Quantifying the Economic Impact of Hydraulic Fracturing Proppant Selection in Light of Occupational Exposure Risk and Functional Requirements

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ABSTRACT

Selection of an effective and economic proppant material for hydraulic fracturing is an important design choice to optimize the production of oil and natural gas. Proppants are made of silica (quartz sand), alumina, resin coated silica, ceramics, and others. These materials can be toxic to varying degrees and lead to health problems in the employees handling them primarily due to inhalation exposure. Proppants are selected based on grain size, shape, strength, and cost. Current use is dominated by crystalline silica - the proppant that also has the greatest hazard as an inhalation toxin. Existing research describes the effect of silica on human health, but little research has been done to determine the risk-reduction and social-cost-effectiveness associated with using alternative proppants in light of the health risks. This study quantifies the relative risks or benefits to human health by the use of these proppants through an economic analysis considering the health-related economic impact and its technical attributes. Results show that the use of each ton of silica proppant results in $123 of external costs from fatalities and non-fatal illness arising due to...
exposure to silica for a crew handing 60,000 tons of proppants. If these health-related externalities were incorporated into the cost silica proppant could be economically replaced by less harmful, more expensive alternatives for hydraulic fracturing crews handling less than 60,000 tons of proppant each year.

1. INTRODUCTION

Treatment of wells using proppants (particulate material used to prop open the fractures) in hydraulic fracturing has been recorded as early as the early 1940s [1]–[3]. As unconventional reservoirs (“shales”) have begun to be exploited for oil and gas, the use of large volume, multi-phase hydraulic fracturing operations, particularly in horizontal wellbores with long laterals has increased substantially. With this increase in the utilization of advanced reservoir simulation technology, there has been an increasing challenge in fracturing, including the selection of appropriate proppant. Proppants with different characteristics have been developed to successfully achieve higher production rates from a variety of complex low permeability reservoirs. Waxman et al. (2011) describe the development of over 2,500 different proppants between 2005 and 2009 made of various substances [4]. Numerous proppants with different combinations of technical capabilities are available, which can be used for different applications based on the stress regime and petrophysical characteristics of a given reservoir. The development of low permeability reservoirs at greater depths has further incentivized the proppant industry to develop high-strength proppants that can effectively keep the fractures open in higher closure stress environment. Based on the material used, proppants can be broadly classified into four broad categories, namely silica-based proppant, resin-coated silica-based
proppant, bauxite-based proppant, and ceramic-based proppant. Silica-based proppants and resin-coated silica-based proppants are primarily made up of quartz sand wherein the sand in the later is coated with resin to enhance its strength. Ceramic-based proppants are mainly made up of sintered bauxite, kaolin, and magnesium silicate whereas bauxite-based proppants are primarily made up for bauxite. Silica-based proppant is used in shallower wells having lower closure stress. At higher closer stress, the sand particles are crushed due to the high pressures, thereby closing the fractures and rendering this material ineffective. Ceramic and bauxite-based proppants are used in deeper wells having higher stress environments and resin-coated proppants are used for increased durability and resistance to degradation [5].

Choice of the optimal proppant is vital in any hydraulic fracturing operation for maximizing production. However, the cost and availability of proppant appear to play an important role in determining the design of any fracturing operation as this cost can constitute a significant portion of the total cost of well treatment [5]. Despite the development of different types of proppant, high-silica quartz sand (hereafter: sand) continues to be the most widely used proppant [1][5]. Reports show that from the early 1940s to 2010, sand dominated the proppant use with over 99% of fractured wells using sand as a proppant [6]. The proportion of sand in the proppant quantity placed in various non-conventional shale basins in the U.S during four consecutive quarters in 2013 and 2014 is over 90% [7] (Figure 1).
Figure 1 Estimated fracture sand consumption among major U.S. unconventional oil and gas shale basin. The estimated share of fracture sand to total proppant consumed in ten major non-conventional fields was over 90 percent for all the fields except Bakken (Data from [7]).

Among the different types of proppant used in the hydraulic fracturing industry from the year 2001 to 2010, over 99% of the reported proppants selected were silica-based (Figure 2) which pose a health risk due to exposure [8]. Studies have confirmed the presence of respirable crystalline silica beyond the Occupational Safety and Health Administration (OSHA) Permissible Exposure Limit (PEL) and National Institute for Occupational Safety and Health (NIOSH) Recommended Exposure Limit (REL) at hydraulic fracturing sites, which indicate health hazards for workers [9]. Personal breathing zone samples collected from 11 hydraulic fracturing sites by researchers from NIOSH showed that over 68% of the people working at
these hydraulic fracturing sites were exposed to more than 50 μg/m$^3$ of respirable silica, the NIOSH REL and OSHA PEL [8].

Figure 2 Number of different types of silica and non-silica-based proppants by year [10]. The number of different types of silica-based proppants used between 2001 and 2010 far exceeds the number of different types of non-silica-based proppants.

