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Abstract

Oil and gas wells have been drilled for over a century. In the early years of the industry, little attention was usually given to suitable management of drilling wastes.

In accordance with the legislation of the Russian Federation regarding the collection and disposal of drilling wastes, it is necessary to introduce the most environmentally safe methods. Russian law requires removal of all drill cuttings for disposal in an approved method immediately after installation of the conductor casing. Moreover, as a precondition to the development of the field the law requires assessment of the impact of the project on the environment and society, and the chosen method of disposal must be approved by local and Federal authorities.

A choice of several suitable drilling waste management practices currently exists. Operators select the most appropriate waste management option on the basis of regulatory requirements, cost and the concerns of future environmental liability.

The objective of the work is to analyse different methods of drilling waste disposal and make an analysis of effectiveness for these methods regarding Russian arctic offshore conditions.

Content

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Abbreviations

CHS – cuttings handling system

CRI – cuttings re-injection

E&P – exploration and production

ERD – extended reach drill

HAZID – hazard identification

MAC – maximum allowable concentration

NORM – naturally occurring radioactive material

NOW – nonhazardous oilfield waste

OBM – oil based mud

ROP – rate of penetration

SBM – synthetic based mud

SDU – slurry disposal unit

SFI – slurry fracture injection

SWI – slurry waste injection

TEJ – techno-economic justification

UF – universal fluid

WBM – water based mud

Introduction

Oil and gas wells have been drilled for over a century. In the early years of the industry, little attention was usually given to suitable management of drilling wastes.

Over time, state and federal regulatory requirements become stricter, drilling and mud system technologies advance, and some companies may voluntarily adopt waste management options that have even less environmental impacts that those in use today.

The well-drilling process generates large volumes of two types of wastes - used drilling fluids and drill cuttings. Drilling fluids (or muds) are used to aid the drilling process. Muds are circulated through the drill bit to lubricate the bit and to aid in carrying drill cuttings to the surface, where the muds and cuttings are separated by mechanical means. Most onshore wells are drilled with water based or oil-based muds, while offshore wells may also use synthetic-based muds.

Historically, oil field wastes were managed in ways that were found to be most convenient or least expensive. Over the past decade, oil and gas operators have looked to waste management approaches that minimize the generation of wastes and to disposal techniques that offer greater environmental protection and public safety. A three-tiered waste management hierarchy is followed, in which the operator attempts to manage wastes in the most environmentally friendly tier first, then progresses to the second and third tiers as necessary. In the first tier (waste minimization), processes are modified, technologies are adapted, or products are substituted so that less waste is generated. When feasible, waste minimization can often save money for operators and can result in greater protection of the environment. For those wastes that remain following waste minimization, operators next move to the second tier, in which wastes are reused or recycled.

Some wastes cannot be recycled or reused and must be managed through the third tier (disposal).

1. Historical background

In the early years of the oil and gas industry, drilling wastes were looked upon as undesirable commodities that needed to be disposed of in the easiest or quickest way possible. Waste management practices were nearly all in the third waste management tier – disposal. The oil and gas industry was not unique is this approach; 50 to 100 years ago, nearly all of the major industries were growing and the economy was expanding. Given the prevailing philosophy of those earlier times, few coordinated or environmentally beneficial waste management approaches were employed. Onshore drilling wastes were generally discarded on lease sites or on nearby roads or properties, and offshore drilling wastes were typically discharged to the ocean (Veil, 2002).

Some practices are carried over to the present, but now are controlled by suitable restrictions and requirements.

Examples of these are landspreading, road spreading, and ocean discharge.

Landspreading. In the early days, landspreading was used solely to get rid of drilling waste with little concern about the biological degradation of organic constituents of the waste. In more current times, regulatory agencies have established more formal guidelines on landspreading practices. Restrictions are now placed on:

- the chemical constituents of wastes to be landfilled (e.g. chlorides, total petroleum hydrocarbons),
- the application rates,
- the distance from property boundaries,
- the need to add fertilizer and till the waste mixture into the soil.

Road Spreading. It was recognized early on that oily cuttings and spent muds could be used to apply a more weather resistant surface to dirt roads on leases or surrounding lands. Presumably, little concern was given to runoff or groundwater contamination. In contrast, current standards for roadspreading often include similar restrictions to those listed above for landspreading.

Ocean Discharge. In early offshore oil and gas development, drilling wastes were generally discharged from the platforms directly to the ocean. Until several decades ago, the oceans were perceived to be limitless dumping grounds. During the 1970s and 1980s, however, evidence mounted that drilling waste discharges could have undesirable effects on local ecology, particularly in shallow water. When waterbased fluids were used, only limited environmental harm was likely to occur, but when operators employed oil-based fluids (usually for deeper sections of wells), the resulting cuttings piles created impaired zones beneath and adjacent to the platforms. Nowadays, special regulatory acts exist in countries which have offshore oil production facilities which establish:

- restrictions on oily sheens (precluded discharges of oil-based muds and cuttings),
- aquatic toxicity testing using the mysid shrimp for drilling waste discharges, and
- limits on the amount of mercury and cadmium in the raw barite used as part of the drilling fluids.

2. Present law requirements

Restrictions on the discharge of drilling mud and cuttings around the world are governed by standards, norms, laws and regulations designed to provide protection to the surrounding marine environment. Each region and country has the right and legal and moral obligation to assure that any industrial activity off their coasts is controlled and the environment proven safe from these activities.

Russian Federation legislation connected to waste management regarding offshore facilities is relatively complicated. It combines a number of international conventions, internal federal laws, codes and regulations. All of these documents regulate sea water protection and ecological requirements for industrial works at the territorial sea.

All russian companies are obliged to follow the legislation requirements for territorial sea protection during all works including transportation of the drilling rig, installation, drilling and production , which are governed by a number of laws and sublegislative acts.

Water Code of Russian Federation (ВОДНЫЙ КОДЕКС РФ)

According to section 8 of Water Code (further – «Code») territorial sea is the object of water relations. The rules of Russian Federation territorial sea utilization and protection (section 15 of Code) are regulated by Code and other federal laws. These federal laws include Federal Law «Internal sea waters, territorial sea and adjacent zone of Russian Federation» («О внутренних морских водах, территориальном море и прилежащей зоне Российской Федерации», № 155-ФЗ) from 31 July 1998 (further Law № 155). Furthermore, regulation of territorial sea and adjacent zone utilization and protection may be governed by sublegislative normative acts of Rissian Federation. The procedure of territorial sea and adjacent zone utilization and protection is defined not only by russian legislation but also by international laws, which corresponds section 4 of Water Code.

According to section 145 of Code the utilization of water objects for above-water and underwater objects building and exploitation is done on the basis of licence for water use which is given in established order.

Water objects' protection is regulated by sections 94-120 of the Code. Section 1 explains the main terms of water pollution.

Water object pollution – disposal or income in any alternative way to the water objects, as well as formation of harmful or toxic materials which deteriorate the quality of surface and subsurface water, limit the utiliation or affect negatively on the bottom and shore properties of water object.

Water object contamination - disposal or income in any alternative way to the water objects of any items or any slurried particles which worsen the condition and limit the utilization of water object.

Water object pollution and contamination is usually done by uncontrolled disposal of waste waters and othes wastes into the water object.

According to section 1 of code, *waste water* is water which is disposed to the water object after being used in any technical process or which came from the contaminated territory.

Term *Waste* is explained in section 1 of Russian Federation Federal Law «Industrial and domestic wastes» («Об отходах производства и потребления», 24.06.98 № 89-ФЗ).

Industrial and domestic wastes (further - wastes) – residues of raw, materials, semiproducts or other products which are generated during any industrial or domestic process, as well as products which lost their consumptive qualities.

In definition of Code and Federal Law waste water and wastes are <u>not</u> regarded as materials that should be regulated while being disposed.

Defining waste water and industrial waste, legislator did not put any clear borders between them. This uncertainty is extremely important from the point of further utilization of waste water and drilling waste, especially in terms of their handling methods.

Water objects protection from the pollution is done by regulation of different pollution sources activities (section 95 of Code). This regulation is done by normative water quality, which has exposure limits. These limits guarantee the ecological safety of water object. Requirements for water composition and properties and Maximum Allowable Concentration (MAC) serves as a criterion for water quality assessment. The list of toxic substance MAC for water objects is established by Russian Federation Committee of fishing.

According to section 96 of Code «Water objecst protection from pollution» («Охрана водных объектов от засорения») the disposal and burial of any industrial or domestic waste in any water object is prohibited.

As far as water object pollution is defined as disposal or income in any alternative way to the water objects, as well as formation of harmful or toxic materials which deteriorate the quality of surface and subsurface water (section 1 of Code), the prohibition of any industrial or domestic waste disposal and burial refers to any certain objects such as rubbish, metal junk, ect. Disposal or income in any alternative way of any slurried particles is permitted by Code in case that waste meets certain requirements. These requirements include MAC for slurried particles.

According to section 99 of Code, fossil minerals' extraction from the sea bottom has to be conducted in such a way that it does not cause harm to water surface, sea bottom, shoreline and water bioresources. There requirements get in line with the requirements of Federal Law «Subsurface» (Закона РФ «О недрах»), which demand all companies to limit in a specified manner a negative influence on grounds, forests and water objects of all technical processes connected to subsurface exploitation (section 22).

The Code also prohibit to dispose any radioactive or toxic materials to water objects (section 104). It is only admitted to dispose waste water containing toxic materials if it is cleaned in a certain manner.

According to section 105 of Code, it is prohibited to put into operation:

- any objects that are not equipped with cleaning means preventing contamination and pollution of water objects;
- facilities for oil or chemical products transportation without means of water objects pollution prevention and control and measuring equipment for leakage indication.

During the techno-economic justification (TEJ) of the project which has an impact on any water object special measures of water pollution prevention should be thoroughly concidered. TEJ of any project which has an impact on any water object are subject for state ecological expertise in a mandatory manner.

During the exploitation of an object it is prohibited (according to section 106 of Code):

- to dispose to a water object any waste water which is not cleaned and treated in a certain way;
- to dispose waste water which contain substances which does not have MAC or contain agents of infection.

The disposal should be conducted according to a permission (license) which gives normatives of maximum allowable disposal volume (disposal limit) and requirements that assure environment protection and health care. This license is given by a special governmental agency of water fund utilization and protection. The order of development and comfirmation of waste water disposal normatives is defined by Covernment decree «Development and comfirmation of disposal ecological normatives» (Постановление Правительства РФ «О порядке разработки и утверждения экологических нормативов выбросов и сбросов загрязняющих веществ в окружающую природную среду, лимитов использования природных ресурсов, размещения отходов» от 03.08.92 № 545.)

Section 144 of Code defines water objects where disposal of waste is totally prohibited. These objects include:

- especially protected water objects;

- places of especially protected species of fish spawing and wintering

Protection and utilization of especially protected water objects is regulated by Russian Federarion Law « Especially protected territoties » (Закон РФ «Об особо охраняемых природных территориях»).

Thereafter, The Water Code prohibits to dispose any radioactive or toxic materials to water objects, and also to dispose any waste water which is not cleaned and treated in a certain way or waste water which contain substances which does not have MAC or contain agents of infection. It also prohibits the dislosal of waste to especially protected water objects and places of especially protected species of fish spawing and wintering. The disposal of slurrified waste should be governed by MAC normatives.

Moreover, for the purpose of territorial water protection from pollution, Russian Federation came in on a number of international conventions.

Russian Federation Law «Russian Federation internal waters, territorial sea and shore zone» (Закон РФ №155 «О внутренних водах, территориальном море и прилежащей зоне РФ»)

Waste burial and contaminants discharge to territorial sea are governed by Russian Federation Law «Russian Federation internal waters, territorial sea and shore zone» (further - Law). Generally, according to article 2 in section 37 of Law, uncontrolled waste burial and contaminants discharge to the territorial sea is prohibited.

Article 1 of section 37 defines:

- *burial of waste and other materials* – any purposive removal of waste or other materials from ships, flying objects, artificial islands, installations and constructions, as well as purposive destruction of ships and other floating objects, flying objects, artificial islands, installations and constructions;
- *contaminant* – substance that in case of sea discharge may cause danger for health, harm the environment, marine life, deteriorate recreation or interfere other

ways of sea utilization , as well as substance that has to be controlled according to international agreements of Russian Federation;

- *discharge of contaminants and waste water*, which contain such substances – any discharge from ships and other floating objects, flying objects, artificial islands, installations and constructions despite of the facts that caused the discharge, including any leakage, removal, seepage pumpdown or unloading.

On the other hand, according to article 1 of section 37:

- the removal of waste or any other materials which are inevitable part of normal exploitation of ships and other floating objects, flying objects, artificial islands, installations and constructions is NOT CONCIDERED as burial providing that they do not exceed MAC of dangerous and toxic substances or normative negative influence on marine environment;
- contaminants discharge does not include removal of hazardous substances which occures during processes of offshore mineral resources fields exploration, development and processing.

These statements correspond to London Convention on sea protection from pollution with waste and other materials (London Convention, 1972).

However, neither the Law nor London Convention do not define waste or any other materials which are inevitable part of normal exploitation.

State and industrial standarts and rules

During 1970s -1980s a number of state and industrial standarts such as ГОСТ 17.1.3.02-77, ОСТ 51.82.-82, ОСТ 51.01-06-85 were passed in USSR which limit and/or prohibit drilling waste and waste muds disposal into the sea.

These prohibitions and limitations were in power until 1970s in other countries which have their own offshore oil and gas exploration and production projects. Such strict requirements were governed mainly because of mass oil-based muds utilization, as well as low quality of drilling technologies and low level of knowledge about oil influence on marine life. These rules became less strict in most oil producing countries with changes in conditions listed above and transition to less toxic drilling muds and ocean discharge of such muds was permitted. Regulatory documents regarding these questions are listed below.

Rules of coastal waters protection from pollution.

Territorial waters and shore zone 2 kilometers width protection from pollution is regulated by Rules of coastal waters protection from pollution («Правила охраны от загрязнения прибрежных вод морей») approved in 1984 by Ministry of water facilities, Ministry of health and Ministry of fishing facilities of USSR (further – Rules). These rules take into account the requirements of international agreements of USSR regarding coastal waters protection from pollution. The Rules do not regulate cases of waste burial in seas.

