PWR, but to show too much enthusiasm could have been counterproductive, as it was in 1974. This time the industry played a more careful game, designed to appease the AGR supporters while obtaining the clearest commitment to the PWR that was politically possible. An argument which carried weight with some sections of the industry is that orders for one or two AGR stations could be placed immediately, providing much needed work, while a PWR order would be delayed by the need to get clearance from the safety inspectorate and the planning authorities.

In any case, the immediate prize is less important than the long-term prospects for power station ordering through the 1980's and 1990's. In common with most industrial countries, Britain assumes that thermal nuclear plants will play a major role in energy supply toward the end of the century, and present projections suggest that by the year 2000 some £20,000 million will have been invested in such plants. Starting in the early 1980's, according to this plan, series ordering of nuclear plants will have to begin, and the PWR supporters have concentrated on making sure that they will be well placed to win those orders when the time comes. According to this view, the one or two immediate orders "lost" to the AGR matter less than the fact that the PWR will be designed, passed by the Nuclear Installations Inspectorate, and ready to build when the nuclear bonanza begins.

Benn and the AGR supporters are reasonably happy with the decision because it has at least delayed a firm PWR order for another few years—and the experience of British nuclear policy shows that that is time enough for several somersaults. Benn himself says he is skeptical that everything from the other side of the world is necessarily better, and muses about what would happen if some generic fault were to be discovered in the PWR. (His opponents say this fate is much more likely to befall the AGR, and point out that the term PWR now covers a multitude of different designs, so that any fault that did show up would be unlikely to affect them all.) "Should we throw away 27 years of experience of gas-cooled systems?" Benn asks. "Yes," say his opponents, pointing out that France had the courage to abandon her gas-cooled reactors in the 1960's in favor of light-water reactors and is now building and exporting light-water reactors successfully.

Whatever the merits of the argument on either side, the British nuclear experience provides a perfect example of the difficulty of pursuing an independent path in face of American influence and technological skill. If Westinghouse had developed the AGR and Britain the PWR, would the contest have had the same result? That question can perhaps be left to historians. What is becoming clear is that there are now only two generic types of thermal reactor surviving: the light-water reactors, and the Canadian CANDU system. The luxury of diversity has proved too expensive to enjoy.—NIGEL HAWKES

Erratum: In the 3 February issue (p. 508), the proposed budget increase for the National Institutes of Health was incorrectly given as $4.2 million. The correct figure is $42 million.

Erratum: In the report by F. B. Krasne and S. H. Lee entitled "Regenerating afferents establish synapses with a target neuron that lacks its cell body," there were two errors: in reference (2) the papers by R. D. Clark, *J. Comp. Neurol.* **170**, 253 and 267 were published in 1976, not 1977; and in reference (*3*), the paper by F. B. Krasne and S. H. Lee, *Brain Res.* **121**, 43 was published in 1977, not 1976.

RESEARCH NEWS

Tar Sands: A New Fuels Industry Takes Shape

The huge tar sands deposits of northeastern Alberta are covered by as much as 6 meters of muskeg, a semifloating mass of partially decayed vegetation. In summer, land vehicles are swallowed up by the morass. In winter, the muskeg freezes so solidly that the earth beneath is virtually inaccessible. To reach the tar sands, it is necessary to begin draining water from the muskeg at least 2 years before any digging is planned; the remaining vegetation must then be removed while it is frozen. Despite these difficulties, muskeg removal is one of the simpler problems which confront companies that attempt to exploit tar sands. The more severe problems include the inhospitable weather and the exceptional difficulties of handling the tar sands.

These problems have delayed exploitation of tar sands, but they have certainly not halted it. One by one, these problems have been overcome until, today, tar sands are the most promising near term alternative source of fossil fuels. One company has been mining tar sands and extracting oil from them for 10 years, the last 2 years at a profit. A second, much larger plant is now about 95 percent complete, and a third plant and a possible fourth are on the drawing board. More than 20 companies, furthermore, have operated pilot projects for in situ recovery of oil from the tar sands. About 16 of these pilot projects are still in operation and one commercial facility may be under construction within 2 years.

This is the last of three articles exploring unconventional approaches to fossil fuels.

