LIGHT NON-AQUEOUS PHASE LIQUID TRANSMISSIVITY (T_N) ACCEPTANCE AND USE BY THE REGULATORY COMMUNITY

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ABSTRACT

The remediation of a petroleum hydrocarbon release often involves the removal of light non-aqueous phase liquids (LNAPL) from the subsurface. Historically, apparent NAPL thickness (ANT) has commonly been utilized as the metric for determining when LNAPL recovery was needed, and to signify the end-point to LNAPL recovery.

LNAPL transmissivity (T_n) provides a reliable metric for gauging LNAPL remediation. T_n is increasingly being used to quantify the feasibility of recovering LNAPL via hydraulic recovery methods, to optimize LNAPL recovery efforts, and to determine if LNAPL has been removed to the "Maximum Extent Practicable". However, adoption of T_n to date by state environmental regulatory agencies has not been universal.

This paper presents the results of a "snapshot in time" (2016) survey indicating how T_n is being used by state regulatory agencies to make decisions regarding the feasibility of hydraulic LNAPL recovery. Regulatory agencies in the United States, Canada, Australia, and New Zealand were surveyed.

INTRODUCTION

The remediation of a petroleum hydrocarbon release often involves the removal of light non-aqueous phase liquids (LNAPL) from the subsurface. Historically, apparent NAPL thickness (ANT) gauged in wells has been commonly utilized as both the threshold metric for determining when LNAPL recovery was needed and the shutdown metric to signify the end-point to LNAPL recovery (i.e., when LNAPL could be said to be recovered to the 'maximum extent practicable'). However, in-well LNAPL thickness has been demonstrated to be unreliable in this regard as it provides a poor correlation to LNAPL mobility or recoverability at many sites and does not normalize data to account for differences in LNAPL types, LNAPL mass, soil properties or LNAPL hydraulic conditions.

Transmissivity provides a scaling metric for hydraulic recoverability of any liquid that exhibits Darcian flow through porous media. Groundwater transmissivity rather than groundwater aquifer thickness has long been accepted as a reliable metric to calculate the recoverability of groundwater from water wells. Similarly, LNAPL transmissivity (T_n) is an improved metric over ANT to quantify LNAPL recoverability. As a result, T_n provides a reliable metric to define when LNAPL has been removed to the "Maximum Extent Practicable" (MEP), and may also be used to determine when hydraulic recovery of LNAPL may be a feasible LNAPL mass reduction technology. However, T_n should not be used as an arbitrary threshold metric to require hydraulic recovery of LNAPL, because any such recovery requirement should be based on a broader risk-based evaluation rather than simply whether or not it is feasible to hydraulically remove LNAPL. T_n is defined as the quantity of LNAPL that will flow through a unit aquifer width for the full thickness of the mobile NAPL interval (MNI) in a unit time for a unit gradient, and provides a numerical metric that normalizes sites to a single hydraulic recoverability standard that accounts for differences in LNAPL type, LNAPL mass, soil properties, and LNAPL hydrogeologic condition from site to site, or even location to location within a given site.

T_n provides more value than merely identification of a hydraulic recoverability threshold. It may be used as a threshold to determine when hydraulic recovery of LNAPL is practicably feasible, but it can also be used as a calibration parameter for multiphase models such as the LNAPL Distribution and Recovery Model (LDRM) (1) and as an engineering design parameter for hydraulic LNAPL recovery systems. Multiple methods for the estimation of LNAPL transmissivity have been developed, and can be used as both threshold and progress metrics throughout the life of a hydraulic LNAPL remedy. Even when a regulatory agency does not recognize the use of T_n as a threshold metric for LNAPL recoverability, T_n still provides substantial value for the correct modeling and design of hydraulic recovery remedies.

Methods for calculating T_n were originally published by Lundy and Zimmerman (2) using a modified Bouwer Rice Slug Test (3) and by Huntley (4) using a modified Bouwer Rice Slug Test, and Jacob and Lohman's (5) modification of the Cooper-Jacob (6) method. However, none of these approaches satisfactorily accounted for changes in groundwater elevation during testing, and they resulted in calculation of different T_n values for the same test data. Kirkman (7) unified these methods with the introduction of the J Ratio, which relates the change in LNAPL drawdown observed during a T_n test to the overall change in ANT. Kirkman demonstrated that the Lundy and Zimmerman and Huntley methods were endpoints on a continuum of conditions that could be accounted for by incorporating the J Ratio into the modified Bouwer-Rice equation for calculation of LNAPL transmissivity.

In 2009 the Interstate Technology & Regulatory Council (ITRC) published the Technical/Regulatory guidance document entitled *Evaluating LNAPL Remedial Technologies for Achieving Project Goals* (8). The guidance defined three LNAPL scenarios: migrating LNAPL (expanding downgradient); mobile LNAPL (can move into a well but has insufficient head to expand downgradient); or residual LNAPL (immobile discrete blobs in porous media). It also proposed that hydraulic recovery of LNAPL reaches the practicable threshold for hydraulic recoverability at a T_n range of 0.1 to 0.8 feet squared per day (ft^2/d).

