PETROLEUM DEVELOPMENT OFFSHORE AND ONSHORE IN COLD REGIONS

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Summary

Petroleum has been exploited for millennia, but on a small scale. The quantity of petroleum produced has hugely increased since the start of modern development in the middle of the nineteenth century, but demand too is increasing, and demand drives development in regions once considered too difficult. Environmental challenges in cold regions must be overcome to drill, produce, and transport the petroleum product from its source to various end points. Onshore development encounters problems with permafrost, and development offshore has to contend with sea ice. Very large scale engineering projects have been conducted successfully, both onshore and to a lesser extent offshore: The Trans-*Alaska* pipeline, the Russian developments on the Yamal' peninsula and off the coast of Sakhalin, and the North Star development off the coast of Alaska are among the examples.

1. Introduction

Most geologists think that petroleum was formed from animal life, buried in sediments and cooked for many tens of millions of years under increasing temperature and pressure, though there is a minority opinion that at least some petroleum has an abiotic origin in chemical processes. Human beings have exploited petroleum for more than two millennia, but at first on a small scale (Yergin, 1991): the people of ancient Iran and Iraq worshipped fires at natural oil seeps and used bitumen as a cement, and in China natural gas was discovered, piped to the surface, and burned to evaporate brine (Zheng, 2009).

Oil companies search for petroleum in sedimentary basins, but look too for a reassuring level of political and economic stability, so that they can minimize the risk that they will make large investments and then find that they risk expropriation, or that they cannot operate without harassment.

These conditions are met in Arctic North America, and to a lesser extent in Arctic Russia, whereas Antarctica and the surrounding oceans are currently closed to exploration under the provisions of the Antarctic Treaty. Some areas of the Arctic have been relatively thoroughly explored, among them the North Slope of Alaska, the Beaufort Sea, the Canadian Arctic Archipelago, the Barents Sea, the Yamal' peninsula, Sakhalin, and parts of Sakha and the Komi Republic. That exploration has made major discoveries, including the large gas fields on Yamal', which have for many years supplied much of the gas consumed in Europe, and the Prudhoe Bay oilfield in Alaska, which went into production before the 1980s. Other discoveries have been confirmed but not yet developed, among them the Shtockmannovskoye gasfield in the Barents Sea, the large gas reserves close to Prudhoe Bay, and the gas reserves at Kovykta.

At the time of this writing (2010), there has been a brisk increase in the prices of oil and gas, prompted in part by economic growth in China and India. That increase seems likely to continue, though it may be tempered by economic recession, by unexpected political change and by the exploitation of unconventional sources such as shale gas and gas hydrates. It has become attractive to pursue petroleum developments that would not have made sense at the lower prices of the 1980s.

2. Environmental Conditions

Oil and gas development has to take careful and sensitive account of the physical and biological environment, in terms both of its impact on the design of facilities and of the possibility that development might generate adverse effects. The Arctic takes up a huge fraction of the earth's surface, and its physical conditions vary enormously. It makes no more sense to think of 'the Arctic' as a homogeneous area than it would to think of 'the tropics' as homogeneous. In some locations with continental climates, winter temperatures are extremely low, below -50ºC. Table 1 below lists temperatures on a particular winter day (December 8, 2008) at places in the Arctic and sub-Arctic. It includes wind chill indexes calculated by the US National Weather Service 2001 formula. The table shows that there is a high level of variability, that the coldest places are not the furthest north but in places like Oymyakon, and that in Europe and Asia temperatures fall as you go east. Another day would of course be different in detail, but the same pattern would be apparent.

Location	**Latitude**	**Longitude**	**Temperature**	**Wind**	**Windspeed**	**Windchill**
			(ºC)	direction	(km/hour)	index (ºC)
Murmansk, Russia	68º57' N	33º18' E	-5	N	4	-7
Archangel'sk, Russia	63º34' N	40º37' E	-1	SW	2	-1
Amderma, Russia	69º47' N	61º51' E	-6	SW	22	-13
Vorkuta, Russia	67º23' N	63º58' E	-19	SW	4	-22
Dudinka, Russia	67º24' N	86º11' E	-27	S	11	-36
Irkutsk, Russia	52º17' N	104º18' E	-17	NW	25	-28
Mirnyi, Russia	62º32' N	113º58' E	-45		7	-55
Oymyakon, Russia	63º28' N	142º40' E	-48		0	-17
Magadan, Russia	59º34' N	150º46' E	-15	NW	4	-18
Pevek, Russia	69º42' N	170º19' E	-15		43	-28
Vrangel' Island, Russia	71º14' N	179º25' E	-8	SE	11	-13
Nome, AK, USA	64º30' N	165º24' W	-13	NE	11	-19
Barrow, AK, USA	71º18' N	156º18' W	-24	SE	24	-37
Fairbanks, AK, USA	64º50' N	147º43' W	-26	NE	6	-32
Anchorage, AK, USA	71º18' N	156º18' W	0		0	13
Cambridge Bay, NU, Canada	69º07' N	105º03' W	-29	N	28	-44
Resolute, NU, Canada	74º41' N	90º50' W	-32	NE	46	-51
Qaanaaq, Greenland	77º29' N	69º20' W	-16	E	10	-22
Iqaluit, NU, Canada	63º45' N	68º31' W	-17	SE	17	-26
Alert, NU, Canada	82º28' N	62º30' W	-34	W	7	-42
Goose Bay, NFL, Canada	53º18' N	60º25' W	-5	NE	17	-11
Nuuk, Greenland	64º10' N	60º25' W	-5	S	37	-14

