*Analysis of Pipeline and Hazardous Materials Safety Administration Proposed New Safety Rules*

# Pipeline Blowdown Emissions and Mitigation Options

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## About M.J. Bradley & Associates LLC

M.J. Bradley & Associates LLC (MJB&A) provides strategic and technical advisory services to address critical energy and environmental matters including: energy policy, regulatory compliance, emission markets, energy efficiency, renewable energy, and advanced technologies.

Our multi-national client base includes electric and natural gas utilities, major transportation fleet operators, clean technology firms, environmental groups and government agencies.

We bring insights to executives, operating managers, and advocates. We help you find opportunity in environmental markets, anticipate and respond smartly to changes in administrative law and policy at federal and state levels. We emphasize both vision and implementation, and offer timely access to information along with ideas for using it to the best advantage.

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# Executive Summary

This document summarizes the results of an analysis of total methane ($CH_4$) emissions that may result from operator compliance with new natural gas pipeline safety rules recently proposed by the Pipeline and Hazardous Materials Safety Administration (PHMSA). In accordance with the rules, these methane emissions could result from pipeline "blowdowns" required to conduct hydrostatic pressure tests or other pipeline assessments, in order to establish the maximum allowable operating pressure (MAOP) for certain sections of natural gas transmission pipeline. Generally, a blowdown is the release of gas from a pipeline to the atmosphere in order to relieve pressure in the pipe so that maintenance, testing or other activities can take place.

In addition to calculating the magnitude of potential blowdown emissions that could result from the proposed rules, this analysis identified available mitigation methods to reduce blowdown emissions and quantified the respective emissions reductions. These methods include the use of gas flaring, pressure reduction prior to blowdown using in-line or portable compressors, pressure reduction via gas injection to a near-by low pressure line, and reduction of the length of pipe requiring blowdown using stopples. This analysis also calculated the costs and benefits (i.e. blowdown gas reduction) for each method, assuming the method was applied to average blowdown events that might result from the proposed PHMSA rules.

**<u>POTENTIAL BLOWDOWN EMISSIONS</u>**

PHMSA estimates that the proposed rules will require pipeline operators to establish MAOP on 11,757 miles of natural gas transmission pipeline, and that the required assessment methods for 3,509 of these miles (30%) will result in blowdown of the pipe section. The amount of methane released during a blowdown is related to: 1) the diameter of the pipe, 2) the pressure of the gas in the pipe, and 3) the length of the section that must be blown down. The larger the diameter, the greater the pressure, and/or the longer the blowdown section, the more gas will be released.

Based on the weighted average diameter of pipeline segments that will require MAOP determination under the proposed rules, and assuming 400 pounds per square inch (psi) average operating pressure, unmitigated blowdown from 3,509 miles of transmission pipeline in order to accommodate MAOP determination will release 20,291 metric tons of methane to the atmosphere, which correlates to an average of 1,353 tons per year for the 15 year compliance period proposed by PHMSA.

The most recent National GHG Emissions Inventory (GHGI) [1] indicates that routine transmission system maintenance/upset emissions are 184,000 metric tons per year and that total transmission system emissions are 1.28 million metric tons per year. The additional estimated 1,353 annual metric tons of methane emissions related to the testing requirements under the new PHMSA rule could therefore increase annual transmission system methane emissions attributed to routine maintenance/upsets by less than 1%, and could increase total annual transmission system methane emissions by less than 0.1 percent.

**BLOWDOWN MITIGATION OPTIONS**

Using the five blowdown mitigation options investigated, pipeline operators could reduce blowdown methane emissions by 50% to 90%. Estimated out of pocket costs for blowdown mitigation, as applied to projects associated with MAOP determination, will average between $17 per metric ton (MT) and $1,161/MT of avoided methane emissions. The most cost effective option is use of in-line compression, followed by transfer of gas to a low pressure system, and flaring, with costs ranging from $17/MT to $32/MT. Use of a mobile compressor is significantly more expensive than these other options, at $127/MT to $232/MT, but the use of stopples is by far the most expensive option ($613/MT to $1,161/MT).

However, for all mitigation options except flaring and the use of stopples, the economic value of the natural gas that is saved is greater than the cost of mitigation, resulting in *net cost savings* to the pipeline operator. Transfer of gas to a low pressure system creates the highest net savings per event, while in-line compression creates the highest net savings per ton of methane mitigated. Net savings from blowdown mitigation ranges from $77/MT to $188/MT of methane saved.

Additionally, there is a social benefit to avoiding methane emissions from pipelines via blowdown mitigation. This value, associated with the avoided future climate damages of methane emissions, does not accrue to the pipeline operator, but to society at large.

The societal benefits of reducing blowdown methane emissions are significantly greater than mitigation costs for every mitigation option investigated. Net societal benefits range from $524/MT to $1,665/MT of avoided emissions. This analysis indicates that mitigating blowdown emissions associated with MAOP determination to comply with the proposed rules would yield net societal benefits of $13 million or more.

# 1 Background – Proposed PHMSA Rules

On April 8, 2016 PHMSA issued a Notice of Proposed Rule Making related to Safety of Gas Transmission and Gathering Pipelines [2]. The proposed changes to existing pipeline safety rules include a requirement for pipeline operators to establish, or re-establish, maximum allowable operating pressure (MAOP) for certain sections of transmission pipeline for which MAOP had not previously been established, or for which the prior methods used to establish MAOP are deemed inadequate. The specific sections of pipeline for which PHMSA is proposing that MAOP must now be established include:

- Pre-1970 pipe in high consequence areas (HCA)[1] that operates at greater than 20% of specified minimum yield strength (SMYS)[2].
- Any pipe in an HCA, or in a Class 3 or 4[3] non-HCA, for which PHMSA has "inadequate records" on MAOP.
- Any pipe in a Class 3 or 4 area which has never been tested.
- Pipe in newly designated "medium consequence areas" (MCA)[4].

PHMSA's pipeline safety rules that require the establishment of MAOP using specific test methods were first issued in the 1970's, and at that time existing (pre-1970) pipe was grandfathered, so much of that pipe has never been tested to establish MAOP.

Based on data submitted annually by pipeline operators, PHMSA determined that 11,757 miles of transmission pipeline (out of a total of 297,885 on-shore miles) would be subject to the proposed new requirements to establish, or re-establish, MAOP. PHMSA allows three different assessment methods to establish MAOP: 1) inline inspection (ILI), 2) hydrostatic pressure testing (PT), and 3) direct assessment (DA).

In-line inspection involves the use of in-line inspection tools ("smart pigs") that are inserted inside the pipeline and which measure and record data on interior pipe condition as they move through the pipe. ILI does not directly require gas to be removed from the pipe (i.e. does not require blowdown); however, to use ILI the specific section of pipeline must be equipped with launcher and receiver ports

[1] High Consequence Areas are specific locations designated by PHMSA where a pipeline gas release could have the most significant adverse consequences. HCAs are defined as locations where the "potential impact circle" from a pipeline incident contains: 20 or more structures intended for human occupancy; buildings that would be hard to evacuate (e.g., nursing homes, schools); or buildings and outside areas occupied by more than 20 persons on a specified minimum number of days each year.

[2] SYMS is the "specified minimum yield strength" of a pipe, which is based on the dimensions of the pipe and its material properties. SYMS is an indication of the minimum stress a pipe may experience that will cause permanent deformation. The higher the pressure at which a pipe operates the higher the percentage of SMYS.

[3] PHMSA divides all areas along pipelines into Classes based on the density of buildings within 220 yards on either side of the center line of the pipe. Class 3 areas are those with more than 46 buildings per mile intended for human occupancy in this zone. Class 4 areas are those where buildings with four or more stories above ground are prevalent.

[4] The proposed definition of Medium Consequence Areas is locations where the "potential impact circle" from a pipeline incident contains 5 or more structures intended for human occupancy.

for the in-line tools, and not all pipelines are currently equipped with a launcher and receiver. Upgrading a non-equipped section of pipeline for ILI would involve blowdown of some portion of the affected section in order to install the launcher and receiver ports on the pipe.

Hydrostatic pressure testing requires a pipeline section to be isolated and blown down, after which the section is filled with water and pressurized to a specific test pressure, then held at that pressure for a specified period of time.

Direct assessment is based on collection and analysis of various data which is then used to calculate MAOP based on engineering calculations. Establishment of MAOP using direct assessment does not require blowdown of the pipe section.

Using data submitted annually by pipeline operators, and judgement based on industry experience, PHMSA estimates that MAOP for 70% of the pipe mileage subject to the proposed requirements to establish MAOP will be determined either by using direct assessment or by using ILI on segments already ILI-equipped. PHMSA estimates that pipeline operators will establish MAOP using hydrostatic pressure testing for 1,283 miles of pipe (11%), and that the remaining 2,226 miles (19%) of pipe subject to the new rules will be upgraded to be ILI capable, after which ILI will be used to establish MAOP. See Table 1 for a summary of PHMSA's analysis.

**Table 1 PHMSA Mileage Estimates by Test Method**

| | | Interstate | Intrastate | TOTAL |
|---|---|---|---|---|
| Mileage for Which MAOP will be established by | Pressure Test | 197 | 1,086 | **1,283** |
| | ILI Upgrade | 578 | 1,648 | **2,226** |
| **TOTAL** | | **776** | **2,733** | **3,509** |

*Source: PHMSA, Regulatory Impact Assessment, Notice of Proposed Rulemaking- Pipeline Safety: Safety of Gas Transmission and Gathering Pipeline, March 2016.*

PHMSA estimates that a total of 3,509 miles of pipe will therefore have MAOP established based on methods that will require pipeline blowdown (e.g. pressure test or ILI upgrade). PHMSA is proposing to allow industry 15 years to accomplish this testing. In order to comply with the proposed rules approximately 234 miles of pipe per year will need to have MAOP established based on methods that will require pipeline blowdown.