In 2011 (updated in 2013), ASTM International published ASTM E2856-13, the *Standard Guide for Estimation of LNAPL Transmissivity*, (9), which describes field and analytical procedures to measure T_n in detail. To complement the ASTM E2856-13, the American Petroleum Institute (API) released an Excel® spreadsheet tool and supporting documentation for calculating T_n from baildown test data (10).

T_n is increasingly being used to quantify the feasibility of recovering LNAPL via hydraulic recovery methods, to optimize LNAPL recovery efforts, and to determine if LNAPL has been removed to the "Maximum Extent Practicable" (MEP) as defined by the US EPA in 40 CFR 280.64. However, adoption of T_n to date by state and federal environmental regulatory agencies has not been universal. The purpose of this article is to present the results of a "snapshot in time" survey indicating how T_n is being used by state regulatory agencies to make decisions regarding the feasibility of hydraulic LNAPL recovery. In addition to regulatory agencies in the United States (US), agencies in Canada, Australia, and New Zealand were surveyed to provide some international contrast to current practice in the US.

It is important to note that the results presented in this article are based on responses from a sample of the regulatory agency population. The results represent an indication of regulatory trends and do not purport to supplant state regulations or replace site-specific team decisions with a regulatory project manager. In addition, while T_n provides a line of evidence relating to the feasibility of LNAPL recovery and potentially a practical end-point to LNAPL recovery activities, it will typically be necessary to consider other lines of evidence along with T_n in a comprehensive LNAPL Conceptual Site Model to determine whether LNAPL recovery is required or will provide an overall benefit in terms of mitigating the potential for LNAPL body expansion/migration at a given site.

Survey Goals

The survey presented here was designed to address two major questions with regards to T_n: 1. How is T_n being used (at the time of the survey) in the decision process to determine the feasibility of or regulatory requirement for hydraulic LNAPL removal; and, 2. How is it being used to support the cessation of hydraulic LNAPL recovery while LNAPL is still present at a site.

Surveyed Community

The survey was created through an internet application and a link was emailed to regulatory contacts in the United States (US), Canada, Australia and New Zealand. The survey took 10 to 15 minutes to complete and provided check-box answers to 10 questions, opportunities for write-in answers, and concluded with a request for contact information.

Twenty-six responses were received from US States. The confidence interval for 26 responses out of a population of 50 ranges from approximately ±8% (if 89% of the respondents agree) to approximately ±13% (if 65% of the respondents agree).

As previously noted, the survey was also submitted to agencies in other countries to sample the international use of T_n. It was submitted to the Canadian Provincial Environment Ministries and Environment Canada (10 Provinces and the Federal Agency) and five responses were received. Three of the six Australian State Environmental Protection Authorities/Agencies responded and one response was received from the New Zealand Regional Councils.

The survey results for US agencies will be the primary focus of this article, with a comparison where appropriate to the international response results.

Results Summary

Approximately 65% of the survey respondents accept T_n as a metric to determine if LNAPL recovery is required, is completed, or to track remediation progress.

Most regulatory agencies do not have a published T_n threshold value for hydraulic LNAPL recovery. The ITRC 2009 (8) proposed range for effective LNAPL recovery (0.1 to 0.8 ft^2/d) is often considered a potential benchmark. Relatively few States have numerical T_n thresholds in their regulations or guidance, examples being the States of Michigan and Nebraska that have published guidance that uses a T_n threshold of 0.5 ft^2/day, and the state of Massachusetts that has published guidance specifying 0.8 ft^2/d as a threshold for LNAPL recoverability.

The overwhelming majority (89%) of responding agencies would consider closing a site that had LNAPL remaining on site. Human health risk, use of institutional controls, and groundwater plume stability were also considered key factors in the decision.
The use of ASTM E2856-13 (9) and the API 2011 (10) calculation worksheet are generally accepted, though not necessarily required, for the determination of T_n.

HOW IS T_n USED BY THE REGULATORY COMMUNITY?

Overall responses in the US to the survey are presented on Figure 1. Twenty-six (26) responses were received. Responses are grouped into those that accept T_n as a quantifiable metric for decision making and those that do not:

- Eighteen (18) or 69% of the respondents accept T_n as a metric in the determination of the feasibility of LNAPL remediation (blue color on Figure 1).
- Eight (8) or 31% of the respondents do not accept T_n as a metric (orange color on Figure 1).

A common theme for states not accepting T_n was an emphasis on contaminant plume stability and health risk factors regardless of T_n quantification.

Internationally, the response is similar with 67% of the respondents accepting T_n as a metric (Canada 60%, Australia 100%, and New Zealand 0%).

Remediation

When does your regulatory agency accept LNAPL transmissivity as a metric to determine if LNAPL hydraulic recovery is feasible or required?

Sixty-nine percent (69%) of the respondents use T_n as a metric for making decisions.

When T_n is an accepted metric, 66% of the time it is a primary metric to determine if LNAPL recovery is feasible (leading metric 31% of the time, Figure 2) or should be continued (lagging metric 35% of the time).

T_n is also used as an additional line of evidence (11%), or to track the ongoing progress of recovery (11%). Approximately 12% of the time the use of T_n is contingent on site specifics, which we assume to be geology, distance to receptors / wells, and other human health or ecological risk factors.

Internationally, 43% would use T_n as a leading metric, and 43% would use it as a lagging metric (two respondents used it as both a leading and a lagging metric). As in the US, some considered it one line of evidence and would assess its use on a site-specific basis.