The greatest immediate beneficiary of this activity will be Canada, where most of the work is taking place. Canada has the largest confirmed deposits of tar sands in the world—the equivalent of more than 900 billion barrels of oil, not counting some large, unexplored deposits in the Northwest Territories. By the 1990's, production of oil from tar sands could approach 1 million barrels per day (bpd), or nearly a third of Canada's domestic requirements. Little or none of this oil will reach the United States, but the experience gained in Canada will have application here and elsewhere. The United States has the equivalent of more than 30 billion barrels of oil embedded in tar sands, 90 percent of it in Utah. The equivalent of some 200 billion barrels of oil is known to lie in tar sands along the north bank of the Orinoco River in Venezuela, and some geologists speculate that there may be as much as 2 trillion barrels. Smaller deposits are scattered throughout the world, and it is thought that a substantial deposit exists in the Soviet Union.

Tar sands, also known as oil sands and heavy oil, are a mixture of 84 to 88 percent sand and mineral-rich clays, 4 percent water, and 8 to 12 percent bitumen. Bitumen is a dense, sticky, semisolid that is about 83 percent carbon. At room temperature, it does not flow and is heavier than water; at higher temperatures, it flows freely and floats on water.

Tar sands can be divided roughly into three categories, depending on their viscosity. The viscosity, in turn, depends primarily on reservoir temperature. Tar sands near Lloydminster in Alberta are about 300 times as viscous as conventional petroleum; part of the bitumen there can be pumped directly from the ground. Deposits in the Peace River and Cold Lake regions are about 1000 times more viscous than those at Lloydminster, and must be heated substantially before they are mobile enough to pump. Deposits near the surface in the Athabasca and Wabasca regions are another ten times more viscous and can be mined in open pits.

An important feature of the deposits in Athabasca and Wabasca is that the bitumen is separated from the sand by a thin film of water that surrounds each grain of sand. The bitumen will thus separate readily from the sand in hot water. In the absence of this film, separation of bitumen from rock is much harder.

Federal and provincial governments in Canada and private companies have attempted to exploit the tar sands since the 1880's. The basic flotation technique for separating bitumen from sand was developed in the 1920's by Karl Clark of the Scientific and Industrial Research Council of Alberta and Sidney Ells of the Ottawa Department of Mines. The economics of mining and processing the sands, however, prevented any commercial development until recently.

The pioneer in development and application of tar sands technology is unquestionably Great Canadian Oil Sands Ltd. (GCOS), which is 96 percent owned by the Sun Company Inc. of Philadelphia. In 1964 GCOS began construction of an extraction facility on a 1600-hectare site about 30 kilometers north of Ft. McMurray, Alberta, and in 1968 began commercial production. The plant now produces an average of about 50,000 bpd of synthetic crude oil. The plant had a remarkably low capital investment, in today's terms, of about $300 million. Even so, GCOS operated at a loss for 8 years. Even with a profit of $25 million the last 2 years, the company still has an operating deficit of $54 million.

By far the greatest expense and difficulty lie in mining and handling the tar sands. For each 50,000 barrels of oil produced, approximately 33,000 cubic meters of overburden must be removed, and about 100,000 tons of tar sand must be mined and disposed of. The tar sands are more difficult to handle than any other substance that has been mined on a large scale.

In summer, the tar sand can be mined with a bucket wheel without prior preparation of the deposit, but the sands are highly abrasive. During the first summer of mining, the 120 teeth of the bucket wheel—each of which then weighed about 46 kilograms—would wear out in 4 to 8 hours of digging; replacements had to be flown in from throughout the world. Blades on bulldozers and scrapers would last for only about 40 percent of their expected life. The tar sands also stick tenaciously to everything they touch. They thus clog the cooling systems and external controls of vehicles, stick to conveyer belts and accumulate at transfer points on the belts, and create general havoc with machinery. The bitumen, furthermore, slowly dissolves natural rubber in tires, conveyer belts, and other machinery.

