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FINAL REPORT

PARSC 007

Recommended Practice for Cleaning Pipelines for Abandonment

Petroleum Technology Alliance of Canada

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Customer:	Petroleum Technology Alliance of Canada, Pipeline Abandonment Research Steering Committee Suite 400 500 Fifth Avenue S.W. Calgary, Alberta T2P 3L5	
Customer contact:	Marc Godin	
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Objective:
DNV GL USA. Inc. (DNV GL) was contracted by the Petroleum Technology Alliance of Canada (PTAC) to develop a draft Recommended Practice (RP) to establish technical guidelines and recommendations for cleaning of pipelines for abandonment, and present appropriate levels of cleanliness for abandoned pipelines below which residuals remaining in a pipeline would pose acceptable low risk of impact to the environment.

Prepared by:	Verified by:	Approved by:
Shane Finneran Head of Section Materials Advisory Services	Steinar Nesse Vice Preseident Environmental Technology & Advisory	Lynsay Bensman Head of Department Pipeline Services
Allan Browne ROSEN Group Business Line Manager Field Products & Services		

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1 INTRODUCTION

Pipeline abandonment occurs when a pipeline is permanently removed from service at the end of its useful life, which may consist of abandonment in place or excavation and physical removal of the pipeline. The need for understanding possible long-term concerns associated with pipeline abandonment has become increasingly prevalent in industry. The cleaning of a pipeline for abandonment is an important factor to consider during development and implementation of an abandonment program.

Past reports from 1996 and 2007 posed the question of "How Clean is Clean?" as a guide for industry to consider both the condition inside an abandoned pipeline and the potential for migration of any materials out of an abandoned pipeline. [1,2] In 2007 the NEB established the Land Matters Consultation Initiative (LMCI) to consider land related matters with input from various stakeholders including industry members and land owner groups [3], and in 2010, the NEB commissioned a literature review to summarize known technical issues related to pipeline abandonment and to identify knowledge gaps to be addressed in future studies. [4, 5] This review identified several knowledge gaps and recommended topics for future studies.

General cleaning guidelines were published within the 1996 Discussion Paper on Technical and Environmental Issues and the Pipeline Abandonment Research Steering Committee (PARSC) has recently published an industry report summarizing existing practices and technologies for cleaning; however, currently there are no published standards that define acceptable levels of cleanliness for decommissioned or abandoned pipelines. [6] A key recommendation from this Discussion Paper was to pursue development for a set of criteria for allowable levels of residuals in an abandoned pipeline, to establish an acceptance level below which residuals remaining in a pipeline would pose no detrimental impact to the environment if integrity of the abandoned pipeline was compromised.

In the context of permanent abandonment, it has previously been acknowledged that corrosion will eventually result in through-wall perforations of the pipeline over a significant time. [1, 4, 5] These perforations could result in the abandoned pipeline allowing water or soil to enter the pipe through the pipe wall perforations and then under certain circumstances, flow to lower elevations, with the pipeline acting as a water conduit. Water and soil flowing through an abandoned pipeline could carry residual contaminants through the pipeline, depending on the level of cleaning performed prior to abandonment. Additionally, even without water flow along the abandoned line, once the abandoned pipeline is perforated an opportunity exists for residual internal contaminants to be exposed to the surrounding soil and groundwater. Therefore, a systematic cleaning program development is recommended as part of a thorough pipeline abandonment program.

In the context of this work, abandonment and decommissioning are considered comparable from a technical perspective relevant to cleaning, as both will involve permanent abandonment in place or removal of the pipeline. For sake of simplicity the term abandonment will be used throughout this report, but for most cases, findings are applicable to either. The one noted exception however is with respect to either an abandonment or decommissioning program development, where there may be site specific considerations to address that may be treated differently for either decommissioning or abandonment projects. For example, considerations for future use of the abandoned pipeline and the adjacent land, and maintenance planning for the Right of Way (ROW) may vary depending on the chosen approach.

Decommissioning of pipelines and oil and gas facilities in the offshore industries is considered a more mature field, having been studied and documented for decades longer than onshore abandonment. [7] An understanding and appreciation of approaches considered from offshore decommissioning areas, while not directly relevant to onshore transmission lines, was also considered as many of the observations may translate to onshore applications. [7]

This report presents Stage 1 of the PARSC project "Recommended Practice for Cleaning Pipelines for Abandonment." Based on input from PARSC it is expected that the Stage 1 Draft recommended practice (RP) will be used in the latter stages of this project toward development of a final RP, following the completion of planned abandonment and decommissioning programs.

For reference, proposed additional stages of this project may include:

- Stage 2: Case study of abandonment of Peace River Mainline (natural gas) by TransCanada (2018)
- Stage 3: Case study of decommissioning of Line 3 (liquids) by Enbridge (2019)
- Stage 4: Validation of the draft Recommended Practice based on the case studies (2020).

1.1 Objective

For the scope of this study, the primary concerns related to pipeline abandonment are pipe cleanliness, considering eventual pipe degradation, possibility for creation of water conduits, and corresponding impact to surrounding soil and groundwater. The primary objective of this study is therefore to develop a draft RP to establish technical guidelines and recommendations for cleaning of pipelines for abandonment, and present appropriate levels of cleanliness for abandoned pipelines below which residuals remaining in a pipeline would pose acceptable low risk of impact to the environment.

1.2 Clarifications and Limitations

The draft RP is intended to provide guidance on the development of a cleaning program for pipeline abandonment, and clarify options to be considered, and opportunities for improvement. Where possible, it provides prescriptive guidelines or framework, following current industry best practices. However, it is expected that the specific and comprehensive details on how to execute all activities be developed as part of a specific abandonment program.

Generally, the term pipeline abandonment may refer to abandonment in place or excavation and physical removal of a pipeline. However, for the sake of this document, unless otherwise noted, "abandonment" refers to abandonment in place. Specific statements are made to removal where relevant.

Development for any specific abandonment program should consider the site-specific conditions, as different circumstances and conditions may require different execution options. Additionally, as technologies in tools, and cleaning products evolve, consideration should allow for use of improved techniques and products, based on site-specific cleaning program approval.

2 TERMINOLOGY AND DEFINITIONS

Table 1. Definition of terms

Term	*Definition*
Abandonment	to permanently cease operation such that the cessation results in the discontinuance of service; majority of pipe remaining in-situ.
Acceptance Criteria	criteria used to express an acceptable level of risk to humans or to the environment from residual contaminants.
Consequence	describes the result of an event. The consequence is normally evaluated for human safety, environmental impact and economic loss.
Decommission	to permanently cease operation such that the cessation does not result in the discontinuance of service.
Regulator	relevant national, state, or provincial authority and/or international regulatory body
Risk	expression of the product of the frequency (probability) and the consequence of an event
Operator	party legally responsible for planning and execution of the abandonment program
Contractor	party to whom the work (i.e., pigging, cleaning, waste disposal, etc.) has been contracted
Report and Notify	refers to an action by contractor in writing
Stakeholders	individual, group of individuals, or organization whose interests are substantially affected by the project Stakeholders can include employees, shareholders, community residents, landowners, customers, non-governmental organizations, governments, regulators, and other individuals or groups.

Table 2. Organization Names and Acronyms

Acronym	*Organization*
AER	Alberta Energy Regulator
AEUB	Alberta Energy and Utilities Board
AITF	Alberta Innovates Technology Futures
CAPP	Canadian Association of Petroleum Producers
CCME	Canadian Council of Ministers of the Environment
CEPA	Canadian Energy Pipeline Association
CER	Canada Energy Regulator (formerly the National Energy Board)
CSA	Canadian Standards Association
EPA	Environmental Protection Agency
LMCI	Land Matters Consultation Initiative
NEB	National Energy Board (now the Canada Energy Regulator)
PARSC	Pipeline Abandonment Research Steering Committee
PTAC	Petroleum Technology Alliance Canada

Table 3. Technical Acronyms

Acronym	*Description*
APB	Acid-Producing Bacteria
BTEX	Benzene/Toluene/Ethylbenzene and Xylene
HC	Hydrocarbon
MIC	Microbiologically Influenced Corrosion
NORMs	Naturally Occurring Radioactive Materials
PCBs	PolyChlorinated Biphenols
PHC	Petroleum Hydrocarbon
PPM	Parts Per Million
ROW	Right of Way
RP	Recommended Practice
SRB	Sulfate-Reducing Bacteria
THC	Total Hydrocarbon
TPH	Total Petroleum Hydrocarbons
TSS	Total Suspended Solids

Table 4. Definition of verbal forms

Term	*Definition*
shall	verbal form used to indicate requirements strictly to be followed in order to conform to the document
should	verbal form used to indicate that among several possibilities one is recommended as particularly suitable, without mentioning or excluding others, or that a certain course of action is preferred but not necessarily required
may	verbal form used to indicate a course of action permissible within the limits of the document

3 INDUSTRY REVIEW

3.1 Technical Literature Search

In 1996, representatives from the Canadian Association of Petroleum Producers (CAPP), CEPA, the former Alberta Energy and Utilities Board (AEUB), and the NEB prepared a Discussion Paper [1] outlining the technical and environmental considerations relevant to pipeline abandonment. Several of the primary considerations presented in the Discussion Paper were land use management, soil and groundwater contamination, and the potential to create water conduits. CEPA published a report in 2007 by the Terminal Negative Salvage Working Group [2] whereby many of the same concerns from the 1996 Discussion Paper were reiterated. In 2007 the NEB established the LMCI to consider land related matters with input from various stakeholders including industry members and landowner groups. In 2010, the NEB commissioned a literature review to summarize known technical issues related to pipeline abandonment and to identify knowledge gaps to be addressed in future studies. [4] This review identified several knowledge gaps and recommended several topics for future studies.

