

**HEALTH, SAFETY AND ENVIRONMENTAL STUDY OF
GLASS BUBBLE APPLICATION IN DRILLING AND
COMPLETION FLUIDS**

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**FACULTY OF ENGINEERING
UNIVERSITY OF MALAYA
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**HEALTH, SAFETY AND ENVIRONMENTAL STUDY
OF GLASS BUBBLE APPLICATION IN DRILLING AND
COMPLETION FLUIDS**

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**RESEARCH REPORT SUBMITTED TO
THE FACULTY OF ENGINEERING
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HEALTH, SAFETY AND ENVIRONMENTAL STUDY OF GLASS BUBBLE APPLICATION IN DRILLING AND COMPLETION FLUIDS

ABSTRACT

Lightweight drilling and completion fluids are widely used for near-balanced, balanced or under-balanced drilling to reduce loss of fluids which can cause serious problems. They are also used to protect the reservoirs during the drilling process. As a newly introduced technology, glass bubbles, also known as Hollow Glass Spheres (HGS), are now being used to obtain lightweight fluids instead of other technologies such as air/dust drilling, as they are more environmentally friendly and low-cost. The health, safety, and environmental impacts of the application of glass bubbles in drilling and completion fluids have been previously reviewed and studied. By doing literature review and analyzing the process of their application, two health, safety, and environmental risks were found: lung disease attributable to inhalation of glass bubble dust and physical injury resulting from direct contact with glass bubbles. To avoid such risks, several suggested measures have been proposed. Moreover, the environmental impact of the application of glass bubbles in drilling and completion fluids is quite unobvious, and so there is an opportunity and reason to conduct further investigation and research on this subject matter.

Keywords: Safety; Health; Environment; Glass Bubble; Drilling and Completion Fluid.

**KAJIAN KESIHATAN, KESELAMATAN DAN ALAM SEKITAR MENGENAI
PENGUNAAN GELEMBUNG KACA DALAM CECAIR PENGGERUDIAN
DAN PENYELESAIAN**

ABSTRAK

Cecair penggerudian dan penyelesaian yang ringan amat biasa digunakan untuk aktiviti penggerudian secara hampir-seimbang, seimbang atau kurang-seimbang, supaya dapat mengurangkan situasi kehilangan cecair yang boleh menyebabkan masalah yang lebih serius. Cecair ringan ini juga digunakan untuk melindungi takungan-takungan semasa aktiviti penggerudian dijalankan. Selain daripada teknologi-teknologi lain seperti penggerudian udara-debu, *Hollow Glass Spheres* (HGS), merupakan sejenis gelembung kaca yang baru dikemukakan untuk dijadikan cecair ringan, boleh digunakan sebagai cara alternatif disebabkan oleh sifat mesra alam dan kosnya yang rendah. Kesan penggunaan gelembung kaca dalam cecair penggerudian dan penyelesaian dari segi kesihatan, keselamatan dan alam sekitar telah diulas dan dikaji sebelum ini. Melalui kajian kesusasteraan dan proses analisis, sebanyak dua risiko dari segi kesihatan, keselamatan dan alam sekitar telah didapati, iaitu penyakit paru-paru disebabkan penyedutan debu daripada gelembung kaca, dan juga kecederaan fizikal daripada sentuhan terus dengan gelembung kaca. Untuk mengelakkan risiko-risiko tersebut, beberapa langkah-langkah telah dicadangkan. Selain itu, kesan dari aspek alam sekitar dalam aplikasi gelembung kaca dalam cecair penggerudian dan penyelesaian amat tidak ketara. Oleh itu, kajian yang lebih dalam perlu dijalankan mengenai kesan tersebut.

Kata-kata kunci: Keselamatan; Kesihatan; Alam Sekitar; Gelembung Kaca; Cecair Penggerudian dan Penyelesaian.

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CHAPTER 1: INTRODUCTION

Under-balance drilling (UBD) and near-balance drilling (NBD) techniques mainly using lightweight drilling and completion fluids are drawing more and more attention in drilling projects all over the world comparing with other conventional drilling techniques like over-balance drilling (OBD). In the UBD or NBD techniques, the lightweight drilling and completion fluids generate nearly equal or less pressure in the downhole than the pressure in the formation (Alawami, Al-Yami, Wagle, Alhareth, & Aramco, 2015). There are many benefits associated with using these techniques in drilling and completion projects such as reducing fluid loss, well-hole cleaning, increasing the well's output, protecting weak formation, and helping avoid down hole problems while drilling (Medley, Maurer, & Garkasi, 1995).

The conventional methods followed in preparation of lightweight fluids involve mixing air or dust into water-based or oil-based fluids. These conventional methods are costly and present added risk because of the technology and equipment used and the environmental threats they pose (Khodja, Khodja-Saber, Canselier, Cohaut, & Bergaya, 2010). In addition, maintenance works and safety of the machine operators are both compromised because of the high pressure and the complexity of the equipment (Mokhalalati, Reiley, & Neidhardt, 1996).

Glass bubbles, also known as Hollow Glass Spheres (HGS), are micro hollow glass balls that are usually made with soda-lime borosilicate glass. This is because borosilicate glass exhibits remarkable tolerance for sudden temperature changes. It can also inhibit the expansion of material due to the stresses experienced as a result of changes in temperature (AlBahrani, Al-Yami, & Amanullah, 2017). The main component of hollow glass spheres is SiO_2 , which makes up 50% to 57% of the glass bubble, and several other substances (Block, Lau, & Rice, 1991) (Kenneth E. Goetz,

James A. agarman, & Joseph P. Giovene, 1991). Glass bubbles are widely used to make self-propelled plastisol, syntactic foam buoyancy units, and other aerospace equipment (Arco, et al., 2000). In the petroleum industry, the chemical stability and high strength-to-weight ratio of glass bubbles make them one of the best density-reducing agents for lightweight fluids used in the drilling and completion processes.

However, compared with other agents, the health, safety and environmental impacts related to the application of glass bubbles into drilling and completion fluids are not fully studied yet. During the application process, glass bubbles are released into the environment as dust and somehow come into contact with the operators. Will the application of glass bubbles result in any health, safety and environmental hazards? To answer this question, a risk assessment was carried out when doing this research to generally identify the health, safety and environmental issues related to glass bubbles application into drilling and completion fluids, and control measures that can help to reduce these risks.

The main objective of this research is to generate a comprehensive report on the health, safety and environmental risks that result from the application of glass bubbles into drilling and completion fluids. This objective can be divided further into the following sub-objectives:

- i. To outline the main procedure of glass bubbles' application in drilling and completion fluids;
- ii. To identify the main health, safety and environmental risks;
- iii. To analyze the impairments caused by the hazards;
- iv. To suggest control measures to reduce the risks.

