Appendix A

Frequency – Volume Study of Keystone Pipeline

DNV CONSULTING

Frequency-Volume Study of Keystone Pipeline:

Report for TransCanada PipeLines Limited
Report no.: 70015849-2
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MANAGING RISK DNV

Frequency-Volume Study of Keystone Pipeline

for

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Report No.: 70015849-2 **Subject Group:**

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Summary: DNV Consulting is assisting TransCanada with risk management and regulatory compliance for the Keystone Pipeline, specifically, assessing the U.S. portion of the Keystone Pipeline to quantify oil spill risk in terms of frequency and volume.

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Executive summary:

TransCanada Pipelines Limited is proposing the Keystone Pipeline Project to transport a nominal 435,000 bpd (591,000 bpd maximum) of crude oil from facilities near Hardisty, Alberta, to the vicinity of Patoka, Illinois, and to Cushing, Oklahoma.

DNV Consulting is assisting TransCanada with risk management and regulatory compliance for the Keystone Pipeline, specifically, assessing the U.S. portion of the Keystone Pipeline to quantify oil spill risk. The outputs will enable refinement of the ecological assessment being conducted for compliance with the National Environmental Policy Act. This report documents the frequency of potential spilled volumes from the Keystone Pipeline. The current design of Keystone was reviewed and the latest techniques in quantitative risk analysis were used to quantify the likelihood of realistic maximum spill volumes.

The pipeline spill frequency was estimated by adjusting historical pipeline failure frequencies using Keystone-specific modification factors. This study segmented the pipeline into lengths that each pose virtually constant spill frequency based on causes of failure. The relevant failure mechanisms specific to Keystone that could impact the frequency of leaks were identified.

The frequency of failure was estimated for three hole sizes for each cause of failure, for each segment. Overall, the likelihood of a leak greater than 50 barrels anywhere along the pipeline is estimated to be about 0.14 per year, or once every 7 years. The leak volume per mile for Keystone is approximately 0.37 bbl per mile per year. For purposes of comparison, pipelines in the U.S. had a leak frequency of 0.49 bbl per pipeline mile per year during the period 1992 to 2003 (OPS, 2006).

Approximately 53.5% of the spills would be from small holes (pinholes), 32.5% would be from medium sized holes (1 in), and 14% would be from large holes (10 in or greater). The most likely cause of a leak is estimated to be corrosion.

Realistic maximum spill volumes were calculated based on estimated leakrates for each segment and each hole size. Draindown procedures and line depressurization were not accounted for in the spill volume estimates, resulting in conservative estimations of potential maximum spill volumes.

Two throughput scenarios were evaluated, a 435,000 bpd throughput scenario (nominal case) and a 657,000 bpd throughput scenario (best available data to represent the 591,000 bpd case). Cumulative frequency-volume curves were developed, describing the likelihood of a spill of a given volume occurring from the Keystone Pipeline in its current design phase. These curves provide a visual illustration of the risk profile of Keystone.

These two scenarios bound this study of Keystone Pipeline. However, alone they do not provide an accurate picture of potential spills from Keystone. Evaluation of risk requires assessing frequency and consequence together rather than separately, because the worst risk scenario is often not the greatest volume release, because a large volume release often is associated with the smallest frequencies.

To identify the worst-case pairing on frequency and volume, the frequency and volume were multiplied and summed per segment, providing a "risk" number with which to compare the segments of Keystone. The segment with the largest frequency-volume pairing was at milepost 208, with an estimated volume of 3.6 bbl/yr.

At the appropriate design phase, a consequence study should estimate the severity of potential spills from Keystone (paired with their respective frequencies) and identify those segments posing the greatest risk to the environment. Potential preventive measures could then be evaluated on a cost-benefit basis to determine which are the most effective in reducing environmental risk.

Contents:

1.0 Introduction

TransCanada is proposing the Keystone Pipeline Project, which would transport a nominal 435,000 bpd (591,000 bpd maximum) of crude oil from facilities near Hardisty, Alberta, to the vicinity of Patoka, Illinois and Cushing, Oklahoma. The pipeline would interconnect with other existing crude oil pipelines that supply refinery markets in the U.S.

In the United States, the Keystone Pipeline Project will require federal approvals from agencies such as the U.S. Department of State and the U.S. Army Corps of Engineers. In Canada, approvals from the National Energy Board (NEB) will be required. The project may also require additional local, state, and regional approvals.

DNV Consulting is assisting TransCanada with risk management and regulatory compliance for the Keystone Pipeline, specifically, assessing the U.S. portion of the Keystone Pipeline to quantify oil spill risk in terms of frequency and volume of potential spills. The outputs will enable refinement of the ecological assessment being conducted for compliance with the National Environmental Policy Act.

This two-phase study focuses on quantifying the risk of a spill of crude oil, in terms of the frequency related to a given volume of oil that may potentially be spilled to the environment. This report encompasses both phases: Phase I the frequency study; and Phase II the volume study. The study estimated the frequency and volume of releases for each segment for three postulated hole sizes, and developed a frequency-volume curve for the pipeline as a whole.

Two throughput scenarios were evaluated, a 435,000 bpd throughput scenario (nominal case) and a 657,000 bpd throughput scenario (best available data to represent the 591,000 bpd case). A detailed hydraulic profile is not yet available for the nominal and maximum throughput cases, but will be developed when there is additional certainty regarding the locations of pump stations and other design details.

The project background is described briefly in Section 2.0. A methodology overview is presented in Section 3.0.

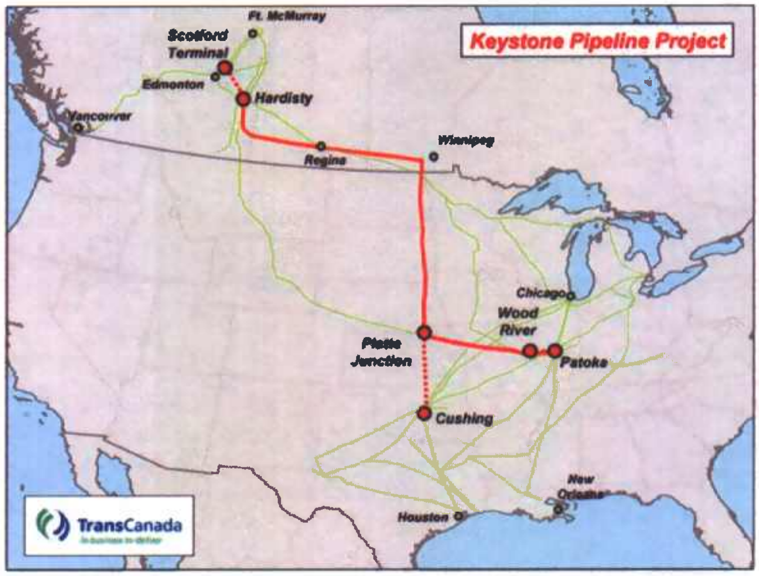
Section 4.0 describes the base leak frequencies and modification factors relevant for Keystone.

Section 5.0 describes the methodology used to calculate realistic maximum spill volumes

The final summary and conclusions are provided in Section 6.0.

This study is a quantitative assessment of risks for the pipeline as a whole, and of individual segments of the pipeline. Each segment was defined so that it would comprise a virtually consistent risk profile, using the best available quantification techniques to represent the risk profile of the pipeline.

2.0 Background



The total length of the proposed Keystone Pipeline is 1830 mi, comprising about 760 mi in Canada and 1073 mi in the U.S. The U.S. portion consists of newly-constructed pipeline and 24 new pump stations..

