Natural Gas Processing and Utilisation

An international conference organised
by the Irish Group of the Institution
of Chemical Engineers with the
co-operation and assistance of the
Institution of Engineers of Ireland

Dublin, Republic of Ireland 6–9 April 1976

THE INSTITUTION OF CHEMICAL ENGINEERING SYMPOSIUM SERIES NO. 44

EUROPEAN FEDERATION OF CHEMICAL ENGINEERING MEETING NO. 171

Published by
I Chem E Services for
The Institution of Chemical Engineers,
George E. Davis Building,
165–171 Railway Terrace,
Rugby CV21 3HQ.

Printed by The Chameleon Press Limited, 5–25 Burr Road, Wandsworth, London SW18 4SG

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Foreword

In recent years, there has been considerable offshore activity in the seas surrounding the North West corner of Europe in the search for oil and natural gas. Substantial finds of both of these scarce hydrocarbon resources have been made and the exploration is continuing.

These discoveries come at a most opportune time for the countries of Northern Europe. Traditionally large importers of oil, the 'energy crisis' of current times has created major problems for the economies of our countries and has given rise to a new emphasis on fuel efficiency and optimisation of scarce resources. It is now cogently recognised that these resources have a limited lifespan and that they must be used so that the maximum benefits are obtained not necessarily for the source country but for all mankind. The universities, the research institutes and the research and development sectors of governments and industry are each, in their different ways applying themselves to the formulation of and solution to these new problems which have arisen. With natural gas, there are three main options: it may be burned to produce electricity or piped for use in domestic gas systems, or rather used as a feedstock for petrochemical and fertiliser industries. Is there an optimum 'mix' of these possibilities which might be different from one country to another? Chemical engineers are particularly interested to know what new processes have been developed for the treating and conversion of natural gas to other products.

It was with this background that the Institution of Chemical Engineers decided to organise this international conference where the most recent technological developments and economic theories relating to natural gas use would be given a forum for presentation and discussion. I am confident that the papers presented, and which are reproduced in full in this volume, give an up to date picture of this important subject. I am pleased to express here, on behalf of the Institution of Chemical Engineers, our thanks to all the authors for the effort they have put into their papers and for presenting them at this conference.

JOHN J. KELLY
Conference Chairman

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INDUSTRY'S APPRAISAL OF GAS TECHNOLOGY

James D. Wall*

New directions in gas processing in North America create needs for additional information about processes, fundamental data and policies of operation. These changes are identified along with the needs that they create and the research and development direction that is being followed.

INTRODUCTION

Changes in North America set new tasks for gas processing that create needs for clearer policies and improved technology. This technology can be developed and tasks can be accomplished if adequate policies are set in a timely fashion to clearly define conditions under which industry must work.

TASKS

Tasks required of industry must be considered in a matrix influenced by world energy supply/demand imbalance, expansion of industry to an international scope, pricing and environment. Previously, industry was local in nature because gas was processed at its origin. Now, world energy imbalance requires that all energy, including gas, be considered available for worldwide use. Furthermore, pricing is based on overall world energy and influenced by other countries and materials. Interwoven throughout this matrix is world interest in environmental protection and adoption of equipment designs and industry operations to meet environmental and economic needs. In this new and unstable operating matrix, North America's gas industry must accomplish several well-defined tasks:

- Use energy more efficiently within the industry
- Use industry products more efficiently
- Develop adequate feedstocks
- Optimize industry logistics
- Optimize environmental protection

Efficiency

North America's gas industry has set a record of problem-solving in growing from accidental recovery of liquids from gas to its present sophistication and integration. However, gas processing evolved almost as an economic stepchild because it was long considered merely a by-product of oil production and refining. Little economic incentive was provided for liquids recovery from gas or for processing improvements. Furthermore, regulations that forced industry to stop wasteful gas disposal created an economic system based on distressed product prices. Nevertheless, industry has grown and developed technologically to the limit of these economic incentives. Technology initially borrowed from coke and town gas industries was supplemented by research which gave the industry its present levels of competence. Product emphasis evolved from original interest in casing-head gasoline, through interest in LPG, and on to today's concern for full ethane and heavier recovery for petrochemicals feedstock.