CHAPTER 2: LITERATURE REVIEW

Glass bubbles are micro Hollow Glass Spheres (HGS) that exhibit high strength-to-weight ratios and impressive chemical stability even in extreme environments. Thus, glass bubbles can be used as density-reducing agents in drilling and completion fluids in the drilling industry (Mata, 2011). To fully comprehend how they work as density-reducing agents, a good understanding of the properties of glass bubbles is necessary.

Table 2.1: Series of 3M™ Glass Bubbles (3M™, 2009)

Products	Typical True Density (g/cm ³)	90% Crush Strength (psi)	Particle Size (D50 μm)
HGS2000	0.32	2000	40
HGS3000	0.35	3000	40
HGS4000	0.38	4000	40
HGS5000	0.38	5500	40
HGS6000	0.46	6000	40
HGS8000X	0.42	8000	26
HGS10000	0.60	10000	30
HGS18000	0.60	18000	30

The main component of glass bubbles is soda-lime borosilicate glass. Glass bubbles are categorized into different series based on their density, crush strength and median diameter value (D_{50}), as shown in Table 2.1 (3M™, 2007). During the application process of glass bubbles, different series of glass bubbles are used depending on the situation, target density, cost and technique requirements. The other component of glass bubbles is synthetic amorphous crystalline-free silica, which is a by-product of the production process of glass bubbles (3M™, 2016). It can be found in the package of the glass bubbles.

Since the main component of glass bubbles is soda-lime borosilicate glass, their chemical properties are similar to those of soda-lime borosilicate glass. The chemical

composition of soda-lime borosilicate glass is as follows: SiO_2 (50% to 57%); R_2O (alkali metal oxides)(2% to 15%); B_2O_3 (0% to 20%); S (0.05% to 1.5%); RO (2% to 25%); RO_2 (other than SiO_2)(0% to 5%); R_2O_3 (other than B_2O_3) (0% to 10%); R_2O_5 (0% to 5%); and F(0% to 5%) (Kenneth E. Goetz, James A. agarman, & Joseph P. Giovene, 1991).

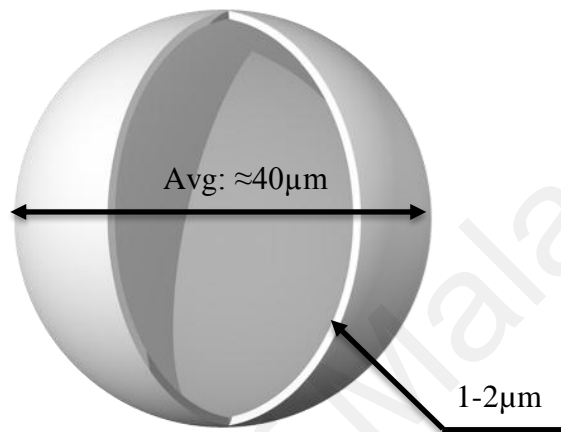


Figure 2.1: A Glass Bubble (3M™, 2007)

Glass bubbles are odorless and look like a white, dry powder to the naked eye. Their density ranges from 0.32g/cm^3 to 0.60 g/cm^3 depending on the type of series. In micro view, a glass bubble is a hollow glass sphere with an average diameter of $40\mu\text{m}$. The thickness of its wall is about $1\mu\text{m}$ to $2\mu\text{m}$ as shown in Figure 2.1 above (3M™, 2007).

When glass bubbles are mixed with deionized water at a volume of 5%, the pH of the slurry is about 9.1 to 9.9. When exposed to temperature of 600°C , glass bubbles start to soften. Their crush pressure ranges from 2000 psi to 18000 psi depending on the type of series (3M™, 2009). They are highly resistant to rapid temperature changes and pressure, which makes them good density-reducing agents in drilling and completing fluids because of the high temperatures and pressure present in a down hole environment.

In the petroleum industry, drilling and completion fluids are what blood is to the human body. The density of the drilling and completion fluids is one of the most important parameters in this drilling. Here are the benefits of reducing fluid density. The first benefit of low-density fluids is that when drilling and completing an interval that has low fracture pressure, the fluids can prevent the formation from fracturing and causing cyclic losses during the drilling and completion processes. The second benefit is that lightweight fluids can help reduce the damage brought about by fluid pressure on the formation. Drilling processes such as under-balanced drilling, pilot-controlled drilling and double-gradient drilling, all try to achieve these objectives. The third benefit is that lightweight fluids provide the perfect fluid density required when drilling and completing a depleted formation where formation pressure is lower than hydrostatic pressure, which is the pressure generated by a column of water at the same depth (AlBahrani, Al-Yami, & Amanullah, 2017).

There are the conventional measures taken to obtain lightweight drilling and completion fluids are: adding dust or air into these fluids; or using oil-based drilling fluids with a lower density rather than using water-based fluids. However, using oil-based drilling fluids inflates the cost and also raises environmental concerns. Similarly, dust or air drilling fluids require specific equipment and techniques which makes costs to go up.

Therefore, the use of glass bubbles as density-reducing agents is a welcome idea especially when you consider their remarkable chemical and physical characteristics. Glass bubbles have already been successfully used in many different cases over the years. The first cases of their application were in the mid-1990s in Colombia, Venezuela and Brazil (3M™, 2007). Since then, many more cases have been carried out successfully (Mata, 2011).

One case was in a well drilled in the Montney formation in northwest Alberta, Canada, glass bubbles were applied in drilling fluid in a horizontal pattern during the drilling process. The Montney formation is a sedimentary wedge formed during the earliest Triassic period that contains shale, fine-grained sandstones and siltstones (Teichrob, et al., 2012). The components of the Montney formation are mostly quartz and dolomite, which exhibit low fracture pressure and can be easily broken by hydraulic fracturing. This unstable wellbore presented high risks during the drilling process. The wellbore became even more unstable as the drilling continued. Therefore, improvements on the rate of penetration (ROP) were necessary to reduce costs. Using lightweight glass bubble-based drilling fluids is an effective way of increasing the ROP at the horizontal section, and this at a reasonable cost.

A volume of 9 to 11% HGS8000X from 3M™ was thus added into an oil-based drilling fluid. The challenge in this case was how the suspension of glass bubbles would perform during the drilling process and in storage, with such low viscosity. It was observed that the glass bubbles suspended well without any issues arising while drilling the horizontal section. And after being stored for four days without being touched, the glass bubbles regained suspension after they were put back into circulation to be reused in another well.

