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QUANTIFYING THE ECONOMIC IMPACT OF HYDRAULIC FRACTURING PROPPANT SELECTION IN LIGHT OF OCCUPATIONAL PARTICULATE EXPOSURE RISK AND FUNCTIONAL REQUIREMENTS

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by

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ABSTRACT

Selection of the proppant material for hydraulic fracturing is an important design choice to optimize the production of oil and natural gas. Some of these proppants are made up of substances like 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. Factors affecting the selection of proppants are closure stress of reservoir, required conductivity, and permeability of the deposit. With increased depth of wells, several types of proppants have been developed to meet the formation characteristics for achieving higher production. 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 taking the health-related economic impact into consideration as well as technical attributes. Results show that the use of each ton of silica-based proppants 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. It also suggests that silica-based proppants could be economically replaced by less harmful, more expensive alternatives for hydraulic fracturing crews handling less than 60,000 tons of proppant each year, provided the technical requirements are met.

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Chapter 1

Introduction

Treatment of wells using proppants in hydraulic fracturing has been recorded as early as the early 1940s [1]–[3]. With the advent of the shale gas boom at the dawn of the twenty-first century, hydraulic fracturing operations have increased substantially and various proppants have been developed to achieve higher production in deeper wells. Waxman et al. (2011) in their report have indicated the development of over 2,500 different proppants between 2005 and 2009 made up of different substances [4]. Numerous proppants with different combinations of technical capabilities are available which can be used for different deposits based on the closure stress, permeability of the deposit and required conductivity. Horizontal drilling technology has further incentivized the proppant industry to develop proppants with high conductivity which can effectively keep the fractures open at high closure stress. In particular, ceramic proppants have been developed to be used in deeper wells having higher closure stress and resin coated proppants for increased conductivity. [5]

Various proppant types are readily available to meet the varying technical requirements like closure stress, permeability, and conductivity to maximize production. Choice of the optimal proppant is important in any hydraulic fracturing site for maximizing production. However, the cost and availability of proppant appear to play an important role in determining the economics of any fracturing site as it can constitute a significant portion of the total cost of well treatment [5]. Despite the development of different types of proppant, 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 U.S during 4 consecutive quarters in 2013 and 2014 is over 90% [7] (**Figure 1-1**).

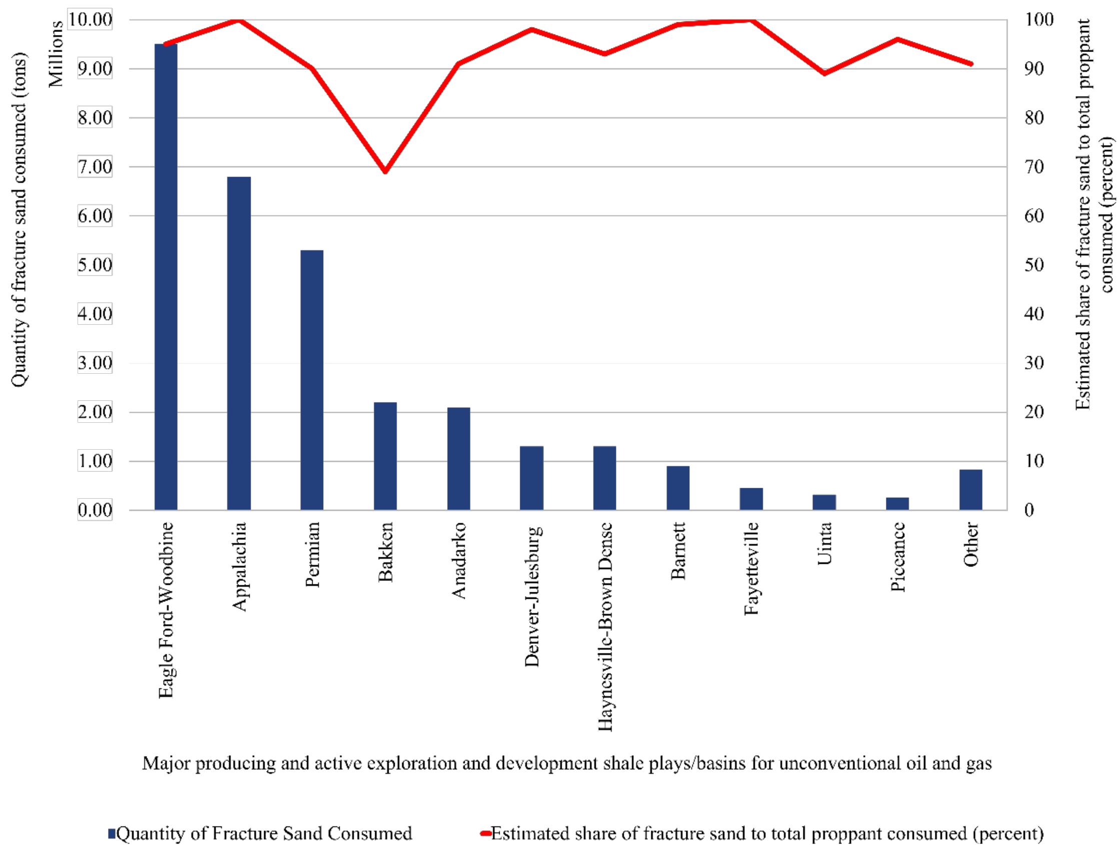

Figure 1-1 Estimated fracture sand consumption among major U.S. unconventional oil and gas shale basin. The estimated share of fracture sand to total proppant consumed in ten major non-conventional fields was over 90 percent for all the fields except Bakken (Data from [7])

Among the different types of proppant used in the hydraulic fracturing industry from the year 2001 to 2010, over 99% of the total types of proppants reported were silica-based (**Figure 1-2**). Available research indicates the risks of silica on human health from exposures similar to that of hydraulic fracturing. Studies have confirmed the presence of respirable crystalline silica beyond the Occupational Safety and Health Administration PEL (Permissible Exposure Limit) and National Institute for Occupational Safety and Health REL (Recommended Exposure Limit) at hydraulic fracturing sites, which likely indicate health hazards for workers [8]. Personal breathing zone samples collected from 11 hydraulic fracturing sites by researchers from National Institute for Occupational Safety and Health showed that over 68 % of the people working at these hydraulic fracturing sites were exposed to more than 50 $\mu g/m^3$ of respirable silica, the NIOSH REL and OSHA PEL [9].

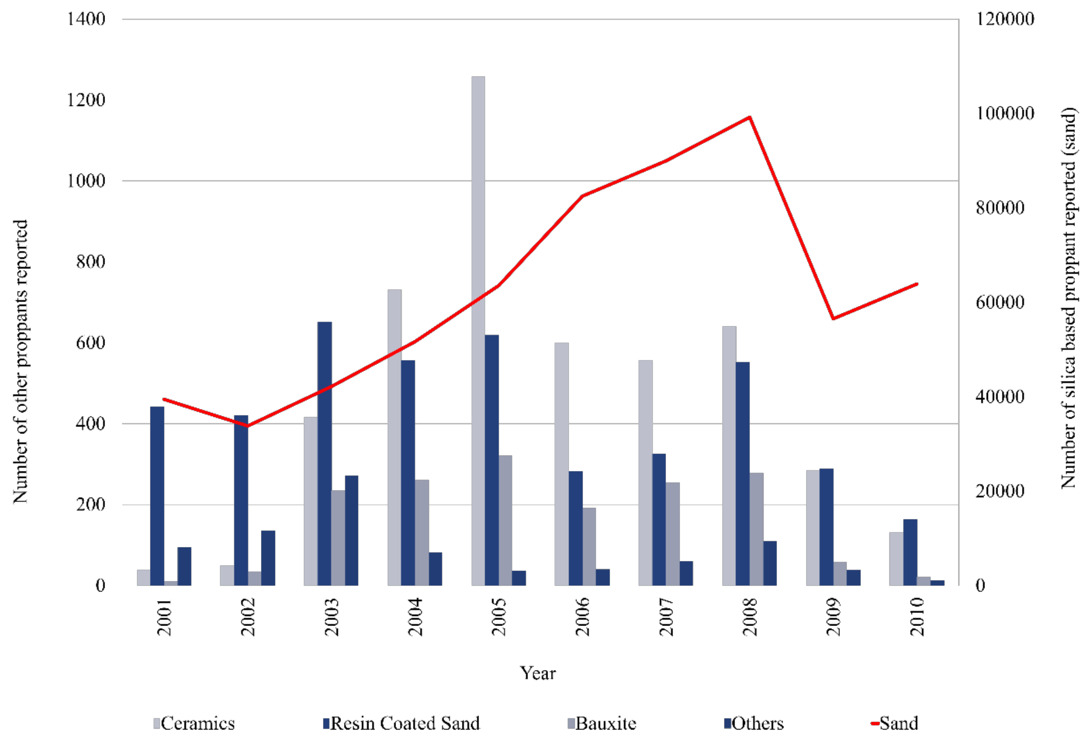

Figure 1-2 Number of different types of silica and non-silica-based proppants by year [10]. The number of different types of silica-based proppants used between 2001 and 2010 far exceeds the number of different types of non-silica-based proppants.

Proppant demand is expected to increase in the future and with rising use of silica-based proppants. This study examines the health risks and project tradeoffs of replacing silica-based proppants with other commercially available proppants. Reports show that the proppant supply increased by over 50% in the year 2014 as compared to 2013 [11] 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 United States is expected to increase by 5.8 billion cubic feet per day in the year 2018 as compared to production of 73.7 billion cubic feet per day in 2017 [12]. Moreover, the U.S. Energy Information Administration (EIA) expects an increase of 45% in the production of dry gas by the end of 2045 [13]. With demand expected to soar in future years [14], the use of silica-based proppant is expected to rise in the future. With different kinds of proppants (ceramic, bauxite, and resin-coated) now being developed and used [15]–[17], this research examines how the potential use of these proppants in place of silica-based proppants may reduce occupational health-related costs. The choice of proppant is solely based on its performance and direct economic costs and benefits. This paper seeks to determine the health impact of various proppants choices and determines the 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 cost of proppant but also including the health-related costs associated with worker exposure to such substances.

Chapter 2

Literature Review

Hydraulic fracturing was first introduced nearly 70 years ago, and since then it is estimated that over 2.5 million wells have been hydraulically fractured [1]. U.S Energy Information Agency reported that in the year 2016, nearly two-thirds of the total natural gas production in the United States was from hydraulically fractured wells [18] and it is expected to grow in future. A successful fracture depends on various factors and several studies have been conducted to maximize productivity. Proppant selection contributes substantially to the outcome of any fracturing operation. This chapter introduces hydraulic fracturing process, proppants, and its selection process. Further, it reviews the relevant research done in the past for optimal selection of proppants and presents the motivation and objective of this research.

2.1 Hydraulic Fracturing

Hydraulic fracturing is a technology used since the mid-twentieth century [1]–[3], [19] to create a network of interconnected openings for increased production and productivity [20]–[22]. Proppant and fluids along with additives are injected to fracture the sub-strata to create openings for movement of gas and oil [23], [24]. The fracturing fluid is pumped into the wells at a pressure higher than the sub-strata pressure to keep it open [3], [24]. Proppants are then injected into the wells to keep the fractures open to allow the flow of gas and oil [24]. A typical hydraulic fracturing process is shown in **Figure 2-1**. The diagram shows the process of hydraulic fracturing wherein a mixture of water, proppants and chemicals are injected at high pressure to create fissures and keep them open.

