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Re-Evaluation of F2 and F3 Petroleum Hydrocarbon Management Limits

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1.0 INTRODUCTION

Management limits for petroleum hydrocarbon (PHC) fractions were established to indicate concentrations where factors other than toxicity, such as aesthetics, mobile free-phase formation and explosion hazards may be of concern. Two sets of management limits for PHC fractions F2 and F3 are currently applicable in Alberta, one set in the Tier 1 guidelines document (AEP, 2022) applicable to all land uses, and one set specific to remote parts of the Green Area (ESRD, 2014).

The existing management limits are based on consideration of a range of factors. This document examines the scientific basis for the management limits assessed for each of these factors, reports on additional research and analysis completed to refine the understanding of these factors and makes recommendations for updated F2 and F3 management limits.

1.1 Objective

The objectives of the current project are to re-examine the scientific basis for the current petroleum hydrocarbon fraction F2 and F3 management limits and, where appropriate, to develop revised management limits with a more robust scientific basis.

1.2 Scope of Work

The scope of work for this project includes the following tasks:

1. Review the background and context for the existing PHC management limits;
2. Re-evaluate the relevant factors to include in calculating PHC management limits in various land uses in Alberta;
3. Clearly summarize the scientific basis of the management limit component associated with each factor considered in the current PHC management limits;
4. Evaluate the scientific defensibility of each management limit component;
5. As required, commission or conduct additional research and analysis to improve the scientific defensibility of each management limit component; and,
6. If appropriate, make recommendations for updated management limits for F2 and F3.

1.3 Funding Acknowledgements

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1.4 Key Source Documents

Three documents are referenced extensively through the current work. These documents are listed below for convenience:

1. CCME (Canadian Council of Ministers of the Environment), 2008. *Canada-Wide Standard for Petroleum Hydrocarbons (PHCs) in Soil: Scientific Rationale*. This document explains how the original PHC management limits were derived by CCME in 2008. The original 2001 version of this document was also consulted for historical details, as well as unpublished documents and communications from the 2008 update of the Canada-Wide Standard.
2. Alberta Environment and Sustainable Resource Development (ESRD), 2014. *Subsoil petroleum hydrocarbon guidelines for remote forested sites in the Green Area*. This document provides updated PHC management limits for F2 and F3 for use in remote parts of the Green Area of Alberta.
3. Petroleum Technology Alliance Canada (PTAC), 2013. *Proposed management limits for F2 and F3 Petroleum Hydrocarbons at Remote Alberta Green Area Sites*. This document provides more details of the new research findings upon which the above document (ESRD, 2014) was based.

2.0 BACKGROUND AND CONTEXT FOR PHC MANAGEMENT LIMITS

The Alberta Tier 1 guideline framework (AEP, 2022) sets soil remediation guidelines based primarily on a range of exposure pathways related to avoiding adverse toxicity-based effects on a range of human and ecological receptors. It is acknowledged that there are other considerations relevant to setting soil remediation guidelines. Within the Tier 1 soil guideline framework, these other considerations are grouped together as a guideline called a management limit. Two documents have developed management limits for PHCs, the CCME (2008) "Canada-Wide Standard for Petroleum Hydrocarbons" and the ESRD (2014) document "Subsoil Petroleum Hydrocarbon Guidelines for Remoted Forested Sites in the Green Area". The management limits developed in these two documents are summarized below.

2.1 Petroleum Hydrocarbon Canada-Wide Standard (2008)

The management limits for petroleum hydrocarbon fractions currently used in the AEP (2022) Tier 1 guidelines were adopted without change from the CCME (2008) Petroleum Hydrocarbon Canada-Wide Standard. CCME (2008) recognized that the potential adverse effects of PHC are not limited to chronic toxicity to human and ecological receptors. CCME (2008) identified six factors that were considered to develop their management limits. Those six factors were as follows:

1. Mobile free phase formation;
2. Exposure of workers in trenches to PHC vapours;

3. Fire and explosion hazard;
4. Effects on buried infrastructure;
5. Aesthetic considerations; and
6. Technological factors.

These factors were evaluated quantitatively, semi-quantitatively or qualitatively as available data permitted. The rationale for setting the existing value for each factor is summarized in Section 4. An assessment of the scientific defensibility of each factor, together with additional research and analysis conducted in relation to each management limit component is provided in Section 5.

The overall PHC management limits that were developed by CCME (2008) were adopted without change in the current Alberta Tier 1 guidelines document (AEP, 2022) and are summarized in Table 1.

Table 1 Existing Overall PHC Management Limits – Alberta Tier 1

PHC Fraction	Management Limit (mg/kg)	
	Fine Soil	Coarse Soil
F1	800	700
F2	1,000	1,000
F3	3,500	2,500
F4	10,000	10,000

2.2 Subsoil Petroleum Hydrocarbon Guidelines for Remote Sites in the Green Area

Alberta (ESRD, 2014) has also published PHC management limits for PHC fractions F2 and F3 that can be applied in subsoils in the Green Area of Alberta when the site meets the following five conditions:

1. The site is within the Green Area;
2. The site is in a forested area and is, or will be reclaimed to a forested ecosystem;
3. The site is remote from existing residences and roads;
4. There is no dugout on site and future construction of a dugout is unlikely; and,
5. The site is stable.