Does your regulatory agency use LNAPL transmissivity as a metric to define when LNAPL has been removed to the "Maximum Extent Practicable"?

When asked specifically about using T_n to support that LNAPL has been removed to the MEP, 50% indicated that it is accepted as a line of evidence.

Internationally, the strict EPA definition of MEP may be less relevant, but 43% responded they would accept T_n as a line of evidence, while 57% said they would not.

What T_n value does your regulatory agency accept as a threshold for making decisions?

The respondents that accept T_n as a metric do not have a strong consensus on what the threshold value should be (Figure 3). Only two states (11% of the respondents accepting T_n as a metric) have set a numeric threshold value below which hydraulic recovery is not effective or efficient (0.5 ft^2/d and 0.8 ft^2/d). Half (50%) have numeric guidelines with a range as proposed by the ITRC 2009 (8) guidelines (0.1 to 0.8 ft^2/d). The remaining respondents (39%) have not offered numeric guidelines but consider it to be negotiable dependent upon site conditions.

Internationally, one respondent said they use 0.8 ft^2/d on a case by case basis. The remaining responses indicated that no set value or specific policy was in place.

What other metrics in addition to or in lieu of LNAPL transmissivity does your agency accept or require to determine when LNAPL has been removed to the "Maximum Extent Practicable"?

Along with T_n, other lines of evidence are often requested. States accepting T_n were the most open to alternate lines of evidence that LNAPL recovery was complete. In addition, half (50%) of the states that don't accept T_n as a metric, indicated that they accept other lines of evidence to determine if LNAPL has been removed to the MEP. Twenty-five percent (25%) of those not accepting T_n as a metric determine the attainment of the LNAPL recovery end-point based on measured LNAPL thickness in wells.

The most accepted alternate metric is an asymptotic trend in recovery (Figure 4). Eighty-nine percent (89%) of those accepting T_n as a metric and 25% of the respondents who don't will accept an asymptotic trend as a line of evidence.

The second most popular alternate metric is demonstrating that LNAPL is at residual saturation levels. Sixty-one percent (61%) of those accepting T_n as a metric and 13% of the respondents who don't, will accept laboratory determined LNAPL saturations and residual LNAPL saturations as a line of evidence.

Additional metrics included specific recovery thresholds such as gallons per time, cost per gallon recovered, and limited acceptance of an oil/water ratio. The least accepted metric is the approach of recovering a certain percentage of the expected ultimate recovery of LNAPL derived from Decline Curve analysis, though it is unclear if respondents were familiar with this method.

US respondents also offered additional requirements to determine if MEP had been achieved:

- Stable delineated groundwater contaminant plumes
- No unacceptable health risks
- Demonstrated Natural Source Zone Depletion of the LNAPL
- Demonstrated dissolved phase natural attenuation
- Had evaluated alternative remediation methods

Internationally, the distribution of alternative lines of evidence was very similar; an asymptotic trend in recovery and demonstrating that LNAPL is at residual saturation levels each garnered 56% of the responses. The remaining categories were accepted by approximately 11% of the respondents, and site-specific criteria were cited including risk to receptors and plume stability.

Site Closure

Would your regulatory agency "close" a site with mobile (not migrating) LNAPL present if acceptable risk thresholds are met and LNAPL transmissivity is below the threshold for LNAPL transmissivity accepted by your agency?

The question of closing a site with LNAPL present was answered by all 26 respondents regardless of their acceptance of T_n. Overall 89% of the responding states considered it a possibility (Figure 5).

"Maybe" constituted 58% of the responses and typically was dependent on groundwater plume delineation, whether LNAPL had been removed to the MEP, and site-specific health risk factors. One respondent indicated it was possible but rarely done.

Thirty-one (31%) percent said they would close a site with LNAPL without further explanation, and 11% percent simply said no.

Internationally, the response was very similar 87.5% considered site closure with non-migrating LNAPL a possibility (75% maybe, 12.5% yes, 12.5% no).

Would your regulatory agency require an institutional control (e.g., environmental covenant, deed restriction) in order to "close" a site with LNAPL left in place?

The question of requiring institutional controls in order to close a site resulted in almost half (46%) saying they would require an institutional control to close a site with LNAPL remaining, and 25% say they would consider it (maybe) depending on site-specific conditions including health risks (Figure 6). Interestingly, the 11% who responded earlier that they would not close a site with LNAPL said they might require an institutional control.

Approximately 29% said they would not require an institutional control.

Internationally, Canada was overwhelmingly in favor of institutional controls (80% yes, 20% maybe). Australia indicated that they don't have authority to impose institutional controls and instead require a commitment to ongoing groundwater monitoring. New Zealand indicated that they do not close sites with LNAPL.

Determination of T_n

Does your regulatory agency require that LNAPL transmissivity testing be conducted in accordance with ASTM International guidance E2856 titled "Standard Guide for Estimation of LNAPL Transmissivity"?

The question regarding how to determine T_n indicated that 55% of the respondents required or recommended the ASTM guidance, ASTM E2856-13, (9) be followed. Forty-five percent (45%) did not require the use of the ASTM guidance, though some required that the methods employed have been published. States that did not accept T_n as a metric and answered "No" to requiring ASTM guidance were considered void and not counted.