In development of this report, a literature review identified and reviewed more than fifty additional technical references including guidance documents, technical symposia papers, and recent abandonment program reports. Of the technical resources reviewed for this study, DNV GL focused on approximately forty resources which encompassed the most significant and relevant information relative to pipeline cleaning and preparation for abandonment and decommissioning. A brief overview is summarized in this section to highlight the key contributions and conclusions.

The consistent conclusion and recommendation throughout the literature reviewed acknowledged the industry need for a cleanliness criteria for pipeline abandonment, however several of the more recent references also cite the need for site-specific limits, considering a risk-based approach. [1,2,4,8] While there are various possible definitions of "clean", they all relate to some level of perceived risk to human health, environment, local economy, or ecosystem stability or productivity. [9] Therefore, the definition of "clean" for a particular abandonment project should be determined on a site-specific basis, subject to local regulations, such that it limits these risks.

While the desire for a simplified prescriptive limit is understood, when attempting to develop a cleanliness criterion, one should consider that the numerous threats identified within this report may not be relevant to specific products or operations, e.g. sweet versus sour gas, versus liquids. If operational history can demonstrate that a specific threat is not present for a given line segment, the requirements to sampling and testing to meet a prescriptive criterion may be overly onerous. Additionally, among other site-specific parameters, various hydrocarbons are likely already present in a given environment, and the levels of which can vary considerably. [4, 9] It is therefore unlikely that any single definition or criterion will be applicable and practical to all scenarios, environments, and land use profiles.

3.2 Cleaning as a Key Consideration

The cleaning of a pipeline prior to abandonment is an important factor, from both an environmental and economic standpoint, to consider during development and implementation of an abandonment program. The question "How Clean is Clean?" is often posed for industry to consider both the condition inside an abandoned pipeline and the potential for migration of any materials out of an abandoned pipeline. [1, 2, 8] Cleaning Guidelines were published within the 1996 Discussion Paper, and PARSC has recently published an industry report summarizing existing practices and technologies, however currently there are no published standards that define acceptable levels of cleanliness for decommissioned or abandoned pipelines. [1, 6] A key recommendation from this report was to pursue development for a set of criteria for allowable levels of residuals in an abandoned pipeline, to establish an acceptance level below which residuals remaining in a pipeline would pose no detrimental impact to human health, environment, local economy, or ecosystem stability or productivity if integrity of the abandoned pipeline was compromised.

In 2015, PARSC published a report titled, "Cleaning of Pipelines for Abandonment", prepared by Alberta Innovates Technology Futures (AITF). [6] The primary focus of this report was to assess the effectiveness of cleaning methods for pipeline abandonment, and address potential residual contaminants in abandoned pipelines, and methods for detection. Additionally, this report provides a thorough review of federal and provincial regulations and standards addressing pipeline abandonment, and a sample of industry abandonment programs at the time of writing.

AITF confirmed through interviews conducted with provincial and federal regulators that few specific regulations exist governing cleaning procedures for pipeline abandonment, and no acceptance criteria has been established defining the acceptable levels of residual contaminants. Interviews conducted indicated that CSA Standard Z662 was generally used by different provinces and companies to define minimum requirements for abandonment programs. The report found that operating companies will typically work with mechanical cleaning suppliers and chemical suppliers to determine the appropriate pig and cleaning agent products based on the history of the pipeline, product, and expected contaminants.

3.2.1 Detection of Residual Contamination

Various methods exist for detection of residual contaminants in soil and wastewater specimens. Historically however, many required laboratory analyses, and are not readily deployable for field use during cleaning processes in preparation for abandonment. A study completed for the 1996 Discussion Paper concluded that swab testing was the only reliable method identified for assessment of residual contaminants in pipelines prepared for abandonment. [10] Such swab test would then require laboratory chemical analysis to assess levels of specific contaminants.

With respect to possible soil or water contamination, the total local volume of residual contaminants available for possible exposure to the soil or water is most relevant. In order to assess viable cleanliness criteria, consideration must be given to the likely type, volume, and distribution of any debris remaining in the pipeline and how this debris is expected to behave when liberated from the pipeline walls during the cleaning process. Swab sampling however only provides a measure of concentration of residuals on a given area of the pipe wall and cannot be readily adapted to a concentration level associated with possible soil or groundwater contamination.

Improvements and developments of commercial field-testing instruments have improved in-field detection, making on-site testing more feasible. PARSC 004 and 005 cited numerous in-field instruments and test methods available to allow for on-site assessment for the presence and concentration of certain contaminants [6], as summarized in Table 5 and Table 6.

3.2.2 Potential Contaminants Associated with Oil and Gas Pipelines

A 1996 study performed by Biophilia Inc, for the Pipeline Abandonment Environmental Working Group included a detailed literature review, and interviews of industry experts to identify and assess contaminants which might be released from pipelines abandoned in place. [10] This was further reviewed by the 2010 Scoping Study, and again in the PARSC 004-005 report. [4, 6] The literature reviewed identified a number of different contaminants which may be present in oil and gas pipelines during operation, and therefore have the potential to be present as residual contaminant in abandoned pipelines.

The constituents and possible contaminants of typical gas and liquid petroleum transmission line products are summarized in the sections below to provide perspective on the type of debris which can form. [4, 6] Additionally, areas for debris assessment, for volume and/or distribution, are indicated in the respective sections.

While identifying the types and volume of debris is essential to the development of an effective cleaning program, assessing the level of residual contaminants is similarly essential to verifying the effectiveness of the cleaning program, and confirming acceptable levels of cleanliness have been achieved.

Table 5. Recommended test methods for residual contaminants in recovered fluid (reproduced from PARSC 004 and 005)

Contaminant	Test Method
NORMs	Geiger counter or laboratory analysis
PCBs	EPA 3510/8082-GC/ECD
TSS	2540 D. Total Suspended Solids Dried at 103 - 105 °C
BTEX	EPA 5021/8015&8260 GC/MS & FID and EPA 3510/CCME PHC CWS-GC/FID
pH	pH Meter
Iron, dissolved	3500-Fe B. Phenanthroline Method
Total Hydrocarbons (Oil and Grease)	ASTM D7678
Additives	Method of detection specific to the additive
Acute Toxicity test using Rainbow trout, or Daphnia Magna, or Microtox	Environment Canada Report EPS 1/RM13, July 1990 or Environment Canada Report EPS 1/RM14, July 1990 or Environment Canada Report EPS 1/RM24, November 1992
PAHs	EPA 3510/8270-GC/MS
Carbonates/bicarbonates	Alkalinity
Total Sulphides	APHA 4500-S
SRB/APB Bacteria Concentrations	Culturing Techniques (e.g., BART Test Kit)
Mercaptans and H2S	UOP 163
Total Organic Carbon and Total Inorganic Carbon	TOC and TIC
Heavy Metals	ICP-MS
Total Purgeable Hydrocarbons	Purge and trap gas chromatography (EPA Preparation Method 5030)
Total Extractable Hydrocarbons	Dichloromethane-extractable (EPA Preparation Method 3540A, EPA SW-846)

Table 6. Recommended test methods for residual contaminants on pipeline surface (reproduced from PARSC 004 and 005)

Contaminant	Test Method
Total Hydrocarbons (Oil and Grease)	ASTM D7678
PAHs	EPA 3540/8270-GC/MS
Heavy Metals	ICP-MS
PCBs	EPA 3550/8082-GC/ECD
NORMs	Geiger Counter or laboratory analysis

3.2.2.1 Typical Pipeline Products and Constituents

NATURAL GAS PIPELINES

Natural gas primarily consists of methane, but may contain small amounts of butane, ethane, pentanes, propane, or other hydrocarbons. [6] Whether processed or raw, natural gas may also contain water vapor, various hydrocarbons, and other impurities, such as hydrogen sulfide, carbon dioxide, helium, and nitrogen. [6,11] Typically processing separates the various hydrocarbons, water, and impurities; however, the quality of natural gas and liquid petroleum products vary even when meeting required specifications. Consequently, any residual contaminants found are expected to vary as well depending on the quality of gas transported. [1] Contaminants typically found in natural gas and liquid transmission lines are summarized in Section 3.2.2.2.