With the predicted increase in demand for natural gas, proppant demand is expected to increase in the future [11], especially the use of silica-based proppants. This study examines the reduction in health risks and economic impacts of replacing silica-based proppants with other commercially available proppant materials. Reports show that the proppant supply increased by over 50% in the year 2014 as compared to 2013 [12] which was synchronous with an increase in gross natural gas production in the year 2014 as compared to 2013. Further, reports from the U.S. Energy Information Agency predicts that the natural gas production in the U.S. is expected to
increase by 5.8 billion cubic feet per day in the year 2018 as compared to the production of 73.7 billion cubic feet per day in 2017 [13]. Moreover, the U.S. Energy Information Administration (EIA) expects an increase of 45% in the production of dry gas by the end of 2045 [14]. With the demand for natural gas expected to increase in future years [15], mostly from unconventional reservoirs that require hydraulic fracturing to facilitate production, the use of silica-based proppant is expected to rise in the future. With different proppants like ceramic-based proppant, bauxite-based proppant, and resin-coated silica-based proppant now being developed and used [16]–[18], this research examines how replacing silica-based proppants with these proppants may reduce occupational health-related costs. Currently, a proppant is chosen solely based on its engineering performance and the direct economic costs and benefits to a given project. This paper seeks to quantify the likely health impact of these proppant choices and determine the external costs related to exposure to such proppants. Further, the paper quantifies the economic impact of proppant selection not only based on its engineering performance and the direct cost of proppant but also including the health-related costs associated with worker exposure to such substances.

2. METHODOLOGY

2.1 Data Collection

The first step involved the compilation of a database of different proppants commercially available in the market. Material Safety Data Sheets (MSDS) and Technical Data Sheets of 94 commercially available proppants were collected from the websites of different companies. A
database of proppants suited for reservoirs with specific parameters like the ranges of closure stress, and the corresponding conductivity and permeability was populated from the technical data sheets. The chemical composition of each proppant was assessed from the MSDS and included in the database as well. The proppants were then divided into four major categories based on the material they were made from, namely, ceramic-based (C), bauxite-based (B), resin-coated (RC) and silica-based (S) proppant. *Figure 3* shows the number of proppant of each type included in the study. The study incorporated 33 ceramic-based proppants, 28 bauxite-based proppants, 22 resin-coated proppants, and 11 silica-based proppants. It should be noted that only the proppants with available MSDS and Technical Data Sheets were included in this study. Further, 1 in 5 of the MSDS did not list the exact composition of the proppant since they were listed as trade secrets, but sufficient data was available to divide the proppants into one of the four major categories. The proppants with missing technical datasheets were excluded from this study because the optimal ranges of reservoir properties (conductivity and permeability) conducive to use a given proppants are listed in the datasheets and those data are the required for this study.

The particle size, shape, and composition of proppants govern the inhalation health risks. For this study, the exposure limits for each of the particulate materials as defined by the existing rules or guidelines established by regulatory or advisory bodies, i.e., OSHA PEL, NIOSH REL, and ACGIH TVL were collected to indicate the health impact of exposure to each proppant.
Figure 3 Numbers of four major categories based on their type, namely ceramic-based (C), bauxite-based (B), resin coated (RC) and silica-based (S) proppant.

The database consisted of a wide array of proppants that can be used for fracking in reservoirs with closure stress of 2000 to 18000 psi, the conductivity of 60 to 42000 md-ft and permeability of 5 to 2750 Darcy (1 Darcy = 9.869233×10^{-13} m²). In order to determine the availability of proppants that can be used in reservoirs with given permeability and conductivity, the range of these reservoir properties associated with each proppant were collected. Figure 4 shows the number of proppants commercially available that can be used at a given range of reservoir conductivity, and Figure 5 shows the number of proppants available at different permeability ranges.
Figure 4 Number of proppants available at different permeability ranges

Figure 5 Number of proppants available at different conductivity ranges

A higher number of proppants are available that can be used in the reservoirs having intermediate ranges of permeability and conductivity as compared to deep reservoirs with high conductivity and permeability. Fracturing in deeper wells in the recent past has led to the development of “high performance” proppants appropriate for these more extreme environments.
2.2 Willingness-to-pay for Avoided Fatality and Morbidity

The willingness to pay for an avoided fatality is defined as the money an individual is willing to expend to avoid a marginal increase in the risk of a fatality [19], which has interested many researchers. Hintermann et al. have developed models to determine statistically robust estimates [20]. Viscusi and Aldy conducted an extensive analysis of multiple studies to determine the values of a statistical life in the U.S labor market. They estimated that the mean willingness to pay for the avoided fatality was $7 million in the year 2000 [21]. Over the past decade and a half, OSHA has used the willingness to pay method to calculate the benefits of reduced risk in proposing various rules [9], [22], [23] and has estimated the benefit of an avoided fatality to be $8.7 million in the year 2009 [19]. Using the Consumer Price Index for Medical Care [24], the cost of each avoided fatality has been calculated to be approximately $10.2 million in 2015 dollars, the base year for this analysis.

Working in an environment with any mineral-based particulate inhalation hazards like respirable silica dust, asbestos, and coal-dust leads to several related malignant and non-malignant illnesses [25]–[34]. Exposure to 1 fiber/cm\(^3\) of asbestos over 50 years for textile workers accounts for nearly 8% of deaths in asbestos workers [35]. Studies indicate that the risk of coal workers pneumoconiosis ranges from 1.5% to 9% at 1.5 mg/m\(^3\) and 6 mg/m\(^3\) coal dust, respectively [36]. Exposure to respirable silica leads to cancer, silicosis, and renal diseases. For a comprehensive accounting of the impact of use of silica, the cost of such illness needs to be determined. Since the intensity and duration of these illnesses vary in each case, many studies are taken into consideration when evaluating the monetary value for non-fatal illnesses [19]. Studies have shown that the cost of treating a non-fatal form of lung impairment in 2008 dollar value is $460,000 [19]. The cost of treating each case of the renal disease was estimated to
be approximately $620,000 in 2002 dollars [19]. Using the willingness to pay method, OSHA in its proposed rulemaking for occupational exposure to silica has estimated the cost of various non-fatal illness avoided to lie in a range of $62,000 to $5.1 million in 2009 dollars [19]. In this study, the same range of cost is used to determine the willingness to pay for avoided non-fatal illness. Using the Consumer Price Index for medical care [24], the cost of each non-fatal illness (silicosis, lung cancer, and renal disease) has been calculated to lie between $72,000 and $5.95 million in 2015 dollars.