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Gas processing economics fixed industry operating efficiency. Equipment design and operation was based on optimizations within industry's economic framework. Consequently, heat recovery, fuel economy, and materials use were set for low thermal efficiencies. Today, major attention is given to revising this condition since fuel prices are rising to equal other energy sources. Exact levels are not clear because gas value is not yet fully defined.

Several markets compete for products of gas processing. Light hydrocarbons formerly left in natural gas were used efficiently for heat without serious economic misallocation. Now, limited supply of petrochemicals feedstock tends to make light hydrocarbons more valuable as petrochemical feed. Consequently, industry faces uncertainty as it considers new equipment design. Thus, the decision to burn or recover these hydrocarbons must be clarified before optimum goals for industry efficiency can be fixed.

Feedstock Supply

Diminishing supplies of natural gas cause North America's gas industry to search for new feeds to include streams heretofore uneconomical--streams containing excessive amounts of hydrogen sulfide (H_2S), nitrogen (N_2) and carbon dioxide (CO_2). Attempts have been made to process streams containing as much as 50-plus percent H_2S, CO_2 or combinations of these two. Also, high-nitrogen-content streams have been utilized commercially. Not all efforts have been successful nor has increased supply been sufficient to meet demand. Consequently, gas companies search for alternate supplies, focusing mainly on conversion of coal to gas. These efforts have been frustrating, expensive and nonproductive. Although much has been done to research and develop process technology for coal-to-gas conversion, commercial plants have not been built because of inordinate delays in obtaining permits and because of questionable economics. Just the same, long-range, these plants will be built.

Most efforts center on conversion of coal to substitute natural gas suitable for inclusion in distribution systems. However, the industry is also considering alternatives such as production of intermediate and low-Btu gas for use in dedicated industrial distribution systems or for mine mouth power production in conventional boilers or combination-cycle power plants, respectively.

Other alternate raw material supplies under consideration are tar sands, shale and miscellaneous materials such as manure, domestic garbage and municipal waste. Obviously, these could be burned directly for heat.

Logistics

A key issue facing gas processors is where to locate processing plants with respect to markets and feed source. The answer was simple when processing had to be carried out at or near production fields. But today gas is moved across oceans and solid materials are converted to gas. Under these conditions, where do you build? Some suggest converting gas into a transportable liquid. Others consider choice of liquid. Still others consider feedstock movement as opposed to process placement at raw material site.

In moving excess natural gas from remote areas to other continents, which is best--LNG or methyl fuel? This decision is a trade-off between high ship investment cost and high plant operating cost for LNG, and relatively higher production cost and lower thermal efficiency for methyl fuel. Generally, the decision favors LNG use for all systems where transportation routes are relatively short. Another choice is whether to convert coal to natural gas or methyl fuel. Some say methyl fuel produced in Western United States and transported to distant markets can be more economical than mine mouth conversion into gas for consumption in the same markets. Such considerations obviously create interest in competing processes and require studies outside normal natural gas processing.

Environment

A ground-swell concern for environmental protection is now worldwide. This concern strongly impacts on gas processing in facility operation, products utilization and plans for developing alternate feedstocks. Many studies have been undertaken to assure that conventional gas processes do not harm the environment. Of particular interest has been work done by those interested in sulfur both with respect to eliminating sulfur incineration and eliminating sulfur dioxide from Claus unit tail gas. Gas, along with other hydrocarbon processing products has added new processes for tail gas desulfurization, and the industry has studied improvements in performance of conventional Claus units. Of less direct industry interest--but, nevertheless of importance--are studies to define relative merit of direct combustion of primary fuels such as coal or their conversion to alternate energy forms.

The gas industry has an obligation to help fix pollution levels and make known costs that result from their meeting various levels of criteria. Therefore, industry must help define optimum environmental criteria for best use of all resources. So far, this optimization has not been sought by regulatory agencies and has seldom received proper review by industry.

