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PAPER 4D1 PETROLEUM ENGINEERING

Solutions

1(a) Hydrocarbons are formed in sedimentary basins. Combinations of high pressure and low temperature are likely to be found under deep water in the Arctic. At the seabed at the North Pole, for instance, the pressure under 4000m of water is 40 MPa, and the sea temperature is not far above the freezing point of seawater, -1.8 C. Large areas of very deep water are found in the Angara Basin N of Svalbard, in the Laurentian Basin N of Alaska and around Antarctica. The diagram indicates that only about 3 MPa (300 m of water) is required to stabilise hydrates at freezing point.

Favourable conditions may also be found in sedimentary basins close to the surface in permafrost areas where the mean surface temperature is well below 0 C. Hydrates are less likely in volcanic areas (where the geothermal gradient is very high) and in the tropics (too warm both near the surface and at depth).

Many gas reservoirs contain substantial fractions of hydrocarbons higher than methane: the diagram shows that the presence of these fractions makes the formation of hydrates more likely.

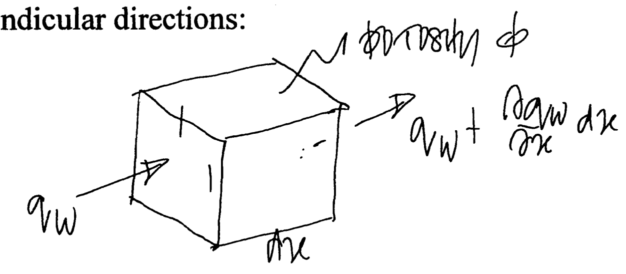
(b) Hydrates will normally occur in the pore space of sedimentary rocks. It is unlikely to be practicable to mine sediments containing hydrates, though this may just be possible for near-surface deposits in the Arctic. The hydrate would need to be kept under pressure to prevent dissociation before the gas could be captured, and this would require new mining techniques – since mine interiors are normally at atmospheric pressure – and careful control of mine temperature and pressure. There would be substantial safety an d fire problems.

A more attractive alternative is to heat the formation so that the hydrate dissociates. High pressures occur at the dissociation front, and drive the gas towards wells. This is broadly similar to steam-assisted gravity drainage (SAGD) used to produce oil from tar sands, but the gas flows much more easily. Water might be produced with the gas. The heat might be generated by circulating hot water, made by heating recovered formation water or heated by nuclear energy or hydropower (often available in remote areas of the Arctic onshore). An alterative is to pump heated oxygen into the formation, ignite the gas, and generate in-situ combustion.

The first task is to locate the hydrates, measure the in-situ composition, and to delineate the reservoir. The best place to look would be onshore in the Arctic. The extent could be determined by a combination of seismic and exploration drilling. Measurement while drilling could be extended to include tests in which heat sources are lowered into the well.

As with oil sands, it would be important to carry out some serious thermal calculations, and to link them with economic studies, since the cost of the energy used would not be negligible compared with the value of the gas recovered.

2 (a)(i) Consider a parallelipiped element whose sides are *dx* in the x direction and 1 in the two perpendicular directions:



In time *dt,* the flow of water into the element on the left is $q_w dt$, and the flow out of the element on the right is $(q_w+(\partial q_w/\partial x)dx)dt$. The volume of the pore space is φdx, and the volume of water in the pore space is $\varphi S dx$. In time *dt*, the change of the volume of water in the pore space is $\varphi(\partial S/\partial t)dtdx$. Since water is essentially incompressible, by conservation of volume

$$\varphi(\partial S/\partial t)dtdx = q_w dt - (q_w+(\partial q_w/\partial x)dx)dt$$

which simplifies into the conservation equation.

(ii) If water saturation is *S*, oil saturation is 1-*S.* The corresponding equation for oil is therefore obtained by replacing *S* by 1-*S,* and subscript *w* by *o*.