LIQUID PETROLEUM PIPELINES

Liquid petroleum products can consist of a complex mixture of paraffinic, cycloparaffinic, and aromatic hydrocarbons covering carbon chains ranging from C1 to C60+. The composition varies depending on the source of crude and/or the refining process. Some products can contain minor amounts of sulphur, nitrogen and oxygen compounds as well as trace amounts of heavy metals such as nickel, vanadium, or lead.

A summary of Canadian Crude Streams collated in PARSC Report #004 and 005, demonstrates a wide range in properties from, for example the lighter Fort Saskatchewan, Peace, and Pembina Condensates with API Gravities ranging between 55-78.4 (approximate density of 673-758 kg/m^3) to the heavier Albian Heavy Sour Dilsynbit with an API Gravity of 19 (approximate density of 939 kg/m^3). [6] Between the two extreme ends of the crude stream range, the presence and concentration of total sulphur, sediment, salts, trace-metals and Benzene/Toluene/Ethyl Benzene and Xylene (BETEX) can vary significantly.

3.2.2.2 Deposits and Contaminants

Over time, deposits may build up in pipelines depending on the commodity being transported, the material of the pipeline and the operating conditions and configuration of the pipeline (ex. process parameters, pipeline geometries, etc.). The type of debris deposited results from a combination of changes in the conditions of the transported product (ex. temperature and/or pressure) over the length of the pipeline, a chemical or microbiological reaction between the transported product, and the metallurgy of the pipe.

Debris and deposits on the internal surfaces of pipelines exist in a number of forms. Both liquid and gas lines may have various scale deposits and internal corrosion products. For natural gas transmission lines, possible contaminants are scales, black powder, hydrocarbons, Naturally Occurring Radioactive Materials (NORMS), and PolyChlorinated Biphenols (PCBs). Possible contaminants for liquid lines include various sludge deposits, including paraffin wax, asphaltenes, cycloparaffin, and aromatic hydrocarbons.

Additionally, cleaning chemicals may be used during pigging of both liquid and gas pipelines and could potentially result in residual contaminants on the pipe wall post-cleaning for abandonment. [14] When developing a cleaning program for pipeline abandonment, the order of cleaning stages and chemicals used during the pigging process should be considered, to minimize the potential for introducing hazardous residual chemicals during the cleaning process. Cleaning chemicals are addressed further in Section 6.2.1.1.

Scales

Scale deposits generally occur when waters from different sources, and different ion content, are mixed. In many cases, scale deposits can be dissolved, (water Soluble Scales and Acid Soluble Scales) but for some scales (Acid In-soluble Scales) mechanical removal is often the only remedy.

With respect to risks associated with abandonment in place, the need for scale removal should consider the threat of the specific scale deposits. Water soluble scales pose the threat of leaching into the surrounding soil and groundwater. Preparation of a site-specific cleaning program should consider the composition of specific scales and the hazards associated, such as speed and decomposition, transport and ultimate leaching into the soil.

Internal Corrosion Products and Black Powder

Corrosion is the degradation of a material due to natural electrochemical reactions. In the case of carbon and low-alloy steels used in underground pipelines, the electrochemical reactions consist of two "half-cell" reactions, the anodic reaction and the cathodic reaction. The anodic reaction involves a loss of electrons and is referred to as "oxidation." The cathodic reaction involves a gain of electrons and is referred to as "reduction." [5] Internal corrosion occurs where naturally occurring elements and compounds commonly introduced into a pipeline system interact and react with the pipeline steel through chemical and or microbiological activity.

Corrosion products found in gas pipelines are often referred to as "black powder" and can have a dry, fine, powdery consistency or can resemble a wet, sticky, tar-like material. Black powder is a generic term for debris that can accumulate in gas-transportation pipelines. It exists in many forms and may include in its composition iron oxide combined with a number of iron-sulfide variants. Black powder is transported with the flowing gas and may cause wear on system components such as compressors, valves, and instrumentation. It is created through several different mechanisms. The iron oxide component of black powder is caused by the presence of oxygen and moisture, but the iron sulfides are typically caused by both chemical and microbiological sources. Bacteria such as the sulfate-reducing bacteria (SRB) and acid-producing bacteria (APB) can exacerbate the corrosion process. [14]

Depending on composition, the presence of black powder itself may not necessarily be toxic to the environment in an abandoned pipeline, however a thorough cleaning program still generally requires removal of black powder, both for sake of minimizing residual contaminants, and to allow passage of further cleaning tools. Additionally, the presence of black powder can, in some instances, increase corrosion rates by providing suitable environment for SRBs. Mechanical removal of black powder is generally recommended as the breakdown of iron sulphide in black powder could liberate sufficient H_2S to be a danger to humans or wildlife.

NORMs

NORMs are radon and radon-decay products which have been reported throughout from natural gas production, processing, and transportation systems. NORMs can potentially contaminate scale and sludge deposits which may then pose a hazard to health and safety during maintenance, waste transport and processing, and decommissioning activities. Accurate detection for the presence of NORMs generally requires laboratory analysis of samples taken from the internal surface. [6]

PCBs

PCBs are toxic chlorine compounds that were historically used in hydraulic oils and lubricants throughout oil and gas facilities and have been identified as residual contaminants in a limited number of gas pipelines. Manufacture and release of PCBs to the environment has been prohibited in North America for more than 30 years, however due to their chemical stability, PCBs may still be present in a limited number of natural gas pipelines. [12, 15, 17]

In the US, the EPA presented test procedures and categories for disposal of any PCB-contaminated pipe. The EPA classification system breaks down PCB levels into three categories [40 CFR Part 761], considering PCB levels less than 50 ppm, between 50-500 ppm, and greater than 500 ppm. Environmental reports, prepared for the 1996 Discussion Paper recommended that for the case of pipeline abandonment, these categories should be reduced to simply PCB concentrations above or below 50 ppm. [15, 17]

Per 40 CFR 761.30, pipeline waste or cleaning fluids with PCB concentrations of less than 50 ppm, are considered unregulated with respect to PCBs, and can be disposed of in accordance with other applicable regulations and requirements. [17, 18] For PCB concentrations greater than 500 ppm, reduce all sources to PCB concentrations of <50 ppm through, for example, pigging, decontamination, or other engineering measures. [17]

Paraffin-Wax:

Wax is not a single compound but rather a wide range of high molecular weight paraffins that solidify from crude oil primarily due to a decrease in the crude oil temperature. These can be hard or soft solid deposits formed in crude oil and condensate liquids. Deposition is highly dependent on oil heavy-end composition and in a pipeline, deposition is characterized by an increased pressure drop.

Asphaltenes

The term "asphaltene" is applied to the black, carbonaceous components of crude oil. Asphaltic compounds occur in many crude oils in the form of colloidal suspended solid particles. Asphaltene precipitation takes place when the crude oil loses its ability to disperse the particles. The balance tending to hold asphaltenes in a stable suspension is susceptible to some of the same conditions causing paraffin to separate from the crude.

3.2.3 Hydrocarbon Cleanliness Limits

With respect to possible soil or water contamination, the total local volume of residual contaminants available at the time of abandonment for possible exposure to the soil or water is relevant. In order to assess viable cleanliness criteria, consideration must be given to the likely type, volume, and distribution of any debris remaining in the pipeline and how this debris is expected to behave when liberated from the pipeline walls during the cleaning process. Throughout the literature review, a notable technical knowledge gap was identified between the measurable levels of residuals, using either surface swab sampling or wastewater measurements, and the corresponding levels of eventual groundwater or soil contamination associated. It can be assumed that some percentage of residuals contaminants may be exposed to groundwater or soil, if the abandoned pipe wall is eventually breached, however the magnitude and rate of this exposure is not well known. It can be assumed that any residual contaminants will degrade over time and be diluted if eventually exposed to the environment. However, the extent of this reduction is not known. Additionally, multiple references cited the variability in naturally occurring HC levels as a factor contributing to the difficulty of setting a general cleanliness limit, and driver for the use of site specific risk analysis. [9, 10, 22, 23]

4 PRE-DISPLACEMENT ACTIVITIES

4.1 In-Service (Pre-Abandonment) Considerations & Practices

Where a pipeline is scheduled for abandonment, preparations for displacement and cleaning should begin as early as feasible while the pipe is still in service. While the pipeline is still in service, it is recommended to increase the frequency and intensity of cleaning operations to reduce the amount of debris in the line whilst product flow remains and well ahead of the cessation of operations. Additionally, waste fluid from in-service cleaning efforts should be analyzed and documented to assess the presence of contaminants as identified in Section 3.2.2 (asphaltenes, paraffin, PCBs, NORMs, MIC, etc.).