In another case, three wells with a 6-inch horizontal section were drilled by a Gunung Kembang drilling company in Indonesia (Pratama, Rachman, Martin, & Purwanto, 2010). Drilling in two of the wells failed due to the total circulation loss experienced during the drilling process. There are two main factors that caused the circulation loss: low pressure in the depleted formation and the presence of natural fractures. The pressure in the depleted formation was a mere 6.8 lbf/gal, which presented a very narrow margin for range of the over-balance fluid density.

Additionally, since the drilling fluid is oil-based, diesel-oil supply after the circulation loss occurred was not sufficient.

Lightweight water-based fluids were therefore the solution to drilling the horizontal section in this formation. To meet the required density of the drilling fluid, glass bubbles were added to a water-based fluid and drilling continued. To minimize the reoccurrence of circulation loss, the fluid formulation had a density of 6.9-7.1 lbm/gal, which is slightly higher than that of the formation pressure (6.8 lbm/gal). By using a water-based drilling fluid, the team not only reduced the environmental impact but also solved the fluid supply problem. After undergoing several laboratory tests, the water-based drilling fluid exhibited a 15% reduction in permeability. Using a water-based drilling fluid that had glass bubbles added to it as density-reducing agents offered a better solution for the Gunung Kembang drilling company because of its low costs and less-environmental impairment.

In yet another case, lightweight completion fluid combined with 3M's Glass Bubbles was successfully applied in Well BKC-18, which is in Block PM-3, where reservoir pressure is approximately 2200 psi (Jan, Rae, Noor, Suhadi, & Devadaas, 2009). During the perforation process, if normal completion fluids were used, an over-balanced pressure of approximately 246 psi could have been produced. This over-balanced pressure would push the completion fluids into the format which would cause formation damage due to the block of the porosity of reservoir rock by the solids in the fluids. Over-balanced pressure also would cause circulation loss or other downhole failures. But with the application of the lightweight completion fluid, which was approximately 5.5 lbm/gal, an under-balanced condition of approximately 177 psi was achieved. The lightweight completion fluid was pumped with a 2-bbl head and tail of Sarapar oil at a rate of 0.5 to 1.0 bbl/min. The application of the lightweight completion fluid in Well

BKC-18 did not raise any issues, because of the experiences and the solutions of general issues that already experienced in the two previous test wells. The subsequent pressure buildup revealed that BKC-18 had a skin of only 1, indicating the well was undamaged.

During the literature review, several advantages of the application of glass bubbles into drilling and completion fluids were observed:

i. They can greatly help to save on costs in terms of equipment, techniques and staff training. There is no need to purchase special surface high-pressure equipment to prepare lightweight drilling and completion fluids unlike when using other fluids like air or dust drilling fluids or foam cement slurry. Due to their chemical and physical characteristics, the preparation process of glass bubbles is easy to master by using standard drilling and completion fluids preparation and treatment equipment.

ii. Drilling and completion fluids formulated with glass bubbles have been proved to be highly resistant to high pressure and temperature, which is attributed to their chemical and physical properties. There are many cases where glass bubbles were successfully applied as density-reducing agents in drilling and completion fluids. The range of density that glass bubbles can provide is highly suitable for many kinds of drilling and completion. Additional benefits have also been observed during the drilling and completion processes such as reducing pressure fluctuations, friction, and permeation of drilling fluids, and avoid format damage due to over-balanced pressure.

iii. Compared with other kinds of formulations like oil-based fluids, lightweight glass bubble-based drilling and completion fluids are more environmentally friendly. It also costs less energy to maintain the density of the glass bubbles and they can possibly be recycled after use. Although glass bubbles are relatively costly, their ability to be

recycled and re-used after minimal separation work makes the total cost of glass bubble-based mud favorable compared to that of a barite-based mud.

However, there is no health, safety and environment related research about the application of glass bubbles in drilling and completion fluids yet.

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CHAPTER 3: METHODOLOGY

The methodology used for this health, safety and environment study is similar to the methodology used in conducting the risk assessment. It involves four main steps as follows (Wells, 1997):

- i. Identify the hazards;
- ii. Identify who and how the hazards will affect;
- iii. Evaluate the risks arising from the hazards;
- iv. Record the findings.

By applying this methodology in the application processes of glass bubbles into drilling and completion fluids, the main health, safety and environment issues that were found are explained in following paragraphs.

3.1 Drilling Fluids

The first step in the application of glass bubbles into drilling fluids is dispensing the glass bubbles into the base fluids. This is done using gravity feed (Figure 3.1) or a diaphragm pump (Figure 3.2) to avoid caking and bridging of glass bubbles in the fluids (3M™, 2012).

During the application process, there is a possibility of having glass bubbles dust and crystalline-free silica dust released into the air. Over exposure to silica dust is thought to cause silicosis (Normohammadi, Kakooei, Omid, Yari, & Alimi, 2016) which is defined as nodular lesions that may be followed by progressive massive fibrosis in lungs (Yucesoy, et al., 2001). It is one of the major industrial causes of lung disease. Coming into direct contact with glass bubbles can possibly happen during the application process, which may cause mechanical skin irritation or eye irritation. Possible

symptoms include abrasion, redness, skin pain or itchy skin, and redness, tearing or corneal abrasion of the eyes (3M™, 2016).

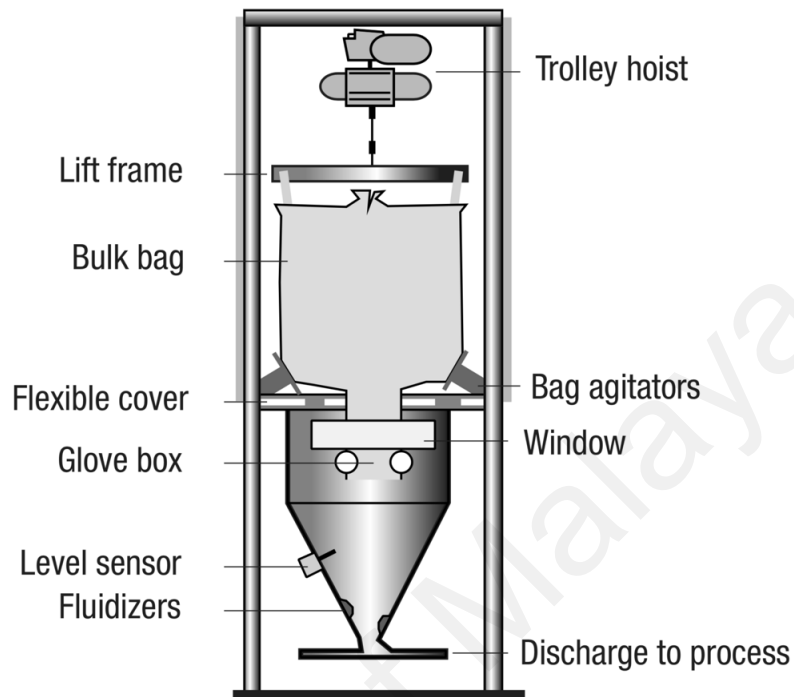


Figure 3.1: Glass Bubble Transfer via Direct Gravity Feed (3M™, 2012)