(iii)

$$q_w = q_{tot}F(S)$$

then if q_{tot} is independent of x

$$\frac{\partial q_w}{\partial x} = q_{tot}\frac{dF}{dS}\frac{\partial S}{\partial x}$$

and so

$$\frac{\partial S}{\partial t} + \frac{q_{tot}}{\phi}\frac{dF}{dS}\frac{\partial S}{\partial x} = 0$$

In general, $\frac{\partial S}{\partial t} + k\frac{\partial S}{\partial x} = 0$ is the kinematic wave equation, whose solutions are waves that move with vel

(b) The governing equations are highly nonlinear, and almost always have to be solved numerically. Simple idealised cases such as 1-D Buckley-Leverett enable us to study the behaviour of the solutions, such as the formation of shocks and fingers, and to be sure that they are genuine features and not artefacts of the numerical scheme. We can then compare numerical solutions with analytical solutions, and assess the accuracy and stability of the numerical results.

(c) Real reservoirs are highly inhomogeneous, and the permeability varies through orders of magnitude over very short distances (0.01 to 0.1 m), tiny by comparison with the scale of the reservoir (1000 to 10000 m), while vertical and horizontal permeabilities can be hugely different. Cores can be recovered from exploration wells, but the volume of a typical core is 10^{-13} of the volume of a reservoir. Information about permeability is very scant. We cannot hope to represent the totality of a reservoir in a computational model. We therefore apply the principle of upscaling: we analyse blocks that simulate the inhomogeneity of the reservoir, and derive equivalent permeabilities that can be applied at larger scales.

The governing equations are solved by finite difference methods. The reservoir is divided into blocks, and each block is assigned a permeability tensor derived from upscaling. The governing equations describe the relationship between pressure and flow, and the continuity conditions for each of the fluids. The boundary conditions reflect the production scheme: for example, at a water injection well the water injection flow rate can be prescribed.

3 (a) An advantage is that the reservoir has held gas for a long time (150 million years for Jurassic gas): if the reservoir leaked seriously the gas would have disappeared long ago. The platform and pipeline facilities exist, and could be acquired cheaply, sine there are few other uses for them. The public is accustomed to those facilities, and would not have to accept the social and environmental impacts of the construction of new facilities. Re-use of existing facilities is desirable for sustainability.

Among the disadvantages are the limited volumes that can be stored in depleted gas fields, in comparison with the huge scale required of carbon capture and storage (CCS) schemes if they are to have a significant impact on climate change. The present rate of dumping into the atmosphere is 6.5 Gtcarbon/year, about 200 tonnes a second. The facilities are old, and were typically designed for a 40-year life, which is now almost up. They will be beginning to suffer from fatigue and corrosion, and will deteriorate further if they are mothballed for the next 15 years. Wet carbon dioxide is corrosive in the presence of water: it would be essential to dry pipeline systems, particularly if they were stabilised by flooding them with water. Many of the pipelines go towards London, whereas major fixed sources of carbon dioxide are at coalfields and ports.

Experience shows that some environmental NGOs object on principle to any CCS scheme, on the grounds that successful CCS will make it more likely that people will continue to use fossil fuels, which they see as inherently harmful.

(b) Faults in the caprock might let carbon dioxide escape to the sea. Sealed faults might open up if the reservoir were repressurised, particularly if the pressure were higher than the original reservoir pressure. Carbon dioxide is chemically very different from natural gas, and in the presence of water might dissolve carbonates and other kinds of rock.

It would be necessary to map and understand the existing system of faults, and to look at tectonic movements that might mobilise new faults. The geochemistry of the reservoir system would need study. The corrosion status of the existing facilities would need to be surveyed.

(c) CCS under the North Sea could be argued to be 'dumping', forbidden by the UN convention on dumping. The pipelines and terminals required planning permission and a licence to operate from the then UK Department of Energy, and those permissions might not cover a major change of use. Owners of facilities would not want to have an ongoing responsibility for their maintenance and ultimate removal, and would want to transfer that responsibility to a new authority responsible for CCS. Objectors would seek every possible avenue of legal objection.

(d) Offshore platforms could be used to support large wind turbines. Other uses such as prisons and tourist centres are rather fanciful. Land pipelines could be used to distribute water, important since East Anglia has a growing water problem and new reservoirs are unpopular.

Platforms can be toppled into the sea, where they would form artificial reefs for fish and ultimately might nucleate new sandbanks. Both platforms and pipelines could be recovered for scrap.