Recent pipeline decommissioning programs [8, 25] specified cleaning on a quarterly basis for approximately three (3) years prior to the displacement and decommissioning of the pipeline. For liquids lines it is recommended that cleaning activities be performed on no less than a biannual basis, unless the operator can provide a site-specific assessment justifying a less frequent interval. Cleaning intervals for gas lines should be defined based on a product specific assessment. Such assessment should document that existing levels of identified contaminants are low, and that typical operations are not expected to introduce additional build-up of solids or contaminants prior to abandonment.

In conjunction with pre-displacement in-service cleaning, a study of the detailed operational history of the pipeline and its contents, operating conditions, and maintenance records is essential. A detailed understanding of transported fluids and gases, any injected inhibitors or chemicals, and where possible, chemical analysis of any deposits will aid in the selection of a suitable treatment program and the development of appropriate procedures. The geometry of the system, valve type and design, valve seal material, any wall-thickness variations and piping modifications may also have an impact on the cleaning methodology. Therefore, access to system and component drawings and specifications is required. Previous pipeline failures should be reviewed, and repairs assessed. Additionally, any historical in-line-inspection (ILI) reports should be reviewed to identify areas which may be compromised and where corrosion was a concern.

Additionally, the system should be reviewed to ensure that appropriate traps exist for launching and receiving pigs. Where pipelines are not traditionally piggable, this may require temporary assemblies, and preparations should be made to facilitate this as necessary. Where lines cannot be made piggable due to other circumstances, other considerations will need to be made to facilitate cleaning. Where the pipeline segment to be abandoned is part of a larger system, the abandoned segment should be physically segmented and isolated from the remaining system. [1]

4.2 Cleaning Program Development

4.2.1 Debris Assessment

Understanding the volume of deposits, and if possible the distribution, within a pipeline is a critical part of the development of a cleaning program for pipeline abandonment. If a material of high specific gravity is in the pipeline, such as “black powder” or barium sulphate, it will be very difficult to remove large volumes of the material if the fluid system in the pipeline has not been designed with the capacity to transport the debris.

An understanding of the debris within a system can be gleaned from several sources including:

- Client knowledge and information
- Operational pigging Information
- Pressure / flow historical data review
- Caliper pigging information
- ILI Run information
- Time of Flight Survey information
- Thermal imaging
- Sampling & analysis of debris

4.3 In-Service (Pre-Abandonment) Cleaning

A critical determinant for ensuring pipe cleanliness is effective pigging. Multiple factors influence the efficacy of pigging operations such as pipeline configuration, proper pig type selection, and proper pig use. [4]

Full development of an effective cleaning program for pipeline abandonment requires a site-specific assessment, considering line specific parameters, such as the product, contaminants, operating history, and the potential structural and environmental threats. However, guidance is provided for the recommended practices that should be considered as part of this program development. Where significant contaminants such as paraffin waxes, asphaltenes, scales, and corrosion products are found to be present, in-service cleaning programs should be targeted to reduce these while the line is still in service and product propellant readily available.

Where the pipeline in question is known to be heavily contaminated with debris such that routine pigging operations have limited effect in debris removal, Progressive Pigging whilst the line is still in service should also be considered and whilst facilities (launching & receiving traps, separators, and propellant) are all still available. Progressive Pigging is covered in further detail in 6.1.4.

4.3.1 Recommended product sampling and testing prior to abandonment

Prior to abandonment, pigging waste can be sampled and tested to identify specific composition and concentration of contaminants in the active pipeline. AITF found that field testing is not typical and common industry practice involves sampling the recovered waste products, and sending samples to testing laboratories for analysis. Following a review of typical testing laboratory procedures, the recommended test methods for various contaminants are provided in Table 7.

Where possible, testing of in-service pigging waste, prior to displacement in preparation for abandonment, can provide useful data to identify or rule out specific contaminates for consideration during post-displacement cleaning. For example, if there is no history of NORMS or PCBs in a pipeline to be abandoned, testing can be completed during the in-service cleaning, and at the initial cleaning stage of the abandonment program. If the contaminants are not present, further testing would not be required through all stages of cleaning.

Table 7. Tests Performed on Pigging Waste Samples. (reproduced from PTAC 004, 005) [6]

Parameter	Test Method
Anion Presence	Spot test for Chloride, Sulphide, Sulphate, Carbonate
Asphaltene	ASTM D3279/D6560
C30+	GPA 2013
High Temperature Simulated Distillation	ASTM D7169
Loss on Ignition	Standards Method 254
Metals ICP	EPA SW-846-6010C
Solubility	In house method
Wax	UOP 46M
Elemental Analysis/ Chemical Characterization	XRD/XES
	Dean Stark (Reference Method 1.00, 1983)
Flash Point	ASTM D3828, D56 or D93
Oil & Grease Breakdown	Reference Method for the Canada-wide Standard for Petroleum Hydrocarbons in Soil – Tier 1 Method
PCBs (leachable)	EPA 3510/8082-GC/ECD
NORMs	EPA 901.1/903.1/904.0 & Geiger D3972
Chlorides (leachable)	EPA 1311/300.1

5 COMBINED DISPLACEMENT AND CLEANING ACTIVITIES

There are several approaches that may be implemented to displace pipelines of hydrocarbon product for abandonment and to subsequently clean these pipelines. Two approaches are identified by Enbridge Pipelines Inc. for their Line 3 oil pipeline replacement program following either a combination approach, where the displacement and cleaning programs are run into one operation or performing as a separate approach, where the displacement and cleaning programs are run over two distinct operations. [8]

With either approach the product in the pipeline will be removed by pigging, with tool selection based on characteristics of the final product. The final displacement and cleaning will then be performed using cleaning fluid stages, either as separate displacement and cleaning stages as shown in Figure 1 A and B, or as a combined cleaning train as shown in Figure 1 C.

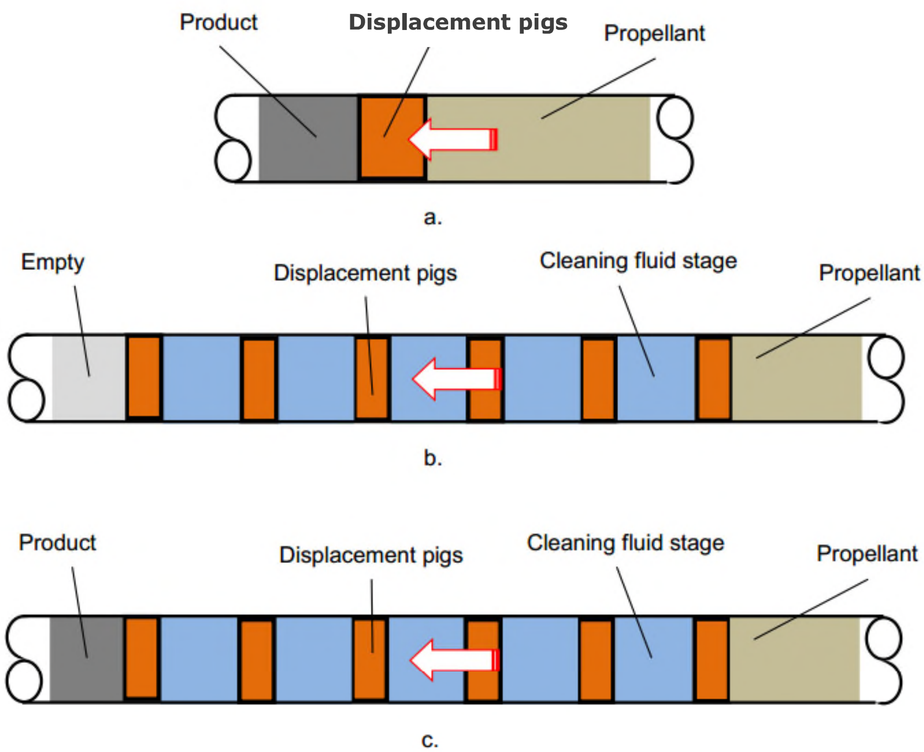


Figure 1. Schematic of possible displacement and cleaning stages (reproduced from Enbridge [8]) Image A and B show separate displacement and cleaning stages, while Image C shows a combined displacement and cleaning train.