Concerning drilling operations, drilling waste and waste waters discharge, the Rules contain following refquirements:

- disposal of any industrial, domestic or other type of waste to coastal sea waters is prohibited (section 3.6);
- waste water discharge to coastal sea waters is permitted provided that they are properly cleaned in such way that their contaminants content does not exceed certain limits specified by authorities; also provided that it will not lead to increase of pollutants content in sea waters more than specified normatives (section 3.7);
- protected coastal zone borders are defined by regional health, safety and environment authorities (section 3.9). Overall length of protected coastal zone might be up to 12 naval miles (section 3.10);
- drilling operations in coastal zones and on continental shelf of Russian Federation are carried out only after receiving special permission given in a specified manner (section 3.15);

- water quality normatives are stated depending on water object category (section 4.4). Water object categories are stated by fish protection authorities (section 4.5);
- at the waste water discharge site sea water content and properties should satisfy stated requirements at the distance of 250 or more meters in every direction from the point of discharge (section 4.6);
- it is prohibited to dispose any cleaned waste water to especially protected water objects, as well as marine regions which are prospective for fishing activities and especially protected species of fish spawing, wintering and migration (section 4.7);
- the disposal of any substances that do not have MAC approved by authorities to the coastal sea waters is prohibited. In case of MAC absence company has to do research to examine the substance influence on marine life and approve MAC for this substance (section 4.11);
- the disposal of waste water containing contaminants which are prohibited for disposal or which have exceeded MAC is prohibited (section 5.2.);
- the disposal of cleaned waste water to legislatively preserved areas is prohibited (section 5.3);
- slurry reservoirs accomodation is prohibited along 2 kilometers width coastal zone (section 5.6);

Rules of water protection from pollution during offshore oil and gas wells drilling and completion operations.

State standart ГОСТ 17.1.3.02-77 makes up rules that prevent pollution of territorial waters during drilling and completion operations. This standart includes following requirements:

- carbohydrates, containers, technological waste, drill cuttings, combustive and lubricating materials which lost their properties have to be transported to shore facilities or have to be burnt using special equipment. Drill cuttings may be used as additives for drilling mud;

- during drilling upper intervals of the well with sea water as drilling fluid drill cuttings can be discharged to the sea floor;
- cleaned domestic waste and drilling waste water are permitted to be discharged to the sea if their composition does not exceed normatives and MACs.

Discussion.

The analysis of existing legislative and governmental documents which regulate environment protection from pollution during drilling operations in territorial seas of Russian Federation allows to make following conclusions:

- there is no special regulation which governs drilling waste disposal in Russian Federation legislation;
- Russian Federation legislation and international conventions do not contain strict prohibition on drilling waste discharge to territorial sea.

Drilling muds and drill cuttings can be regarded as waste water contaminated by slurrified particles and some chemical substances as there is no other legislative definition exist. Waste water mentioned above is inevitable part of normal exploitation of drilling rig.

If drilling muds and drill cuttings are regarded as contaminated industrial waste water as inevitable part of normal exploitation of drilling rig, the process of their disposal to sea should be regulated by Water Code.

The disposal of water-based muds and drill cuttings at the production site in territorial sea is considered as justified and viable from the juridical point of view:

- drilling waste and drill cuttings are results of normal exploitation of drilling rig so their disposal is not concidered as burial of industrial waste. As every drilling rig is constructed for wells drilling, this activities are concidered as normal.

- drilling waste is waste water, not industrial waste. Thus, the disposal of waste water is governed by relevant legislation, not by one governing industrial waste disposal.

The ability of drilling waste disposal at the production site entails in case if waste is a result of normal exploitation of drilling rig and it does not exceed MAC of contaminants and toxic substances and any other normatives.

This statement is regulated by section 37 of Federal Law №155 of Russian Federation «Internal waters, territorial sea and shore zone of Russian Federation» («О внутренних морских водах, территориальном море и прилежащей зоне Российской Федерации», №155-ФЗ).

The process of wase disposal at the production site in territorial sea is also limited by other requirements in addition to MACs:

the limitation is prohibition on the disposal of any substances that do not have MAC approved by authorities to the coastal sea waters. This statement is constated by Water Code (section 106) and Rules of coastal waters protection from pollution (section 4.11). In case of MAC absence company has to do research in close coordination with authorities to examine the substance influence on marine life and approve MAC for this substance. Special rules are established for this procedure by Russian Federation fishing Committee («Порядок организации разработки и утверждения ПДК и ОБУВ загрязняющих веществ в воде рыбохозяйственных водных объектов» от 14.08.95 №12-04-11/454.)

- it is prohibited to dispose any waste water which is not cleaned and treated in a certain way or which contain substances which does not have MAC or contain agents of infection. Section 108 of Water Code and section 5.2 of Rules regulate this issue. Therefore, drilling rigs have to be equipped with special cleaning facilities
- one more limitation is prohibition on discharge of certain substances stated in international conventions. Water Code prohibit to dispose any radioactive or toxic materials to water objects (section 104). Waste water discharge to coastal sea waters is permitted provided that they are properly cleaned in

such way that their contaminants content does not exceed certain limits specified by authorities.

Substantial limitation might be attribution of production site to especially protected areas or places of especially protected species of fish spawing and wintering. This limitation is governed by section 144 of Water Code and section 4.7 of Rules.

Especially protected areas or places of especially protected species of fish spawing and wintering are conserved in a particular way according to Russian Federation Law «Especially protected areas» (Закон РФ «Об особо охраняемых природных территориях» от 14.03.95 №33-ФЗ)

Fishery value of water object is determined according to State Standart (ГОСТ 17.1.2.04-77. Показатели состояния и правила таксации рыбохозяйственных водных объектов).

Summing everything up, the conclusion is as follows:

The disposal of drilling waste and drill cuttings at production site is juridically allowable and viable on conditions that this process takes place within all limitations duscussed above. These limitations are connected with waste content requirements, waste components MACs as well as fishery value category of water object.

Due to the fact that companies are obliged to obey all legislative requirements during the whole cycle of offshore wells construction, the usual strategy of every company is «zero emission» principle when all waste generated by drilling and production is eliminated with avoidance of any contact with sea water. This strategy is obviously chosen because of extremely difficult, expensive ant time-consuming procedures for establishing MACs for every component of drilling waste, waste muds and water.

For every company 2 main options of waste handling exist – transportation to shore and at-site subsurface burial, mainly by means of injection.

The following chapters include calculations of average volumes of drill cuttings and drilling waste generated by one offshore platform, discuss options mentioned above and extensively analyze each method of drilling waste management.

3. Drilling waste managemenent options

The current suite of drilling waste management practices contains options, but all options are subject to restrictions. The countries' environmental awareness grew during the 1970s as the U.S. Congress passed laws to protect water (Clean Water Act, Safe Drinking Water Act) and air (Clean Air Act) and to control new and past wastes (Resource Conservation and Recovery Act, Comprehensive Environmental Response, Compensation, and Liability Act). Faced with this national direction, companies began developing oil field waste management practices that met the needs of both the environment and the business community in their countries.

To help assure the successful development and implementation of the most appropriate waste management strategy, all variables which may affect the operation should be thoroughly considered. These factors may come from any number of areas, including but not limited to operations, logistics, regulatory policies, internal company strategy or equipment availability. As the cost for waste management approaches and surpasses the cost of the actual fluid services, the importance of the development of the proper response to the challenge only increases (Collins and Stanley, 2005).

An environmental management strategy should address every portion of the fluid systems. Drilling fluid, completion fluid, production fluid, stimulation fluid and cement slurries can all have different residual effects which must be considered. Coupled with generated solids such as drilled cuttings and produced sands, the task of deciding on the correct disposal option becomes critical. By understanding the factors that effect each individual operation and area and utilizing correct management practices and procedures, a purpose-designed, compliant option should be identified and implemented. This strategy, backed with proper monitoring and documentation, can provide the operator with a sustainable environmentally responsible and compliant solution.

Environmental legislation varies from country to country, and even specific region to region within a country, and the legislation may be subject to frequent changes. Another critical component is the operator's own corporate standards. These can often be more stringent than regulatory limits, which can help prevent future liability for actions taken today. Therefore, proper knowledge of all applicable legislation and the operator's internal standards is critical. The costs, both direct and in-direct, of non-compliance should be considered.

Different wastes are managed with different approaches. Some of the methods used for managing drilling wastes include:

- land spreading,
- road spreading,
- burial in pits or landfills,
- injection,
- salt caverns,
- thermal treatment, and
- reuse following treatment.

Each of these methods is discussed below in relation to the waste management hierarchy.

In conditions of changing legislation, growing attention to environmental impact from industry and control of nature protection organizations there are usually two options for drilling waste management: cuttings disposal offshore, or transport to shore for disposal.

As an example, present regulations on the Norwegian shelf states 0% oil content in the cuttings (Arnhus and Slora, 1991). The following two options are then given for disposal of oily cuttings:

1. Platform installed waste handling and cleaning system capable of cleaning cuttings to 0% oil content for further discharge to the sea;
2. Transport of cuttings to shore for cleaning and/or disposal.

Nowadays, no proven cleaning equipment can assure design requirements to minimum weight, power and area for installation on new rig developments or rigs in operation. Due to this fact, contaminated drill cuttings have to be brought ashore for disposal.

Disposal decision matrix shown below in figure 1 is intended as a general guideline for the decision-making process. The final decision concerning the best disposal method is as complex and critical as any other decision in the life of a well. By applying research and a methodical evaluation process, the operator can achieve real world solutions for today's environmental challenges.

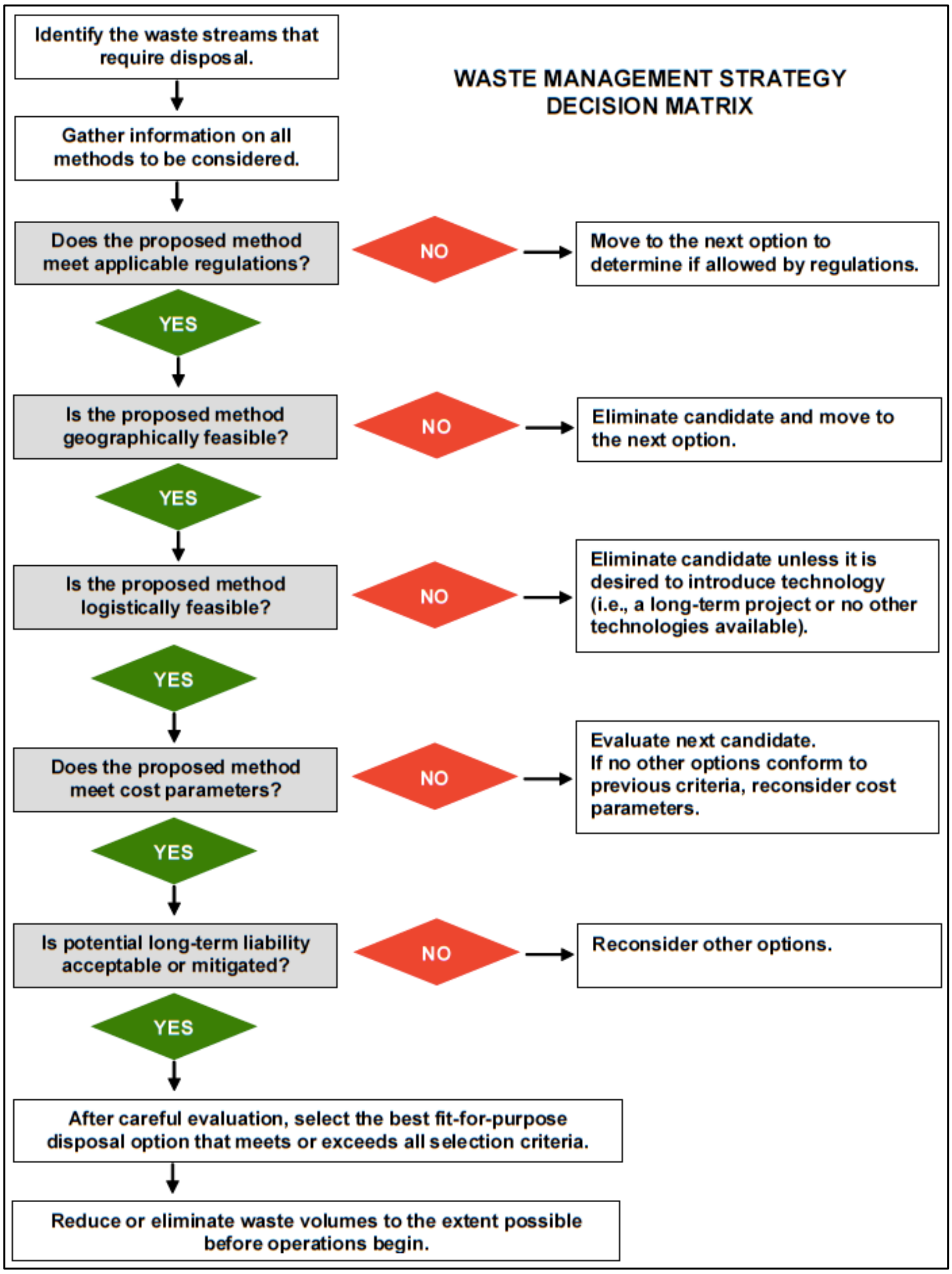

Figure 1. Disposal decision matrix

Before making decision which option is the most favorable for particular project, some rough calculations have to be done to estimate approximate volumes of drill cuttings, waste mud and waste water generated by drilling.

Assume the following data as average for one offshore well. Figure 2 reflects typical construction of well.

Table 1. Initial data

№	Parameter	Conductor	Technical 1	Technical 2	Technical 3	Exploitational
1	Diameter of the bit, м	0,508	0,4445	0,3937	0,2699	0,1905
2	Interval length, м	800	450	3200	400	500

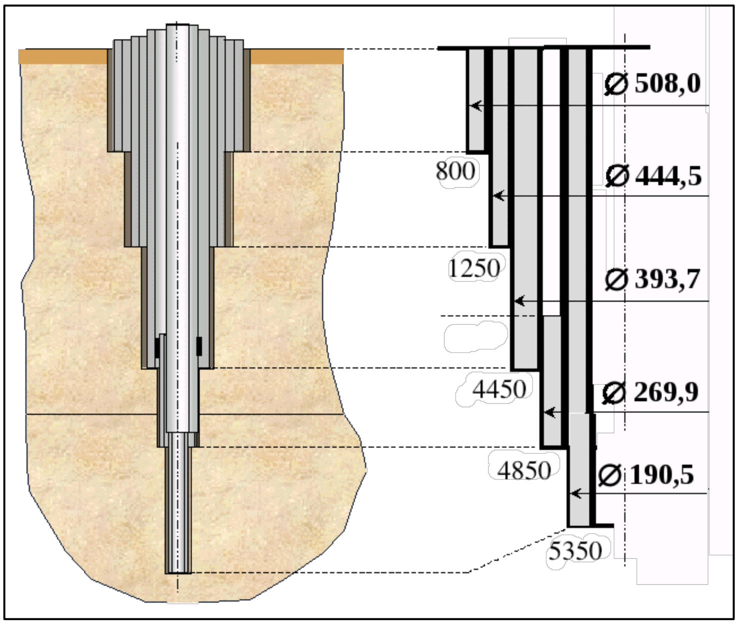

Figure 2. Typical well construction

Secondly, cross section area and total volume of each interval are calculated:

$$\text{Cross section area} = \frac{\pi d^2}{4}$$

where *d* is diameter of the bit,

$$Volume\ of\ interval = Cross\ section\ area \cdot l$$

where l is length of the interval.