2.3 Willingness-to-pay for Avoided Fatality and Morbidity for One Hydraulic Fracturing Crew

OSHA estimated that a typical hydraulic fracturing crew consists of 16 members assigned to different job profiles [19].
Table I shows the distribution of typical hydraulic fracturing crew based on their job description.
Table I Number of people in a typical hydraulic fracturing crew based on their job description.

<table>
<thead>
<tr>
<th>Primary Function</th>
<th>Estimated number of workers per site</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand Mover Operator</td>
<td>5</td>
</tr>
<tr>
<td>Conveyor Belt Tender</td>
<td>1</td>
</tr>
<tr>
<td>Blender Tender</td>
<td>2</td>
</tr>
<tr>
<td>Hydraulic Unit Operator</td>
<td>1</td>
</tr>
<tr>
<td>Water/ Chemical Hands</td>
<td>2</td>
</tr>
<tr>
<td>Pump Operator Technicians</td>
<td>3</td>
</tr>
<tr>
<td>Supervisor</td>
<td>1</td>
</tr>
<tr>
<td>Ground Guide</td>
<td>1</td>
</tr>
<tr>
<td>Total Employees</td>
<td>16</td>
</tr>
</tbody>
</table>

No study has yet been conducted to estimate the number of fatalities & non-fatal illnesses due to crystalline silica exposure higher than the prescribed exposure limit of 50 μg/m³ by OSHA for at-risk workers at a hydraulic fracturing site. OSHA, in their study of preliminary economic analysis and initial regulatory flexibility analysis, estimated that around 16,000 workers in hydraulic fracturing industry are exposed to silica levels of 50 μg/m³ [19]. In order to estimate the number of fatalities and non-fatal illness due to exposure of these 16,000 workers to silica, the ratio of the number of fatality and non-fatal illness to the number of people exposed to silica in the hydraulic fracturing industry was assumed to be similar to general, maritime, and construction industry. Using equations 1, 2, and 3, the cost of avoided fatality and non-fatal illness was calculated for a hydraulic fracturing crew typically consisting of 16 members.

\[ P_{all} = (n_{all} \times 100) / N_{all} \]  

(1)
N_{all} = \text{Number of people exposed to silica of } 50 \, \mu g/m^3 \text{ in the U.S. in construction and general and maritime industry (The estimated number of workers exposed to silica levels of } 50 \, \mu g/m^3 \text{ in construction and general maritime } 770,000 \text{ workers [19]).}

n_{all} = \text{Estimated number of fatality & non-fatal illnesses due to crystalline silica exposure of } 50 \, \mu g/m^3 \text{ for at-risk workers over a 45-year working life in construction and general maritime industry (}}
Table II).

\[ P_{\text{all}} = \text{Estimated percentage of fatal \& non-fatal illnesses due to crystalline silica exposure of 50 \mu g/m}^3 \text{ for at-risk workers over a 45-year working life.} \]

The percentage of avoided fatalities and non-fatal illnesses resulting due to a reduction in crystalline silica exposure of 50 \mu g/m3 for at-risk workers over a 45-year of working life was calculated using equation 1 /
Table II).
Table II Estimated number and percentage of avoided fatalities & non-fatal illnesses in the U.S. construction and general and maritime industry due to a reduction in crystalline silica exposure of 50 μg/m³ for at-risk workers over a 45-year of working life [41]. OSHA applies the dose-response relationship to project the number of avoided fatality and non-fatal illness.

<table>
<thead>
<tr>
<th></th>
<th>Total estimated number</th>
<th>Estimated percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lung Cancer</td>
<td></td>
<td></td>
</tr>
<tr>
<td>High</td>
<td>12000</td>
<td>1.60</td>
</tr>
<tr>
<td>Mid</td>
<td>7000</td>
<td>0.95</td>
</tr>
<tr>
<td>Low</td>
<td>2000</td>
<td>0.30</td>
</tr>
<tr>
<td>Silicosis &amp; Other Non-Malignant Respiratory Diseases</td>
<td>17000</td>
<td>2.20</td>
</tr>
<tr>
<td>End-stage Renal Diseases</td>
<td>7000</td>
<td>0.90</td>
</tr>
<tr>
<td>Total Number of Fatal Illness Prevented</td>
<td></td>
<td></td>
</tr>
<tr>
<td>High</td>
<td>36000</td>
<td>4.65</td>
</tr>
<tr>
<td>Mid</td>
<td>31000</td>
<td>4.00</td>
</tr>
<tr>
<td>Low</td>
<td>26000</td>
<td>3.40</td>
</tr>
<tr>
<td>Total Number of Silicosis Morbidity Cases Prevented</td>
<td>71000</td>
<td>9.25</td>
</tr>
</tbody>
</table>

\[ n_{\text{hf}} = (P_{\text{all}} \times N_{\text{hf}})/100 \] (2)

\[ N_{\text{hf}} = \text{Number of people exposed to silica over } 50 \, \mu\text{g/m}^3 \text{ over the years in the U.S. in one hydraulic fracturing site} (\text{Table III}). \]
\( n_{nf} = \) Estimated number of fatality & non-fatal illnesses due to crystalline silica exposure of 50 \( \mu g/m^3 \) for at-risk workers over a 45-year working life in one hydraulic fracturing site.

*Table III* Number of affected workers exposed to silica level of 50 \( \mu g/m^3 \) or more in a typical hydraulic fracturing crew.