INDUSTRY NEEDS

New tasks adopted by and imposed on North America's gas processing industry cannot be fulfilled without first recognizing and satisfying certain needs. None of these are formidable problems except establishing policies and business conditions within which industry must work. Answers can be developed technologically from normal research and development without significant delay in accomplishing industry goals. However, these goals will not be reached unless industry makes its needs known and helps define policies within which it must work.

Policy

North America, particularly the United States, was built on low-priced energy. Raw material conservation was given a low priority. Consequently, energy was wasted. People demanded instantaneous gratification of their desires. These combine to create national energy policies which are being slowly changed because of public unwillingness or inability to recognize any energy imbalance. Consequently, politicians are beset by public demands to force industry to produce ample low-priced energy, while industry itself warns of urgent needs for change. Confusion results. The problem is being pursued politically. This involves debate over imposition of regulations and laws to dampen demand, regulate price and wrestle energy-industry control from industry. Meanwhile, industry wrestles with efforts to create new industry, build new facilities, protect the environment and maintain sufficient economic incentive to satisfy investors.

No national consensus has been clearly defined in either Canada or the United States. Consequently, progress is thwarted. Management is confused. People are dissatisfied. Therefore, the hydrocarbon processing industry and its gas processing segment must quickly and clearly define an objective for energy policy including gas and alternate fuels.

Policy definition is partially the responsibility of the gas processing industry. Industry must clearly define its needs and identify consequences of alternate actions. Required policy includes many elements relating to pricing, profit, level of national self-sufficiency, industry freedom and definition of protection level to be given to the environment.

Much that must be done in other areas of process design, technology, operations, etc., depends upon these clear understandings. Continued procrastination in determining these goals will compound inefficiencies, result in mounting waste and delay accomplishment of any meaningful industry development. Nor is indecision in North America without its effect on the rest of the world's gas processing industry. America's indecision has impacted other nations by confusing arrangement of international LNG projects and by election of bad process objectives such as conversion of liquid feed to substitute natural gas (SNG). Furthermore, continued indecision in North America can result in improper development of raw material supplies. This could affect world energy balances.

Similarly, conflicting objectives between national and provincial governments in Canada bear on development of their energy, petrochemicals and gas processing industries which will impact other world activities.

Unclarified national policies defer capital development, technical support, manpower supply and training, and materials production and selection. Until clear policies are established, all industry can do is assume that reasonable answers will be developed for use of new energy supplies, and continue to pursue projects that are most likely to be successful in the future.

Equipment

Gas processing has a vested interest in improving equipment efficiency as it tries to conserve energy internally. However, basic studies in these areas are not normally carried out by user industry but, rather, by those who supply equipment.

In some areas, studies are required of gas processing that are being conducted by industry. For example, materials of construction are being selected and developed for use in coal gasification for regimes where temperature, pressure and solids content require unusual operations, and designs are being developed to minimize erosion and corrosion. Furthermore, elimination of NO_x in stack gases to protect the environment is under study for industry use.

Some work is being done to improve operational safety while handling increased concentrations of hydrogen sulfide. These studies are designed to improve equipment normally used in this service.

Technology

Industry's interest in new technology concerns natural gas, LNG, methyl fuel, coal conversion and property data. Obvious differences in operating regimes, materials processed and products create requirements for fundamental data as well as for processes and unit operations.

Natural gas. No new processes are needed for natural gas in conventional activities apart from processing those streams that were heretofore uneconomical. Such streams include those with excessive amounts of CO_2, H_2S and N_2. Various cryogenic approaches for handling high-nitrogen streams have been proposed and some have been tried based on technology adapted from well-understood processing. However, there is reason for their improvement since they are cryogenic and tend to high investment and operating costs.