Internationally, one respondent said yes while the remainder indicated they might but they would need to better understand the guidance.

Does your regulatory agency accept LNAPL transmissivity values calculated using the baildown testing analysis spreadsheet tool developed and freely distributed by The American Petroleum Institute?

Regarding the calculation of T_n, 75% said they accept the API spreadsheet tool (10), while the remaining 25% said they would likely accept it.
Internationally, one respondent said yes while the remainder indicated they might but they would need to better understand the tool.

PLANNING FOR T_N IN THE FUTURE

Has your regulatory agency written LNAPL transmissivity thresholds into rules or guidance documents?

Twenty-seven percent (27%) of the responding states are planning to propose written T_n thresholds as rules or guidance. One of the respondents planning to propose written thresholds does not currently accept T_n as a metric.

Two states, (8% of the responding states), have written guidance that includes T_n thresholds. No states have thresholds written as rules.

Fifteen percent (15%) indicated that there could be written thresholds on a site-specific basis. Some had procedures but no thresholds, another would consider a lagging threshold depending on the site conditions.

Just under half (46%) do not currently have plans to incorporate T_n thresholds into rules or guidance documents.

Internationally, most indicated no plans to write T_n thresholds into rules or guidance. One Canadian province indicated plans to do so and a second province indicated they will consider it in the future.

COMPARED TO 2009

The ITRC 2009 guidance document (8) included the results of a survey of all 50 states. Seventy-eight regulators from 38 states responded. The following responses to the 2009 survey were compared with the results of this 2016 survey:

- In 2009, 60% of the responding states indicated that the requirement for LNAPL remediation was site-specific, and 18% said it was based on direct in-well LNAPL thickness measurements; sheen, measurable amount, or the requirement to remove all.
  - In 2016 site-specific conditions are still very important in the decision-making process and are indicated as a determining factor 50% to over 60% of the time.
  - Using LNAPL thickness as a basis to determine if remediation is required appears to carry less weight dropping from 18% in 2009, to approximately 3% in 2016.
- In 2009 when considering the conditions needed to terminate active remediation systems, 40% responded that all measurable LNAPL must be removed. In addition, 40% required a long-term monitoring plan, 23% required engineering controls, 37% required institutional controls; and 26% indicated multiple requirements (monitoring and engineering and/or institutional controls).
  - In 2016, only 8% of respondents indicated that LNAPL thickness is a primary factor for ending remediation, as opposed to 2009 when 40% of the respondents indicated that all measurable LNAPL in wells must be removed.
  - Institutional controls were required or considered a possibility for closure of a site with LNAPL remaining by 75% of the 2016 respondents.

INFORMAL SURVEY

As a counterpoint to the formal survey, an informal survey of stakeholders (potentially responsible parties and consulting firms) was conducted to determine where they have successfully used T_n with state agencies on either a formal or informal (i.e., project specific) basis (11). Figure 10 shows those states where T_n has been accepted per this informal survey. The difference from the formal survey of regulatory agencies is likely due to respondents not being aware of every individual case in which T_n was accepted in their state agencies.

CONCLUSIONS

The determining factor for the feasibility of LNAPL hydraulic recovery continues to move away from using measurable thickness in a monitoring well (ANT) as the primary factor. Remediation efforts and site closure are considering site-specific geologic conditions, receptor health risks and a growing acceptance of T_n as a way to quantify the recoverability of LNAPL. For most, T_n is primarily a line of evidence, but some regulatory agencies are beginning to establish thresholds for when hydraulic LNAPL recovery could be initiated or may be terminated.

We hope this "snapshot in time" survey relative to the application and use of T_n as a threshold metric for the hydraulic recoverability of LNAPL provides a useful synthesis both of current conditions, and also to track the increased adoption and use of T_n over the last decade. Future such surveys would be beneficial to track these trends, and might consider incorporation of factors that limit adoption in those jurisdictions that lag behind.