MJB&A has fully reviewed the methodology used by PHMSA to calculate these values, including verifying many of the baseline assumptions based on review and analysis of the underlying data from which they were developed. The reviewed assumptions include industry reported mileage of previously untested pipe by type (interstate, intrastate) location (HCA, non-HCA) and pressure (% SMYS); and historical data on miles of pipe for which MAOP was determined with different test methods. Based on our review we believe that, within the constraints of available information, this is an accurate assessment of pipeline mileage that will require MAOP to be established based on methods requiring pipeline blowdown.

# 2 Estimated Blowdown Emissions

See Appendix A for the equation used to calculate potential blowdown emissions for this analysis[5]. In accordance with this calculation, the amount of methane released during a blowdown is proportional to: 1) the cross sectional area of the pipe, 2) the pressure of the gas in the pipe, and 3) the length of the section that must be blown down. The larger the pipe diameter, the greater the pressure, and/or the longer the blowdown section, the more gas will be released.

The natural gas transmission pipeline system is highly varied: pipe diameters range from less than four inches to more than 48 inches, and operating pressures range from 200 to 1500 pounds per square inch (PSI). As such, the magnitude of blowdown emissions (per mile of pipe) will vary significantly across the system. The approach taken by PHMSA in the proposed rule regulatory impact assessment to calculate total blowdown emissions that would result from the proposed rules was to calculate average per-mile blowdown emission (thousand cubic feet per mile, Mcf/mi) based on the weighted average pipe diameter and pressure of the sections of pipe which will require blowdown to establish MAOP, and to multiply this by the length (miles) of these sections. MJB&A has reviewed PHMSA's methodology and believe that it is a valid approach, but there are some significant uncertainties associated with the values chosen for some key assumptions, especially the values for weighted average pressure and pipeline blowdown length.

As such, each of these major assumptions required to calculate blowdown emissions (pipe diameter, pressure, and pipe length) are discussed separately below, followed by a discussion of the magnitude of potential blowdown emissions that result from these assumptions.

## 2.1 Pipe Diameter

Using data submitted annually to PHMSA by pipeline operators [4] it is possible to calculate the weighted average pipe diameter for interstate and intrastate transmission pipelines in various size bins, as well as the percentage of pipeline mileage which falls into each bin, as shown in Table 2.

As shown, interstate pipelines have, on average, a slightly larger diameter (22 inches) than intrastate pipelines (15.2 inches). The values shown in Table 2 for over-all weighted average pipe diameter were used by PHMSA to calculate blowdown emissions from the proposed regulations; these are also the values used in this analysis.

While individual sections of interstate or intrastate transmission pipeline that would be subject to the proposed regulations might have significantly different diameter than the values shown in Table 2, these

[5] MJB&A used the same equation that was used by PHMSA to calculate blowdown emissions for the Regulatory Impact Assessment, with only minor modification. See Appendix A.

values are appropriate for calculating average emissions (Mcf/mi) and total emissions that could result from the need to establish MAOP under the proposed regulations.

**Table 2 Weighted Average Pipe Diameter (inches), Transmission Pipelines**

| Size Bin | Interstate | | Intrastate | |
|---|---|---|---|---|
| | WTD AVG Diameter [in] | % of Pipeline Mileage | WTD AVG Diameter [in] | % of Pipeline Mileage |
| < 12 inches | 8.0 | 27% | 8.2 | 56% |
| 12 – 34 inches | 24.3 | 57% | 21.7 | 37% |
| >34 inches | 37.8 | 16% | 38.7 | 7% |
| **OVERALL WTD AVG** | **22.0** | | **15.2** | |

*Source: PHMSA, Regulatory Impact Assessment, Notice of Proposed Rulemaking- Pipeline Safety: Safety of Gas Transmission and Gathering Pipeline, March 2016.*

## 2.2 Pipeline Operating Pressure

PHMSA used a value of 400 pounds per square inch (psi) as the weighted average operating pressure of the pipeline sections, both interstate and intrastate, that would need to be blown down to establish MAOP. There is little information in PHMSA's RIA document to justify this value, however a PHMSA representative indicated that it was based on conversations with industry representative and "professional judgement".

MJB&A was not able to independently verify the accuracy of this value for weighted average operating pressure, due to a lack of publicly available data. The data submitted annually to PHMSA by pipeline operators does not include direct information about pipeline operating pressure[6]. Numerous industry publications reference the range of operating pressures for the natural gas transmission system as 200 psi to 1500 psi [5], but none give information about what percentage of pipeline mileage operates at each pressure. Discussion with representatives of several different pipeline operators confirmed the above range of values for operating pressure, but did not uncover any data source that could be used to independently calculate a system-wide weighted average pressure. One operator indicated that it thought the average pressure of its system was closer to 800 psi, but this was based on a general

[6] This information includes data on the percentage of pipe operating at various percentages of SMYS, which could be used to back-calculate operating pressure if it could be correlated to pipe diameter. However, the structure of the PHMSA database that contains this information does not allow for this calculation.

impression not a specific analysis of data. Another operator indicated that the operating pressures in its system varied widely, but might average to between 400 psi and 600 psi.

Given the lack of data that could be used to support the choice of a different assumption, for this analysis MJB&A has used PHMSA's assumption of 400 psi as the average operating pressure of pipeline sections that would need to be blown down to establish MAOP to comply with the proposed regulations. See section 3.3 (sensitivity analysis) and Appendix A for a discussion of how different pressure assumptions would affect the results.

## 2.3 Average per-Mile Blowdown Emissions

Using the assumptions for average pipe diameter and average operating pressure discussed above, MJB&A used the equation shown in Appendix A to calculate average blowdown emissions for the interstate and intrastate transmission system (Mcf/mi). These values are shown in Table 3. Table 3 includes values for the volume of natural gas released (Mcf/mi) as well as the mass of methane (metric tons per mile, MT/mi) released.[7] As shown, average blowdown emissions will be higher from interstate pipelines than from intrastate pipelines due their larger weighted average diameter.

See Table 4 for a summary of estimated average blowdown emissions (Mcf/mi) from sections of pipeline that will have MAOP established based on pressure testing and ILI upgrade; these values were calculated by applying the values shown in Table 2 to PHMSA's estimates of interstate and intrastate pipeline mileage that would be subject to each test method (Table 1). Also shown in Table 4 are the equivalent values calculated and reported in PHMSA's regulatory impact assessment [6].

**Table 3 Average Blowdown Emissions for the Natural Gas Transmission System**

| | | Interstate | Intrastate |
|---|---|---|---|
| Average Blowdown Emissions | Natural Gas (Mcf/mi) | 443.1 | 234.2 |
| | Methane (MT/mi) | 9.1 | 4.8 |

*Source: MJB&A Analysis.*

**Table 4 Average Blowdown Emissions (Mcf/mi) for Pipelines Subject to Different Test Methods**

| | | Pressure Test | ILI Upgrade | WTD AVG |
|---|---|---|---|---|
| Average Blowdown Emissions | MJB&A Analysis (Mcf/mi) | 266.3 | 288.5 | 280.4 |
| | PHMSA Analysis (MT/mi) | 297.3 | 316.0 | 309.8 |

*Source: PHMSA RIA, MJB&A Analysis.*

[7] The methane calculation assumes that natural gas will, on average be 95.7% methane and have a density of 21.6 g/scf. These are the same assumptions used by PHMSA.

As shown in Table 4, the values calculated by MJB&A for average blowdown emissions (Mcf/mi) by test method are approximately 10% lower than the values calculated by PHMSA. This difference is explained by the use of a higher gas compressibility factor and potential differences in how temperatures and pressures were applied in the blowdown calculation; see Appendix A.

## 2.4 Blowdown Mileage

In the regulatory impact assessment for the proposed rule, PHMSA multiplied the values shown in Table 3 (average Mcf/mi) times the mileage shown in Table 1 to calculate total blowdown emissions from the proposed regulations. This implies that regardless of test method (pressure test or ILI upgrade) establishment of MAOP for one mile of pipe will require one mile of pipe to be blown down; however, this is not necessarily true given the complexity of the pipeline system and the practical constraints imposed by system layout. There are situations in which pressure testing would require more than one mile of pipe to be blown down per mile tested. Conversely, upgrading a section of pipe to accept ILI tools so that ILI can be used to establish MAOP may require significantly fewer miles to be blown down than the miles ultimately tested by ILI.

In order to blowdown a section of pipe, that section must be isolated from upstream and downstream pipe sections by closing valves. Valve spacing varies across the system but is generally ten to twenty miles between valves [17]. This means that, without installing a new temporary valve (see Section 3), the minimum distance that can be blown down in order to allow for establishment of MAOP using pressure testing is 10 – 20 miles (i.e. the valve spacing on that segment of pipeline). As such, if only a two-mile section of pipe between valves needed to be pressure tested (for example because it was pre-1970 pipe in an HCA) but the rest of the section between the valves did not need to be tested (because it was not in an HCA), then the total miles that would need to be blown down to accommodate the pressure testing could be five to ten times longer than the actual pressure test mileage.

Upgrading a pipeline to accept ILI tools requires adding a launcher port, and a receiver port further downstream, so that a smart pig can be inserted and removed. If MAOP needed to be determined on a very long section of pipe, say 100 miles, then it might be possible to accommodate this testing via ILI upgrade by blowing down as little as 20 miles of pipe (one section between valves on either end), resulting in blowdown emissions from as little as 20% of the pipe mileage that was ultimately tested to determine MAOP.