For reference, the multistage pig train approach has been regularly used to effectively clean offshore pipelines, in preparation for decommissioning. A typical multistage pig train may utilize a combination of displacement, cleaning, and flushing stages separated by bidirectional brush pigs and batching pigs. In a recent industry case, in preparation for abandonment of a 16-inch gas pipeline, after running a single proving pig propelled with nitrogen gas, a four pig multistage train was run, with a lead parcel of solvent based cleaning agent, second parcel of surfactant based de-oiling agent (to aid the removal of compressor lube-oil), and a third parcel of debris transportation gel (to help with suspending any remnant solids) was propelled through the line using treated water to effectively clean the line in a single pass as illustrated in Figure 2.

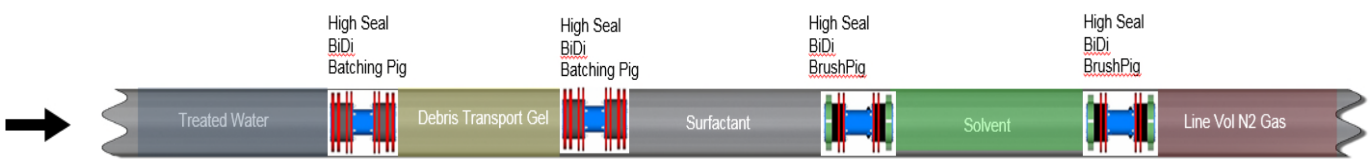


Figure 2. Illustration of Typical Multi-Compartment De-Gassing, Cleaning & Flushing Pig Train

Prior to cessation of operations and product flow, the product must be displaced from the pipeline to be abandoned. For liquid pipelines, a series of scraper pigs can be run to remove the bulk of any solids or waxy build-up, in preparation for and prior to the cleaning program. Where needed, a batch of detergent or solvent-type hydrocarbon, such as diesel fuel or condensate, can be inserted between two scraper pigs, as a means to further reduce solids or waxy build-up, as illustrated in Figure 1. This process should be repeated until solids are no longer visibly detectable on the pigs as they are removed from the receiving traps. [1]

Figure 3. In-Service Initial Cleaning for Liquid Pipelines

5.1 Recommendations for product removal and displacement tool propellant

Development of a displacement program should include assessment and selection of the appropriate propellant. Fresh water, air, or inert gas may be used for liquids or gas lines respectively.

For gas pipelines, product displacement typically involves reducing the pressure and product in the line using existing operating facilities or a pull-down compressor, to whatever extent possible. Any residual gas can be vented or flared in accordance with standard practice and regulations. Residual product should be monitored and assessed for contaminants and liquid.

5.2 Flushing / Cleaning

Various studies have been presented for flushing and cleaning of both onshore and offshore. All approaches typically involve some variation of water or combination of water and cleaning agents pushed with pigs to discharge and break down residual film on the pipe walls. The water cleaning stages are then repeated until a target level of residual Total Hydrocarbon (THC) in the discharge water has been achieved, as summarized Section 6.2.1.1.

Recent onshore cleaning programs proposed by Enbridge [8] indicated the number of cleaning stages required to meet the target Total Petroleum Hydrocarbon (TPH) concentration in the residual film to be between 4 and 8 stages, varying as a function of expected mixing efficiency, as shown in Figure 4. It should be noted that this is based on an assumed ratio of water to residual film of 18.9, and the measured residual ppm in the wastewater is expected to be lower.

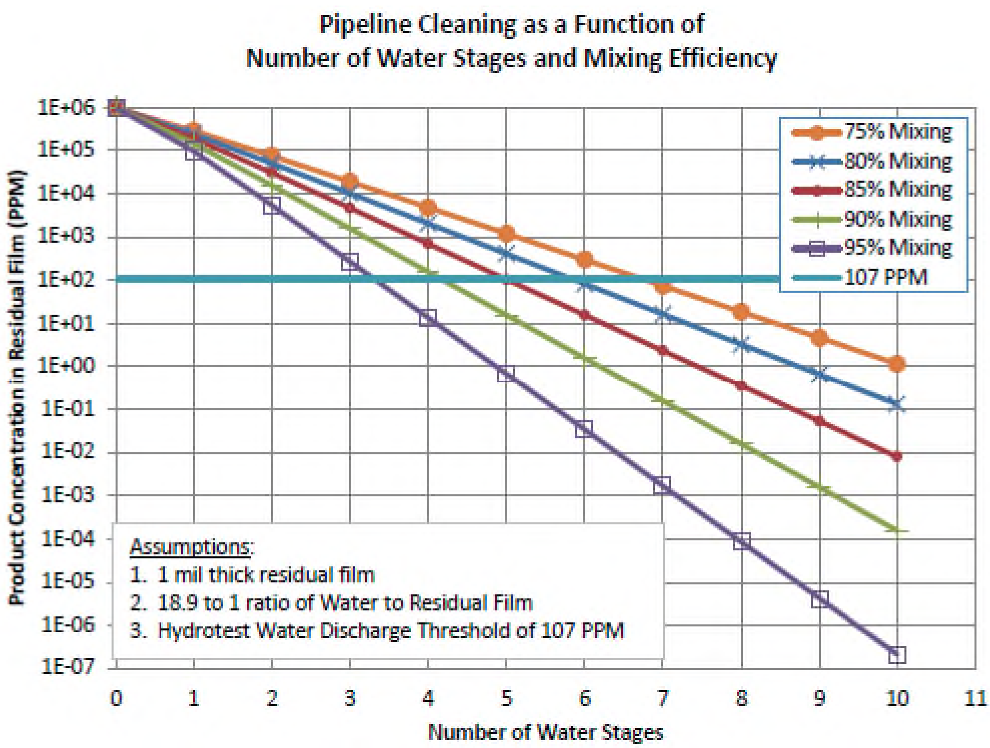


Figure 4. Estimate of residual HC concentration as a function of water stages and mixing efficiency (reproduced from Enbridge [8])

A review of offshore decommissioning projects summarized that flushing of crude oil from liquid pipelines has typically been accomplished by pumping high seal batching pigs with 1 to 3 line volumes of water through the pipeline, monitoring the ppm of HC in wastewater to reach levels below 300 ppm target threshold. Figure 5 shows the results of various flushing tests for both oil and gas lines. The results of these flushing tests indicated a water flushing volume of 1.3 to 1.8 pipeline volumes for flushing of oil pipelines, and 0.3 to 1.0 pipeline volumes for flushing of gas pipelines, at a reference flushing rate of 100 gallon/min, to reduce below 300 ppm of HC in wastewater. [20, 21]

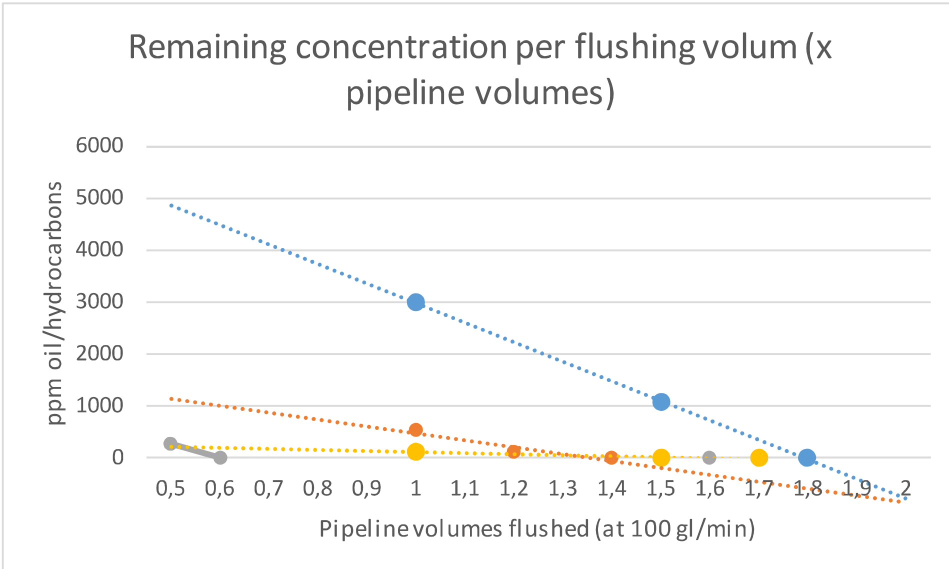


Figure 5. Flushing volume required to bring concentration towards zero (based on data from Winmar 2001; 2002) [20, 21]

6 DISTINCT CLEANING ACTIVITIES

6.1 Recommendations for cleaning tool propellant (ex. Water, inert gas, etc.)

The factors impacting the effectiveness of any pig cleaning procedure will vary with each pipeline. Cleaning activities should therefore be developed considering the specific circumstances of the pipeline to be abandoned. [1] Choice of pig design, displacement, and cleaning fluids are key factors in achieving the intended cleaning levels. As noted in Section 4.3.1, many parameters should be assessed and considered. With regards to dry black powder, this debris can be very abrasive on poly pigs and to discs and cups on mandrel cleaning pigs, thus line distance & pig velocity for example play a significant part in selection of appropriate pigs. Specialist pigging contractors and pig suppliers may be consulted to ensure that a fit for purpose cleaning program is designed. This program should consider the use of appropriate tools and cleaning methodologies, and pipeline parameters including (but are not limited to):