Detailed guidance on how to assess these five conditions is provided in ESRD (2014).

In developing these revised management limits, ESRD (2014) and PTAC (2013) considered the six factors considered by CCME (2008) (Section 2.1 above). Some of these factors were not considered relevant to the remote Green Area setting and were not included. Conversely, some factors not considered by CCME (2008) were included for consideration by ESRD (2014). The factors included for detailed consideration by ESRD (2014) were:

1. Mobile free phase formation;
2. Fire and explosion hazard;
3. Hydrophobicity; and
4. Upwards migration of hydrocarbons into the root zone.

These factors were evaluated quantitatively, in several cases by commissioning new experimental research. The ESRD (2014) rationale for setting the existing value for each factor is summarized in Section 4, while scientific defensibility, both in the context of remote Green Area sites, and more widely in Alberta, is discussed in Section 5.

The overall PHC management limits that were developed by ESRD (2014) for remote Green Area subsoils are summarized in Table 2.

Table 2 Existing Overall PHC Management Limits – Alberta Remote Green Area Subsoil

PHC Fraction	Management Limit (mg/kg)	
	Fine Soil	Coarse Soil
F2	10,000	9,000
F3	14,000	4,000

Note: ESRD (2014) notes that when applying these management limits, the sum of the concentrations of PHC fractions F1 to F4 must not exceed 30,000 mg/kg.

3.0 FACTORS TO BE CONSIDERED IN SETTING MANAGEMENT LIMITS

Existing sources of PHC management limits (Sections 2.1 and 2.2) identified an aggregate of 8 potential factors to be evaluated when developing management limits.

1. Mobile free phase formation;
2. Exposure of workers in trenches to PHC vapours;
3. Fire and explosion hazards;
4. Effects on buried infrastructure;
5. Aesthetic considerations;

6. Technological factors;
7. Hydrophobicity; and,
8. Upwards migration of hydrocarbons into the root zone.

No other relevant factors were identified in the current review, and the above list is considered to be complete. Note that issues related to toxicity are evaluated elsewhere in the Tier 1 guideline framework.

3.1 Relevance of Factors by Land Use

The following factors are assessed as being relevant in all land use designations:

1. Mobile free phase formation;
2. Fire and explosion hazards;
3. Hydrophobicity; and
4. Upwards migration of hydrocarbons into the root zone.

The "Technological Factors" consideration is not retained going forward (see Section 5.6).

Three factors are considered relevant only to land uses outside the remote Green Area, as discussed below.

The remote Green Area is defined (ESRD, 2014) as an area within the Green Area of Alberta and sufficiently remote from human activities that it can be safely assumed that the soil profile will not be disturbed by human activities in the foreseeable future. Under these conditions, the following factors are not considered relevant in this land use:

1. Exposure of workers in trenches to PHC vapours;
2. Effects on buried infrastructure; and,
3. Aesthetic considerations.

The exposure of workers in trenches to PHC vapours and effects on buried infrastructure are not relevant in a remote Green Area setting because the construction or presence of utility lines and trenches is highly unlikely in such remote areas.

Aesthetic considerations are also not relevant in a remote green zone setting as the subsoil profile is unlikely to be disturbed and therefore aesthetic issues are not relevant.

4.0 BASIS FOR CURENT VALUE FOR EACH FACTOR

4.1 Mobile Free Phase Formation

Both CCME (2008) and ESRD (2014) considered mobile free phase formation to be a relevant factor in setting management limits. The threshold at which free phase hydrocarbon starts to be mobile is often referred to as the residual saturation for that hydrocarbon fraction in a given soil type.

4.1.1 CCME (2008)

A narrative is provided in Section 5.3.1 of CCME (2008) discussing some of the thinking behind the limits adopted to manage this factor. The overall objective was to set concentration limits for each PHC fraction below which the presence of mobile free phase was considered unlikely. However, at the time there were no available relevant experimental data for PHC hydrocarbon fractions F1 to F4, and limits were extrapolated from more general observations on whole hydrocarbon products.

The approach adopted was semi-quantitative for PHC fractions F2 to F4, and somewhat more quantitative for F1 (though still not based on experimental data).

The approach for fractions F2 to F4 was semi-quantitative and based on some general statements attributed to Mercer and Cohen (1990) for a range of soils and petroleum hydrocarbon types that "mobile free-phase formation is often observed when 10% to 20% of the soil pore space contains hydrocarbons". CCME (2008) used this to estimate that the residual saturation limit occurs with total PHC concentrations on the order of 20,000 mg/kg to 30,000 mg/kg (2% to 3% total PHC by weight). A management decision was made to set a limit of 2% total PHC in soil, of which no more than 1% should be the sum of fractions F1 to F3, and 1% F4.

