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SOLUTIONS

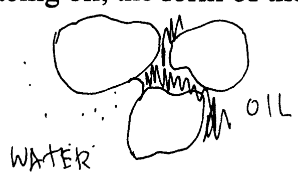
1(a) v_w is the velocity of the water phase (averaged over the whole area)
k is the permeability
η_w is the viscosity of water
k_{rel} is the relative permeability for water in a two-phase system, a function of the water saturation S_w
P_w is the pressure in the water phase
S_w and S_o are water and oil saturations (the fraction of the pore volume occupied by water and oil
P_w and P_o are water and oil pressures
P_{cap} is capillary pressure

(b) the first equation says that the velocity of the water phase is the gradient of the water pressure, multiplied by the permeability kk_{rel} and divided by the viscosity;

the second equation says that the system is two-phase, and that the fraction of the pore volume occupied by water and the fraction occupied by oil sum to 1;

the third equation says that the pressures in the water and oil pressures can be different, because interfacial tension requires a pressure difference to force water through the narrow 'throat' between particles

(c) if water is displacing oil, the form of the interface is schematically

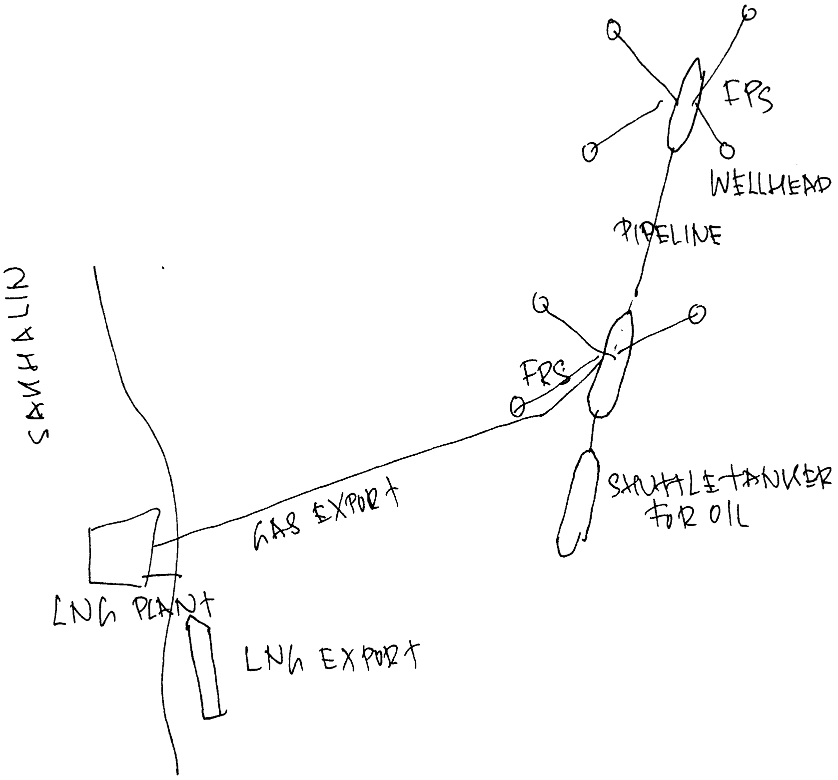


the interfacial tension creates a pressure difference, and the pressure is higher in the water. A reduction in injection rate may be accompanied by a local reduction in water pressure, and oil may then flow back towards the water. The pressure difference then reverses:

(d) most reservoir analysis programs are based on finite-difference methods. The scheme has to accept very large local differences in local permeability, because real reservoirs are highly heterogeneous. The time step has to be small enough for instability not to occur. Physical instabilities such as fingering have to be distinguishable from numerical instabilities. Buckley-Leveret theory for the simple 1D case shows that shocks can occur, and so the numerical scheme has to be able to deal with shocks.

2 (a) Japan has almost no hydrocarbons of its own, and is a huge potential market for both gas and oil, though a difficulty with for gas is that Japan has no gas grid. The Chinese economy is growing very rapidly, and its demands are increasing. The oilfields in eastern China have been exploited for a long time (a Maoist slogan was 'gongye, xue Daqing' ('in industry, learn from Daqing')), and the new fields are far to the west. Much of the industrial demand is close to the Pacific coast, and could easily be reached by tankers from Sakhalin.

700 m is too deep for a fixed platform to be an economical solution, even in ice free seas such as the Gulf of Mexico. This suggests a floating production and storage (FPS) system with one or more floaters. The wells are linked to the FPS by subsea flowlines and flexible or steel catenary risers. On the FPS the oil and gas are separated. The gas flows to Sakhalin by an export pipeline, and thence to Japan either as LNG or though a pipeline. The oil is loaded onto shuttle tankers. The FPS can be ice-strengthened, and weathervane to head into the direction the ice is coming from. It can be further protected by icebreakers. If the ice becomes too thick for the FPS to hold station, the catenary risers can be disconnected.