- Pipeline length
- Pipeline diameter(s)
- Pipeline components (T's, Y's, etc.)
- Resident product
- Target level of cleanliness
- Types of debris to be removed
- Pig Launcher & Receiver capacities

6.1.1 General -Cleaning Methods for Natural Gas Pipelines

For natural gas pipelines, which have not presented significant amounts of debris over time, a Batching Pig (as shown in Figure 6), or similar stiff rubber scraping pig, is recommended to be pushed through the pipeline at a constant speed consistent with the pig manufacturer's recommendation, using inert gas to prevent explosive mixture. Typical recommended speeds for Batching Pigs may vary between 0.6 to 1.0 ft/sec (0.2 to 0.3 m/s). Liquids, product, and contaminants ahead of the pig may be displaced from the section to be abandoned and collected for assessment and disposal in accordance with applicable Provincial or local legislation and company standards. This process should be repeated until free liquids are no longer evident by visual inspection. [6]

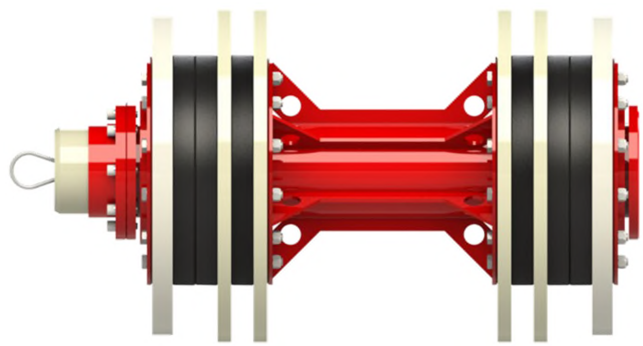


Figure 6. Example of a typical Batching Pig

After the initial displacement pig runs, the waste water should be checked for cleanliness. If visible contamination is evident, the cleaning pigging procedure should be repeated using either freshwater, or a stage of solvent or cleaner between pigs to breakdown the residual film. The waste solvent or cleaner should similarly be collected and disposed of in accordance with applicable Provincial or local legislation and company standards.

6.1.2 General - Cleaning Methods for Liquid Pipelines

For liquid pipelines, having undergone the recommended in-service cleaning, as described in Section 4.3, a final displacement and cleaning step should be performed. The following general procedure is provided as a common approach for reference; however project specific plans can be developed in conjunction with consultants specializing in the cleaning of contaminated facilities, who can advise on the appropriate tools for both normal and unusual circumstances.

A Batching Pig (as shown in Figure 6), or similar stiff rubber scraping pig, is recommended to be pushed through the pipeline at a constant speed consistent with the pig manufacturer's recommendation. One or more stages of liquid hydrocarbons having solvent properties, such as condensate or diesel fuel, may be pushed through, between two Batching Pigs, followed by a propellant stage of inert gas. PTAC 004 – 005 recommends sizing the stages so as to maintain a minimum pipe wall contact time by the fluid ranging from five to ten minutes or longer, depending on the level of residual build up and effectiveness of the in-service cleaning efforts. [6]

For liquid lines having high contaminant build-up, additional stages of solvent should be considered. Contact time should be increased when needed to ensure the solvent is not saturated before completion of the run. Figure 7 illustrates the various displacement and solvent stages.

Figure 7. Diagram of the displacement and cleaning stages recommended for liquid lines

6.1.3 Multistage Pig Train Cleaning for Debris Removal

As outlined in the example in Section 5, hydrocarbon inventory displacement and pipeline cleaning can sometimes be accomplished in a single operation using a multistage pig train. Similarly, pipeline cleaning following a separate hydrocarbon displacement operation can be supported sometimes by running a multistage water flushing train and or combination flushing / cleaning train.

The recent Enbridge cleaning programs noted the focus of the displacement and cleaning program for the line was on the removal of the hydrocarbon inventory, as the existence of asphaltene or paraffin contaminants, PCBs or NORMs were considered highly unlikely. [8, 25] The proposed cleaning program was therefore based on the intended use of a multistage pig train comprising of multiple pigs separated by water parcels containing, if needed, an environmentally acceptable cleaning agent. Cleaning agents were proposed as possible, to be used as needed to *reduce the interfacial tension between the product and water* much like surfactants. [8] Enbridge also acknowledged that the use of brushes on the cleaning pigs would improve mixing efficiencies within the system during transit of the train through the line. This "mixing efficiency" or agitation was recognized as a key component to efficiently remove the hydrocarbon film from the pipe wall.

This approach is sound and has been practiced in many pipeline decommissioning and abandonment projects around the globe where the removal of hydrocarbons from the system was not complicated by the presence of other contaminants. However, where this is not the case, and other contaminants may be present after cleaning of liquid lines, further consideration to the specific contaminants must be reviewed and the cleaning program adjusted accordingly to ensure effective removal of debris using suitable methodologies. Possible solutions are identified below.

6.1.3.1 Black Powder Removal

Generally, a combination of pigging and chemical treatments is used to remove debris; these two techniques are commonly used in isolation. Incorporation of specialized fluids with enhanced solid-transport capabilities, specialized dispersants, or specialized surfactants can improve the success of routine pigging operations. [14] Black Powder in particular can present as a dry, fine, powder or can resemble a wet, sticky, tar-like material. Generally, a combination of pigging and chemical treatments can help provide a more effective method for its removal. [14]

Removal of debris with high specific gravity e.g. black powder (primarily iron oxide and iron sulfide), materials can be enhanced with the incorporation of specialized gelled fluids (debris-transportation gels) which offer enhanced solid transport capabilities. The success of this method is highly dependent upon both the properties of the debris and the debris-transport capabilities of the fluid resident in the pipeline during the pigging operation. It is important to note however that gels are effective in transporting only loose materials and will not remove deposits that are strongly bound to the pipe internal surface. Chemical (surfactant, solvent, etc.)

or mechanical (brush pigs) treatment is required to make the solids mobile before any desired transport with a gel cleaning system is utilized.

An approach initially using low-density poly pigs in a pig train can be used. These pigs can contain parcels of gel in compartments and reduce the dilution of the gel by pipeline products. The mechanical action of the pigs assists in mobilizing debris from the pipe wall and subsequently entraining the gel.

Further cleaning may be performed with additional poly pigs or with more aggressive cup/disc pigs in a progressive cleaning program as depicted below in Figure 8.

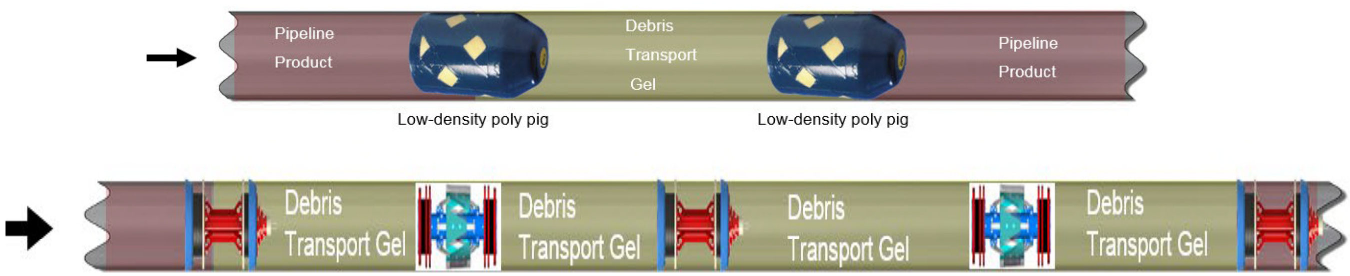


Figure 8. Example of pipeline gel-cleaning program involving poly pigs followed by more aggressive cup/disc pigs.

Where the black powder deposit presents as a dry powder and the introduction of support liquids or gels to the pipeline as part of a cleaning pig train is not permitted, a modified progressive approach can be adopted.

6.1.4 Progressive Pigging

Progressive Pigging- For Black Powder Removal

The progressive cleaning program example outlined below provides a conservative approach to cleaning heavily contaminated lines or lines where the internal conditions are not known. A careful selection of cleaning pigs should be considered which provide a gradual increasing aggressiveness for cleaning and pipe-wall debris removal capability.

The pigs used in this example are divided into three distinct categories and launched in sequence for a black powder removal and cleaning project:

- Phase I: Foam Pigging
- Phase II: Mechanical Pigging
- Phase III: Specialized Pigging - Active Cleaning

During each phase of a project it may be necessary to repeat runs with the same pig before progressing to the next more aggressive pig. It may also be necessary to regress. Details referring to a decision-making process for the deployment of the following pig type is provided in Figure 9.