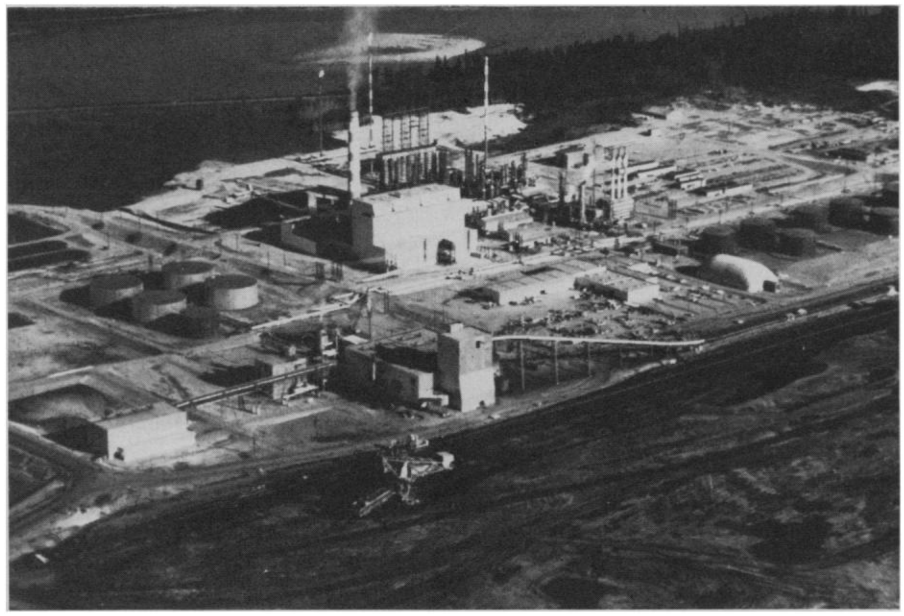

Fig. 1. The GCOS plant near Ft. McMurray. This picture was taken when the plant first opened, so the bucket wheel excavator is next to the plant. [Source: Sun Company Inc.]

In winter, when temperatures drop to −50°C, an undisturbed deposit of frozen tar sands resembles carborundum, according to GCOS president Stanley A. Cowtan. The teeth of a bucket wheel digging in a frozen deposit glow red. The steel plates, 0.6-centimeter thick, from which the buckets are made would frequently be ripped apart, and the teeth torn from their sockets. Other equipment failures also become more frequent.

The problem of winter mining was largely overcome by dynamiting the tar sands in the summer so they cannot freeze as solidly. The teeth on the bucket wheels were redesigned to minimize friction, and improved alloys are now used. Different rubber formulations were developed for tires and conveyer belts, and vehicle maintenance schedules were refined and rigorously adhered to. Similar refinements were developed throughout the complex. These refinements are now being licensed to other tar sands operations.

Once the tar sands reach the extraction plant—a process that now involves transporting them more than 11 kilometers by conveyer belts—the process is relatively straightforward. The tar sand is first mixed with alkaline water at about 80°C in a rotating drum. The resulting slurry is dumped into separation cells where the sand and clay settle out and bitumen floats to the surface. The bitumen is then coked, a process in which large, nonvolatile organic molecules are broken down into products that can be distilled; by-product coke from this process is used to fuel the facility's electric generating station, and gases are used for the manufacture of hydrogen. Distillation of the products from the coking produces naphtha, kerosene, and gas oil, each of which is treated with hydrogen to remove sulfur. Aromatic and olefin components are also removed, gasified, and used as fuel for the power plant. The three distillates are then blended into a synthetic crude oil that is shipped by pipeline to Edmonton, about 400 kilometers to the south. GCOS recovers 92 to 93 percent of the bitumen in place.

The first beneficiary of GCOS's problem-solving experience will be Syncrude Ltd., which is now building a 129,000 bpd plant about 7 kilometers north of the GCOS site. Syncrude is a consortium of three companies (Imperial Oil Ltd., Gulf Oil Canada Ltd., and Canada-Cities Service Ltd.), the Canadian government, and the governments of Alberta and Ontario. The three governments purchased 30 percent of the project when one of the original partners dropped out because of escalating costs. The cost of the facility was originally planned to be less than $1 billion, but it is now expected to total about $2.5 billion, including the power station and pipeline.

Syncrude has licensed much of the proprietary technology developed by GCOS, so initial operations there should proceed much more smoothly. Among the important lessons learned from the GCOS project was the necessity of having duplicate systems so that the entire facility will not be shut down if one subsystem fails. The plant is expected to begin production this spring, and Syncrude estimates the cost of producing oil at about $9.50 per barrel.

The overall scale of the project is staggering. Mining will be performed by four draglines, each of which has a 60-cubic meter bucket on the end of a 110-meter boom. Electricity for the draglines and for the rest of the project is provided by a coke-fired 260-megawatt generating plant, large enough to light a city of 300,000. The total area to be mined is about 2800 hectares, and the tailings pond for disposal of clean sand occupies an area of 3000 hectares, making it one of the largest lakes in the area. Considering the isolated location, there have been few other projects like it.