(b) One exploration well is not enough to delineate the field in the detail required for such a large capital investment, or to establish important parameters such as porosity, permeability and connectivity. Assuming that seismic exploration had preceded the discovery well, additional wells along the 50 km length are recommended. They can be designed and constructed so that they can later be converted to producers.

The export gas pipeline route to Sakhalin would need to be established. It might be feasible to take the oil to one of the platforms already in place off the east coast.

At the present time, all FPS operate in ice-free water, and there are no FPS in the Arctic. The safety and economy of the field depend on being able to operate in sea ice with few shutdowns. This suggests that it would be prudent to carry out extensive studies of the ice climate, and to investigate by model tests the interaction between a moored or dynamically-positioned FPS, the mooring system, and the icebreaker support.

Cleanup after an accidental oil spill would be made more difficult by the presence of ice. The company management and the Russian and Japanese authorities would require to be reassured by location-specific studies.

3 (a) Scaling from the diagram, the sandstone reservoir containing oil is roughly 30 m thick, and an ellipse 8 km NE to SW and 15 km broad. The reservoir volume is

$$30\times\pi\times4000\times7500 = 2.8\times10^9 \text{ m}^3$$

The volume recoverable is obtained by multiplying this by four factors:

porosity	0.2 (mean of given values)
oil saturation	0.6 (typical)
net-to-gross	0.8 (guess)
recovery factor	0.5 (reasonable for current practice)

and is $2.8\times10^9\times0.2\times0.6\times0.8\times0.5 = 1.34\times10^8 \text{ m}^3 = 850$ MMbbl.

(b) The gas reservoir lies at a depth of 2700 m. If the pressure is hydrostatic, since 10 m of seawater corresponds to 1 atmosphere, the pressure is 270 atmospheres (about 27 MPa).

(c) The mean thickness of the gas cap is about 40 m. It is about 6 km NE to SW and 10 km broad . The reservoir volume is

$$40\times\pi\times3000\times5000 = 1.9\times10^9 \text{ m}^3$$

The volume recoverable is obtained by multiplying this by four factors:

porosity	0.2 (mean of given values)
gas saturation	0.95 (typical)
net-to-gross	0.8 (guess)
recovery factor	0.8

and is $1.9 \times 10^9 \times 0.2 \times 0.95 \times 0.8 \times 0.8 = 2.3 \times 10^8$ m^3

This is at reservoir pressure and temperature. The volume at normal conditions can be determined by multiplying by 270, multiplying by 288/373 (ratio of temperatures, assuming reservoir temperature 100 C) and dividing by 0.9 (compressibility factor), and is

5.3×10^{10} m^3 = 1.9 Tcf

(d) The oil and gas may originate from different source rocks. The oil may have migrated along the sandstone from a reservoir further to the S or N. The gas may originate from the Carboniferous.

(e) This is an excellent reservoir. The porosity is slightly higher than usual for sandstone, and the permeability is high.

4(a) This suggestion offers the possibility of moderating global warming by independently controlling radiation input to the Earth. Global warming is at present essentially out of control, and the prospects of securing effective international agreement to control carbon dioxide emissions are very limited, especially since the US, Russia, India and China show no sign of taking significant action. Even if action is taken, atmospheric carbon dioxide will not level out below 550 m, and some climate change is inevitable (according to the general scientific consensus).

In contrast, control of radiation input does not require international action or agreement. It could be carried out by one or two technologically advanced societies, probably the US or Russia, if necessary acting on their own.

If this happened, it would reduce pressure on us as a company to stop supplying our customers with carbon-bearing fuels. Pressure on suppliers is politically easier than pressure on consumers, since suppliers do not have votes (cf. the 'war on drugs'). We ought therefore discretely to encourage this alternative.

(b) An argument <u>against</u> the moratorium is that the US currently imports more than half its oil (and an increasing proportion of its gas), and is vulnerable to supply disruption (by a war in the Middle East, for example). It has to develop every domestic resource it can, because those resources are politically safe. Moreover, the example of oil fields in environmentally sensitive areas such as Wytch Farm shows us that oil can be produced with minimal effects on the environment, and that when it is depleted the facilities can be removed and the area returned to its original state. Imports of foreign oil generate other kinds of environmental and societal damage, for example by wars in Iraq.

An argument <u>for</u> the moratorium is that wilderness is beyond price, and that once its delicate balance is disrupted it can never be recovered. Any development will bring roads to the area, and naturalists, tourists and hunters will follow the roads. It will never be possible to erase the facilities completely. The oil will only make a marginal contribution to US consumption, and the supposed need for it can be moderated by conservation measures. Oil can be bought cheaply elsewhere, and US supplies are sufficiently geographically diverse that loss of supply is unlikely.