corrosion. FEA was performed to understand how cover depth and trench design affects susceptibility to rock damage. A cost-benefit analysis of increased depth of cover was performed. Sensitivity of transported product (gas vs liquid) to the benefit of cover was determined. Recommendations were made for improved codes content.

Objective

At the request of the ASME Section Committees responsible for maintaining the B31.4 and B31.8 standards, a study was carried out to understand and reconcile, if possible, the differing requirements that have evolved for the cover depth of pipelines. The scope of the project included: review and comparison of the standards to requirements in US pipeline safety regulations, and selected industry standards from other countries; analysis of the relationship between depth of cover and the risk of pipeline failures; review of industry studies of the effects of depth of cover on pipeline safety; a survey of US pipeline operators of cover practices and experience; analysis of the benefit of cover on a pipeline subject to ground surface loads in rock soil; consideration for cover requirements for other crossing configurations; considerations for the transported product; the impact of increased cover on maintenance activities; and consideration of changes in pipeline service.

The study was carried out with funding from ASME Standards Technology, LLC. This paper presents selected findings from the study, which has not yet been made available to the public. The paper will examine:

- Treatment of cover in codes and standards
    - Historical, current, US, and international
- Analysis of incidents data
    - Trends in US and Europe
    - Sensitivity of damage rate to cover and other parameters
    - Impact of service type on consequences
- Impact of cover on vulnerability
    - Encroachment
    - Other threats
    - Treatment in risk models
- Impact of cover on pipeline construction and operation
    - Cost-benefit analysis
    - Role of rock in the ditch
    - Service conversions
- Identified gaps in standards

https://doi.org/10.52202/072781-0060

Treatment of cover in codes and standards

Chronology of US Standards

Design requirements for petroleum and natural gas pipelines were provided in the 1935 ASA B31.1 Tentative Standard, however, the details of installation for buried pipelines were not provided for until the separate publication of pipeline-specific B31 Codes, B31.8 for natural gas (NG) in 1955 and B31.4 for hazardous liquids (HL) in 1959. However, even then the depth of cover was either given only cursory or no attention in early editions. From 1959 until 1965, B31.4 provided no requirements; from 1966 through 1974, B31.4 referred to API Bulletin 1105. From 1955 through 1974, B31.8 only provided a default cover of 24 inches. The current requirements in B31.4 have been stable since 2002, and in B31.8 since 1975. The requirements for differing timeframes is presented in Table 1 for soil cover only. (Rock excavation cover was also reviewed but has been omitted due to space limitations.)

Default minimum cover applies in rural or unpopulated areas requiring normal excavation methods. These regions account for about 75% of the pipeline mileage in the US. The required cover evolved from 18 inches (0.5 m) to the present 24 inches (0.6 m) in B31.8 in 1955 and 36 inches (0.9 m) in B31.4 in 2002. Both standards required less cover in rock, and increased cover in developed areas and at highway and railroad crossings. B31.4 also requires greater cover at watercourse crossings and tilled land. B31.8 recommends greater cover in these areas without specifying a minimum.

Table 1. Evolution of cover requirements in ASME Codes

Standard	Start Yr	End Yr	Location	Cover, in.
API Bulletin 1105	1955	1956	*Normal farmland*	*18*
			Farmland with drain tiles	30
			RR crossing, ditches	36
			RR crossing, rails	54
			Hwy crossing, ditches	24
			Hwy crossing, pavement	48
ASME B31.8 (NG)	1955	1975	*Recommended minimum*	24
	1975	2020	*Class 1, normal soil*	24
			Class 2-3-4, normal soil	30
			RR-Hwy, ditches, normal soil	36
ASME B31.4 (HL)	1959	1966	Not addressed	–
	1966	1974	Ref. API Bulletin 1105	18
	1974	2002	Industrial-Commercial-Residential, soil	36[(a)]
			Watercourse, soil bed	48
			RR-Hwy, ditches, normal soil	36[(b)]
			All other areas, normal soil	30[(c)]
	2002	2020	Cultivated, plowing areas	48
			Industrial-Commercial-Residential, soil	48
			Watercourse, soil bed	48
			RR-Hwy, ditches, normal soil	48
			All other areas, normal soil	36

Notes: (a) 48 inches for LPG; (b) 48 inches for LPG; (c) 36 inches for LPG.

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US regulations

The evolution of cover requirements in US regulations, 49 CFR 192 (NG) and 49 CFR 195 (HL) is presented in Table 2. As with Table 1, separate requirements for rock were reviewed but are omitted here. The default requirement for rural areas in normal excavation is 30 inches (about 0.75 m) in both regulations, compared with 36 inches in B31.4 and 24 inches in B31.8.

Table 2. Evolution of cover requirements in US regulations

Regulation	Start Yr	End Yr	Location	Cover, in.
49 CFR 192 (NG)	1970	1976	*Class 1, normal soil*	*30*
			Class 2-3-4, normal soil	36
			RR-Hwy, ditches, normal soil	36
	1976	2020	*Class 1, normal soil*	*30*
			Class 2-3-4, normal soil	36
			RR-Hwy, ditches, normal soil	36
			Navigable waterway, soil	48
			Offshore d < 12 ft, soil	36
49 CFR 195 (HL)	1970	1981	Industrial-Commercial-Residential, soil	36
			Watercourse > 100 ft wide, soil bed	48
			RR-Hwy, ditches, normal soil	36
			Any other area, normal soil	*30*
	1981	2020	Industrial-Commercial-Residential, soil	36
			Watercourse > 100 ft wide, soil bed	48
			RR-Hwy, ditches, normal soil	36
			Any other area, normal soil	*30*
			Deepwater port safety zone, soil	48
			Offshore, water d < 12 ft, soil	36
	2004	2020	Gulf of Mexico, water d < 15 ft, soil	36
			All other categories, same as 1981-2020	–

Non-US standards

The following non-US standards were reviewed: India PNGRB-TS4:2009; ISO 13623:2009; BS/EN 1416:2003; AUS/NZS 2885.1:2018; and CSA Z662:2019. A side-by-side comparison is difficult because the standards recognize differing location categories. However, similarly to the US, each standard typically requires less cover in areas of rock soil, and greater cover at crossings of highways, railroads, and watercourses, across tilled land, and in populated areas. As a generalization, the non-US standards require somewhat greater cover than the US standards at most types of crossings, particularly for natural gas.

Analysis of incidents data

US incident data

The rate of excavator damage incidents in the US began to decline in the mid-1980s for NG distribution, NG transmission, and HL transmission in terms of absolute incident count. All incident counts were also declining for NG distribution and NG transmission, while they were steady or even jumping upward in HL transmission due to changes in reporting criteria (higher cost thresholds but

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smaller release thresholds) and integrity management programs. Thus, the proportion of all incidents due to excavator damage remained steady on average (overlooking large year-to-year swings) for NG service but declined for HL service. These trends are shown in Figure 1.[1]

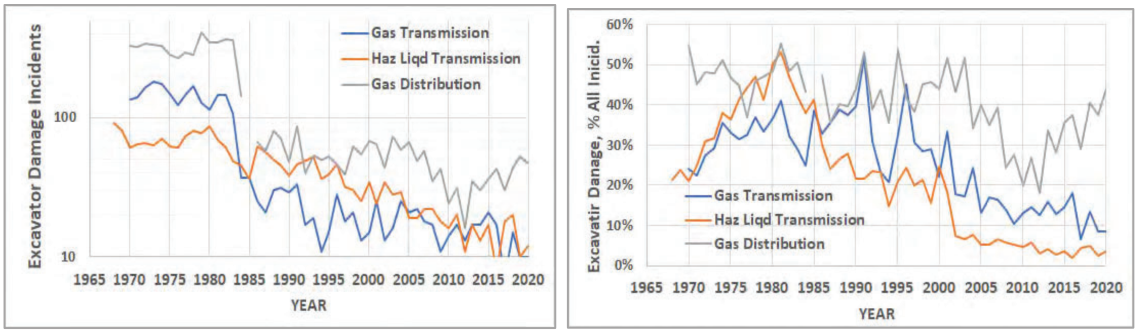

Figure 1. US excavator damage incident trends, damage incidents (left) and proportion of all incidents (right)

Figure 2 shows that the rate of excavator damage incidents declined to levels consistently fewer than corrosion incidents starting around 1995 for HL service and 2000 for NG service.

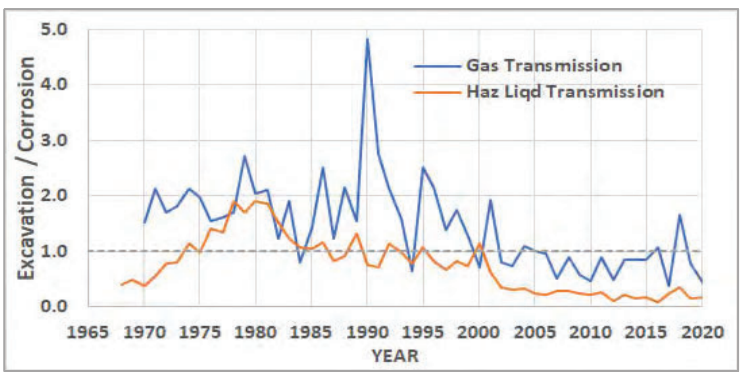

Figure 2. Ratio of excavation damage incidents to corrosion incidents

A reasonable question is: what drove these trends—cover requirements or something else? Figure 3 shows year-by-year and 5-year-average smoothed trends with relevant revisions in ASME Codes and US regulations. New requirements for cover depth are shown in green, new requirements for damage prevention programs are shown in red, and changes in incident reporting thresholds are shown in black.

It is impossible to point to a single specific event in regulations or standards as definitively causal. Evidence for increased minimum soil cover in new construction as causal to overall reduced damage incident rates is weak, but a regulatory requirement for NG operators to develop damage prevention programs in 1982 appears to have been influential. By the time the excavator notification ("one-call") systems were mandated in all US states in 1990, and damage prevention programs for HL service was established in 1995, incident rates had already dropped significantly for both NG and HL services. Contributing factors could have been the previously mentioned requirement for damage prevention programs for NG pipelines, that 39 states had already initiated excavator notification systems, as well

[1] https://www.phmsa.dot.gov/data-and-statistics/pipeline/data-and-statistics-overview. Note that data for gas distribution systems in 1985 were unavailable.

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as operator awareness through experience sharing at conferences and industry-sponsored damage incident tracking initiatives.[2]

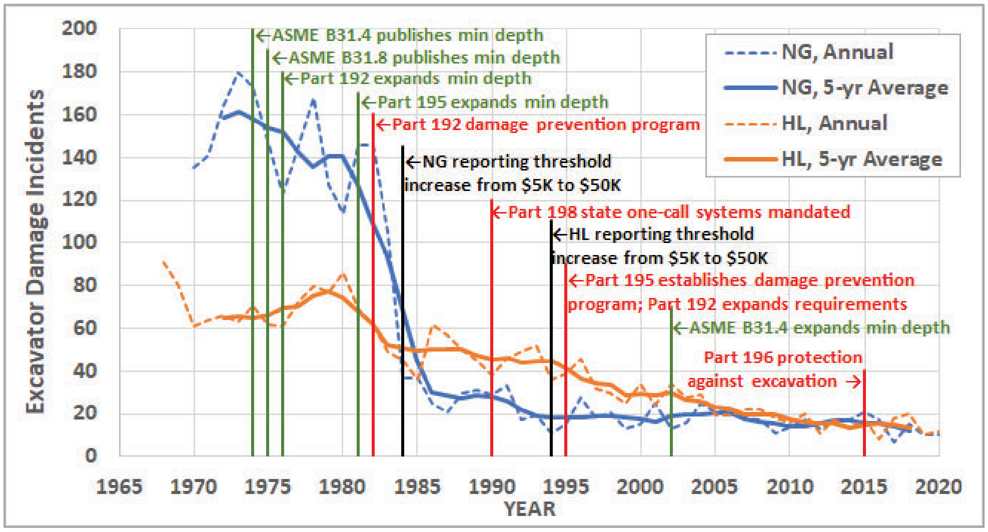

Figure 3. Excavator damage trends with codes and standards revisions

Non-US incident data

Excavator damage incidents and incidents due to all causes have been compiled for the European NG and petroleum industries in annual review studies by EGIG[3] and CONCAWE[4], respectively. Those studies show a decline in excavator damage from the late 1980s over the following 10 years, along with a decrease in incidents due to other causes, Figure 4. The studies did not credit increased cover for these changes but there could be several explanations for the lack of supporting evidence in favor of greater cover, such as: (a) more cover does not really decrease the chance that much; (b) operators had more cover depth where the risk was higher and lower cover depth where the risk was lower; or (c) cover depth requirements in older standards was too low so most operators used greater cover depth than the minimum requirements

[2] Examples include the Common Ground Alliance (CGA) Damage Information Reporting Tool (DIRT), and the American Petroleum Institute (API) Pipeline Performance Tracking System (PPTS). Each program produced annual compilation reports.

