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THE SCALE OF ETHYLENE PLANTS: BACKGROUND AND ISSUES

Prepared for the IIASA Workshop
"Size and Productive Efficiency--
The Wider Implications"

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PREFACE

Questions of scale have been the subject of research at IIASA since January 1978. Following the publication in September 1978 of the IIASA Research Memorandum "'Problems of Scale' - The Case for IIASA Research" (M.F. Cantley and V.N. Glagolev; RM-78-47), plans were made for a workshop to be held in June 1979 on the topic "Size and Productive Efficiency - The Wider Implications". This workshop is planned around a selected list of "Key Topics" and specific industries - the latter including initially electricity generation, ethylene plants, and coal liquefaction.

Since not all workshop participants can be familiar with all topics and industries, it was felt that it would be useful to provide background material where necessary. This paper is intended to provide sufficient up-to-date factual information on the petrochemical industry to enable participants to understand and contribute to discussions about questions of size in ethylene plants, and to relate these to the more general issues raised at the workshop.

The information presented here is based on the published articles listed in the references, and on correspondence and conversation with experts in the industry; but the author, while wishing to acknowledge the extensive help received from these sources, accepts responsibility for any inaccuracies or over-simplifications he has introduced.

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1 INTRODUCTION

The context of this paper is a program of research into questions of scale. In this context, ethylene plants have been selected for consideration as an example of an important industry and technology in which scale changes have been a significant feature of the last thirty years' development. Both the physical and the financial scale of the plants place them in the forefront of large-scale manufacturing investments, and in the history, current pre-occupations and prospects of such an industry, our hope is that lessons may be learned of relevance beyond the immediate boundaries of the industry.

In the following sections, a basic introduction is given to the product and its co-products, the feedstocks, the production process, and the current shape of the industry. Against this background, the final section suggests some more general issues arising from consideration of ethylene; topics which may be further developed in the context of workshop discussons and future research.

Figures in the text have been expressed (except where otherwise stated) in metric tons/year, but capacities should be taken as approximate. U.S. and British usage is often pounds(lbs.)/year; the British "ton" is 1.7% heavier than a metric ton, the U.S. ("short", 2,000lb.) ton is 9% lighter. A "billion lbs./year" U.S. plant is 500,000 (U.S.) tons/year or 450,000 (metric) tons/year.

2 PRODUCTS AND FEEDSTOCKS

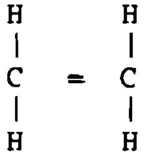
2.1 The Product, its Co-Products and Derivatives*

Organic chemicals, originally so called because they were derived from living organisms, all contain the element carbon whose atomic structure enables it to combine readily with itself and with other elements, such as hydrogen, oxygen, nitrogen, chlorine and sulphur. The range of obtainable compounds is vast, and many are produced as intermediate materials for use in other sectors of the chemical industry. The products of the organic chemicals sector are broadly divisible into two groups: the heavy organic chemicals, produced in bulk and used in large quantities, and the speciality products.

Of the heavy organic commodities produced in bulk, the largest groups are the olefins - ethylene, propylene and butadiene - and the aromatics - benzene, toluene and the xylenes (BTX). From these are derived intermediate chemicals and other "downstream" products. The growth of ethylene and propylene capacity is the basis for expansion of the organic chemicals sector as a whole, and provides capacity in bulk chemical production to meet demand by users further "downstream".

Ethylene is one of the most vital and versatile substances produced by the chemical industry, being used in about one-third of all chemical products. It goes directly for polymerisation to produce polyethylene, a widely used plastic; oxidized to form ethylene oxide, it is then converted to ethylene glycol for anti-freeze; also through ethylene oxide, it produces polyesters, polyethers, solvents and synthetic fibres; ethylene is combined with benzene to produce styrene and polystyrene. Ethyl alcohol and vinyl chloride are other important derivatives.

This versatility arises from the basic molecular structure of ethylene's two carbon and four hydrogen atoms; $\mathrm{C2H4}$:



$$\begin{array}{ccc} \mathrm{H} & & \mathrm{H} \\ | & & | \\ \mathrm{C} & = & \mathrm{C} \\ | & & | \\ \mathrm{H} & & \mathrm{H} \end{array}$$

The propensity of carbon to form bonds, which is the basis for the fundamental role this element plays in organic compounds, is a propensity markedly present in this particular structure - hence the widespread reference to it as a basic "building block".

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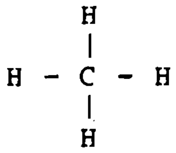
* This section has drawn extensively on Central Office of Information (1978) [referred to after this as COI].

Various hydrocarbon feedstocks can be used as the source of ethylene, and feedstocks are discussed in the following section. The yield of ethylene depends first of all on the nature of the feedstock used, and then on the technical characteristics of the plant, described in section 3.1.