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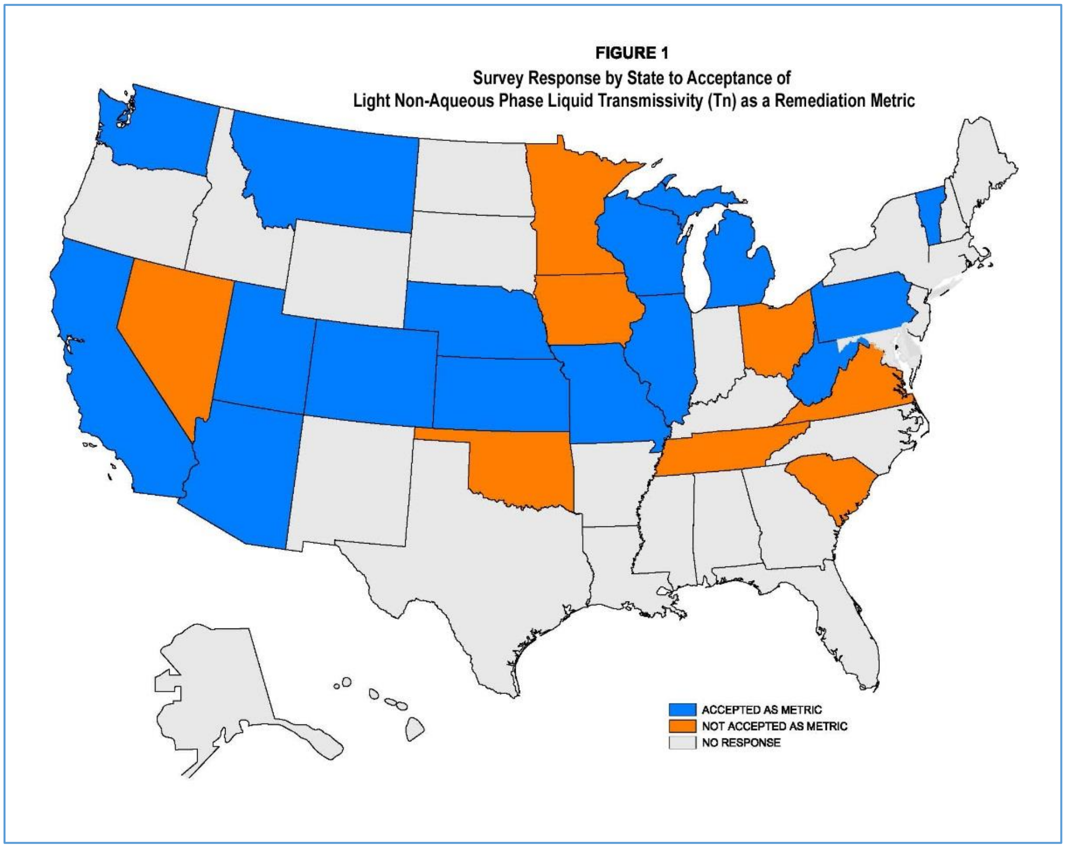


FIGURE 1
Survey Response by State to Acceptance of
Light Non-Aqueous Phase Liquid Transmissivity (Tn) as a Remediation Metric
ACCEPTED AS METRIC
NOT ACCEPTED AS METRIC
NO RESPONSE

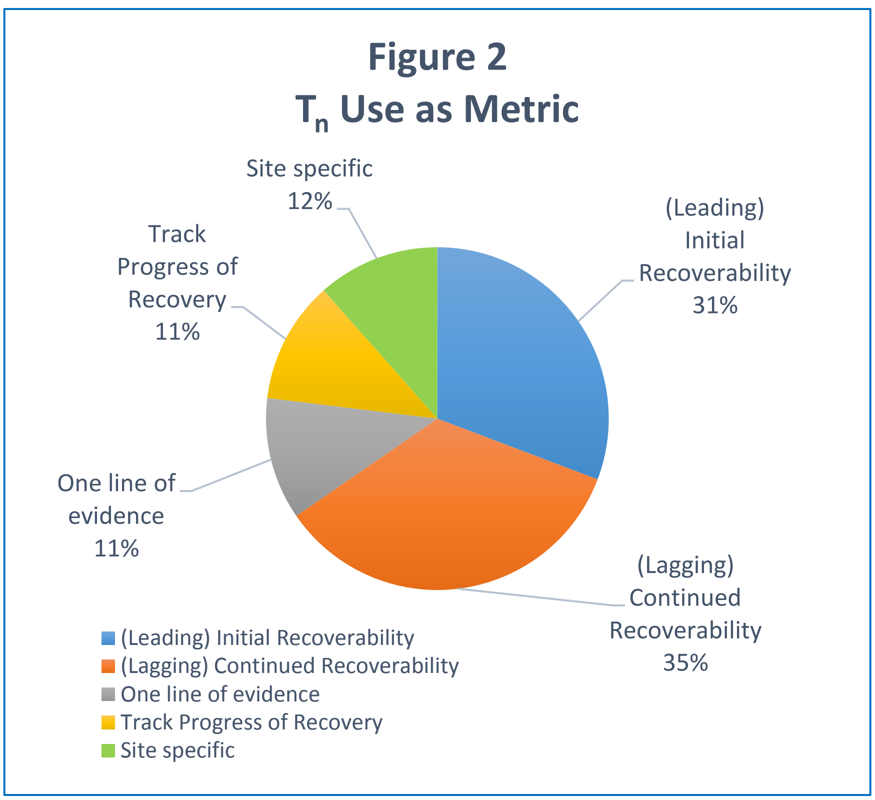


Figure 2
Tn Use as Metric
Site specific 12%
Track Progress of Recovery 11%
One line of evidence 11%
(Leading) Initial Recoverability 31%
(Lagging) Continued Recoverability 35%
(Leading) Initial Recoverability
(Lagging) Continued Recoverability
One line of evidence
Track Progress of Recovery
Site specific