The timeline for the project includes submission of major regulatory applications in the U.S. and Canada in Spring 2006, with completion of associated field studies and environmental assessments throughout 2006. Route refinement may continue as commercial requirements and input from agencies, stakeholders, and design teams are gathered.

In 2007, the engineering design is expected to be complete, with the necessary approvals and licenses. The construction and conversion of facilities and startup are anticipated in 2008 and 2009.

The pipeline is expected to be designed and operated within the following key parameters (Table 2-1) relevant to spill risk, which were provided by TransCanada:

Table 2-1 Key Study Input Parameters

Parameter	Value
Diameter	30 in; 24 in
Above vs. below ground	Belowground mainline; aboveground within pump station battery limits
Pipe wall thickness	0.375 in; 0.343 in
Remote gate valves	58 (including 30 at Pump Stations)
Check valves	45 (each with two flanges), each associated with a (powered) manual gate valve
Mainline location	In GIS
Pump station locations	In GIS; not aligned with current hydraulic profile
Pump station equipment	3 pumps per station; additional piping
Leak detection	Capable of detecting 1.5% leak in 138 mi and a 15% leak in 18 min

Parameter	Value
Surveillance	Within U.S. DOT requirements
Hydraulic profile	Base case 435,000 bpd; high throughput case 657,000 bpd. This study is being conducted prior to the detailed hydraulic analysis.

3.0 Methodology

All spills begin with an initiator, or cause, of an initial loss of crude oil from the pipeline. Once the leak starts, the scenario unfolds in four phases: leak detection, mainline shutdown, leak isolation, and stoppage of flow from the pipe (if possible). The duration of each phase ultimately determines the quantity of crude spilled.

This study segmented the pipeline to allow estimation of leak frequency and realistic maximum leak volume for portions of the pipeline over which the frequency and volume were virtually constant. The frequency of failure for three hole sizes (small, medium, and large) was estimated for each segment by identifying the relevant failure mechanisms specific to Keystone that could impact the frequency (or volume) of leaks. Historical base frequencies were adjusted using Keystone-specific modification factors for each cause of failure.

Each segment was analyzed to estimate the maximum realistic volume of a leak for each hole size from each failure cause. For small and medium hole leaks, it was assumed that a trained response crew would be able to plug or block the hole and stop the leak within a certain timeframe.

The remainder of this section discusses the potential causes of spills, describe the methodology used for the segmentation process, and presents relevant baseline frequencies and Keystone modification factors.

3.1 Causes of Spills

More than 17 factors (not necessarily independent) could influence pipeline spill initiation (Table 3-1). These factors were identified via literature review and DNV experience in assessing this type of pipeline risk. It should be noted that the factors are similar but not identical to the U.S. Department of Transportation Office of Pipeline Safety (OPS) categories of failure (e.g., third party harm).

Table 3-1 Factors Influencing Pipeline Spill Initiation

Factor	Description
Flange, seal, and fitting leak	A leak from a flange, seal, or fitting.
Mechanical defect	Failures due to flaws within the material structure of the pipe, caused by material or manufacturing defects, improper welding, or installation errors.
Corrosion (external or internal)	Failures due to general and pitting type corrosion caused by fluids inside the pipeline or corrosive soils or conditions outside of the pipe.
Corrosion assisted initiators	These are several rather than one, and include operational transients, error in pressure setpoint control, material property deviations, etc.
Hydraulic (pressure surge) event	Overpressure caused by human or mechanical error, combined with overpressure protection failure.
Excavation damage	Excavation equipment damages underground piping; by Keystone maintenance personnel or by third parties
Maintenance damage	A leak caused by crews conducting maintenance work on the pipeline.
Third party harm	Accidental acts by a third party (such as a hunting accident) that cause a leak (vehicle, train, and aircraft operation were evaluated separately) This study scope excludes strategic, intentional acts.
Human/operator error	Improper performance of maintenance or operating procedures leading to a line failure.
Seismic event	Earthquake or other vigorous displacement of the pipeline due to seismic activity or ground movement.
Settlement	Thaw settlement or frost jacking causes line to buckle.
Slope instability	Avalanche damages piping or instability lead to loss of piping support.
Washout/bridge failure	River bottom pipe exposed by heavy runoff, line may float and buckle. Bridge supports may corrode and cause line failure (no bridge crossings are planned for Keystone).
Vehicle impact	Line failure due to large vehicles, typically transport trucks, leaving the roadway and impacting the line.
Aircraft impact	Impact fractures underground piping
Train derailment	Impact fractures underground piping
External fire or explosion	Fire impinging on the pipe, or an explosion resulting in a leak.

From the above 17 factors that could influence pipeline spills, six distinct and practically independent causes (from a frequency estimation point of view) were identified as applicable to Keystone and evaluated in detail in this study (see Section 4.0).

1. Corrosion (external or internal)
2. Excavation damage
3. Mechanical defect
4. Hydraulic (pressure surge) event
5. Flange, seal, and fitting leak
6. Washout

Table 3-2 lists the eight factors that were not quantified as separate causes in this study, with explanation.

Table 3-2 Factors not Individually Quantified in this Study

Factor	Reason
Corrosion assisted initiators	This failure frequency is incorporated into other historical causal frequencies (such as hydraulic event and corrosion).
Maintenance damage	This is included in the excavation cause for belowground pipeline
Third party harm	Accidental harm to the pipeline was considered only credible for above ground pipe. For Keystone, the only above ground pipe is within Pump Stations, which are secured. As a result, this cause was deemed not relevant
Human/operator error	After detailed design and operating procedures are drafted, this cause can be evaluated in detail.
Seismic Event	DNV was unable to quantify this very low level of risk in the timeframe required with the conceptual level of design currently available for the pipeline. It is unlikely that this risk factor would contribute significantly to the pipeline risk picture.
Settlement	Major settlement is often associated with thaw which causes a deformation of the pipe and subsequent pipe failure. DNV was unable to quantify this very low level of risk in the timeframe required with the conceptual level of design currently available for the pipeline. It is unlikely that this risk factor would contribute significantly to the pipeline risk picture, as less than 1% of 1986-2001 recorded incidents were attributable to the OPS category "subsidence".
Slope instability	Substantial slope instability risk is not anticipated in the areas near the proposed Keystone Pipeline based on a preliminary review of terrain near the pipeline.
Vehicle impact	A truck-pipe collision with sufficient momentum to break the pipe. The probability of a belowground portion of pipe being affected by a vehicle impact results in a frequency less than 1×10^{-7}, which is not a credible scenario.
Train derailment	DNV was unable to quantify this very low level of risk in the timeframe required with the conceptual level of design currently available for the pipeline. It is unlikely that this risk factor would contribute significantly to the pipeline risk picture.
Aircraft impact	Since the Keystone mainline is belowground, aircraft impact risk is estimated at less than 1×10^{-6}. This could be quantified based on sizes of aircraft and activity levels, if desired; however, it is unlikely to contribute to the pipeline risk picture.
Fire or explosion	Since the majority of the pipeline is belowground, this is a credible scenario only at the pump stations. The primary sources of ignition might be station equipment fire, agricultural burns, and wildfires. These can be evaluated in detail when exact pump station locations have been determined and detailed equipment descriptions are available, but are expected not to affect the frequency or volume study outputs for the pump station segments.

Distribution of Hole Sizes for Each Cause

A specific distribution of small, medium and large sized holes was developed and applied for each spill cause (described further in Section 4.0). Note that hole size is not the same as spill volume. Some leaks from small holes could occur for a long period of time and result in a large spill volume because they would not be detected as quickly as some leaks from larger holes.