4 (a) Each reservoir is roughly elliptical in plan, 50 km long (NNE-SSW) and 30 km broad). The reservoir in the upper Jurassic is 70 m thick (scaling from the diagram). The reservoir in the middle Jurassic is 110 m thick.

The reservoir volume is therefore $\pi \times (2.5 \times 10^4) \times (1.5 \times 10^4) \times (70 + 110) = 2.1 \times 10^{11} m^3$

Taking the porosity as 0.2 and the gas saturation and net-to-gross as 1, the volume of gas under reservoir conditions is 4.2×10^{10} m^3. The assumed saturation and net-to-gross are optimistic, and represent maxima.

The mean depth, taking both reservoirs together, is 2000 m. 2000 m of water corresponds to a pressure of 20 MPa. Normal conditions correspond to 0.1 MPa.

The gas law is

$$\frac{p_n V_n}{Z_n R T_n} = \frac{p_r V_r}{Z_r R T_r}$$

and so

$$V_n = \frac{p_r}{p_n}\frac{T_n}{T_r}\frac{Z_n}{Z_r}V_r = \frac{20.1}{0.1}\frac{273.1+15}{273.1+140}\frac{1}{0.8}2.1\times10^{11} = 3.7\times10^{13}\ m^3$$

(which is a very large field indeed)

(b) The simplest scheme is a one or more fixed platforms on the field, with flowlines from remote wellheads, connected by an export pipeline to a shore-based LNG plant on Novaya Zemlya, and then export by LNG tankers operating from a sheltered deep-water inlet. Ice breaker support would be needed. The feasibility of a fixed platform depends on the ice conditions, which would have to be investigated. Another possibility is a floating LNG plant, but the huge scale of the project means that that would be a step forward from existing technology.

(c) Novaya Zemlya is earthquake-prone, and an earthquake might damage LNG facilities and might cause a tsunami. Fire is difficult to fight in the Arctic, and the LNG plant might be at risk. Either a floating system or a fixed platform might be at risk from icebergs, particularly if global warming leads to a change in weather patterns and to disruption of the North Atlantic Drift. Novaya Zemlya is treeless tundra, and is home to Arctic fox, caribou and many migratory birds, which would be disturbed by large-scale construction such as an LNG plant. Whales might be disturbed by construction noise and increased marine traffic. Plant personnel might attempt to hunt. Drill cuttings have to be managed and disposed of in a way that will not cause environmental damage, by shipping them out or perhaps by injecting them into subsurface formations.

In addition, there are of course general objections to any hydrocarbon developments, because of their effects on climate change (in the absence of carbon capture and storage).

5 If you are feeling courageous, you might say the following:

We are determined to maintain economic growth, and so we shall need energy. I intend to introduce a new scheme to encourage energy efficiency. Among the mechanisms will be a punitive tax on large cars and SUVs, a tax credit to households that do not own or operate cars, and subsidies for houses built to demanding insulation standards (such as those that are applied in Canada). I will introduce measures that make it less attractive for companies to provide cars for their employees.

Energy efficiency will not be enough, and renewables alone will not be enough. I shall introduce measures to encourage oil companies to recover more of the oil that conventional production leaves in the ground, since recovery factors are normally only about 50 per cent. Research in other parts of the world indicates that here is more much to be done to applied more sophisticated methods of enhanced oil recovery, such as miscible carbon dioxide injection (which also helps to reduce emissions to the atmosphere).

Our existing system of nuclear power stations was designed 50 years ago, and much of it is worn out. I shall commission urgent studies to see how far the life of the system can be safely extended, as is being done in other countries such as Sweden. New designs such as pebble-bed reactors are inherently safer and are less exposed to terrorist attack. Public opposition to nuclear power is diminishing, here as in other countries, and we shall embark on a new building program, following the advice of the Royal Society and the Royal Academy of Engineering. If we are to meet our Kyoto targets, nuclear power is an important component of the power mix. However, the new power stations will not come on stream for 10 years.

In an uncertain world, it is important that the country not be left vulnerable to disruption of supplies from large producers of gas, such as Russia, Nigeria and Norway. We may have to accept that the era of very cheap energy belongs to history.