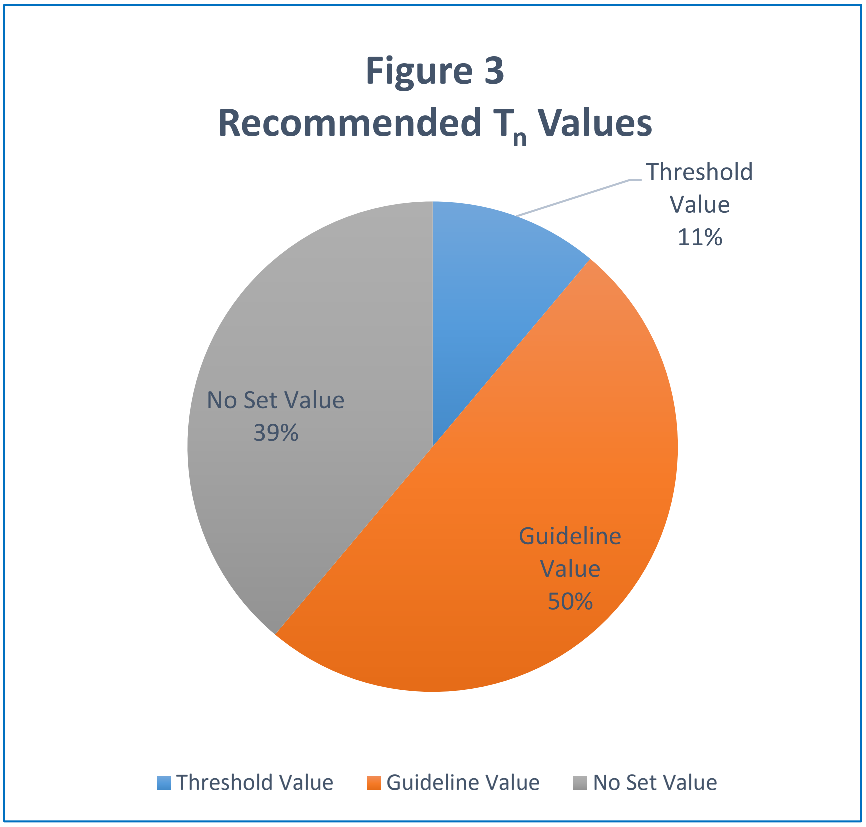


Figure 3
Recommended T_n Values
Threshold Value 11%
Guideline Value 50%
No Set Value 39%
Threshold Value
Guideline Value
No Set Value