The estimation of frequency for a given spill volume is linked to hole size, because for any failure cause, one hole size is more or less likely than another. In assessing the distribution of hole sizes for each cause, the failure mechanism and pipe material properties were considered. The size of the hole is a function of many factors including stress levels and material properties such as ductility. For instance, corrosion is characterized by a failure mechanism of slow removal of metal, and therefore is generally prone to result in pinhole-type leaks rather than full bore failures. In contrast, outside forces such as vehicle impact on aboveground pipeline are more likely to cause larger holes.

Three sizes of leak were assessed for each cause:

- Small, equivalent to 0.1 inch diameter hole
- Medium, equivalent to 1 inch diameter hole
- Large, equivalent to 10 inch diameter hole and larger

The representative hole sizes were chosen to allow use of the best statistically significant set of data for pipelines. Further detail regarding the generic data sets used in this analysis is provided in Appendix I..

3.2 Segmentation

The pipeline was segmented for this assessment based on an offset of factors, all related to the physical and environmental characteristics that would create unique failure mechanisms for various lengths of pipe. These segments were used as the basis for calculating frequency of spill volumes. DNV defined each segment as the length of pipe over which none of the risk characterization parameters changes significantly.

An alternative approach would have been to define each segment by a static geographic distance; however, the current approach was deemed more suitable for any future spill risk studies incorporating consequence of a spill.

Table 3-3 lists the characterization parameters used as inputs to segmentation.

Table 3-3 Segmentation Parameters

Parameter	Related cause	Discussion
Above versus below ground location of pipeline	Excavation damage Corrosion (external or internal)	The majority of Keystone Pipeline is below ground, with transitions to above ground only within secure areas at pump stations.
Pipe wall thickness	Excavation damage Corrosion (external or internal)	Wall thickness is a risk factor for both excavation (mechanical) damage and corrosion caused leaks.
Excavation activity level	Excavation damage	This input factor characterizes segments by the potential for excavation activity. *Road crossings per mile* was the best available data for estimation of excavation activity (because of the potential for impact to the pipe from activities related to roadside drainage ditches and culverts). In the future, additional data may come available concerning utility crossings and crossings with other pipelines. The additional data should be incorporated into the frequency study when it becomes available.
Hydraulic event susceptibility	Hydraulic (pressure surge) event	The sections of Keystone operating closer to MAOP are assigned greater susceptibility to hydraulic damage in the event of human or mechanical error.
Washout event susceptibility	Washout	The washout event susceptibility is used to identify segments that cross rivers with a potential to remove sediments surrounding the pipe.
Pipeline patrol frequency	NA (related to leak detection time)	The patrol frequency contributes to both the likelihood of finding unauthorized excavation and the timeliness of detection for small hole leaks.

A new segment was created at each point where a change in any of the risk characterization parameters occurred. This approach minimized the number of segments necessary to analyze the entire pipeline at the full resolution of the input data. Figure 3-1 provides a visual representation of the segmentation process.

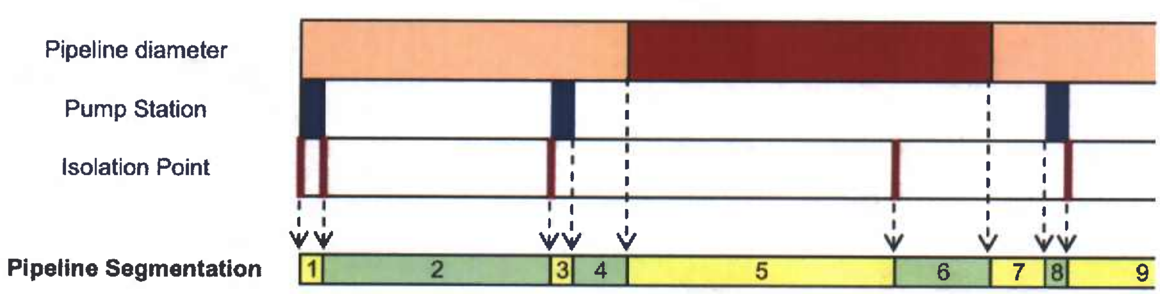


Figure 3-1 Segmentation Process Diagram

Non-discrete (or nearly continuous) risk characterization parameters are not suitable inputs to a segmentation process. These parameters have either a continuously varying value or a large number of values along the length of the pipeline, and would result in a very large number of segments. Instead of using these as inputs to the process, a single value for each parameter was established for each segment after segmentation is complete. The segment value was assigned by analyzing the range of values for a given parameter within a given segment, and assigning either the maximum, minimum, count, or average to the entire segment. This resulted in a representative but conservative value being applied to each segment.

The values for such non-segmentation parameters were assigned as follows (Table 3-4):

Table 3-4 Non-Segmentation Parameter Values

Parameter	Related cause	Discussion
Depth of cover	Excavation damage Washout Vehicle impact Aircraft impact Train derailment	Depth of cover is currently assigned a constant value of 4 ft for the entire pipeline. When additional detailed data are available, the *minimum* depth of cover between the start and end mileposts of each segment will be applied to the entire segment, since this will provide the best reasonable conservative estimate as an input to excavation leak frequency.
Pipeline internal pressure	NA (volume related)	The *maximum* pipeline internal pressure between the start and end mileposts of each segment will be applied to the entire segment, since this will give the most conservative estimate of before isolation release rate.
Pipeline elevation	NA (volume related)	The *minimum* pipeline elevation between the start and end mileposts of each segment will be applied to the entire segment, since this will give the most conservative estimates of before isolation and after isolation release rates.
Fittings count	Flange, seal, and fitting leak	The number of fittings between the start and end mileposts of each segment will be *counted* and applied to the segment.

4.0 Base Frequencies and Modification Factors

The frequency of an event is the expected number of times per length of pipe that an event will occur in a year. As an illustration, the excavation damage frequency for a given segment might be 1.4×10^{-6}. That frequency represents the number of times that a vehicle is expected to impact that segment of the pipe in a year.

For each segment of the pipeline, the frequency of events (and thus possible leaks) was determined by first assessing the frequency of each spill cause individually, distributed among the three hole sizes. These were summed to give the total leak frequency.

$$f = f_{co} + f_{ex} + f_{md} + f_{hy} + f_{fl} + f_{wo} \quad (4.2) \quad (4.1)$$

Where:

f = the total leak frequency for a section

f_{co} = leak frequency from corrosion

f_{ex} = leak frequency from excavation

f_{md} = leak frequency from mechanical defect

f_{hy} = leak frequency from hydraulic event

f_{fl} = leak frequency from flange(s)

f_{wo} = leak frequency from washout event

The individual frequencies were determined by applying modification factors to a base leak frequency for each spill cause. The specific modification factors and hole size distributions are discussed for each of the relevant causes in the following subsections.

4.1.1 Corrosion

This event is defined as the failure of mainline pipe to withstand internal pressure due to a transient, at a location of external or internal corrosion-degraded (thinned) pipe. The reliability of the pressure relief system is directly accounted for in the analysis.

Analysis by Taylor (1995) suggests a base frequency for corrosion leaks of 6.0×10^{-5} per mile of pipeline per year. DNV considers that because of the expected frequency of intelligent pigging (every three years) in the Keystone system, and the comprehensive use of active cathodic protection along the pipeline, a reduction is warranted in the base frequency (also see generic analyses in Appendix I). A 50% reduction was applied, resulting in a base frequency for corrosion leaks of 3.0×10^{-5} per mile of pipeline per year.