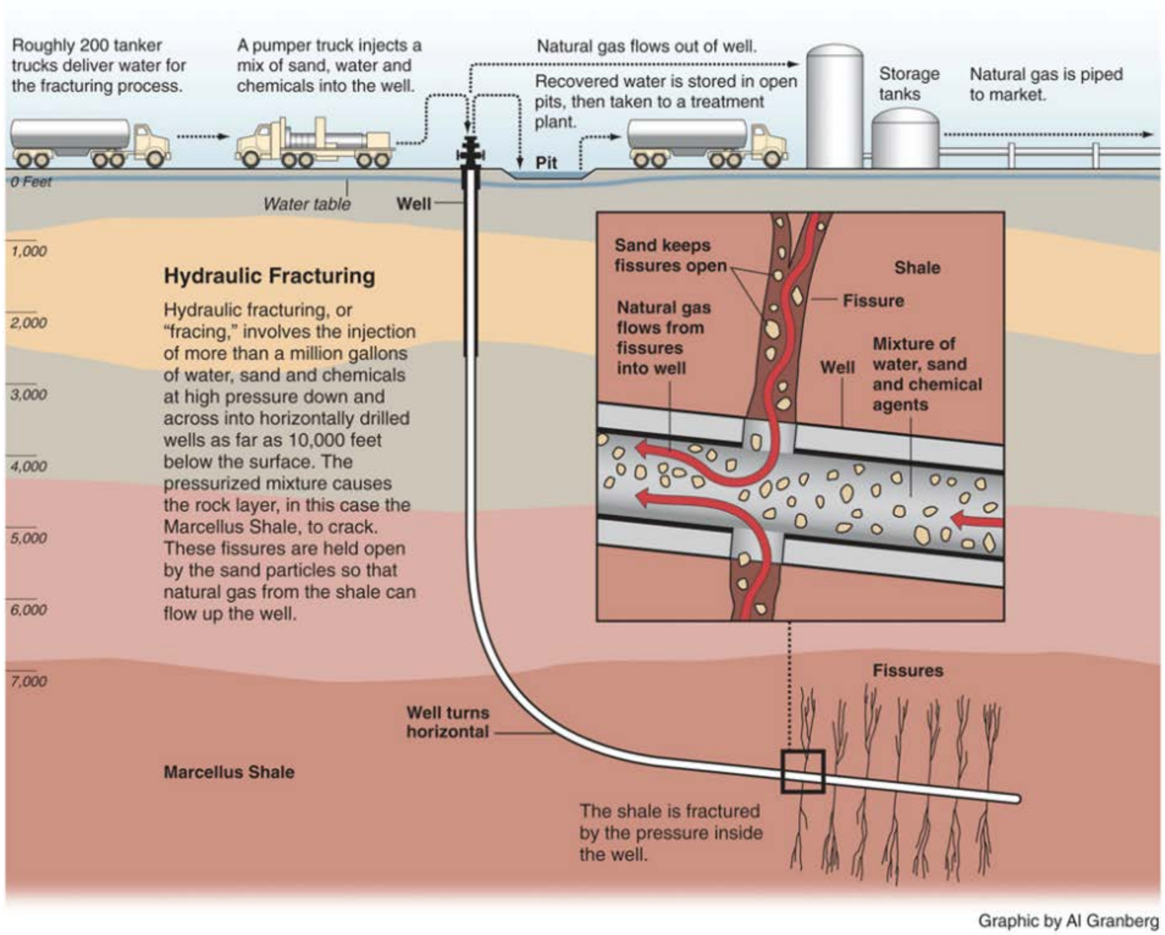

Figure 2-1 Hydraulic Fracturing Process [23]–[25]. Used by permission.

Since the first recorded fracturing in 1947 [2], [5], there has been a substantial increase in the number of wells hydraulically fractured and with the shale gas boom at the dawn of the twenty-first century [24]–[27], there has been significant increase in number of gas wells hydraulically fractured. **Figure 2-2** shows the trend in the number of wells hydraulically fractured since 1947 to 2010. Close analysis of this activity shows that the number of gas well fractured between 2000 to 2010 has increased substantially (**Figure 2-2**).

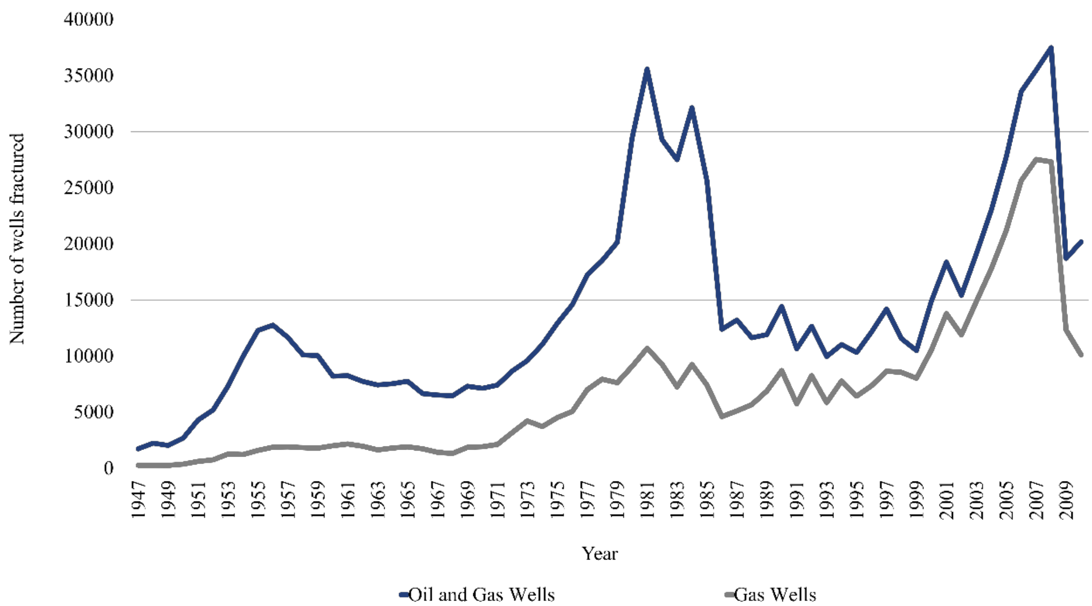

Figure 2-2 Number of wells hydraulically fractured from 1947 to 2010 (Data from [10])

2.2 Proppants

Proppants are essential in hydraulic fracturing to keep the fractures open for increased productivity [5]. Sand was first used as proppant in 1947, and since then different materials like ceramic, bauxite, resin coated, walnut hulls, and gravel have been reported to be used as proppant material [10], [28]. In the recent past, the major broad categories of proppants manufactured and used in hydraulic fracturing industry have been ceramic-based, silica-based, resin-coated sand, and bauxite-based proppant [5], [15]–[17], [19].

Silica-based proppant, commonly called as ‘frac sand’ or ‘silica sand’ is the most commonly used proppant which was first used in 1947 [5], [7], [15], [19]. Silica-based proppant is typically used in shallow wells having closure stress below 6000 psi [29]. At higher closer stress, the sand particles are crushed due to the high pressures thereby closing the fractures and rendering it ineffective. Data show that silica sand captured over 85 percent of North American proppant market by weight and 95 percent of all fractured wells in the year 2013 [7].

Ceramic-based proppants were first introduced in the year 1983 and resin-coated proppant was used in 1984 [30]. Resin-coated proppant has better performing characteristics as compared to sand because it offers higher resistance to closure stress as compared to sand and thus reduces proppant crushing. This, in turn, provides higher conductivity and permeability. [7]. Ceramic proppants are typically used in deeper wells where fractures are subject to higher closure stress [29], [31] as it offers even higher resistance to closure stress as compared to resin-coated proppant.

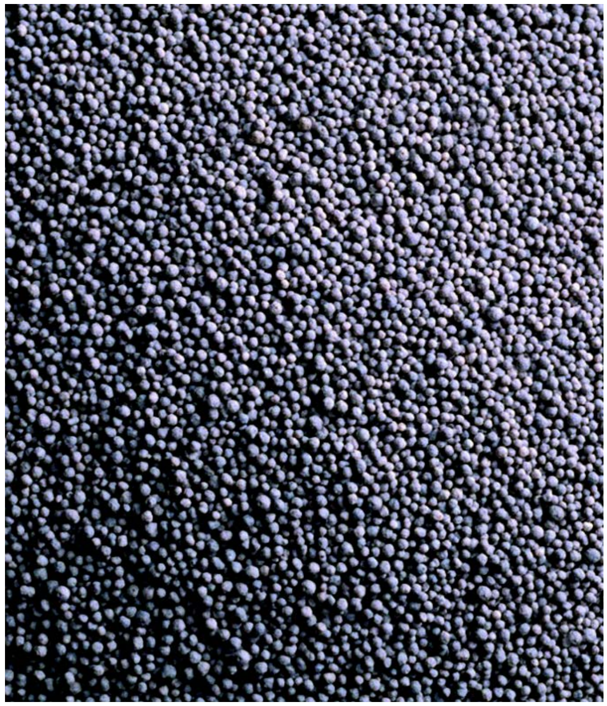

Figure 2-3 Ceramic proppant (CARBOEconoprop 20/40, a high-conductivity, lightweight ceramic proppant from CARBO Ceramics)

2.3 Selection of Proppants

Selection of proppant is key to achieving a successful fracture for improved productivity [32]. With various proppant types commercially available, the total proppant cost and the combination of technical specifications are the basic criteria for selection of proppant [19], [29], [31], [33]–[35]. Several studies have been conducted to determine the optimum choice of proppant.

Proppant selection has been addressed as early as in 1985 when Montgomery et. al. (1985) studied various factor governing successful fracturing operation. The study found that the selection of proppant depends on the well formation and fracture conductivity [33]. Vincent (2002) reviewed 80 field studies to determine the factors for increased productivity and found that increase in fracture conductivity increases well production [31]. Fracturing treatments were reviewed in the Fayetteville Shale, Bakken Shale and Haynesville Shale by Terracina et. al. (2010) which not only studied the importance of conductivity, cost and availability of proppant for optimal proppant choice but also conducted studies to determine the optimal proppant for these fields through a combination of field data and laboratory experiments [34].

The cost of proppant also significantly affects the choice of proppant. Studies show that the cost of proppant could be as low as 10% to over 50% of the total well treatment cost depending on the size of the treatment and the proppant choice [5]. Mack et. al. (2013) have shown that use of advanced ceramic proppants increases production and net present value in low-permeability reservoirs [36]. Yang et. al. (2013) discuss the design flaws in proppant selection and conclude that natural sand proppants are economically more viable than synthetically manufactured proppants i.e. bauxite and ceramic-based proppants in Permian basin in Texas [37]. The effect of formation type, well depth and the fracture job size was studied for well in the Texas shale plays and it was found that natural brown sand resulted in higher net present value (NPV) in reservoirs with closure stress less than 6,000 psi as compared to ceramic proppants [29]. All these studies optimized the choice of proppant not only based on the technical requirements but also financial returns, but none of the studies incorporated the health-related costs in their analysis.

2.4 Motivation for the Study

Many researchers have reported the presence of toxic air pollutants at oil and gas development sites like Nitrogen Oxides (NO_x) Volatile Organic Compounds (VOCs) and Particulate matter ($PM_{2.5}$) [4], [27], [38]–[40]. Esswein et. al. (2013) studied the exposure of work crew to crystalline silica in 11 hydraulic fracturing site collecting 111 personal breathing dust samples. Results showed that over 83 percent samples exceeded crystalline silica concentration beyond American Conference of Governmental Industrial Hygienists Threshold Limit Value (ACGIH TVL) of 0.025 mg/m^3, 68 percent exceeded crystalline silica concentration beyond National Institute for Safety and Occupational Health Respirable Exposure Limit (NIOSH REL) of 0.05 mg/m^3, and 57 percent were exposed to crystalline silica concentration beyond Occupational Safety and Health Administration Permissible Exposure Limit (OSHA PEL) of 0.1 mg/m^3 [9]. It should be noted that with the change in OSHA PEL from 0.1 to .05 mg/m^3, the percent of samples exposed to silica level above current OSHA PEL is 68%. This silica comes from the handling of proppants on site.

Figure 2-4 shows the presence of respirable crystalline silica beyond the OSHA PEL, NIOSH REL and ACGIH TVL at different hydraulic fracturing sites. All the sites except Bakken reported 62 to 85 percent of total samples exceeding the OSHA PEL. Only one sample out of ten collected in Bakken reported respirable silica to be beyond OSHA PEL. This can be attributed to the fact that over 60% of proppants used in the site, during sampling were ceramic-based proppant [9].