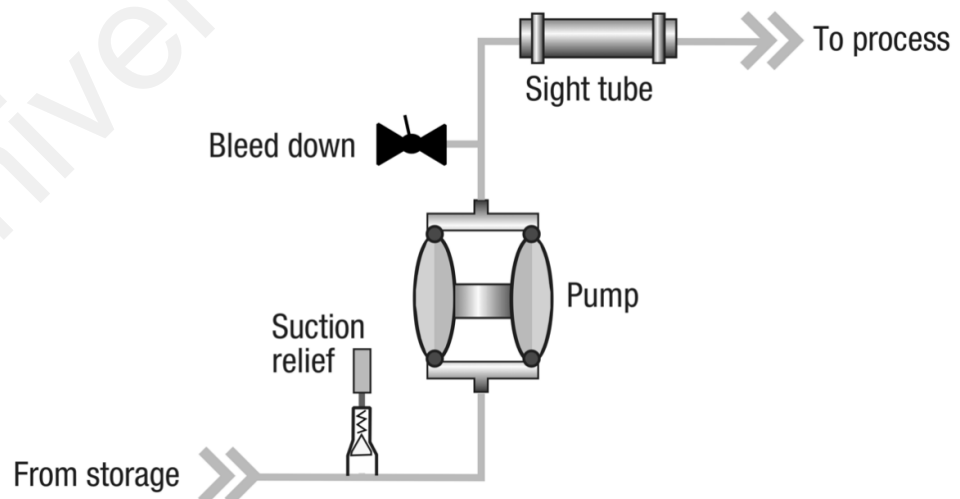


Figure 3.2: Glass Bubble Transfer via Double Diaphragm Pump (3M™, 2012)

The second step of the application process is pumping the glass bubble-based drilling fluids into the wells to kick off circulation. A simple illustration of the circulation of drilling fluids is shown in Figure 3.2 above. When the fluids are flowing into the borehole, some will permeate into the formation through the formation pores. Because of their extreme chemical and physical stability, glass bubbles can remain in the groundwater for a long time and then be transferred to other water bodies through the normal water cycle. Thus, this situation may come to affect both human health and the environment when they reach surface waters (through rain) and underground waters (Khodja, Khodja-Saber, Canselier, Cohaut, & Bergaya, 2010).

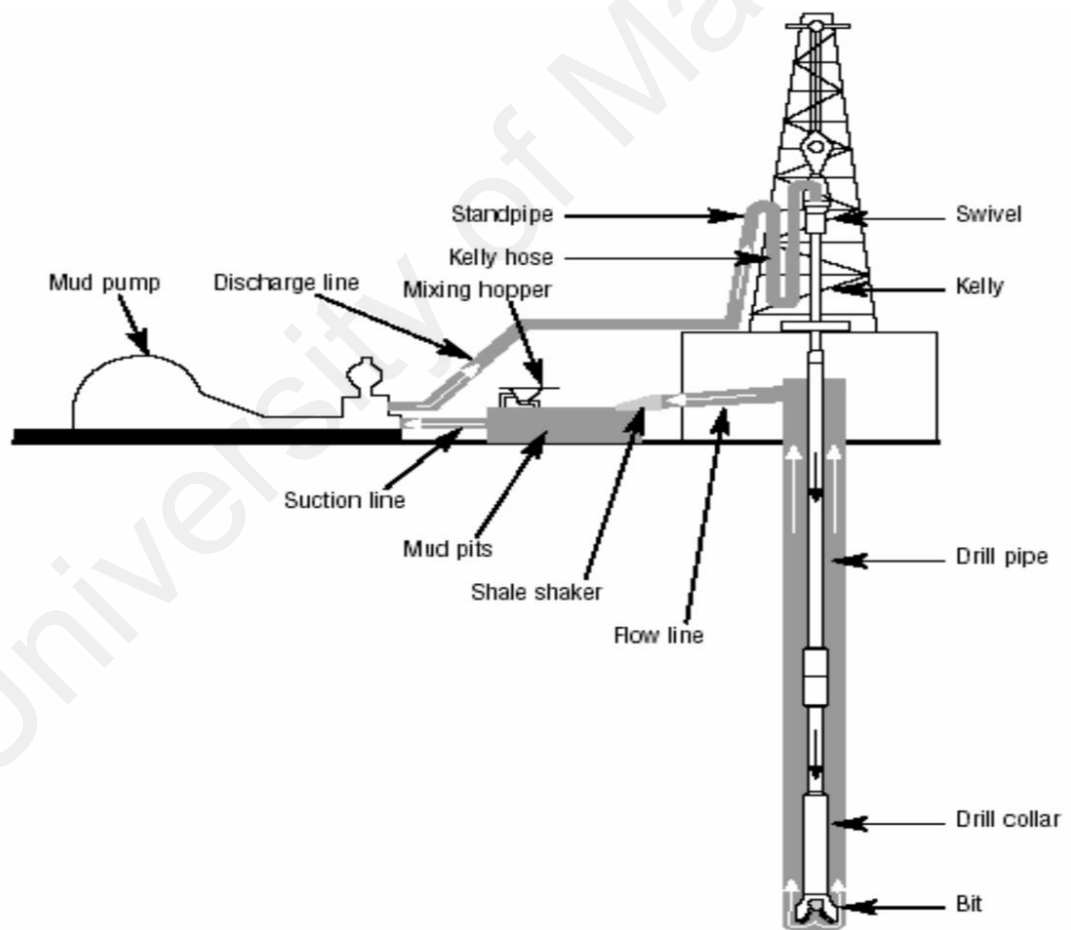


Figure 3.3: Diagram of the Circulation of Drilling Fluids

During the fluid circulation process, continuous mixing of the fluids using mixers in the fluid tanks is needed to ensure the distribution of glass bubbles in the fluids is homogeneous. It is also important to note that when doing this, the shear mixer will possibly cause the breakage of the glass bubbles (3M™, 2012).

To control the solid content in the fluids, shale shakers, hydrocyclones (desander and desilter) and centrifuges are used. During this operation, drilled solid (cuttings) together with some glass bubbles are separated from the fluids, although the separation of glass bubbles is not intentional. The glass bubbles that are present in the solid waste can also find their way into the environment the same way the other glass bubbles escaped into the groundwater as mentioned above.