Modification factors were applied to the base frequency to represent the following issues:

- Whether the segment was above or below ground
- Initial wall thickness of the segment

f_{co}, the leak frequency from corrosion, was therefore calculated as follows:

$$f_{co} = f'_{co}(M_{Location} M_{Thickness}) \quad (4.3)$$

Where:

f'_{co} = the base frequency of corrosion resulting in a leak (3×10^{-5} per mile year)

$M_{Location}$ = modification factor whether the segment was above or below ground

$M_{Thickness}$ = modification factor for initial wall thickness (set to 1 for Keystone)

Above or Below Ground Location

The Keystone Pipeline is being designed to consist entirely of below ground pipe except within Pump Station fence lines. Segments of the pipeline below ground were considered to be more likely to incur corrosion than above ground sections.

Based on proprietary analysis of CSFM (1993), CONCAWE (1998), and EGIG (1993) data for external corrosion, DNV developed modification factors for below ground versus above ground piping. The modifying factors shown in Table 4-1 were used to account for the effect of the location of the pipeline on corrosion leak frequencies.

Table 4-1 Corrosion Location Modifying Factor

Location	Factor
Above Ground	0.2
Below Ground	1

Engineering judgment was used to develop the hole size distribution shown in Table 4-2, which were applied to leaks resulting from corrosion.

Table 4-2 Hole Size Distribution for Corrosion Leaks

Hole Size	Distribution
Small	87%
Medium	10%
Large	3%

4.1.2 Excavation Damage

This event is defined as a leak resulting from digging equipment striking the pipeline. The base frequency of excavation resulting in a leak is 8.4×10^{-5} per mile of pipeline per year. This value was based on DOT data for "external force" type incidents for natural gas transmission lines. Natural gas pipeline data is appropriate for excavation damage because the product being carried in the pipe has almost no effect on whether excavation damage will occur, or how severe it will be. The frequency is essentially the same for gas and for oil pipelines.

Leaks caused by excavation damage are considered only for below ground sections of the pipeline. Modification factors were applied to the base frequency to represent the following features:

- Depth of cover – assigned as a nominal 4 ft.
- Wall thickness of the pipeline – assumed to be 0.375 in for the 30-in sections and 0.343 in for the 24-in sections of pipe.
- Patrol frequency for the pipeline – assumed to be every two weeks.
- Level of excavation activity – estimated based on the number of road crossings in a given segment, with the numbers of crossings summed for each mile. The values were then compared to the criteria in Table 4-4 to assign an excavation activity level for the segment. A new segment was created at each milepost where the excavation activity level changed, resulting in a constant activity level for each segment.

f_{ex}, the leak frequency from excavation activity, was therefore calculated as follows:

$$f_{ex} = f_{ex}^{'}(M_{Activity} M_{Depth} M_{Thickness} M_{Patrol}) \tag{4.4}$$

Where:

$f_{ex}^{'}$ = the base frequency of excavation resulting in a leak (8.4×10^{-5} / mile year)

$M_{Activity}$ = modification factor for activity level

M_{Depth} = modification factor for depth of cover

$M_{Thickness}$ = modification factor for wall thickness

M_{Patrol} = modification factor for patrol frequency

The hole size distribution shown in Table 4-3 was applied for excavation damage leaks. The distribution was based on EGIG (1993) data, details of which can be found in Appendix I.

Table 4-3 Hole Size Distribution for Excavation Damage Leaks

Hole Size	Distribution
Small	25%
Medium	55%
Large	20%

Activity Level

Data for the activity levels along the pipeline were assessed using a system suggested by Muhlbauer (1992). This presented three levels of activity: high, medium and low. DNV also identified areas of no expected activity (none).

Table 4-4 Excavation Activity Categorization

Level	One or more of the following
High	Frequent construction activities High volume of on-call or reconnaissance reports (> 2 / week) Significant roadway culvert risk – summed road crossing value greater than 30 per mile Many other buried utilities nearby
Medium	No routine construction activities that could pose a threat Moderate roadway culvert risk – summed road crossing value greater than 10 to 30 per mile Few on-call or reconnaissance reports (> 2 / week) Few other buried utilities nearby
Low	Virtually no activity reports (< 10 / year) No routine harmless activities in area. Agricultural activities that cannot penetrate to within 1 ft of the pipeline depth may be considered harmless. Very low roadway culvert risk – summed road crossing value greater than 0 to 10 per mile
Very Low	No expected excavation activity, except from maintenance activities Trivial roadway culvert risk – summed road crossing value of 0

When available, utility line crossings can be identified along the Keystone route. The utility crossing areas will be designated as medium activity, with the remainder of the pipeline assigned a lower activity level.

The modifying factors shown in Table 4-5 were used for excavation activity level.

Table 4-5 Excavation Activity Level Modifying Factor

Level of Activity	Factor
High	1.5
Medium	1
Low	0.5
None	0.01

Depth of Cover

Detailed data for the depth of cover of below ground sections of the pipeline is currently not available for Keystone. The modifying factors shown in Table 4-6 were used for depth of cover, and can be applied in a comprehensive manner when detailed data is available. The modifying factors in the table were based on detailed analysis of the UK Health & Safety Executive (HSE) data (ADL, 1999) and DNV engineering judgment for interpolation. They are discussed further in Appendix I.

Table 4-6 Depth of Cover Modifying Factor

Depth of Cover	Factor
0-3 ft	1
3-6 ft	0.7
6-9 ft	0.5
> 9 ft	0.01

4.1.3 Mechanical Defect

This event was defined as a break in the mainline pipe caused by material or manufacturing defects, improper welding, or installation errors. Empirical data was used to quantify this value.

For the period 1988-2000, DOT data shows the base frequency of mechanical or material defects causing leak as 3.81×10^{-5} leaks per mile of pipeline per year (DOT, 2001). This is based upon 34 reported leaks for 893,061 miles of pipeline, utilizing a population of pipelines constructed over a wide range of years. Pipelines built more recently will have been designed and built using more modern codes and standards, and inspected using more advanced techniques. These pipelines, such as Keystone, are less likely to suffer leaks as a result of mechanical or material defects in the pipeline.

Data provided by Kiefner and Trench (2001) supports the conclusion that pipelines constructed after 1970 have a reduced likelihood of construction related defects than those built prior to 1970. This decrease is most significant for longitudinal welds, which are typically performed during manufacturing. A lesser decrease is seen for girth welds, which are typically performed during installation. The following are key inputs to the assessment of mechanical defects:

A 50% reduction in the DOT leak frequency was applied to the entire pipeline because the U.S. portion of Keystone will consist of entirely new materials and be constructed to meet current standards and requirements.

Mechanical defects were considered equally likely to occur anywhere along the pipeline, and no modification factors were applied based on location.

The hole size distribution is based on European Gas Pipeline Incident Data Group (EGIG) (1993) data, details of which can be found in Appendix I. DNV's analysis of the data resulted in the a hole size distribution (Table 4-7) applicable to leaks caused by mechanical defects.

Table 4-7 Hole Size Distribution for Mechanical Defect Leaks

Hole Size	Distribution
Small	65%
Medium	25%
Large	10%

Wall Thickness

Additional wall thickness beyond that required for the pipeline operating pressure could protect the pipe from external damage. Data concerning the minimum wall thickness was provided to DNV by TransCanada.

The modifying factors shown in Table 4-8 are used for wall thickness. These factors are based on a baseline wall thickness of approximately 0.3 in, and the calculation of the modifying factor for thickness relative to the baseline value from EGIG (1993) data, as detailed in Appendix I.