Table 2. Dimensions of sections

№	Parameter	Conductor	Technical 1	Technical 2	Technical 3	Production
1	Diameter of the bit, m	0,508	0,4445	0,3937	0,2699	0,1905
2	Interval length, m	800	450	3200	400	500
3	Cross section area, m^2	0,051	0,039	0,03	0,014	0,007
5	Volume of interval, m^3	40,5	17,5	97,4	5,7	3,6
6	Total length of the well, m	5350				
7	Total volume of the well , m^3	164,7				

The well known fact is that every rock being underground is tightly packed, but being drilled out it increases in volume because of surface area growth. Figure 3 visualises this process.

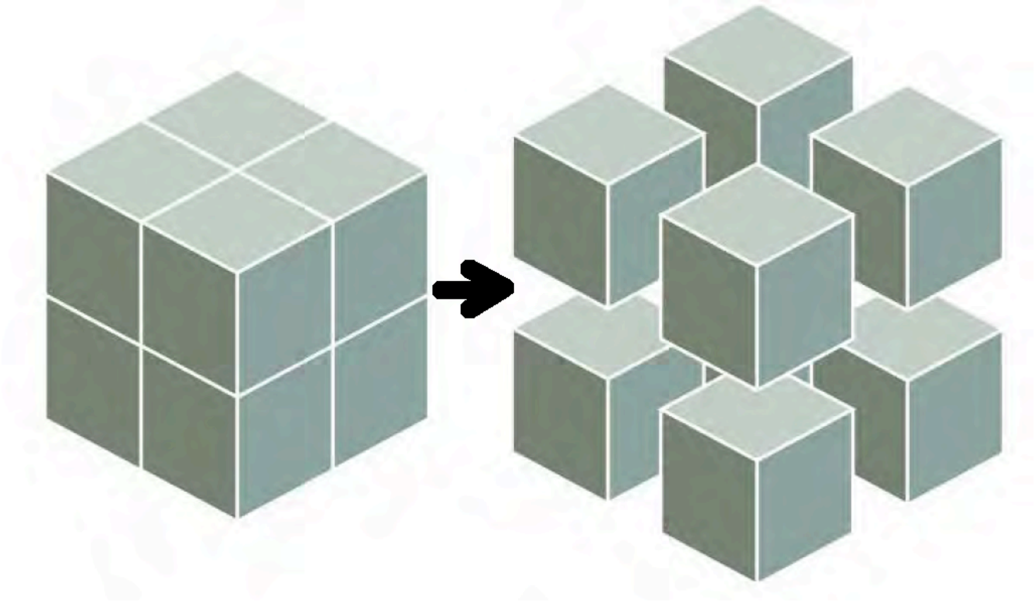

Figure 3. Surface area growth process

Thus, the volume of drill cuttings is higher than volume of well itself.

For each type of formation special coefficients exist which reflect ratio between initial volume of formation and volume of drill cuttings generated during drilling. They are called expansion factors and usually established by survey of core samples. For calculations, we may assume these factors basing on industrial data.

Using the formula:

$$V_{drill\ cuttings} = Expansion\ factor \cdot V_{interval}$$

and assuming expansion factors as follows, it is possible to calculate total volume of drill cuttings generated by drilling one well:

Table 3. Volumes of cuttings

Parameter	Conductor	Technical 1	Technical 2	Technical 3	Production
Volume of interval, m^3	40,5	17,5	97,4	5,7	3,6
Expansion factor	3	3	2	2	2
Volume of cuttings, m^3	121,6	52,4	194,8	11,4	7,1
Total volume of cuttings, m^3	387,3				

It should be noted that the calculated volume refers to dry cuttings. Due to the interaction with drilling mud, capillary tension and surface-activity of mud the real volume of wet cuttings is much higher.

Moreover, mud circulation system is not perfect and it cannot assure 100% division of cuttings from mud. Waste mud also has to be disposed, so the best solution is disposal of mixture of drill currings and waste mud.

Assuming the content of solid waste in mixture by 20%, one well generates approximately $\frac{390}{0,2}$ =1950 cubic meters of waste to be handled.

Assume that offshore project includes drilling of 35 wells. Every well generates approximately 400 m^3 of drill cuttings.

The overall volume of cuttings will be :

$400\ \frac{\mathrm{m}^3\ \mathrm{of\ cuttings}}{\mathrm{well}} \cdot 35\ \mathrm{wells} = 14000$ m^3 of dry cuttings.

Calculated as slurry volume, it is $\frac{140000}{0,2} = 70000$ m^3 of drilling waste.

Referring to existing projects, the following table represents drilling waste volume at Prirazlomnoye field in Russia (Waste injection project for Prirazlomnoye field):

Table 4. Prirazlomnoye field waste volumes

Group of wells	Average volume of cuttings per well, m^3	Drilling waste volume, m^3	Slurry volume, m^3	Number of wells, m^3	Total slurry volume, m^3
Group 1	402	1126	2026	1	2026
Group 2	477	1334	2042	10	24017
Group 3	679	1902	3424	19	65050
Group 4	776	2173	3911	3	11732
Group 5	841	2354	4238	2	8475
Group 6	463	1296	2333	1	2333
Totally				36	113634

As we can see, the average volume of dry cuttings per well is slightly higher than calculated previously. This, in turn, confirms the accuracy of assumption made above.

According to this table, 36 wells at Prirazlomnoye field will generate more that 113000 m^3 of slurry which means that average length of one well is more than 6000 meters or average diameter of the well is larger than in calculations.

The following chapters discuss different scenarios of waste disposal problem solutions.

3.1. Transportation to shore

This method is easy in principle. Drill cuttings are accumulated in special contaiers of mud circulation system. When containers are full, they are replaced with empty ones. Full containers are loaded on support vessel by platform cranes and transported to the shore facilities for treatment/recycling/burial.

There are three main operational limits for this method for disposal of cuttings.

1. Storage areas for full containers are limited on the platform. This issue may be improved by utilising the support vessel as a storage area. This, however, depends on the accessability of platform cranes.
2. Cranes are needed for moving containers off. Platform cranes do not operate at wind speeds higher than 45 m/s because it might be dangerous to perform lifting and loading operations during windy weather. It means that the drilling operation will have to be stopped if storage containers are full and the wind speed is too high.
3. From the above mentioned points it is obvious that the platform will be more dependent on external factors than what is normal today. The extensive use of boats and cranes together with the limited storage area will be a possible restriction during the drilling program.

As for logistics involved for cuttings transport to shore, there is a constant demand for boats to transport the full containers for disposal. To avoid any unnecessary stops in the drilling operation, there should be a boat available whenever the storage area is filled up with full cuttings containers. Estimated need for supply boats for transport of cuttings:

Input data:

Maximum weight per. container: 6.5 tonnes

Maximum volume of cuttings per. container:

$$\frac{6.5\ \text{tonnes}}{3\ \text{tonnes/m}^3} = 2{,}16\ m^3$$

Platform mud circulation system capacity is 8 containers for drill cuttings.

While drilling conductor:

Average rate of penetration (ROP): 25 m/hour

Average volume of cuttings per section (from table 3): 122 m^3

Average time for drilling conductor: 5 days

Number of containers:

$$\frac{122\ m^3}{2{,}16\ m^3/\text{container}} = 57 \text{ containers}$$

Containers per day:

$$\frac{57 \text{ containers}}{5 \text{ days}} = 12 \text{ containers/day}$$

Assume that storage capacity of support vessel is 6 containers.

Thus, number of platform to boat operations:

$$\frac{12 \text{ containers/day}}{6 \text{ containers}} = 2 \text{ times}$$

While drilling technical columns 1 and 2:

Average ROP: 15 m/hour

Average volume cuttings:

52,4 + 194,8 = 248 m^3

Average time for drilling technical columns 1 and 2: 20 days

Number of containers:

$$\frac{248\ m^3}{2{,}16\ m^3/\text{container}} = 115 \text{ containers}$$

Containers per day:

$$\frac{115 \text{ containers}}{20 \text{ days}} = 6 \text{ containers/day}$$

Number of platform to boat operations:

$$\frac{6\ \text{containers/day}}{6\ \text{containers}} = 1\ \text{time}$$

While drilling technical column 3 and production column:

Average ROP: 10 m/hour

Average volume cuttings:

11,4 + 7,1 = 19 m^3

Average time for drilling technical column 3 and production column: 5 days

Number of containers:

$$\frac{19\ m^3}{2{,}16\ m^3/\text{container}} = 9\ \text{containers}$$

Containers per day:

$$\frac{9\ \text{containers}}{5\ \text{days}} = 2\ \text{containers/day}$$

During drilling these sections of well there is no need in daily support in transportation of waste. Maximum quantity of platform to boat operations is 2 times.

The above calculations shows that the availability of boats will have to be 2 boats continuously while drilling of conductor, and 1 boat per day while drilling of technical columns 1 and 2. If the storage area on the platform is improved, the demand for continuous boat availability will be reduced according to the increased storage area.

The cuttings containers will be shipped to a suitable disposal plant ashore.

Taking in focus Russian arctic offshore fields that are located in Barents and Kara seas, we face a great problem – ice conditions (Gudmestad et al., 2000). Every operation involving transportation requires specific vessels which have ice breaking capabilities. Another solution is support vessel guided by ice breaker.

Ice conditions put limitations on choice of transportation vessel which lead to significant increase in costs of any transportation operations. This case turns into growth of capital costs of arctic offshore field development.

Another problem is extremely poor infrastructure at shore line. Lagre amount of drill waste requires special facilities for waste treatment and recycling. Nowadays, there are no such facilities at Russian arctic shore line.

All these facts lead to the conclusion that another method of drilling waste management has to be chosen. The most appropriate state-of-the-art technology for drilling waste handling at offshore fields is underground injection.

3.2. Underground injection

Another option for drilling waste management is underground injection.

During the last two decades, various forms of injection have been used in the oil and gas industries to achieve permanent disposal of exploration and production wastes (Marinello et al., 2001).

Injection of these solid wastes usually entails the slurrification of the solids following some degree of particle sizing connected with the limitations of the targeted receiving formation, pumps characteristics and the process employed. Disposal operations are done in subsurface structures ranging from salt caverns to highly consolidated formations that are fractured to achieve transport, containment and isolation of the injected slurried wastes. Certainly the bulk of the solid wastes disposed of by injection have utilized slurry fracture injection (SFI) or sub-fracture pressure injection methods. All of the methods have the same goal: the safe and permanent disposal of solid wastes such that they are placed below the surface and isolated from any environmentally sensitive receptor or aquifer in order to eliminate or minimize long term liabilities associated with the waste.

Deep well injection as a means of solid waste disposal has become the preferable solution in offshore exploration and production sector due to its' significant advantages in terms of potential environmental and economic impacts versus the previously preferred methods of land treatment or landfill disposal. Key factors involved with any of the three methods being discussed include:

1. Minimization of potential impacts on surface and subsurface waters;
2. Smaller operational footprint;
3. Minimization of air quality impacts associated with handling, processing and treatment;
4. Reduced long-term liability and risk for the waste generator.

3.3. Preliminary conclusions

There are some basic advantages and disadvantages to each disposal method, either transportation to shore or underground injection. But transportation of drilling waste to shore requires a great number of additional factors such as extra space on a platform for garbage containers, constant support of vessel, demand of lifting operations. Furthermore, this method depends on weather conditions in terms of lifting operations.

In comparison with transportation, slurry fracture injection has the major advantage of being applicable in the widest possible area, especially in Arctic regions with fragile and sensitive environment as disposal zones potentially exist in almost any given stratigraphic sequence where a drilling operation is ongoing. Therefore, this method tends to be the most preferable for arctic offshore fields development.

4. Disposal of exploratory & production waste by injection

Injection of solid waste under fracturing pressure into permeable strata is becoming a widely accepted technology. This process consists of grinding the solids to fine-grained consistency, mixing the solids with suitable liquid to form a slurry, and pumping it down a well under fracturing pressure. This part of the project presents reservoir selection criteria for deep waste injection operations, that is, what qualities and parameters a geological lithostratigraphic unit should possess to act as a target reservoir; ground facilities and necessary equipment are described; technical parameters of the process are presented.

4.1. Description of methods

Deep slurry injection is a process of solid waste disposal that is used by the petroleum industry to permanently dispose of non-hazardous oilfield solid waste. This process consists of grinding the solid waste to a relatively fine-grained consistency (e.g. <5mm), mixing the solid cuttings with water or other liquids (e.g. waste oily liquids or emulsions) to form a slurry of suitable density, and injection of the slurry by pumping it down a well at a high enough pressure so that hydraulic fracturing is continuously taking place within the target geological formation. The injection force of the slurry serves to create the fractures, which are therefore filled with the slurry.

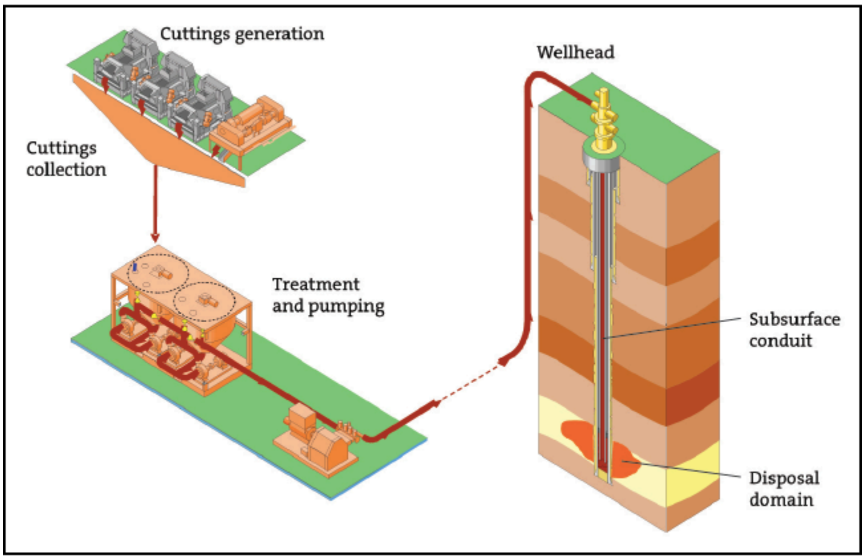

Figure 4. Cuttings re-injection process

Deep under the subsurface, waste is injected into a suitable reservoir where it can be permanently isolated both from the atmosphere and the potable water hydrosphere. Selection of a suitable target reservoir for injection predominantly depends upon the geology of an area and the geomechanical and reservoir characteristics of a target geological lithounit.