The final step is the treatment of the glass bubble-based fluids after use. Currently, the treatment of used drilling fluids involves physical, chemical and biological processes. There are a number of methods that are used in managing the used fluids (Argonne National Laboratory, 2004), including: waste minimization, recycle/reuse, and other miscellaneous drilling waste management methods. No matter what kind of treatment method is used, glass bubbles will remain in the fluids as solid waste due to the chemical and physical stability of the borosilicate glass in their composition.

3.2 Completion Fluids

Completion involves a series of activities that are done to make sure oil wells are ready for production after the drilling process. During the completion process, completion fluids will be pumped into the well to facilitate final operations prior to initiation of production. These operations may include setting up of screens, packers, production liners, downhole valves or shooting perforations into the formation. The completion fluid is the key to protecting oil wells from downhole problems, without damaging the production formation or completion components (Schlumberger, 2017).

Similar to the steps followed in the application of glass bubbles into drilling fluids, the first step in the completion process is dispensing glass bubbles into the base fluids. When this is being done, glass bubbles and crystalline-free silica dust can possibly be generated which is hazardous to the operators' lung. And glass bubbles also will come into contact with the operators' eyes and skin causing eyes and skin injury.

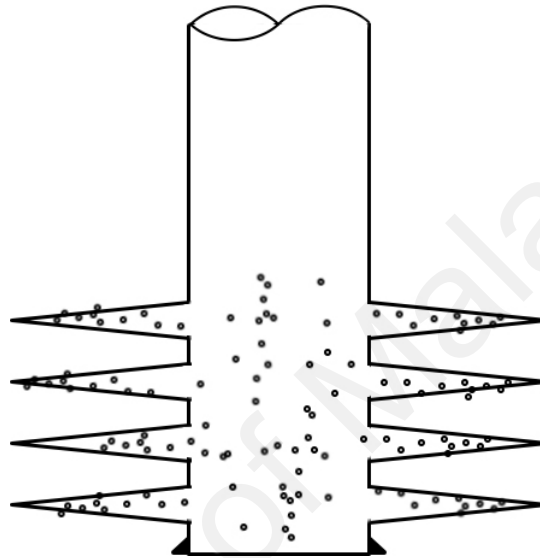


Figure 3.4: Glass Bubbles in Well after Shooting Perforations

Following the first step, completion fluids are then pumped into the well to maintain stable downhole environment by the pressure of the completion fluids to the formation for further completion operations. While the completion processes proceeding, the completion fluids will stay still in the well for a period and go into the formation due to over-balanced pressure, diffusion, and completion operations. Especially during the shooting perforations, glass bubbles will directly go into the formation with completion fluids through the opening of the formation and remain in it as shown in Figure 3.4. These glass bubbles in the formation will be migrated by the underground water along the normal water cycle into the environment as mentioned above in the drilling process.

CHAPTER 4: RESULTS

Throughout the application process of glass bubbles into drilling and completion fluids, there are several health, safety and environmental hazards that may be experienced. These are:

4.1 Glass Bubble Dust

According to the "Glossary of Atmospheric Chemistry Terms" (IUPAC, 1990), "Dust: Small, dry, solid particles projected into the air by natural forces, such as wind, volcanic eruption, and by mechanical or man-made processes such as crushing, grinding, milling, drilling, demolition, shoveling, conveying, screening, bagging, and sweeping. Dust particles are usually in the size range from about 1 to 100 μm in diameter, and they settle slowly under the influence of gravity."

When dispensing glass bubbles into the base drilling and completion fluids, airborne mineral dust may escape. According to the SDS of the glass bubbles provided by 3M™ (3M™, 2016), the ingredients in the packaging are Soda Lime Borosilicate glass and Synthetic Amorphous Crystalline-Free Silica. Soda Lime Borosilicate glass is the major composition of the glass bubbles, while Synthetic Amorphous Crystalline-Free Silica is a by-product of their preparation process and is only about 0-3% of the composition. So, it's almost obvious that there will be silica dust within the work environment. Over exposure to silica dust can lead to serious lung disease such as silicosis or lung cancer.

When operators inhale silica dust, the particles will remain in their heads or lungs for long depending on the size of the particles. These particles have the potential to cause serious harm to either local or other parts of the body. The longer they remain in the body, the more apt they are to cause a heavier damage.

Terminal velocity and aerodynamic diameter are two important parameters of dust. These two parameters decide how long the silica dust will remain in the air and which part of human body the dust will be deposited on.

4.1.1 Terminal Velocity

After the glass bubble dust escapes into the air, it will be deposited on the ground afterwards, due to gravity. At first, the speed of the deposition will increase from zero to terminal velocity. After reaching the terminal velocity, ignoring the effect of the movement of air and other human factors, the glass bubbles will be deposited on the ground at the same terminal velocity.

The formula of terminal velocity is as follow (MediaWiki, 2018):

$$v_t = \sqrt{\frac{2mg}{\rho AC}}$$

v_t = terminal velocity

m = mass of the falling object.

g = the acceleration due to gravity.

ρ = the density of the fluid the object is falling through.

A = the projected area of the object.

C = the drag coefficient.

In this research, the object is the glass bubble. So, the parameters are:

$$m = \rho_p V = \rho_p \cdot \frac{4}{3} \pi \left(\frac{d_p}{2} \right)^3$$

$$A = \frac{1}{4} \cdot \pi d_p^2$$

ρ_p = the density of the glass bubbles.

d_p = the diameter of the glass bubbles.

When the parameters are put into the formula for terminal velocity, the equation becomes:

$$v_t = 2 \sqrt{\frac{\rho_p d_p g}{3\rho C}}$$

The drag coefficient for a sphere is 0.5, the density of air is 1.29kg/m^3 , the acceleration due to gravity on earth is 9.8m/s^2 . After calculations, the terminal velocities of different series of glass bubble dust are as highlighted in Table 4.1 below:

Table 4.1: Terminal Velocity of Different Series Glass Bubbles

Products	Density (g/cc)	Diameter (μm)	Terminal velocity (m/s)
HGS2000	0.32	40	0.00051
HGS3000	0.35	40	0.00053
HGS4000	0.38	40	0.00055
HGS5000	0.38	40	0.00055
HGS6000	0.46	40	0.00061
HGS8000X	0.42	26	0.00047
HGS10000	0.6	30	0.00060
HGS18000	0.6	30	0.00060

As shown in the table, the average terminal velocity of the glass bubbles when moving in the air is 0.00056m/s . This implies that it will take an average of 30 minutes for a glass bubble to hit the ground from a height of 1 meter, when the air is totally stable. If the glass bubbles were blown into the air, it will take a long time before they finally settle on the ground.