<table>
<thead>
<tr>
<th>Classification by Function</th>
<th>Numbers of Affected Workers Exposed to Silica level of 50 ( \mu g/m^3 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand Mover Operator</td>
<td>4.55</td>
</tr>
<tr>
<td>Conveyor Belt Tender</td>
<td>1.00</td>
</tr>
<tr>
<td>Blender Tender</td>
<td>1.73</td>
</tr>
<tr>
<td>Hydraulic Unit Operator</td>
<td>0.50</td>
</tr>
<tr>
<td>Water/ Chemical Hands</td>
<td>1.00</td>
</tr>
<tr>
<td>Pump Operator Technicians</td>
<td>1.00</td>
</tr>
<tr>
<td>Supervisor</td>
<td>0.50</td>
</tr>
<tr>
<td>Ground Guide</td>
<td>0.50</td>
</tr>
<tr>
<td>Total</td>
<td>10.79</td>
</tr>
</tbody>
</table>

Using equation 2, it is estimated that the number of workers prone to non-fatal illness because of exposure to silica level of 50 \( \mu g/m^3 \) or more for at-risk workers over a 45-year working life in one hydraulic fracturing crew is 1 in every 16 workers. Similarly, the number of workers prone to fatality in a typical hydraulic fracturing crew is calculated to be 1 in every 48 workers.
\[ c = (n_f \times a) \]  
\[ (3) \]

a = Willingness-to-pay for avoided fatality and silica-related disease (As calculated using
the Consumer Price Index, US Department of Labor, BLS).

c = Total Cost for fatality and non-fatal illness for one typical fracturing crew.

Using equation 3, the total cost of fatality and non-fatal illness for a typical hydraulic fracturing
crew was calculated to lie in the range of $3.8 million to $11 million, in 2015 dollars (Table IV)

*Table IV Estimated cost of fatalities & non-fatal illnesses due to crystalline silica exposure of 50
μg/m³ for at-risk workers over a 45-year of working life for one typical fracturing crew.*

<table>
<thead>
<tr>
<th>Total Cost for Fatal Illness</th>
<th>Total Cost (In millions)</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>$5.10</td>
</tr>
<tr>
<td>Mid</td>
<td>$4.40</td>
</tr>
<tr>
<td>Low</td>
<td>$3.70</td>
</tr>
<tr>
<td>Total Cost of non-fatal illness (Low)</td>
<td>$0.07</td>
</tr>
<tr>
<td>Total Cost of non-fatal illness (High)</td>
<td>$5.94</td>
</tr>
<tr>
<td>Total Cost of fatality and non-fatal illness (Low)</td>
<td>$3.80</td>
</tr>
<tr>
<td>Total Cost of fatality and non-fatal illness (High)</td>
<td>$11.00</td>
</tr>
</tbody>
</table>

The willingness to pay for an avoided fatality and non-fatal illness was calculated for
silica exposure of 50 μg/m³ using silica-based proppants. The alternative proppants like ceramic-
and bauxite-based are made up of several materials, including aluminum oxide, magnesium iron
silicate, magnesium silicate, and aluminum silicates, which also pose a risk from inhalation
exposure. The American Conference of Governmental Industrial Hygienists Threshold Limit
Value (ACGIH TVL) exposure limit to such materials is given in Table V. The ACGIH TVL is used in this study because ACGIH has defined an exposure limit for each these materials. However, these are not regulatory limits, which compromise the promotion of worker health with the technological and economic feasibility of the limit (such as OSHA’s permissible exposure limit).

Table V Material exposure limit as per the American Conference of Governmental Industrial Hygienists Threshold Limit Value (ACGIH TVL)

<table>
<thead>
<tr>
<th>Material/Chemical Name</th>
<th>ACGIH TVL Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silica</td>
<td>0.025</td>
</tr>
<tr>
<td>Aluminum Oxide</td>
<td>3.000</td>
</tr>
<tr>
<td>Aluminum Silicate</td>
<td>3.000</td>
</tr>
<tr>
<td>Magnesium Silicate</td>
<td>2.000</td>
</tr>
</tbody>
</table>

Since no studies have been conducted to directly measure the costs of exposure to these materials, equation 4 was used to calculate the costs of exposure for the proppants made up of these materials. The calculations assume that the particulate size distributions for fugitive dust emission from the various proppant types are similar. Moreover, it is assumed that the biological effect from exposure to these materials is similar, though not the potency, or the risk of illness due to exposure to the same amount or dose of each material. It is also assumed that other particulate substances cause fatalities and non-fatal illnesses in proportion to an individual’s exposure relative to the recommended exposure limit of that substance. For instance, a person exposed to 50% of the REL for silica will be at the same probability of developing a fatal illness as a person exposed to 50% of the REL for another substance. The cost of fatality and non-fatal
illnesses for a proppant was expressed as the sum-product of the percentage of chemicals in the proppant and the ratio of the exposure limit of silica to that of the chemical, multiplied by the range of exposure-related cost for silica exposure.

\[
\left( \frac{E_s}{E_1} \cdot c_1 + \frac{E_s}{E_2} \cdot c_2 + \frac{E_s}{E_3} \cdot c_3 + \cdots \right) \cdot C
\] (4)

Where

\( E_s \) - Exposure limit of silica (0.025 mg/m\(^3\)) as per ACGIH TVL.

\( C \) - Cost of fatality and non-fatal illness due to silica exposure of 50 \( \mu \)g/m\(^3\)

\( E_n \) - Exposure limit of chemical ‘n’ in mg/m\(^3\)

\( c_n \) - Percentage of chemical ‘n’ in the proppant

Equation (4) calculates the cost of fatality and non-fatal illness as a result of exposure to harmful particulates associated with various commercially available proppants.