Streams containing high concentrations of CO_2 are being processed using physical absorption. Many problems have been resolved such that technology is acceptable. However, streams containing both high CO_2 and H_2S create particular problems in downstream processing in sulfur plants. Presence of CO_2 with H_2S necessitates use of bypass mode operation of Claus units which leads to low catalyst life and impaired recovery. Consequently, either greater atmospheric pollution is encountered or a larger tail gas desulfurization plant is required. Better technology for removal and separation of H_2S and CO_2 is needed to avoid blanketing caused by high CO_2 contents. Although selective solvent extraction has been tried for large-volume throughput, it does not appear to be economically attractive. Thus, considerably more work is required (1). Such studies are useful for SNG processing where CO_2 is frequently an unwanted upstream diluent.

Unprocessed reservoirs containing high H_2S concentrations ($\geq$ 60%) create new gas processing problems related to corrosion, sulfur plant operation, tail gas desulfurization and safety. More accurate determination of acid gas solubility in amine treating solutions is needed as well as better understanding of amine regeneration.

Claus unit operation is of interest to all the hydrocarbon processing industry. Much effort is under way to improve conversion efficiency by defining operating conditions and improving plant design including unit control, catalyst performance and new catalysts (2). Better equilibrium data for Claus conditions is needed and closer control of operations are required because the reaction is sensitive to variation.

Sulfur emission elimination emphasizes use of add-on processes for tail gas desulfurization. Increasing in popularity are processes involving subdewpoint operation wherein elemental sulfur is deposited on the catalyst and subsequently removed through regeneration. Relatively little is known about removal of deposited sulfur; yet, experience indicates that corrosion problems that arise during regeneration need resolution.

H_2S content of elemental sulfur is another problem associated with recovery since it creates environmental hazards and reduces mechanical properties of sulfur. Processes are being developed to remove H_2S to solve this problem.

Refrigerated absorption has become increasingly more valuable thus justifying work in the area. Vapor liquid equilibria for conditions ranging from -20 to -100°F and from 100 to 1,000 psi show a large dependency on lean oil type. These data are adequate for plant design, but some feel that more data are needed. Precise data on ethane condensation as a function of temperature is not available. Such ethane data are now being developed and will be used to establish accurate design values with existing correlations and improve system design.

There is concern for discontinuity in thermodynamic and physical property data between low- and high-temperature regions because data were developed from different sources. Since some low-temperature processes fall at this interface, any discontinuity becomes critical (3).

Hydrate formation needs better understanding and is being studied as is water solubility below -20°F.

LNG. Cryogenic processing is used both to improve ethane recovery and to produce LNG. Recent trends in cryogenic ethane recovery include use of indirect refrigeration and indirect cooling using turboexpanders. Much essential information needed for these operations and for LNG production is available. One area of need involves LNG custody transfer since a two-phase system is involved. Additional work is under way on hazards related to LNG handling (4).

Most experimental work, at cryogenic conditions, is related to pure compounds or very simple systems. Many significant gaps exist in thermodynamic data for pure light hydrocarbons as evidenced by a program to collect, assemble and process data in this area (5). Other data related to nonhydrocarbon components such as nitrogen, hydrogen and helium need supplementing with respect to equilibrium phase behavior for typical multicomponent systems involved. Little reliable data exists on this. Thus, no way is available to positively evaluate applicable predictive procedures or equations of state. Programs are under way involving enthalpy data for methane, ethane, propane and their binary and ternary mixtures from -245 to +80°F and from 250 to 2,500 psi (6). Computational methods using available data have been evaluated and several predict enthalpies accurately enough to avoid major overdesign. However, increased demand for design efficiencies may require even further work.

Although much data have been collected on experimental K-ratios for methane, ethane and propane binaries and ternaries at cryogenic temperatures, additional work is being done and more is needed for systems involving methane and nitrogen with heavy hydrocarbons. Experimental data will then need incorporation into generalized correlations. Other systems under study are ethane-carbon dioxide and nitrogen-pentane for conditions down to -200°F and pressures from 250 to 4,000 psi. Also, nitrogen-hydrogen and ethane-H_2S need to be evaluated from -150°F and 150 to 3,000 psi (6).