Unfortunately it is very difficult to determine the average blowdown mileage per mile of pipe for which MAOP must be determined. As noted above, in the regulatory impact assessment PHMSA implicitly assumes a one-to-one correlation (one mile of blowdown per mile of pipe for which MAOP must be determined). However, PHMSA does not provide any justification or discussion about this assumption.

Absent better information, this analysis is consistent with PHMSA's regulatory impact assessment; estimated total blowdown emissions discussed below are based on 3,509 miles of blowdown, to accommodate MAOP determination on 3,509 miles of transmission pipeline.

## 2.5 Total Blowdown Emissions

Based on the assumptions discussed in sections 2.1 – 2.4, MJB&A estimates that PHMSA's proposed regulations requiring MAOP determination on various transmission pipeline segments will result in 20,291 metric tons of methane being released to the atmosphere as blowdown emissions, if pipeline operators do not implement blowdown mitigation measures. Annual additional blowdown emissions resulting from the proposed rule would average 1,353 tons per year for 15 years. This estimate is within 10% of PHMSA's estimate as presented in the regulatory impact assessment.

As noted in Sections 2.1- 2.4, there is significant uncertainty associated with two key assumptions used to derive this estimate, namely the weighted average pressure at which the affected pipeline segments operate, and the ratio of blowdown mileage to mileage for which MAOP must be determined. As such, this estimate may understate total blowdown emissions, since the actual weighted average pressure at which affected pipeline segments operate could be higher than assumed here. Alternately this estimate may overstate total blowdown emissions by overstating the miles of pipeline that would be required to be blown down to establish MAOP. See section 3.3 below (sensitivity analysis).

In addition, as noted by PHMSA pipeline operators "are already required to complete integrity management assessments of HCA segments under Subpart O of the Pipeline Safety Regulations. The MAOP re-verification tests required under the proposed rule [in subpart L] would fulfil the operator's obligation to complete integrity management assessments"[8]. As such, up to 93%[9] of the blowdown emissions estimated here would likely be required at some point under existing rules, in order for pipeline operators to fulfill existing integrity management obligations, and would therefore not represent an absolute increase in emissions attributable specifically to the currently proposed rules. The proposed rules will, however, likely shift some emissions from later to earlier years based on PHMSA's proposed completion date for testing under the new rules.

To put this estimate of blowdown emissions in perspective, the 2014 National Inventory of Greenhouse Gases and Sinks [1] indicates that total methane emissions from the natural gas sector were 7.05 million metric tons in 2014. Of these, 1.28 million metric tons (18%) were from the natural gas transmission and storage segment. Of the emissions from the transmission and storage segment, 184,000 metric tons (0.014%) were from "routine maintenance/upsets" (i.e. blowdowns).

This analysis indicates that PHMSA's proposed rule could increase annual transmission system methane emissions attributed to routine maintenance/upsets by less than 1%, and could increase total annual transmission system methane emissions by less than 0.1 percent.

[8] PHMSA Preliminary Regulatory Impact Assessment, Pg. 45

[9] Approximately 7% of the estimated blowdown emissions are associated with MAOP determination in the newly designated MCAs, which currently do not require integrity management assessments under subpart O.

# 3 Blowdown Mitigation Options

Based on a literature review and discussion with industry representatives, MJB&A identified five options that a pipeline operator could use to mitigate pipeline blowdown emissions. Using these methods, an operator could reduce total blowdown methane emissions by 50% - 90%. This section provides a brief description of each option and discusses an analysis of the costs and benefits if applied to blowdowns associated with determination of MAOP for transmission pipelines, to comply with PHMSA's proposed new safety rules.

## 3.1 Description of Mitigation Options

Each of the five blowdown mitigation options is described briefly below.

### 3.1.1 Flaring

Rather than venting natural gas released from a pipeline to the atmosphere, the gas can be combusted in a flare. Mobile flares (trailer or skid-mounted) designed for temporary use are commercially available for this purpose. The capital costs for a flare sized to handle the volume from a 12 to 36 inch transmission pipeline range from $10,000 to $50,000, and annual maintenance costs could be $1,000 per year [7] [8] [9] [10]. Set-up and removal of the flare will take approximately eight man-hours, and one to two people will be required to be present while the flare is operating [10].

Flaring operations for a ten mile section of transmission pipeline could take 10 - 30 hours, depending on starting pressure level and flare size. In practical terms a flare can reduce pipeline pressure down to 10 – 20 psi, resulting in a 95% pressure reduction from a 400 psi starting pressure. Methane destruction efficiency of flares ranges from 95% to 98%, for a net reduction in blowdown methane emissions of up to 95%. For every metric ton of methane destroyed in the flare 2.75 tons of carbon dioxide ($CO_2$) is produced; net GHG reductions in carbon dioxide equivalents ($CO_2$-e) would therefore be as high as 95% compared to releasing the natural gas to the atmosphere.[10]

### 3.1.2 Pressure Reduction with In-Line Compressors

The pressure in a section of pipeline can be reduced from normal operating pressure, prior to blowdown, by continuing to operate downstream compressors after the upstream valve has been closed to isolate the section. The pressure can only be reduced to the minimum suction pressure of existing downstream in-line compressors, which is often about 50% of operating pressure for the line. As such, the practical reduction in blowdown methane emissions that can be achieved using in-line compression is often approximately 50% [11].

Using in-line compression to reduce pressure prior to blowdown does not require any new capital equipment and does not incur any labor costs for set up. However, there are costs associated with

[10] Assuming a $GWP_{20}$ of 84, consistent with the 20-year GWP for methane in the most recent IPCC report (AR5). Using a value of 25 for $GWP_{100}$, per the current EPA GHG inventory, the net reductions in $CO_2$-e would be 87%.

planning for the event and for monitoring system pressure during pump down. The duration of pump down for a ten mile section of transmission pipeline could be 5 - 30 hours, depending on starting pressure level, in-line compressor size, and system layout. Note that while valve spacing on pipelines is typically 10 – 20 miles, compressor stations are typically 50 to 100 miles apart. As such, a much longer section of pipe may need to be pumped down than the section of pipe which is ultimately isolated and vented. This affects both the time required for pump down, as well as the amount of fuel used by the in-line compressors for the pump down.

Many compressors on the natural gas transmission system are powered by natural gas from the pipeline on which they operate. In most cases, the volume of natural gas used by in-line compressors to reduce operating pressure prior to blowdown would be significantly less that the volume of gas that would otherwise have been released to the atmosphere if the pump down had not taken place. As such, there is no net "cost" associated with this fuel, but it does reduce the "savings" associated with the economic value of the retained natural gas (not blown down).

### 3.1.3 Pressure Reduction with Mobile Compressors

After a section of pipeline is isolated by valves, and prior to blowdown, the pressure in the line can be reduced from normal operating pressure by using a mobile compressor(s) to pump gas from that section to a downstream section of the pipeline.

The necessary mobile compressor(s) can be skid, truck, or trailer mounted. A typical set-up sized for use on a transmission pipeline might include an 8,500 scfm compressor powered by a 750 kW natural gas engine; such a system could cost $500,000 to $1.6 million, and annual maintenance costs could be $10,000 [10] [11] [12] [13]. There is at least one service company that currently rents compression equipment/provides temporary compression services to pipeline operators for this purpose [14].

Set up and removal of the mobile compressor equipment will take approximately 30 man-hours, and two people will be required on-site for the duration of the pump down [10].

Pump down operations for a ten mile section of transmission pipeline using a mobile compressor could take 5 - 20 hours, depending on starting pressure level and compressor size. Mobile compressors can reduce pipeline pressure down to 80 – 90 psi (minimum suction pressure) [13], resulting in an 80% pressure reduction from a 400 psi starting pressure, and an 80% reduction in blowdown methane emissions.

These mobile compressors are typically powered by natural gas from the pipeline they are pumping down. The volume of natural gas used by mobile compressors to reduce operating pressure prior to blowdown will always be significantly less than the volume of gas that would otherwise have been released to the atmosphere if the pump down had not taken place. As such, there is no net "cost" associated with this fuel, but it does reduce the "savings" associated with the economic value of the retained natural gas (not blown down).

### 3.1.4 Transfer of Gas to Low Pressure System

In limited cases it may be possible to reduce the pressure in a section of transmission pipeline by transferring the gas to a near-by transmission or distribution pipeline that operates at lower pressure, if such a system is available. In this instance, pipeline pressure can only be reduced to the pressure of the system being transferred to; for example, if the pipeline to be blown down operates at 400 psi and the lower pressure system operates at 200 psi then blowdown emission could be reduced by 50% via the transfer.

The required equipment (piping, valves, regulator) could cost $10,000 or more, and might take 10 man-hours or more to set up and remove. At least one person would be required on-site for the duration of the transfer, which could take 5 – 15 hours depending on the size of the systems [9] [15] [16].

### 3.1.5 Isolate Small Section Using Stopples

A small section of pipe between existing valves can be isolated using temporary isolation valves, or stopples. In some instances this method could be employed to reduce total blowdown emissions by reducing the length of pipe required to be blown down. For example, if a four mile section of pipe needed to be pressure tested, but valves on that section of pipe were 16 miles apart, the entire 16-mile section between valves would need to be blown down to accomplish the pressure testing. The use of stopples to isolate only the section that required pressure testing, prior to blowdown, could therefore reduce blowdown emissions by as much as 75%.