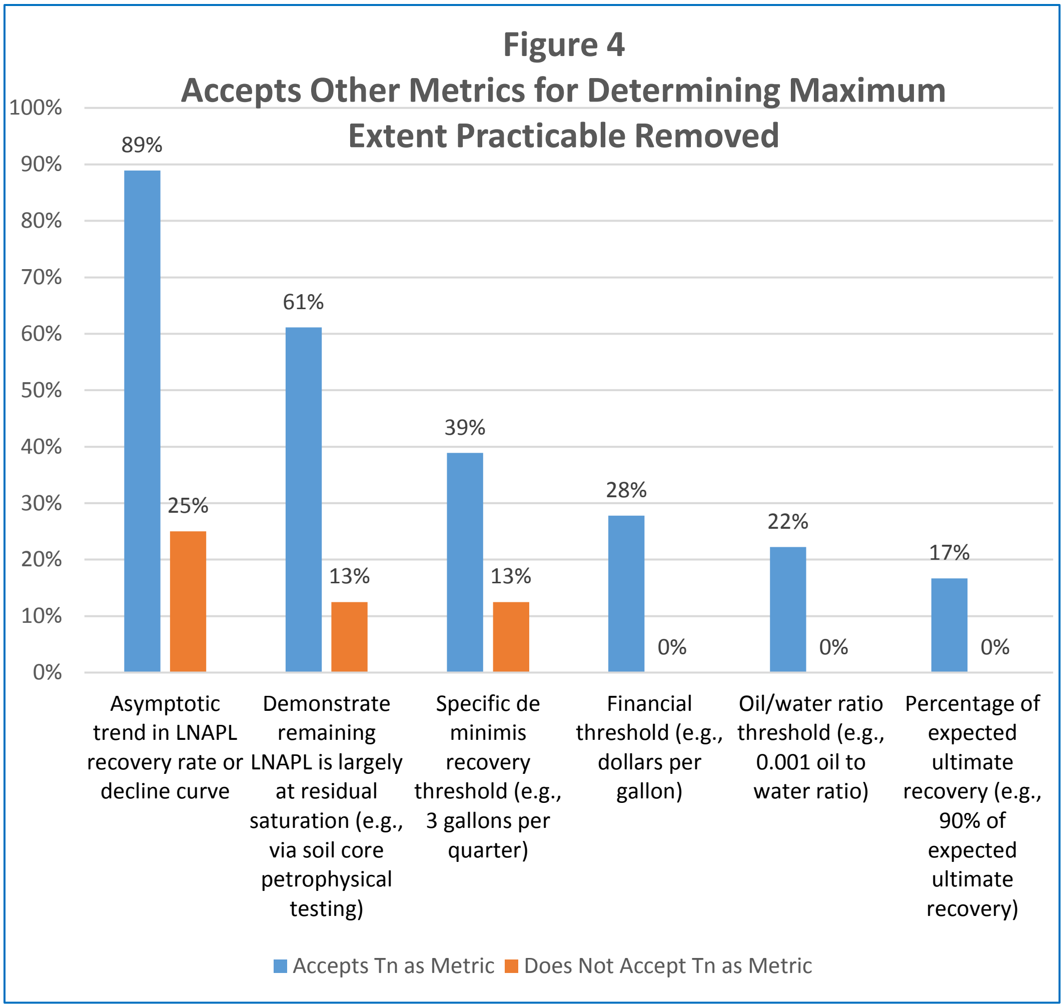


Figure 4
Accepts Other Metrics for Determining Maximum Extent Practicable Removed
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
89%
25%
61%
13%
39%
13%
28%
0%
22%
0%
17%
0%
Asymptotic trend in LNAPL recovery rate or decline curve
Demonstrate remaining LNAPL is largely at residual saturation (e.g., via soil core petrophysical testing)
Specific de minimis recovery threshold (e.g., 3 gallons per quarter)
Financial threshold (e.g., dollars per gallon)
Oil/water ratio threshold (e.g., 0.001 oil to water ratio)
Percentage of expected ultimate recovery (e.g., 90% of expected ultimate recovery)
Accepts Tn as Metric
Does Not Accept Tn as Metric

Figure 5
Would you Close a Site with Mobile, Not Migrating LNAPL

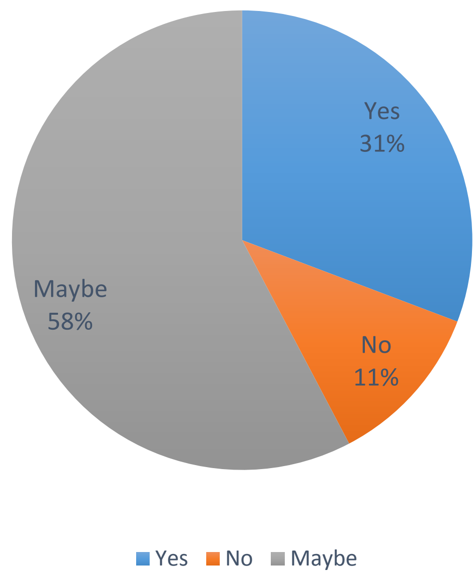


Figure 6
Would you Require Institutional Controls to Close a Site with LNAPL

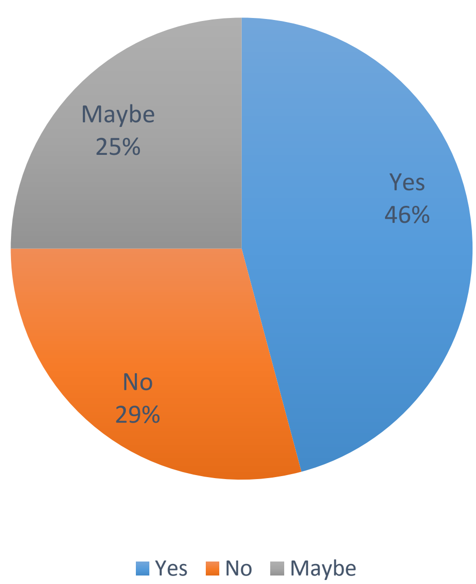


Figure 7
Require ASTM Guidance for T_n Testing

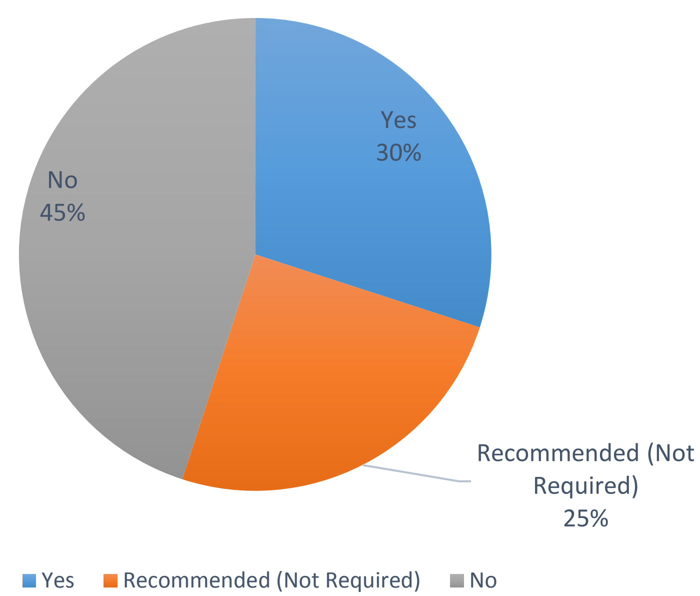
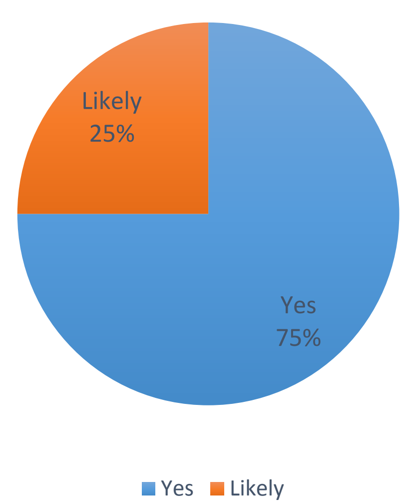