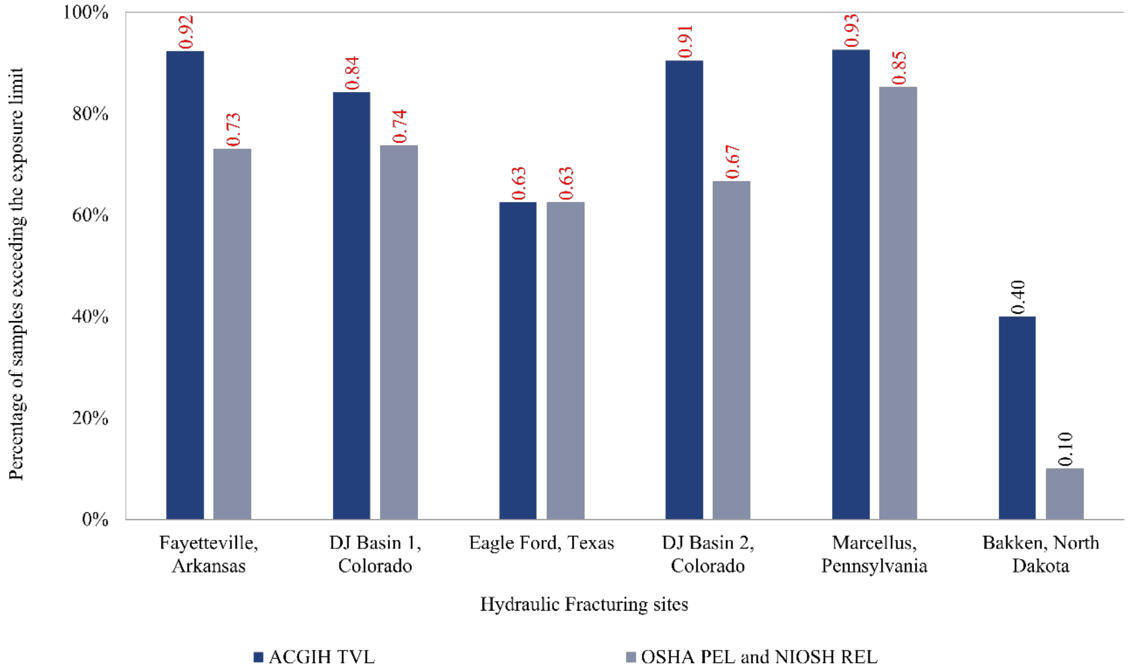

Figure 2-4 Percentage of sample collected at various hydraulic fracturing sited having silica exposure levels above the National Institute for Safety and Occupational Health Respirable Exposure Limit (NIOSH REL), Occupational Safety and Health Administration Permissible Exposure Limit (OSHA PEL) and American Conference of Governmental Industrial Hygienists Threshold Limit Value (ACGIH TVL) (Data from [9]).

Available research indicates that there are risks to human health due to silica exposure and this study conducts a cost-benefit analysis to examine if silica-based proppant can be replaced by alternate proppant to reduce health impacts on workers in hydraulic fracturing industry.

2.5 Objective of the Study

The optimal choice of proppants is attributed to technical requirements and economic considerations and many researchers have recommended various selection process to maximize productivity and NPV. But as far as the knowledge of the author, no study has been conducted to select the optimal proppant taking into consideration health-related cost incurred due to worker exposure to such proppants. This research focuses on quantifying the health-related economic impacts of the use of various proppant types. Further, the study develops a decision tree to choose the most optimal proppant by taking into consideration both the technical and internal and external financial implications of their use.

Chapter 3

Methodology

3.1 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. The technical parameters like the ranges of closure stress, and the corresponding conductivity and permeability for each proppant was collected from the technical data sheets and a database of such proppants was created including their name. The fracture conductivity is the product of the permeability of the proppant and the width of the propped fracture. 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 3-1** shows the number of proppant of each type included in the study. The study incorporated 33 ceramic-based proppant, 28 bauxite-based proppant, 22 resin-coated proppant and 11 silica-based proppant. It should be noted that the proppants with available MSDS and Technical Data Sheets were included in this study. Further, 1 in 5 of the MSDS did not cite the exact composition of the proppant since they are trade secrets but sufficient data was available to divide the proppants into one of the four major categories. It should also be noted that proppants missing technical datasheets were excluded from this study since it did not have the basic information like permeability, and conductivity for various ranges of closure stress, required to conduct this study. The exposure limits for 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 tabulated to indicate the health impact of exposure to each proppant.

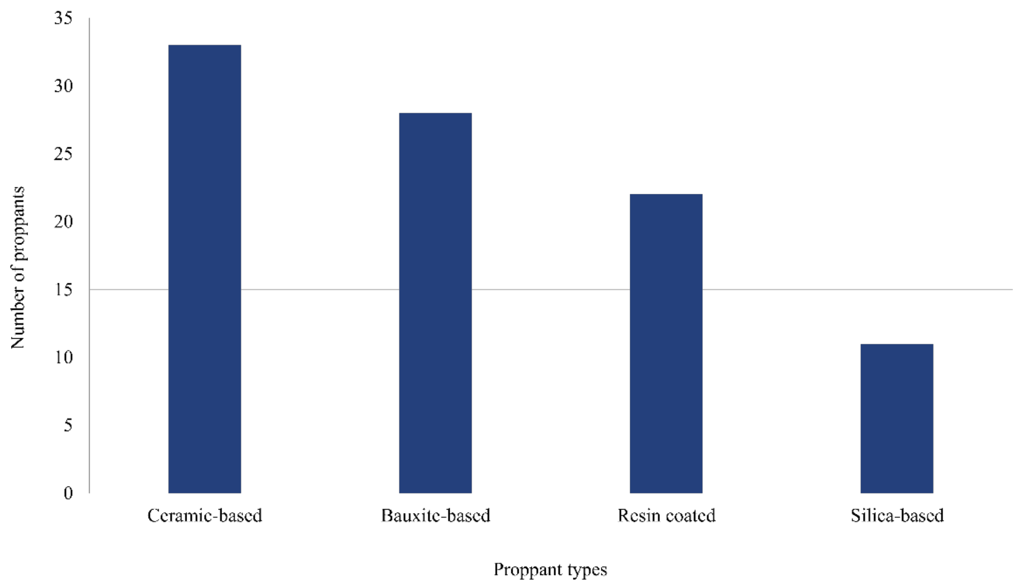

Figure 3-1 Numbers of four major categories based on their type namely, ceramic-based (C), bauxite-based (B), resin coated (RC) and silica-based (S) proppant.

The database consisted of a range of proppants, including silica-based, ceramic and bauxite-based used over a range of closure stress ranging from 2000 to 18000 psi.

The conductivity ranges from 60 to 42000 md-ft with a permeability range of 5 to 2750 Darcy (1 Darcy = 9.869233×10^{-13} m²).

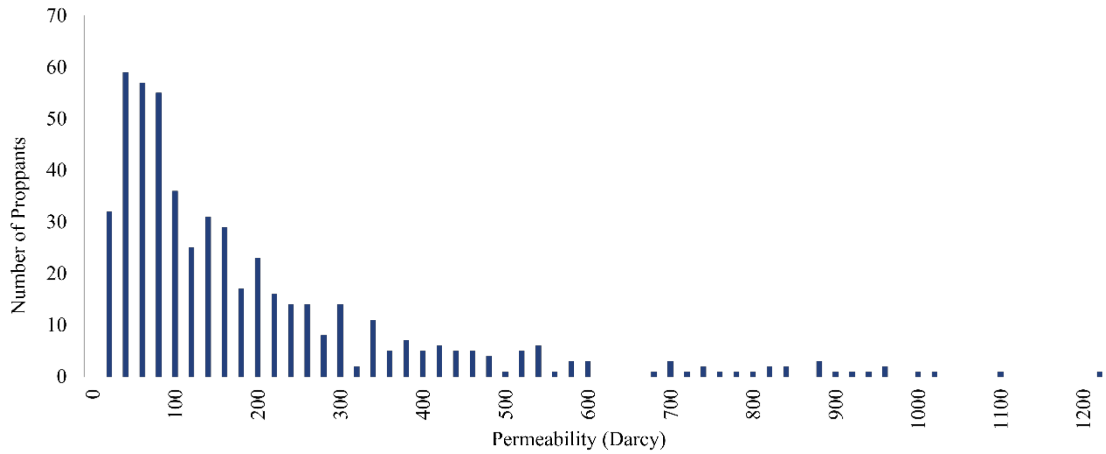

Figure 3-2 Number of proppants available at different permeability ranges

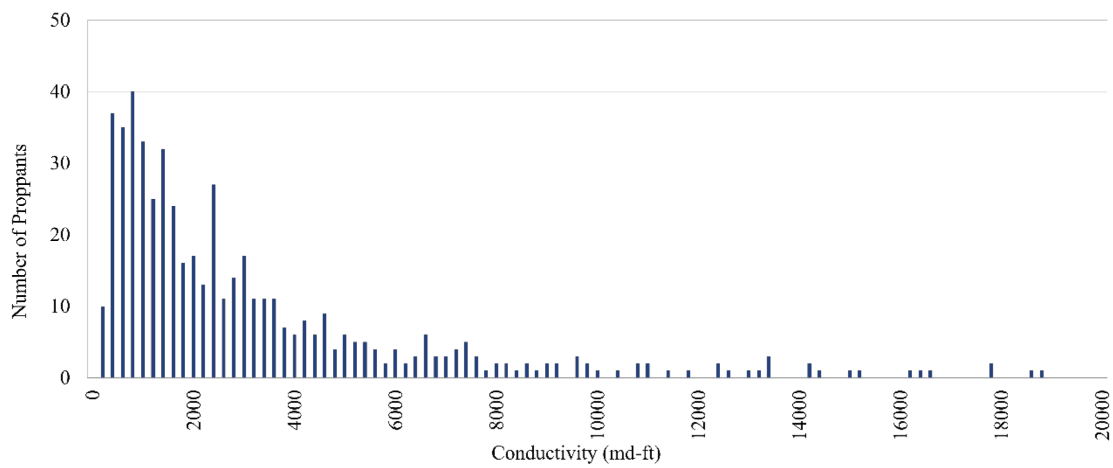

Figure 3-3 Number of proppants available at different conductivity ranges

Analyzing the technical data sheet, it is found that for each combination of permeability or conductivity with closure stress, there are multiple options available for proppant selection. **Figure 3-2** shows the number of proppants available at different conductivity ranges and **Figure 3-3** shows the number of proppants available at different permeability range. It was found that there are more proppants available at intermediate ranges of permeability and conductivity as compared to the higher values. Fracturing in deeper wells in the recent past has led to the development of proppants with higher ranges of permeability and conductivity.

3.2 Willingness-to-pay for Avoided Fatality and Morbidity

Willingness to pay for an avoided fatality is defined as the money an individual is willing to pay to avoid a marginal increase in the risk of fatality [41]. It has been studied by various researchers and statistically robust estimates have been given Hintermann et. al. [42]. Extensive analysis of various studies conducted to determine the values of statistical life in U.S labor market has been done by Viscusi and Aldy and they have estimated that the mean willingness to pay for avoided fatality to be $7 million in 2000 dollars [43]. Over the past decade and a half, OSHA has used the willingness to pay method for calculating the benefits of reduced risk in proposing various rules [8], [44], [45]. The benefit of avoided fatality has been estimated to be $8.7 million in 2009 dollars [41]. Using the Consumer Price Index for Medical care [46], 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 respirable silica dust leads to a number of related illnesses like cancer, silicosis, and renal diseases and the costs of such illness needs to be determined. Since the intensity and duration of these illnesses vary in each case, a number of studies are taken into consideration when evaluating the monetary value for non-fatal illness [41]. Studies have shown that the cost of treating non-fatal form of lung impairment in 2008 dollar value is $460,000 [41]. The cost of treating each case of the renal disease was estimated to be approximately $620,000 in 2002 dollars [41]. Using the willingness to pay method, OSHA has estimated the cost of various non-fatal illness avoided to lie in a range of $62,000 to $5.1 million in 2009 dollar value [41]. We have used this range of values in our studies since this value has been used by OSHA to calculate the willingness to pay for avoided non-fatal illness for proposed rulemaking for occupational exposure to crystalline silica. Using the Consumer Price Index for medical care [46], 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.