Methyl fuel. Methanol manufacture has not been a part of gas processing but now becomes one because methyl fuel may be used for transporting energy. Some are studying production of methyl fuel from gas for international exchange compared to LNG and others are looking at converting coal from western states to methyl fuel rather than to gas. Processes are essentially available but proof is needed that adequate scale-up is feasible. Economic advantage of such ventures has not been clearly determined.

Solubility of carbon dioxide in heavy hydrocarbons and LNG is also being studied.

Coal conversion. Many public and private organizations are developing SNG processes. Some studies involve fixed-bed gasification improvements while most are directed to establishing continuous systems. Studies done outside the gas industry demonstrate relative values of direct coal combustion and stack gas scrubbing as compared with fixed-bed gasification.

Additional work is needed to determine best conversion systems for maximum heat use of coal since several end products are possible ranging from low-Btu to 1,000-Btu gas.

Other studies involve materials of construction, improved methanation catalysts, gas purification and devolatilization kinetics in rapid-rate methane formation, acid-gas and trace-impurity removal, improved shift conversion catalysts and hydrogen recycle coal gasification processing.

RESEARCH

Industry associations, government agencies and private organizations are doing research.

The Gas Processors Association (U.S.A.) is developing data to improve plant efficiency and presenting data in a workable form. They are supplementing data on natural gas to cover SNG needs by specific acquisition and correlation relative to enthalpy, vapor-liquid equilibria and generalized equations of state.

The Canadian Natural Gas Processors Association is primarily concerned with sulfur and its related problems. They are working to improve design and operation of sulfur recovery plants and to eliminate atmospheric pollution by either improved unit design and operation or addition of tail gas desulfurization facilities. This work includes additional data on hydrogen sulfide, carbon dioxide, various heavy hydrocarbons and improved Claus plant instrumentation.

The American Gas Association is vitally interested in new feedstocks for alternate gas supply. Their objective is to provide new processes for more efficient conversion of coal to low-, intermediate- and high-Btu gas. In addition, they are considering safety and fundamental data for LNG plants.

The Electric Power Research Institute sponsors coal gasification studies involving process design, materials of construction and economic evaluations between coal gasification and stack gas cleanup.

Alberta Sulphur Research Ltd., which is sponsored by industry, considers sulfur recovery and use with emphasis on Claus operations, plant corrosion problems, materials of construction, sulfur handling and end product use.

The U.S. Energy Research and Development Administration seeks to improve coal-to-gas systems for near-term use and to develop other supplies for synthetic fuels from coal and shale for long-term use.

Private industry keeps much of its research confidential or does it in association with institutes or government agencies. Organizations of particular significance in this area are Battelle Institute, Southwest Research Institute, Exxon R&E, FMC Corporation, Gulf General Atomic, Stanford Research, Institute of Gas Technology, and various colleges and universities throughout Canada and the United States.

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THE ACHIEVEMENTS AND POTENTIAL OF LNG FOR ENERGY STORAGE AND TRANSPORT

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The location and magnitude of world reserves of natural gas are reviewed, highlighting those factors which are likely to make LNG transport attractive. The bulk ocean transport of LNG is examined in terms of liquefier and tanker design. The economical and safety aspects of large scale LNG storage are discussed, particularly in the context of peak-load shaving. Other applications for satellite stations and as a fuel for vehicles and aircraft are examined.

INTRODUCTION

Some of the largest world reserves of natural gas are located in areas which are not only inhospitable, but are separated by considerable areas of sea, or very difficult terrain, from large centres of population. Since natural gas is a clean, high-grade fuel, it is appropriate to use it in reasonably sophisticated ways. Such uses normally arise in well populated areas, therefore the challenge to transport the gas economically is very real - as is also the attendant problem of storing it economically to meet fluctuations of demand.