Table 1. Temperatures on December 8, 2008

In most places the average summer temperature is above freezing, sometimes a long way above freezing, but the summer is rather short. Similarly, the surface topography varies, from level plains and swampy deltas to high mountains, sometimes with permanent icecaps.

Permafrost is encountered almost everywhere, and has a major influence on construction (Johnston,1981; Tsytovich, 1973). The depth that permafrost extends to depends on the mean annual temperature, but reaches 700 m in the most severe climate in north-eastern Sakha. There is an active layer just below the surface that thaws in summer and reaches 1 or 2 m, depending on the geology and the surface vegetation. Towards the southern boundary the permafrost becomes discontinuous and patchy, and ‘warm’, so that it is very sensitive to changes in ground surface cover.

As long as the ground remains frozen, it is a strong and competent geotechnical material, much stronger than most soils, even if the ice content is large and some of the ice has segregated into lenses, though under high stresses ice slowly creeps. Thawed ground is completely different: it usually has a high water content, often higher than the liquid limit of geotechnics, and then has a very low shear strength. It follows that if a structure such as a power station or a pipeline is built on frozen ground, and then disturbs the temperature field so that the ground thaws, the structure will settle dramatically. Many examples have been recorded. Russian authors say that the first principle of construction on frozen ground is to maintain the temperature conditions so that the soil remains frozen (Tsytovich, 1973).

The sea freezes, and again there are many varying conditions (Sanderson, 1988; Wadhams, 2000). Ice begins to form as single crystals, and they grow and agglomerate as ‘pancake ice’. That in turn agglomerates, and an ice sheet grows in thickness. Sea ice has a complex internal structure that reflects the growth process, and has randomly-oriented small crystals in the upper layers, but lower down there are much larger columnar crystals whose c-axes are oriented with the prevailing current. Often the surface of the ice is covered with snow. Between the large crystals near the bottom are near-vertical brine channels.

Wind and currents push the ice, and create stresses that break the ice sheet and form pressure ridges composed of ice fragments that afterwards freeze together. A typical scenario has a level ice sheet 2 m thick with ridges 4 m high (above the general level of the ice) and 20 m deep at 100 m intervals; all these numbers vary greatly. Fresh first-year ridges initially have an open and fragile structure, but in some locations ridges survive from one winter to the next, and they then consolidate and freeze together more strongly. In some locations the sea is ice covered for only a fraction of the early part of the year, but in others breakup may not occur until July, and the sea begins to refreeze in September. In the Arctic Archipelago there are drifting ice islands that have broken away from ice shelves in the northernmost islands, and they can reach to depths of 50 m. In the eastern Canadian Arctic south of Greenland, near Svalbard, and in the Southern Ocean there are true icebergs, composed of freshwater ice from glaciers: they can be very large indeed, and can reach depths of 300 m.

Other features occur when moving ice runs aground in shallow water. One piece of ice grounds, and other pieces strike it and break up, forming piles of fragments, often called by the Russian term ‘stamukhi’. Driven the ice behind, a fragment or a ridge can cut deep gouges into the seabed, a possible hazard to a seabed pipeline. In some places frozen rivers melt while the sea ice is still frozen, and fresh water floods out over the ice, breaks through cracks and holes, and rushes downward, forming powerful vortices that erode deep holes in the seabed (‘strudel scours’).

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Biographical Sketch

Andrew Palmer has divided his career equally between practice as a consulting engineer and university teaching. In 1975 he joined R.J. Brown and Associates, at that time the leading consultant in this field. In 1985 he founded Andrew Palmer and Associates, a company of consulting engineers who specialize in marine pipelines, and have been engaged in projects in almost every part of the world. In 1996 he returned to research and university teaching as Research Professor of Petroleum Engineering at Cambridge University in England. He was a Visiting Professor in the Division of Engineering and Applied Sciences at Harvard University, 2002-03. He is a Fellow of the Royal Society, a Fellow of the Royal Academy of Engineering, a Fellow of the Institution of Civil Engineers, and a Chartered Engineer. He is currently Keppel Professor in the National University of Singapore, where he is engaged in teaching and research and has an active consulting practice. He is the author of three books and more than 200 papers on pipelines, offshore engineering, geotechnics and ice.