[3] European Gas Pipeline Incident Data Group (EGIG), "Gas Pipeline Incidents", 9th Report (period 1970-2013), EGIG 14.R.0403, February 2015; 10th Report (period 1970-2016), VA 17.R.0395, March 2018; 11th Report (period 1970-2019), VA 20.0432, December 2020.

[4] CONCAWE, "Performance of European Cross-Country Oil Pipelines", Report No. 12/20, July 2020.

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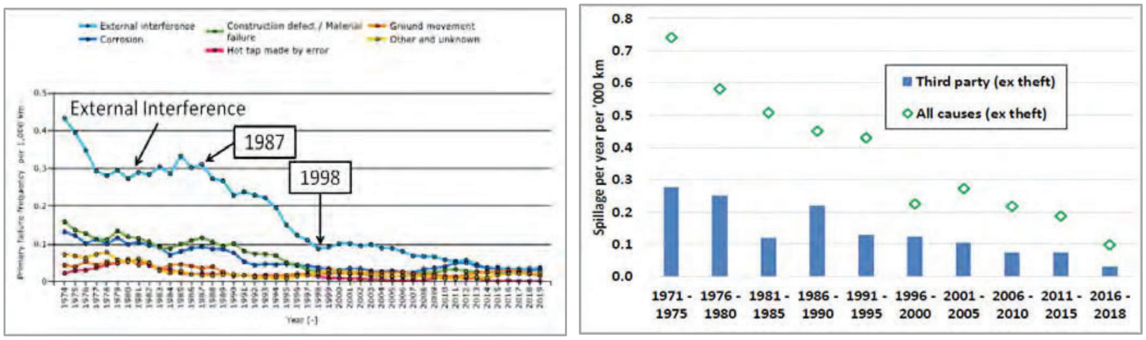

Figure 4. EGIG (left) and CONCAWE (right) excavator damage trends

Influence of pipe size on damage trends

Pipe attributes (e.g., pipe size or grade) do not affect whether a pipeline is struck by an excavator, but may influence whether the damage event results in a reportable failure incident. The 2019 11th EGIG and 2020 CONCAWE data compilations confirm these trends with respect to pipe diameter and wall thickness. A probabilistic study[5] showed lower likelihood of puncture with increasing wall thickness and increasing strength, validated by EGIG incident data.

The distribution of pipe sizes in US natural gas and hazardous liquid transmission pipelines is shown in Figure 5 as reported by operators in their 2019 annual reports to DOT. HL pipelines tend to be smaller in diameter than NG pipelines. Thinner pipe wall is generally associated with smaller pipe diameters. Actual wall thickness can vary greatly along a pipeline, so it is not a parameter reported to DOT in the operator annual reports. As a rough generality, D/t varies somewhat linearly from around 30 for small pipe sizes to around 90 for large pipe sizes as typical values. Figure 5 presents an estimate of the quantity of pipe installed with typical wall dimensions extrapolated from the pipe diameters divided by the typical D/t values. The distribution of estimated wall thickness mirrors the distribution of reported pipe diameters in Figure 5.

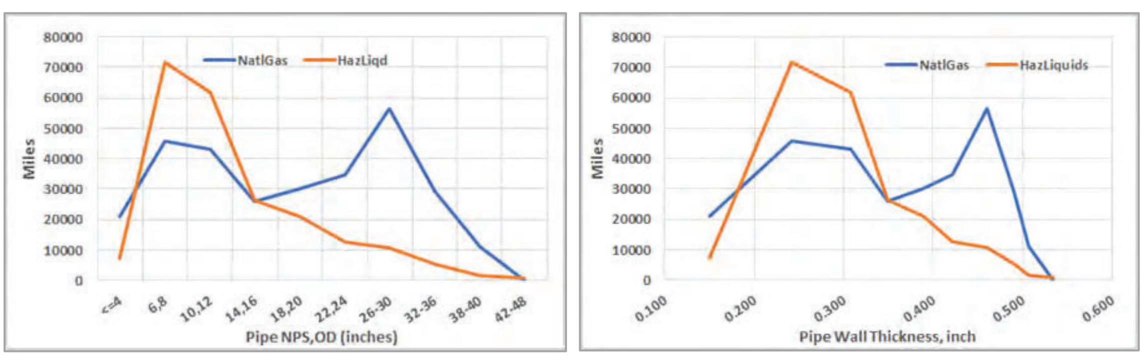

Figure 5. Distribution of reported US pipeline diameters (left) and estimated US pipeline wall thicknesses (right)

The distribution of incidents due to encroachment damage, external loads due to natural events, and corrosion by pipe diameters is presented in Figure 6. Corrosion was included because it is an important threat, and it might not be influenced by pipe attributes. If the proportion of incidents

[5] Chen, Q., and Nessim, M., "Reliability-based Prevention of Mechanical Damage to Pipelines" C-FER Report to PRCI, Project PR-244-9729, Cat. No. L51816, August 1999.

reasonably matches the proportion of mileage of a given pipe size category there is no apparent effect of diameter on vulnerability to the threat. A higher or lower incident rate than the proportion of mileage indicates an apparent detrimental or beneficial effect, respectively, associated with diameter. HL pipelines exhibit greater vulnerability to all three threat categories in small pipe and less vulnerability in large pipe with a crossover at NPS 12. NG pipelines exhibit exaggerated effects of small or large diameter on vulnerabilities, compare with HL pipelines. Diameter may not be a directly causal factor; the explanation for these trends and relative differences may involve several factors including pipe flexibility, wall thickness, buoyancy, location classes, hydraulic gradients, and capability for being in-line inspected, among others.

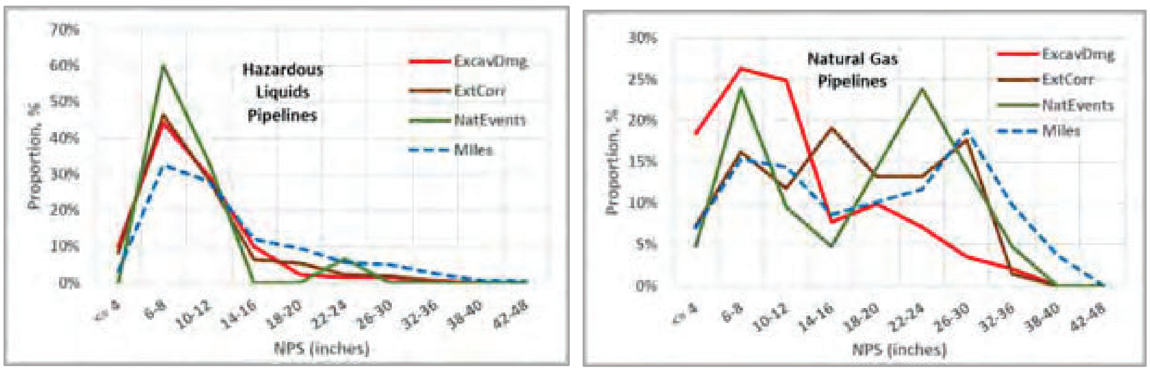

Figure 6. Distribution of incidents by pipe diameter for HL pipelines (left) and NG pipelines (right)

The distribution of incidents due to encroachment, natural events, external corrosion across wall thickness are shown in Figure 7. The vulnerability appears to be disproportionately greater where wall thickness is less than approximately 0.35 inch (8.9 mm), and disproportionately less for heavier wall pipe. The trend of damage incidents in US pipelines with respect to wall thickness is not unlike what was observed for European natural gas pipelines. The trends seem to confirm that wall thickness is a significant factor in the vulnerability of pipe to failure from damage.

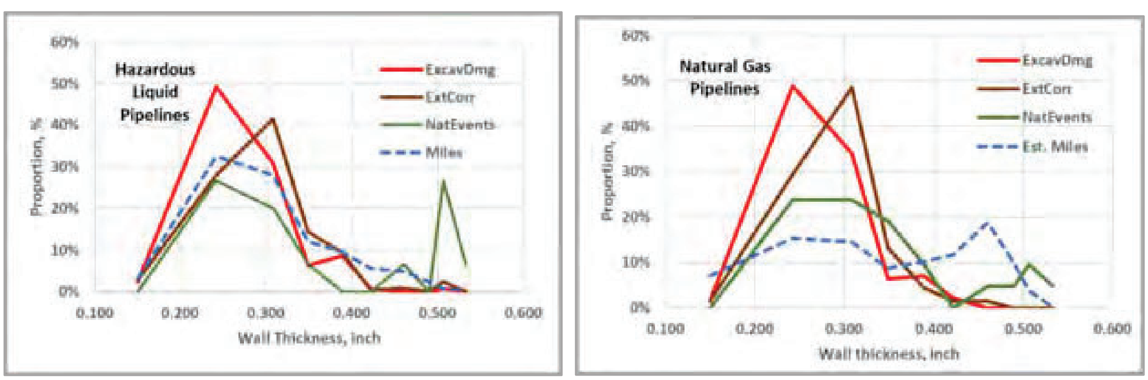

Figure 7. Distribution of incidents by pipe wall thickness for HL pipelines (left) and NG pipelines (right)

The above data suggest that pipe smaller than NPS 12 or having wall thinner than 0.35 inches is more vulnerable to damage from encroachment as well as external forces due to natural events. If increased soil cover over a pipeline improves protection against these threats, could it make sense to specify greater cover over small-size pipe? Whether soil cover does provide the expected benefit will be examined in the next section.

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Influence of depth of cover – European experience

Logic suggests that if pipelines are damaged by excavation from above, greater amounts of soil over the pipeline provides greater protection by reducing the likelihood of the pipe being struck in routine shallow excavation activity. Several studies report this effect to varying degrees:

- Mather, et al[6] reported that for cover from 0.8-1.0 m (30 to 40 inches), failure frequencies per 1000 km-yr dropped to 31% of the failure rate for cover less than 0.8 m (30 inches); and for cover greater than 1.0 m (40 inches), the failure rate dropped to 12% of the failure rate for cover less than 0.8m (30 inches).
- Knight and Grieve[7] concluded that increasing cover beyond 3 ft appeared to have little effect on the susceptibility of pipelines to external interference.
- Neville[8] determined that increasing cover from 3 ft to 4 ft reduced the encroachment incident rate by 38%, while increasing the depth of cover to 5.25 ft reduced the incident rate by 68% compared to 3 ft of cover.
- Fearnehough and Corder[9] determined that 50% of the damage was concentrated in 30% of pipelines with cover less than 1.05 m (41 inches); increasing the cover from 1.1 m (43 inches) to 2 m (80 inches) reduced the encroachment damage failure rate by a factor of 6.
- Fearnehough, G.D. and Corder, I., "The Effect of Pipeline Depth of Cover on Mechanical Interference", BG Transco R.4132, 1989.

These studies are now 25 to 50 years old based on data from a time when incident rates were much higher than they are today, and predate modern damage prevention techniques. They might pertain to a pipeline system operating today in areas that lack the institutional structures needed to support an effective excavator notification program.

A slightly more recent study by Jager, et al[10] analyzed encroachment damage incident data for two natural gas pipeline systems in the Netherlands. The two systems were classified as "Suburban" and "Rural". Their analysis showed a strong overall decrease in normalized frequency of pipeline hits with increasing depth of cover, Figure 8. Note that the frequency levelled off in the suburban locations (blue dashed line, added for clarity) and rebounded in the rural locations for depths greater than 1.5 m (green dashed line, added for clarity).