In the Middle East the reserves are estimated at about 10 x $10^{12}m^3$ which at the current production rate would last for more than 300 years. The known reserves in Africa are at about half this level, but production is at only one fifth the rate. Thus there are large surpluses to be sold. There are other known large reserves in Russia, the Far East and in Alaska. Often the most attractive way of using these reserves is to liquefy the gas and transport LNG to the point of use in special ocean-going tankers. The only serious competitor at this stage is conversion to methanol (or methyl fuel) as described, for instance, by P.Soedjanto et al (1974). Whilst the shipping costs for methanol are well under half those for LNG there are compensating advantages for LNG which generally give it the edge. The overall thermal efficiency is much higher (90% as compared to about 75%), the cost and complexity of the installed process plant is appreciably less, and LNG is a more flexible fuel.

The U.K. Gas Council played a leading part in the early 1960's in launching the first commercial LNG transport scheme. Since then, although deliveries of Algerian LNG to Canvey Island have continued, six other international LNG transport schemes have come into being and have dwarfed the original. The largest present project liquefies Brunei natural gas at a rate of 21 x 10^6m^3/day for ocean transport to Tokyo and other Japanese ports. In total the present projects have a capacity of about 54 x 10^6m^3/day, whilst there are five other schemes under construction to handle a further 90 x 10^6m^3/day. Together these projects represent about 5% of world natural gas consumption.

The other main area in which LNG has made great strides is for peak-load storage at the consumer end of gas pipelines. It took many years to expunge the memory of the Cleveland Plant, which failed so disastrously in 1944. In fact it needed the confidence inspired by the U.K. and French LNG import schemes to trigger the renewed interest. Two peak-load storage plants were successfully commissioned in the U.S.A. in 1965, and since then the total number of such plants in the U.S.A. and Canada has mushroomed to 63. There are also 8 in the U.K. and a further 4 in other parts of Europe.

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Finally there is a miscellany of smaller uses of LNG. Some of these involve satellite storage tanks, either stationary or mobile, from which evaporated gas is distributed to localised users. Others involve the use of LNG as a fuel for vehicles or aircraft.

All the above uses of LNG will now be explored in greater detail to see what scope exists for further development and improved technology.

BULK OCEAN TRANSPORT

(a) Liquefaction

The natural gases normally considered for liquefaction contain between 80 and 95% CH_4. If they contain more than about 1% N_2 then it is generally worth removing the greater part of it before liquefaction, to save the expense of storing and transporting inert material. Also if the higher hydrocarbons are present in larger quantities than the limit of 80% CH_4 would imply it will usually be economic to separate them as LPG. Even so this range of CH_4 concentration has a large influence on the liquefaction plant since it takes only a few percent of miscible higher hydrocarbons to modify significantly the isothermal condensation portion of the cooling curve. Equally the liquefier design is substantially influenced by the supply pressure of the natural gas, since this is normally sufficient for liquefaction without further compression.

Figure 1, which may be taken as the temperature-entropy diagram for pure methane illustrates the calculation of the minimum work of liquefaction as a function of feed gas pressure. Starting at 30°C (303K), for methane at atmospheric pressure, liquefaction occurs along the line ABC, and the minimum work of liquefaction is given by the area ABCF (assuming heat is rejected also at 303K). Moreover the total duty may conveniently be divided into a cooling duty AB (minimum work ABJ) and a condensation duty BC (minimum work BCFJ), and it is apparent that the characteristics of the refrigerator needed for each differs greatly. If, however, the feed gas is already at a supercritical pressure (above 45.99 bar for pure methane), represented by point G, then the cooling process lies along GHC and the minimum work is given approximately by the area GHF (to be exact, it will be less by the amount of the isentropic work output HC). Furthermore the cooling is all required over a temperature range, and none at constant temperature. For methane the respective cooling duties and minimum work requirements are as follows:

TABLE 1 - Cooling duties and minimum work requirements for Methane

Feed gas pressure	Cooling to the dew point		Cooling and Liquefaction	
bars	Duty, J/mol.	Min.work J/mol.	Duty,J/mol.	Min.work J/mol.
1	6456	3702	14672	17577
36	9201	4032	14022	9007
52	-	-	13722	8252
70	-	-	13384	7689

The large reduction on work requirement for high pressure feed gas is clearly evident.