A higher level of concern was noted for F1 due to the higher mobility and solubility of this fraction and limits of 800 mg/kg and 700 mg/kg were set for F1 in fine and coarse soil, respectively based on considerations relating to the solubility of individual sub-fractions of F1.

Thus, the limits set by CCME (2008) to manage mobile free phase formation were:

1. F1: 800 mg/kg (fine soils) and 700 mg/kg (coarse soils);
2. F2+F3: 9,200 mg/kg (fine soils) and 9,300 mg/kg (coarse soils); and
3. F4: 10,000 mg/kg.

4.1.2 ESRD (2014)

ESRD (2014) management limits are based on a research document by PTAC (2013) (Also reported in Drozdowski *et al*., 2013) which determined that the lack of experimental data on the residual saturation for hydrocarbon fractions F1 to F4 was a data gap in the CCME analysis.

PTAC (2013) commissioned a program of experimental research to determine scientifically defensible values for the residual saturation of F2 and F3 in coarse and fine soil types. This program involved setting up soil in 1,000 ml glass cylinders, saturating the soil with F2 or F3 hydrocarbon, and allowing the soil to drain until no further mobile free phase was released. The concentration of hydrocarbon remaining in the soil was interpreted as the residual saturation for that hydrocarbon fraction and soil type. An additional check was made by flooding the equilibrated columns with water from below and determining whether further hydrocarbon could be mobilized. The residual saturation was revised downward to account for any hydrocarbon mobilized in this way.

Two phases of experimentation were undertaken. The experimental design for Phase 1 (range finding) included two soil types (coarse and fine), two hydrocarbon fractions (F2 and F3), two initial moisture conditions (dry, and field capacity) and 3 replicates of each condition (total 24 columns). The drainage period for Phase 1 was 7 days. The experimental design for Phase 2 (definitive) included two soil types (coarse and fine), two hydrocarbon fractions (F2 and F3), one initial moisture condition (field capacity) and 3 or 6 replicates of each condition (total 21 columns). The drainage period for Phase 2 was 21 days.

The thresholds recommended by PTAC (2013) and adopted by ESRD (2014) to prevent the risk of formation of mobile free phase PHC fractions F2 and F3 in coarse and fine soil are summarized below.

1. F2 in fine soils: 10,000 mg/kg;
2. F2 in coarse soils: 9,000 mg/kg;
3. F3 in fine soils: 14,000 mg/kg; and
4. F3 in coarse soils: 34,000 mg/kg.

4.2 Exposure of Workers in Trenches to PHC Vapours

Exposure of workers in trenches to PHC vapours was considered by CCME (2008), but not by ESRD (2014) since this factor was not considered relevant in the Green Area (Section 3.1).

CCME (2008) evaluated risks to workers in trenches using a vapour model published by Virginia Department of Environmental Quality (VDEQ, 2005). Two separate scenarios were evaluated:

- Vapour intrusion into a trench with width greater than depth (reflecting >45° sloped sidewalls). For this scenario it was assumed that workers could spend significant time in the trench, and the same toxicity reference values were applied as for indoor vapour inhalation.
- Vapour intrusion into a trench with depth greater than width, with assumed air exchange rate similar to residential buildings. It was assumed that workers would spend limited time in these trenches. For F2, model results were compared to the occupational exposure limit for jet fuel/kerosene in the absence of relevant short-term exposure limits for F2; the occupational exposure limit for gasoline was used for F1.

For both scenarios it was assumed that the PHC were in direct contact with the trench.

A value of 1,000 mg/kg was determined to be protective for both F1 and F2 for coarse and fine soils.

4.3 Fire and Explosion Hazards

Both CCME (2008) and ESRD (2014) considered fire and explosion hazards.

4.3.1 CCME (2008)

CCME used the VDEQ (2005) trench model to determine threshold concentrations for PHC fractions in soil below which the migration of hydrocarbon vapours into a nearby confined space was not a concern from a fire and explosion perspective.

Limiting concentrations were calculated for fractions F1 and F2 as follows:

1. F1: 1,700 mg/kg (fine soils) and 1,400 mg/kg (coarse soils); and
2. F2: 5,200 mg/kg (fine and coarse soils).

4.3.2 ESRD (2014)

ESRD (2014) management limits are based on a research document by PTAC (2013). PTAC (2013) took an experimental approach to evaluating threshold concentrations of PHC fractions F2 and F3 in soil in relation to fire and explosion hazards. PTAC (2013) conducted a simple ambient temperature flammability test by passing an open flame directly over a series of soil samples spiked with a range of concentrations of the hydrocarbon fraction being tested.