A prospective waste disposal site requires certain quantitative or qualitative criteria for every parameter that is involved in assessment (Nadeem et al., 2005).

To select a suitable target reservoir for injection, a comprehensive geological assessment model is required which can account for all the important parameters. Using such a model, it is possible to more easily rank and select a suitable disposal site for a given project on both a commercial basis and an environmental security basis (minimize both costs and environmental liability).

There are a few methods of drilling waste injection (Marinello et al., 2001). Each different injection technology has its' own set of issues relative to its' applicability to a particular situation. These include regulatory controls and limitations, engineering parameters and guidelines, disposal capacities available, potential environmental and safety issues and liabilities and the public and regulatory community perception of all of the above. The continually changing regulatory framework and its' interpretation within a given region or state affects the implementation of the different injection technologies, as well as their commercialization.

There are some basic advantages and disadvantages to each the targeted disposal methods. Slurry fracture injection has the major advantage of being applicable in the widest possible area, as disposal zones potentially exist in almost any given stratigraphic sequence where a drilling operation is ongoing. Geological sections allowing significant sub fracture pressure slurry injection are much more restricted in location, requiring consideration of waste transport costs and issues, but not requiring the cost of high pressure pumps. The main advantage perceptually and from a regulatory standpoint is that the lower injection pressures minimize the possibility of breakout. Likewise, cavern disposal is limited to locations where a solution cavern exists or where its' dissolution is acceptable in the overall economic picture. Technical issues regarding cavern, and therefore, tubular integrity play against limited available disposal volume.

Slurry fracture injection. The critical regulatory issue concerning the use of SFI for disposal is the containment of the injected waste within the targeted zone. This is equivalent to concerns in the design of a hydraulic fracture well treatment to stay within the bounds of the defined confining zones. The increased solids being injected over an extended period of time required extension of fracture concepts to understand the long-term operation that would be required for high volume/long term disposal.

Slurry fracture injection entails the grinding or particle sizing of the waste solids and their slurrification with a liquid, usually fresh water, produced brine or sea water, and may take place through the casing in an annular injection mode or through tubing as a dedicated injection well. The concept and implementation of re-injecting drill cuttings began in the 1980's with the need to address real and perceived environmental impact of the disposal of drill cuttings offshore and in other environmentally sensitive areas. The determination of the correct slurry and injection parameters for optimum fracture capacity is critical in reducing overall costs. The proper design will reduce premature fracture screen-out at maximize the volume of solid waste that can be placed in each set of fracture wings. Initial efforts in this area took place offshore and dealt with relatively small volumes in short term applications. These operations were initiated after consultation with regulatory agencies to gain approval for the operations. They provided data necessary for the continued development of a model of the controlling parameters and likely formation responses during cyclic or periodic injection of the slurried solids.

The developing projects were located offshore, for the most part, due to existing concerns and/or regulations specifically prohibiting the downhole injection pressures in excess of the formation fracture pressure.

Sub-fracture pressure slurry injection. The principle of low, sub-fracture pressure injection for disposal of slurried waste is simple. If the fracture threshold of the receiving formation is not reached, a fracture will not be initiated that could cause a breach of containment. This method of disposal has accounted for in excess of 80% of the commercially disposed drilling waste from offshore and transition zone operations in the Gulf of Mexico and nearby producing regions. It has also accounted for the disposal of more than 90% of the exploration and production (E&P) nonhazardous oilfield waste (NOW) containing naturally occurring radioactive materials (NORM) that has been disposed. The limited geologic locations able to support this type of operation clearly limit the applicability of the process. It is through the efficiencies of size and operation and the existence of the needed geology in relative proximity to high volume activity that has made the existing operations a success.

The key to success in this form of injection is the disposal zone geology. The geologic structures that have been targeted in the two main commercial operations exhibit permeabilities in excess of 50 Darcy, porosities of 30% or more in the primary contact zone and subpressure with respect to the surrounding formations.

These are characteristics of a dynamic geohydrologic setting that provides and maintains the low reservoir pressure, the capacity to transport slurried solids at high injection rates and the ability to dissipate imposed injection pressures in the very short term.

Operational issues of concern with this type of process include maintaining proper control over particle sizing and suspension, as well as well injection parameters. Experience has shown that periodic injection can work, but that it must be optimized to reduce premature falling out of injected solids or sanding out of the injection wellbore. The correct combination of receiving geology and surface injection parameters can significantly prolong the overall life of a subfracture pressure in slurry injection well.

The main limitation of this method is that successful targeting of these prolific injection horizons and the location of the injection wells is dependent on extensive review of drilling and coring records, as well as the use of close grid 3D seismic and/or magnetotelluric surveys of the substructure geology.

Cavern Injection. The disposal of solid wastes into the void space of a dissolution salt cavern has been a significant topic of discussion over the last ten years. The reasons are readily apparent; take a waste and place it in an underground void within an impermeable and self-healing matrix and the possibility that the waste will have negative interactions with anything in the biosphere is relatively low. As with all injection disposal methods, the surface footprint and chance of surface related problems are greatly reduced from that of a land treatment or landfill operation. Injection into a cavern also does not require as significant particle sizing and injection requirements as compared with both SFI and sub-fracture pressure slurry injection methods. The slurry may also be of much greater solids concentration and the oil content is not as critical for injection, which reduces operational costs.

While salt formations do exist in fairly wide regions elsewhere in the world, the proximity of the cavern space to operations and the volume of void available for waste disposal limit the use of this method. The relatively inexpensive cost of disposal in caverns only partially offsets transportation costs.

Regulatory concerns with cavern disposal have stimulated discussions on the interaction of waste components and the potential generation of gases that will raise the cavern pressure. This could potentially cause loss of containment, particularly after disposal operations have ceased and the cavern well is plugged and abandoned. The actual dimensions and depths of the cavern are of concern so that any destabilization of the cavern shape and/or reduction of the amount of free volume over time can be ascertained. A pre-operation evaluation of the cavern parameters utilizing sonar, high resolution seismic and/or magnetotelluric methods is necessary to fully assess the suitability of a cavern disposal operation at a particular site. These methods are all applicable, depending on the specifics of a particular cavern or cavern well, to the monitoring of the cavern status during its' life cycle. Such monitoring is necessary to determine cavern stability and extent. Salt dissolution caverns exist in both dome-shaped and bedded salt horizons. The overall shape of a domal cavern is critical in determining the stability of the roof and in being aware of impacts to tubulars that can affect the injectivity and overall safety of the operation. In bedded salt caverns, the issue of roof stability is increased with the increased potential to extent the cavern out of the salt beds vertically which may incur regulatory problems and complicate operations due to increased destabilization of the roof and the potential movement out of the permitted zone.

Summarising everything discussed above, all three methods of waste disposal by injection have proven themselves for drill cuttings and other E&P solid wastes disposal. The availability and regulatory parameters affecting each method will determine their usage. Overall economics and applicability must be considered in determining the method to employ.

Sub-fracture pressure disposal of solid waste slurried has been the dominant commercial method in the region where it exists. Overall success, reduction of long term liability, considerable available disposal volume and competitive costs have enabled its' success. The application of this technology to other locations is necessary to overcome the cost of transport to a distant facility. Consideration of the possibility that this option may exist in a future area of development could be considered as part of the pre-planning for a given development. The availability of the low-pressure injection option may provide significant cost savings during a given project.

Likewise, where cavern volume is available and disposal is permitted, the cost of disposal and the reduction of liability as compared to land surface methods of disposal give it a set of advantages. Both of these types of disposal methods have gained acceptance by regulatory bodies.

Slurry fracture injection has also proven itself as a method of disposal, providing isolation and containment of injected wastes by design. Despite problems with annular injection projects where injection and disposal zone parameters are not fully defined prior to implementation, the success of the many projects that have performed full design evaluations shows the viability of the basic process. As acceptance grows, the weight of success and the lobbying of the industry can be expected to bring about a greater acceptance of the process. SFI has the greatest advantage in terms of locations where it might be used. In addition, where oil and gas drilling is ongoing, wells exist and/or are planned that may be used as disposal wells if a successful match between slurry parameters and target zone characteristics can be made. The overall cost of implementation, including the particle sizing and high pressure pumping costs, should be compared to any nearby options, but in more remote locations their absence may clearly point to the application of SFI onsite as the most cost effective, environmentally sound and liability reducing option.

4.2. Assessment criteria for disposal site

The parameters recognized as the most important for a suitable target reservoir are permeability, porosity, thickness, depth, and structural geology characteristics of the area (Nadeem et al., 2005). Additional factors affecting the "security level" of a site (i.e. the "risk") include the details of the lithostratigraphic column overlying the target reservoir, cap rock thickness and nature, the presence of overlying fracture blunting horizons in the form of alternating sand-shale sequences, the tensile strength and compressibility of the reservoir, and the geographical distance between a waste source and the disposal site. Some of these parameters are discussed here briefly.

Permeability

Geomechanical Issues: When waste slurry is injected under high pressure into a subsurface formation, a zone of abnormally high pore pressure can be generated in-situ. This high-pressure zone and its outward growth could affect existing faults or trigger slip along bedding planes; therefore, it is important that induced pressure at a modest distance from the injection point be dissipated quickly after each interval of injection. Permeability plays a key role in the dissipation of pressure; high permeability allows the injected liquid to leak-off rapidly from the point of injection, allowing rapid pressure decline.

In general, stiff materials (e.g. shales and limestone etc.) tend to produce thin and long fractures, whereas porous and permeable materials having low stiffness (e.g. cohesionless sandstones etc.) evidence thick (wide in aperture) and short (in length) fractures. This contrast in fracture geometry also comes in part because of the different fluid leak-off rates associated with the permeabilities. Depending on aperture, thick, short fractures can entomb substantially larger amounts of solid waste than thin, long fractures. High permeability, however, makes fracture injection more difficult through rapid solids screen-out (a filtration process), which limits extensional fracture growth, leading to a wide "disposal domain" in the target reservoir through creation of multiple fractures . This disposal domain of multiple fractures allows a large volume of solid waste to be placed close to the injection well, therefore high permeability is favorable for the disposal of high volumes of waste, in spite of the potential greater difficulty in generating and sustaining a fracture during injection. In the case of small waste volumes, high permeability is not as critical a factor because a single hydraulic fracture plane may have sufficient “storage” volume. In case of strata of quite high permeability, for example more than 10 Darcy, build-up of enough pressure during a clear (no solids) water injection initiation phase is difficult because of high and rapid leak-off; therefore, permeability greater than 10 Darcy is considered as a negative factor for slurry fracture injection.

Fluid Flow Issues: In a permeable rock, the liquid phase of the slurry that enters into the rock mass during the solids filtration process will displace the natural waters of the rock. This process will allow polyvalent cations and other dissolved constituents to become diluted, dispersed, and adsorbed on clays and other minerals, and therefore be attenuated with distance from the point of injection, eventually making the injectate environmentally friendly. Based on previous slurry injection practice, multiple layers of shale (low permeability) and sandstone (high permeability) are considered best as a general geological target stratigraphy for solid waste disposal. When injection takes place into one of the lower sandstone layers in such a sequence, the upper layers of high and low permeability help to arrest upward fracture growth. The low permeability layers act as barriers for vertical fluid flow by Darcian advection, whereas the high permeability layers act as a rapid fluid leak-off zones which will tend to arrest upward fracture propagation and foster a solids screen-out blunting process whereby the high permeability rapidly dehydrates the slurry, causing sudden formation of a solid that can no longer flow within the fracture.

Porosity

Geomechanical Issues: High porosity media generally exhibit high compressibility, considered favorable for deep solids injection. Based on fieldexperience, injection pressures must be 15-30% more than shear stress to sustain continuous fracture injection of a slurry with solids. Thus, high pressure near the fracture reduces effective stresses, leading to a small expansion of the rock, and more importantly to a reduced effective confinement and shearing resistance. For weak sandstones, shear dilation takes place with high induced pressure; even 30% porosity unconsolidated sandstones exhibit shear dilation. Once injection ceases and leak-off is complete, the solids in the fractures are compacted and fully trapped by the high effective stresses in the disposal domain. At this stage, horizontal effective stresses will have permanently increased in response to the volume increase in the formation from high pore pressures, shear dilation and solids placement.

Fluid Flow Issues: High porosity is a valuable asset for a target reservoir for slurried waste. Empirically, for the same rock type (e.g. sandstone), the higher the porosity, the higher the permeability. Exceptions arise when pore throats can be blocked with mobilized fine-grained materials (interstitial clay and silt), but during slurry injection, large amounts of fine-grained materials are being injected in any case, partially blocking the pore throats as filtration takes place. This degrades local permeability massively because fluid discharge is proportional to pore throat radius to the fourth power: Poiseulle's Law,

$$Q = (\pi r^4/\mu l)$$

where μ is viscosity,

l is the length of the pore throat.

To permit sufficient leak-off capacity to be accessed by sequential fracturing episodes, high porosity is a positive factor for solids injection, as new fractures in different directions will encounter zones that permit good fluid leak-off. Secure deep disposal requires minimal vertical fluid migration from the repository; argillaceous rocks (clay, shale, smectitic sandstones etc.) overlying the target reservoir can act as cap rock. Therefore, a thick, wide-spread shale unit can prevent vertical fluid migration, especially if there is a high horizontal permeability because of interbedded sandstone layers. Both fracture and granular (matrix) porosities are important in rocks with low matrix permeability, such as jointed limestones. The fracture network provides sustained leak-off capability even if the fractures become largely blocked by injected solids because unit discharge is proportional to the third power of the fracture aperture: $Q \propto a^3 b/\mu l$, where a is aperture, b is fracture extent, and l is the flow path length in the fracture. Furthermore, distortions generated in the fractured target rock by packing induced fractures with solids should increase the aperture of many of the fractures in the natural network, opening blocked fractures and allowing new flow paths to develop for leak-off. Matrix porosity, even with low permeability, provides some volume for injectate after it is filtered near the facture walls. However, natural porosity does not provide the solids storage capacity needed; this is provided by the volume of the induced fractures. Nevertheless, low porosity implies less storativity and more difficulty in compressing the rock mass to achieve the apertures needed, and the development of a stable disposal domain is far more problematic in stiff, low porosity rocks. At present, solids injection into low porosity fractured rocks is deemed feasible, but such conditions would in general be less desirable than those associated with high porosity sandstones.