Since natural gas in the ground is normally at a pressure in excess of 100 bar, and in many cases it can be presented to the liquefaction plant at about 50 bar, a considerable power economy is possible. In practice large base-load liquefiers consume about 450 bhp/mm scf per day (24540 J/mol) corresponding to an efficiency of 71.6% when related to gas at atmospheric pressure, but only 33.6% when related to methane at 52 bar (740 psig).

The flow sheet of a modern liquefier is given in Figure 2. A recirculated mixed refrigerant, condensed and evaporated in stages, is used to meet the distributed cooling requirement of the high pressure feed gas. In fact the main justification for the use of mixed refrigerants is the reduction of capital cost achieved by using a single very large axial compressor in place of the two or three pure gas compressors, and a single composite heat exchanger in place of the multiple units, used in the classical cascade. In the latest practice, as shown in Figure 2, reduced power consumption is achieved by using a pure refrigerant (normally propane) for initial cooling applied in 3 stages. Since the mixed refrigerant compressor is already at the limit of size of available axial flow compressors (about 60,000 HP), the use of a second compressor does not adversely affect capital cost.

The multi-stream heat exchangers used in these plants have generated one of the most challenging design problems which chemical engineers have been called on to solve in recent years. Normally 4 streams are exchanging heat, all of which can be mixtures of at least six components, and two are at pressures around the critical. Three of the streams are 2-phase, two condensing and one evaporating. It is necessary to be able to calculate phase equilibria, enthalpies, pressure drops and heat transfer coefficients in an integrated design so that the mean temperature difference for heat exchange is maintained at about 5°C along its length. Maldistribution, especially of the evaporating liquid in the shell, would cause havoc with performance, and this liquid must be distributed uniformly across coiled tube bundles nearly 4m in diameter. Each exchanger may contain several hundreds of miles of tubing. Pilot scale experiments are of little value in guiding the design.

The efficiency of these very large liquefiers (35 - 40%) would appear to give considerable scope for further improvement, but in practice economies are hard won. The main natural gas components have rather low heat capacities and thermal conductivities, and high specific volumes. Hence irreversible heat transfer losses can only be reduced by using uneconomically large heat exchangers, and the efficiency of the large compressors cannot readily be increased. The use of cold compression is one possibility but it would require machinery specially developed for the purpose.

A fascinating challenge is that of developing a floating liquefier for use adjacent to oil production platforms. A new sight which is likely to become familiar on clear nights, to those living on the North East coast of Scotland, will be the flares burning far out at sea. This waste of fuel is likely to occur because it will not be economic to pipe it back to shore, neither will the money be available in some cases for the compression equipment necessary for re-injection. Yet this free fuel could be liquefied and brought ashore, or exported as LNG, if only the Government had the initiative to recognise and tackle the challenge. I deliberately single out the Government (or possibly the British Gas Corporation) because present economic factors and taxation are unlikely to make such a development profitable for oil companies.

(b) Tankers

For bulk LNG transport tankers of 75,000 m^3 capacity (35,000 tonnes) are in regular service, and vessels of up to 125,000 m^3 capacity are projected. The low density of LNG (s.g. = 0.45) results in vessels with a high free board, whilst other problems are posed by the need to minimise friction-based evaporation due to liquid sloshing in rough water, and the need to keep tanks cold during the return voyage. There is vigorous competition between proponents of two quite different forms of tank construction. The first uses rigid spherical tanks supported at the equator in such a way that flexing of the ship does not transmit direct strain. The second method uses tanks contoured to the shape of the hull, rigidly attached to the hull, and internally lined with insulation. LNG is prevented from penetrating the insulation by an inner metal membrane constructed from a low shrinkage material such as invar, and made flexible in some designs by a pattern of bi-directional corrugations. This membrane is tied back through the insulation to the tank wall, and a second simpler membrane is provided part way through the insulation for greater security. The membrane design generally allows more efficient utilisation of the hull volume, though this is off-set to some extent in the case of spherical tanks by allowing them to protrude above the main deck level.