PTAC (2013) found that even at the maximum concentration tested, 64,000 mg/kg, neither F2 nor F3 spiked samples ignited in either soil type when a flame was applied. Subsequently a flame was applied directly to F2 and F3 product, and neither would ignite.

The conclusion of the PTAC (2013) work, therefore, was that fire and explosion hazards were not a concern for either F2 or F3 under any circumstances.

4.4 Effects on Buried Infrastructure

This factor was considered by CCME (2008) but was not considered relevant to a remote Green Area setting by ESRD (2014).

CCME (2008) noted that this issue was of potential concern, particularly in relation to the possibility of PHC entering water distribution systems. However, CCME (2008) referenced a review of all information available on this subject by Stantec (2003) and concluded that available data were not adequate at that time to derive meaningful thresholds for the PHC fractions on a generic basis. CCME (2008) recommended that potential effects of PHC on buried infrastructure should be addressed on a site-specific basis where utilities or other infrastructure are in contact with contaminated soil.

In summary, CCME (2008) flags this issue as being of potential concern, but recommend it be managed on a site-specific basis where potential issues arise.

4.5 Aesthetic Considerations

This factor was considered by CCME (2008) but was not considered relevant to a remote Green Area setting by ESRD (2014).

CCME (2008) flagged odours, visible effects on soil, effects on the taste of potable water and visible plant damage as potential issues but noted that aesthetic effects are somewhat subjective and may be highly dependent on site-specific factors. CCME (2008) did not set quantitative thresholds in relation to this issue due to lack of available data and the considerations noted above. CCME (2008) noted that other issues evaluated as part of management limits and/or other exposure pathways within the Tier 1 guidelines will generally be sufficient to manage aesthetic issues. However, aesthetic impacts should be addressed on a site-specific basis when they occur.

In summary, CCME (2008) flags this issue as being of potential concern, but recommend it be managed on a site-specific basis where issues arise.

4.6 Technological Factors

This factor was considered by CCME (2008) but was not considered relevant to a remote Green Area setting by ESRD (2014).

The term “Technological Factors” appears to be used by CCME (2008) to describe a set of thresholds for F3 that were adopted “without review” from the previous (2001) version of the document. These thresholds appear to be a catch-all for a range of potential issues including "toxic risk, aesthetics, effects on infrastructure and bioremedial capabilities". Several of these issues are managed elsewhere within the CCME (2008) management limits or the Tier 1 guidelines. The exception is bioremedial capabilities. It is understood from discussions that took place around the time of the CCME (2008) document that these thresholds are related in some way to aged and weathered sites where bioremediation of F3 hydrocarbons had initially been successful but had "stalled" at concentrations in this range, but the details are now unclear, and not recorded in the CCME (2008, 2001) documentation. The F3 thresholds indicated in CCME (2008) are as follows:

1. F3: 2,500 mg/kg (coarse subsoils, agricultural and residential uses);
2. F3: 3,500 mg/kg (coarse subsoils, commercial and industrial uses);
3. F3: 3,500 mg/kg (fine subsoils, agricultural and residential uses); and,
4. F3: 5,000 mg/kg (fine subsoils, commercial and industrial uses).

In summary, CCME (2008) provides thresholds for "Technological Thresholds" for F3 only. These values may be based to some extent on practical considerations relating to bioremediation of F3 in soils, but the rationale provided in CCME (2008) is vague, and the current relevance of these values is unclear.

4.7 Hydrophobicity

This factor was considered by ESRD (2014) but was not included in the issues considered by CCME (2008).

When soils are exposed to high concentrations of hydrocarbons, they can become hydrophobic. Hydrophobic soils tend to repel water rather than allow it to penetrate, and this is clearly a condition that could impact the normal functioning of a soil and therefore should be avoided.

The ESRD (2014) approach to this issue was based on PTAC (2013) research using the molarity of ethanol droplet (MED) test on soil concentration series (coarse and fine) spiked with F2 and F3 hydrocarbons. In the MED test, water droplets with increasing concentrations of ethanol are placed on the surface of the soil, and the result of the test is the lowest concentration of ethanol that allows the droplet to penetrate the soil within 10 s. For non-hydrophobic soils, a droplet of pure water will be absorbed within 10s. In practice, therefore, this test was conducted by testing a concentration series of F2 or F3 spiked into coarse or fine soil. The highest concentration of hydrocarbon that did not cause any trace of hydrophobicity (*i.e.,* a drop of pure water would be absorbed within 10s) was deemed to be the conservative hydrophobicity threshold.

The results of the PTAC (2013) hydrophobicity testing of F2 and F3 hydrocarbons in fine and coarse soil were as follows:

1. F2 in fine soil, hydrophobicity threshold >64,000 mg/kg.
2. F2 in coarse soil, hydrophobicity threshold >64,000 mg/kg.
3. F3 in fine soil, hydrophobicity threshold approximately 40,000 mg/kg.
4. F3 in coarse soil, hydrophobicity threshold approximately 4,000 mg/kg.