Table 4-8 Wall Thickness Modifying Factor

Keystone Pipeline Diameter	Minimum Wall Thickness	Factor
30 in	0.375 in	0.5
24 in	0.343 in	1

Patrol Frequency

Regular patrols of the pipeline result in earlier identification of excavation activities and improved advance management of such activities. Patrols reduce the likelihood of excavation damage to the pipeline. Patrol frequency is expected to be every two weeks for Keystone, with a resultant modifying factor of 1.3.

Patrol frequency is required by pipeline safety regulations as at least 26 times a year (averaging at two week intervals), but not exceeding intervals of three weeks (49 CFR 195.412). The modifying factors shown in Table 4-9 were used for patrol frequency. The more frequent the patrols, the more likely the patrol is to observe excavation and assure it is being conducted in a appropriate manner, and the greater benefit the patrolling has in reducing spill risk from excavation.

Table 4-9 Patrol Frequency Modifying Factor

Frequency	Factor
Monthly – Weekly	1.3
Weekly	1
2 times per week	0.8
4 times per week	0.65
Daily	0.5

4.1.4 Hydraulic Event

This event is defined as an overpressure of the pipeline severe enough to cause a leak or rupture of the line. This scenario involves a series of concurrent hardware or human errors and can occur at a limited number of locations.

Overpressure pipe failures can occur through two distinctly different means. Pipe can fail due to overpressurization if the internal pressure surpasses the designed bursting strength of the pipeline; however, corroded or fatigued pipe will have a reduced bursting strength and may fail at lower pressures. The following scenarios could result in overpressurization:

- Failure of pressure relief system
- Uncommanded closure of battery limit or gate valves
- Failure of RGVs downstream of high elevation areas to fully close during line shutdown. Hydraulic head will create a high pressure at first sealed valve
- Weakening of pipeline at point where slack and tight line meet, due to the impact of pigs, will reduce bursting strength
- Corrosion damage may reduce the bursting strength of the pipeline

The base frequency for hydraulic event leaks is 9.3×10^{-5} per mile of pipeline per year, based on analysis by Taylor (1995). A modification factor was applied to the base frequency to represent susceptibility to hydraulic events. f_{hy}, the leak frequency from hydraulic events, was therefore calculated as follows:

$$f_{hy} = f'_{co} M_{Hyd} \qquad (4.5)$$

Where:

f'_{hy} = the base frequency of hydraulic events resulting in a leak (9.3×10^{-5} per mile year)

M_{Hyd} = modification factor for susceptibility to hydraulic events

The hole size distribution shown in Table 4-10 was applied for hydraulic event leaks. This is based on engineering judgment concerning the types of leaks represented.

Table 4-10 Hole Size Distribution for Hydraulic Event Leaks

Hole Size	Distribution
Small	20%
Medium	50%
Large	30%

<u>Hydraulic Event Susceptibility</u>

The modifying factors shown in Table 4-11 were used for Hydraulic Event Susceptibility. Given the current design phase of the pipeline and the design criteria, it appears that the pipeline warrants a hydraulic susceptibility level of "low", resulting in a modifying factor of 1. Should additional detailed information be developed, the hydraulic event susceptibility should be re-assessed.

Table 4-11 Hydraulic Event Susceptibility Modifying Factor

Susceptibility		Factor
High	Expected operating pressure >1390 psi	3
Medium	Expected operating pressure between 1000 psi and 1390 psi	1
Low	Expected operating pressure between 500 psi and 1000 psi	0.1
None	Expected operating pressure <500 psi	0

4.1.5 Flange or Seal Leak

A flange is a rim at the end of a section of pipe. For Keystone, bolted flange connections will be installed at checkvalve connections along the pipeline. A section of pipe ending in a flange will be bolted to a checkvalve with a flange. They will compress a gasket at a specified load and form a seal.

The base frequency for flange and seal leaks is 1.0×10^{-4} per fitting per year and is taken from Taylor (1995). This value is in line with other flange leak data such as that discussed in Lees (1996). No modification factors were applied to this base frequency. It was assumed that each checkvalve has two flanges. A segment break was introduced at each check valve, resulting in one flange being counted in each of the adjacent segments.

The hole size distribution shown in Table 4-12 was applied for flange leaks. This is based on engineering judgment concerning the types of leaks represented.

Table 4-12 Hole Size Distribution for Flange Leaks

Hole Size	Distribution
Small	100%
Medium	0%
Large	0%

4.1.6 Washout

This event is defined as failure of the mainline pipe below a river bottom due to severe water erosion. Under severe runoff conditions, pipelines have been known to leak due to the forces applied during pipe displacement. The base frequency of failure (Table 4-13) was estimated using proprietary pipeline washout data and engineering judgment.

Table 4-13 Frequency Estimate for Washout Failures

Basis	Source
0.1 pipe exposures / yr assuming 1000 river crossings	proprietary data
0.1 failure probability on exposure	engineering judgment
= 1×10^{-5} failures / per crossing	

The total pipeline frequency was applied to a stream crossing segment by ratioing the number of stream crossings for the segment to the number for the entire system (806). Each mile of pipeline was assigned a river crossing "value" based on the river type (Table 4-14). This was used to segment the pipeline where the density of river crossing varied. Each segment's frequency was then calculated by applying two modification factors to the base frequency:

- River type - National Hydrological Dataset (2006) (F Code) in Table 4-14.
- Depth of cover in Table 4-15

Table 4-14 River Crossing Modification Factors

River Type	Modification Factor
River	1
Intermittent/ephemeral stream	0.5
Canal/ditch	0.2
Artificial path or none	0

Table 4-15 Depth of Cover Modifying Factor for Washout Leaks

Depth	Factor
0-10 ft	1
>10 ft	0.5

Engineering judgment was used to develop the hole size distribution shown in Table 4-16, which were applied to leaks resulting from washout.

Table 4-16 Hole Size Distribution for Washout Leaks

Hole Size	Distribution
Small	90%
Medium	9.9%
Large	0.1%

5.0 Realistic Maximum Spill Volume

The second phase of this assessment calculated the quantity of crude oil that could be lost from each segment of the pipeline. The quantity of material released during a spill is dependent upon the following parameters:

1. Time until leak is detected, verified and pipeline isolated
2. Initial leak rate, under pipeline pressure
3. Quantity of material in isolated section of pipeline
4. Leak rate after isolation, driven by hydrostatic head in the pipeline

And, depending on whether containment of the leak source is being considered:

5. Time to effectively contain the leak source (via clamping or some other method)

Detection time is the time required for a potential leak to be identified as such. Verification time is the time required for an operator to confirm that a leak is occurring and decide to take action. Isolation time is the time required from completed leak verification to closure of the remote gate valve(s) (RGV)and a relevant downstream check valve, if applicable. Effective valve closure limits the spill volume to the amount trapped between the valves.

A remote gate valve is a block valve that stops oil flow in both directions when given a command from a remote location, such as an operations center (or locally if such an option is provided in the design). RGV are located at every pump station and at every major river crossing.

A check valve allows one-way flow only and prevents the reverse flow of oil. Check valves are designed to be held open by flowing oil and to drop closed automatically and nearly effective immediately when oil flow stops or is reversed. Check valves are located on the downstream side of major river crossing along the pipeline. Co-located with each check valve, there is also a manual valve.

Prior to valve closure, the leak rate from the pipe ("initial leak rate") is estimated to be the rate that oil would flow out of the hole size being evaluated assuming that the mainline pumps continue to operate. After valve closure, the volume trapped between the upstream RGV and the downstream checkvalve ("isolated section volume") is the maximum that could practically be released. For every potential leak location, the relevant RGV are identified and valve closure times applied based on the values in the tables presented in following subsections.