Figure 8
Accept API Worksheet to Calculate T_n



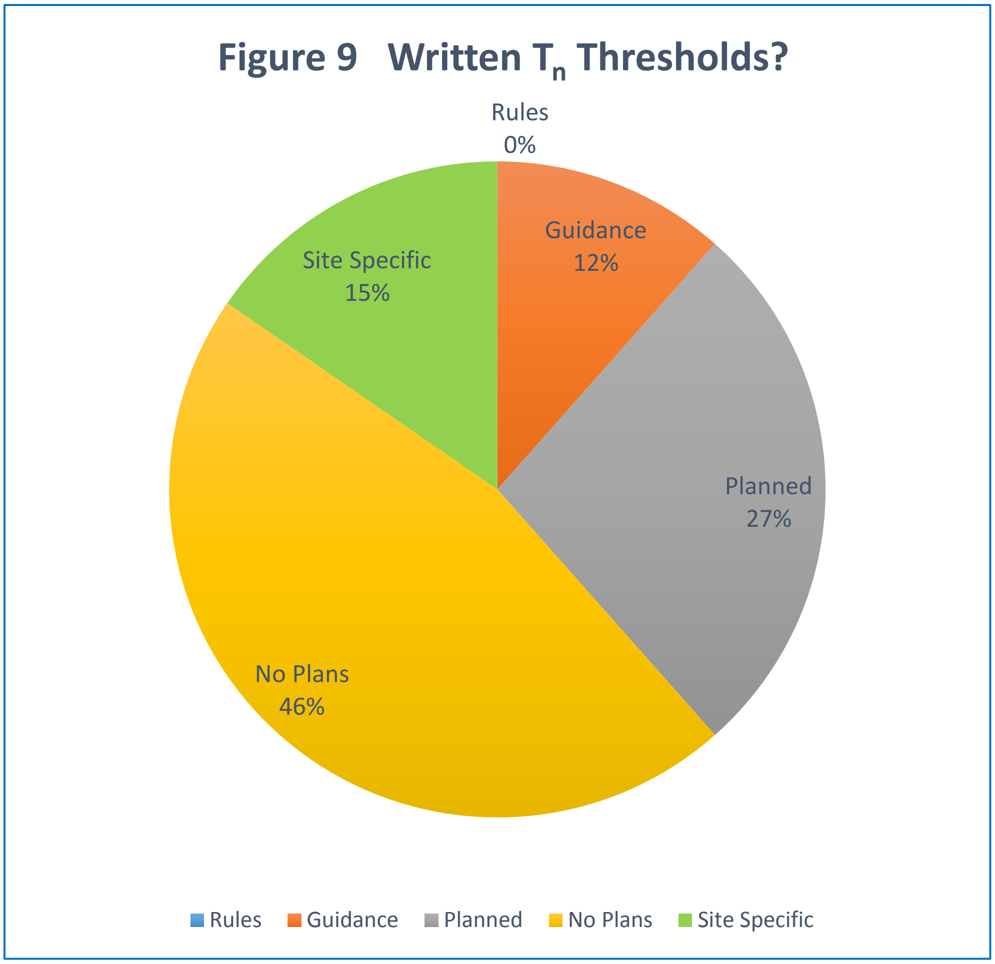
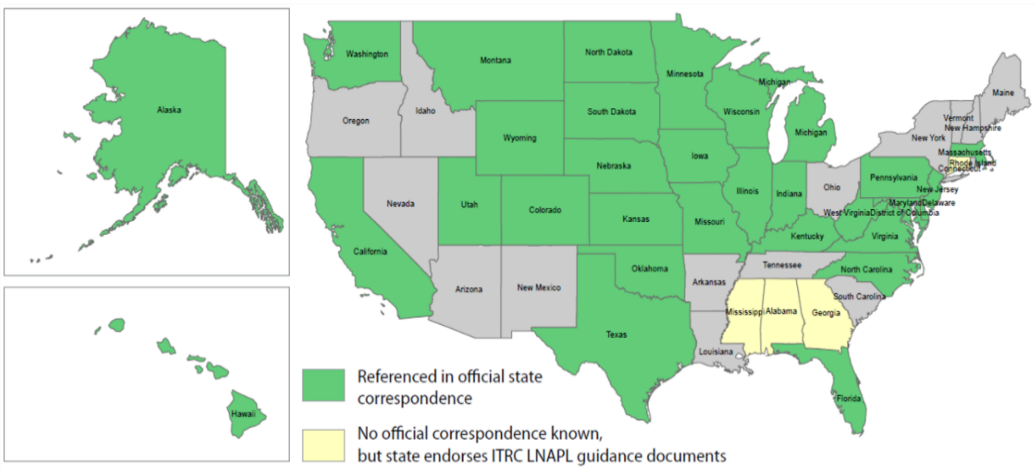


Figure 9 Written T_n Thresholds?
Rules
0%
Guidance
12%
Planned
27%
No Plans
46%
Site Specific
15%
Rules
Guidance
Planned
No Plans
Site Specific

Figure 10 **A regulatory framework exists. T_n has been accepted in most states in official state correspondence as a remedy start-up metric, progress metric, remedy shutdown metric, and/or to represent MEP.**



Several states have also included Tn metrics in regulations and/or official guidance documents.

State	T_n Threshold	Metric Use
Massachusetts	0.8 ft^2/day	MEP
Kansas	0.8 ft^2/day	MEP
Michigan	0.5 ft^2/day	MEP
Colorado	Site-Specific	MEP
Virginia	Site-Specific	MEP
Iowa	N/A	Site Characterization

Modified after Hawthorne et al (2016)