4.8 Upwards Migration into Root Zone

ESRD (2014) and PTAC (2013) also investigated whether upwards migration of hydrocarbons from subsoil back up into the root zone might be a limiting consideration. This question had been previously investigated in a series of column experiments by Startsev (2009).

In the Startsev (2009) experiment, 2 m columns were packed with soil that was contaminated with either jet fuel or crude oil in the bottom 50 cm, and soil without any PHC in the top 1.5 m. Control columns had soil without PHC over the whole 2 m profile. Alfalfa was planted in the columns. The experiment was run for 15 months, during which time the above ground parts of the alfalfa were harvested 5 times. Appropriate moisture content for alfalfa growth was maintained in the test columns by supplying capillary water at the bottom of each column, and accordingly there was an upwards moisture gradient in the columns throughout the experiment. These experimental conditions represent a worst-case scenario for potential upwards movement due to the strong and continuous upwards moisture gradient. Actual conditions in Alberta soil would typically not have such a strong upwards moisture gradient.

Comparison of the chemical analysis of the contaminated 1.5 m to 2 m zone with the overlying 1.0 to 1.5 m zone indicated that, at most, trace amounts of PHC migrated up into the root zone over the 15-month duration of the experiment. Over this same time period there was significant upwards migration of salts through the soil columns in the fine soils experiment.

Overall, ESRD (2014) and PTAC (2013) concluded that upward migration of F2 or F3 hydrocarbons from subsoil up into the root zone was not a limiting concern in setting management limits for hydrocarbons at Green Area sites.

5.0 REASSESSMENT AND RECOMMENDATIONS FOR EACH FACTOR

5.1 Mobile Free Phase Formation

Mobile free phase formation is evaluated as a relevant consideration in all land uses, as the presence of free phase hydrocarbon is undesirable. This consideration should be included in setting management limits in all land uses and situations.

The ESRD (2014) approach to setting F2 and F3 thresholds for mobile free phase formation is based on PTAC (2013) data with a high degree of relevance to the question at hand, and has a high degree of scientific defensibility for the following reasons:

1. The thresholds are based on actual measurements of free phase mobility.
2. The experiments were conducted with F2 and F3 hydrocarbon fractions generated by distilling crude oil sourced from Alberta.
3. The coarse and fine soils used in the experiments were field-collected soils from Alberta.
4. Adequate replication was conducted.
5. Results were corrected for any free phase that could be re-mobilized by simulated changes of water table depth following initial equilibration.

These high-quality data were not available at the time of the CCME (2008) evaluation, and accordingly that study was obliged to extrapolate from a 1990 paper that made some general statements about residual saturation thresholds for unspecified whole hydrocarbon products in unspecified soil types.

Overall, it is clear that the PTAC (2013) data are more relevant and more scientifically defensible than the data on which the CCME (2008) evaluation was based. Accordingly, the ESRD (2014) thresholds are adopted in the current work and are relevant and applicable in all soil types and land uses.

5.2 Exposure of Workers in Trenches to PHC Vapours

The exposure of workers in trenches to PHC vapours is evaluated as a relevant consideration in all land uses except for remote Green Area. It is assumed that utility trenches will rarely be installed in areas classified as remote Green Area. The CCME (2008) limits for this factor (1,000 mg/kg for F2 for both coarse and fine soils) were established based on a trench vapour model published by VDEQ (2005). A range of trench scenarios were investigated including trenches with their width greater or less than their depth, and with the contaminated soil either at 30 cm distance or directly in contact with trench walls. Some details of the modelling scenarios considered are available in Meridian (2006), and subsequently, Meridian (2010) conducted a review of other possible modelling approaches.

There is significant uncertainty surrounding the CCME (2008) management limit of 1,000 mg/kg calculated for this factor. The two primary reasons for this uncertainty are:

1. The VDEQ model, and most of the other models identified by Meridian (2010) are based on diffusion of vapours through soil close to the trench wall. Such diffusion-based models tend to be extremely sensitive to the model parameters selected, including soil porosity, soil moisture, and particularly the assumed distance between contamination and trench wall.
2. A lack of field verified air exchange rate values for trenches. The CCME (2008) calculations adopt the recommended trench air exchange rates in the VDEQ model, which are 360/hour where trench width is greater than depth and 2/hour otherwise.

The current project significantly reduced these two primary uncertainties as follows.

A literature review was carried out to see whether better data on field verified air exchange rate values for trenches were available since the CCME (2008) work was completed. Thompson *et al*. (2017) conducted an empirical field study specifically to investigate the validity of the default air exchange rates of 360/hour and 2/hour in the VDEQ model. These authors measured the air exchange rate in five trenches all 3 feet wide and 8 feet deep in various orientations to the prevailing wind direction and under various conditions. They found an average air exchange rate of 46/hour and that figure is adopted here.