### 3. Analysis and Results

#### 3.1 Cost of fatality and non-fatal illness for various proppants

The cost of fatality and non-fatal illnesses is the estimated cost of exposure to the various materials in the proppant. This cost was calculated for the four broad categories of proppants using equation (4) and is calculated based on the estimated cost of fatality and non-fatal illness due to exposure to silica (Table IV).
Table VI Cost of fatality and non-fatal illness for various proppant types. The wide range of costs is due to the estimated percentage of fatal & non-fatal illnesses due to crystalline silica exposure and a range of cost of non-fatal illness depending on the type of non-fatal illness. The cost of fatality and non-fatal illness is negligible for ceramic and bauxite based proppant as compared to silica-based proppant.

<table>
<thead>
<tr>
<th>Proppant Category</th>
<th>Range of cost of fatality and non-fatal illness (in millions)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silica-based</td>
<td>$3.80 to $11.00</td>
</tr>
<tr>
<td>Resin-coated</td>
<td>$3.80 to $11.00</td>
</tr>
<tr>
<td>Bauxite-based</td>
<td>$0.03 to $0.09</td>
</tr>
<tr>
<td>Ceramic-based</td>
<td>$0.04 to $0.12</td>
</tr>
</tbody>
</table>

The cost of fatality and non-fatal illness for both silica-based and resin-coated silica proppant was the same since the silica content reported in the MSDS was the same for both the proppant. The cost of fatality and non-fatal illnesses for ceramic-based proppant and bauxite-based proppant were around 0.1% of the silica-based proppant.

The cost of fatality and non-fatal illness or health-related cost for using proppant types is shown in Figure 6. The range of cost of fatality and non-fatal illness for silica-based proppant is approximately 1,100 times higher than that of ceramic-based and bauxite-based proppant.
Figure 6 Cost of fatality and non-fatal illness for different proppant types. The range of cost of fatality and non-fatal illness is approximately 1100 times higher for silica-based proppant as compared to ceramic and bauxite-based proppant.

3.2 Silica exposure in the hydraulic fracturing industry

Research shows that approximately 17,000 workers in the hydraulic oil and gas industry come in direct contact with proppants, out of which nearly 50% of them are exposed to silica levels over 50 μg/m³ [19]. Assuming that the percentage of fatality and non-fatal illness due to silica exposure in hydraulic fracturing industry is similar to that in general and maritime and construction industry for same silica exposure levels, it is estimated that 1 in 16 workers would be expected to develop a non-fatal illness based on this level of exposure. It is also estimated that 1 in 30 to 1 in 48 workers would be expected to develop a fatal illness due to exposure to silica in a typical hydraulic fracturing crew. Table VII shows the estimated number of fatality and non-fatal illness due to crystalline silica exposure of 50 μg/m³ for at-risk workers over a 45-year career in the hydraulic fracturing industry.
Table VII Estimated number of fatality & non-fatal illnesses due to crystalline silica exposure of 50 μg/m³ for at-risk workers over a 45-year of working life in the hydraulic fracturing industry.

<table>
<thead>
<tr>
<th></th>
<th>Total Number of avoided cases in the hydraulic fracturing industry</th>
<th>Total Number of avoided cases in a typical hydraulic fracturing crew</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Lung Cancer</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High</td>
<td>260</td>
<td>0.17</td>
</tr>
<tr>
<td>Mid</td>
<td>155</td>
<td>0.10</td>
</tr>
<tr>
<td>Low</td>
<td>50</td>
<td>0.034</td>
</tr>
<tr>
<td><strong>Silicosis &amp; Other Non-Malignant Respiratory Diseases</strong></td>
<td>358</td>
<td>0.236</td>
</tr>
<tr>
<td><strong>End-stage Renal Diseases</strong></td>
<td>144</td>
<td>0.095</td>
</tr>
<tr>
<td><strong>Total Number of Fatal Illness Prevented</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High</td>
<td>760</td>
<td>0.502</td>
</tr>
<tr>
<td>Mid</td>
<td>656</td>
<td>0.433</td>
</tr>
<tr>
<td>Low</td>
<td>552</td>
<td>0.365</td>
</tr>
<tr>
<td><strong>Total Number of Silicosis Morbidity Cases Prevented</strong></td>
<td>1512</td>
<td>0.999</td>
</tr>
</tbody>
</table>

### 3.3 Sensitivity Analysis

In order to understand how the cost of proppant, the quantity of proppant handled by a typical hydraulic fracturing crew each year, and the cost of avoided fatalities and non-fatal...
illnesses impacted the total cost (the cost of proppant and cost of avoided fatality and non-fatal illness) associated with each proppant, a sensitivity analysis was conducted. For the analysis, the quantity of proppant handled by a typical hydraulic fracturing crew was varied from 10,000 to 100,000 tons per year. Different ranges of the expected cost of realized fatality and non-fatal illness (Table VI) were used to determine the impact of the cost of fatality and non-fatal illness for silica, ceramic, and bauxite-based proppants. Table VIII lists the average cost per ton (in $) of each proppant [37] and the expected cost of realized fatalities and non-fatal illness (in $). The expected cost of realized fatality and non-fatal illness per ton of proppant used has been calculated based on the assumption that the average quantity of proppant handled by each crew every year is 60,000 tons.

Table VIII Average cost per ton and the average cost of fatality and non-fatal illness for proppant for a typical hydraulic fracturing crew.