[6] Mather, J., Blackmore, C., Petrie, A., and Treves, C., "An Assessment of Measures in Use for Gas Pipelines to Mitigate Against Damage Caused by Third Party Activity", HSE Report 372/2001.
[7] Grieve, B. and Knight, R.C.A., "Influence of Depth of Cover on Incidents on High Pressure gas Transmission Pipelines", BG Transco, R0637, 1974.
[8] Neville, D., "Hazard Analysis of the Transmission System, Part 4, Influence of Depth of Cover on the Incidence of External Force", BG Transco, R.2308, 1981.
[9] Fearnehough, G.D. and Corder, I., "The Effect of Pipeline Depth of Cover on Mechanical Interference", BG Transco R.4132, 1989.
[10] Jager, E., Kuik, R., Stallenberg, G., and Zanting, J. "The Influence of Land Use and Depth of Cover on the Failure Rate of Gas Transmission Pipelines", IPC2002-27158, 2002.

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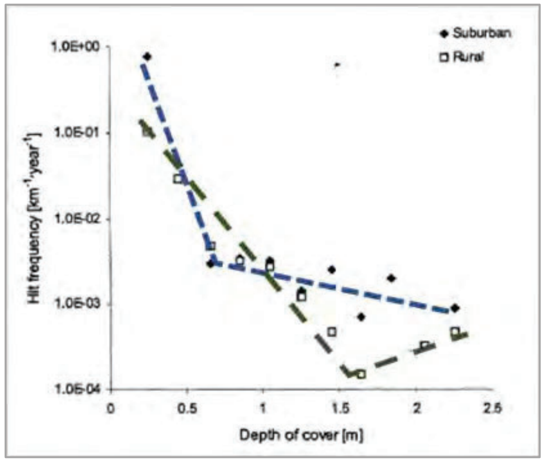

Figure 8. Observed encroachment damage frequency vs depth (from Jager, et al)

Influence of depth of cover – US experience

In 1996, Golub, et al[11] analyzed the DOT incident database. As with some of the European data analyses cited earlier, the Golub analysis is a bit dated as it was performed before many present US regulations were in place, but it is still informative. For the reporting period of 1970-1993, "outside force" (encroachment) was the most frequent cause of failure, and inadequate depth of cover was identified as a primary factor in those incidents.

The distribution of incidents due to four causal categories is shown in Figure 9 (left), with respect to depth of cover for incidents reported between 1970 and 1981. The profile of incidents that inherently have low dependence, if any, on cover such as corrosion or construction and materials defects, appear to reflect the relative mileages at depth, peaking in the cover range of 30-36 inches. Where cover exceeded 42 inches, external force damage was not worse than corrosion. External force incidents become increasingly dominant as cover decreased below 30 inches. When viewed as a proportion of incidents of all causes, Figure 9 (right), it is apparent that outside force is the dominant cause where the cover depth is below 24 inches. There is a slight rebound where depth exceeds the 48-54 inch category.

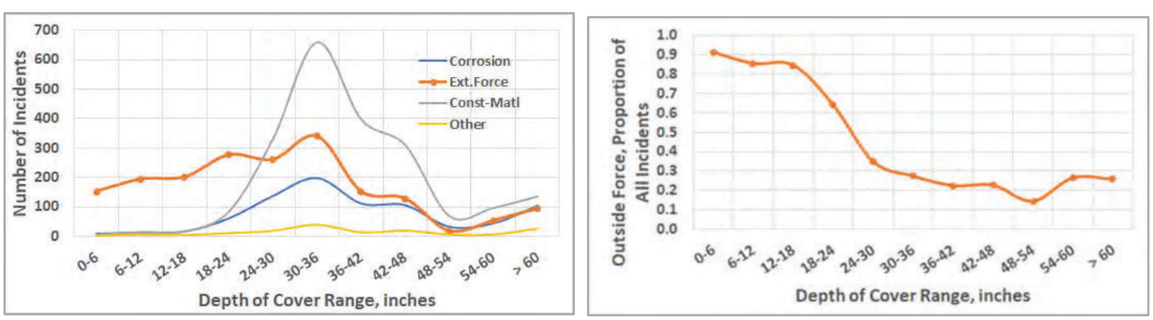

Figure 9. Distribution of incidents by cause (left) and proportion of outside force incidents (right) by depth, 1970-1981 (from Golub, et al)

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[11] Golub, E., Greenfeld, J., Dresnack, R., Griffis, F.H., and Pingataro, L.J., "Pipeline Accident Effects fo Natural Gas Transmission Pipelines", NJIT Report to US Department of Transportation, #DTRS 56-94-C-0006, August 1996.

https://doi.org/10.52202/072781-0060

The data from Golub, et al reveals a definite trend of earlier installation years associated with shallow cover regardless of the cause of failure, shown in Figure 10. The likely shallower depth of initial installation with older vintage pipelines has been noted in one industry analysis of the significance of pipeline vintage to the integrity of petroleum pipelines.[12]

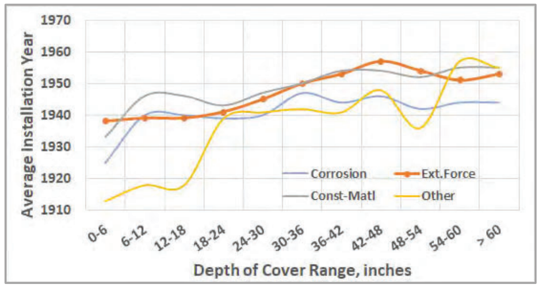

Figure 10. Distribution of installation year vs depth, 1970-1981 (from Golub, et al)

The American Petroleum Institute (API) provides a forum for periodic reviews of hazardous liquid pipeline reportable incident data through the Pipeline Performance Tracking System (PPTS). The PPTS participants operate approximately 85% of the regulated HL pipeline mileage in the US. PPTS-2[13] focuses on "Third Party" incidents involving farming, agricultural businesses, and homeowners. These causative actors are grouped together because they are not traditional "excavators" and therefore require more targeted prevention strategies. As a group they accounted for 35% of the damage events in the 8-year sample period from 1999-2006. PPTS-3[14] focuses on incidents affecting belowground assets of which operators are required by state law to participate in One-Call programs. Typical One-Call partners include pipeline operators and utilities. As a group they accounted for 27% of the damage events in the 8-year sample period from 1999-2006.

Both documents reported incident counts as a function of depth of cover. The data are presented in Figure 11 as the proportion of PPTS-2 and PPTS-3 incidents attributed to specific activities, and where the depth of cover was known. The results indicate a trend of decreasing incidents with increasing depth of cover for agricultural activity. The trend is of increasing incident occurrences with increasing depth of cover for drilling and boring activities that generally occur at greater depths. The trend for trenching, grading, and backfilling, i.e., general construction activity, peaks in the 16- to 36-inch depth range, probably reflecting the combined prevalence of pipelines with 24 to 36 inches of cover and the prevailing surface and general construction excavation work in that range.

[12] Kiefner, J.F., and Trench, C.J., "Oil Pipeline Characteristics and Risk Factors: Illustrations from the Decade of Construction", API, December 2001.
[13] API, Pipeline Performance Tracking System, "PPTS Operator Advisory: Landowner/Tenant Activity Impact on Third Party Damage", PPTS Advisory 2009-2.
[14] API, Pipeline Performance Tracking System, "PPTS Operator Advisory: The Role of One-Call partner Activity on Third Party Excavation Damage Incidents", PPTS Advisory 2009-3.

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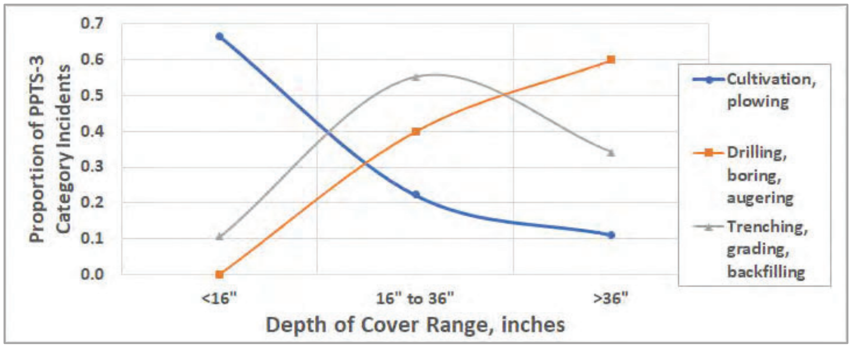

Figure 11. US petroleum pipeline encroachment damage incidents, 1999-2006

Incident data for onshore hazardous liquids and natural gas pipelines in the US and reportable to DOT from 2002 to the 2021 were reviewed for this study. The data were screened for failures due to:

- Excavation damage caused by a First, Second, or Third Party, or prior damage
- Damage by motorized vehicles or equipment
- Natural events including rains, floods, earth movement
- Nearby industrial or other fire or explosions
- Damage by boats, barges, other unmoored vessels, or fishing
- Other outside force damage, or vandalism

These were grouped as excavation damage, natural force damage, and other outside force damage, and were then classified by depth of cover ranges, as shown in Figure 12 (left).

The reported incidents were classified by decade of installation and depth of cover range. Pre-1940 and Unknown vintages were combined (understanding that later installations may be encompassed). Similarly, all post-1969 installations were grouped as essentially "modern" in character.[15] Results are presented in Figure 12 (right).

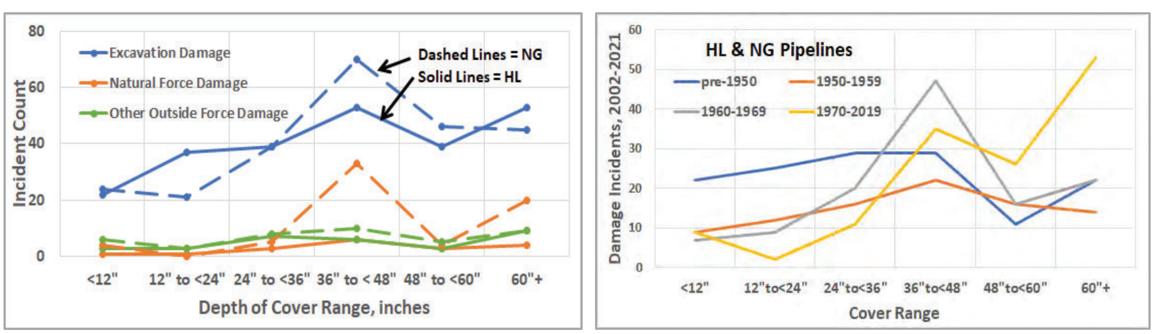

Figure 12. US pipeline incidents 2002-2021, causal classification vs cover (left), and damage incidents by era of installation (right)

[15] One could further establish a break between 1970-1989 and 1990-2020. There were more incidents in the 1970s vintage lines, and incidents below 24 inches of cover in post-1990 pipelines were quite rare. On the other hand, 1970 established minimum cover requirements in US regulations and 1970 is a common demarcation between modern and vintage pipelines.

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The following observations were made from the data in Figure 12:

1. There is little difference between NG and HL pipelines in terms of sensitivity to damage causal category.
2. Excavation activity in its various forms is the predominant cause of damage incidents.
3. Susceptibility to non-excavation damage is not very sensitive to depth of cover.
4. The incident count due to excavation damage peaks in the 36-48 inch range, most likely due to the prevalent mileage of pipelines installed at that depth.
5. The occurrence of damage differs with era of installation, particularly with respect to occurrences at low or high amounts of cover.

Without a normalizing basis by mileage, the incident trends in Figure 12 suggest that increasing the depth of cover increases susceptibility, which is not in line with most other studies. The operator annual reports to DOT give mileage of pipelines by various attributes useful for evaluating risk, but mileage by depth of cover is unavailable because (a) most pipeline operators cannot easily provide this data for existing systems, (b) it would be highly variable if it was known, and (c) it can vary over time due to natural and artificial causes.