In order to reduce the uncertainty associated with diffusion-based models it was decided to measure the actual flux rates and vapour concentrations that occur when coarse- and fine-grained soil spiked with F2 is exposed to the air. Three phases of experiments were conducted by InnoTech Alberta as follows:

- Phase 1 measured the equilibrium headspace vapour concentrations of F2 in equilibrium with F2 spiked soils.
- Phase 2 measured how the transient headspace vapour concentrations of F2 increased over time in a static headspace in contact with F2 spiked soils.
- Phase 3 measured the F2 vapour concentration in flow-through cells containing F2 spiked soils with an air exchange rate of 46/hour.

Full experimental details are available in the InnoTech reports included in Appendix A (Phase 1) and Appendix B (Phases 2 and 3).

The InnoTech Phase 3 data were used, together with the updated trench air exchange rate noted above to calculate revised management limits for this factor. Full details of these calculations are provided in Appendix C. The revised management limits for F2 for the exposure of workers in trenches to PHC vapours factor are:

- Fine-grained soil: 17,000 mg/kg.
- Coarse-grained soil: 4,000 mg/kg.

These values are based on measured data for trench air exchange rate and F2 flux rate and a very simple box mixing model for trench air. As such, these values have a much lower uncertainty than the values developed in CCME (2008) and are adopted in the current work.

5.3 Fire and Explosion Hazards

Fire and explosion hazards are evaluated as a relevant consideration in all land uses, since it is clearly important that residual hydrocarbon concentrations are not present in soils at concentrations that could result in these risks.

Experimental work reported in PTAC (2013) confirmed that neither F2 nor F3 is flammable under ambient environmental conditions, and therefore there is no guideline required (NGR) in relation to this issue for F2 and F3. The experimental finding that F2 is not flammable when a flame is directly applied to the free product supersedes the F2 guideline of 5,200 mg/kg calculated indirectly by CCME (2008) using modelling approaches (see Section 4.3).

5.4 Effects on Buried Infrastructure

Effects on buried infrastructure are evaluated as a relevant consideration in all land uses except for remote Green Area, since it is important that residual hydrocarbon concentrations are not present in soils at concentrations that could result in these risks in areas where buried infrastructure could reasonably be expected.

CCME (2008) considered a review by Stantec (2003) that evaluated the data available at that time to support an evaluation of these risks. Stantec (2003) and CCME (2008) concluded that the data available at that time were not sufficient to enable a quantitative evaluation and recommended that any issues be dealt with on a site-specific basis. The current project collected additional empirical data to help identify whether the above approach is reasonable.

In Phase 2 of this project, additional data were gathered to strengthen the scientific rationale behind setting management limits for this consideration. The primary focus was on water distribution systems, consistent with the primary concern identified by CCME (2008). Of the other types of buried infrastructure listed by AEP (2022), it seems unlikely that the vulnerability to PHCs of steel or concrete infrastructure such as pilings, pipelines or foundations would be a limiting concern.

Considerations related to fibre-optic cable were included in a literature review in the InnoTech (2020) report (Appendix A). Information from utility companies indicated that fibre-optic cable is usually laid at depths shallower than 1.5 m where other exposure pathways such as the ecological direct contact pathway will typically limit PHC concentrations. In addition, fibre-optic cable is typically laid inside a protective conduit and will not generally be directly exposed to PHC-impacted soil.

Underground power cables were not explicitly considered in the InnoTech review, but it is assumed that, as with fibre-optic cable, power cable will normally be laid inside a protective conduit, and that the cable would not be directly exposed to PHCs in sub-surface soil.

For the reasons indicated above, experimental work in the InnoTech (2020) study focused on the possible effects of PHCs on water distribution piping. The two main concerns for water distribution piping exposed to PHCs in soil are possible physical deterioration of the pipe resulting in integrity issues, and potential infiltration of PHCs into the interior of the pipe where drinking water could be tainted. The InnoTech (2020) literature review indicated that the commonest materials used for water distribution piping in Alberta were polyvinyl chloride (PVC), high density polyethylene (HDPE), and fibre-reinforced plastic (FRP), with PVC being the commonest.

Full details of the experimental work conducted to investigate these two concerns are available in the InnoTech (2020) report (Appendix A). Two experimental programs were conducted. Key findings are summarized briefly below.

The intent of the first program was to assess possible degradation of water supply piping in the presence of F2 or F3 hydrocarbons. Coupons of PVC, HDPE, and FRP pipe material were incubated in pure F2 or F3 for 80 days. No significant changes were apparent to either the appearance of the coupons or to their physical properties over the incubation period.