3.3 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 jobs [41]. **Table 3-1** shows the distribution of typical hydraulic fracturing crew based on their job description.

Table 3-1 Number of people in a typical hydraulic fracturing crew based on their job description.

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

No study has been conducted to estimate the number of fatalities & non-fatal illnesses due to crystalline silica exposure higher than the prescribed exposure limit of 50 $\mu g/m^3$ by OSHA for at-risk workers at a hydraulic fracturing site. Occupational Safety and Health Administration 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 $\mu g/m^3$ [41]. To estimate the number of fatalities and non-fatal illness due to exposure of these 16,000 workers to silica, we assume that the ratio of number of fatality and non-fatal illness to the number of people exposed to silica in hydraulic fracturing industry is similar to the construction and general maritime 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.

$$\text{Pall} = \frac{\text{nall}}{\text{Nall}} * 100 \qquad (1)$$

N_{all} = Number of people exposed to silica of 50 μg/m^3 in the United States in construction and general and maritime industry (The estimated number of workers exposed to silica levels of 50 μg/m^3 in construction and general maritime 770,000 workers [41]).

n_{all} = Estimated number of fatality & non-fatal illnesses due to crystalline silica exposure of 50 μg/m^3 for at-risk workers over a 45-year working life in construction and general maritime industry (**Table 3-2**).

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

Table 3-2 Estimated number of avoided fatalities & non-fatal illnesses due to a reduction in crystalline silica exposure of 50 μg/m^3 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.

	Total estimated number of avoided cases in U.S. general maritime and construction industry due to reduction of silica exposure to 50 μg/m^3
Lung Cancer	
High	12000
Mid	7000
Low	2000
Silicosis & Other Non-Malignant Respiratory Diseases	17000
End-stage Renal Diseases	7000
Total Number of Fatal Illness Prevented	
High	36000
Mid	31000
Low	26000
Total Number of Silicosis Morbidity Cases Prevented	71000

Using equation 1, we estimate the percentage of avoided fatalities and non-fatal illnesses resulting due to a reduction in crystalline silica exposure of 50 μg/m^3 for at-risk workers over a 45-year of working life which is shown in **Table 3-3**.

Table 3-3 Estimated percentage of avoided fatalities & non-fatal illnesses due to reduction in crystalline silica exposure of 50 µg/m^3 for at-risk workers over a 45-year of working life

	Estimated percent of avoided cases of fatalities and non-fatal illness in U.S. general maritime and construction industry due to reduction of silica exposure to 50 µg/m^3
Lung Cancer	
High	1.60
Mid	0.95
Low	0.30
Silicosis & Other Non-Malignant Respiratory Diseases	2.20
End-stage Renal Diseases	0.90
Total Number of Fatal Illness Prevented	
High	4.65
Mid	4.00
Low	3.40
Total Number of Silicosis Morbidity Cases Prevented	9.25

$$n_{hf} = (P_{all} * N_{hf})/100 \quad (2)$$

N_{hf} = Number of people exposed to silica over 50 µg/m^3 over years in the United States in one hydraulic fracturing site (**Table 3-4**).

n_{hf} = Estimated number of fatality & non-fatal illnesses due to crystalline silica exposure of 50 μg/m^3 for at-risk workers over a 45-year working life in one hydraulic fracturing site.

The number of workers exposed to silica levels of 50 μg/m^3 or more in a typical hydraulic fracturing crew is shown in **Table 3-4.**

Table 3-4 Number of affected workers exposed to silica level of 50 μg/m^3 or more in a typical hydraulic fracturing crew.

Classification by Function	Numbers of Affected Workers Exposed to Silica level of 50 μg/m^3
Sand Mover Operator	4.55
Conveyor Belt Tender	1.00
Blender Tender	1.73
Hydraulic Unit Operator	0.50
Water/ Chemical Hands	1.00
Pump Operator Technicians	1.00
Supervisor	0.50
Ground Guide	0.50
Total	10.79

Using equation 2, it is estimated that the number of workers prone to non-fatal illness because of exposure to silica level of 50 μg/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.

$$c = (n_{hf}*a) \quad (3)$$

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 1-3, 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 dollar value (**Table 3-5**).

Table 3-5 Estimated cost of fatalities & non-fatal illnesses due to crystalline silica exposure of 50 $\mu g/m^3$ for at-risk workers over a 45-year of working life for one typical fracturing crew.

	Total Cost (In millions)
Total Cost for Fatal Illness	
High	$5.10
Mid	$4.40
Low	$3.70
Total Cost of non-fatal illness (Low)	$0.07
Total Cost of non-fatal illness (High)	$5.94
Total Cost of fatality and non-fatal illness (Low)	$3.80
Total Cost of fatality and non-fatal illness (High)	$11.00

The willingness to pay for avoided fatality and non-fatal illness was calculated for silica exposure of 50 µg/m^3 using silica-based proppants. The alternate proppants like ceramic and bauxite based are made up of several materials like aluminum oxide, magnesium iron silicate, magnesium silicate, and aluminum silicates which also pose threat on exposure. The American Conference of Governmental Industrial Hygienists Threshold Limit Value (ACGIH TVL) exposure limit to such materials is given in **Table 3-6**. We use the ACGIH TVL because ACGIH has defined an exposure limit for each these materials. But, 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 3-6 Material exposure limit as per American Conference of Governmental Industrial Hygienists Threshold Limit Value (ACGIH TVL)

Material/Chemical Name	ACGIH TVL Limit
Silica	0.025
Aluminum Oxide	3.000
Aluminum Silicate	3.000
Magnesium Silicate	2.000

Since no studies have been conducted to calculate the costs of exposure to these proppants, equation 4 was used to calculate the costs of exposure for the proppants made up of these materials. This assumes 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 fatalities 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.

$$\left(\frac{Es}{\mathrm{E1}} * c1 + \frac{Es}{E2} * c2 + \frac{Es}{E3} * c3 + \cdots\right) * C \qquad (4)$$

Where

Es – 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 µg/m^3

E_n - Exposure limit of chemical ‘n’ in mg/m^3 (**Table 3-6**)

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.

Chapter 4

Analysis and Results

4.1 Cost of fatalities and non-fatal illness for various proppants

The cost of fatalities 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). **Table 4-1** shows the cost of fatalities and non-fatal illnesses for exposure to various proppant types. Our calculations assume that the particulate size distributions for fugitive dust emission from the various proppant types are similar. Moreover, we assume that the biological effect from to 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. We calculate a range of estimated cost of fatality and non-fatal illness based on the estimated cost of fatality and non-fatal illness due to exposure to silica (**Table 3-5**).

Table 4-1 Cost of fatalities and non-fatal illness for various proppant types. The cost of fatalities and non-fatal illness is negligible for ceramic and bauxite based proppant as compared to silica-based proppant.

Proppant Category	**Range of cost of fatalities and non-fatal illness (In millions)**
Silica-based	\$3.80 to \$11.00
Resin-coated	\$3.80 to \$11.00
Bauxite-based	\$0.03 to \$0.09
Ceramic-based	\$0.04 to \$0.12

It shows that the cost of fatalities and non-fatal illness for both silica-based proppant and resin-coated silica proppant was equal since the silica content in both proppant types as reported in the MSDS were equal. The cost of fatalities and non-fatal illnesses for ceramic-based proppant and bauxite-based proppant were around 0.1% of the silica-based proppant. The range of cost of fatality and non-fatal illness or health-related cost for using different kind of proppants is shown in **Figure 4-1.** 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.

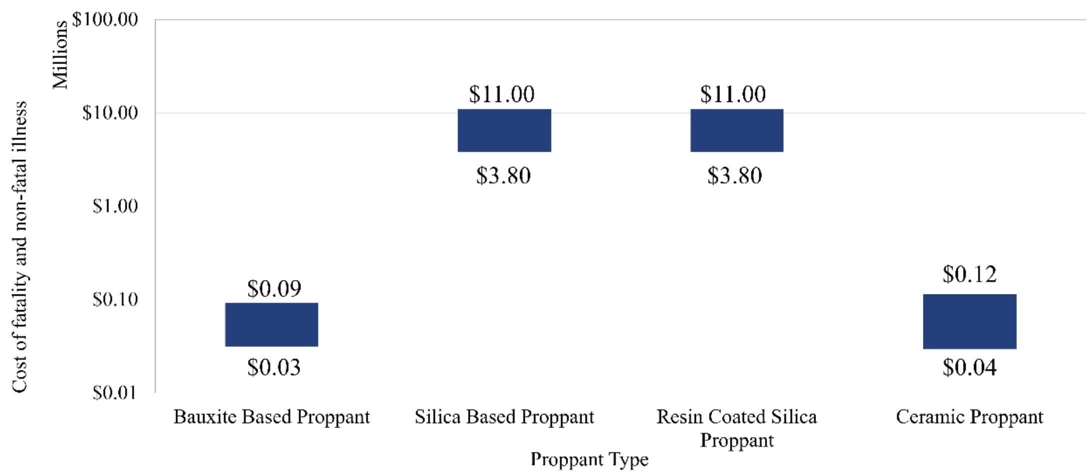

Figure 4-1 Cost of fatality and non-fatal illness for different proppant types. The range of cost of fatality and non-fatal illness is approximately 1100 times higher for silica-based proppant as compared to ceramic and bauxite based proppant.

4.2 Silica exposure in hydraulic fracturing industry

Research shows that approximately 17,000 people are directly involved in hydraulic fracturing industry out of which nearly 50% workers are exposed to silica levels over 50 μg/m^3 [41]. Assuming that the percentage of fatality and non-fatal illness due to silica exposure in hydraulic fracturing industry is similar to that in general maritime and construction industry for same silica exposure levels it is estimated that 1 in 16 workers are prone to non-fatal illness. We also estimate that 1 in 30 to 1 in 48 workers are prone to fatal illness due to exposure to silica in a typical hydraulic fracturing crew. **Table 4-2** shows the estimated number of fatality and non-fatal illness due to crystalline silica exposure of 50 μg/m^3 for at-risk workers over a 45-year of working life in hydraulic fracturing industry.

Table 4-2 Estimated number of fatality & non-fatal illnesses due to crystalline silica exposure of 50 μg/m^3 for at-risk workers over a 45-year of working life in hydraulic fracturing industry.

	Total Number of avoided cases in hydraulic fracturing industry	**Total Number of avoided cases in a typical hydraulic fracturing crew**
Lung Cancer		
High	260	0.17
Mid	155	0.10
Low	50	0.034
Silicosis & Other Non-Malignant Respiratory Diseases	358	0.236
End-stage Renal Diseases	144	0.095
Total Number of Fatal Illness Prevented		
High	760	0.502
Mid	656	0.433
Low	552	0.365
Total Number of Silicosis Morbidity Cases Prevented	1512	0.999

4.3 Sensitivity Analysis

To determine the effect of changes in the cost of proppant materials, the quantity of proppant handled by a typical hydraulic fracturing crew each year and the cost of avoided fatalities and non-fatal illnesses, we conducted sensitivity analysis to determine the effect of variation in these components to the total cost (includes the cost of proppant and the cost of avoided fatality and non-fatal illness) of using different proppant type. For carrying out the sensitivity analysis, the quantity of proppant handled by a typical hydraulic fracturing crew was varied from 10,000 to 100,000 tons per year. To determine the impact of the cost of fatality and non-fatal illness, different ranges of the expected cost of realized fatality and non-fatal illness were used as calculated in **Table 4-1**.

Table 4-3 lists the average cost per ton (in $) of each proppant [19] 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 4-3 Average cost per ton and the average cost of fatality and non-fatal illness for proppant for a typical hydraulic fracturing crew.

Proppant Type	**Average cost per ton**	**Expected cost of realized fatalities and non-fatal illness**	**Expected cost of realized fatalities and non-fatal illness per ton of proppant used**
Silica Based	$ 275	$ 7.40 million	$ 123.00
Bauxite Based	$ 400	$ 0.061 million	$ 1.01
Ceramic Based	$ 475	$ 0.072 million	$ 1.20

Figure 4-2 (a) shows the changes in the total cost of proppant including the cost of fatalities and non-fatal illnesses for varying ranges of proppant quantity from 10,000 to 100,000 tons, proppant cost from \$350 to \$600 per ton and the cost of fatality and non-fatal illness from \$40,000 to \$120,000 for ceramic-based proppant. We find that varying proppant quantity and proppant cost of the ceramic-based proppant has a substantial contribution to the total cost. It is also evident from the **Figure 4-2** (a) that the costs of fatality and non-fatal illnesses for ceramic-based proppants are negligible as compared to the costs of proppant.