Reservoir Depth

Depth of a target reservoir for solids injection affects site location in several ways. First, the target reservoir should be isolated from drinking water aquifers and distant from any location of economic interest such as active oil reservoirs or mines. Remoteness from drinking water almost always is directly related to depth because the great majority of aquifers are within 200 m of ground surface. Hence, $z < 200$ m is considered a “no-go” condition, but this must be re-assessed in regions that have deep potable water aquifers.

Cost Related Issues: Depth affects both capital and operating costs. Capital costs involve the higher cost of deep wells, and need for more robust surface equipment. Operating costs are increased because horsepower requirements and well maintenance costs increase. For each km depth, approximately 18-20 MPa excess surface pressure is needed to achieve a typical slurry injection rate of 2.5 m^3/min. Furthermore, well servicing and maintenance costs are greater, thus at some depth economic penalties impinge upon the value of reduced environmental liability.

Environmental Issues: Deep disposal in a permeable geological formation minimizes chances of leachates leakage through conventional fluid flow. Leak-off during fracturing weak, unconsolidated, and permeable formations dissipates pressures rapidly, therefore fractures cannot remain open and the pressure gradients required for fluid migration to shallower depths can not be sustained. Even if pathways existed, deep placement implies that the paths are long, dominated by horizontal flow because of stratification, and characterized by slow flow rates once injection ceases. Along possible pathways there are more storage sites, dispersion, and interaction of liquid phase constituents with fine-grained minerals that provide sorption and cation exchange sites that reduce or eliminate transport of dissolved heavy metals or polar organic molecules. Thus, there is a natural “purification” or “decontamination” process that reduces environmental risk while leachates are migrating, and liquids would be “cleaned” long before reaching the surface or potable water sources, providing that the injection sites have been properly chosen.

Waste Type Issues: Depth is also related to the amount and type of solid and liquid wastes that are being injected and the perceived or assessed risk. In the case of non-hazardous material, for example non-toxic municipal waste, a shallow target depth does not pose any serious environmental concern. On the other hand, hazardous waste, for example nuclear and toxic waste, requires a high level of security. For hazardous waste, environmental agencies have specific regulations for deep injection operations depending upon the nature of the material. Generally, for such materials, deep target reservoirs with multiple impermeable to semipermeable rock layers in between the reservoir and the water aquifer would be desirable. Minimum injection depth would be far greater than the 200 m mentioned earlier.

Reservoir Thickness

The liquid volume that can be disposed by hydraulic fracturing depends upon the liquid storage capacity of the target reservoir rock; i.e., the thickness, areal extent, and porosity of the contiguous reservoir body. An ideal target is thick and extensive to accommodate a large waste volume (liquid and solid) without pressure build-up, and to allow multiple wells to be placed in a convenient and efficient pattern. On average, waste slurry will have a volumetric fraction of 0.10 to 0.25 solids, which will reside in emplaced fractures at a porosity of ~30%. Thus, for each m^3 of slurry, there is from 0.65 to 0.85 m^3 liquid to dissipate (store) in surrounding rocks. A thick and areally wide-spread target unit will accommodate this liquid through displacement, with a factor (0.4 to 0.6) applied for some of the pore volume that might not be displaced. For example, assuming 0.50 for incomplete displacement, a channel sand averaging 30% porosity, 25 m thick and 2 km width could store at least 7.5×10^6 m^3 per kilometer length ($2000 \times 25 \times 1000 \times 0.30 \times 0.50$) of the aqueous phase. Assuming slurry average injection rates of 2000 m^3/day, each km of the channel could accommodate injection for over 10 years. Since blanket sands of great lateral extent are fairly common in sedimentary basins, areal extent is rarely an issue in site selection. A thick geological formation composed of alternating litho-units of high and low permeability will be more conducive to the identification of zones of multiple layers of suitably porous and permeable beds at different depths for injection operations.

Structure and Tectonic Setup

Because solids are permanently immobilized, aqueous phase leakage from the target disposal stratum and the surrounding security zones is the most critical issue related to deep waste injection. Natural faults, fractures, solution chimneys, and steeply dipping formations could provide channels for fluids to move towards the ground surface and interact with aquifers in a short time frame and over a short distance, so that the waters are not cleaned sufficiently by sorption processes. Potentially, seismic activity could accelerate this process if the deformations are appropriate. In cases that are not flat-lying sedimentary strata, detailed study of the local structure (faults, fractures, folds and so on), inclination of sedimentary strata, and regional study of the tectonic framework are used to refine site selection. This is performed at a suitable scale, perhaps as much as an area five to ten times the expected area of influence of the injection well (r = 200 to 1000 m). From a primary reconnaissance level, the tectonic or structural framework of a region can be classified as complex, intermediate, or simple on the basis of structural and tectonic studies. An ideal site for a deep waste disposal project should be tectonically and structurally simple and passive, with no history over a period of several million years of massive seismicity or large deformations. Ideal geological settings are, of course, related to undeformed forelands, passive continental margin basins, flat lying or low dip strata in small stable basins, and so on. Furthermore, if it is evident that pore pressures will be easily dissipated, one may be confident that there will be no impact on large amplitude seismicity.

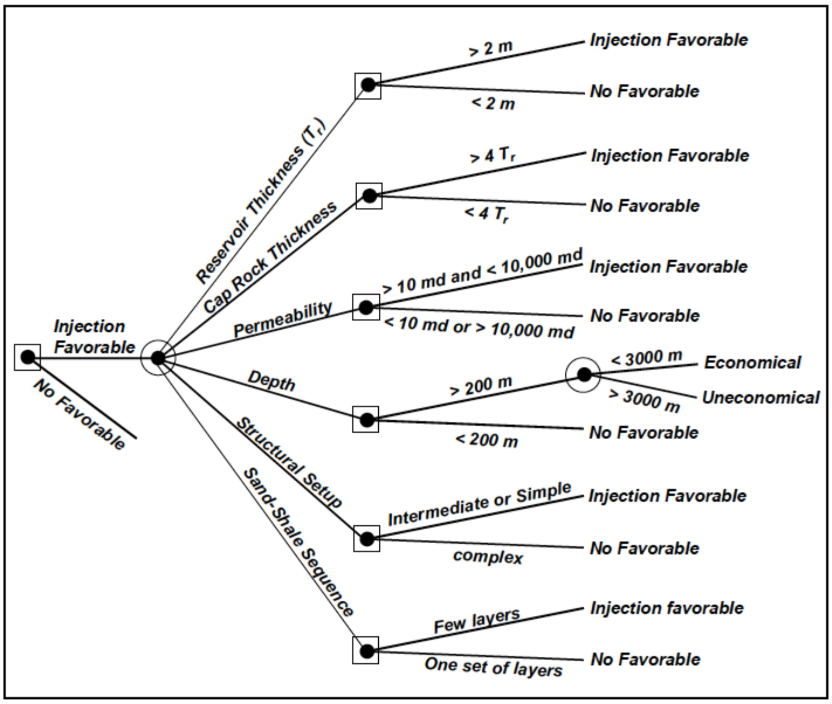

Figure 5. Decision tree showing limits for critical value

4.3. Necessary ground facilities and equipment

SFI field equipment are positioned onsite within 60 meters of the injection well (Margaret Sipple-Srinivasan et al., 1997). The field equipment for a typical SFI project is a Slurry Disposal Unit (SDU) including feed hopper and conveyance system for the waste material grinding and slurry mixing components, a water supply pump, and a high pressure downhole pump (Figure 6).

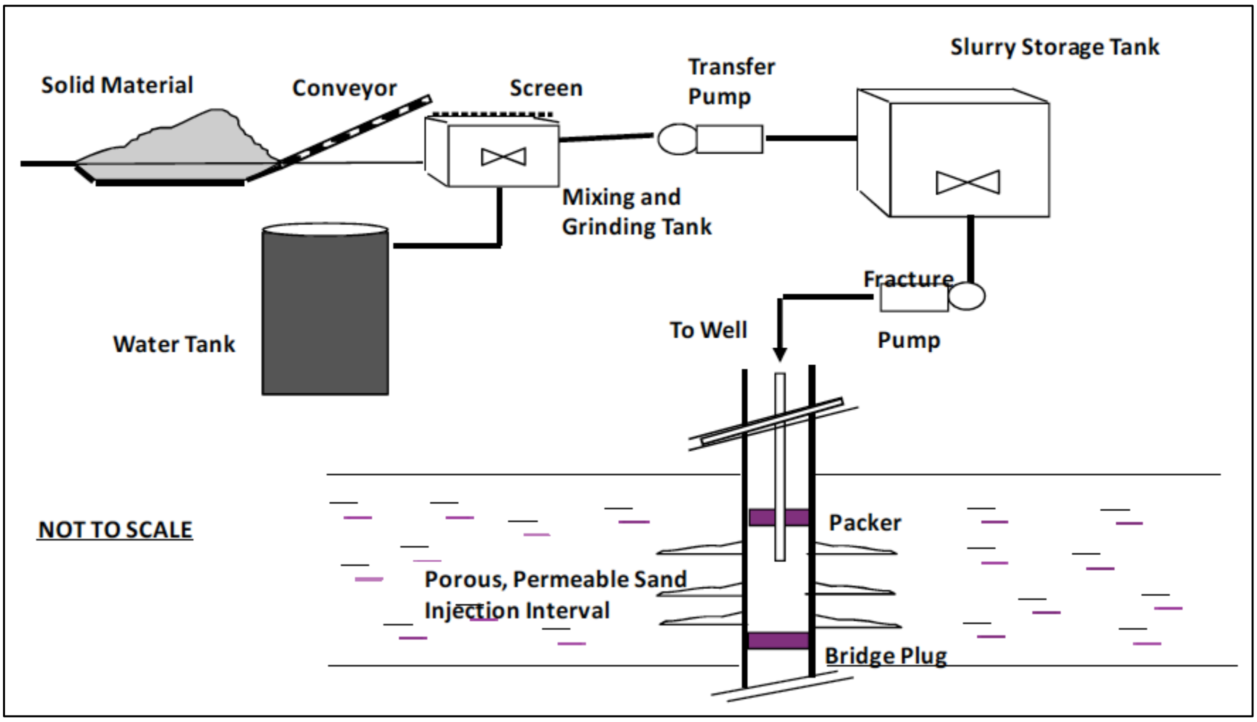

Figure 6. Components of a typical slurry fracture injection process

Other critical field elements include a pad with appropriate overspill containment features and an impermeable liner for the SDU, sufficient storage area (tanks or pits) for the solid and liquid waste, and tanks for the water supply. In addition, appropriate monitoring equipment to optimize operations, electrical power, and adequate infrastructure to access the field location are required.

Figure 7 shows an example of slurry processing and injection equipment.

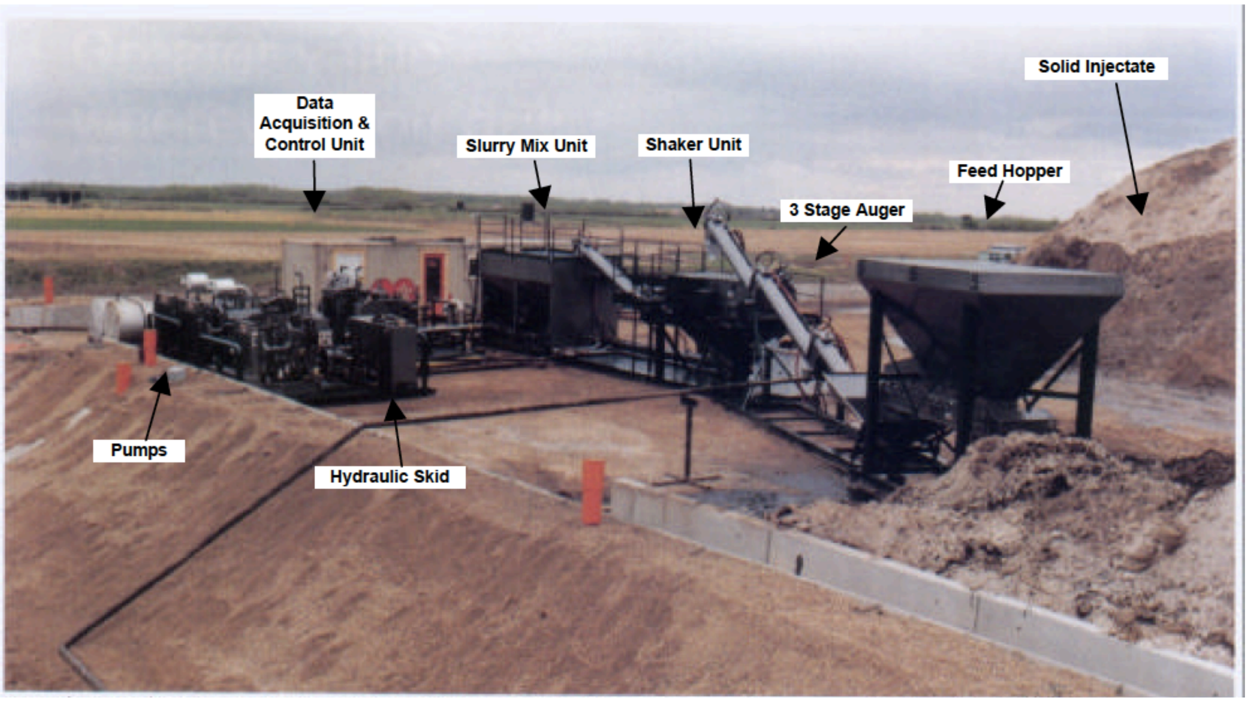

Figure 7. Photo of slurry processing and injection equipment

As for offshore platforms, the whole injection system has to be «packed» to occupy as less area as possible. For example, figure 8 shows waste injection system at russian platform Prirazlomnaya.