The intent of the second program was to assess whether PHC F2 could infiltrate into water distribution piping. PVC piping was selected for this experiment as the literature review had indicated that PVC was the most common material used in Alberta for this purpose. No experiment was conducted with PHC F3, as F3 is effectively insoluble (AEP, 2022). Full details of the experimental setup are available in Appendix A. In summary, the experimental setup involved 15 cm lengths of 150 mm internal diameter water distribution piping with 11 mm wall thickness. The pipe sections were capped at both ends using an epoxy and silicone caulking and filled with water. Each pipe segment was surrounded by cotton batting soaked in F2. The pipes were incubated for 80 days and then water samples were collected and analyzed. There was no measurable infiltration of F2 from pure F2 in contact with the outside of the pipe into water inside the pipe when incubated for 80 days. This length of time is extremely conservative for how long water would be expected to remain stagnant in a water distribution system because a pipe of this size would be expected to supply many residences. In addition, exposing a water filled pipe to pure F2 is very conservative in relation to exposing a pipe to soil with F2 at a nominal level of 10,000 mg/kg, for example.

Given the findings from the experimental work presented in this report, there seems to be no realistic possibility that F2 infiltration into water distribution piping would be a concern under any circumstances. In addition, fibre-optic cable and underground power cable would normally be protected in a conduit and not directly exposed to PHC-impacted soil. Other buried infrastructure constructed from concrete or steel is considered highly unlikely to be adversely affected by PHCs in soil.

No change is therefore recommended from the CCME (2008) conclusion that effects on buried infrastructure are not expected, and any issues should be addressed on a site-specific basis.

5.5 Aesthetic Considerations

Aesthetic considerations are evaluated as a relevant issue in all land uses except for remote Green Area. CCME (2008) identified a range of aesthetic considerations potentially associated with high concentrations of residual PHC in soil. They identified some of these potential considerations as being sufficiently managed through various exposure pathways evaluated in the Tier 1 guideline framework (odour issues in indoor dwellings, tainting of drinking water, and visible plant damage). The remaining issues identified by CCME (2008) that would fall within the scope of a management limit were soil odours and visible effects on soil. CCME (2008) noted that aesthetic effects are somewhat subjective and may be highly dependent on site-specific factors. CCME (2008) did not set quantitative thresholds in relation to this issue due to lack of available data and the considerations noted above.

As noted by CCME (2008), these aesthetic issues are somewhat subjective and may be highly dependent on site-specific factors. Management limits typically are only ever limiting for subsoils below 1.5 or 3 m. Accordingly, the issue of odours and visible effects really only applies in a situation where subsoil is excavated or otherwise disturbed. Data on olfactory thresholds for PHC fractions in soil are not currently available. However, even if they were, it is unclear how to include these aesthetic considerations in a management limit value, given the above considerations and also the expectation that even if soils are disturbed or excavated and brought to surface, degradation of hydrocarbons will occur on soil surfaces exposed to the air.

CCME (2008) elected to retain aesthetics as a relevant consideration, but not to attempt to set a generic numerical threshold for this issue, and to manage any issues on a site-specific basis. On balance this still appears to be a reasonable and appropriate way to manage this issue and this approach is retained in the current work.

5.6 Technological Factors

As noted in Section 4.6, the term "Technological Factors" appears to be used by CCME (2008) to describe a set of thresholds for F3 that were adopted "without review" from the previous (2001) version of the document. No quantitative information is provided in CCME (2008) concerning how these thresholds were calculated beyond a vague statement referencing a range of potential issues including "toxic risk, aesthetics, effects on infrastructure and bioremedial capabilities". Since most of these issues are dealt with elsewhere in this document or in the Tier 1 guideline framework, "Technological Factors" were not included in the list of valid factors for calculating management limits for petroleum hydrocarbons.

5.7 Hydrophobicity

Hydrophobicity is evaluated as a relevant consideration for all land uses, since it is important that residual hydrocarbon concentrations are not present in soils at concentrations that could result in soils becoming hydrophobic.

The PTAC (2013) approach to setting F2 and F3 thresholds for hydrophobicity has a high degree of relevance to the question at hand, and has a high degree of scientific defensibility for the following reasons:

1. Hydrophobicity thresholds were determined experimentally using F2 and F3 hydrocarbon fractions generated by distilling crude oil sourced from Alberta.
2. The coarse and fine soils used in the experiments were field-collected soils from Alberta.
3. Adequate replication was conducted.

The PTAC (2013) hydrophobicity thresholds are adopted in the current work.

5.8 Upwards Migration into Root Zone

Upwards migration of hydrocarbon fractions from subsoil into the rooting zone is evaluated as a relevant consideration in all land uses, since this could result in possible future impact on plant growth, which would be undesirable.

Experimental work conducted by Startsev (2009) evaluated this consideration under worst case conditions (strong upward moisture gradient). Evaluation of the results of the Startsev (2009) work by PTAC (2013) indicated that at worst only trace amounts of hydrocarbon moved up into the rooting zone and therefore there is no guideline required (NGR) in relation to this issue for F2 and F3.