Figure 4-2 (b) shows a similar analysis for bauxite-based proppant. We find that the bauxite-based proppant has a sensitivity similar to that of ceramic-based proppant. The contribution of proppant quantity and proppant cost towards the total cost is significant for bauxite-based proppant. Moreover, the cost of fatalities and non-fatal illnesses have less of a contribution towards the total cost.

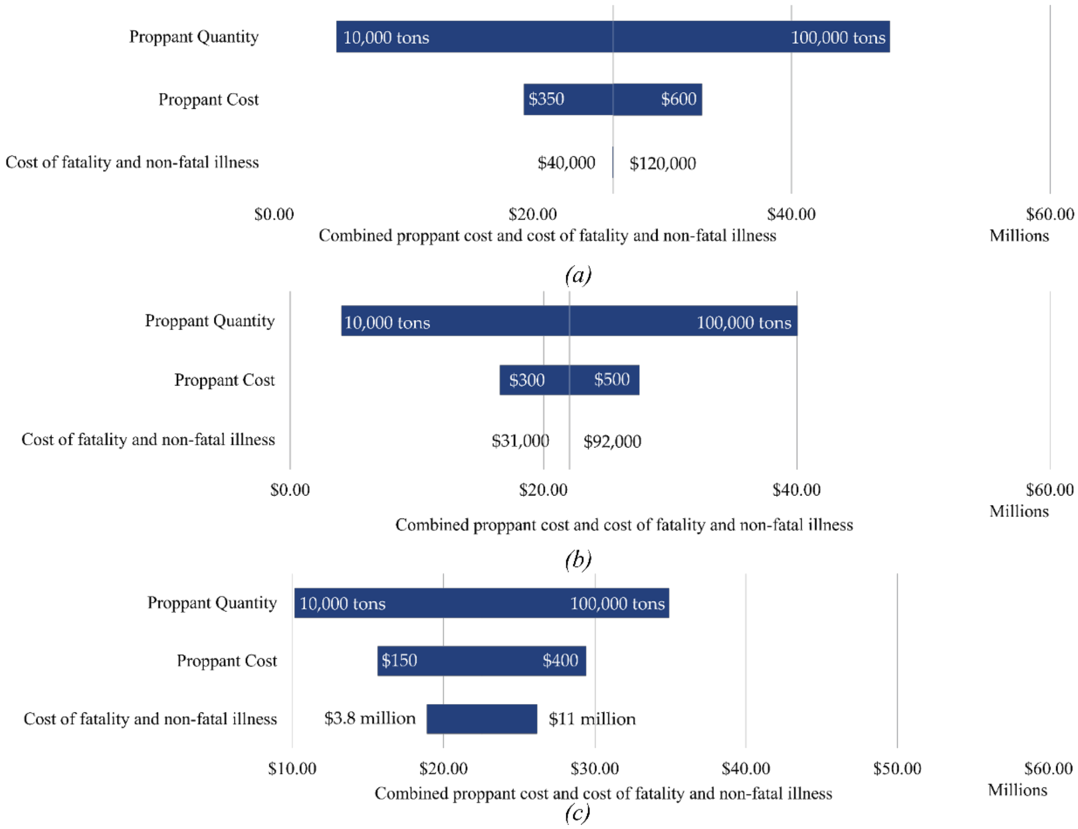

Figure 4-2 (a) Sensitivity analysis for ceramic-based proppants. The total combined cost is negligibly affected by the change in the cost of fatality and non-fatal illness as compared to proppant quantity and the proppant cost. (b) Sensitivity Analysis for bauxite based proppants. The total combined 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 4-2 (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. We find that 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 4-3 shows the cost of different proppants with increasing proppant quantity without any external health-related costs. We find that the ceramic-based proppant is the most expensive type whereas silica-based proppant is the cheapest proppant available.

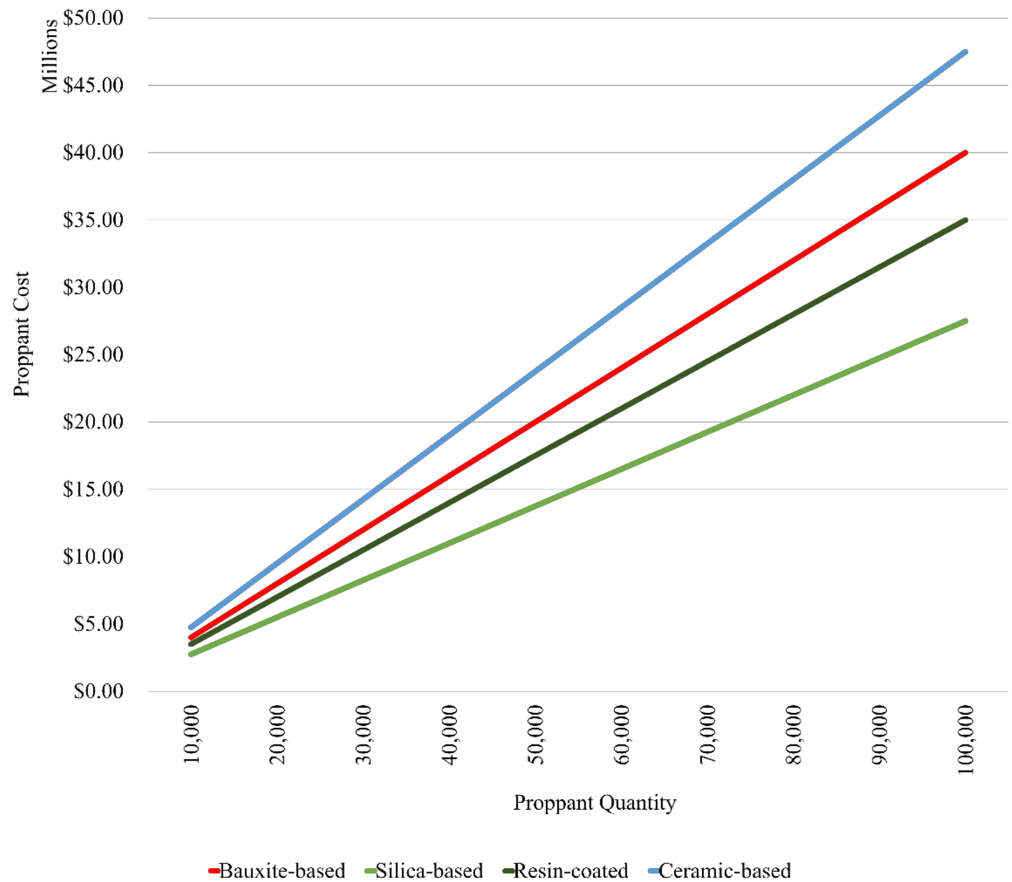

Figure 4-3 Comparison of cost of different types of proppants. The cost of silica-based proppant is lowest and the cost of ceramic-based proppant is highest.

With the addition of costs associated with fatalities and non-fatal illnesses for each proppant, we compare 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 which is shown in **Figure 4-4**. For calculating the total combined cost, we take the average cost of proppant and the average cost of fatality and non-fatal illness associated with each proppant, as given in **Table 4-3**. We find that there is an increase in the total combined cost with an increase in the proppant quantity. We find that for lower proppant quantities, the total combined cost of bauxite and ceramic-based proppant are lower than that of silica-based proppant. This indicates that for hydraulic fracturing crews handing approximately less than 60,000 tons of proppant every year, ceramic and bauxite-based proppants are more economical if the cost of fatality and non-fatal illness are taken into overall cost consideration. We find that for crews handling approximately 55,000 tons of proppant per year, 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 less than 58,000 tons of resin coated silica-based proppant per year.

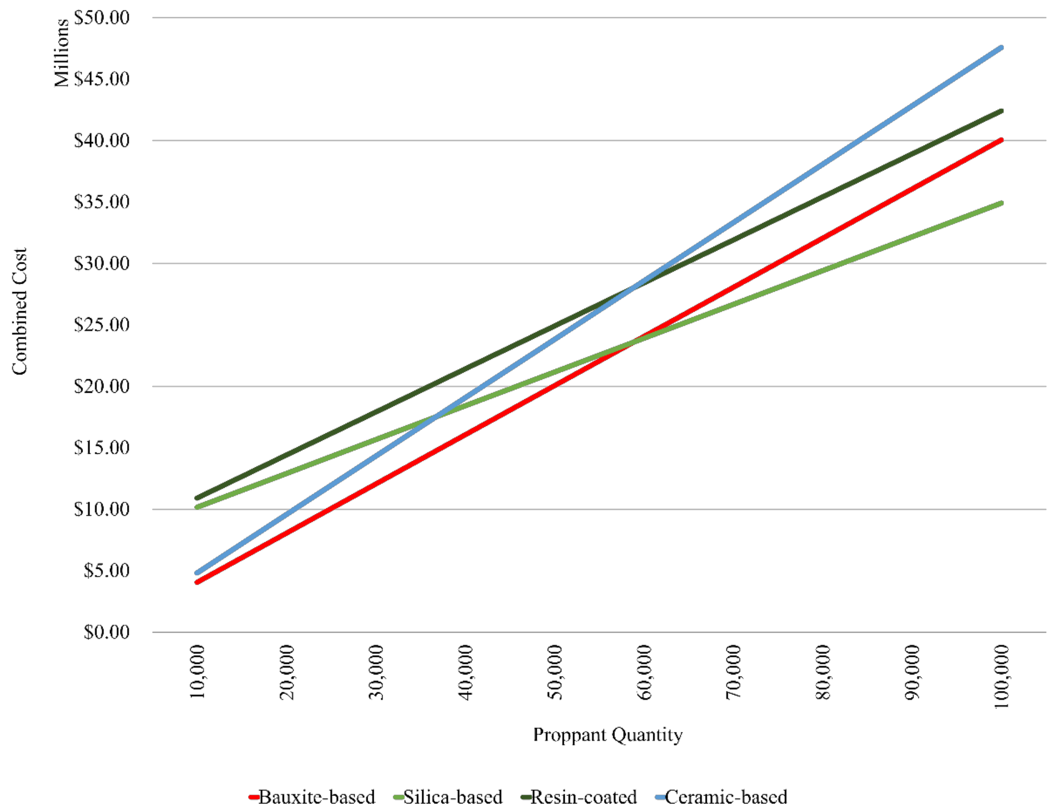

Figure 4-4 Comparison of total combined raw material and health cost for different types of proppants. The combined cost for bauxite based proppant is less than silica-based proppant and ceramic-based proppant has lower combined cost as compared to bauxite based proppant for crews handling slightly less than 60000 tons of proppants per year.

In practice, the selection of proppant material is based on the type of deposit, performance of the proppant, and economics. A good proppant achieves required conductivity and permeability for the given closure stress to create a good fracture for sustained production. 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 the fracturing sites have used sand as proppant [1]. Studies suggest that sand-based proppant should always be selected unless ceramic proppant justifies the economic benefits [5]. But these studies do not take into consideration the health-related financial implications of the use of sand-based proppants. So we develop a proppant selection strategy map taking into consideration the technical requirements and the financial implications associated with selection of any proppant.

From **Figure 4-4** we already know that silica-based proppant and resin-coated silica-based proppant can be replaced by bauxite-based proppant and ceramic-based proppant respectively for fracturing crews handling approximately 60,000 tons or less of proppant. 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 United States in 2013 [41] and reports show that the total quantity of proppant used in hydraulic fracturing industry in 2013 was approximately 33 million tons [11]. Based on this data, we estimate 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, we plot a proppant selection strategy map for hydraulic fracturing crew which handles 45,000 tons of proppant every year (**Figure 4-5**).