<table>
<thead>
<tr>
<th>Proppant Type</th>
<th>Average cost per ton</th>
<th>Expected cost of realized fatalities and non-fatal illness</th>
<th>Expected cost of realized fatalities and non-fatal illness per ton of proppant used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silica Based</td>
<td>$ 275</td>
<td>$ 7.40 million</td>
<td>$ 123.00</td>
</tr>
<tr>
<td>Bauxite Based</td>
<td>$ 400</td>
<td>$ 0.061 million</td>
<td>$ 1.01</td>
</tr>
<tr>
<td>Ceramic Based</td>
<td>$ 475</td>
<td>$ 0.072 million</td>
<td>$ 1.20</td>
</tr>
</tbody>
</table>

Figure 7 (a) shows the changes in the total cost of proppant including the cost of fatality and non-fatal illnesses for different ranges of proppant quantity (10,000 to 100,000 tons), proppant cost per ton ($350 to $600), and the cost of fatality and non-fatal illness ($40,000 to $120,000) for ceramic-based proppant. The change in proppant quantity and proppant cost
significantly change the total cost for ceramic-based proppant. It is also evident from Figure 7(a) that the costs of fatality and non-fatal illnesses for ceramic-based proppants are negligible as compared to the costs of proppant.

Figure 7(b) shows a similar analysis for bauxite-based proppant. Bauxite-based proppant has a sensitivity similar to that of ceramic-based proppant. The change in proppant quantity and proppant cost significantly impact the total cost. Moreover, the cost of fatality and non-fatal illnesses have less of a contribution to the total cost.
Figure 7 (a) Sensitivity analysis for ceramic-based proppants. The total combined cost is negligibly affected by the change in the cost of fatality and non-fatal illness as compared to proppant quantity and the proppant cost. (b) Sensitivity Analysis for bauxite-based proppants. The total combined cost is negligibly affected by the change in the cost of fatality and non-fatal illness as compared to proppant quantity and the proppant cost. (c) Sensitivity Analysis for silica-based proppants. The change in the cost of fatality and non-fatal illness has a substantial effect on the total cost.

Figure 7 (c) shows the sensitivity of total cost to changing proppant quantity, proppant cost, and cost of fatality and non-fatal illness for silica-based proppants. The cost of fatality and non-fatal illness was a significant contributor to the total cost, unlike the ceramic and bauxite-
based proppants. The cost of the proppant material was also a significant contributor to the total cost.

*Figure 8* shows the cost of different proppants with increasing proppant quantity without any external health-related costs. Ceramic-based proppant is the most expensive type, whereas silica-based proppant is the cheapest proppant available.

![Graph showing cost of different types of proppants](image)

*Figure 8 Comparison of the cost of different types of proppants. The cost of silica-based proppant is lowest and the cost of ceramic-based proppant is highest.*

With the addition of costs associated with fatalities and non-fatal illnesses for each proppant, the total combined cost, i.e., cost of proppant plus the cost of fatality and non-fatal illness for each
proppant for varying values of proppant quantity are compared (Figure 9). For calculating the total combined cost, the average proppant cost and the average cost of fatality and non-fatal illness associated with each proppant was considered (Table VIII). The results show an increase in the total combined cost with an increase in the proppant quantity. It also shows that for lower proppant quantities, the total combined cost of bauxite and ceramic-based proppant are lower than that of silica-based proppant. Based on these calculations, it is evident that ceramic and bauxite-based proppants are economical for hydraulic fracturing crews handling approximately less than 60,000 tons of proppant every year if the cost of fatality and non-fatal illness are included in the overall cost consideration. For crews handling approximately 59,000 tons of proppant per year, it was found that the total combined cost for bauxite-based proppant is less than silica-based proppant. The same is true for ceramic-based proppants. Ceramic-based proppants are cheaper if the cost of fatality and non-fatal illness is added to the proppant cost for crews handling approximately 59,000 tons of resin coated silica-based proppant per year.
Figure 9 Comparison of total combined raw material and health cost for different types of proppants. The combined cost for bauxite-based proppant is less than silica-based proppant and ceramic-based proppant has lower combined cost as compared to bauxite based proppant for crews handling slightly less than 60000 tons of proppants per year.

In practice, the selection of proppant material is based on the type of reservoir, performance of the proppant, and economics. With the development of new engineered types of proppants, various options are available to cater to these technical requirements.

The other factor considered during the selection of proppant is the cost of the proppant since the cost of proppant can contribute anywhere from 10% to over 50% of the total cost for any hydraulic fracturing operation [5]. Generally, a cost-benefit analysis approach is used to determine the type of proppant used. Statistics show that over 99% of hydraulic stimulations
have used sand as proppant [1]. Studies suggest that sand-based proppant should always be selected unless ceramic proppant justifies enhanced economic benefits [5]. However, these studies do not take into consideration the health-related financial implications of the use of sand-based proppants.

For a fracturing crew handling approximately 60,000 tons or less proppant annually, silica-based proppant and resin-coated silica-based proppant can be replaced by bauxite-based proppant and ceramic-based proppant respectively (Figure 9). Studies conducted by OSHA for the preliminary economic analysis and initial regulatory flexibility analysis reported that there are approximately 17,000 workers employed in hydraulic fracturing crew in the U.S. in 2013 [19] and reports show that the total quantity of proppant used in hydraulic fracturing industry in 2013 was approximately 33 million tons [12]. Based on this data, it is estimated that the total quantity of proppant handled by each hydraulic fracturing crew is approximately 31,000 tons every year. Based on the threshold limit of 60,000 tons for using bauxite and ceramic-based proppant and the estimated quantity of proppant handled by each fracturing crew, a proppant selection strategy map for hydraulic fracturing crew handling 45,000 tons of proppant every year is developed (Figure 10). The strategy plot was created from a database of commercially available proppants at 162 different ranges of permeability (ranging from 0 to 1220 Darcy at an interval of 20 Darcy), and 208 different ranges of conductivity (ranging from 0 to 18800 md-ft at an interval of 200 md-ft) for given closure stress. The lowest-cost proppant was selected for each specific permeability and conductivity ranges, which is shown in Figure 10 (a) and Figure 10 (c). Cost of fatality and non-fatal illness were then added to the proppant cost and the lowest cost proppant for the same range of permeability and conductivity was selected, which is shown in Figure 10 (b) and Figure 10 (d).
Figure 10 Proppant Selection Strategy Map. (a) Least expensive proppants available at various closure stress and permeability excluding financial implications of health into account. (b) Least expensive proppants available at various closure stress and permeability, including financial implications of health into account. (d) Least expensive proppants available at various closure stress and conductivity, including financial implications of health into account. (c) Least expensive proppants available at various closure stress and conductivity, excluding financial implications of health into account.