Therefore, an attempt was made to normalize the data using synthesized depth distributions by mileage for decades of installation, considering that: (a) prior to the decade of the 1950s, there was no standard guidance; (b) during the 1950s and the 1960s the guidance for cover was 24 inches for NG pipelines and 18 inches for HL pipelines except at crossings or in other special locations; (c) since 1970, regulations specified a minimum cover of 30 inches for both NG pipelines in Location Class 1 and HL pipelines in “Any Other Locations”. The 30-inch minimum falls in the 24-inch to 36-inch range bin and is thought to represent 75% of the aggregate mileages in both NG and HL pipelines, extrapolated from NG pipeline operator annual reports of mileage by location class. The assumed proportional distributions of mileage by cover depth for each decade of installation are shown in Figure 13 (left). They were multiplied by reported mileage within each decade averaged over the past 10 years to obtain the postulated distributions of mileage and cover in Figure 13 (right). This suggests that the peak depth of cover shifted from the 24-36 inch range for pre-1970 pipelines to the 36-48 inch range for post-1969 pipelines.

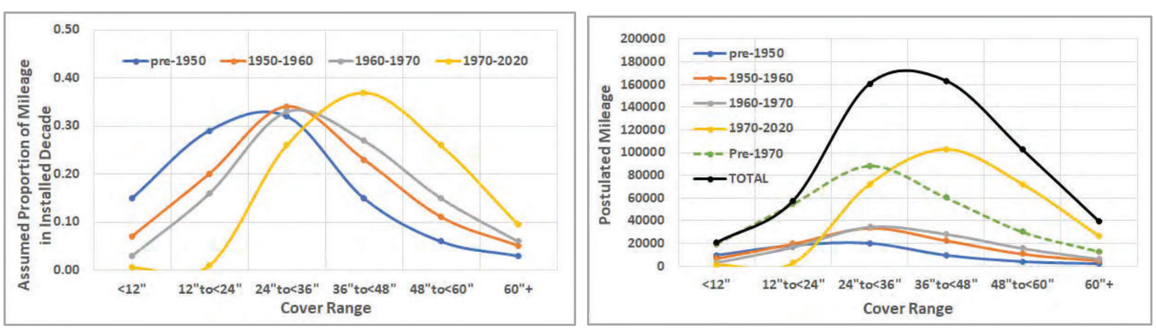

Figure 13. Assumed distribution of cover (left) and postulated aggregate mileage (right) by installed decade

The composite distribution for the mileage-weighted total was compared against the distribution of cover reported in actual incidents (1,070 of 1,477 incidents affecting buried HL pipelines, and 555 of 634 incidents affecting buried NG transmission pipelines). The composite cover profile is a good representation of the actual incidental cover profiles within 5%, except for depths of cover exceeding 72 inches. The estimated number of damage incidents by installed decade were considered with postulated distributions of cover presented in Figure 13 to obtain estimated incident rates per mile per year, shown by installed decade groups in Figure 14 (left). The results are recast as pre-1970, post-1969, and a mileage-weighted average for all vintages (right).

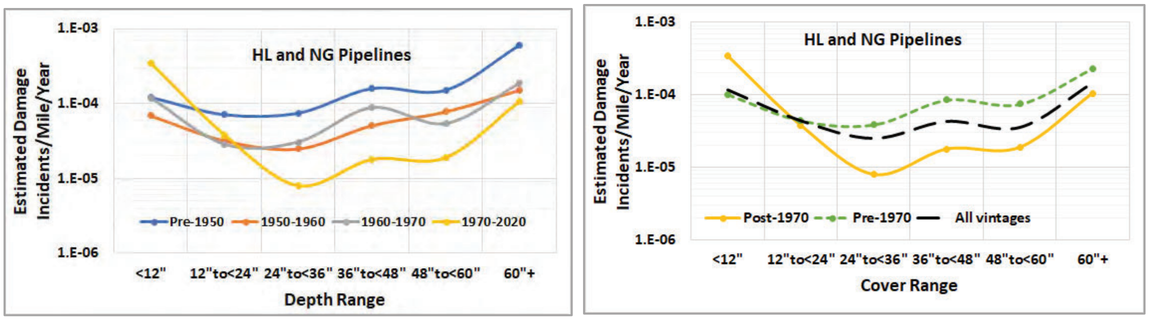

Figure 14. Estimated damage incidents per mile per year for US transmission pipelines vs cover, by installed decades (left), and overall (right)

The incident rates are highest for pre-1950 pipelines, lowest for post-1969 pipelines, and intermediate between those rates for 1950s and 1960s vintage pipelines. The distribution by amount of cover is hammock-shaped: highest for low amounts of cover and for significant depths of cover. The incident rates vary over only a small range between 24 inches and 48 inches of cover, reflecting the prevalence of mileage at these levels. The reasons for high damage rates with very shallow cover are obvious. The reasons for high damage with deep cover are less obvious but are suggested by the PPTS data shown in Figure 11. Although greater cover increases protection against normal excavation, it can be adverse in two ways: it makes it harder to locate the pipeline with confidence, and the pipe is more vulnerable to construction activities that occur at greater depths in the soil such as boring, drilling, augering, or piledriving. (Pipe buried at normal depths is also vulnerable to piledriving, but that form of damage is a smaller proportion of damage causes at normal depth.)

The DOT data were also reviewed for damage incidents that occurred at crossings of any type – highway, railroad, and streams or rivers. The crossings incident count in the sample period, aggregated for both hazardous liquid and natural gas transmission pipelines, is shown in Figure 15 (left). The effective damage incident rate per pipeline mile per year was estimated considering the 544,960 aggregated miles of transmission pipeline over the 19-year reporting period, and further considering that perhaps 2% of the pipeline mileage lies within designated crossing corridors.[16] This results in the estimated damage incident rate per pipeline mile per year at crossings shown in Figure 15 (right). The incident rate exhibits a hammock-shaped distribution with a minimum in the 36-48 inch range, and higher rates at the low and high amounts of cover.

[16] Nanney, S., PHMSA presentation to NACE ECDA Seminar, J.W. Marriott Hotel, January 26. 2009.

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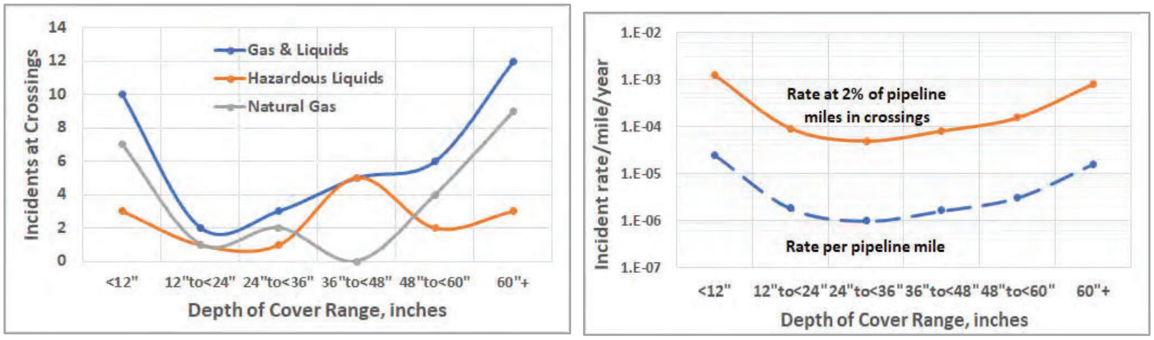

Figure 15. Crossings damage incidents count (left) and incidents rate (right)

Impact of service type on damage incident consequences

The prior analyses have noted that pipelines smaller than NPS 12 or with wall thinner than 0.35 inch more vulnerable to damage, and that such pipelines are more prevalent in HL pipelines than in NG pipelines. Yet, when it comes to actual incident rates, HL and NG pipelines do not necessarily exhibit widely divergent normalized damage incident rates. A related question is whether damage incidents in the two product categories differ significantly in terms of consequences or public risk. There are two ways to compare the influence of the transported product on consequences: physical effects of a release, and incident cost.

The proportion of encroachment incidents involving HL or NG pipelines and that caused a fire or explosion, or injuries or fatalities, were compared in Table 3. Encroachment damage incidents involving natural gas pipelines are approximately twice as hazardous as those that involve hazardous liquids pipelines. This may be due to either the release of stored energy from the compressed gas, or the lower spark ignition energy of natural gas compared with some commonly transported liquids (e.g., crude oil, kerosene, or gasoline, but not ethane, butane, propane).

Table 3. Influence of transported commodity on consequences of encroachment damage incidents, US, 2010-2021

	HL	NG
Count	153	149
Incidents involving fire or explosion	8	14
Incidents involving fatality or injury	3	6
Number of fatalities	4	6
Number of injuries	9	19

The release of a hazardous liquid due to encroachment damage will almost certainly require a cleanup response including removal of contaminated soil, management of product movement in drainage paths, deployment of booms on surface waters, installation of wells to monitor long-term transport of underground plumes, closure of public water supply intakes, compensation to farmers for crop loss, and special care for affected waterfowl or other species, depending on the location and circumstances of the spill. If the spill results in a fire, residues from firefighting chemicals may also require cleanup. Natural gas is not considered a pollutant when released from a pipeline. However, if the released gas ignites, residues from firefighting chemicals may require cleanup as with a spill.

The adjusted current costs (USD) of encroachment damage incidents from 2010-2021 in HL and NG pipelines are compared in Figure 16, with specific metrics listed in Table 3. Encroachment accidents involving hazardous liquids pipelines tend to cost more than those involving natural gas pipelines. This is likely due to the cost of the environmental cleanup associated with a product release.[17] The higher consequences of damage incidents in HL pipelines may provide some incentive to increase cover, it that is deemed to be an effective preventive measure.

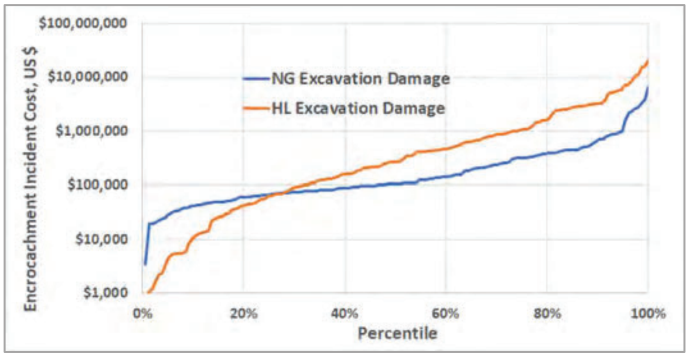

Figure 16. Percentile distribution of excavation damage incident costs, 2010-2021

Table 3. Excavation damage incident costs, US HL and NG pipelines, 2010-2021

	HL	NG
Count	153	157
Median	$270,939	$107,847
75th Percentile	$1,100,275	$317,339
90th Percentile	$3,212,518	$703,472
95th Percentile	$5,804,304	$1,009,737
Maximum	$20,149,830	$6,397,779

Excavator damage in HL pipelines tend to cost double those at the same percentile of all underground HL failures, but are about half those at the same percentile of major incidents that involve injury or fatality. Excavator damage in NG pipelines tend to cost about half those at the same percentile of all underground HL failures, and about one-tenth of those at the same percentile of major incidents that involve injury or fatality.

Impact of cover on risk

How cover affects vulnerability to encroachment and other integrity threats

The amount of soil cover could influence the vulnerability of a pipe to encroachment, and to other integrity threats. The US DOT reportable incident data from 2010-2021 were reviewed to identify tendencies for cover to, favorably or unfavorably, influence the occurrence of incidents due to broad causal categories.

[17] Regardless of cause, costs presented reflect what was reported by operators in their initial or updated incident reports to PHMSA. The amount of gas or liquid released, cost of product loss, property damage, and environmental cleanup can often be approximately estimated soon after an incident or during the ensuing response. Other costs such as regulatory fines, litigation, or plaintiff awards may not be finalized until years later and often are strictly confidential. These likely are not reflected in the reported costs.

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The cumulative distributions associated with various incident causes are shown in Figure 17 with HL pipelines on the left and NG pipelines on the right. The influence of cover was evaluated by comparing the cumulative distribution of incidents by integrity threat or cause to a baseline consisting of the cumulative distribution of all incidents where the amount of cover was reported. The baseline is indicated as the black dashed line. Where there was no effect of cover, the integrity-threat incidents distribution aligned closely with the baseline. Where the integrity-threats distribution lies above or to the left of the baseline, risk is increased with less cover; where the integrity-threats distribution lies below or to the right of the baseline, risk is increased with greater cover.