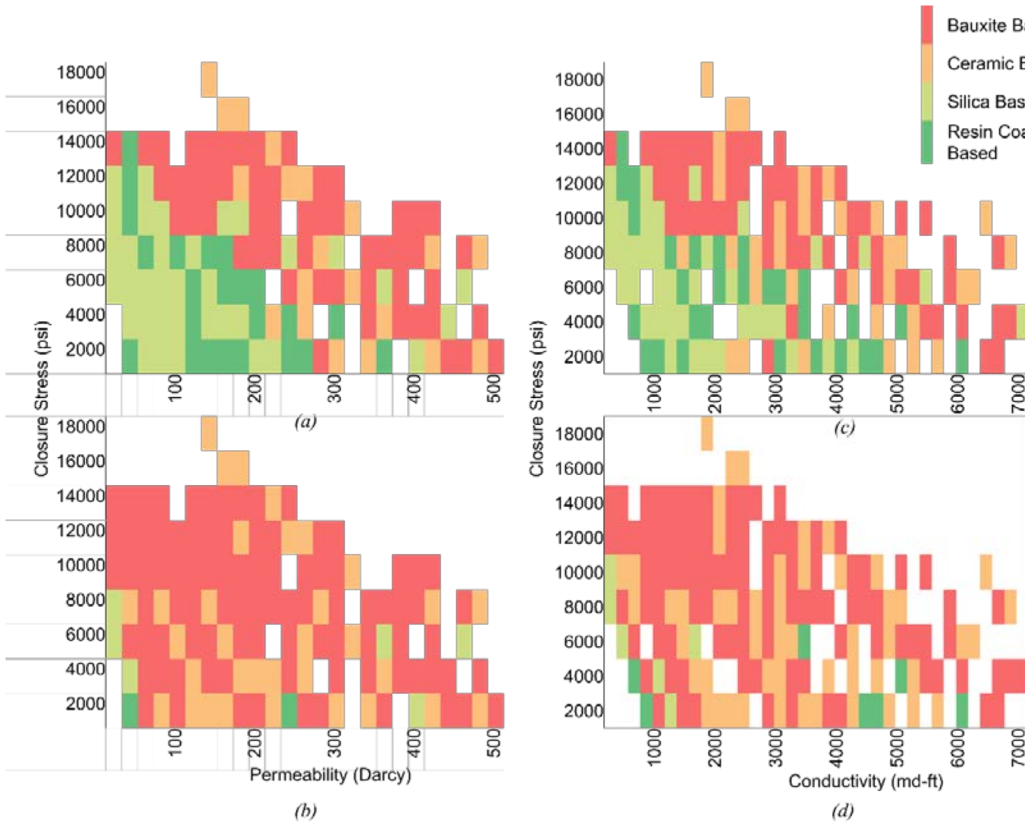

Figure 4-5 Proppant Selection Strategy Map. (a) Least expensive proppants available at various closure stress and permeability excluding financial implications of health into account. (b) Least expensive proppants available at various closure stress and permeability including financial implications of 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.

Taking the financial implications of health-related costs into consideration, we find that it is possible to replace silica-based proppants with less harmful and technically equivalent ceramic and bauxite based proppants. To create the strategy plot, we developed 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 represented in **Figure 4-5** (a) and (c). Cost of fatalities and non-fatal illness were then added to the proppant cost and the cheapest proppant for the same range of permeability and conductivity was selected, which is represented in **Figure 4-5** (b) and (d). It was found that silica-based proppant could be replaced by bauxite or ceramic based proppant 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.

Chapter 5

Discussion

This research was conducted to study the economic impact of the selection of different proppant types in hydraulic fracturing industry 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], [32], [33], [36], [47] but none of these analyses incorporated healthcare costs associated with worker exposure to those proppants. This study focuses on incorporating health-related cost for the socially optimal selection of proppant. This chapter summarizes the research, discussing its findings, assumptions, and limitations, and outlining the future work.

5.1 Alternate proppants are available but rarely used

The database of commercially available proppants created for this study demonstrated that multiple proppants types were available to cater 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 1-1**). This indicates that silica-based proppants were 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 crushes due to high stress in deep wells rendering it ineffective.

5.2 Health-related Costs of Proppant Choice

To determine the health-related costs due to exposure to different proppant types, we conducted a review of the literature to find their corresponding health-related costs, especially costs related to exposure to silica-based proppant i.e. silica, which is elaborated in chapter 3. 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 (**Table 3-5**). We used the Consumer Price Index for Medical care to calculate the value from various other basis years since it closely reflected the changes in healthcare costs over time (Table in the appendix). This health-related cost substantially increases the overall cost of using silica-based proppant and changes the economic dynamics for proppant selection.

Further, it was found that the financial implications of silica-based proppants for health-related costs were substantially higher as compared to ceramic or bauxite based proppants (**Table 4-1**). 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.[48]–[52]. 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.

5.3 Socially Optimal Proppant Selection

The review of available literature shows that silica-based proppant is given precedence over bauxite and ceramic-based proppants due to its low upfront cost which is half the cost or even lesser as compared to that of bauxite or ceramic-based proppants. Drilling and fracturing companies apparently do not incorporate potential costs from health risks into their decision-making because they do not bear most of 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 $\mu g/m^3$ [9]. 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 (**Figure 4-5**) 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. For example, substantial transportation cost of silica-based proppant may encourage companies to use safer bauxite or ceramic proppants owing to 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 hydraulic fracturing industry [41]. 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 $\mu g/m^3$ to 50 $\mu g/m^3$ for a

45-year working life for approximately 16,000 workers are exposed to silica level of 50 μg/m^3.

5.4 Encouraging alternatives to Silica-based proppants

The inclination to use sand-based proppant is based on supply and availability, a cheaper price per ton as compared to other materials, and acceptable, though not excellent technical properties. Levying some sort of 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 [53], hazardous substance tax [54], air emission permit fees, effluent permit fees, and petroleum product tax to name a few. Implementation of a silica tax for 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 based on the technical requirements and the cost of the proppant, and non-silica-based proppants are only selected only if it is technically required. 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 $\mu g/m^3$ [8]. OSHA analysis demonstrated that while health risks remained at 50 $\mu g/m^3$ for many industries it was not feasibly cost effective to reduce exposure levels to 25 $\mu g/m^3$ 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, it seems doubtful that these potential technologies could reduce risk more significantly than a change of proppant material, which eliminates 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 work does not include the health-related costs of the silica mine workers either 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 greater than those calculated here focused solely on the drilling and fracturing crews.

Chapter 6

Summary and Conclusions

The widespread use of silica-based proppants in hydraulic fracturing poses significant health impacts on 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. 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.

Based on this study we can make the following conclusions:

a) Alternate proppants are commercially available to replace silica-based proppant. Yet, this research has made no assessment of 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.

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Appendix A

Details of Proppants used in this research

Table A- 1 List of commercially available proppants used in this research.

Sl. No.	Company	Proppant
1	Saint Gobain	Ultra Prop
2	Saint Gobain	Sinistered Bauxite 16/30
3	Saint Gobain	Sinistered Bauxite 20/40
4	Saint Gobain	Sinistered Bauxite 30/50
5	Saint Gobain	Sinistered Bauxite 40/80
6	Saint Gobain	VersaProp
7	Saint Gobain	InterProp 12/18
8	Saint Gobain	InterProp 16/30
9	Saint Gobain	InterProp 20/40
10	Saint Gobain	InterProp 30/50
11	Saint Gobain	InterProp 40/80
12	Saint Gobain	InterProp 35/140
13	Saint Gobain	BauxLite Plus 12/18
14	Saint Gobain	BauxLite Plus 16/20
15	Saint Gobain	BauxLite Plus 20/40
16	Saint Gobain	VersaLite
17	Saint Gobain	BauxLite 16/30
18	Saint Gobain	BauxLite 20/40
19	Saint Gobain	BauxLite 30/50
20	Saint Gobain	BauxLite 40/80
21	Carbo Ceramics	CarboHydroProp
22	Carbo Ceramics	CarboEconoprop 20/40
23	Carbo Ceramics	CarboEconoprop 30/50
24	Carbo Ceramics	Carbolite 12/18
25	Carbo Ceramics	Carbolite 16/20
26	Carbo Ceramics	Carbolite 20/40
27	Carbo Ceramics	Carbolite 30/50
28	Carbo Ceramics	Carbolite 40/70
29	Carbo Ceramics	Carboprop 12/18
30	Carbo Ceramics	Carboprop 16/30

31	Carbo Ceramics	Carboprop 20/40
32	Carbo Ceramics	Carboprop 30/60
33	Carbo Ceramics	Carboprop 40/70
34	Carbo Ceramics	CarboHsp 12/18
35	Carbo Ceramics	CarboHsp 16/30
36	Carbo Ceramics	CarboHsp 20/40
37	Carbo Ceramics	CarboHsp 30/60
38	Carbo Ceramics	KryptoSphereHD 25 Mesh
39	Carbo Ceramics	KryptoSphereHD 20 Mesh
40	Carbo Ceramics	CarboBond Lite 12/18
41	Carbo Ceramics	CarboBond Lite 16/20
42	Carbo Ceramics	CarboBond Lite 20/40
43	Carbo Ceramics	CarboBond Lite 30/50
44	US Silica	Inno Prop CR 20/40
45	US Silica	Inno Prop CR 30/50
45	US Silica	Inno Prop CR 30/50
46	US Silica	Inno Prop CR 40/70
47	US Silica	Inno Prop PR 20/40
48	US Silica	Inno Prop PR 30/50
49	US Silica	Inno Prop PR 40/70
50	US Silica	Premium Hickory 16/30
51	US Silica	Premium Hickory 20/40
52	US Silica	Premium Hickory 30/50
53	US Silica	Premium Hickory 40/70
54	US Silica	20/40 US Silica White
55	US Silica	30/50 US Silica White
56	US Silica	40/70 US Silica White
57	Rainbow Proppants	Prop Raider 16/30
58	Rainbow Proppants	Prop Raider 20/40
59	Rainbow Proppants	Prop Raider 30/50
60	Rainbow Proppants	Prop Raider 40/70
61	Rainbow Proppants	Prop Light 20/40
62	Rainbow Proppants	Prop Light 30/50
63	Rainbow Proppants	Prop Light 40/70
64	Rainbow Proppants	Prop Master 16/30
65	Rainbow Proppants	Prop Master 20/40
66	Rainbow Proppants	Prop Master 30/50
67	Rainbow Proppants	Prop Master 40/70

68	Rainbow Proppants	ReaLite 30/50
69	Rainbow Proppants	ReaLite 40/70
70	Imerys	Imerys ProLite 20/40
71	Imerys	Imerys ProLite 30/50
72	Imerys	Imerys ProLite 40/70
73	Imerys	Imerys ShaleProp 20/40
74	Imerys	Imerys ShaleProp 30/50
75	Fores	ForeRCP MgLight 20/40
76	Fores	Fores MgLight 20/40
77	Fores	Fores MgLight 30/50
78	Fores	Fores MgLight 40/70
79	Badger Mining	CRC-LT 16/30
80	Badger Mining	CRC-LT 20/40
81	Badger Mining	CRC-LT 30/50
82	Badger Mining	PRC 20/40
83	Badger Mining	PRC 40/70
84	Badger Mining	PCR P 16/30
85	Badger Mining	PCR P 20/40
86	Badger Mining	PCR P 30/50
87	Badger Mining	PCR P 40/70
88	Badger Mining	CRC E 20/40
89	Badger Mining	CRC E 30/50
90	Badger Mining	CRC E 40/70
91	Badger Mining	CRC C 16/30
92	Badger Mining	CRC C 20/40
93	Badger Mining	CRC C 30/50
94	Badger Mining	CRC C 40/70

Table A- 2 List of commercially available proppants designed to be used at a closure stress of 2000 psi with varying conductivity and permeability.