The selection strategy map shows the choice of proppants solely based on the proppant cost in Figure 10 (a) and Figure 10 (c) and the corresponding choice of proppant after adding the costs associated with the proppants to the total cost in Figure 10 (b) and Figure 10 (d).
respectively. The results show that if financial implications of health-related costs are taken into consideration, silica-based proppants can be replaced with less harmful and technically equivalent bauxite and ceramic-based proppants for 32% and 26% of different ranges of permeability and conductivity respectively.

This analysis found that silica-based proppants can be replaced with less harmful bauxite and ceramic proppants for permeability range between 0 to 400 Darcy and conductivity range between 0 to 6,000 md-ft. At higher conductivity and permeability range, silica-based proppants are generally not a viable option due to technical constraints, so the inclusion of health implications into the decision-making process does not affect the selection of proppant at higher ranges of conductivity and permeability.

4. Discussion

This research was conducted to study the economic impact of the selection of different proppant types in hydraulic fracturing operations based on the technical design requirements and costs associated with them including the health-related costs related to workers’ exposure to particulate matter created by handling such proppants. Several previous studies in the field optimized the selection of proppant based on technical requirements and cost-benefit analysis to maximize productivity and NPV [5], [38]–[41] but none of these analyses incorporated fatality and illness costs associated with worker exposure to those proppants. This study focuses on incorporating health-related cost for the socially optimal selection of proppant. This section summarizes the research, discussing its findings, assumptions, and limitations, and outlining the need for future work.
4.1 Alternate proppants are available but rarely used

The database of commercially available proppants created for this study demonstrated that multiple proppants types are currently available to meet similar technical design requirement for most of the possible combinations of reservoir characteristics.

The historical pattern in proppant consumption for the hydraulic fracturing industry shows that over 90% of the total proppants used for fracturing were silica-based proppants (Figure 1). It indicates that silica-based proppants are given precedence over other proppants due to their low upfront cost (since silica is no more functionally beneficial than alternative materials, and the risks of exposure to silica have been well known for some time). Bauxite and ceramic-based proppants were used in deep wells with high closure stress since silica-based proppants are crushed due to high stress in such deep wells rendering them ineffective. 4.2 Health-related Costs of Proppant Choice.

The literature was reviewed to calculate the health-related costs due to exposure to different proppant types, especially the costs related to exposure to silica-based proppant. Health-related costs of fatalities and non-fatal illnesses for a typical hydraulic fracturing crew due to silica exposure was calculated to lie in the range of $3.8 million to $11 million, in 2015 dollars. Consumer Price Index for Medical care was used to calculate the 2015 dollar value from base year dollar value since it closely reflected the changes in healthcare costs over time. This health-related cost substantially increases the overall cost of using silica-based proppant and changes the economic dynamics for proppant selection.

It was found that the financial implications of silica-based proppants for health-related costs were over 100 times as compared to ceramic or bauxite-based proppants (}
The cost related to exposure to bauxite and ceramic-based proppants were calculated using equation 4 since no research has been conducted to calculate the direct cost related to exposure to these proppants. Several studies have been conducted to determine the risks associated with exposure to bauxite and alumina dust but none of these studies attribute any respiratory diseases, changes in lung functions or incidences of cancer to exposure to bauxite or alumina dust [42]–[46]. Determining and differences in possible health-related costs due to exposure to these silica-alternative proppants from field data was out of the scope of this research. The assumption that these exposures could nonetheless lead to similarly costly diseases, though at a reduced prevalence for a similar level of exposure, is reasonable under these circumstances.

4.3 Socially Optimal Proppant Selection

The review of the available literature shows that silica-based proppant is given precedence over bauxite and ceramic-based proppants due to its low upfront cost. Oil and gas companies do not incorporate potential costs from health risks into their decision-making because they generally do not bear these health-related costs directly. The financial burden for most of the cases falls either to the family of the employee, the government, the insurance company, or healthcare provider. These externalities result in the over-use of silica, and an excess of silica-exposure-related health impacts to those workers employed in the industry.

Studies show that over 68% of the crew are exposed to silica levels of more than 50 μg/m³ [8]. Such high exposure rate warrants analyzing the health-related cost due to silica exposure and including such costs in the decision-making process. Incorporating the health-
related costs together with the proppant cost shows that silica-based proppants (sand and resin-coated sand) could be replaced by alternative proppants like bauxite and ceramic-based proppants for 29% of the different combinations of permeability and conductivity found in reservoirs. Moreover, silica-based proppants could be replaced by either ceramic or bauxite-based proppant for use in shallow wells wherein each hydraulic fracturing crew handles approximately less than 60,000 tons of silica-based proppant each year. For crews handling more, the costs of the more expensive materials continue to outweigh the health-related costs of using silica.