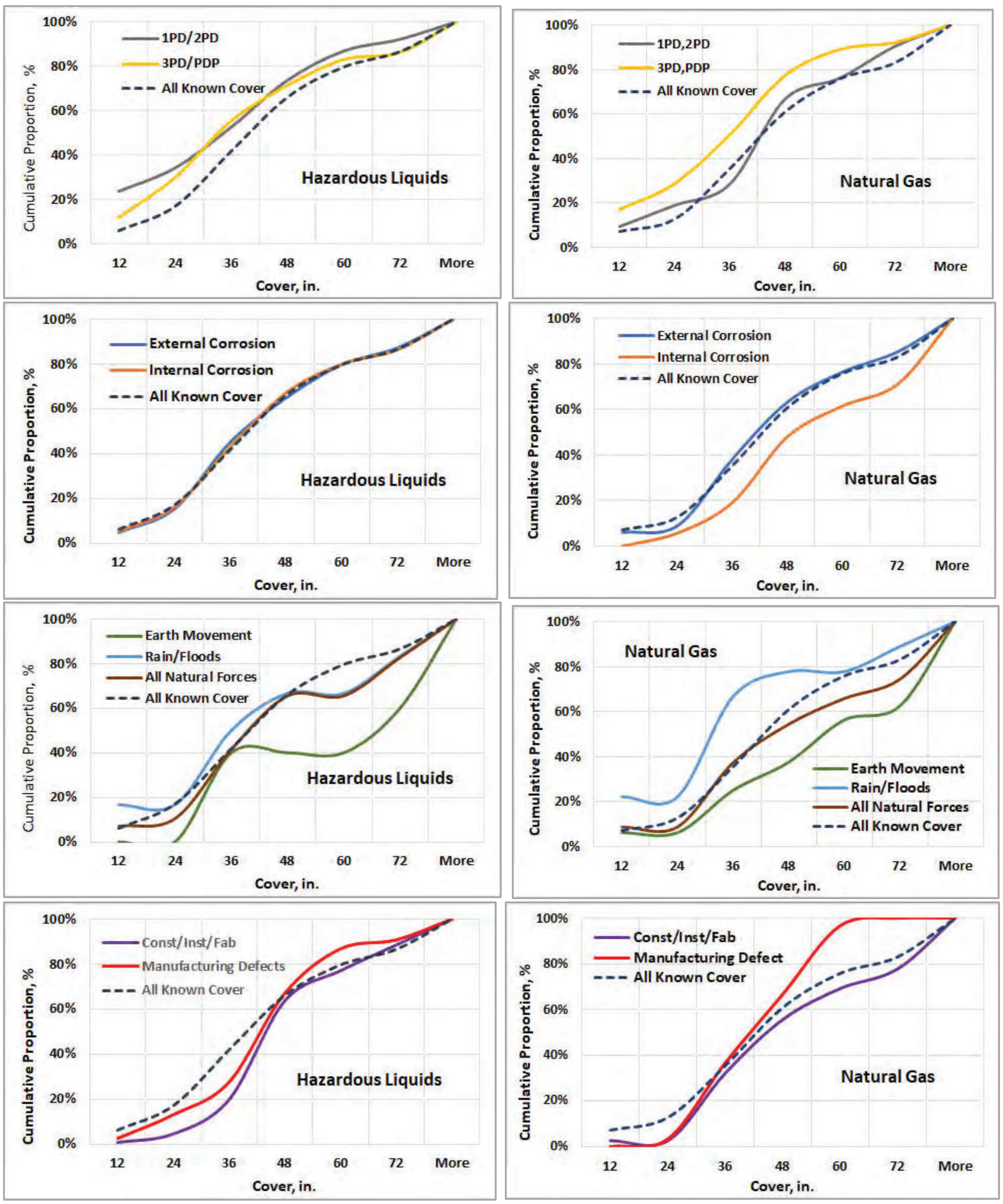

Figure 17. Effect of Cover on Integrity Threats

Some observations are summarized below.

- First/second/third party damage and previously damaged pipe – Shallow cover generally increases risk.
- External corrosion – Cover had no effect on vulnerability to external corrosion, despite increased potential for coating damage due to soil pressure with greater depth, or the reduced ability of DCVG to detect coating damage with greater depth.
- Internal corrosion – Increased cover was associated with increased susceptibility to internal corrosion in natural gas pipelines. This is thought to be due to sag bends that may hold up water associated with greater soil cover.
- Heavy rains/floods – Shallow cover increased vulnerability to heavy rains and floods. The effect was stronger for natural gas pipelines than hazardous liquid pipelines, perhaps due to buoyancy effects.
- Earth movement and other natural forces – Greater cover appeared to increase risk from earth movement and other natural forces in both liquids and natural gas pipelines. This was unexpected because greater cover was thought to improve the chances that a pipe would be installed below hazard boundaries such as the frost line, the slip plane of an unstable slope, or the scour depth of a watercourse. It is possible that shallower cover may promote shear failure in the soil as it interacts with the pipe, reducing friction or bearing loadings acting on the pipe.
- Construction and installation defects – Shallow cover was somewhat beneficial, suggesting that shallower trenches could promote better workmanship or inspection during construction.
- Manufacturing defects – The observed pattern for manufacturing defects represents a distribution wherein the actual occurrences are below the baseline at very low or very high amounts of cover but exceed the baseline in the middle depth ranges. This probably reflects the dominance of the 1950s and 1960s decades of installation in the US pipeline network. It was noted that one operator's data showed a strong increase in risk with shallow cover which is explained by a significant population of older vintage pipe being prone to both manufacturing defects and shallow cover.

Treatment in risk models

The methods of accounting for depth of cover in risk evaluations adopted by several pipeline operators were reviewed. Two operators apply a probability curve proposed in a study for the Pipeline Research Council International, Inc. (PRCI) by Chen and Nessim[18], referred to as the "C-FER model". The C-FER model was developed using statistical distributions of depths of excavations in areas of differing land uses and climates, excavation time, excavation equipment size, and impact force. The model also considers 14 other factors, mainly behavioural, that influence the probability of the pipeline being damaged by encroachment activity having to do with the effectiveness of the pipeline marking, the excavator's awareness of the pipeline and notification practice, the pipeline operator's response to notification, and the operator's patrolling practices, based on operator surveys. The various permutations are accounted for in a fault tree analysis. Probabilities are combined as AND or OR conditional gates. (At AND gates, the aggregate probability is the product of n component probabilities, $P=p_1 \times p_2 \times \ldots p_n$. At OR gates, the probability is $P=1-[(1-p_1) \times (1-p_2) \times \ldots (1-p_n)]$.) Hence, depth of cover usually contributes only a small component to the probability of damage occurring.

[18] Chen, Q. and Nessim, M., "Reliability-Based Prevention of Mechanical Damage to Pipelines", PR-244-9729, Catalog No. L51816, August 1999.

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The C-FER model shows a nonlinear decrease in the probability that excavation will be deeper than the depth of the pipeline, with increasing amounts of cover. One operator using the C-FER model applies the fault tree in its entirety; the other applies the probability curve to its own internally developed risk model.

Another operator applies a relative risk factor model in which the likelihood factor decreases linearly with increasing depth. In that model, depth of cover is one of 9 equally weighted factors, so as with the C-FER model, the amount of cover contributes only a small component to the likelihood score. Another operator does not use depth of cover in its third-party damage risk assessment because they do not have and cannot reasonably get data about cover in sufficiently good quality and quantity to be very useful in a risk model. It is highly likely that this problem is not unique to this one operator. The alternative would be to make default assumptions about the cover, which would not inherently improve the estimate of risk. The operator in question does use depth of cover for site-specific geohazard risk modelling.

One risk model software developer was interviewed. The model is described as relative risk but hybridized with empirical and probabilistic inputs. Their input data set includes a field for entering information about the amount of cover. but it is not weighted heavily because the available data on cover is usually not good quality or consistent quality from one line to another. This inconsistency then creates problems for comparing risk between pipeline segments.

A risk modelling guidebook[19] identifies soil cover as a barrier against several types of physical threats including excavation, agricultural activity, geohazards, or large falling objects. The effectiveness of cover as a barrier is not uniform for all threats: a small amount of cover that hides the pipe from view may increase risk compared with no cover at all; cover may need to exceed some minimum to act as a barrier against hazards such as frost heave, slope failure, or washouts; ordinary amounts of cover may protect a pipeline from trees falling during a storm but not from a train derailment. The benefit of cover will be dependent on the hazard and the location of the pipeline. Other physical barriers such as a casing, a concrete slab, or placed rock may usefully add to protection provided by cover or compensate for ineffective protection provided by inadequate soil cover. The risk model should employ different relationships for differing categories of equipment (plows versus excavators) or differing threat mechanisms. A probabilistic model (e.g., C-FER) is suggested as the most robust approach. Alternatively, a model can be presupposed, or rationalized on experience or empirical data with assumed factors for mitigation effectiveness. A simple relationship given as Effectiveness = 1— exp[(cover) x (factor)] is offered as an example.

The user's guide of another pipeline risk model[20] widely used by many natural gas transmission pipeline operators was reviewed. In that model the depth of cover was not accounted for because whether the excavating equipment operator knows that a pipeline is present and knowing the depth (which can be determined by probing or pipe locating equipment) were considered more important than a specified depth of cover. Moreover, pipe under pavement was considered to present a greater risk (at the time of that study) because the pavement interferes with locating the pipeline.

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[19] Muhlbauer, W.K., Pipeline Risk Assessment – The Definitive Approach and its Role in Risk Management, Expert Publishing LLC, 2015.

[20] Kiefner, J.F. and Baker, M.A., "NYGAS Risk Assessment Model", 2002; and Kiefner, J.F., Baker, M.A., and Morris, W.G., "NGA Risk Assessment Model", 2006.

https://doi.org/10.52202/072781-0060

The role of damage prevention

To pick up on this last point, prior studies quantitatively evaluated the effectiveness of US pipeline operators' damage prevention practices and identify areas for improvement.[21,22,23] These studies consistently found that the most significant factors had to do with excavator awareness of the pipeline and willingness to provide notification, and the timeliness and effectiveness of the operator's response, not the depth of cover.

Comparing damage incidents by which party caused the damage can be instructive. Excavation damage is caused by one of three parties: the pipeline operator (the first party), the operator's contractor (a second party), or someone else unrelated to the operator (a third party). Previously damaged pipe is presumed to be caused by a third party since the operator or his contractor would likely know to repair the pipe rather than hide or ignore the damage. Third parties are responsible for 78% of damage-caused incidents (including the previously damaged pipe), which is not necessarily surprising. But the operator's contractor caused a dismaying 21% of damage incidents (and another 1% by the operator), despite knowing that a pipeline is there and either having information about the pipe depth or having the ability to determine the depth. This can only be explained by a lack of discipline in the field and possibly a poor safety culture. The effectiveness of a damage prevention program can be degraded by poor diligence on the part of operators.

The damage prevention studies, and the C-FER model, suggest consideration of the "Swiss cheese" model of barriers against an accident or loss event.[24] The concept is that all barriers are imperfect—they appear to be solid, but they have holes. Therefore, a single barrier against an accident is inadequate. Multiple barriers, though each is imperfect, reduces the probability of an accident because a dangerous condition that penetrates a gap in the first barrier has a high likelihood of being stopped by the second barrier. In the unlikely event that the condition makes it through two barriers, it has a high likelihood of being stopped by a third barrier. With a technical system such as a pipeline, barriers are sometimes classified as engineering controls, administrative controls, or behavioural controls.

In the context of damage prevention, engineering controls include soil cover, design to resist puncture, or barrier slabs over the pipeline. Watercourse crossings may be installed with barriers of increased cover, placed rock or concrete mats over the pipeline to protect against scour, or extended crossing length to protect against bank erosion.

The various elements of the damage prevention program comprise the prevalent administrative controls barriers in the US. These elements include an organized system for excavators to notify of an intent to dig, a coordinated process to mark the location of the pipeline, and statutory support. Other administrative controls may be applied in the form of an operator's policy to excavate by hand as the dig depth approaches that of the pipeline, or a policy to monitor excavations.