4.1.2 Aerodynamic Diameter

The aerodynamic diameter of an irregular particle is defined as the diameter of a spherical particle with a density of 1000 kg/m³ and the same settling velocity as the irregular particle (Hinds, 1999). So, if we take this formula:

$$v_t = 2 \sqrt{\frac{\rho_p d_p g}{3\rho C}} = 2 \sqrt{\frac{\rho_a d_a g}{3\rho C}}$$

ρ_a = the standard particle density (1000 kg/m³).

d_a = the aerodynamic diameter of glass bubbles

And transform it, the aerodynamic diameter of a glass bubbles is:

$$d_a = d_p \frac{\rho_p}{\rho_a}$$

After calculations, the aerodynamic diameters of the different series of glass bubbles are shown in Table 4.2.

Table 4.2: The Aerodynamic Diameters of Glass Bubbles

Products	Density (g/cc)	Diameter (μ m)	Aerodynamic diameter (μ m)
HGS2000	0.32	40	12.80
HGS3000	0.35	40	14.00
HGS4000	0.38	40	15.20
HGS5000	0.38	40	15.20
HGS6000	0.46	40	18.40
HGS8000X	0.42	26	10.92
HGS10000	0.6	30	18.00
HGS18000	0.6	30	18.00

As shown in Table 4.2, the aerodynamic diameters of glass bubbles range from 10.92 μ m to 18.40 μ m. Because the 10 μ m diameter is usually considered as the practical

upper-size limit for penetration to the alveolar region (J.R., 1999), glass bubble dust particles with an aerodynamic diameter more than $10\text{ }\mu\text{m}$ will mainly penetrate the nose, pharynx, larynx and trachea. This can cause rhinitis, pharyngitis, laryngitis and bronchitis as shown in Figure 4.1.

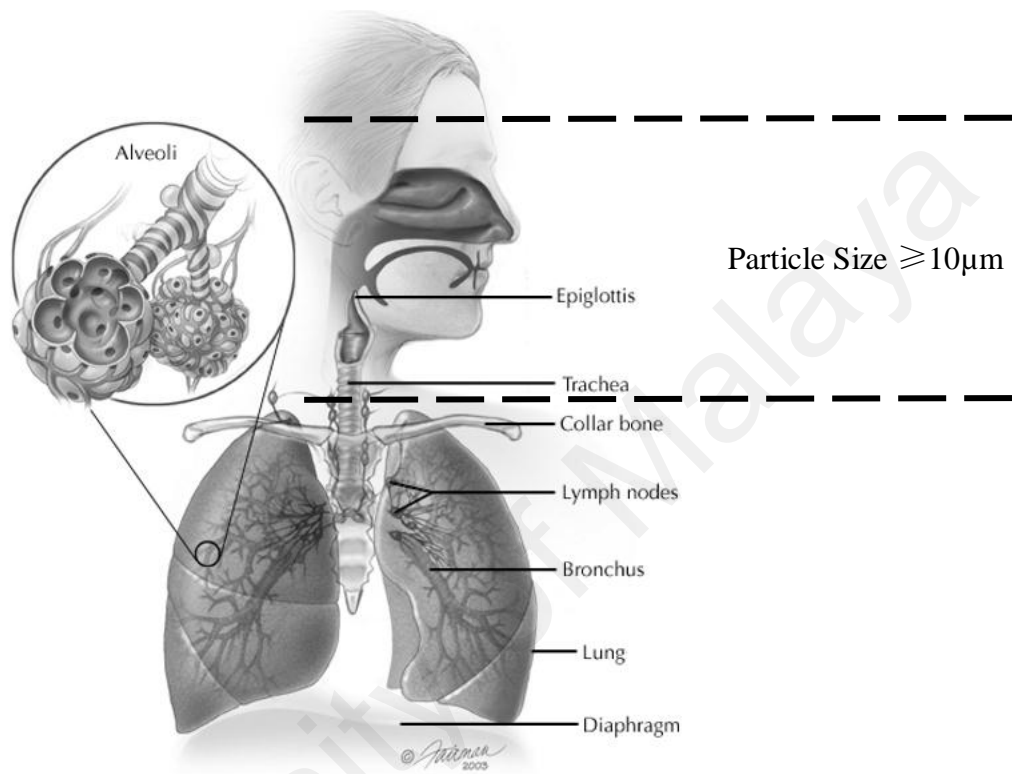


Figure 4.1: Human Respiratory System

Present in the silica dust is the glass bubbles themselves, as well as crystalline-free silica dust, which is even more dangerous than the glass bubble dust. According to Factories and machinery (mineral dust) regulations 1989, the exposure limit of silica dust is separated into two case scenarios (DOSH, 1989). If the crystalline-free silica in the dust is less than 1% in weight, the exposure limit is 5 mg/m^3 of respirable dust or 10 mg/m^3 of the total dust averaged over an eight-hour period. If the dust contains crystalline-free silica equal to or more than 1% in weight, the exposure limit is 0.05

mg/m³ of respirable cristobalite and respirable tridymite and 0.1 mg/m³ of respirable quartz.

Moreover, inhaling the 0-3% of crystalline-free silica dust that's mixed up with glass bubbles can cause silicosis, which can be disabling or even fatal in severe cases (OSHA U.S. Department of labor, 2002). If the respirable crystalline-free silica dust reaches the lungs through breathing, it can cause the formation of a scar tissue that can reduce the ability of the lungs to take in oxygen. As of now, there is no cure for silicosis. It is irreversible, progressive, incurable, and during later stages, it can be disabling and fatal.

4.2 Physical Injury to Operators

When operators come into contact with glass bubbles, there are two kinds of physical injury that can possibly occur. The first one is mechanical skin irritation whose symptoms include abrasion, redness, pain, and itching (3M™, 2016). The other one is eye injury caused by entry of the glass bubbles into the eyes as foreign objects.

4.2.1 Skin Irritation

Regular and direct contact with glass bubbles will possibly cause mechanical irritation to the skin depending on skin sensitivity (3M™, 2016). Additionally, the glass bubbles can attach to clothing and skin until measures are taken to remove them. These glass bubbles will also irritate the skin.

Generally, human skin follicles are elastic and can have a diameter of 40 to 100 µm (Blume-Peytavi, 2008). On the other hand, the diameter of glass bubbles is about 26 to 40 µm. This presents a chance for the glass bubbles to enter the follicles shown in Figure 4.2, which often results in clogged pores. The glass bubbles that remain on the skin's surface will irritate the skin too. Consequently, direct skin contact with glass bubbles may cause abrasion, redness, pain or itching of skin.