Proppant	Conductivity (md-ft)	Permeability (Darcy)
CRC E 40/70	660	37
CRC C 40/70	679	34
PCR P 40/70	762	50
PRC 40/70	800	43
Inno Prop CR 40/70	876	50

InterProp 35/140	936	58
Inno Prop PR 40/70	1001	55
40/70 US Silica White	1082	58
CRC-LT 30/50	1183	66
Premium Hickory 40/70	1191	67
Sinistered Bauxite 40/80	1324	88
InterProp 40/80	1330	83
CRC C 30/50	1338	76
Prop Raider 40/70	1391	99
CRC E 30/50	1452	75
CRC-LT 20/40	1482	82
BauxLite 40/80	1500	85
Prop Master 40/70	1564	96
CarboHydroProp	1570	80
Inno Prop CR 30/50	1573	84
Prop Light 40/70	1677	84
Carboprop 40/70	1680	140
Premium Hickory 30/50	1758	96
30/50 US Silica White	1871	99
PCR P 30/50	1883	95
ReaLite 40/70	1925	91
CRC E 20/40	1970	105
Fores MgLight 40/70	2031	112
Carbolite 40/70	2200	135
Imerys ProLite 40/70	2282	110
Sinistered Bauxite 30/50	2710	185
Inno Prop PR 30/50	2801	146
Carboprop 30/60	2870	175
CRC C 20/40	2932	132
CarboBond Lite 30/50	2985	155
BauxLite 30/50	3045	170
Prop Master 30/50	3061	187
InterProp 30/50	3138	192
Inno Prop CR 20/40	3166	170
ReaLite 30/50	3216	151
Imerys ProLite 30/50	3351	183
PRC 20/40	3417	183

Fores MgLight 30/50	3552	198
Prop Light 30/50	3663	194
20/40 US Silica White	3676	202
CarboHsp 30/60	3720	255
Imerys ShaleProp 30/50	3815	182
Prop Raider 30/50	3829	269
PCR P 20/40	3904	213
Premium Hickory 20/40	4023	217
CarboEconoprop 30/50	4150	220
Inno Prop PR 20/40	4285	230
CRC C 16/30	4451	246
CRC-LT 16/30	4524	250
Carbolite 30/50	4640	250
Imerys ProLite 20/40	5109	261
ForeRCP MgLight 20/40	5449	281
PCR P 16/30	5929	345
CarboEconoprop 20/40	6300	340
Prop Raider 20/40	6302	442
BauxLite 20/40	6515	360
Sinistered Bauxite 20/40	7065	424
Imerys ShaleProp 20/40	7145	338
Carboprop 20/40	7290	455
Premium Hickory 16/30	7299	395
CarboBond Lite 20/40	7715	420
InterProp 20/40	7830	485
CarboHsp 20/40	8170	540
Prop Light 20/40	8175	426
Prop Master 20/40	8314	509
BauxLite Plus 20/40	8490	460
Ultra Prop	8535	585
Fores MgLight 20/40	8656	472
VersaProp	9120	540
VersaLite	9735	530
Carbolite 20/40	10700	570
Prop Raider 16/30	11282	787
Carboprop 16/30	13400	875
CarboBond Lite 16/20	14355	770
Prop Master 16/30	14920	865

BauxLite 16/30	16185	865
Sinistered Bauxite 16/30	16375	1098
InterProp 16/30	16560	1020
CarboHsp 16/30	18410	1205
BauxLite Plus 16/20	18725	995
Carbolite 16/20	24630	1290
CarboBond Lite 12/18	24670	1305
Carboprop 12/18	30940	1900
BauxLite Plus 12/18	33555	1730
InterProp 12/18	34915	2034
Carbolite 12/18	38795	2000
CarboHsp 12/18	42265	2750

Table A- 3 List of commercially available proppants designed to be used at a closure stress of 4000 psi with varying conductivity and permeability.

Proppant	Conductivity (md-ft)	Permeability (Darcy)
CRC E 40/70	599	34
CRC C 40/70	612	32
PCR P 40/70	648	44
Premium Hickory 40/70	661	37
PRC 40/70	720	39
Inno Prop CR 40/70	735	42
InterProp 35/140	735	47
Inno Prop PR 40/70	744	42
40/70 US Silica White	877	48
InterProp 40/80	1088	70
CRC-LT 30/50	1105	62
Sinistered Bauxite 40/80	1118	77
Premium Hickory 30/50	1151	65
Prop Raider 40/70	1157	84
CRC C 30/50	1206	71
CarboHydroProp	1210	60
CRC E 30/50	1272	70
BauxLite 40/80	1300	75
30/50 US Silica White	1323	71
Carboprop 40/70	1350	110

Prop Master 40/70	1380	87
Inno Prop CR 30/50	1381	74
CRC-LT 20/40	1384	78
Prop Light 40/70	1489	76
ReaLite 40/70	1534	74
PCR P 30/50	1576	86
Carbolite 40/70	1660	100
Imerys ProLite 40/70	1692	85
Fores MgLight 40/70	1713	97
CRC E 20/40	1728	96
Inno Prop PR 30/50	2211	119
Sinistered Bauxite 30/50	2220	150
Premium Hickory 20/40	2266	128
Inno Prop PR 20/40	2329	128
ReaLite 30/50	2350	113
BauxLite 30/50	2435	140
Carboprop 30/60	2440	150
InterProp 30/50	2525	160
Prop Master 30/50	2566	161
20/40 US Silica White	2685	150
CRC C 20/40	2747	128
CarboBond Lite 30/50	2755	145
Imerys ShaleProp 30/50	2774	137
Inno Prop CR 20/40	2791	152
Imerys ProLite 30/50	2816	158
Prop Light 30/50	2882	155
PRC 20/40	2894	159
Premium Hickory 16/30	2919	167
Fores MgLight 30/50	3032	172
Prop Raider 30/50	3092	225
CarboHsp 30/60	3235	225
PCR P 20/40	3297	189
CarboEconoprop 30/50	3300	180
Carbolite 30/50	3740	200
CRC C 16/30	4012	228
CRC-LT 16/30	4075	228
Imerys ProLite 20/40	4185	219
ForeRCP MgLight 20/40	4445	235

PCR P 16/30	4840	290
Imerys ShaleProp 20/40	5100	252
BauxLite 20/40	5285	300
Prop Raider 20/40	5492	399
CarboEconoprop 20/40	5500	300
Carboprop 20/40	5840	365
Sinistered Bauxite 20/40	5980	334
Prop Light 20/40	6443	345
Fores MgLight 20/40	6477	363
InterProp 20/40	6585	415
CarboHsp 20/40	6595	440
Ultra Prop	6640	469
BauxLite Plus 20/40	6710	375
Prop Master 20/40	6868	432
VersaProp	6930	428
CarboBond Lite 20/40	6960	385
VersaLite	7435	420
Carbolite 20/40	8900	480
Prop Raider 16/30	9687	696
Carboprop 16/30	10920	725
Prop Master 16/30	11607	700
Sinistered Bauxite 16/30	12210	833
CarboBond Lite 16/20	12855	690
InterProp 16/30	13100	815
BauxLite 16/30	13360	730
CarboHsp 16/30	14150	940
BauxLite Plus 16/20	15165	830
Carbolite 16/20	17780	955
Carboprop 12/18	22040	1400
CarboBond Lite 12/18	22315	1195
Carbolite 12/18	24560	1325
InterProp 12/18	25251	1530
BauxLite Plus 12/18	27145	1465
CarboHsp 12/18	36530	2395

Table A- 4 List of commercially available proppants designed to be used at a closure stress of 6000 psi with varying conductivity and permeability.

Proppant	Conductivity (md-ft)	Permeability (Darcy)
Premium Hickory 40/70	266	15
Inno Prop PR 40/70	469	27
CRC E 40/70	497	29
PCR P 40/70	516	34
CRC C 40/70	530	30
InterProp 35/140	539	35
Inno Prop CR 40/70	542	31
PRC 40/70	550	31
Premium Hickory 30/50	590	35
40/70 US Silica White	598	33
Premium Hickory 20/40	847	51
CarboHydroProp	890	50
30/50 US Silica White	903	51
InterProp 40/80	910	61
Sinistered Bauxite 40/80	947	67
CRC-LT 30/50	961	55
Prop Raider 40/70	966	72
Premium Hickory 16/30	1012	61
Carboprop 40/70	1015	80
CRC E 30/50	1021	61
CRC C 30/50	1028	64
Inno Prop PR 20/40	1048	60
BauxLite 40/80	1060	60
Inno Prop CR 30/50	1066	57
ReaLite 40/70	1085	54
Prop Master 40/70	1150	73
CRC-LT 20/40	1209	68
Fores MgLight 40/70	1214	71
PCR P 30/50	1220	73
Inno Prop PR 30/50	1256	70
Carbolite 40/70	1270	80
Prop Light 40/70	1292	67
Imerys ProLite 40/70	1315	67
ReaLite 30/50	1378	69

CRC E 20/40	1388	82
20/40 US Silica White	1484	86
Sinistered Bauxite 30/50	1875	130
BauxLite 30/50	1890	110
Imerys ShaleProp 30/50	1964	100
PRC 20/40	1969	110
Carboprop 30/60	2010	130
InterProp 30/50	2043	131
Prop Master 30/50	2080	134
Inno Prop CR 20/40	2105	118
Prop Light 30/50	2238	124
Imerys ProLite 30/50	2241	128
CRC C 20/40	2333	116
Prop Raider 30/50	2377	175
Fores MgLight 30/50	2408	140
CarboBond Lite 30/50	2415	130
CarboEconoprop 30/50	2550	140
Imerys ShaleProp 20/40	2591	135
PCR P 20/40	2610	148
ForeRCP MgLight 20/40	2771	153
CarboHsp 30/60	2790	195
Carbolite 30/50	2870	160
CRC-LT 16/30	2935	167
Imerys ProLite 20/40	3157	169
PCR P 16/30	3262	203
CRC C 16/30	3277	193
BauxLite 20/40	3955	230
CarboEconoprop 20/40	4100	230
Prop Light 20/40	4429	245
Prop Raider 20/40	4447	332
Fores MgLight 20/40	4744	270
Carboprop 20/40	4820	305
BauxLite Plus 20/40	4925	280
VersaProp	5027	322
Sinistered Bauxite 20/40	5030	299
VersaLite	5190	300
InterProp 20/40	5230	335
Prop Master 20/40	5323	343

CarboHsp 20/40	5370	370
Ultra Prop	5649	406
Carbolite 20/40	6000	340
CarboBond Lite 20/40	6025	340
Prop Raider 16/30	7145	523
Prop Master 16/30	7256	456
Carboprop 16/30	7940	545
InterProp 16/30	8950	580
Carbolite 16/20	9035	510
Sinistered Bauxite 16/30	9505	663
BauxLite 16/30	9555	540
Carbolite 12/18	9940	570
BauxLite Plus 16/20	10390	585
CarboHsp 16/30	10635	720
CarboBond Lite 16/20	10910	595
Carboprop 12/18	12260	820
BauxLite Plus 12/18	13350	755
InterProp 12/18	14137	902
CarboBond Lite 12/18	17640	950
CarboHsp 12/18	23460	1610

Table A- 5 List of commercially available proppants designed to be used at a closure stress of 8000 psi with varying conductivity and permeability.