The Syncrude plant will probably be followed by another plant of similar size to be built about 30 kilometers further north by Shell Canada Resources Ltd. Shell will this summer submit a revised application for a permit to build the plant and is now seeking one or more partners to help provide the $4 billion capital investment that will be required. The plant could be in operation by the summer of 1985. Petrofina Canada Ltd. is also considering a plant of that capacity.

Despite the bright prospects for these surface projects, less than 10 percent of the tar sands in Canada lie within 50 meters of the surface, which is generally considered to be the maximum depth at which open-pit mining is viable. The vast majority of the resources will thus have to be exploited with in situ technology. The in situ processes required for tar sands are somewhat simpler than those required for oil shale, for example, but they are still sufficiently difficult that a great deal of experimental work is required. Private companies have already invested more than $150 million for pilot projects during the last two decades and, in conjunction with the Alberta Oil Sands Technology and Research Authority (AOSTRA), are expected to invest an additional $250 million during the next 10 years. There are 16 pilot projects at which work is being performed; the nature of the technology being used at each of these depends on the character of the tar sands themselves.

The first deep tar sands that will be exploited are at Cold Lake, where reserves are estimated at about 160 billion barrels. The greatest experience at Cold Lake has been obtained by Imperial Oil, which

Ft. McMurray's Lesson: Plan Ahead

Individuals and groups who fear an influx of population to virgin areas of Colorado when an oil shale industry finally takes shape can take some lessons—but little heart—from the experience of Ft. McMurray, the closest town to the Athabasca tar sands in Alberta. Ft. McMurray was a little village of about 1000 people before GCOS began construction of its tar sands plant in 1964. By this spring, its population is expected to have grown to 28,000. That development has been marked by a number of problems, most notably urban sprawl, lack of facilities, exorbitant price increases, and divisions between the town's established residents and new ones. The town has been characterized by some residents as an interesting place to live, but not necessarily a desirable one.

GCOS and Syncrude have played a large role in building up the town, but their help has proved to be a two-edged sword. The companies have provided much of the housing in the area. Syncrude, for example, has built almost 2700 residences, at a cost of about $180 million, for sale or lease to employees. The companies have also made substantial financial contributions to community projects and facilities and have permitted employees to work on community projects and serve as elected officials on company time. On the other side of the coin, the housing projects have been built on a tight schedule reflecting the companies' needs and there has been little time permitted for community input on their design and environmental effects. Many people in the community, says Jim Rogers of Save Tomorrow, Oppose Pollution, also feel that the two companies have been given preferential treatment by community officials who are employed by them.

Despite the great amount of virgin territory around Ft. McMurray, there is already overcrowding in some areas of the town. There is also insufficient parking in the downtown area and too few public services. Perhaps the most severe problem, however, is the exceptionally high cost of living that results, Rogers says, from a combination of greedy speculation and poor planning. Housing lots now sell for as much as $37,000 in Ft. McMurray, he says, and the cost of housing is higher there than anywhere else in Alberta. Some GCOS employees, in fact, recently staged a wildcat strike because they were not working enough overtime; rents and mortgages for many company-owned properties are deducted directly from paychecks and, when some workers didn't get in enough overtime, they ended up owing the company money.

Were the process to be repeated again, as it most certainly will in Cold Lake and other areas, nearly everyone agrees that there should be much more central planning. In what amounts to apostasy for an environmentalist, Rogers argues that future developments should be completely overseen by the government, which could require that concepts such as adequate parking and lack of crowding be incorporated into the master plan. That sentiment is echoed by Alberta's Northeast Regional Commissioner, Vic Hennig, who thinks that such planning should be extended to the entire region. One way to minimize problems, he contends, would be to disperse the population into several communities. That is, in fact, one of the suggestions that will be carried out as Imperial Oil Ltd. establishes its proposed new facility at Cold Lake.

Despite the problems, Hennig says, most people in Ft. McMurray and in Alberta are convinced that Canada's energy problem is critical. They are thus willing to put up with a certain amount of inconvenience and disruption while trying to solve the problem. It is probably impossible, moreover, for rapid growth such as that displayed by Ft. McMurray to be painless. But with sufficient planning in new projects, many problems can be eliminated and the pain minimized.—T.H.M.

has operated a series of pilot projects there since 1964 at a cost of more than $40 million. The most recent project is producing about 5000 bpd of bitumen by steam stimulation, or what is known colloquially as the "huff and puff" process. Steam at 350°C and a pressure of 2000 pounds per square inch is injected into the 500-meter-deep formation through a pattern of wells for 4 to 6 weeks (huff). Bitumen can then be pumped from the wells for as long as 6 months (puff). The primary goals of the pilot projects have been to find the best ways to bring the steam into intimate contact with the bitumen and to determine the optimum configuration and spacing for the wells.