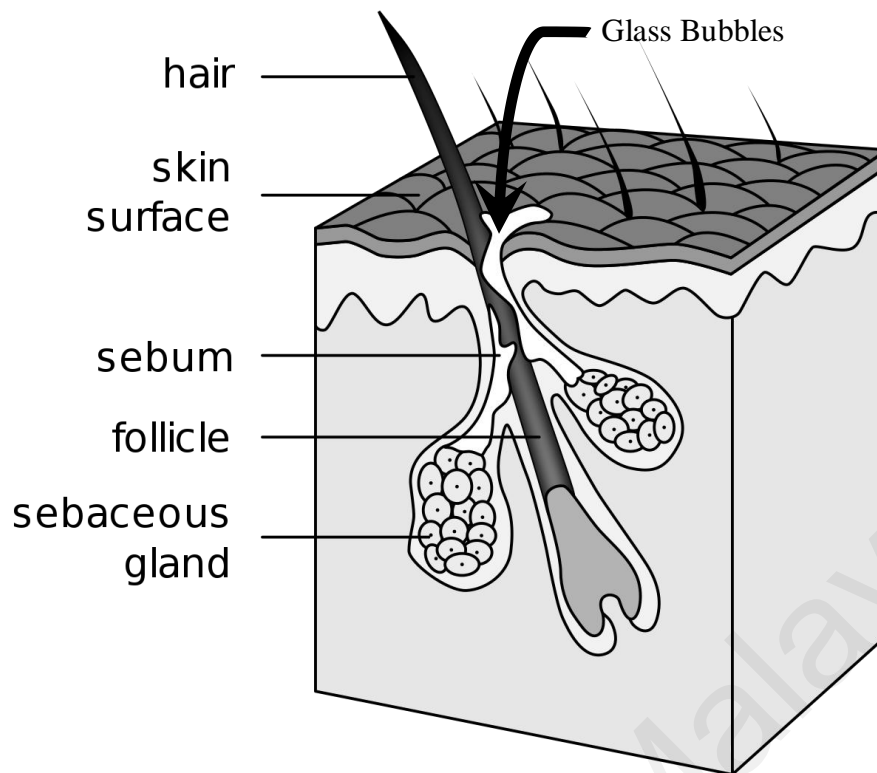


Figure 4.2: Dermal Structure

4.2.2 Eye Injury

Glass bubble dust particles can enter the eyes as foreign objects if an operator is exposed to them without protection. They are likely to damage the cornea and the conjunctiva shown in Figure 4.3.

The cornea is a clear dome that covers the front surface of the eye. It serves as a protective cover for the front of the eye. Light also enters the eye through the cornea and it helps focus light on the retina at the back of the eye (Giorgi, 2016).

The conjunctiva is the thin mucous membrane that covers the sclera, or the white of the eye. The conjunctiva runs to the edge of the cornea. It also covers the moist area under the eyelids (Giorgi, 2016).

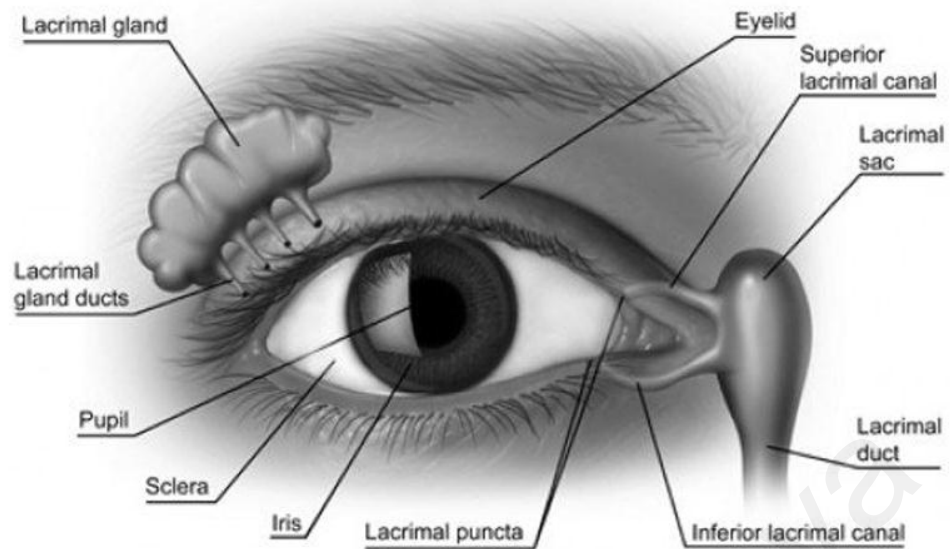


Figure 4.3: Eye (Doctor Eye Institute Pvt. Ltd., 2017)

Even though glass bubbles that land on the front part of the eye cannot get past the eyeball, they are likely to cause scratches on the cornea or the conjunctiva, which will cause pain, redness, tearing and corneal abrasion. Usually, these injuries are minor. However, if not handled properly, sometimes these glass bubbles can cause infection or even damage one's vision. When an operator is exposed to glass bubbles, there is high possibility that the glass bubbles will enter the eyes. An example is when the operator rubs his eyes after touching glass bubbles with the hands.

4.3 Residual in the Environment

As the drilling and completion fluids flow round the circulation system, between the surface and the downhole, not all of the fluids remain in circulation. When the fluids are pumped through the pipe into the borehole, some of the fluids leak into the formation. This is due to the pressure exerted by the fluids on both the hole-wall and the pores on the hole-wall. This is how glass bubbles in the fluids go into the formations, where they

remain for a long time and then they seep into underground water systems. From here, they will enter the water cycle and find their way into rivers, lakes and oceans.

However, the levels of these glass bubbles in groundwater and other water bodies are very low. Additionally, the major composition of glass bubbles is borosilicate glass which is not reactive in water. According to the SDS of glass bubbles provided by 3M™, the LD50 of ingestion of soda lime borosilicate glass is estimated to be 2000 - 5000 mg/kg, while the LD50 of ingestion of crystalline free silica is estimated to be more than 5000 mg/kg (3M™, 2016). Hence, the concentration of glass bubbles in water is not high enough to cause prominent impairment to the ecosystem.

On the other hand, by the end of the life cycle of the drilling and completion fluids, the glass bubbles will be mixed in the final solid waste extracted from these fluids. Glass bubbles will slightly change the soil texture if this waste is mixed with soil. Natural soil contains particles of different sizes. Silt particles have a diameter of 2-50 µm. The influence of glass bubbles on silt is similar to that of silt. Silty soil can hold more water and store more plant nutrients. But, this compatibility attribute can make the soil to become too waterlogged. This will inhibit air circulation, drown the roots, and impede their function of absorbing the much-needed nutrients.

However, soil texture is generally considered a permanent feature. It is not easily influenced by human activities. For example, consider a typical mineral soil that is 2-meter deep on an area of 5000 m². Assuming the soil weighs about 1 million kilograms, changing its sand content by just 1% would require adding 10,000 kilograms (or 10 tons) of glass bubbles. Furthermore, a 1% change in sand content would have minimal effect. A significant effect might require at least a 10% change, which would mean adding 100 tons of glass bubbles to the soil, something that is almost impossible.