Capital costs for the required stopples and fittings could be as high as $90,000 depending on the size of the pipeline, and much of this equipment can often only be used once [17]. Installation could take 50 man-hours or more, and requires specialized skills (i.e. welders).

## 3.2 Blowdown Mitigation Costs & Benefits

This analysis evaluated the potential costs and benefits of the five blowdown mitigation options discussed in Section 3.1, as applied to blowdowns that might be associated with MAOP determination in accordance with the recently proposed PHMSA safety rules. In order to conduct this analysis we developed a "typical" or "average" blowdown scenario which is consistent with the analysis of blowdown emissions in Section 2.

**Table 5 Blowdown Scenarios Used**

| Parameter | | unit | Pipeline Type | |
|---|---|---|---|---|
| | | | Interstate | Intrastate |
| Blowdown Length | | mi/event | 15.0 | 15.0 |
| Blowdown Natural Gas Volume | | Mcf/mi | 443.1 | 234.2 |
| | | Mcf/event | 6,647 | 3,513 |
| Blowdown Methane Mass | | MT/mi | 9.1 | 4.8 |
| | | MT/event | 137.1 | 72.4 |
| Blowdown Natural Gas Economic Value | | $/mi | $1,865 | $986 |
| | | $/event | $27,982 | $14,789 |
| Social Cost of Blowdown Methane | 5% AVG | $/mi | $6,256 | $3,306 |
| | | $/event | $93,837 | $49,595 |
| | 3% AVG | $/mi | $13,526 | $7,149 |
| | | $/event | $202,892 | $107,233 |
| | 2.5% AVG | $/mi | $17,632 | $9,319 |
| | | $/event | $264,484 | $139,786 |
| | 3% 95th Perc | $/mi | $36,231 | $19,149 |
| | | $/event | $543,460 | $287,231 |

*Source: MJB&A Analysis.*

The details of this blowdown scenario are shown in Table 5. As shown, this scenario assumes that an average blowdown event would require blowdown of 15 miles of pipeline, which represents a typical distance between valves on the pipeline system. Based on the analysis described in Section 2, the average interstate pipeline segment subject to MAOP determination would contain 443.1 Mcf of natural gas per mile, so 6,647 Mcf of gas would be blown down from a 15-mile segment, releasing 137.1 metric tons of methane to the atmosphere. The economic value of this released gas would be $27,982 dollars[11] [18]. Consistent with the analysis in Section 2, a 15-mile blowdown event of an average intrastate pipeline segment subject to MAOP determination would release only 72.4 MT of methane to the atmosphere (worth $14,789) due to its smaller diameter.

Table 5 also shows the "Social Cost" of the methane released via blowdown, based on EPA analysis of methane's climate impacts[12] [19]. Since the effects of methane in the atmosphere vary over time, the net social cost varies significantly depending on one's choice of discount rate. Table 5 includes a range of values for the social cost of blown down methane, based on discount rates from 2.5% to 5%. As

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[11] This assumes that natural gas is worth $4.21/Mcf. This is the average value used by PHMSA in the Regulatory Impact Assessment. See section 3.3 (sensitivity analysis) for the effect of varying the gas value from $2.06/Mcf (current Henry Hub spot price) to $6.07/Mcf (average Henry Hub spot price over the next 15 years, as projected by the Energy Information Administration).

[12] The values used for social cost of methane range from $685/MT (5% discount rate, average result) to $3,966/MT (3% discount rate, 95th percentile result). For this analysis EPA values for the years 2015 – 2030 were averaged, and escalated from 2012$ to 2016$ using the GDP Price Deflator Index. See Appendix C.

shown, the social cost varies from $94,000 to $543,000 per event for blowdowns from interstate pipelines and from $50,000 to $287,000 per event for blowdowns from intrastate pipelines.

See Table 6 for a summary of the estimated out of pocket costs[13] (not including the value of saved gas), associated methane reductions, and the average mitigation cost per metric ton of the blowdown mitigation options applied to the average blowdown scenarios shown in Table 5. The details of how these costs and benefits were calculated are included in Appendix B. Note that the costs in Table 6 do not account for the value of the saved gas or for the social cost benefits of methane reductions.

**Table 6 Costs and Benefits of Blowdown Mitigation Options**

| MITIGATION OPTION | Cost ($/event) | | Methane Reduction (MT/event) | | Average Cost ($/MT) | |
|---|---|---|---|---|---|---|
| | Interstate | Intrastate | Interstate | Intrastate | Interstate | Intrastate |
| Flaring | $2,665 | $2,014 | 123.7 | 65.4 | $22 | $31 |
| In-line Compression | $1,013 | $710 | 61.2 | 32.3 | $17 | $22 |
| Mobile Compressor | $13,747 | $13,282 | 108.3 | 57.3 | $127 | $232 |
| Transfer to Low Pressure | $1,309 | $1,164 | 68.5 | 36.2 | $19 | $32 |
| Stopples | $63,059 | $63,059 | 102.8 | 54.3 | $613 | $1,161 |

*Source: MJB&A Analysis.*

As shown, estimated out of pocket costs for blowdown mitigation, as applied to projects associated with MAOP determination, will on average cost between $17/MT and $1,160/MT of avoided methane emissions. The most cost-effective option is use of in-line compression, followed by transfer of gas to a low pressure system, and flaring, with costs ranging from $17/MT to $32/MT. Use of a mobile compressor is significantly more expensive than these other options, at $127 - $232/MT, but the use of stopples is by far the most expensive option ($613 – $1,161/MT).

Note that the cost assumptions used to estimate mitigation costs are conservative. In particular, we have assumed that mobile compressors would only be used 15 times per year. At this utilization level amortized equipment costs account for 80% of the cost of mitigation using mobile compressors. Given enough demand, a third party leasing company might be able to utilize a mobile compressor for 40 or more mitigation events per year[14]. At this level of utilization the cost of blowdown mitigation using a mobile compressor would fall to $63 - $112/MT.

[13] Out of pocket costs include labor, capital, and maintenance costs for mitigation, before gas savings

[14] As shown in Appendix B, this analysis assumes that mobile compressors used for blowdown mitigation would be leased from a third party, and that per-event lease costs would be sufficient to amortize capital costs and annual maintenance costs, based on 15 mitigation events per year, plus 50% for overhead and profit of the leasing company.

See Table 7 for a summary of the private economic value of the natural gas that would be saved by the various blowdown mitigation options, as well net costs and average net cost of methane mitigation when this value is taken into account. Flaring converts to carbon dioxide the methane that would otherwise be emitted to the atmosphere, so there is no value associated with saved gas for this option. All other mitigation options keep gas in the pipeline that would otherwise be released, so these options do "save" natural gas for which there is an associated private economic value. Note the net cost figures in Table 7 do not include social cost benefits of methane reductions.

**Table 7 Economic Value of Saved Natural Gas, Net Costs, and Net Cost Effectiveness**

| MITIGATION OPTION | Value of Saved Natural Gas ($/event) | | Net Cost (Savings) of Methane Mitigation ($/event) | | Average Net Cost ($/MT) | |
|---|---|---|---|---|---|---|
| | Interstate | Intrastate | Interstate | Intrastate | Interstate | Intrastate |
| Flaring | $0 | $0 | $2,665 | $2,014 | $22 | $31 |
| In-line Compression | $12,485 | $6,599 | ($11,473) | ($5,889) | ($188) | ($182) |
| Mobile Compressor | $22,115 | $11,688 | ($8,367) | $1,594 | ($77) | $28 |
| Transfer to Low Pressure | $13,991 | $7,395 | ($12,682) | ($6,231) | ($185) | ($172) |
| Stopples | $20,986 | $11,092 | $42,073 | $51,967 | $409 | $956 |

*Source: MJB&A Analysis.*

As shown in Table 7, for all mitigation options except flaring, the use of mobile compressors on intrastate pipelines, and the use of stopples, the private economic value of the natural gas that is saved is greater than the cost of mitigation, resulting in net cost savings. Transfer of gas to a low pressure system creates the highest net savings per event, while in-line compression creates the highest net savings per ton of methane mitigated.

Given that transmission pipeline operators typically do not own the gas in their pipelines, it might be assumed that they cannot accrue the benefit of saved gas from blowdown mitigation, but in most cases operators actually can accrue these benefits. Pipeline operators earn a fixed fee for every unit of gas transferred through their pipes, based on contracts with natural gas suppliers or marketers [17]. It is understood by both parties that some gas will be lost during the process – through leaks or blowdowns, or to power pipeline compressors. Delivery contracts therefore typically specify a loss rate. In the event that the actual loss rate is higher than specified the pipeline operator must make up the difference to account for gas not delivered. In the event that the actual loss rate is lower than specified the supplier or marketer must pay the pipeline company for the extra gas that was delivered. In this way, pipeline operators may recover the value of the natural gas that is retained in the pipeline via the implementation of blowdown mitigation measures, either from avoiding fees for undelivered gas or via compensation for extra gas delivered.

If methane is retained in a pipeline via blowdown mitigation, rather than being emitted to the atmosphere, there is social value associated with future damages not incurred because the methane was not emitted. This value does not accrue to the pipeline operator, but to society at large.

See Table 8 for a summary of the social value associated with methane reductions from each mitigation option as applied to the blowdown scenarios. The values in Table 8 are based on the social cost of methane emissions calculated with a 3% discount rate. The net cost and cost-effectiveness figures in Table 8 include both the social cost value and the saved gas value.

As shown, the societal benefits of reducing blowdown methane emissions are significantly greater than mitigation costs, for every mitigation option. Net societal benefits are generally higher than $1,300/MT of methane saved when using a discount rate of 3%. Even using the more conservative discount rate of 5%, net societal benefits are higher than $600/MT for all mitigation options except the use of stopples.