Proppant	Conductivity (md-ft)	Permeability (Darcy)
Premium Hickory 40/70	95	5
Premium Hickory 30/50	247	16
Inno Prop PR 40/70	269	16
Premium Hickory 20/40	319	20
40/70 US Silica White	323	19
CRC E 40/70	351	21
Inno Prop CR 40/70	361	21
InterProp 35/140	361	25
PCR P 40/70	370	30
PRC 40/70	410	24
CRC C 40/70	418	26
Premium Hickory 16/30	445	28

30/50 US Silica White	474	28
Inno Prop PR 20/40	480	29
Inno Prop PR 30/50	531	30
ReaLite 40/70	583	30
CarboHydroProp	610	35
Inno Prop CR 30/50	620	34
CRC E 30/50	642	45
20/40 US Silica White	652	40
ReaLite 30/50	657	35
Inno Prop CR 20/40	724	41
InterProp 40/80	739	51
CRC-LT 30/50	748	43
Carboprop 40/70	770	65
Fores MgLight 40/70	772	46
Prop Raider 40/70	779	59
CRC C 30/50	787	55
Sinistered Bauxite 40/80	792	58
PCR P 30/50	825	50
Imerys ProLite 40/70	837	44
CRC E 20/40	844	58
BauxLite 40/80	845	50
Carbolite 40/70	870	60
Prop Light 40/70	889	48
CRC-LT 20/40	952	55
Prop Master 40/70	956	62
Imerys ShaleProp 30/50	1108	59
PRC 20/40	1168	67
ForeRCP MgLight 20/40	1303	76
Imerys ShaleProp 20/40	1419	77
BauxLite 30/50	1420	85
Sinistered Bauxite 30/50	1430	100
CRC C 20/40	1455	88
CRC-LT 16/30	1494	88
Imerys ProLite 30/50	1528	90
Prop Light 30/50	1562	90
Carboprop 30/60	1575	105
CarboEconoprop 30/50	1600	90
Prop Master 30/50	1611	106

PCR P 20/40	1657	94
InterProp 30/50	1721	113
PCR P 16/30	1809	126
Fores MgLight 30/50	1835	110
Carbolite 30/50	1900	110
CarboBond Lite 30/50	1910	100
Prop Raider 30/50	1931	146
Imerys ProLite 20/40	2026	113
CRC C 16/30	2259	143
Prop Light 20/40	2334	136
CarboHsp 30/60	2345	165
CarboEconoprop 20/40	2500	150
BauxLite 20/40	2670	160
Fores MgLight 20/40	2952	174
Prop Raider 20/40	3107	242
VersaProp	3292	220
BauxLite Plus 20/40	3340	200
VersaLite	3445	205
Prop Master 20/40	3478	232
Carboprop 20/40	3540	230
InterProp 20/40	3615	235
Carbolite 20/40	3700	210
Sinistered Bauxite 20/40	4140	240
Prop Master 16/30	4202	282
CarboHsp 20/40	4285	300
Prop Raider 16/30	4425	336
Ultra Prop	4552	331
CarboBond Lite 20/40	4580	260
Carboprop 16/30	4620	330
Carbolite 16/20	4625	275
Carbolite 12/18	4840	295
InterProp 16/30	5630	375
BauxLite 16/30	6070	360
BauxLite Plus 16/20	6495	390
Carboprop 12/18	6750	470
Sinistered Bauxite 16/30	7155	511
CarboBond Lite 16/20	7340	415
CarboHsp 16/30	7385	515

InterProp 12/18	7428	501
BauxLite Plus 12/18	7435	450
CarboBond Lite 12/18	9525	535
CarboHsp 12/18	12520	895

Table A- 6 List of commercially available proppants designed to be used at a closure stress of 10000 psi with varying conductivity and permeability.

Proppant	Conductivity (md-ft)	Permeability (Darcy)
Inno Prop PR 40/70	146	9
40/70 US Silica White	168	10
Inno Prop CR 40/70	187	11
Inno Prop PR 30/50	203	12
Inno Prop PR 20/40	223	14
30/50 US Silica White	231	14
CRC C 40/70	237	17
InterProp 35/140	242	17
Inno Prop CR 20/40	244	15
PCR P 40/70	244	21
PRC 40/70	250	16
ReaLite 40/70	285	16
20/40 US Silica White	321	20
Inno Prop CR 30/50	326	18
ReaLite 30/50	336	19
CarboHydroProp	360	20
CRC E 30/50	360	27
CRC E 20/40	384	32
PCR P 30/50	445	28
Imerys ProLite 40/70	448	24
CRC-LT 30/50	454	27
CRC C 30/50	459	37
Fores MgLight 40/70	470	29
Prop Light 40/70	486	28
Imerys ShaleProp 30/50	533	30
Carbolite 40/70	555	35
CRC-LT 20/40	566	33
Prop Raider 40/70	566	44

Carboprop 40/70	570	50
InterProp 40/80	593	42
Sinistered Bauxite 40/80	642	48
PRC 20/40	655	39
CRC C 20/40	662	46
Imerys ShaleProp 20/40	665	38
ForeRCP MgLight 20/40	665	41
BauxLite 40/80	700	40
Prop Master 40/70	765	52
CRC-LT 16/30	803	49
Prop Light 30/50	826	51
PCR P 16/30	884	74
PCR P 20/40	893	49
CRC C 16/30	914	71
Prop Master 30/50	926	64
Imerys ProLite 30/50	939	57
CarboEconoprop 30/50	975	65
Carboprop 30/60	990	70
BauxLite 30/50	995	60
Sinistered Bauxite 30/50	1100	80
Fores MgLight 30/50	1160	73
Imerys ProLite 20/40	1184	69
Prop Light 20/40	1249	77
Carbolite 30/50	1270	75
InterProp 30/50	1299	88
CarboEconoprop 20/40	1300	85
Prop Raider 30/50	1441	115
CarboBond Lite 30/50	1445	80
Fores MgLight 20/40	1683	103
BauxLite 20/40	1750	105
CarboHsp 30/60	1850	135
Carbolite 20/40	2000	120
VersaLite	2155	135
Carbolite 12/18	2235	140
VersaProp	2238	158
Prop Master 20/40	2250	159
BauxLite Plus 20/40	2270	140
Prop Master 16/30	2345	167

Prop Raider 20/40	2358	195
InterProp 20/40	2375	160
Carbolite 16/20	2400	150
Carboprop 20/40	2400	160
Sinistered Bauxite 20/40	2800	178
Carboprop 16/30	2930	215
Prop Raider 16/30	3080	246
InterProp 16/30	3180	220
KryptoSphereHD 25 Mesh	3400	245
CarboHsp 20/40	3405	245
Ultra Prop	3469	260
CarboBond Lite 20/40	3580	205
Carboprop 12/18	3810	280
BauxLite 16/30	4140	255
InterProp 12/18	4222	300
BauxLite Plus 16/20	4260	265
BauxLite Plus 12/18	4395	285
KryptoSphereHD 20 Mesh	4500	315
CarboBond Lite 16/20	4870	290
Sinistered Bauxite 16/30	4875	361
CarboHsp 12/18	5380	410
CarboHsp 16/30	5430	395
CarboBond Lite 12/18	6310	370

Table A- 7 List of commercially available proppants designed to be used at a closure stress of 12000 psi with varying conductivity and permeability.

Proppant	Conductivity (md-ft)	Permeability (Darcy)
Inno Prop PR 30/50	88	5
40/70 US Silica White	107	7
30/50 US Silica White	125	8
InterProp 35/140	153	11
20/40 US Silica White	163	11
CRC E 30/50	210	18
CRC E 20/40	213	20
CRC-LT 30/50	239	15
Imerys ProLite 40/70	246	14

CRC C 30/50	260	22
CRC-LT 20/40	296	18
Carbolite 40/70	340	25
Prop Raider 40/70	398	34
CRC-LT 16/30	400	25
InterProp 40/80	416	31
Carboprop 40/70	440	40
Sinistered Bauxite 40/80	501	40
BauxLite 40/80	525	30
Prop Light 30/50	527	34
CRC C 16/30	534	41
Prop Master 30/50	634	47
Imerys ProLite 30/50	649	41
Carbolite 30/50	650	40
Carboprop 30/60	665	50
BauxLite 30/50	695	45
Prop Light 20/40	741	48
Imerys ProLite 20/40	767	43
Sinistered Bauxite 30/50	845	65
Prop Raider 30/50	896	77
CarboBond Lite 30/50	965	55
InterProp 30/50	994	69
BauxLite 20/40	1165	75
CarboHsp 30/60	1335	100
VersaLite	1365	90
Prop Raider 20/40	1373	124
VersaProp	1397	104
BauxLite Plus 20/40	1410	90
Prop Master 20/40	1435	107
InterProp 20/40	1720	110
Carboprop 20/40	1900	130
Sinistered Bauxite 20/40	2030	132
Prop Raider 16/30	2086	184
Carboprop 16/30	2120	155
InterProp 16/30	2260	150
Carboprop 12/18	2270	175
Ultra Prop	2348	185
CarboBond Lite 20/40	2605	155

InterProp 12/18	2621	195
CarboHsp 20/40	2720	205
BauxLite Plus 16/20	2815	190
KryptoSphereHD 25 Mesh	2900	215
BauxLite Plus 12/18	2975	200
BauxLite 16/30	3005	195
CarboBond Lite 16/20	3270	205
Sinistered Bauxite 16/30	3515	265
KryptoSphereHD 20 Mesh	3600	260
CarboHsp 12/18	3600	285
CarboBond Lite 12/18	3655	225
CarboHsp 16/30	3975	300

Table A- 8 List of commercially available proppants designed to be used at a closure stress of 14000 psi with varying conductivity and permeability.

Proppant	**Conductivity (md-ft)**	**Permeability (Darcy)**
InterProp 35/140	105	8
InterProp 40/80	302	24
Prop Raider 40/70	315	29
CRC C 16/30	332	23
Sinistered Bauxite 40/80	379	32
Sinistered Bauxite 30/50	615	50
Prop Raider 30/50	659	62
CarboHsp 30/60	925	75
Prop Raider 20/40	1097	107
Prop Raider 16/30	1321	126
Sinistered Bauxite 20/40	1595	130
Ultra Prop	1727	146
CarboBond Lite 20/40	1825	110
CarboHsp 20/40	2140	165
CarboHsp 12/18	2325	195
Sinistered Bauxite 16/30	2470	195
KryptoSphereHD 25 Mesh	2475	185
KryptoSphereHD 20 Mesh	2875	215
CarboHsp 16/30	2975	230

Table A- 9 List of commercially available proppants designed to be used at a closure stress of 16000 psi with varying conductivity and permeability.

Proppant	Conductivity	Permeability
KryptoSphereHD 25 Mesh	2050	155
KryptoSphereHD 20 Mesh	2300	175

Table A- 10 List of commercially available proppants designed to be used at a closure stress of 18000 psi with varying conductivity and permeability.

Proppant	Conductivity	Permeability
KryptoSphereHD 25 Mesh	1650	130
KryptoSphereHD 20 Mesh	1800	140

Appendix B

Data to calculate health-related costs for a hydraulic fracturing crew

Table B- 1 Estimated number of hydraulic fracturing establishments.

Employee Size Category	Estimated Number of Entities in Hydraulic Fracturing	Estimated No. of Establishments per Entity	Total Establishments
10 - 19	100	1.00	100
20 - 99	50	1.20	60
100 - 499	46	4.00	184
>500	4	25.00	100
TOTAL	200		444

Table B- 2 Number of hydraulic fracturing workers exposed to silica level greater than 50 μg/m^3.

Category	Number of affected employees	Numbers of affected workers exposed to silica level greater than 50 μg/m^3	Percentage of affected workers exposed to silica level greater than 50 μg/m^3
Support Activities for Oil and Gas Operations	16960	11964	70.54
Hydraulic Fracturing Workers			
Sand Mover Operators	5300	4828	91.09
Conveyor Belt Tenders	1060	1060	100.00
Blender Tenders	2120	1836	86.60
Ancillary Workers			
Hydration unit operator	1060	530	50.00
Water/chemical hands	2120	1060	50.00
Pump operator technicians	3180	1060	33.33
Supervisor	1060	530	50.00
Sand coordinator	1060	530	50.00
Remote/Intermittent Support Workers	8480	4893	57.70
TOTAL	25440	16327	64.18

Table B- 3 Distribution of typical hydraulic fracking crew by function and number of workers exposed to silica level greater than 50 μg/m^3.

Estimated Number of Workers per site	Percent of Total	Classification by Function	Numbers of Affected Workers Exposed to Silica level greater than 50 μg/m^3
5	31.25	Fracturing Sand Worker in Central Area	4.55
1	6.25	Fracturing Sand Worker in Central Area	1.00
2	12.5	Fracturing Sand Worker in Central Area	1.73
1	6.25	Ancillary Support Worker	0.50
2	12.5	Ancillary Support Worker	1.00
3	18.75	Ancillary Support Worker	1.00
1	6.25	Remote/ Intermittent Worker	0.50
1	6.25	Remote/ Intermittent Worker	0.50
16	100		10.79

Table B- 4 Consumer Price Index-All Urban Consumers for Medical Care in the USA.

Year	Annual
2009	3.2
2010	3.4
2011	3.0
2012	3.7
2013	2.5
2014	2.4