Imperial has applied to the Alberta government for permission to build an in situ facility that would produce as much as 160,000 bpd. The cost of the project will probably exceed $4 billion. Fully half that total is for facilities to upgrade the bitumen to a synthetic crude oil that can be used in existing refineries. If approval for the project is obtained in 1979, construction would begin in 1981 and production in 1985.

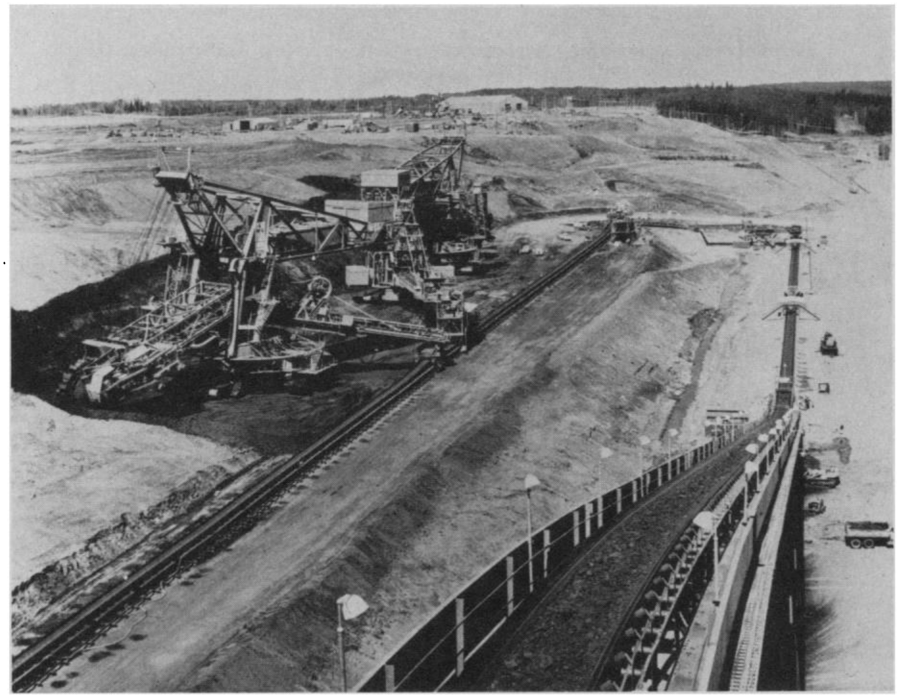

Fig. 2. These two bucket wheel excavators at GCOS load 108,000 tons of tar sands onto the conveyor belt each day. Note the size of the bulldozer and trucks in the lower right foreground. [Source: Sun Company Inc.]

The project will involve drilling about 10,000 wells over a period of 20 years or longer. There will be from 2000 to 2500 wells in operation at any one time, and each is expected to produce for 5 to 8 years. Energy to produce the steam will require burning either about 5 million tons of coal each year or about 25,000 bpd of bitumen. Despite the large capital investment, the cost of producing the oil is expected to be less that that at Syncrude.

Other companies are also conducting pilot operations at Cold Lake. Norcen Energy Resources Ltd. is using much the same process as Imperial. Murphy Oil Ltd. is also using steam stimulation, but is injecting the steam continuously. And AOSTRA, BP Canada Ltd., Hudson's Bay Oil and Gas Ltd., and PanCanadian Petroleum Ltd. are jointly studying a combination method employing steam injection and in situ combustion. This approach is considered desirable because the production rate of each well should be higher than it is with steam injection alone.

Another well-developed approach is known as COFCAW, for combination of forward combustion and water-flood. This process has been developed by Amoco Canada Petroleum Ltd. at a cost of more than $20 million. In its simplest form, four wells are drilled at the corners of a square, and a fifth is drilled at the center. Combustion of the bitumen is initiated at the center well as air is injected at a pressure high enough to fracture the tar sand zone. After fracturing is achieved, the pressure is reduced, and air and water are injected. The water helps to spread the heat evenly and forces the liquid bitumen toward the four production wells. Amoco, AOSTRA, and Pacific Petroleums Ltd. have recently begun production of 1000 bpd at a pilot facility in the Athabasca tar sands. The $69 million program is expected to produce more than 1 million barrels of bitumen by its completion in 1984 and to demonstrate whether commercial production is feasible. The COFCAW process is expected to recover at least half the bitumen in place under the 10-hectare test tract, consuming 4 to 5 percent of the bitumen while doing so.