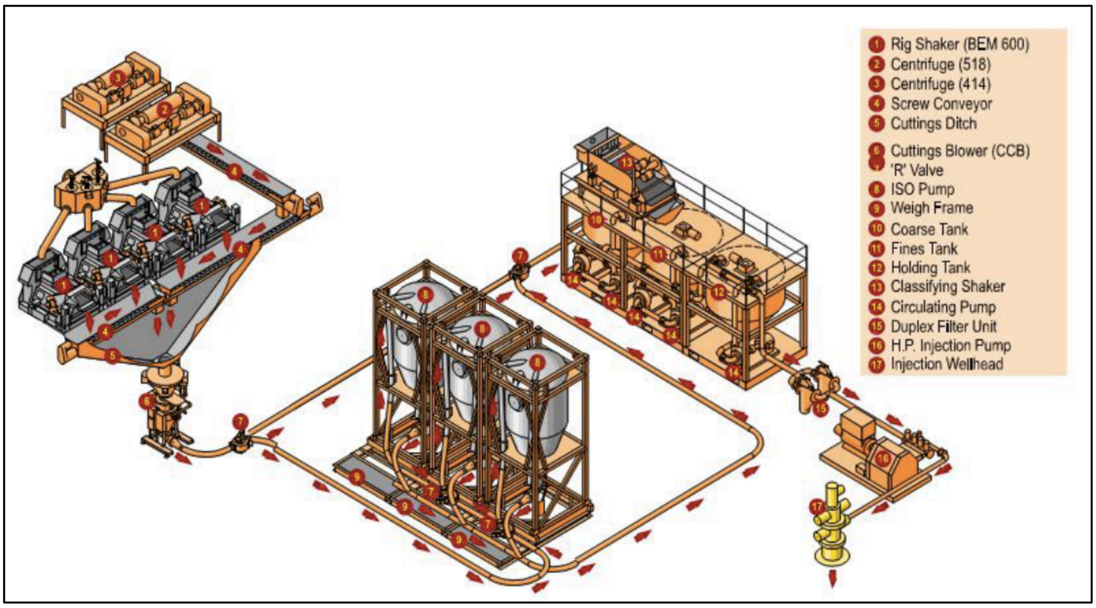

Figure 8. Prirazlomnaya platform waste injection system

Waste injection well profile at Prirazlomnaya platform is shown in figure 9.

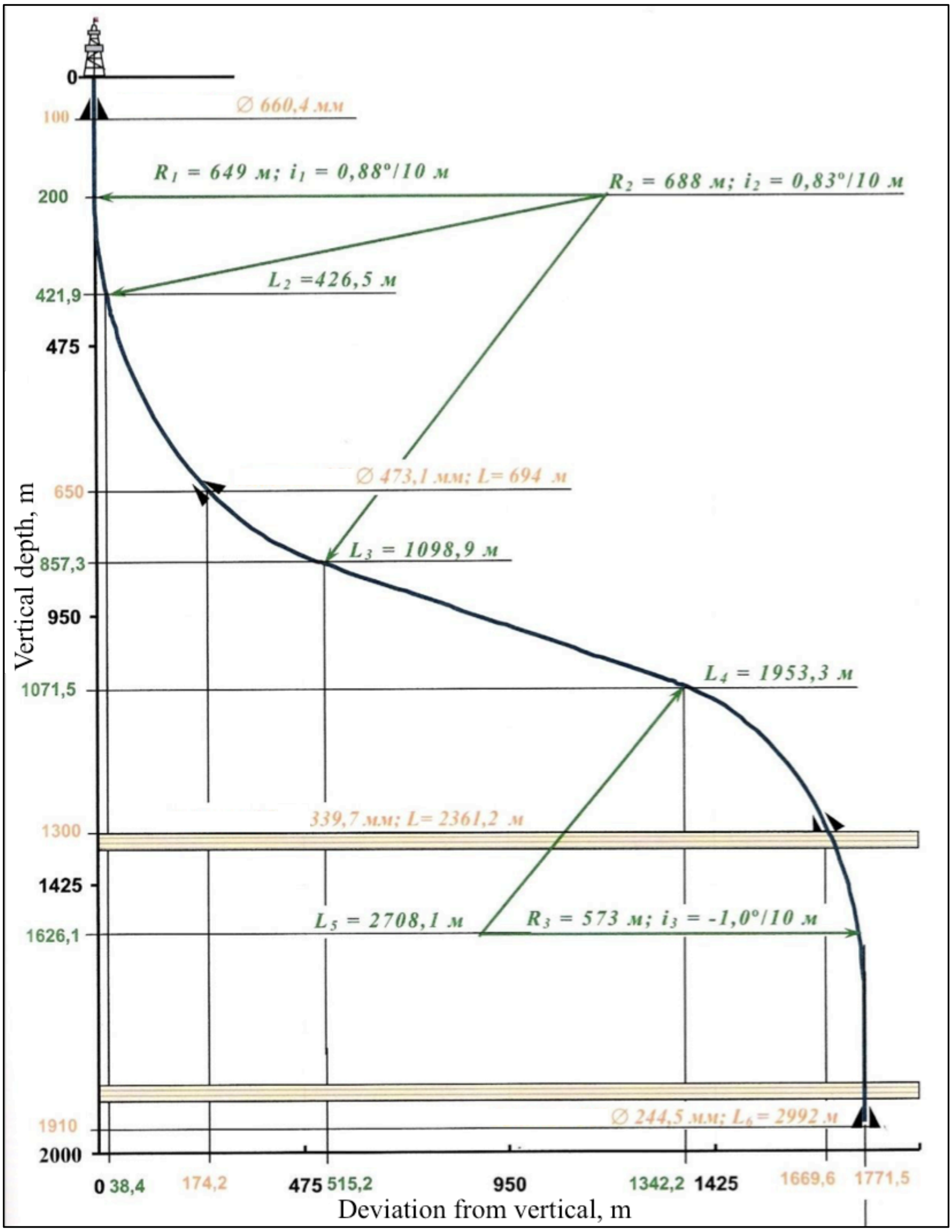

Figure 9. Waste injection well profile

An interesting fact in this profile is that injection well penetrates two target formations. These formations are highlighted with beige colour in the picture. The waste injection program at Prirazlomnaya platform starts with injecting in lower formation located at 1755.8 – 1848.6 meters depth. When the capacity of lower formation is full, this interval is plugged with cement and injection completion is moved up to second target formation located at 1223.4 – 1469.8 meters depth. Perforations and other preparation activities are performed at this interval and waste injection program continues.

A typical well completion for slurry waste injection is presented in Figure 10.

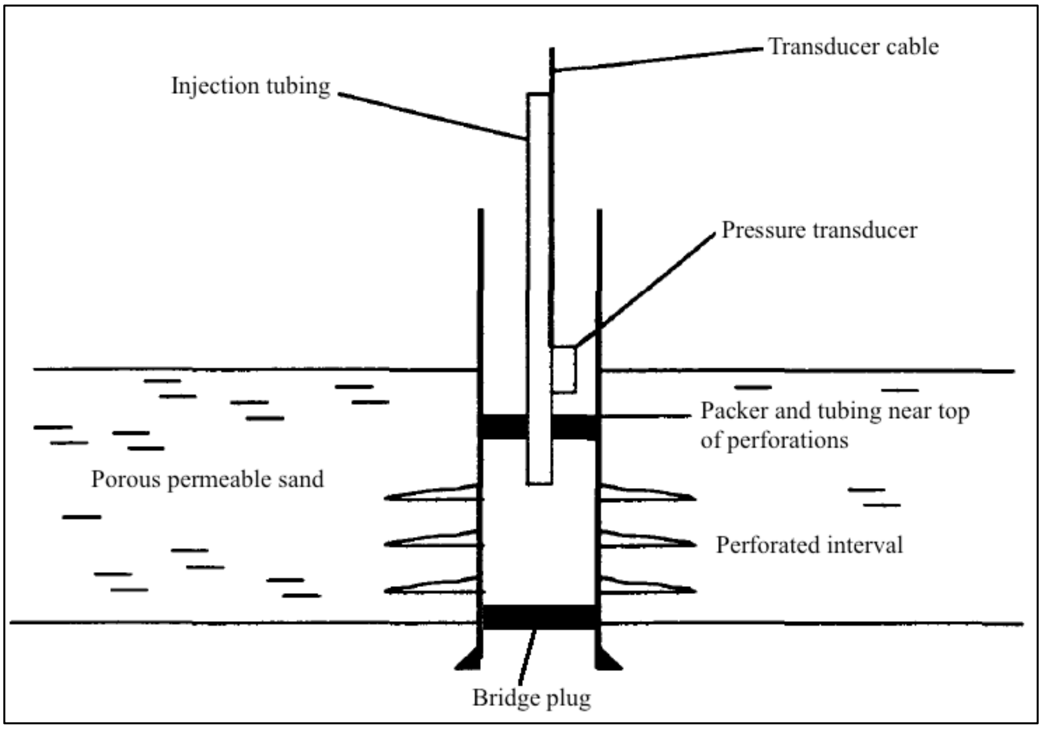

Figure 10. Scheme of typical well completion for slurry fracture injection

The target formation must be hydraulically isolated during SFI operations. Packers are placed above and below the target interval to facilitate formation isolation. Before injection starts, pressure fall-off and step rate tests are performed in order to evaluate flow behavior and injectivity in the target formation. The well casing is perforated begining at the bottom of the injection interval. The perforaton interval should not exceed 10 meters in length in order to sustain high injection pressures and rates. The perforation density is typically 20 shots/meter and covers between 90° and 120° phasing to ensure good radial distribution around the well.

The packer/tubing assembly is installed close to the top of the perforation interval and should not extend into the perforation interval.

The waste material is processed through the SDU which is connected to a supply of fresh or produced water. The resulting slurry is introduced into a slurry pump capable of achieving high pressures and high rates. The slurry is then pumped down the well where it exits through the perforations and enters the formation. The injection pressure of the slurry is sufficient to overcome parting pressures in the formation. The natural pressure in the porous strata is far less than the water pressure in the slurry, providing a strong natural gradient that draws the water away, leaving the solids component behind.

The SFI operations strategy is formulated based on the specific geology of the field location and on the characteristics of the waste stream. The primary geologic considerations are thickness of the target formation, porosity, and permeability of the rock matrix discussed above. The viscosity and composition of the liquid waste stream and the grain size and composition of the solid wastes must be well characterized in order to develop appropriate parameters for successful injection. Optimal grain-size for successful injection ranges from 2 μm to 350 μm. Finer grain material tends to clog the pore space in the disposal formation while coarser grain material settles in the wellbore and interferes with the injection process. The solids concentration in the slurry can be as high as 30 to 40 percent by volume for fine grained material (less than 150 μm) and on the order of 20 percent by volume for coarser materials.

SFI is typically accomplished in periodic stages, generally lasting for 8 to 14 hours of injection with shut-in periods lasting from 10 to 72 hours. This allows the stress and pressure fields generated within the formation to redistribute and dissipate between injection episodes. Local (near wellbore) changes in stress and flow behavior are carefully monitored by surface and wellbore sensors to optimize injectivity and to track formation response to the injected solids. The injected fluid bleeds off and pressure returns to normal. Injection then resumes for another cycle. Figure 11 represents typical pressure history during waste injection operation.

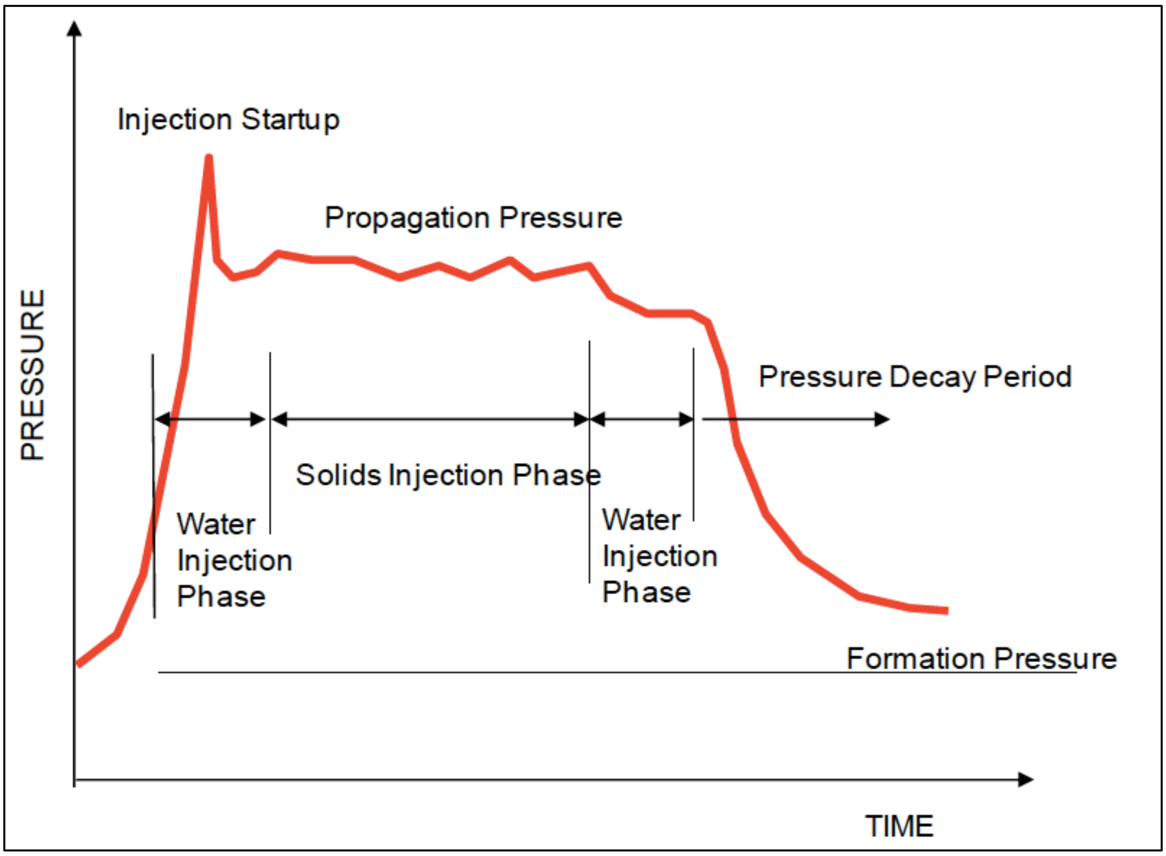

Figure 11. Pressure history during slurry fracture injection

The longterm formation effects of sustained injection are not fully understood at this time. However, experience has shown that it should be possible to inject large volumes (more than 50,000 m^3) of waste solids and liquids into the same formation over extended periods of time.

4.4. Technical parameters of the process

In methods of solid waste disposal such as drill cuttings injection, it is advantageous to inject solids in a cyclic or an intermittent manner in order to control the injection pressure (Bai et al., 2006). The cyclic injection simulations were tailored to meet certain special requirements characteristic of cuttings injection operations. In particular, attention was focused on identifying different fracture responses during shut-in and re-injection cycles in order to deduce if an existing fracture was re-inflated, or a new fracture was generated at an orientation different from the original fracture propagation direction. Comparisons were made between conventional injection and cyclic injection to suggest the role of fluid rheology, screenout, injection rate, fluid leakoff, extent of the disposal domain, and geometry of the hydraulic fracture under various in-situ stress and flow environments. "Typical" hydraulic fracture in a relatively brittle formation, its maximum length and height may be in the range of a few hundred to a thousand meters and its width might be up to 3 cm and this average fracture volume could correspond to on the order of 200 m^3 if the fracture is fairly well contained. In actual cuttings injection situations, millions of barrels of slurry have been injected over periods of years. The standard questions are "Where has it all gone?" or "What sort of fracture network could possibly have accommodated this much material – a single fracture seems unlikely?"