Evaluation Parameters

During a progressive pigging campaign, a wide variety of data is utilized to ensure the correct choice for the next pig to be run in the system as progressed through the project. This data can come from a variety of sources:

- Pipeline flow conditions
- Pipeline pressure conditions
- Tool condition (wear & tear, damage)
- Accumulated amount of debris recovered in receiver
- Pipeline pressure differential (⇒ Indication of bulk dust accumulated in front of the tool)
- Filtration information - accumulated amount of debris found in filtration system
- Tool instrumentation information (where fitted) e.g. could include a Pipeline Data Logger (PDL)- providing information on pressure, differential pressure, tool rotation etc.

6.1.5 Progressive Pigging Program – Decision Matrix

The decision matrix presented as Figure 9 provides guidance on pig selection as the works are progressed. The matrix considers the points above and the feedback information and observations at the pig receiver. Within the matrix, which outlines the sequence and assessments necessary for progression, the flow considers whether progression, regression, or status quo should be preserved:

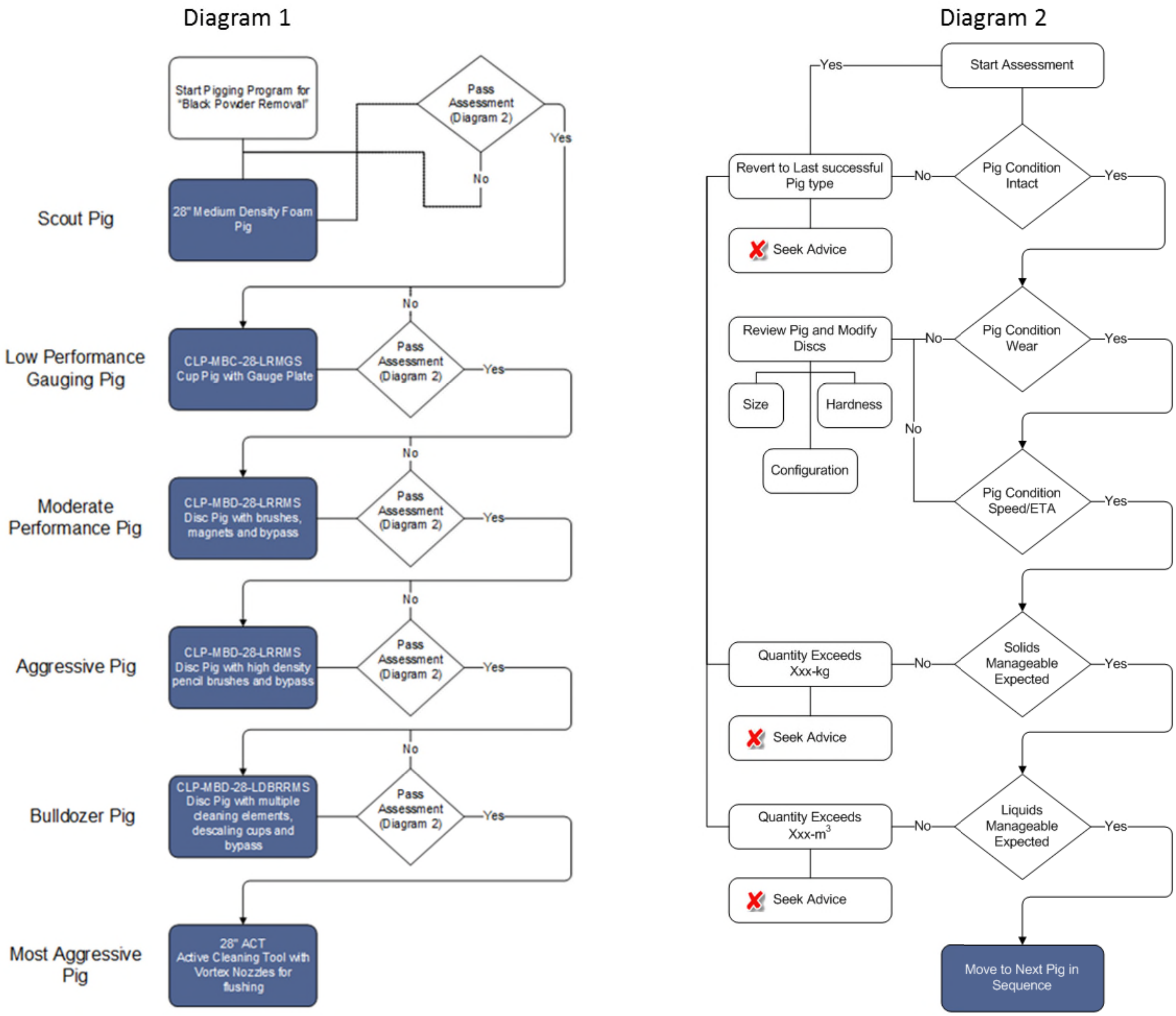


Figure 9. Decision Matrix for Pig Selection during Progressive Pigging Program

Visual examples of some of the above pigs are illustrated in Figure 10 to identify the increase in aggressiveness that can be introduced to a pipeline as part of a progressive cleaning program:

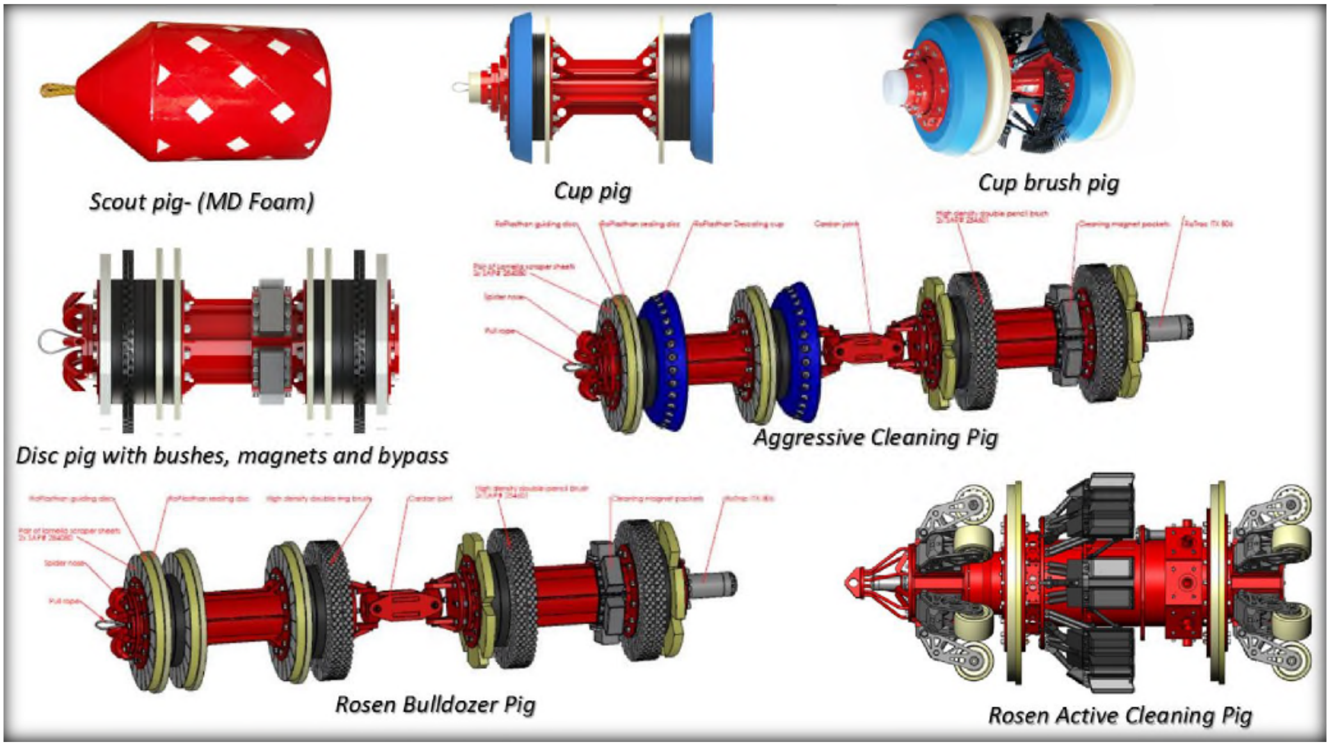
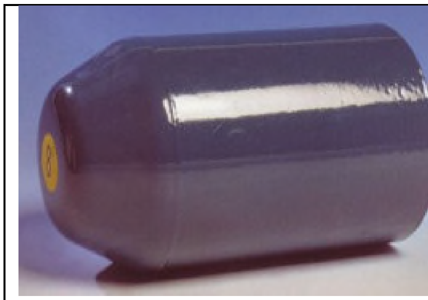
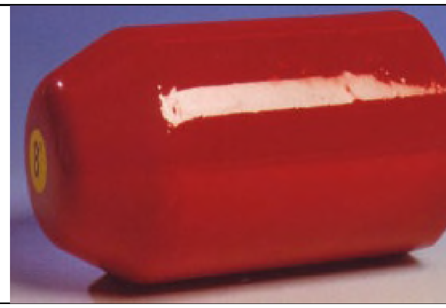


Figure 10. Examples of cleaning pigs, of varying aggressiveness, that may be considered for a progressive cleaning program

Whilst the above example illustrates a broader progressive cleaning program for the removal of large volumes of debris from a medium to large sized pipeline, progressive cleaning approaches can be considered within each phase of the broader program. For example, for smaller diameter pipelines, in the early stages of a cleaning program where typically foam pigs may be used (Phase I), a stepped approach within this category of cleaning can also be adopted such that cleaning aggressiveness is incrementally increased. A selection of foam pigs of varying cleaning aggressiveness is shown in Figure 11.