**Table 8 Social Value of Saved Natural Gas, Net Costs, and Net Cost Effectiveness**

| MITIGATION OPTION | Social Value of Methane not Emitted [3% discount rate] ($/event) | | Net Cost (Savings) of Methane Mitigation ($/event) | | Net Cost Effectiveness ($/MT) | |
|---|---|---|---|---|---|---|
| | Interstate | Intrastate | Interstate | Intrastate | Interstate | Intrastate |
| Flaring | $166,199 | $87,840 | ($163,534) | ($85,826) | ($1,322) | ($1,313) |
| In-line Compression | $89,521 | $47,314 | ($100,994) | ($53,203) | ($1,651) | ($1,646) |
| Mobile Compressor | $160,167 | $84,652 | ($168,534) | ($83,058) | ($1,556) | ($1,451) |
| Transfer to Low Pressure | $101,446 | $53,617 | ($114,128) | ($59,847) | ($1,665) | ($1,652) |
| Stopples | $152,169 | $80,425 | ($110,096) | ($28,457) | ($1,071) | ($524) |

*Source: MJB&A Analysis.*

## 3.3 Sensitivity Analysis

The costs and benefits of blowdown mitigation discussed in Section 3.2 represent industry average costs and benefits for all blowdowns that might be associated with MAOP determination on the pipeline segments subject to PHMSA's recently proposed safety requirements. As discussed in Section 3.2, pressure reduction using either in-line compression or mobile compressors will, on average, produce net cost savings for pipeline operators when the economic value of the natural gas that is saved is taken into account.

However, individual projects may not produce net savings from blowdown mitigation depending on the scope of the project. Differences in operating pressure, pipeline diameter, blowdown length, and natural gas value will result in variable costs and benefits. See figures 1 - 3 which explore these trade-offs.

Figure 1 plots the net cost of blowdown mitigation using in-line compression ($/event) versus blowdown mileage, for different diameter pipelines (18 inch and 24 inch) operating at different pressures (200 psi, 400 psi, and 800 psi), and assuming a gas value of $4.21/Mcf.  Figure 2 plots the same data for blowdown mitigation using mobile compressors.

Figure 3 plots the net cost of blowdown mitigation using mobile compressors versus blowdown mileage at different gas values, for an 18-inch pipeline operating at 200 psi (worst case) and for a 24-inch pipeline operating at 800 psi (best case).  In Figure 3 the gas values vary from $2.06/Mcf (current value) to $4.21/Mcf (value used by PHMSA) to $6.07/Mcf (projected average value over the next 15 years).

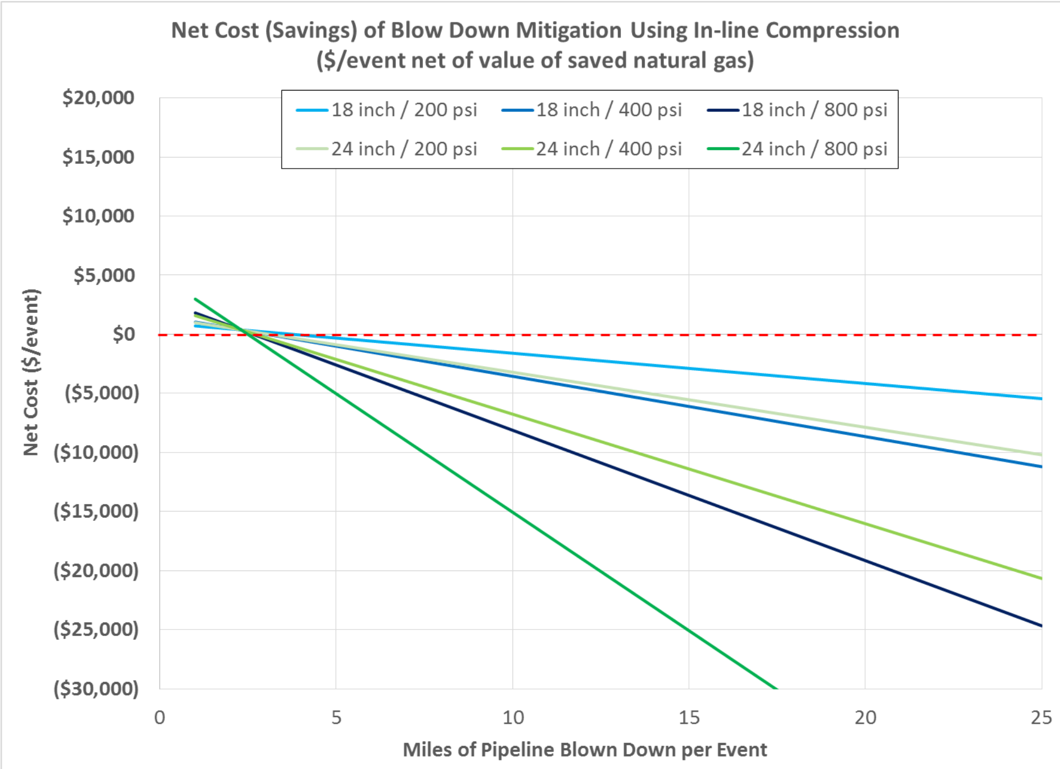
As shown in Figure 1, with a gas value of $4.21/Mcf, the "breakeven" point at which blowdown mitigation using in-line compression will produce a net cost savings is between two and five miles of blowdown mileage, for pipe diameters between 18 and 24 inches, and operating pressures between 200 and 800 psi.

Blowdown mitigation using mobile compressors has significantly different economics.  For a 24 inch pipeline operating at 800 psi the breakeven point is less than five miles of blowdown mileage.  However, for an 18 inch pipeline operating at 200 psi, blowdown mitigation using a mobile compressor will have net cost even if 25 miles of pipeline are blown down (assuming $4.21/Mcf gas value).

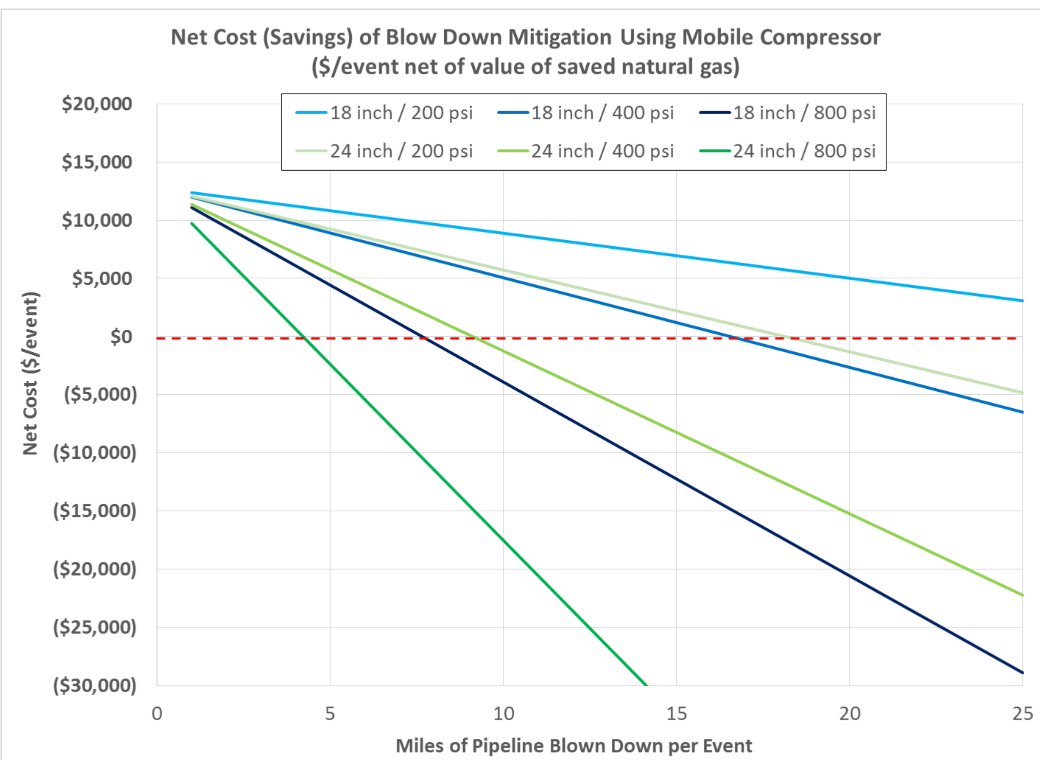
The data in Figure 2 is based on a relatively low utilization rate for mobile compressors (15 events per year).  Higher utilization of this expensive equipment would drive down net costs per event and would move all of the curves in Figure 2 to the left – reducing the breakeven blowdown mileage necessary to achieve net savings.

Also note that blowdown mitigation using in-line compression for a section of 18-inch pipeline operating at 200 psi (worst case shown in Figures 1 and 2) less than one mile long will have social benefits that exceed mitigation costs (using average social value of methane calculated with 3% discount rate).  The breakeven point for having net social benefits from blowdown mitigation of an 18 inch pipeline operating at 200 psi using mobile compressors is four miles of blowdown per event.