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[21] Kiefner, J.F., "Effectiveness of Various Means of Preventing Pipeline Failures from Mechanical Damage", Gas Research Institute, Topical Report GRI-99/0050, February 11, 2000.
[22] Kiefner, J.F., "Survey and Interpretive Review of Operator Practices for Damage Prevention", Pipeline Research Council International, Inc., Project PR-218-06502, April 27, 2007.
[23] Kiefner, J.F., "Effectiveness of Current ROW Monitoring Processes", Pipeline Research Council International, Inc., Project PR-218-074503, September 9, 2009.
[24] Larouzee, J., and Le Coze, J-L., "Good and Bad Reasons: The Swiss Cheese Model and Its Critics", Safety Science, 126, 2020.

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The behavioural controls barrier has proven to be the most difficult to implement, as evidenced by the 20 or so years it has taken for damage prevention programs in the US to effectively reduce the rate of occurrence of encroachment damage. Landowners and excavation contractors have been the most resistant, but that has diminished with time. However, the high proportion of damage incidents caused by second parties suggests that attention and commitment to changing behaviours has been weak, even in the pipeline community.

ASME B31.8, Paragraph 841.1.11(e) "Additional underground pipe protection" advises that additional protection from third party damage may be achieved by using one or more of the following: physical barrier above or alongside the pipe, damage-resistant coating, added depth of cover, warning tape, pipe casing, or added wall thickness." The data reviewed for this study show that without the administrative and behavioural barriers, the engineering controls alone are inadequate to manage the problem. B31.8 recognizes this shortcoming in para. 841.1.11(e) where it goes on to state: *"Additional underground pipe protection shall be used in conjunction with an effective education program (para. 850.4.4), periodic surveillance of pipelines (para. 851.1), pipeline patrolling (para. 851.2), and utilization of programs that provide notification to operators regarding impending excavation activity, if available."* (Italics added for emphasis.)

Added physical barriers are too expensive to install everywhere and may interfere with maintenance operations by encumbering normal access to the pipeline. Therefore, in the absence of effective administrative and behavioural barriers in many parts of the world, too much is probably expected from soil cover alone.

Further support for damage prevention being more important than cover comes from a comparison of damage incidents by NG transmission pipeline Location Class. In the US, Class 1 represents rural or unpopulated areas, Class 2 represents the outskirts of developed areas, Class 3 represents fully developed suburbs, and Class 4 represents urbanized areas. **Table *4*** presents the distribution of excavator damage incidents in US NG transmission pipelines from 2010-2021.

Table 4. Distribution of Excavator Damage Incidents by Location Class, 2010-2021

Class	Damage Incidents Proportion	2010 Mileage Proportion	2019 Mileage Proportion
1	73.9%	77.9%	78.3%
2	9.8%	10.1%	10.1%
3	15.3%	11.5%	11.2%
4	1.0%	0.5%	0.3%

Note that natural gas pipelines in Location Classes 2, 3, and 4 have been required to have 6 inches more cover than Class 1 pipelines. The results show the incident rates in Classes 1 and 2 align closely with the pro-rata proportions of mileage, implying a negligible effect of the added cover in Class 2. The proportions of encroachment damage in Class 3 and Class 4 areas are greater than the pro rata shares of the system mileage, especially in Class 3 despite greater cover compared with Class 1, implying cover alone is an insufficient barrier.

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Impact of cover on pipeline construction and operation

Cost-benefit analysis

Increasing the minimum required amount of soil cover has two cost impacts. One is the pipeline must be installed in a deeper trench. In principle the need for a deeper trench entails more excavated soil volume, the possible need for trench sloping that further increases volume, an increased chance of encountering groundwater, or the need for trench shoring, all of which reduce excavation efficiency or require larger equipment to maintain expected dig rates. The second cost impact may come many years later with maintenance and repair digs. The increased amount of cover will require larger bellholes and possible shoring to access and examine the pipe. The additional volume of excavated soil will be proportional to the increased amount of cover, which adds to the excavation time required at each dig site. The cost of additional excavation was compared to the likely reduction in fatalities that could be expected with the increased amount of cover to understand the cost of the increased safety benefit.

The benefit of increased cover can be quantified in terms of pipeline failures prevented and ensuing consequences avoided. The incident data can be reviewed to estimate the number of incidents that could be avoided.

Table 5 lists the encroachment damage incidents that occurred in each category of cover for pre-1971 and post-1969 pipelines ,HL and NG transmission combined, over 19 years from 2002-2020. The table also lists the estimated mileage in each depth category. The pre-1971 pipelines exhibit significantly higher rates of encroachment damage failures than newer pipelines at every depth range, even where mileages are similar. (The exception is for cover less than 12 inches because post-1970 mileage with such shallow cover is quite low.) The 1970 and newer pipelines clearly present lower risk, perhaps due to heavier wall thickness, stronger and tougher pipe materials, better maps and marking practices, or better external protective measures.

Table 5. Reported encroachment damage incidents, 2002-2020, Pre-1970 and Post-1969 Pipelines

Vintage	Metric	<12 in.	12-24 in.	24-36 in.	36-48 in.	48-60 in.	>=60 in.	Total
Installed <1970	Miles	19,615	54,949	88,422	60,450	30,338	13,111	266,885
	Incidents	38	46	65	98	43	58	348
	Rate*	1.02E-4	4.41E-5	3.87E-5	8.53E-5	7.46E-5	2.33E-4	6.86E-5
Installed >1969	Miles	1,390	2,781	72,299	102,888	72,299	26,417	278,075
	Incidents	9	2	11	35	26	53	136
	Rate*	3.41E-4	3.79E-5	8.01E-6	1.79E-5	1.89E-5	1.06E-4	2.57E-5
Post-1969 / Pre-1970		3.341	0.859	0.207	0.210	0.254	0.454	0.375

An increase in the minimum cover requirements in B31.4 or B31.8 will have no effect on encroachment damage risk for existing pipelines. Moreover, the revision will have no effect for new pipelines in the US unless PHMSA adopts or exceeds an updated ASME requirement. However, the ASME standards are used in other parts of the world where a national standard or some other standard (e.g., ISO) are not in use. More importantly, those installations outside the US and without a national standard may also not have the benefit of effective damage prevention programs. In those

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cases, the possible benefit could be greater, perhaps reflecting the degree of improvement seen over pre-1971 US pipelines.

To meet a minimum cover requirement stepped-up from 30 inches to 36 inches everywhere in a new installation, actual cover will exceed 36 inches in many areas. The benefit of increasing cover from 30 inches to 36 inches was considered as the elimination of all counted damage incidents at depths less than 36 inches in the post-1969 pipelines. The reduction in excavation incidents was estimated as 22 incidents/(19 years x 278,075 miles) = 4.16e-6 incidents/mile-yr. This applies to each operating mile-year of new pipe installed to the increased cover requirement plus the cumulative previously-installed mile-years installed to the increased cover requirement.

The benefit of increased cover requirements only accrues to new construction, as installation requirements are not retroactive to existing facilities. According to the US Bureau of Transportation Statistics, the combined US NG and HL onshore interstate and intrastate transmission pipeline network grew at an average rate of 0.4% per year system-wide for 10 years from 2013-2022, but new mileage was added at the average rate of 1.3%.[25] (Evidently 0.9% was replaced or retired on average each year). It is difficult to know what to expect going forward, nevertheless, the benefit was projected assuming these same rates.. This is shown projected to 20 years by the blue curve in Figure 18 (left).

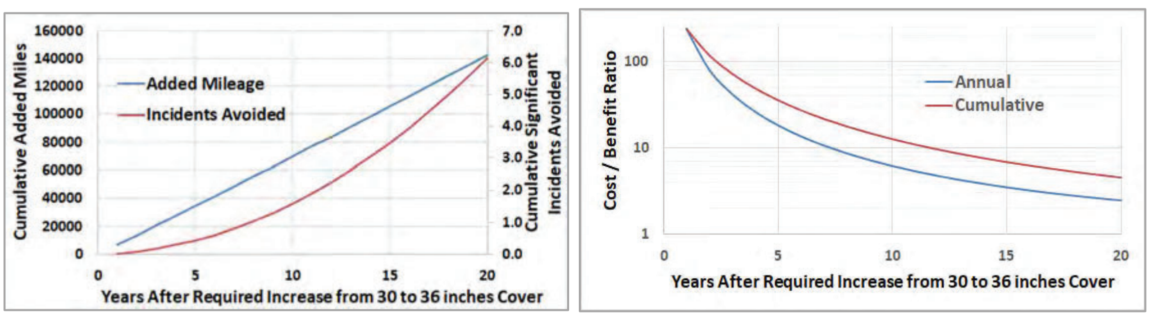

Figure 18. Projected Cumulative New Miles and Incidents Avoided (left) and Cost/Benefit Ratio (right)

The benefit in encroachment incidents avoided compounds over time, assuming continued operation of the newly installed pipe and continued growth of the system. The expected encroachment incidents avoided will build as shown by the red curve in Figure 18 (left). After 20 years, 6 significant incidents will have been avoided.

To quantify the benefit that increased cover would have on the overall risk of incidents, it is necessary to use a common unit of measurement for all incidents that accounts for injuries, fatalities and direct costs reported. Risk can be measured in terms of the value of a statistical life (VSL). The VSL that is

[25] https://www.phmsa.dot.gov/data-and-statistics/pipeline/annual-report-mileage-natural-gas-transmission-gathering-systems; https://www.phmsa.dot.gov/data-and-statistics/pipeline/annual-report-mileage-hazardous-liquid-or-carbon-dioxide-systems; and https://portal.phmsa.dot.gov/analytics/saw.dll?Portalpages&PortalPath=%2Fshared%2FPDM%20Public%20Website%2F_portal%2FPublic%20Reports&Page=New%20Construction

used by the Department of Transportation is $11.6 million baselined to 2020.[26] Injuries are valued at 0.27×VSL, consistent with DOT guidance[27] for severe injuries.

Surprisingly, encroachment damage incidents do not generally constitute the most costly incidents. This could reflect a shortcoming in the reporting of cost data to PHMSA. Approximately 10% of encroachment accidents involving natural gas pipelines also result in fire, fatalities, or injuries; similarly for 5% of encroachment accidents involving hazardous liquids. (Such incidents are referred to by PHMSA as “Significant”.) For natural gas, there is a 5% probability of a fatality, and a 10% probability of an injury. The probabilities are about half that for hazardous liquids, but only the natural gas probability was considered. To bias the outcome in favor of the benefit, the probabilities were assumed to be 10% for fatality and 20% for injury.

To normalize the incidents in the data to a common scale, an equivalent cost in terms of consequence of failure (CoF) was calculated each year for the number of incidents avoided. This cost was taken as the sum of an arbitrary $2 million representing a high threshold baseline cost, plus 10% of the incidents avoided multiplied by the VSL for fatalities, plus 20% of the number of incidents avoided multiplied by 0.27×VSL for injuries. An economic inflation rate of 4% was assumed. The resulting benefit cost initially is low. However, after 10 years, the cumulative benefit is $21 million; after 15 years it is $65 million; and after 20 years, it is $147 million.

The benefit comes at a cost. The primary cost is a deeper trench, which either requires larger excavating equipment, or slows the rate of excavation. Both effects increase the cost of construction. Using the assumption of a standard excavator with a 0.6 yd^3 bucket with trenching production rate of 37 yd^3 per hour (approximately 1 bucket/min. average), Figure 19 shows the excavation costs for 12-, 24-, and 36-inch diameter pipe with between 2 and 4 feet of cover. All costs are per 40-foot joint based on the bottom of the trench being two feet wider than the pipe diameter and sloped at 2:1 with the excavator plus operator cost of $155/hr. The cost of excavation size multiplier was approximately 1.4 for the 36-inch pipeline relative to the 24-inch pipeline, and about the same multiplier for the 24-inch pipeline relative to the 12-inch pipeline. Selecting the mid-sized 24-inch pipeline, the added cost increment to go from 30 to 36 inches of cover is about $24 per 40-ft joint, or $3,168 per mile. In the context of an entire pipeline project, which could cost on average about $8-$10 million per mile for a 24-inch pipeline, the incremental cost is not that large, 0.035%.