The relevance and scientific defensibility of the Startsev (2009) experimental work and the PTAC (2013) analysis are evaluated as high, based on the following:

1. The experimental setup with hydrocarbon contaminated soil placed in columns immediately below 1.5 m of clean rooting zone is relevant to real world situations.
2. Water was provided only to the base of the columns, resulting in a strong upward moisture gradient and therefore experimental results are conservative relative to most real-world conditions.
3. The experiments were run for a sufficient time period (15 months) to see significant upward transport of salts (conservative solutes) thus confirming that the lack of upwards hydrocarbon movement was a meaningful finding.
4. Adequate replication was conducted.

The PTAC (2013) finding that there is no guideline required (NGR) is retained in the current work in relation to the possibility of upward migration of F2 and F3 from subsoil into the rooting zone for F2 and F3.

6.0 RECOMMENDED UPDATED MANAGEMENT LIMITS FOR F2 AND F3

Based on currently available data and the discussion in Sections 4 and 5 of this document, the recommended relevant factors for setting management limits together with threshold values for each consideration summarized in Table 3. Overall recommended management limits for i) remote green zone areas, and ii) all other land uses are summarized in Table 4.

Table 3 Recommended Management Limit Components (mg/kg)

Consideration	F2		F3	
	Fine Soil	Coarse Soil	Fine Soil	Coarse Soil
Factors Relevant in All Land Uses				
Mobile free phase formation	10,000	9,000	14,000	34,000
Fire and explosion hazards	NGR	NGR	NGR	NGR
Hydrophobicity	>64,000	>64,000	40,000	4,000
Upwards migration of hydrocarbons into the root zone	NGR	NGR	NGR	NGR
Factors Relevant in All Land Uses Except Remote Green Area				
Exposure of workers in trenches to PHC vapours	17,000	4,000	NGR	NGR
Aesthetic considerations	SSB	SSB	SSB	SSB
Effects on buried infrastructure	SSB	SSB	SSB	SSB

Notes:
NGR = no guideline required
SSB = any issues should be managed on a site-specific basis

Table 4 Recommended Overall Management Limits(mg/kg)

Land Use	F2		F3	
	Fine Soil	Coarse Soil	Fine Soil	Coarse Soil
Remote Green Access	10,000	9,000	14,000	4,000
All Other Land Uses and Areas	10,000	4,000	14,000	4,000

7.0 CLOSURE

This report was prepared by Millennium EMS Solutions Ltd. ("MEMS") for the Petroleum Technology Alliance of Canada ("PTAC") and has been completed in accordance with the PTAC Technical Steering Committee's ("TSC") terms of reference. This report does not necessarily represent the views or opinions of PTAC or the PTAC members.

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8.0 REFERENCES

Alberta Environment and Parks (AEP), 2022. Alberta Tier 1 *Soil and Groundwater Remediation Guidelines*. Land Policy Branch, Policy and Planning Division. 189 pp.

Alberta Environment and Sustainable Resource Development (ESRD), 2014. Subsoil petroleum hydrocarbon guidelines for remote forested sites in the Green Area. ESRD, Reclamation and Remediation, 2014, No. 4. September 12, 2014.

CCME (Canadian Council of Ministers of the Environment), 2008. Canada-Wide Standard for Petroleum Hydrocarbons (PHCs) in Soil: Scientific Rationale. Supporting Technical Document, January 2008.

Drozdowski, B., Fraught, B., and Degenhardt, D., 2013. Residual Saturation, Fire/Explosion Hazard and Hydrophobicity Methodology and Results. PTAC - Green Zone Subsoil Guideline Project. Report prepared by Drozdowski *et al*., Alberta Innovates Technology Futures for Petroleum Technology Alliance Canada. February 2013. Available at www.ptac.org.

Johnson, P.C., and Ettinger, R.A., 1991. Heuristic model for predicting the intrusion rate of contaminant vapours into buildings. Environmental Science and Technology. 25: 1445-1452.

Mercer, J.W., and Cohen, R.M., 1990. A review of immiscible fluids in the subsurface: Properties, models, characterization, and remediation. Journal of Contaminant Hydrology. 6:107-163.

Petroleum Technology Alliance Canada (PTAC), 2013. Proposed management limits for F2 and F3 Petroleum Hydrocarbons at Remote Alberta Green Zone Sites. PTAC Project #GL09-9178-50.

Stantec Consulting Ltd. (Stantec), 2003. Research for utility criteria development. Contractor report prepared for Alberta Environment.

Startsev, A. 2009. Validation of critical F2 and F3 subsoil concentrations on perennial deeply rooted crop (alfalfa) grown in greenhouse. Unpublished report prepared by Andrei Startsev, Alberta Research Council for Alberta Environment.

Thompson, S, Michalski, P., and Pruis, J., 2017. Empirical Study to Estimate the Air Exchange Rate Within a Trench for Modeling Inhalation Risks. Fourth International Symposium on Bioremediation and Sustainable Environmental Technologies. Battelle Memorial Institute, Columbus, OH.

Virginia Department of Environmental Quality (VDEQ), 2005. Voluntary Remediation Program – Risk Assessment Guidance.