At least two scenarios for accepting these large cuttings volumes have been proposed. Some is certainly accommodated by limited penetration into the matrix; some may be taken by mixing with the matrix; most is speculated to be taken by the development of a complex fracture network.

It has been hypothesized that creation of multiple fractures is a likely mechanism; particularly in stiff formations and that the tendency for multiple complex fractures is enhanced by repeated, cyclic injection and shut-in cycles.

Cyclic injection is a complimentary relationship between operational requirements and physical objectives. Operationally, periodic shut-ins allow adequate time for cuttings slurry generation, equipment maintenance, crew changes, and adjustment of injection schemes, etc. Physically, periodic shut-in allows fluid to leak off into the formation and the fracturing pressure to dissipate. In addition, cyclic injection takes advantage of local re-orientation of the principal stresses due to solids loading and poro- and thermomechanical stress field alterations which likely initiates new fractures at changed directions from that of the initial hydraulic fracture.

A three-dimensional hydraulic fracturing simulator is usually used to simulate cyclic injection and to assess the pressure regimes associated with cyclic injection and shut-in in a single, hydraulic fracture.

4.5. Existing practices in Russia

Prirazlomnoye field development required drilling of separate well which main function is subsurface injection of drilling waste, waste muds and waters. The details of cuttings injection system at Prirazlomnoye field were thoroughly discussed in previous chapters of current work.

Nowadays, subsurface reinjection of drill cuttings and used mud often is the most cost effective, environmentally acceptable method to dispose of drilling waste products. This is particularly true for drilling operations in remote and environmentally sensitive areas.
This method is utilizes offshore Sakhalin Island at Piltun-Astokhskoye field where drilling waste treatment and management facilities are limited at shore areas (Guo et al., 2005).

Company operating Lunskoye offshore gas field located on continental shelf of Sakhalin Island implements the same technology. The environmental commitment to zero discharge means the ability to dispose of drill cuttings and waste fluids from LUN-A platform by injecting them below the Lunskoye producing reservoirs for uninterrupted drilling operations. The first well drilled from the platform was a difficult deep Cuttings Re-Injection (CRI) well (Juun van der Horst et al., 2010).

Chayvo field development process involved drilling waste management option discussed above (Roxburgh and Kostiuk, 2009). In June 2003, the drilling rig Yastreb began drilling a cuttings injection well, and the first well was spud on August 8, 2003. Since then, the Yastreb has successfully drilled and completed 17

Extended Reach Drill (ERD) wells with the longest well reaching more than 13 km.

Even in some onshore areas cuttings re-injection technology is being utilized. For example, the South part of the Priobskoe field, located in Western Siberia on a flood land of the Irtysh River, is an environmentally sensitive area (Fetsenets et al., 2009). Zero discharge regulations prohibit cuttings discharge and spills of liquid wastes on the surface.

The major hurdle for the drilling campaign is the cost of transportation of the vast amount of drilling waste generated from multiple rigs. Moreover, during spring or fall, such transportation is impossible because of the absence of winter roads and rivers are impassable due to flooding or ice movement.

A joint effort between a major oil company in Russia and a waste management service company selected waste re-injection technology as the most efficient, economical and environmentally friendly way to handle the drilling waste in the field.

5. Ways of future improvements

The direction that drilling waste disposal takes in the future will be determined by several factors.

The first key factor is regulatory changes. In developed regions, like the United States and the North Sea, requirements for managing offshore drilling waste are becoming stricter over time and are likely to continue on that course. In regions with developing oil and gas production, regulatory programs are likely to become more mature and better thought out.

A second key factor is waste management cost. If an operator or a service company can develop a method for drilling waste disposal that offers significantly lower cost and equivalent or better environmental protection, operators are likely to shift their waste management patterns to the new options. There will most likely be a delay in wide acceptance of the new approach as both operators and regulators gain familiarity and comfort with the new option.

The third key factor is liability to the operator. The total cost of waste management to an operator includes more than just the immediate cost of managing the waste. For example, in United States under the U.S. Superfund law, a company could dispose of its waste in an approved fashion today yet face remediation liability in the future if the disposal operation later results in environmental contamination or harm. Therefore, operators must make an educated guess about the long-term suitability of their chosen waste management approach. New management options that are believed to reduce long-term liability may be given higher priority.

The next few paragraphs offer some thoughts on how drilling waste management may take in the future.

Waste Minimization. The oil and gas industry has worked diligently to develop new drilling products and technologies that help minimize the volume and environmental impact of drilling wastes. In the 1990s, drilling fluid companies developed new types of fluids that used nonaqueous fluids (but that were not oils) as their base. Examples of these base fluids included internal olefins, esters, linear alpha-olefins, poly alpha-olefins, and linear paraffins. Synthetic-based fluids have revolutionized offshore drilling by creating synthetic-based muds (SBMs) that share the desirable drilling properties of oil-based muds but that are free of polynuclear aromatic hydrocarbons, have lower toxicity, faster biodegradability, and lower bioaccumulation potential. For these reasons, SBM cuttings are less likely than oil-based cuttings to cause adverse sea floor impacts. Synthetic-based muds drill a cleaner hole than water-based muds, with less sloughing, and generate a lower volume of drill cuttings. Synthetic-based muds are recycled to the extent possible, while water-based muds are discharged to the sea.

The advent of coiled tubing drilling equipment allows wells to be drilled with much smaller cross-sectional areas, thereby reducing the volume of cuttings leaving the well and the volume of mud used for the drilling process. While coiled tubing may not be suitable in all applications, where it is employed it will directly help to reduce and minimize waste generation.

Directional (or slant or horizontal) drilling has opened many new opportunities for waste minimization. The most obvious example is that fewer central drilling facilities, such as offshore platforms, need to be established if this type of drilling is employed. Some wells have been drilled to end targets up to thousands of meters of horizontal separation away from the wellhead. Avoidance of multiple drilling facilities is a wonderful environmental benefit, although not one directly related to drilling waste. However, the ability to drill multilateral wells from the same starting wellhead does reduce the volume of drilling waste. The upper portion of each well is larger in diameter than the lower portion of the same well, and drilling the upper section generates more waste per foot drilled than does the lower section. Thus if multiple sidetracks can be drilled at lower depths from the same main well bore, production can be increased without the need to drill several sets of large-diameter upper well bores.

Drilling fluid companies are developing new fluid systems that are much more applicable to different types of land application of the subsequent drilling wastes. It is likely that companies will develop fluids with suitable drilling properties yet that contain fewer components or additives that would inhibit vegetative growth.

Other developments in drilling fluids could lead to entirely different formulations. Drilling fluids based on formate brines were reported to be more environmentally friendly than traditional fluids. Wider use of such drilling fluids may or may not reduce waste volumes, but according to that author, could reduce the mass of undesirable chemical constituents that are released into ocean waters. In a similar way, substitution of some of the key components of drilling fluids with new, more environmentally friendly products could reduce mass loadings to the environment. A proposed example of this practice is the use of ilmenite ($FeTiO_3$) instead of barite ($BaSO_4$) as a weighting agent in drilling fluids.

Another example is utilization of new generation drilling fluids. A universal fluid (UF) provides an example of modern solution. UF is typically a water-base fluid that has been treated with finely ground blast furnace slag and still maintains the appropriate characteristics of a good drilling fluid (Nahm et al., 1998). The slag becomes concentrated in the filtercake formed while drilling permeable formations and slowly sets to form a hard layer intimately bonded to these formations, improved zonal isolation can be obtained by using a UF and subsequently cementing with Slag-Mix (mud-to-cement conversion process using slag) technology.

Complete mud displacement and efforts to remove filtercake are not necessary prior to cementing since the solidfled UF filtercake bonds strongly both to the formation and to the cement. UFs have been used to improve zonal isolation and to reduce or prevent lost circulation or cement fallback during drilling and cementing.

An integrated slag solidtilcation method for environmental management involving the solidification of drilling wastes is possible. All drilling waste such as drilled cuttings, drilling fluids, cement returns, unused or residual cement blends and other wastes can be solidified into a mud concrete which can be land-buried in a reserve pit if needed or discharged to the sea.

If a UF is used as a drilling fluid rather than using a conventional mud system, solidtification of the waste fluids becomes much easier and cheaper since a major part of the required hydraulic material is present. The drilling wastes properly solidified by using slag do not leach volatile or semivolatile organics into ground water. Properly treated waste materials can be safely discharged.

The UF was used while drilling a test well. Caliper logs indicated that the average diameter of the UF drilled section was 0,272 m, considerably better than 0,322 m of the same section of a previously drilled well with conventional drilling mud and same diameter of the bit.

Two benefits derived from the use of a UF have been demonstrated:

(1) reduction of the hole wash-out volume and

(2) solidification of excess drilling fluid and drill cuttings for environmentally acceptable waste disposal.

The improved drilling technologies identified above will be further developed, and new tools and methods will continue to reduce the volume of drilling waste generated.

Recycle/Reuse. Used oil-based and synthetic-based drilling fluids are typically recycled to the extent possible. Recycling avoids the potential release of large quantities of waste to the environment. Most drill cuttings are managed through disposal, although some are treated and beneficially reused. Some drilling wastes are thermally treated to remove the hydrocarbon fractions, many of which can be recovered for reuse, leaving behind a relatively clean solid material that can be used for landfill cover. In other cases where a market exists for concrete aggregate or construction fill, cuttings that have been screened or filtered to remove most of the attached liquid mud fraction can be beneficially reused for such purposes. The chemical characteristics of the cuttings and any remaining fluids must be carefully controlled to avoid any conflicts or problems with the reuse.

Thermal treatment was discussed as a present option. The technology, while certainly in use today, tends to be expensive and not suitable for use onsite at offshore platforms. Improvements will likely be made to thermal treatment technology that result in lower treatment cost, good recovery of organic base fluids, and new models that improve safety sufficiently so that they can be used on platforms.

New beneficial reuses for drill cuttings as additives to products will probably be developed. As waste management costs increase over time, companies are likely to become more creative in developing new reuse strategies.

Disposal. Some of the most basic waste management approaches, such as burial of drilling pit contents, may become used less frequently. A strong motivating factor for this trend to occur would be regulatory pressure against pit burial. The approaches involving underground injection are likely to receive more interest and attention.

Burial in Landfill. Some landfills dedicated to oil and gas waste are located in areas of high oil and gas production. In other areas where insufficient oil and gas production exists to support a network of commercial oil field waste disposal facilities, operators may take drilling wastes to municipal or industrial landfills, as long as the wastes can meet the acceptance requirements for the landfills.

6. Environmental impact and regulatory issues

The elimination of the waste stream from the surface and its’ isolation from any usable subsurface bodies of water and aquifers are two main regulatory drivers impacting all disposal operations. Every country has its own set of regulations and laws that govern industrial waste disposal activities. For instance, in USA there is a special organization called The National Pollutant Discharge Elimination System which targets the elimination and removal of wastes from surface waters as the Safe Drinking Water Act of the Clean Water Act provides for controls assuring protection of subsurface water resources.

The continuing reassessment, reinterpretation and implementation of these basic acts as progress is made towards their ultimate goals provides the major driving force for development and implementation of the aforementioned methods of disposal. And that force is surely affected by the public perception of the issue of disposal, the safety and reliability of a proposed method and the intention of the industry to deal with the issue of disposal.

While the application of each method of disposal by injection has the common goal of satisfying the regulatory, economic and technical issue, each injection method has its’ own set of technical issues that relate to the particular regulatory and economic drivers of each individual project or situation. Such parameters and issues vary somewhat for slurry fracture injection, sub-fracture slurry injection and cavern injection in their various forms as means of solid waste disposal.

Despite of the method chosen for waste disposal, all materials to be injected must be properly tested and classified for the proposed type of injection. The mechanical integrity of the injection well and nearby wells penetrating the injection interval must be confirmed. And finally, containment of the injected material must be clearly demonstrated and documented through design, analysis, and process monitoring.

7. Risk assessment

The term “Risk” can be defined as a possibility of obtaining an unwanted result due to the existing uncertainty in the problem under analysis expressed numerically as a certain number from the interval [0, 1] and identified as a chance of getting an unwanted result (Zolotukhin, 2016).

Hazard identification (HAZID) is “the process of identifying hazards, which forms the essential first step of a risk assessment (GL, 2008). There are two possible purposes in identifying hazards:

- To obtain a list of hazards for subsequent evaluation using other risk assessment techniques. This is sometimes known as “failure case selection”.
- To perform a qualitative evaluation of the significance of the hazards and the measures for reducing the risks from them. This is sometimes known as “hazard assessment”.

The objectives of the HAZID procedure aims are to identify main hazards, to review the effectiveness of selected safety measures and, where required, to expand the safety measures in order to achieve a tolerable residual risk.

The analysis proves that installations are operated such that hazards for employees, assets, the environment and the surroundings can largely be excluded. The operator’s management gets an up-to-date picture of the present hazards and their possible effects. By means of the HAZID analysis the primary process, but also non-process, hazards as well as their possible escalations can be identified due to the structured manner of the procedure. Employees can be advised of the relevant hazards concerning their working area. The system designer considers the analysis results to improve safety concepts for future system development.

The HAZID work process is divided into three steps:

Step 1: Hazard identification

Step 2: Risk estimation

Step 3: Recommended additional safety measures.

In the following paragraph the HAZID Risk matrix was chosen as an instrument for qualitative risk analysis. Figure 12 describes key features and explains the meaning of risk probability and its influence on personnel, assets, environment and company reputation.

Severity code	Consequences				Probability				
	Personnel	Assets	Environment	Reputation	No occurance in industry/	Has occurred in industry	Has occurred within the operating	Has occurred within the operating	Occurres within the operating company
Minimal	Negligable injuries/illness	Negligable damade	Negligable impact	Negligable impact	🟩	🟩	🟩	🟩	🟨
Low	Minor injuries/illness	Minor damade	Minor impact	Minor impact	🟩	🟩	🟩	🟨	🟨
Medium	Major injuries/illness	Medium damade	Locally limited impact	Regional impact	🟩	🟩	🟨	🟨	🟨
High	1-3 fatalities	Major damade	Major impact	Superegional impact	🟩	🟨	🟨	🟨	🟥
Very high	Several fatalities	Total loss	Massive impact	National impact	🟨	🟨	🟥	🟥	🟥

Figure 12. HAZID Risk matrix

Potential risks during waste disposal activities and risk mitigation measures Risks always exist despite waste disposal method was chosen either transportation to shore or underground injection. Both cases are discussed below.

The most dangerous steps in shore transportation method are waste loading to service ship and transportation itself. The following risks may be faced:

Risk: Waste leakage during offloading.