Similarly, in a second phase (Phase II) where mechanical pigs may be introduced to the cleaning program, these pigs can also be incrementally increased in aggressiveness as they are introduced into the pipeline. Cup pigs or disc pigs can be equipped with various cleaning implements ranging from nylon brushes (for coated lines), carbon steel brushes (these can be spring loaded or circular) and magnets (for ferrous debris). Additionally, mechanical pigs can be configured to ensure that a measured amount of bypass is allowed to create a flushing action ahead of the pig and to reduce the effect of bull-dozing debris in front of the pig. Examples of cleaning elements utilized on cleaning pigs are illustrated below in Figure 12.

		
i-Medium Density Coated Foam	*ii-High Density Coated Foam*	*iii-High Density Abrasive Coated Foam Pig*

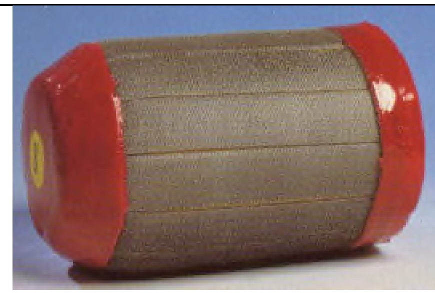
	
iv-High Density Brush Foam (partly covered with brushes)	*v-High Density Brush Foam (fully covered with brushes)*

Figure 11. Examples of foam pigs, of varying aggressiveness, that may be considered for Phase 1 of a progressive cleaning program

Figure 12. Examples of cleaning elements of varying aggressiveness that may be incorporated with mechanical pigs and considered for Phase 2 of a progressive cleaning program

The final stage of a progressive cleaning program may require the use of a specialized cleaning pig or tool as indicated in the above progressive pigging example where a Phase 3 Stage using a specialized pig for "Active Cleaning" was included, as shown in Figure 13. This particular tool was developed specifically to provide a low-effort solution for pipeline operators in the removal of large volumes of dry black powder from gas pipeline systems, as shown in Figure 14.

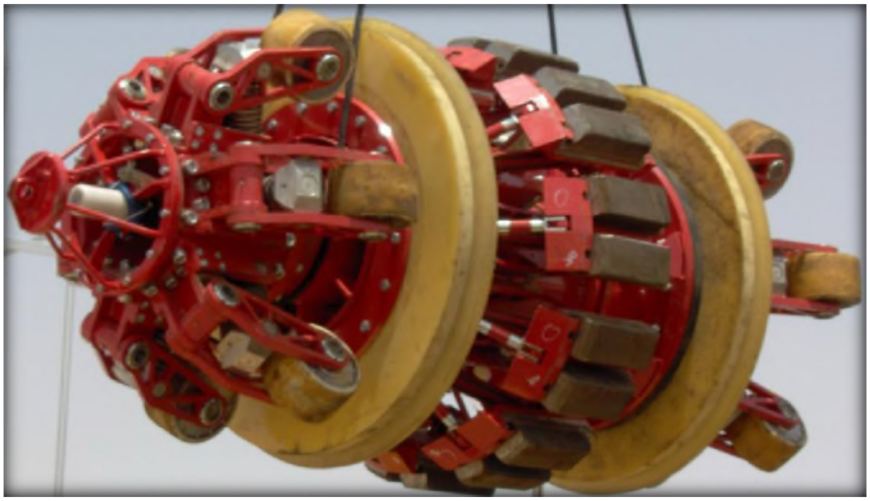


Figure 13. Specialized 48-inch Black Powder Cleaning Tool [Rosen]

Figure 14. Receiver filled with black powder and Cleaning tool after a 170-km run in a pipeline

6.2 Recommendations for cleaning fluids

6.2.1.1 Chemical Cleaning

When debris, contaminants, and scales adhere to the pipeline walls, such that pigging alone cannot sufficiently breakdown, chemical cleaning may be considered, in conjunction with pigging. Chemical cleaning involves the use of chemical solvents, or surfactants to improve cleaning efficiency, offering ability to remove debris with fewer cleaning pig runs, or stages.

The use of chemical cleaning in conjunction with pigging may be necessary to break down scales, HC deposits, debris, or to make the pigging process more effective. Additives may also be used to kill bacteria or remove organic material.

The effectiveness of any chemical cleaning program will highly depend on the effectiveness of the pigging program associated with the overall cleaning process.

Selection of proper cleaning agents for abandonment should first ensure that no harmful chemicals are introduced to the pipeline, that may introduce possible environmental threats. Many corrosion inhibitors for example are non-biodegradable and could contribute to contamination if exposed to surrounding environment due to water infiltration. The development of a chemical cleaning program should also consider the chemical compatibility of selected pigs.

Common cleaning chemicals may include [2, 4, 6]:

- Solvents
- Dispersants
- Surfactants
- Biocides
- Corrosion Inhibitors
- Water Based Cleaners
- Hydrogen Sulfide and Oxygen Scavengers
- Debris Transport Gels
- Gel Pigs
- Water Hardness Scale Removers

Effective chemical cleaner selection may include testing of various cleaning agents on samples obtained from the subject pipeline obtained during in-service cleaning, or during displacement activities.

General industry consensus is toward targeting a water wet surface with low levels of THC present [6], as described in Section 3.2.3. This may require surfactant based cleaning and multiple water rinsing cycles to obtain.

Inactive pipelines, or pipelines of otherwise unknown conditions present special challenges when preparing a cleaning program for abandonment. If lines are dormant, and have been for some time, they may have compromised integrity which may not stand up to pressures required for traditional pig runs. This could pose a potential hazard to worker safety when using compressed gases for propelling the pig, or possible release to environment if the line fails during cleaning. [28]

Special considerations are recommended for inactive and unpiggable pipelines, or where the condition of the pipeline is unknown. Vacuum trucks and coiled tubing units are recommended to first remove as much of the product, cleaning fluids, and contaminants as practical, followed by fresh water displacement. Where lines are unpiggable, the freshwater displacement can continue until the return waste is clean to an acceptable level. Otherwise, cleaning pigs can follow the flushing, at a safe pigging pressure, using water or inert propellant. A safe pigging pressure can be determined using, for example, hydrostatic test with clean water. Once a safe pigging pressure is determined, proceed with progressive pigging program as described in Section 6.1.4.

6.3 Findings and Conclusions

The consistent conclusions and recommendations throughout the literature reviewed acknowledged the industry need for a cleanliness criteria for pipeline abandonment, however several of the more recent references also cite the need for a site-specific guidance, considering a risk-based approach. [5, 6, 10] While there are various possible definitions of "clean", they all relate to some level of perceived risk to human health, environment, local economy, or ecosystem stability or productivity. [9]

General findings, common throughout the of references reviewed are summarized as follows:

- Assessing the levels of residual product and any contaminants in a pipeline after cleaning is critical to evaluating the effectiveness of cleaning program
- The consensus of current literature recommends site specific and/or risk-based assessment as the basis for establishing recommended limits, or as a basis for allowing alternatives to a prescriptive limit. [1, 2, 4, 7, 8, 9, 12]

Therefore, the definition of "clean" for a particular abandonment project should be determined on a site-specific basis, subject to provincial and/or federal regulations, such that it limits the possible consequence with respect to human health, environment, local economy, or ecosystem stability or productivity.

It is recommended that further development of a final RP consider further evaluation of the relationship between residual contaminants within the pipe, and possible soil or groundwater contamination, as well as further understanding of technical factors such as residual contaminant risk at the time of exposure, remaining residual based on volume collected after each cleaning run (specific to length being cleaned), and performance thresholds inherent to physical cleaning methodologies.

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