It should be noted that this study does not include transportation costs and geographic availability of different proppant types. The inclusion of transportation cost and regional availability can significantly influence the choice of proppant [16]. For example, substantial transportation cost of silica-based proppant may encourage companies to use safer bauxite or ceramic proppants owing to the less overall cost. These results presented here assume that such trades balance out in the end (silica alternatives are chosen due to these reasons at the same frequency as silica proppants) and are not responsible for the overall fraction of silica and silica alternatives actually used by the industry.

The recent rule revision by OSHA reducing the silica permissible exposure limit to 50 \(\mu g/m^3\) may decrease the percentage of hydraulic fracturing crews exposed to silica levels of 50 \(\mu g/m^3\), thereby reducing the health-related costs arising from exposure to silica-based proppant. Studies estimate a reduction in 41 cases of silicosis morbidity and 9 to 14 cases of fatality as a result of this new ruling in the hydraulic fracturing industry [19]. This reduction in cases of fatalities and non-fatal illness is due to the reduction of exposure of workers in hydraulic
fracturing industry from 100 μg/m$^3$ to 50 μg/m$^3$ for a 45-year working life for approximately 16,000 workers who are exposed to silica level of 50 μg/m$^3$.

4.4 Encouraging alternatives to Silica-based proppants

The inclination to use sand-based proppant is based on supply and availability, a lower price per ton as compared to other materials, and acceptable, though not excellent technical properties. Levying some tax or fee for the use of silica-based proppants could incline producers to internalize these costs and decide to use other proppants instead of silica-based proppants. It is not uncommon for taxes to be levied on hazardous substances, and environmental pollutants by both federal and state governments like gas guzzler tax [47], hazardous substance tax [48], air emission permit fees, effluent permit fees, and petroleum product tax to name a few.

Implementation of a silica tax for the use of silica-based proppant could be one way to encourage the use of alternatives. A silica tax to compensate for the latent exposure-related costs would encourage drilling companies to use less harmful, non-silica-based proppants. Current decisions are made solely based on the technical requirements and the cost of the proppant, and non-silica-based proppants are selected only if the reservoir properties require proppants other than silica-based proppants. After internalizing health-related costs by the use of such a tax, non-silica-based proppants would be selected for all the cases where it meets the technical requirements for every hydraulic fracturing crew handling approximately less than 60,000 tons of proppant each year which is higher than the average quantity of 31,000 tons of proppant handled by each hydraulic fracturing crew every year.
Greater investment in engineering controls may be another way to reduce silica exposure. More study would be needed to examine the most efficient approach. However, reduction of exposure by the use of engineering and operational controls has been investigated recently (2013) by the Occupational Health and Safety Administration (OSHA), when they issued a new permissible exposure level standard for silica of 50 μg/m³ [9]. OSHA analysis demonstrated that while health risks remained at 50 μg/m³ for many industries, it was not feasibly cost effective to reduce exposure levels to 25 μg/m³ or lower. Alternative exposure reduction technologies may be possible in the oil and gas sector that were not possible for broader industry in the United States, however a change of proppant material can reduce the risk significantly by mitigating the primary source of the harm.

The health-related silica exposure costs described in this paper only reflect the costs for the oil/gas drilling personnel directly involved in hydraulic fracturing operations. It does not include other visiting or temporarily deployed personnel at the site or the people living in the vicinity of the site. This analysis does not include the health-related costs of the silica mine workers or personnel who may be responsible for processing the proppants before they are delivered to the well site. The overall societal costs of health risks arising from the use of crystalline silica proppants are likely to be higher than those calculated here focused solely on the drilling and fracturing crews.

5. SUMMARY AND CONCLUSIONS

The widespread use of silica-based proppants in hydraulic fracturing poses health risks to the population of oil and gas workers. There are alternative materials available on the market
today, including bauxite and ceramics functionally equivalent or superior to silica-based proppants for use in the enhanced natural gas exploration and production. These materials are not generally used in current industry practice except when technically necessary due to their relatively high costs. The reliance on silica-based proppant materials, however, subjects oil and gas workers, their families, health insurance companies, and the government to higher costs as silica exposure-related diseases appear later in the workers’ lives. This analysis finds that under current practices, these costs amount to $123 per ton of silica-based proppant for hydraulic fracturing crews handling 60,000 tons of proppants. Taxes or mandates are possible policy responses to ameliorate this issue and encourage more risk-conscious decision-making in proppant selection.

The following conclusions are based on this study:

a) Alternate proppants are commercially available to replace silica-based proppant. This research has not assessed the feasibility of meeting total proppant demand with these alternatives. Further research in this area is needed.

b) Silica-based proppants are best suited for wells with closure stress of less than 6000 psi (without including health-related costs) and are used almost exclusively in those circumstances.

c) Bauxite and ceramic-based proppants are currently used predominately in deep wells with high closure stress, and rarely in less technically demanding situations.

d) Health-related cost for silica-based proppants ranges from 3.8 to 11 million dollars. The health-related cost for ceramic-based and bauxite-based proppants are around 0.1% of the silica-based proppant.
e) The health-related costs of silica-based and resin-coated proppants were found to be equal. However, this assumes that resin-coated silica generates respirable crystalline silica particulates at the same rate during handling as uncoated silica proppant. Further research is needed to ascertain whether this assumption is valid.

f) The inclusion of health-related costs would substantially change the dynamics of proppant selection. Silica-based proppants could be replaced by alternatives for 29% of the possible combinations of permeability and conductivity found in natural gas reservoirs.

g) If decision makers incorporated health-related costs during the selection of proppants, they would tend to use the less harmful, non-silica-based proppants.
REFERENCES


1927.