AOSTRA is sponsoring studies of four other major approaches to in situ technology. In the first, Shell is studying cyclic pressurization and depressurization of tar sand deposits near the Peace River with steam. These sands are unusual in that there is an underlying zone saturated with water; this zone will provide a path for the steam as it moves between wells. Extension of the approach to other sites, however, will require development of methods to connect the wells underground. One way to do this is with hydraulic fracturing, which will be studied in the Athabasca deposits by Numac Oil and Gas Ltd.

A proprietary steam heating technique for shallow deposits is being studied by In-Situ Research and Engineering Ltd. High pressure steam cannot be used in such deposits because it would disrupt the overburden. AOSTRA and others are exploring a modified in situ process, based on Soviet experience, in which steam is injected through wells emanating from a tunnel drilled through the deposit horizontally. In an independent project, electrical resistance heating of deposits at intermediate depths is being studied by Petro-Canada Exploration Ltd., Canada-Cities Service, and Imperial. The passage of alternating current through the sands would raise the temperature enough so that oil could be flushed out with steam. The potential advantage of this process is that no fracturing should be required. At least one of these techniques, says John H. Nicholls of AOSTRA, should be suitable for any tar sand deposit in Canada.

In the United States, there has been little interest in tar sands because it was thought that the country had deposits equivalent to only about 1 billion barrels of oil. Only recently has it become clear that the deposits total 30 times that amount, at least. Much of the work in the United States has been done by L. C. Marchant and his colleagues at the Department of Energy's Laramie Energy Research Center. They are now conducting their second in situ combustion experiment near Vernal, Utah. The Utah tar sands do not have a film of water between the bitumen and the sand, so separation of the two is more difficult.

The Laramie investigator's first experiment used reverse combustion, in which a fire is ignited in one well and air inject-

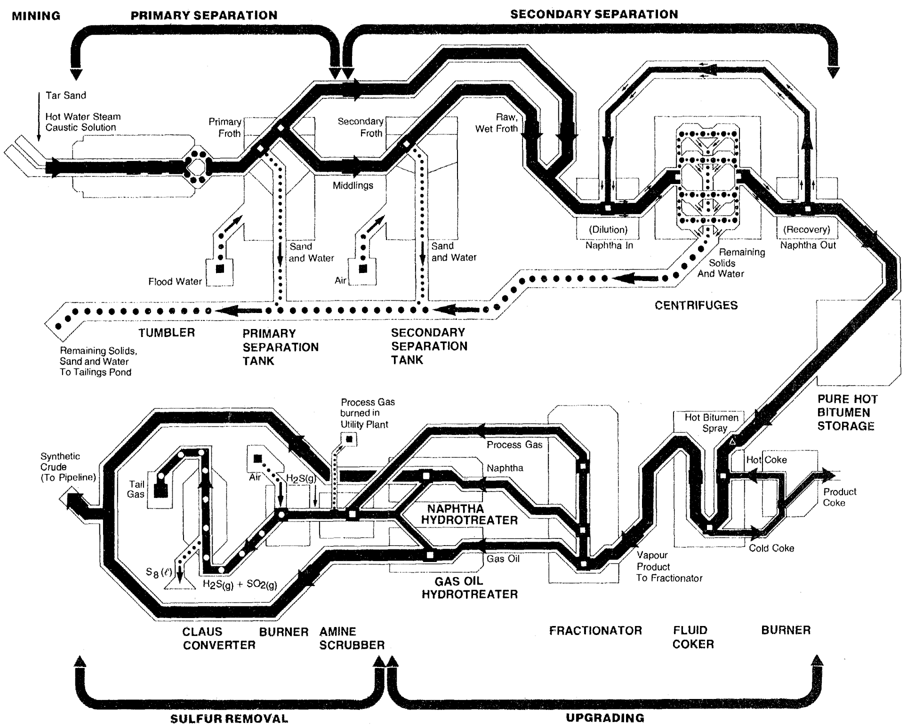

Fig. 3. This flow chart shows how synthetic crude oil is produced by Syncrude from tar sands mined in the Athabasca region of Alberta. [Source: Syncrude Ltd.]

ed into a second well to draw the fire to it. Unfortunately, the tar sands at Vernal are more heterogeneous than the samples that were used for laboratory simulation of the process. The fire channeled through the deposit in a narrow band of high porosity and did not heat the deposit effectively.