[26] https://www.transportation.gov/office-policy/transportation-policy/revised-departmental-guidance-on-valuation-of-a-statistical-life-in-economic-analysis
[27] Department Guidance: “Treatment of the Value of Prevent Fatalities and Injuries in Preparing Economic Analyses”, March 2021, https://www.transportation.gov/resources/value-of-a-statistical-life-guidance

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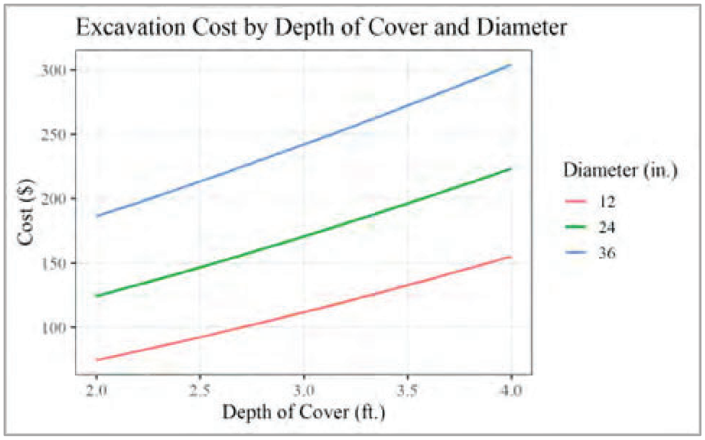

Figure 19. Excavation cost per unit pipe joint

After 10 years the annual added cost is $32 million, but the cumulative added cost is $266 million; after 20 years the annual added cost has only increased to $49 million, but the cumulative cost is $676 million. The cost-benefit ratio on an annual basis and cumulatively are shown above in Figure 18 (right). The cost-benefit ratio greatly exceeds 10 for the first 10 years and reduces to 2.4 and 4.6 for the annual and cumulative cases, respectively, at 20 years. But the ratio never reaches 1.0 (or less) with the assumptions discussed above for installed miles, inflation rate, incremental construction cost, or VSL.

From a cost of excavation standpoint, the added cost would be minimal for a single maintenance excavation of a 40-foot pipe joint length. In the context of a larger remediation program that might involve dozens or hundreds of digs, the cost could be substantial. Note that this increased cost will not be realized until a new, modern pipeline hypothetically installed at greater depth actually deteriorates to the point that large scale remediation is necessary. Intensive maintenance programs would not be expected in the first 20 years. Also this increased maintenance cost has no effect on existing pipelines already installed to current depth of cover requirements.

An important counterpoint must be noted. ASME standards are used worldwide. In many, perhaps most, places where pipelines operate, the institutional structures necessary to support effective damage prevention are unavailable. In those places, added cover might be an effective primary barrier. Also, in some regions the construction cost is considerably lower than in the US. It is conceivable that there are places where the additional cost of increasing the amount of cover provides a realizable cost-benefit. This study did not explore those scenarios.

Effect of rock in the ditch

Pipelines constructed in blasted rock trenches are allowed by most pipeline standards to have a lesser cover depth compared to pipelines buried in soil. Analysis was performed to determine whether a blasted rock trench can provide the same level of protection for a pipeline with shallow burial depth as that of a conventional soil trench with a greater burial depth. A number of parametric finite element analyses (FEA) were carried out to explore stresses in a pipeline installed with shallow fill and low clearance to rock projections and subjected to surface loading from a heavy haul truck. The model consisted of a two-dimensional plane strain pipe installed in a rock trench. To explore the effects of the rock trench the stiffness value of the material surrounding the trench in most of the analyses was selected to represent a typical limestone. To determine if a rock trench offers any benefit

https://doi.org/10.52202/072781-0060

compared to a conventional soil trench (in terms of lowering surface loading induced stresses), the elastic modulus of the bedrock was varied in the analyses.

Surface loading transmitted to a pipeline buried in a rock trench depends on the vehicle footprint. For example, a tracked vehicle with a track length several times greater than the trench width is expected to distribute most of the load to the shoulders of the rock trench as it crosses over the pipeline. A wheeled vehicle crossing over the pipeline tends to concentrate loads directly over the backfill material. A concentrated load is more critical than a longer distributed load (e.g., from a tracked vehicle). Thus, the FEA effort was focused on concentrated loads similar to that of a wheeled vehicle. The surface loading in the analysis was modelled based on the rear axle load (axle load of 37,890 lbf) of a Caterpillar (CAT) 740B articulated dump truck with an impact factor of 1.5. The contact area under each tire was assumed to be a 20- by 28.4-inch rectangle (the tires are 28.8 inches wide) with a contact pressure of 50 psi.

In addition to cover depth, pipe wall thickness, diameter, and trench width affects surface loading induced stresses in a buried pipe. To show these effects, pipe diameter, wall thickness, and trench width were varied in the parametric study and the results compared. The thickness and elastic modulus of the padding material were also varied to determine if padding material can be designed to offset potentially negative effects of a shallow cover depth.

The parametric FEA accounted for the effects from the following parameters on surface loading induced stresses: a) cover depth, b) pipe wall thickness, c) ditch width, d) the elastic modulus of the padding layer, e) the thickness of the padding layer, and the elastic modulus of the bedrock

The effect of cover depth (item 'a') was included because it was directly related to the objective of this study. The effect of wall thickness (item 'b') was included because pipe outer diameter to wall thickness ratio affects the surface loading induced stresses. The effect of ditch width (item 'c') was included because in theory a wider ditch tends to increase the overburden induced stresses . Furthermore, the potential benefit from greater bedrock stiffness (if any) is expected to diminish as ditch width increases. A blasted rock trench is, on average, wider than a trench cut using a rock trencher. In this respect, a rock trencher may offer an advantage over blasting. The effect of padding elastic modulus (item 'd') was included to determine if soil type (e.g., sand versus silt) and soil compaction play a major role in the level of protection that padding provides. The padding thickness (item 'e') was varied to explore its effect on the surface loading induced stresses and to help establish a minimum thickness required to protect the pipe against damage by large rock fragments and uneven trench bottom resulting from blasting. The effect of bedrock elastic modulus (item 'f') was included to determine if and to what extent higher stiffness of a trench constructed in rock can provide additional protection against surface loading as compared to a trench constructed in normal soils.

Two-dimensional plane-strain models were developed for the analysis. Three different pipe outer diameters (OD) of 12.75-inch, 24-inch, and 36-inch were examined. The effects of the parameters 'a' through 'd' listed above were examined for all the three pipe diameters, while the effect of parameters 'e' and 'f' were only examined on the 12.75-inch OD pipe. The surface loading applied to all the models consisted of the loading described above from a rear tire of a fully loaded Caterpillar 740B articulated dump truck with an impact factor of 1.5.

Figure 20 (left) below shows the model for the 36-inch pipe OD with a cover depth of 12 inches and a padding layer thickness of 4 inches under the pipe (minimum clearance between the pipe and bedrock is 3 inches when the protruding rock is considered).

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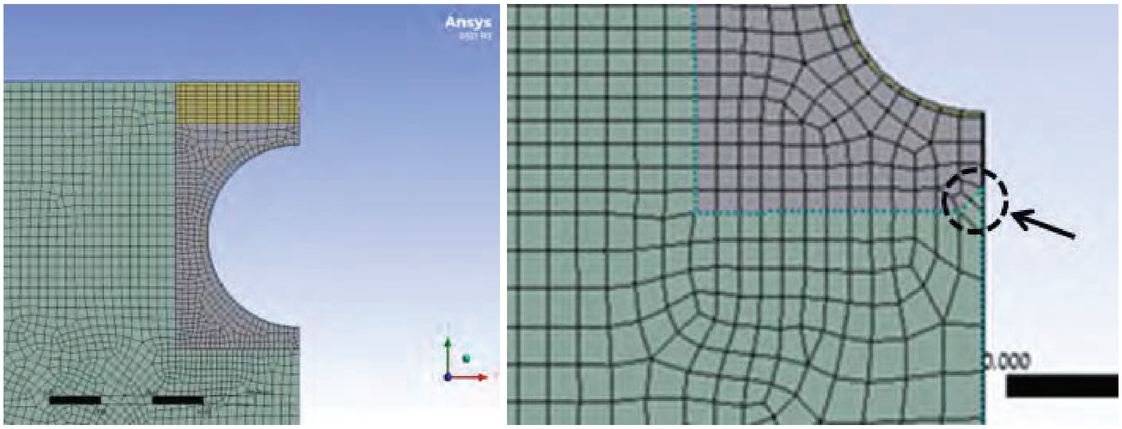

Figure 20. FEA model, example (left), and protruding rock in ditch bottom, detail (right)

The green elements represent the bedrock; the gray elements represent padding consisting of granular soil with no rock fragments larger than ¾-inch; the yellow elements represent coarse sand and gravel of the type produced by blasting operation. The contact between the pipe and soil was frictional contact with a friction coefficient of 0.6. Mohr-Coulomb soil plasticity with a friction angle of 35 degrees and no cohesion was used for the padding layer. All the other materials in the models were linear-elastic. Rock protruding from the ditch bottom with 3 inches of clearance below the bottom of the pipe was modelled into the bedrock geometry, identified in Figure 20 (right).

Selected results are presented below. Figure 21 shows pipe stress versus cover depth for an NPS 12 and a 36-inch OD having differing wall thicknesses. The pipe stress decreases with increasing cover. Figure 22 shows pipe stress versus blasted trench width for the NPS 12 and a 36-inch OD pipe. The pipe stress increases with trench width.

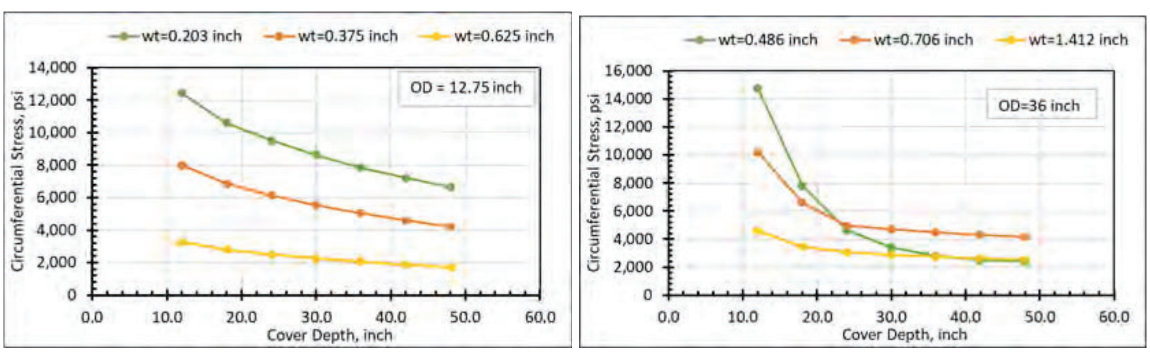

Figure 21. Pipe stress versus cover depth, NPS 12 (left) and 36-inch OD (right)

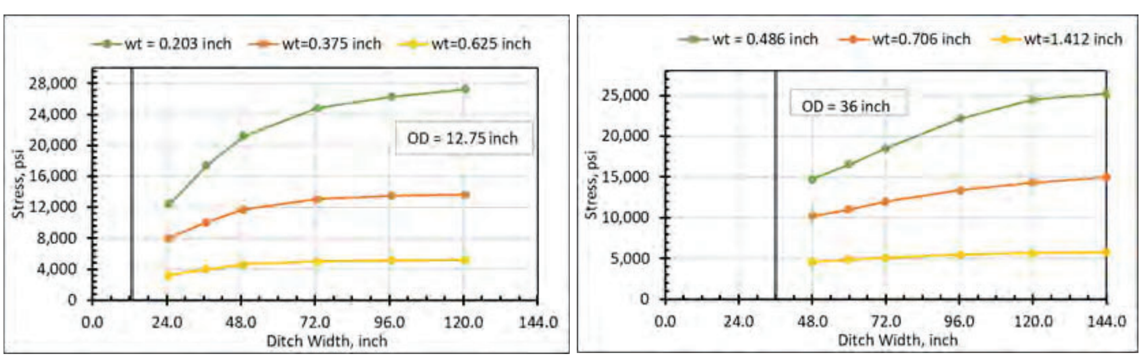

Figure 22. Pipe stress versus trench width, NPS 12 (left) and 36-inch OD (right)

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The FEA study demonstrated that:

- Pipe stress decreases with increasing pipe wall thickness, particularly with D/t less than 50 generally, except that soil arching can alter this effect where the pipe wall is thin or padding elastic modulus is high relative to pipe ring-stiffness;
- Pipe stress decreases with increasing depth of cover, but the additional stress reduction diminishes with cover greater than around 20 inches;
- Pipe stress increases with increasing ditch width; stress in the pipeline decreases with narrower trench width, particularly with pipe D/t less than 50. There is only marginal effect of trench width if the trench is wider than twice the pipe diameter. Therefore, rock excavation using a rock trencher will not provide much benefit unless it can reduce the trench width to less than twice the pipe diameter.
- Pipe stress decreases with increasing modulus of the padding soil;
- Bedrock elastic modulus does not have a significant influence on the surface loading induced stresses for elastic moduli greater than about 60 ksi (a vehicle track long enough to span a trench will distribute some of the load on the two sides of a trench, thus a higher bedrock stiffness is expected to reduce stresses);
- Padding thickness is not an influential factor as long as the bedrock does not come into direct contact with the pipe;
- The thickness of the padding soil on the trench bottom has only a small effect on pipe stress. The stress in the pipe is reduced with padding soil modulus exceeding 3,000 psi, particularly with pipe D/t greater than 50; and
- Stiffening from internal pressure has an effect on surface loading induced stresses, especially on the 36-inch pipe which has a higher D/t ratio.