### Figure 1 Net Cost of Blowdown Mitigation Using In-line Compression versus Blowdown Mileage



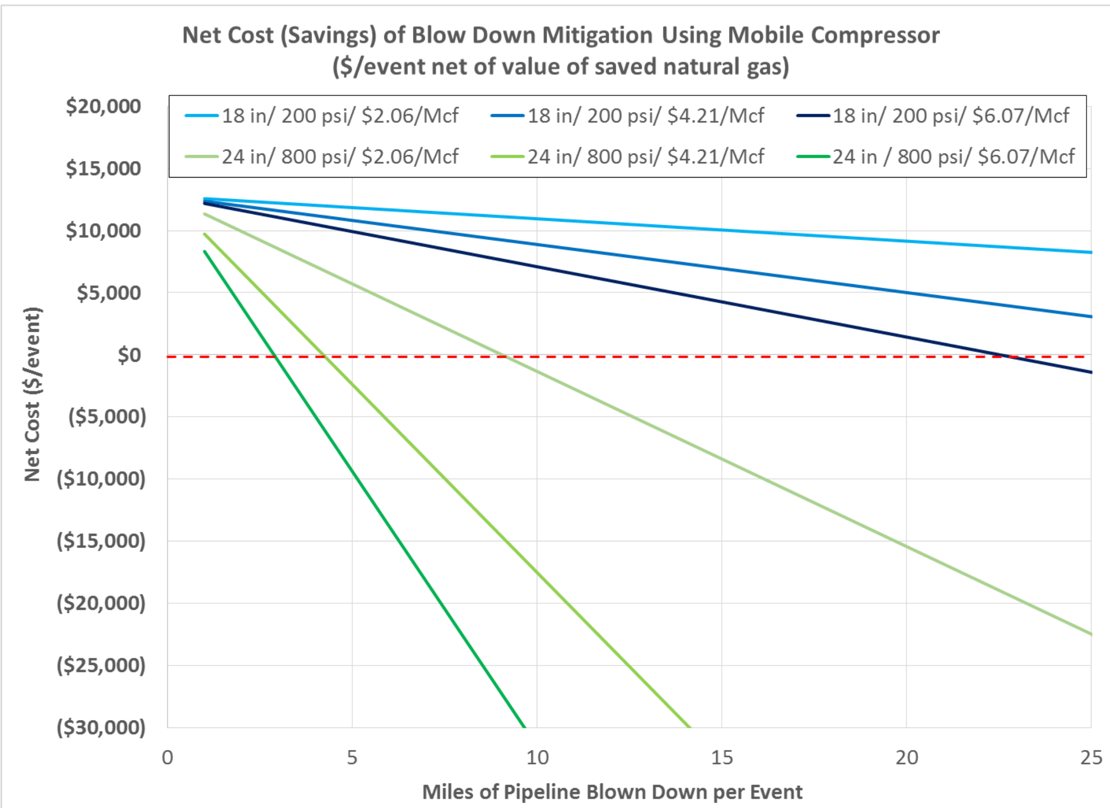

### Figure 2 Net Cost of Blowdown Mitigation Using Mobile Compressor versus Blowdown Mileage



As shown in Figure 3, the higher the value of natural gas ($/Mcf) the lower the break-even mileage at which blowdown mitigation using mobile compressors will produce a net cost savings. At gas values below about $5.00/Mcf blowdown mitigation using mobile compressors for an 18-inch pipeline operating at 200 psi will have net cost, even if more than 25 miles or pipe is blown down. However, at $6.07/Mcf gas value blowdown mitigation using mobile compressors will produce net savings for pipeline sections longer than about 22 miles.

For a 24 inch pipeline operating at 800 psi, an increase in gas value from $2.06/Mcf to $6.07/Mcf will reduce from nine miles to about three miles the breakeven blowdown mileage at which blowdown mitigation using mobile compressors will produce a net cost savings.

**Figure 3 Net Cost of Blowdown Mitigation Using Mobile Compressor versus natural Gas Value**




## 3.4 Summary/Conclusions

This analysis indicates that additional blowdown emissions related to compliance with PHMSA's proposed rules requiring MAOP determination on sections of transmission pipeline will be small compared to existing methane emissions from the gas transmission sector. Nonetheless, the blowdown mitigation options investigated are highly cost-effective and will, on average, result in net savings to pipeline operators when accounting for the value of saved gas.

In addition, the societal benefits from reduced methane emissions ($/MT) are several orders of magnitude greater than out-of-pocket mitigation costs, (i.e., costs not including the value of saved natural gas). Not pursuing blowdown mitigation associated with MAOP determination under PHMSA's proposed rules would result in a net societal loss of $13 million or more[15], due to future climate damages from the released methane.

[15] See table 8; this assumes a 50% reduction in blowdown emissions (10,145 MT) and net societal savings of at least $1,300/MT.

# REFERENCES


[1] U.S. EPA (2016) "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2014". *https://www3.epa.gov/climatechange/Downloads/ghgemissions/US-GHG-Inventory-2016-Main-Text.pdf.* Accessed May 26, 2016.

U.S. EPA (2016) "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2014 Annex 3". *https://www3.epa.gov/climatechange/Downloads/ghgemissions/US-GHG-Inventory-2016-Annex-3-Additional-Source-or-Sink-Categories-Part-A.pdf.* Accessed May 26, 2016.

[2] Department of Transportation, Pipeline and Hazardous Materials Administration, *Pipeline Safety: Safety of Gas Transmission and Gathering Pipelines, Notice of proposed rulemaking;* Docket No. PHMSA-2011-0023; RIN 2137-AE72; Federal Register, Vol. 81, No. 68, April 8, 2016

[3] Department of Transportation, Pipeline and Hazardous Materials Administration*, Preliminary Regulatory Impact Assessment, Notice of Proposed Rulemaking – Pipeline Safety: Safety of Gas Transmission and Gathering Pipelines*, March 2016

[4] U.S. Department of Transportation, Pipeline and Hazardous Materials Safety Administration, *Annual Report For Calendar Year 2014 Natural and Other Gas Transmission and Gathering Pipeline Systems*, Form PHMSA F 7100.2-1 (rev 10-2014)

[5] *The Transportation of Natural Gas, Interstate Natural Gas Pipelines*, NaturalGas.org

American Gas Association, *HOW DOES THE NATURAL GAS DELIVERY SYSTEM WORK?,* www.aga.org/how-does-natural-gas-delivery-system-work

[6] Department of Transportation, Pipeline and Hazardous Materials Administration*, Preliminary Regulatory Impact Assessment, Notice of Proposed Rulemaking – Pipeline Safety: Safety of Gas Transmission and Gathering Pipelines*, March 2016, Table 3-50, Table 3-54

[7] Gas STAR Electronic Flare: U.S. EPA, "Install Electronic Flare Ignition Devices". 2011. Available at: https://www3.epa.gov/gasstar/documents/installelectronicflareignitiondevices.pdf

[8] Gas STAR Flare: U.S. EPA, "Install Flares". 2011. Available at: https://www3.epa.gov/gasstar/documents/installflares.pdf

[9] Sempra 2015: Sempra, "Natural Gas Leakage Workshop: Working Group Workshop on Best Practices". October 27, 2015. Available at: http://www.cpuc.ca.gov/WorkArea/DownloadAsset.aspx?id=8467

[10] NW NATURAL, Methane Abatement Carbon Solutions Project, Draft Proposal 1, February 2015

[11] Gas STAR Pipeline: U.S. EPA, "Using Pipeline Pump-Down Techniques to Lower Gas Line Pressure Before Maintenance". October 2006. Available at: https://www3.epa.gov/gasstar/documents/ll_pipeline.pdf

[12] TransCanada 2009: TransCanada, "Pipeline 'Pumpdown' Compression Barriers to Implementation". October 20, 2009. Available at: https://www3.epa.gov/gasstar/documents/workshops/2009-annual-conf/14cormack.pdf

[13] Hadick, Christian and Scherello, Axel; Avoiding climate-damaging methane emissions during pipeline repairs; Open Grid Europe, the gas Wheel; Krakow, October 14th, 2011

[14] http://www.reserveequipment.com/about-us.php

[15] Gas STAR Low Pressure: U.S. EPA, "Inject Blowdown Gas into Low Pressure Mains of Fuel Gas System". 2011. Available at: https://www3.epa.gov/gasstar/documents/injectblowdowngas.pdf

[16] CPUC 2016: California Public Utilities Commission, "Natural Gas Leakage Abatement, Summary of Best Practices Working Group Activities and Staff Recommendations, Attachment A". January 2016. http://www.cpuc.ca.gov/WorkArea/DownloadAsset.aspx?id=10435

[17] Personal communication with industry representatives.