Drilling waste or waste water might leak during offloading and pollute adjacent water. Another leakage might occur if offloading was not stopped in a certain moment and receiving tanks became overloaded.

Mitigation measures:

This risk probability might be reduced by appropriate maintainance and pre-checking of offloading equipment. Continuous supervision of offloading process should be carried out including controlling of offloading flowline integrity and waste level in receiving tanks.The faster the leakage is detected, the smaller it would be and consequenses will be much less severe. A great mitigation measure might be implementation of emergency automatic shutdown system which would stop offloading process in case of any unforeseen situation.

Personnel should be instructed in safety measures and have special means of personal protection.

Visual image of the risk using **Risk Matrix**:

(A – before mitigation measures; B – after risk mitigation)

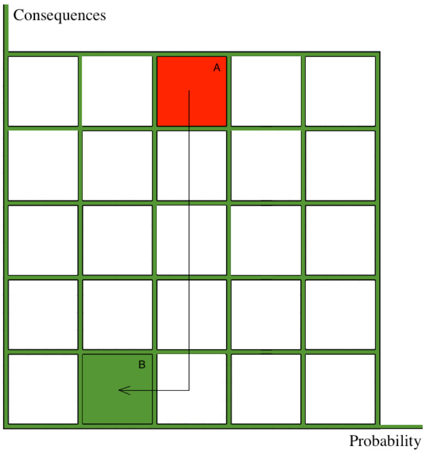

Figure 13. «Waste leakage during offloading» risk matrix

Risk: Weather conditions exceed limits (storm).

There can never be 100% confidence in weather forecast. Every offshore activity has its own number of criteria that put limits on conditions either to start it or not. If these limitations are ignored due to human factor or poor management, the consequences might be severe. This may lead either to big waste leakage or even to service ship capsize leading to giant environment pollution and personnel death.

Mitigation measures:

Waste offloading and transportation processes must not ecxeed any limitations according to technical instructions: either maximum load capacity or weather conditions.

Personnel responsible for operation should thoroughly know all limitations of the process and be instructed in safety measures in case of contingency.

The reliability of the weather forecast shall also be as high as possible.

Risk matrix

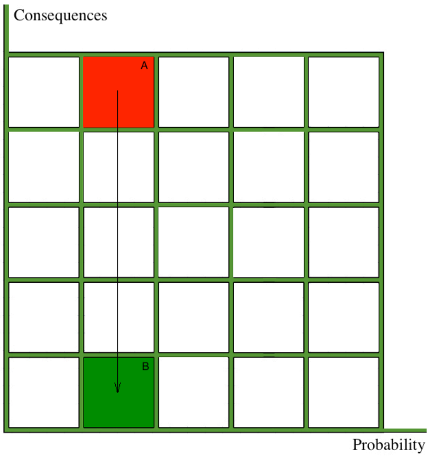

Figure 14. «Weather conditions exceed limits» risk matrix

Risk: Platform tanks overload.

Uncertainty exists in properties and characteristics of subsurfase formations. Rock being underground is tightly packed, but being drilled out it increases in volume because of surface area growth. This issue may lead to drilling waste volume growth rate higher than predicted in project which in turn may lead to receiving tanks overload and waste leakage.

Mitigation measures:

Thorough analysis of rock properties has to be carried out during exploration drillind. Core samples tests should be done to identify characteristics of underlying formations.

According to rock properties a precise calculations of drill cuttings volume should be done. This volume should be the basis of drilling mud circulation and waste storage system design at the planning stage of the project.

Moreover, waste storage system has to be equipped with several additional tanks which will serve as extra volume in any case of contingency.

Risk Matrix:

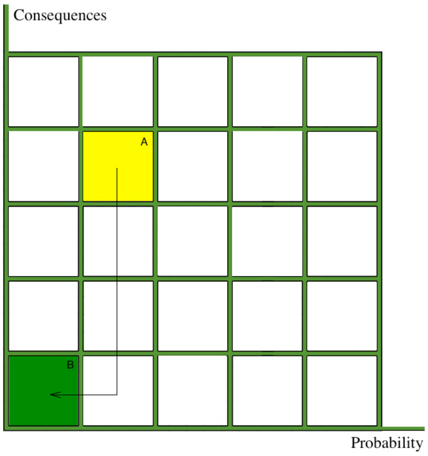

Figure 15. «Platform tanks overload» risk matrix

Risk: Power supply failure.

The power supply failure will lead to the loss of circulation and pump shutdown. The consequences may be difficult to remove – clogging and slugging in any part of circulation system. The most unwanted problem is plugging of bottomhole area.

Mitigation measures:

Offshore vessel has to be equipped with emergency power supply system. There should be redundancy in power supply even in unpredictable emergency cases.

Risk Matrix:

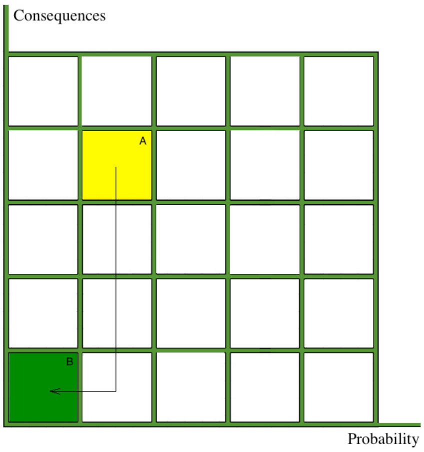

Figure 16. «Power supply failure» risk matrix

Some specific risks are relevant to waste underground injection method. They are presented below.

Risk: Underground leakage from disposal site to upper formations.

Slurried waste might seep through natural cracks and disintegrations in cemented annulus of upper casings. This case may lead to contamination of ground waters and aquifers and it is extremely hard to detect this type of leakage.

Mitigation measures:

As it is impossible to detect waste seepage between formations, this risk should be eliminated at the construction phase of disposal well.

It can be achieved by proper leak-off test of every cemented interval which present in disposal well.

Moreover, a detailed geological survey of disposal site has to be carried out at the design stage of waste disposal system.

Risk Matrix:

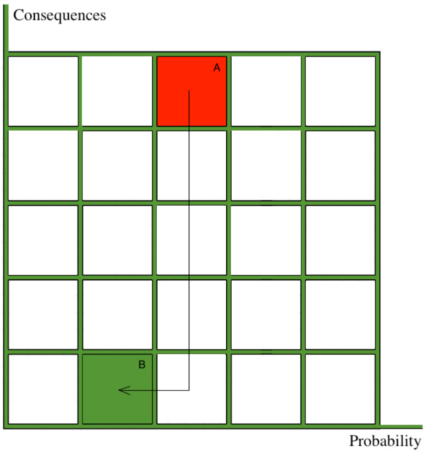

Figure 17. «Underground leakage from disposal site to upper formations» risk matrix

Risk: Unexpected breakdown of any part of injection system.

Breakdown of any part of injection system might lead to shutdown of injection process. This, in turn, will lead to waste tanks overload and leakage of waste mud and drill cuttings to the sea.

Mitigation measures:

This risk may be avoided by proper maintenance of every part of injection system. There should be replacement parts of every mechanism in case of unexpected breakdown. Personnel responsible for the system have to know how to repair the equipment.

Risk Matrix:

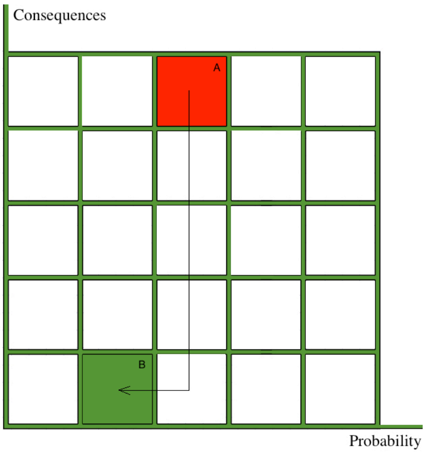

Figure 18. «Unexpected breakdown of any part of injection system» risk matrix

Risk: Operator's failure / poor management

You can never neglect the human factor in the work of any system. The mistake may be of a different nature: operator might just forget to turn the system on or may control the system in inappropriate way. The operator can also be pushed to implement the system in unacceptable conditions by management, this is due to manager's poor knowledge in system work principle and safety measures.

Mitigation measures:

Not only personnel working on the vessel but also the management team should know the basics of work principles of any system which presents on the operated vessel.

Yearly verification of managemet's technical knowledge might be extremely useful for preventing this type of risks.

Risk Matrix:

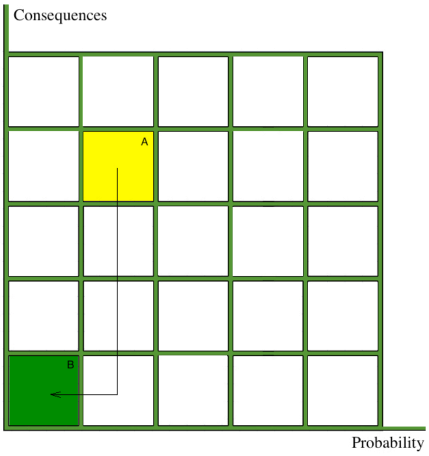

Figure 19. Operator's failure / poor management» risk matrix

8. Economical aspects of the Project

It is usually difficult to find any certain information about costs. In most of the companies this data is confidential. However, it is possible to find average costs for every type of waste disposal methods discussed above.

A great effort was made by John A. Veil from Argonne National Laboratory (Veil, 1998) to collect information about offshore drilling waste disposal practices in different regions in U.S.

In an effort to protect the identity of individual operators, each company wass identified only by a code letter (Company A, Company B, etc.).

Not every company provided a complete set of data. For example, only a few companies provided disposal cost information. The cost estimates cover a wide range, primarily because different operators report different portions of the total cost attributable to waste disposal. Some operators reported only the cost for disposing wastes at commercial disposal company while others included transporatation costs, cuttings box rental and cleanup fees, and other contributions.

According to report, it is possible to get acquainted with waste disposal costs in Gulf of Mexico.

Nearly all water-based muds (WBMs) and cuttings are discharged. The WBMs and cuttings that do not meet the permit limits are brought back to shore for disposal. Companies D and J report that a small percentage of WBMs are recycled, while Company M discharges 50% of WBMs and recycles 50%. None are injected. Four companies reported disposal costs, which range from $7.50/bbl to $150/bbl. It is highly probably that these costs do not cover the same items and are therefore not comparable.

Most oil-based muds (OBMs) are recycled and most OBM cuttings are disposed of onshore. Most companies reported onshore disposal costs ranging from $10/bbl to $40/bbl, but two companies that included more cost components in their estimates reported $107/bbl and $350/bbl. Four companies dispose of some portion of their OBM cuttings by injection. The percentage disposed by injection ranges from 5% to 50%. Costs for injection range from \$5/bbl to \$250/bbl. One company disposes of 10% of its OBMs through injection. No OBMs or OBM cuttings are discharged.

Most SBMs are recycled, and most SBM cuttings are discharged. Some of the operators reported that a fraction of the SBMs were discharged. This was intended to indicate that some of the SBMs adhere to the cuttings particles that are discharged. Other operators did not report in that manner, but noted that all SBMs are recycled. Two companies reported that very small percentages of SBMs are disposed of onshore. The costs reported for this are \$9.50/bbl to \$100/bbl. One company indicated that the cost of hauling SBMs to shore and recycling them is \$40/bbl. One company reported that all of its SBM cuttings are disposed of onshore. No SBMs or SBM cuttings are injected.

Disposal costs are also affected by type of waste (Puder and Veil,2007). Following tables represent american experience that may form overall vision about industrial costs of waste disposal.

Table 5. Offsite commercial disposal costs for oil-based muds and cuttings. (The shadded cellc indicate that no data were provided by disposal companies)

Method	$/bbl	$/yd3	$/ton
Bioremediation	40	20–120	🟥
Burial/landfill	6.67–22	16–18	2.50–128
Burial/pit	2–17	30	🟥
Salt Cavern	2–15	🟥	🟥
Surface Discharge	🟥	🟥	🟥
Evaporation	8.50	🟥	🟥
Injection	🟥	🟥	🟥
Solids Injection	5–10.50	🟥	🟥
Land Application	4–18	7.50–34	55–100
Recycling	5–16	🟥	🟥
Thermal Treatment	🟥	🟥	380–900 100/drum
Other Treatment	11.50–15	🟥	🟥

Table 6. Offsite commercial costs for produced water. (The shadded cellc indicate that no data were provided by disposal companies)

Method	$/bbl	$/yd3	$/ton
Bioremediation	🟥	🟥	🟥
Burial/landfill	15–22	18	15–250
Burial/pit	0.35–4	🟥	🟥
Salt Cavern	0.30–10	🟥	🟥
Surface Discharge	0.75–3.50	🟥	🟥
Evaporation	0.40–84	🟥	🟥
Injection	0.30–10	🟥	🟥
Solids Injection	5.50–10.50	🟥	🟥
Land Application	0.30–18	25	100
Recycling	5	🟥	🟥
Thermal Treatment	🟥	🟥	40–400
Other Treatment	5–14	🟥	🟥

Table 7. Offsite commercial disposal costs for water-based muds and cuttings. (The shadded cellc indicate that no data were provided by disposal companies)

Method	$/bbl	$/yd3	$/ton
Bioremediation	40	20	🟥
Burial/landfill	2.61–22	18	2.50–250
Burial/pit	1–17	🟥	🟥
Salt Cavern	2–15	🟥	🟥
Surface Discharge	🟥	🟥	🟥
Evaporation	0.85–20	🟥	🟥
Injection	0.50	🟥	🟥
Solids Injection	5–10.50	🟥	🟥
Land Application	0.50–12	7.50–25	55–100
Recycling	5	🟥	🟥
Thermal Treatment	🟥	🟥	380–900
Other Treatment	6–15	🟥	🟥

Conclusion

The oil and gas industry has made great strides in environmental protection from its early years. A choice of several suitable drilling waste management practices currently exists. Operators select the most appropriate waste management option on the basis of regulatory requirements, cost, and the concerns of future environmental liability.

Regarding Russian arctic offshore fields, underground injection of drilling waste appears to be the most effective method of waste handling among all discussed in current thesis. This is particularly true for drilling operations in remote and environmentally sensitive areas. Another benefit from utilization of underground injection is independence from weather and ice conditions.

Key advantages of method discussed include:

1. Minimization of potential impacts on surface and subsurface waters;
2. Smaller operational footprint;
3. Minimization of air quality impacts associated with handling, processing and treatment;
4. Reduced long-term liability and risk for the waste generator.

Although the current suite of management options offers alternatives, research efforts are underway to develop improved waste management strategies. Of particular interest are those approaches based on waste minimization and beneficial reuse.

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