Consideration for service conversion

Pipeline service conversion is addressed in this study because of the notable differences in cover depth requirements between the B31.4 and B31.8 codes, particularly in developed areas where liquids pipelines require 18 inches more cover than gas pipelines. Though it is recognized that current design and construction requirements under B31.4 and B31.8 are nonretroactive to in-service pipelines, it is believed the higher cover depth requirements for liquids pipelines could bring about questions or concerns for gas-to-liquids service conversions in a regulatory approval process and potentially influence the outcome of a service conversion application. The differences in code minimum cover requirements are unlikely to pose a problem for liquids-to-gas conversion.

In the event a proposed gas-to-liquids service conversion is questioned under regulatory review due to perceived safety concerns regarding cover depth, a compelling argument could be made that there must be sound reason for B31.4 to require deeper burial for new liquids pipelines than B31.8 does for new gas pipelines. And while in-service pipelines are not subject to code changes concerning design and construction, it could be further argued that a pipeline proposed for alternative service that will operate under a lesser construction standard should not be fully exempted under the broad grandfathering, but rather be subject to corrective action or additional operating measures that would offset the cover deficiency. Also, if the gas pipeline proposed for conversion to liquids service does not meet current cover requirements in B31.8, then the argument could be even more compelling.

It was of interest to learn if some form of remedial action concerning existing cover depth was required for service conversion approval. If cases could be found among past service conversion filings where the reported cover depth was challenged due to a perceived safety or compliance issue, such

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examples could be used to help support a recommendation to bring B31.4 and B31.8 cover requirements into closer alignment.

An extensive literature search was conducted to find relevant documents that cited pipeline cover depth and to understand whether the citations concern specific integrity concerns (e.g., heavy surface loads, third-party damage, or other outside forces), or if the grandfathering of existing cover conditions was noted or implied. Unfortunately, of the many service conversion-related documents reviewed, none was found to address cover depth.

A relevant document discovered in the literature search was the US DOT PHMSA publication "Guidance for Pipeline Flow Reversals, Product Changes, and Conversion to Service", which provides operators PHMSA's expectations with respect to complying with existing regulations and contains recommendations that operators should consider prior to implementing these changes.[28,29] Though the guidance document does not mention pipeline cover, it does state that required written procedures for service conversion must include: "visual inspection of ROW, all aboveground segments and selected underground segments", followed by "correction of all known unsafe defects and conditions." The "selected underground segments" with "known unsafe conditions" could include locations with less than adequate cover to protect the pipeline from surface activities or environmental events, however, if the operator is unaware of cover loss over its pipeline or assumes existing cover conditions are adequate for current gas service and therefore are acceptable for liquids transportation, there is no specific requirement in the guidance document to verify pipeline burial depth, nor is there any guidance to ensure water crossings are safe from damage and potential product loss. It is understood that design and construction requirements under US federal regulations are not retroactive, however, it is believed the language in this guidance document does imply that all potential pipeline safety conditions should be considered and addressed, including those related to inadequate cover depth, although it is not equally apparent as the other requirements presented.

In review of the ASME Codes specific to this topic, it was found that each of the requirements listed in the PHMSA guidance document is included in B31.8, Section 855, Pipeline Service Conversions, however, it was also found that there is no dedicated code section or language addressing the same or similar requirements in B31.4 for converting nonliquids pipelines to hazardous liquids service.

Service conversions are not common in the industry as most pipelines typically are dedicated throughout their lifecycle to transport product for which they were originally designed and constructed. Operators in the US frequently do sell or buy pipeline assets to address business needs as common carriers, so conversion of service may be contemplated with asset acquisitions. Novel potential service conversions are seeing attention as existing HL and NG transmission pipelines are contemplated for conversion to gaseous CO_2 for carbon capture, pure H_2 or blended NG-H_2 service, or ammonia transport.

A new pipeline intended to serve an operating need for a specified duration, either long or short term and with no foreseeable alternative operating use, is typically designed and constructed to current standards without consideration for potential future operating use. And because design and construction requirements under B31.4 and B31.8 are not retroactive, there is little or no incentive

[28] US DOT PHMSA, Guidance for Pipeline Flow Reversals, Product Changes, and Conversion to Service, September 2014.
[29] Federal Register, Vol. 79, No. 181, Thursday, September 18, 2014 /Notices.

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to exceed minimum cover depth requirements in anticipation of future alternative service use, especially given the associated construction and maintenance expenditures.

On the other hand, increased cover could offset potential cover foreseeable shortcomings in some locations. Greater cover could: help avoid consequences of urban development, such as grade changes for stormwater drainage or transportation needs that would otherwise necessitate relocation and typically cause service interruption; or reduce the effects of long-term environmental occurrences such as windstorms or stormwater events or periodic high impact episodes such as flash floods that could require costly periodic maintenance or permanent mitigation including pipeline lowering or relocation. The latter particularly may be worthy of consideration given the threat of global warming and climate change in which areas previously unknown to be susceptible to extreme weather events are becoming more prevalent. Under such conditions where a pipeline may be potentially vulnerable, deeper burial would provide added protection for a pipeline throughout its life cycle. The perception of lower operating risk concerning mechanical damage or consequential situations is desirable from the perspective of a prospective owner or operator when assessing the feasibility of purchasing or leasing the asset. These are general considerations not specific to service conversion.

Conclusions

Key findings

- HL and NG transmission pipelines in the US and in Europe have shown significant reduction over the past 10 years in the rate of failures caused by outside interference or encroachment damage. The rate of such incidents is still significant but is now consistently less than the rate of failures due to corrosion.
- Outside interference remains the single most significant cause of failures in natural gas distribution piping systems, due to the inherently greater exposure and vulnerability of such systems. The exposure arises because distribution piping must be in developed areas where excavation for other purposes commonly occurs. The vulnerability arises because of the prevalence of plastic pipe, and the small diameters and thin walls of steel pipe used in distribution service.
- The evidence in reportable incident data for greater protection with even greater depth of cover, beyond the recognized minimum of 30 inches, is weak or non-existent. In fact, the data suggest that amounts of soil cover greater than approximately 36 inches increases risk of damage from construction activities that take place at increased depth such as boring, augering, drilling, or piledriving. The threat of damage may be enhanced by the increased difficulty in accurately locating pipe when it is at greater depths of burial.
- The notion of soil cover as the primary barrier against encroachment damage only applies in the absence of effective damage prevention. Prior research demonstrated that whether an excavating party is aware that a pipeline is present, the party is willing to notify the pipeline operator, and the operator responds in a timely manner are more effective for preventing excavation damage than depth of cover. In parts of the world where the institutional structures necessary to support effective damage prevention do not exist, the soil cover may have to be increased along with secondary protection such as concrete slabs. B31.8 already states as much, however B31.4 does not.
- Increased soil cover appears to provide some beneficial protection to pipelines from natural events involving heavy rains and floods. Pipe sizes 12 inches in diameter and smaller, or with

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wall thickness less than 0.35 inch, appear to have disproportionate vulnerability to damage from natural events.
- Increased amounts of cover would only apply to new construction, not to existing pipelines. Where an extensive pipeline network already exists, any benefits that do exist with increased cover would only accrue very slowly over time, depending on the rate of new pipeline installed each year.
- Where increased cover is in place, future repair work will take longer and cost more. Since 22% of damage incidents continue to be caused by the operator or its contractor, deeper maintenance digs will contribute to the persistence of this risk rather than alleviate it.

Recommendations for improvement in ASME B31 standards with respect to cover

A few recommendations for improvement in the ASME B31.4 and B31.8 standards were identified and are presented below. Some may also be appropriate to consider for other international standards.

For ASME B31.4:
- Consider adding a cautionary statement that NPS 12 and smaller pipe is more vulnerable to damage from natural events than larger pipe and increased soil cover may enhance protection from some of those threats.
- Consider reducing the default cover for "all other areas" to 30 inches.
- Replace the term "river and stream crossings" in Table 434.6-1 with "watercourse crossings" defined to include natural and artificial unlined channels in which flowing water may be present, including but not limited to major and minor rivers, streams, drainage ditches, and canals.
- Include language for pipelines crossing standing, non-flowing bodies of water, such as lakes and reservoirs.
- Develop requirements for a damage prevention program.
- Develop a Code section on pipeline service conversions.

For ASME B31.8:
- Consider adding a cautionary statement that NPS 12 and smaller pipe may be more vulnerable to damage from natural events than larger pipe and increased soil cover may provide enhanced protection from those threats.
- Consider increasing the minimum cover to 30 inches in Class 1 areas, 36 inches in Class 2, 3, and 4 areas, and 48 inches at railroad and roadway crossings. These recommendations are made mindful of the fact that they do not provide cost-effective protection where construction costs are high and damage prevention is practiced. They are suggested for two reasons: (1) not all places where B31.8 is used support effective damage prevention, and (2) the revision provides some consistency with prevailing practice and regulations in the US, and some other standards internationally.
- Consider adding a line item for watercourse crossings and inland bodies of water to Table 841.1.11-1 with a minimum 48 inches of cover.

For both ASME B31.4 and ASME B31.8, as joint projects:
- Consider reviewing the CEPA "Pipeline Associated Watercourse Crossings", 3rd Ed. 2005 and CEPA "Pipeline Watercourse Management", 1st Ed. 2014 to identify potential improvements in guidance for the design, maintenance, and integrity management of

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pipeline watercourse crossings. The goal should be to provide more complete guidance that is consistent between the two standards to the extent that is appropriate.

- Consider developing similar cover requirements and guidance for the design and integrity aspects of inland bodies of water including ponds, lakes, wetlands, reservoirs, and bays, ports, or harbours that would not be designed and installed as offshore pipelines.
- Consider developing consistent language describing the multilayered barrier concept to damage prevention, consisting of engineering controls (design, installation), administrative controls (damage prevention program, monitoring excavations, other dig practices), and behavioural controls (safety culture, public awareness, damage prevention effectiveness). Refer to existing external guidance documents as appropriate.
- Consider simplifying the variety of cover requirements two four areas: (1) rural or unpopulated areas, (2) developed areas, (3) cultivated areas, and (4) crossings of any type. Cover requirements for categories (2), (3), and (4) might be the same.
- Delete the separate cover requirements for rock and simply allow rock cover to be reduced by 1 ft (0.3 m).
- Consider recommending 1 ft (0.3 m) greater cover, or other barriers, or both where an effective damage prevention program cannot be implemented.
- Include more explicit language in both Codes requiring operators to verify burial depth the entire length of the pipeline subject to service conversion for assessment and ensure water crossings are safe from damage and potential product loss.
- Consider the potential effects of global warming and climate change on gas and liquids pipelines when revising ASME pipeline depth of cover requirements or, as a minimum, include language in B31.4 and B31.8 regarding the potential for such effects. Greater cover depth offers the advantage of maintaining adequate protective cover over the lifecycle of the pipeline to help avoid repositioning, replacement or relocation of the asset within the impacted areas, operation as grade changes, flooding and even wind cause the loss of cover.

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