[18] U.S. Energy Information Administration, *Annual Energy Outlook 2016 early release*, May 2016; Reference Case, Table 13, Natural Gas Supply, Disposition, and Prices; Natural Gas Spot Price at Henry Hub, nominal dollars; average 2017 – 2031

[19] Environmental Protection Agency, *Regulatory Impact Analysis of the Final Oil and Natural Gas Sector: Emission Standards for New, Reconstructed, and Modified Sources*, EPA-452/R-16-002, May 2016, Table 4-3; For this analysis EPA values for social costs of methane in years 2015 – 2030 were averaged, and escalated from 2012$ to 2016$ using the GDP Price Deflator Index

[20] Blue Source Canada, *Blowdown Protocol for Pipeline Systems,* Appendix A GAS DEVIATION FACTOR QUANTIFICATION, April 2011

# APPENDIX A

## Formula for Blowdown Emissions

**Natural Gas Volume [Mcf/mi] =$[(28.798 \times D_{avg}^{2}) \times (T_{std}/P_{std}) \times (P_{avg}/(Z_{avg} \times T_{avg})]/1000$**

| | | | | |
|---|---|---|---|---|
| $T_{std}$ = Standard temperature (deg F) = | 59.0 | = | 288.15 | deg K |
| $P_{std}$ = Atmospheric Pressure (psia) = | 14.70 | = | 101.328 | kPa |

$P_{avg}$ = Average starting pipeline pressure (kPa) before blowdown
$T_{avg}$ = Average starting pipeline temperature (deg K) before blowdown
$Z_{avg}$ = Gas compressibility factor
$D_{avg}$ = Average inside diameter of pipe (inches)

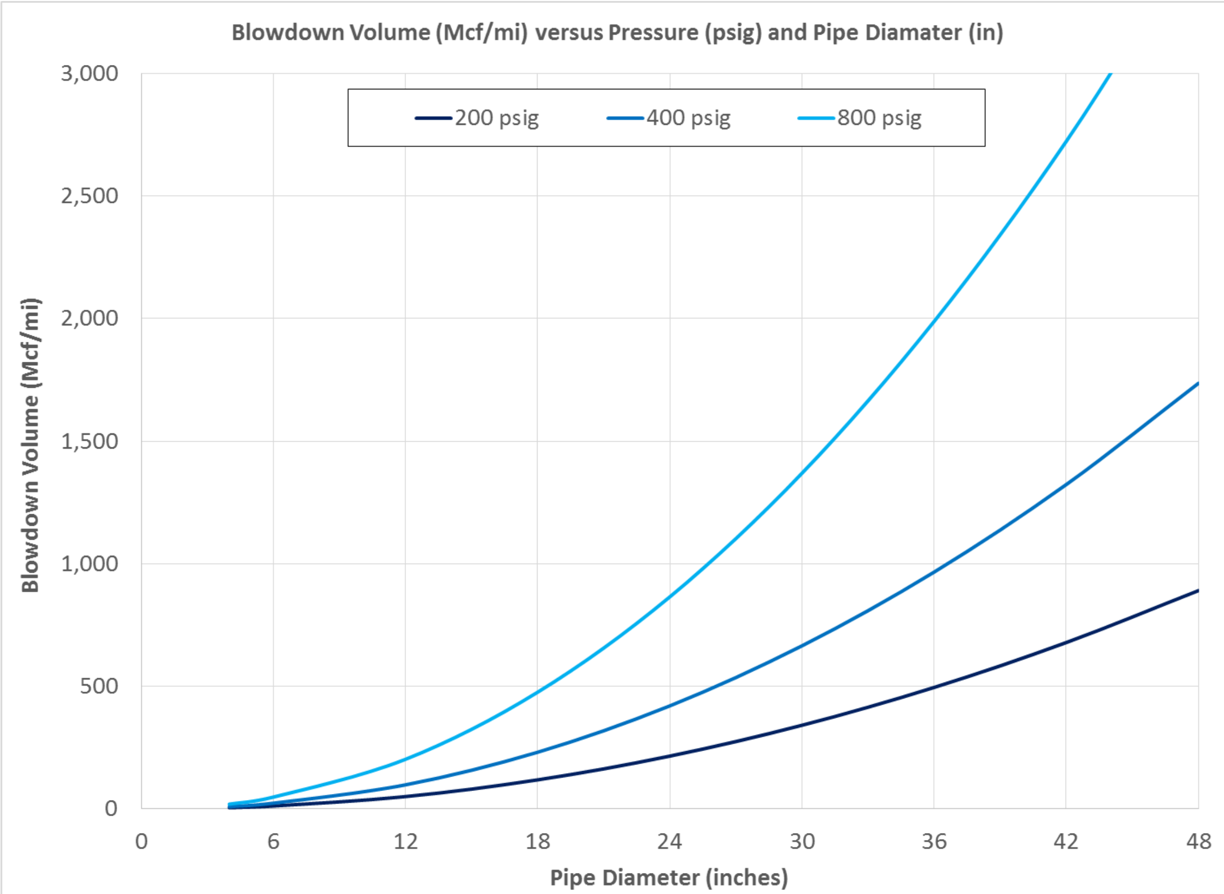
*NOTE: In this equation temperture must be in degrees K and pressure must be in kPa absolute*

*Mcf = 1000 standard cubic feet*

This is the same equation used by PHMSA to calculate blowdown emissions for its Regulatory Impact Assessment (see Equation 1 in PHMSA RIA, page 37 [3]). However, it is not clear from the description in the RIA document whether or not PHMSA used temperature designated in degrees K in the proposed rule analysis, and whether or not they used absolute pressure (as opposed to gauge pressure). In addition, PHMSA used a value of 0.88 for $Z_{avg}$ while MJB&A used a value of 0.926, corresponding to a pressure of 400 psig [20].

See Figure 3 for a Summary of Blowdown emissions (Mcf/mi) based on pipe diameter and pressure, per the above equation.

**Figure 4 Blowdown Emission (Mcf/mi) Versus Pipe Diameter and Pressure**



# APPENDIX B

**Table B1: AVERAGE BLOWDOWN EVENT WITHOUT MITIGATION**

| Parameter | | unit | Pipeline Type: Interstate | Pipeline Type: Intrastate |
|---|---|---|---|---|
| **Blowdown Length** | | mi/event | 15.0 | 15.0 |
| **Blowdown Natural Gas Volume** | | Mcf/mi | 443.1 | 234.2 |
| | | Mcf/event | 6,647 | 3,513 |
| **Blowdown Methane Mass** | | MT/mi | 9.1 | 4.8 |
| | | MT/event | 137.1 | 72.4 |
| **Blowdown Natural Gas Economic Value** | | $/mi | $1,865 | $986 |
| | | $/event | $27,982 | $14,789 |
| **Social Cost of Blowdown Methane** | **5% AVG** | $/mi | $6,256 | $3,306 |
| | | $/event | $93,837 | $49,595 |
| | **3% AVG** | $/mi | $13,526 | $7,149 |
| | | $/event | $202,892 | $107,233 |
| | **2.5% AVG** | $/mi | $17,632 | $9,319 |
| | | $/event | $264,484 | $139,786 |
| | **3% 95th Perc** | $/mi | $36,231 | $19,149 |
| | | $/event | $543,460 | $287,231 |

*Industry average distance between valves*

*From MJB&A analysis of PHMSA RIA data, based on average pipe diameter and pressure*

*From MJB&A analysis of PHMSA RIA data, based on average natural gas composition*

Assumes $4.210 per Mcf.
Source: PHMSA assumption, regulatory impact analysis

Assumes

| $CH_4$ | $CO_2$ | |
|---|---|---|
| $685 | $15 | /MT at 5% discount rate, average |
| $1,480 | $50 | /MT at 3% discount rate, average |
| $1,930 | $74 | /MT at 2.5% discount rate, average |
| $3,965 | $148 | /MT at 3% discount rate, 95$^{th}$ perc |

$CH_4$: Average values over compliance period, in 2016$;
Source: "Incremental $CH_4$ and $N_2O$ mitigation benefits consistent with the US government's SC-CO2 estimates." Marten AL, Kopits EA, Griffiths CW, Newbold SC, Wolverton A. 2014. Climate Policy DOI:10.1080/14693062.2014.912981.

CO2: Average values over compliance period in 2016$,
Source: EPA Technical Support Document, Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866 (May 2013, Revised July 2015)

**Table B2: BLOWDOWN MITIGATION OPTIONS**

| OPTION | Pipeline Pressure | | Blowdown Reduction | Destruction Efficiency | Reduction in Emitted $CH_4$ [1] | | Gas Removal Rate [2] | Duration of Mitigation Operation [3] | | Compressor Fuel Use Natural Gas [1] | | $CO_2$ Emissions | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Starting [psig] | Ending [psig] | [%] | [%] | Interstate [MT/event] | Intrastate [MT/event] | [Mcf/hr] | Interstate [hr/event] | Intrastate [hr/event] | Interstate Mcf/event | Intrastate Mcf/event | Interstate MT/event | Intrastate MT/event |
| Flaring | 400 | 20 | 95% | 95% | 123.7 | 65.4 | 318 | 19.9 | 10.5 | | | 340.2 | 179.8 |
| In-line Compressor | 400 | 200 | 50% | | 61.2 | 32.3 | 1,000 | 11.1 | 5.9 | 357.6 | 189.0 | 20.3 | 10.7 |
| Inject to Low Pressure System | 400 | 200 | 50% | | 68.5 | 36.2 | 500 | 6.6 | 3.5 | | | | |
| Mobile Compressor | 400 | 80 | 80% | | 108.3 | 57.3 | 500 | 10.6 | 5.6 | 64.4 | 34.0 | 3.7 | 1.9 |
| Stopples | NA | | 75% | | 102.8 | 54.3 | NA | NA | NA | | | | |

**Table B3: VALUE OF MITIGATED BLOWDOWN GAS ($/event)**

| OPTION | Economic Value of Saved Natural Gas | | Social Value of Non-emmitted Methane [4] | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Interstate | Intrastate | Interstate | | | | Intrastate | | | |
| | | | 5% AVG | 3% AVG | 2.5% AVG | 3% 95P | 5% AVG | 3% AVG | 2.5% AVG | 3% 95P |
| | [$/event] | [$/event] | [$/event] | [$/event] | [$/event] | [$/event] | [$/event] | [$/event] | [$/event] | [$/event] |
| Flaring | $0 | $0 | $79,537 | $166,199 | $213,525 | $440,130 | $42,037 | $87,840 | $112,853 | $232,619 |
| In-line Compressor | $12,485 | $6,599 | $41,563 | $89,521 | $116,511 | $239,489 | $21,967 | $47,314 | $61,579 | $126,575 |
| Inject to Low Pressure System | $13,991 | $7,395 | $46,919 | $101,446 | $132,242 | $271,730 | $24,798 | $53,617 | $69,893 | $143,616 |
| Mobile Compressor | $22,115 | $11,688 | $74,106 | $160,167 | $208,756 | $428,965 | $39,167 | $84,652 | $110,332 | $226,718 |
| Stopples | $20,986 | $11,092 | $70,378 | $152,169 | $198,363 | $407,595 | $37,196 | $80,425 | $104,839 | $215,424 |