CHAPTER 5: DISCUSSION

As density-reducing agents in drilling and completion fluids, glass bubbles have many advantages than conventional agents with only a few obvious health, safety and environmental effects. But, no matter how few the health, safety and environmental effects there are, they cannot be ignored. Measures and improvements are always needed to reduce health, safety and environmental risks. For each risk mentioned in the previous chapter, there are suggested control measures based on these three categories: engineering controls, administrative controls, personal protective equipment.

5.1 Glass Bubble Dust

Glass bubble dust that is generated during the application of glass bubbles into drilling and completion fluids is the most dangerous health risk in the entire process. All possible and reasonable measures should be taken to reduce the exposure levels of glass bubble dust below the permissible exposure limit (PEL). The most effective strategy to curb this is blocking the source of the dust. The next strategy is to remove any dust that managed to escape as soon as possible to make sure dust levels in the work area remain low enough. The last strategy is having the operators wear personal protective equipment.

i. Engineering Controls:

To reduce the generation of glass bubble dust during the application process, a water spray system can be added to the gravity feeder or diaphragm pump, which are used to dispense glass bubbles into the base fluids. The glass bubbles will stay together so cannot become dust when they are wet due to the water spray system. The amount of the sprayed water shall be adjusted to meet the speed of the generation of glass bubble dust, nether too much nor too less.

Regular and scheduled maintenance of the gravity feed or diaphragm pump and the connect pipes is necessary so as to avoid any leakage or malfunction. Also needed is a local exhaust ventilation system or blower to maintain the exposure levels of glass bubble dust below the PEL in the work environment.

ii. Administrative Controls:

Just like pneumoconiosis, silicosis is a chronic disease, and can take many years before showing any symptoms. However, under significant exposure, it may occur in the accelerated (acute) form. Related training, exposure monitoring, and health surveillance programs should be provided. All operators should participate in the training, health screening and surveillance programs to monitor any adverse health effects caused by exposure to silica dust. The training will make them aware of the safer ways of handling glass bubble dust in workplace environment. It will show them how to best protect themselves from health hazards brought about by exposure to glass bubble dust.

iii. Personal Protective Equipment:

Wearing a suitable certified respirator is highly suggested. This is the last line of defense of the operators from the glass bubble dust. The respirator must be worn in the right way by following instructions from the provided manual. Any altering of the respirator will destroy its functionality.

5.2 Physical Injury to Operators

Glass bubble dust is the main reason how glass bubbles find their way into an operator's eyes. You can refer to the above paragraphs on how to reduce the generation of glass bubble dust. For direct skin or eye contact with glass bubbles, there are

suggested control measures in the following aspects: the source, the path, and the removal.

i. Engineering Controls:

Since operators will have to work with glass bubbles, the best measure to minimize getting into contact with them is aiming to reduce the exposure. Use of tools rather than hands to handle the glass bubbles is one way of minimizing contact.

The moment that an operator is at high risk of coming into contact with glass bubbles is during maintenance of equipment. Hence, it is important to get rid of any material inside the equipment and clean the equipment before any maintenance can be done. Maintaining the equipment in good condition makes them reliable and reduces the occurrence of leakages or unexpected repairs.

ii. Administrative Controls:

When handling glass bubbles, the operator should wear disposable or washable work clothes, and clean the washable clothes after work to remove any glass bubble on the clothes. The operator should also take a shower every time after work to remove any glass bubble lodged on the skin. Such facilities for changing clothes and showering should be provided in the work place.

Eating, drinking, smoking, or applying cosmetics in areas where glass bubble dust is present will only increase the risk of exposure. Hence, these activities should be forbidden inside dusty areas and operators must wash their hands and face outside these areas before performing any of these activities.

iii. Personal Protective Equipment:

The most useful and important personal protective equipment are gloves and goggles. Thus, all the operators should wear gloves and goggles when handling glass bubbles to avoid direct contact with the eyes and skin.

5.3 Residual in the Environment

As explained in the previous chapter, glass bubbles present in the drilling and completion fluids do not present significant risk to the environment, but their emission to the environment should be put under control to avoid any unknown impairments. Solid waste that contains glass bubbles should be handled properly to minimize any possible impairment on the environment. Environmental friendly treatments of the used drilling and completion fluids are always a valuable topic to be studied further.

CHAPTER 6: CONCLUSION

This research is focusing on the health, safety and environment risks that result from the application of glass bubbles into both drilling and completion fluids as density-reduction agents. Based on this study, the following conclusions may be drawn:

The procedure of the application of glass bubbles into drilling and completion fluids can be split into four main steps. The first step is physically dispensing glass bubbles into the base fluids. The second step is pumping the fluids into the well. In this step, the fluids will be flowing in a circulation system for the entire drilling process, while remain in the borehole for the completion process. The third step is solid content management and maintenance of the fluids during the pumping operations. The last step is the treatment of the fluids after use.

The glass bubble dust that is likely to be generated during the adding and mixing processes can be harmful to operators by virtue of the chemical composition of glass bubbles: soda-lime borosilicate glass and free-crystalline silica. Physical injury to the eyes and skin resulting from direct contact with glass bubble powder should not be ignored either.

As powder, glass bubbles can easily turn into dust in work environment. Over-exposure to silica dust, especially the free-crystalline silica dust, can cause silicosis which is a serious occupational lung disease. Additionally, because of their small aerodynamic diameters, glass bubbles normally take a long time before they finally settle on the ground. Direct contact with glass bubbles may also cause abrasion, redness, pain, or itching of the skin. In addition, the glass bubbles will most likely damage the cornea and the conjunctiva if they find their way into the eyes.

Reasonable control measures, as mentioned in the previous chapter, are needed to reduce the generation and concentration of glass bubble dust in a work area. Suggested control measures to reduce direct contact with glass bubbles have also been discussed in the previous chapters. The environmental impacts resulting from the application of glass bubbles are inconspicuous for now, but the few known health, safety and environmental risks need to be paid attention to. In the meantime, any emission of glass bubbles into the environment should be controlled and minimized to avoid any unknown effects.

The application of glass bubbles into drilling and completion fluids is still a new phenomenon, although, 3M company has more than 20 years' experience in producing glass bubbles for use in many different industries. Indeed, the use of glass bubbles as density-reducing agents in drilling and completion fluids has shown very good performance so far and has a promising future. Glass bubbles are for sure providing many advantages to the drilling industry, but their known and unknown health, safety and environment impairments should never be ignored. Further studies on the application of glass bubbles are needed to discover and possibly overcome any unknown issues.

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