The second experiment, which began in late August, used reverse combustion followed by forward combustion. Marchant says this approach will require less air injection and should be easier to control. This experiment has proceeded much more smoothly. At the approximate midpoint of the experiment, the Laramie investigators had recovered about 20 percent of the bitumen in place and expect to recover about 50 percent while consuming about 10 percent. They are presently planning a third experiment to study steam heating. The Department of Energy is also exploring ways to achieve a greater amount of cooperation with Canadian investigators.

In situ recovery of tar sands thus looks promising, but there are several major hurdles that must be overcome. The most important of these is probably capital investment. Whereas in situ recovery of oil shale is expected to be substantially cheaper than surface extraction, this is not the case for tar sands, as is readily seen by a comparison of the costs of the projects. The Syncrude and Imperial projects will require a capital investment of \$20,000 to \$24,000 per daily barrel of oil produced. In Saudi Arabia, in contrast, the comparable cost is about \$325. The companies thus feel, justifiably, that they need some guarantees to keep the price floor from being pulled out from under them.

Most companies feel that the absolute minimum requirement that must be met to justify this large investment is to allow oil from the projects to be sold at the prevailing world price, which is now about \$15 per barrel. (Oil in Canada has a controlled price, which is about \$4 per barrel less than the world price.) The Canadian Parliament has permitted this price for Syncrude, but has made it clear that other projects will be considered on a case by case basis. At present, GCOS is allowed to charge only \$12.30 per barrel, but in July that price will be raised to \$13.30.

Some executives feel that even more could be done to provide incentives. The government of Alberta will receive a royalty of 50 percent of the profits on all oil produced in the province since it owns the land on which the tar sands are located. Several oil companies argue that a reduction in this royalty, combined with some federal tax credits, could make a large number of projects commercially viable. But perhaps the most important thing, according to Russ Powell of Imperial, is that the government establish prices and regulations and stick to them. That kind of stability is needed before the companies will feel confident enough to put up their money.

Environmental problems are not particularly severe. Canadian tar sands contain 4 to 6 percent sulfur, but most of this is removed during processing. Emissions of sulfur dioxide at GCOS have generally been within government guidelines. The Alberta government has given Syncrude permission to emit 287 long tons of sulfur dioxide per day, but Save Tomorrow, Oppose Pollution (STOP), an Edmonton-based environmental group, says that the company could reduce the emissions to 40 long tons per day by installation of about \$35 million worth of equipment. STOP contends that the frequent temperature inversions in winter could trap dangerous quantities of sulfur dioxide, particularly if more tar sand plants are built, and threatens to prosecute the company if the controls are not installed.

Perhaps a more substantive problem are the tailings ponds. STOP contends that these ponds contain substantial quantities of organic chemicals and metals and that the surface is coated with a thin film of bitumen. The group argues that spillover or leakage of these materials into the Athabasca River could cause a severe pollution problem. Syncrude's pond, furthermore, is on a major flyway for migratory waterfowl, and the bitumen is quite toxic to the fowl. Syncrude contends that there is little danger of leakage from the ponds and that there are not toxic levels of pollutants in them anyway. The company concedes the problem with waterfowl and is trying to devise some way to keep them away from the ponds.

Another potential problem is pollution of underground aquifers during in situ extraction, but this does not seem to be insurmountable. There may eventually be a shortage of water for processing the bitumen, but AOSTRA is already sponsoring research on ways to reuse water produced from the sands. Even the effects of an influx of population into the mining area seem to be controllable (see box).

Counterbalancing these potential problems is the industry's greatest asset—the eagerness of the Canadian government to spawn production of alternative fossil fuels. Despite arguments that more tax and royalty breaks should be provided, all levels of government have clearly been supportive of development efforts—even to the point of purchasing a part interest in Syncrude when no other partner could be found. It seems likely that this type of accommodation will continue in the future, and that the extraction of oil from tar sands has a very good chance of developing into a full-fledged industry.

—THOMAS H. MAUGH II