**Table B4: BLOWDOWN MITIGATION COST ELEMENTS (per event)**

| OPTION | CAPITAL EQUIPMENT | | | | | LABOR | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Purchase Cost | Annual Maint | Equip-ment Life | Utilization | Amortized Equip Cost | Planning | Set-Up and Removal | On-site During Blowdown | Total Labor per Event | | TOTAL LABOR COST [5] | |
| | | | | | | | | | Interstate | Intrastate | Interstate | Intrastate |
| | [$] | [$] | [yr] | [Events/yr] | [$/event] | [man-hrs] | [man-hrs] | [FTE] | [man-hrs] | [man-hrs] | [$/event] | [$/event] |
| Flaring | $50,000 | $1,000 | 7 | 15 | $543 | 8.0 | 8.0 | 1.50 | 45.8 | 31.7 | $2,122 | $1,471 |
| In-line Compressor | NA | NA | NA | NA | $0 | 8.0 | 0.0 | 1.25 | 21.8 | 15.3 | $1,013 | $710 |
| Inject to Low Pressure System | $10,000 | $500 | 5 | 15 | $167 | 8.0 | 10.0 | 1.00 | 24.6 | 21.5 | $1,142 | $997 |
| Mobile Compressor | $1,000,000 | $10,000 | 10 | 15 | $11,000 | 8.0 | 30.0 | 2.00 | 59.3 | 49.2 | $2,747 | $2,282 |
| Stopples | $60,000 | $0 | 1 | 1 | $60,000 | 16.0 | 50.0 | NA | 66.0 | 66.0 | $3,059 | $3,059 |

**Table B5: BLOWDOWN MITIGATION TOTAL COSTS ($/event)**

| OPTION | Average Mitigation Cost (Savings) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Cost | | net of Natural Gas Economic Value | | net of NG Economic Value and Methane Social Value | | | | | | | |
| | | | | | Interstate | | | | Intrastate | | | |
| | Interstate | Intrastate | Interstate | Intrastate | 5% AVG | 3% AVG | 2.5% AVG | 3% 95P | 5% AVG | 3% AVG | 2.5% AVG | 3% 95P |
| | [$/event] | [$/event] | [$/event] | [$/event] | [$/event] | [$/event] | [$/event] | [$/event] | [$/event] | [$/event] | [$/event] | [$/event] |
| Flaring | $2,665 | $2,014 | $2,665 | $2,014 | ($76,873) | ($163,534) | ($210,860) | ($437,465) | ($40,023) | ($85,826) | ($110,839) | ($230,605) |
| In-line Compressor | $1,013 | $710 | ($11,473) | ($5,889) | ($53,036) | ($100,994) | ($127,984) | ($250,961) | ($27,856) | ($53,203) | ($67,468) | ($132,464) |
| Inject to Low Pressure System | $1,309 | $1,164 | ($12,682) | ($6,231) | ($59,601) | ($114,128) | ($144,924) | ($284,412) | ($31,028) | ($59,847) | ($76,124) | ($149,846) |
| Mobile Compressor | $13,747 | $13,282 | ($8,367) | $1,594 | ($82,473) | ($168,534) | ($217,123) | ($437,332) | ($37,572) | ($83,058) | ($108,738) | ($225,123) |
| Stopples | $63,059 | $63,059 | $42,073 | $51,967 | ($28,305) | ($110,096) | ($156,290) | ($365,522) | $14,771 | ($28,457) | ($52,872) | ($163,456) |

**Table B6: AVERAGE METHANE MITIGATION COST ($/MT)**

| OPTION | Methane Mitigation Cost | | Methane Mitigation Cost Net of NG Economic Value | | Methane Mitigation Cost net of NG Economic Value and Methane Social Value | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Interstate | | | | Intrastate | | | |
| | Interstate | Intrastate | Interstate | Intrastate | 5% AVG | 3% AVG | 2.5% AVG | 3% 95P | 5% AVG | 3% AVG | 2.5% AVG | 3% 95P |
| | [$/MT] | [$/MT] | [$/MT] | [$/MT] | [$/MT] | [$/MT] | [$/MT] | [$/MT] | [$/Mt] | [$/Mt] | [$/Mt] | [$/Mt] |
| Flaring | $22 | $31 | $22 | $31 | ($621) | ($1,322) | ($1,704) | ($3,536) | ($612) | ($1,313) | ($1,695) | ($3,527) |
| In-line Compressor | $17 | $22 | ($188) | ($182) | ($867) | ($1,651) | ($2,093) | ($4,103) | ($862) | ($1,646) | ($2,087) | ($4,098) |
| Inject to Low Pressure System | $19 | $32 | ($185) | ($172) | ($870) | ($1,665) | ($2,115) | ($4,150) | ($857) | ($1,652) | ($2,102) | ($4,137) |
| Mobile Compressor | $127 | $232 | ($77) | $28 | ($761) | ($1,556) | ($2,004) | ($4,037) | ($656) | ($1,451) | ($1,899) | ($3,932) |
| Stopples | $613 | $1,161 | $409 | $956 | ($275) | ($1,071) | ($1,520) | ($3,555) | $272 | ($524) | ($973) | ($3,008) |

**NOTES TO TABLES B1 - B6:**

[1] Reductions are net of fuel used by compressors:

| | Power (kw) | Load Factor | NG Use (Mscf/hr) |
|---|---|---|---|
| In-line compressor | 4,000 | 85% | 32.28 |
| Mobile compressor | 750 | 85% | 6.05 |
| Compressor efficiency | | 33% | |

[2] Flaring gas removal rate based on

| | |
|---|---|
| Flare diameter (ft) | 0.75 |
| Max tip velocity (ft/s) | 400.0 |
| Removal rate (Mcf/hr) | 318.1 |

[3] In-line compressors assumed 100 miles apart; on average gas must be drawn down from half this length.
Total natural gas drawn down is 3.3 times the avoided blowdown volume, on average.

[4] This is net of the Social cost of $CO_2$ emitted by the mitigation method

[5] Based on:

| | | | |
|---|---|---|---|
| Labor Rate | $/hr | $39.40 | *Based on: Bureau of Labor Statistics; NAICS 486200: Pipeline Transportation of Natural Gas; Occupation Code 459-0000, Installation, Maintenance, and Repair Occupations, Mean Hourly wage. Fringe benefits include insurance, supplemental pay, and retirement.* |
| Labor Availability | % | 85% | |

*The rate for 2015 was escalated by* *11.0%* based on inflation of 1.5% /year for 7 years

[6] This analysis assumes that mobile compressors will be leased from a third party.
Amortized capital caost assumes 50% overhead and profit

# APPENDIX C

**EPA NSPS RIA Table 4-3**
**Social Cost of Methane (Source: Marten *et al*, 2014)**

| YEAR | Social Cost of Methane (2012$) Discount rate | | | |
|---|---|---|---|---|
| | 2.5% AVG | 3% AVG | 5% AVG | 3% 95th perc |
| 2012 | $1,400 | $1,000 | $430 | $2,800 |
| 2015 | $1,500 | $1,100 | $490 | $3,000 |
| 2020 | $1,700 | $1,300 | $580 | $3,500 |
| 2025 | $1,900 | $1,500 | $700 | $4,000 |
| 2030 | $2,200 | $1,700 | $820 | $4,500 |
| 2035 | $2,500 | $1,900 | $970 | $5,300 |
| 2040 | $2,800 | $2,200 | $1,100 | $5,900 |
| 2045 | $3,000 | $2,500 | $1,300 | $6,600 |
| 2050 | $3,300 | $2,700 | $1,400 | $7,200 |

**MJB&A Analysis**

| | | | | |
|---|---|---|---|---|
| **AVG 2015 - 2030 (2012$)** | **$1,825** | **$1,400** | **$648** | **$3,750** |
| **AVG 2015 - 2030 (2016$)** | **$1,930** | **$1,480** | **$685** | **$3,965** |

| | 2012 | 2016 | Ratio |
|---|---|---|---|
| **GDP Price Deflator** | 104.47 | 110.45 | 1.057 |

| Social Cost of $CO_2$, 2015-2050 ($/MT, 2007$) | | | | |
|---|---|---|---|---|
| Source: Technical Support Document (PDF, 21 pp, 1 MB): Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866 (May 2013, Revised July 2015) | | | | |
| Year | Discount Rate | | | |
| | 5% Average | 3% Average | 2.5% Average | 3% 95th percentile |
| 2015 | $11 | $36 | $56 | $105 |
| 2020 | $12 | $42 | $62 | $123 |
| 2025 | $14 | $46 | $68 | $138 |
| 2030 | $16 | $50 | $73 | $152 |
| 2035 | $18 | $55 | $78 | $168 |
| 2040 | $21 | $60 | $84 | $183 |
| 2045 | $23 | $64 | $89 | $197 |
| 2050 | $26 | $69 | $95 | $212 |

**MJB&A Analysis**

| | | | | |
|---|---|---|---|---|
| **AVG 2015 - 2030 (2012$)** | **$13** | **$44** | **$65** | **$130** |
| **AVG 2015 - 2030 (2016$)** | **$15** | **$50** | **$74** | **$148** |

| | 2007 | 2016 | Ratio |
|---|---|---|---|
| **GDP Price Deflator** | 96.65 | 110.45 | 1.143 |

https://research.stlouisfed.org/fred2/series/GDPDEF