Actual spill volumes are expected to be significantly less than the potential drain down volume. Accounting for procedures to reduce spill volume, such as depressurization and drain down, may significantly reduce the predicted spill volumes estimated for the Keystone Pipeline.

5.1 Detection, Verification, and Isolation

The time required to detect and verify a spill is dependent on the leak detection mechanism that would alert an operator, related to leak rate. The type of cause affects the estimate of times to detect and verify. If the spill cause is such that an individual would be expected to be present and report the leak immediately, the detection/verification times would be different than if the leak detection system was the only means of identifying a spill.

For the purpose of discussion, a cause is called, "reported" if a person is expected to be present at the scene, and very likely to observe the leak and called it in within a short timeframe (regardless of whether the leak is detectable by the leak detection system). An example is excavation damage. Such an event would likely be observed at the time of the incident, and a phone call would be placed to report that a pipeline had been hit during excavation activities. The two reported causes are:

- Excavation damage
- Hydraulic (pressure surge) event

For reported causes, it is assumed that the leak is observed, reported, verified, and valves instructed to close in the times indicated in Table 5-1.

Table 5-1 Time from Leak Start to Closure of RGVs for Reported Causes

Hole size	Detection	Valve closure
Small	30 min	2.5 min
Medium	15 min	2.5 min
Large	9 min	2.5 min

Non-reported causes are expected to occur without any person present to witness and report the event; thus, the leak detection system and surveillance is assumed to be the only means of leak detection for these causes. For example, a corrosion leak is not normally related to the presence of people who might observe it, and would have to be detected via the Keystone systems designed for that purpose. The non-reported causes are:

- Mechanical defect
- Corrosion (external or internal)
- Flange, seal, and fitting leak
- Washout

The estimated times to detect, verify, initiate valve closure, and complete valve closure (isolation) for non-reported causes are provided in Table 5-2. For large leaks, the time for detection system response is independent of whether the leak is above or below ground. Small leaks below ground (necessarily detected by surveillance) may take significantly longer to detect than small leaks above ground.

Table 5-2 Time from Leak Start to Closure of RGVs for Non-Reported Causes

Leak Rate	Detection and Verification		Isolation
	Below Ground Pipe	Above Ground Pipe	Time for RGV to Close
Less than 1.5%	90 days	14 days	2.5 min
1.5%	138 min	138 min	2.5 min
15%	18 min	18 min	2.5 min
50%	9 min	9 min	2.5 min

For leak rates between those presented in the above tables, times were interpolated using a logarithmic straight line fit. This gave the profile in Figure 5-1 for detection time versus leak rate.

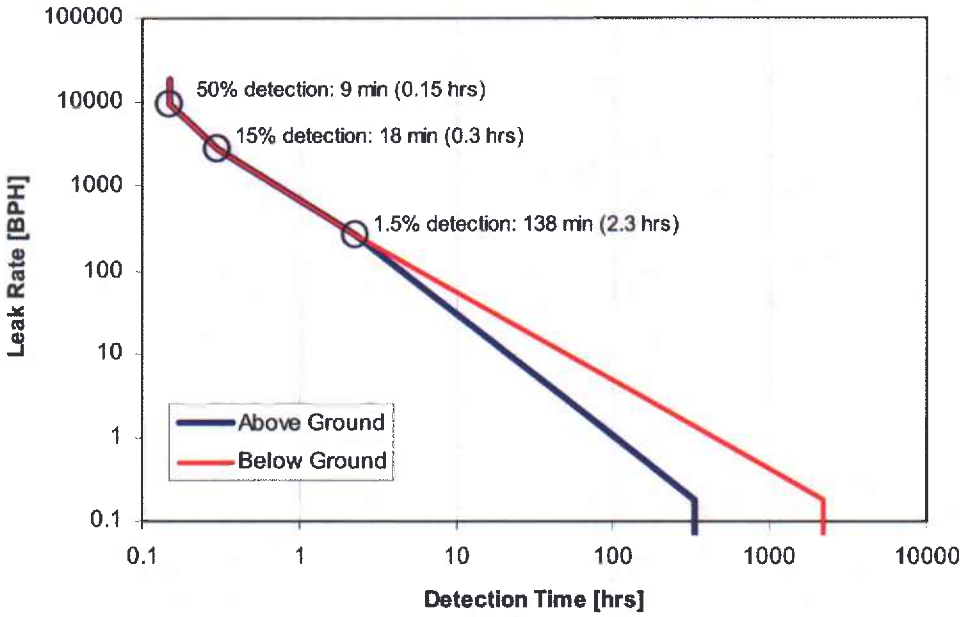


Figure 5-1 Leak Detection & Verification Times

This study assumes that all valves close on demand (0% failure rate). Valve failure concurrent with a leak could result in spill volumes greater than estimated in this study; any failure resulting in a delay in leak isolation would increase the spill volume. Such possible complications in leak isolation are:

- RGV fails to close on command
- Checkvalve fails to drop on loss of flow
- Controller for pump station isolation valves is damaged

5.2 Initial Leak Rate

Standard orifice discharge rates were used based on the representative hole size and the operating pressure of the given segment of the pipeline. This formula is given by:

$$Q_D = C_d A \sqrt{\frac{2\Delta P}{\rho}}$$

where:

Q_D = liquid discharge rate (m^3/s)

C_d = discharge coefficient, set to 0.61

A = hole cross-sectional area (m^2)

ΔP = driving pressure for the leak (Pa)

ρ = density (kg/m^3), 938 kg/m^3 for Keystone

During the initial phase of the leak before the valves close, the driving pressure is based on line pressure at the point of the leak.

5.3 Isolated Section Volumes

Once flow through the pipeline is stopped by shut down of pump stations and closure of RGV, material can still leak from the pipeline via gravitational effects. RGV will stop material flowing in from sections upstream and downstream of the isolation valves, and check valves will stop material flowing back from sections downstream. However, material upstream will be able to flow through check valves, since this is the normal direction of flow.

It was assumed that gravitational effects were the sole mechanism for release after isolation. Siphoning effects, draindown procedures, and line depressurization were neglected. Therefore, the sections of the pipeline that were able to contribute to the spill quantity were those satisfying the following criteria (Figure 5-2):

1. Located between the same two remote gate valves as the leak point
2. No further downstream of the leak point than the first downstream check valve
3. At a higher elevation than the leak point
4. At a higher elevation than any other point located on the same side of the leak, and closer the leak point

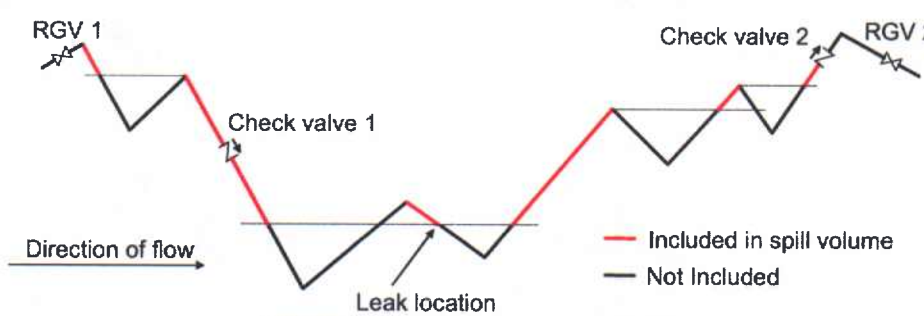


Figure 5-2 Isolated Section Volumes

5.4 Leak Rate After Isolation

In the static phase of the leak, the driving pressure is based on the highest point above the leak, as in isolated volumes, accounting for a closed valve or a peak in the line. For the static phase, the height differential was used to calculate the discharge rate. This formula is given by:

$$Q_S = C_d A\sqrt{2g\Delta h}$$

where:

C_d	=	discharge coefficient, set to 0.61
A	=	hole cross-sectional area (m2)
g	=	gravitational constant 9.81 (m/s2)
Δh	=	differential height of crude in line (m)

5.5 Source Control Time

It is assumed that following leak detection, the pipeline will be shut down by means of stopping the pumps and closing the RGV. For small leaks it is also possible to limit the draininage by various source control measures (clamping, gel block). These means have been assumed to be in place within four hours throughout the pipeline. Therefore the maximum gravity assisted leak is limited to fours hours for medium and small hole sizes.

5.6 Calculation of Spill Volumes

Spill volumes were calculated based on the leak rate and time to isolate. It is important to note that this assessment adopts a conservative approach to estimating spill volumes. The method does not take credit for any reduction in spill volume due to additional actions to control the source aside from shutdown, RGV closure, and plugging. Thus, procedures to reduce spill volume involving depressurization and draindown are not estimated or included. Such procedures would likely be effective for only small and perhaps medium holes. This level of detail could be incorporated into a future study.

6.0 Summary and Conclusions

6.1 Calculated Likelihood of Leaks

The risk analysis of Keystone focused on the likelihood of leaks over the entire pipeline, caused by a variety of factors. Overall, the likelihood of a leak greater than 50 barrels anywhere along the pipeline is estimated to be about 0.14 per year, or once every 7 years.

The calculated likelihood of spills less than 50 bbl is considerably less than practical experience would dictate. This is primarily the result of historical reporting requirements, as 50 bbl spills were not required to be reported to the DOT within the historical data set.

The overall contribution of various causes to leaks along the pipeline is shown in Table 6-1 and Figure 6-1. For each cause, the percent contribution is the total frequency for that cause divided by the total leak frequency for all causes.

Table 6-1 Predicted Pipeline Leak Frequency by Cause

Cause	435K bpd Case		657K bpd Case	
	Percent Contribution	Frequency (per year)	Percent Contribution	Frequency (per year)
Corrosion	28.6%	0.041	22.0%	0.041
Excavation	27.3%	0.039	21.1%	0.039
Hydraulic Event	19.6%	0.028	38.0%	0.071
Mechanical Defect	18.1%	0.026	14.0%	0.026
Flanges	3.3%	0.005	2.6%	0.005
Washout	3.0%	0.004	2.3%	0.004
Total	**100.0%**	**0.143**	**100.0%**	**0.186**

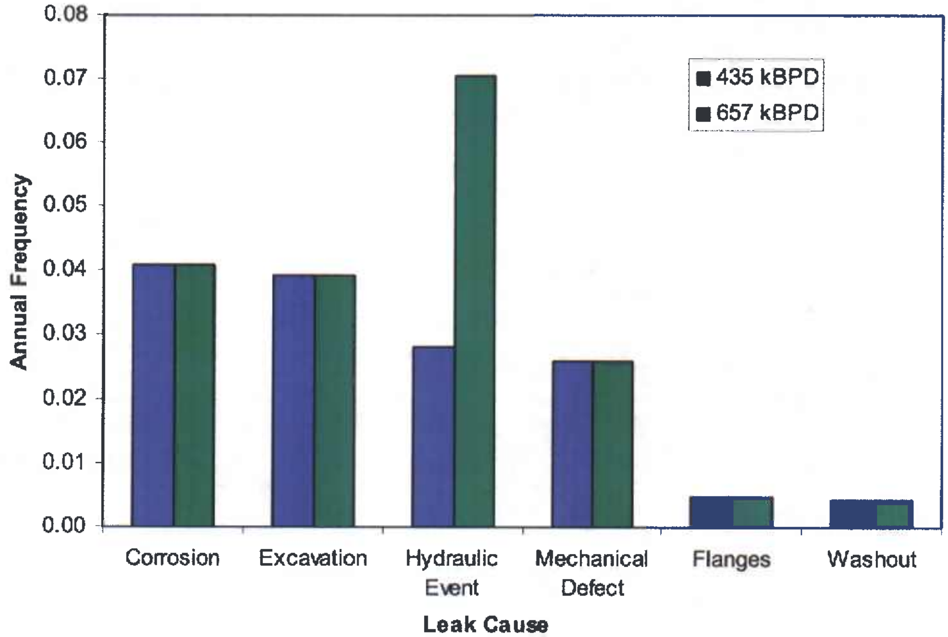


Figure 6-1 Distribution of Pipeline Leak Causes

For the 435,000 bpd case, the greatest contributing cause is corrosion, followed by excavation and hydraulic events. For the 657,000 bpd case, the greatest contributing cause is hydraulic event, followed by corrosion and excavation. However, this is more an artifact of the available hydraulic profile and the method used to differentiate higher risk segments regarding hydraulic risk.

Approximately 53.5% of the spills would be from small holes (pinholes), 32.5% would be from medium sized holes (1 in), and 14% would be from large holes (10 in or greater).

6.2 Summary of Frequency-Volume Results

In general, reported incidents over decades provide a good basis for estimating spill volumes and frequencies for new pipelines. However, there are some key weaknesses in this use of such data:

1. Small volume spills are significantly underreported, particularly those less than the reportable quantity (50 bbl).
2. Extremely infrequent events may not have occurred during the period of data collection of incidents.

Figure 6-2 and Figure 6-3 provide a view of the total frequency of spill volumes.

The necessary assumptions and the current design phase of the pipeline required conservative assumptions to be applied, with the result no identified spill volumes between 50 bbl and 200 bbl. The spill volume risk analysis shows the highest frequency for the 200 to 1000 bbl category of spill volumes. Spill volumes in this category are driven by small leaks that take a long time to detect, as well as medium leaks. Spill volumes between 1000 and 10,000 bbl consist entirely of medium hole leaks, and spills greater than 10,000 bbl consist of large hole size leaks.

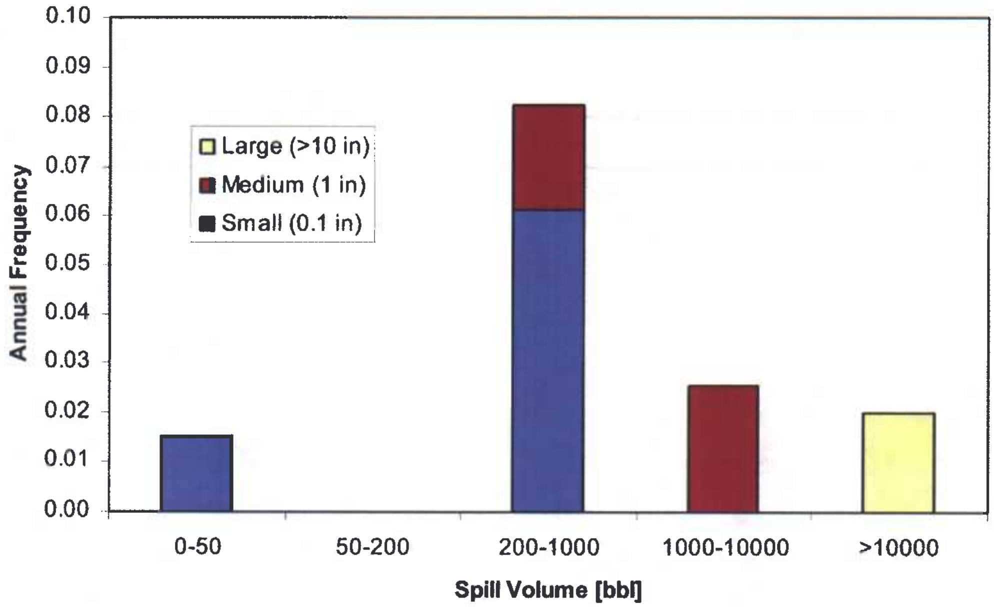


Figure 6-2 Frequency of Spill Volumes by Category (435,000 bpd)

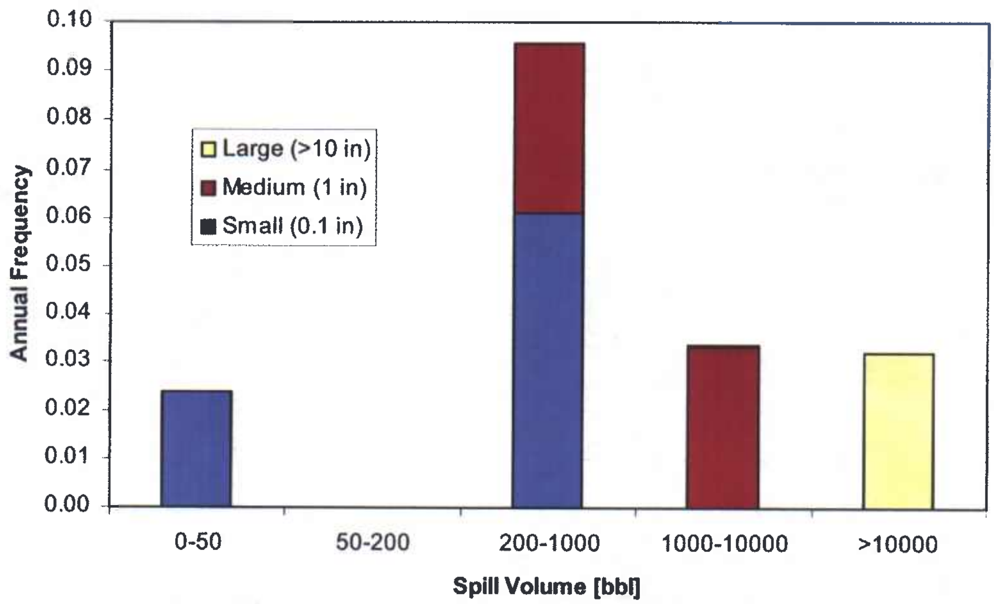


Figure 6-3 Frequency of Spill Volumes by Category (637,000 bpd)

Figure 6-4 provides a view of the spill size distribution. It can be seen that 10% of leaks result in spills greater than 20,000 barrels and only 5% of the leaks evaluated in this study result in spills greater than 30,000 barrels. Note that less than 2 percent of historical hazardous liquid spills released more than 5,000 barrels of product to the environment. Figure 6-4 could be modified to include this estimate; however, the portion of interest (larger spills) would be minimal in perspective.

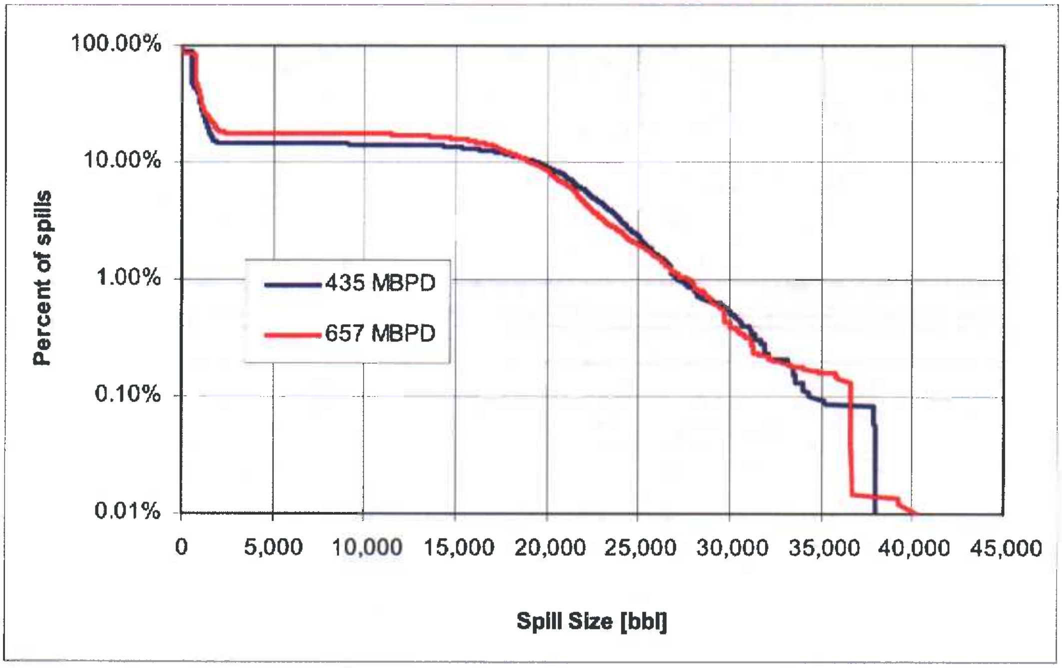


Figure 6-4 Cumulative Spill Volume

These two scenarios bound this study of Keystone Pipeline. However, alone they do not provide an accurate picture of potential spills from Keystone. Evaluation of risk requires assessing frequency and consequence together rather than separately, because the worst risk scenario is often not the greatest volume release, because a large volume release often is associated with the smallest frequencies.

To identify the worst-case pairing on frequency and volume, the frequency and volume were multiplied and summed per segment, providing a "risk" number with which to compare the segments of Keystone. The segment with the largest frequency-volume pairing was at milepost 208, with an estimated volume of 3.6 bbl/yr.

Table 6-2 The Largest Spill Volume Segments

Section of Pipeline	Milepost Begin	Segment Length [mi]	Annual Volume [bbl]	% of Total Length	% of Total Annual Volume
Main line	208.0	6.0	3.6	0.4%	0.7%
Main line	20.0	3.0	3.4	0.2%	0.7%
Main line	732.0	2.0	2.8	0.1%	0.6%
Main line	786.1	3.0	2.7	0.2%	0.5%
Cushing	186.0	4.0	2.6	0.3%	0.5%
Main line	904.0	3.0	2.5	0.2%	0.5%
Main line	158.0	2.9	2.5	0.2%	0.5%
Main line	204.0	2.0	2.3	0.1%	0.4%
Main line	871.0	3.0	2.1	0.2%	0.4%
Main line	200.0	6.0	2.1	0.4%	0.4%

At the appropriate design phase, a consequence study should estimate the severity of potential spills from Keystone (paired with their respective frequencies) and identify those segments posing the greatest risk to the environment. Potential preventive measures could then be evaluated on a cost-benefit basis to determine which are the most effective in reducing environmental risk.

This frequency-volume study provides TransCanada with a detailed database of failure causes, corresponding likelihood, and consequence (in terms of volume released) for the Keystone Pipeline, divided into the smallest relevant subdivisions. The associated database can be used to identify pipeline segments posing the greatest risk (in terms of frequency and volume). This information, taken with fate and transport modeling, can be used to determine where and which additional mitigation measures are appropriate.

6.3 Comparison with Generic Pipeline Leak Frequency

The leak volume per mile for Keystone is approximately 0.37 bbl per mile per year. For purposes of comparison, pipelines in the U.S. had a leak frequency of 0.49 bbl per pipeline mile per year during the period 1992 to 2003 (OPS, 2006).

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