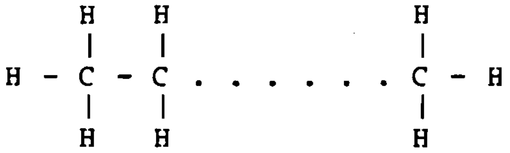
Principal co-products are propylene ($C3H6$) and butadiene ($C4H6$). Propylene is the source of many products, both bulk and speciality; particularly isopropanol, polypropylene and acrylonitrile. Butadiene is used primarily in the production of synthetic rubbers.

2.2 Feedstocks and Flexibility for Olefin Plants*

Crude oil is the world's principal source of all hydrocarbon feedstocks at the present day, although in the longer term the hydrogenation of carbon in coal may become increasingly important. Crude oil as it comes from the well contains a proportion of low hydrocarbons which are gases at normal temperature and pressure - principally methane ($CH4$), ethane ($C2H6$) propane ($C3H8$) and butanes ($C4H10$). These are various lengths of the simplest form of hydrocarbon chain:



$$H - \underset{\underset{H}{|}}{\overset{\overset{H}{|}}{C}} - H$$



$$H - \underset{\underset{H}{|}}{\overset{\overset{H}{|}}{C}} - \underset{\underset{H}{|}}{\overset{\overset{H}{|}}{C}} \;.\;.\;.\;.\;.\;.\;.\; \underset{\underset{H}{|}}{\overset{\overset{H}{|}}{C}} - H$$

Hydrocarbons of various structures are often summarily described by their number of carbon atoms: C1, C2, C3, etc.

The crude oil and the gases cannot be piped together for technical reasons, so the gases are usually separated from the rest of the oil at the well-head, and then further separated into (i) a mixture of methane and ethane gases, and (ii) a mixture of propane and butanes which are liquefied under pressure as "liquid petroleum gases" (LPG).

The gas/oil ratio varies considerably between different crudes. If it is low, the C1/C2 content removed at the well-head may be burnt as local fuel and any small surplus flared. If it is high enough, and depending on local circumstances (Middle East desert, North Sea platform, Gulf Coast U.S.A. ...) the C1/C2 mixture may be piped separately as a gas fuel or as a chemical feedstock. For example, from the North Sea Ekofisk field, gas is piped to North Germany and the crude oil to Teesside, England.

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* This section quotes extensively from Appendix D of U.K. Chemicals Economic Development Committee (1976) [referred to after this as UKCEDC].

Methane ($\mathrm{CH4}$) is the starting material for the manufacture of ammonia and methanol. It cannot form a feedstock for ethylene, and if present in the feedstock has to be removed in the "de-methaniser" unit. It constitutes 98% of North Sea gas.

Ethane ($\mathrm{C2H6}$) can be readily cracked to make ethylene. This is the normal route in the U.S.A., where large quantities of ethane have arisen, mainly from natural gas processing.

Propane ($\mathrm{C3H8}$) can also be cracked to produce ethylene and propylene.

Naphtha is a refinery product, the standard feedstock currently used in Europe and Japan, to produce ethylene, propylene and aromatics (butadiene, toluene and xylene). With the reduction of fuel demand and therefore refinery outputs, the availability of this feedstock is tending not to keep pace with petrochemical requirements, and encouraging a shift towards the heavier, but more readily available gas oil.

Gas Oil is a higher boiling point (more viscous) refinery product which has in recent years been coming into use as a feedstock for olefin plants.

Ethylene crackers have usually been designed to use a single type of feedstock. Greater flexibility can be built in, at increased capital costs and probably operating costs. It is however unlikely to be economic to alter a cracker to use a different feedstock from the one for which it was initially designed. For profitable operation, it is generally necessary to use the valuable co-products, propylene and butadiene, usually by converting them into downstream products in associated plants. Basic changes in feedstocks would therefore require substantial changes in the pattern of downstream operations, making some existing plants redundant and other new plant necessary. While a major existing petrochemicals complex could probably accept and accommodate a shift to an alternative feedstock for a part of its ethylene output, particularly if planned as an extension of output, it could not change over for all or a major part of its output.

The cracking of naphtha produces, besides ethylene and propylene, butadiene, large quantities of gasoline, and other valuable products. Gas oil would also produce a wide, though a somewhat different, range, but cracking the lower hydrocarbons would yield only a limited range of related products, e.g., ethane would only give ethylene, as cracking breaks the higher and more complex hydrocarbons down to lower ones and not vice versa. In comparing the prices at which alternative feedstocks are available, account must be taken of the whole range of their cracker products and not merely of their ethylene content.

The very substantial differences in feedstock are illustrated by the ethylene yields shown in Table 1, which range from 80% (ethylene feedstock) to 25% (gas-oil).

Table 1. Ethylene Yields from Different Feedstocks: Parts per 100 Parts Feed

		Feedstock						
					Full-range naphtha			
	Product	Ethane	Propane	Light naphtha	High sulfur	Medium sulfur	Low sulfur	Gas oil
Olefins	Ethylene	80.0	45.0	36.2	31.4	29.7	28.2	25.7
	Propylene	1.4	14.5	16.7	11.9	14.1	15.4	13.3
	Butadiene	0.0	2.7	4.3	4.3	4.5	4.7	4.2
Aromatics:	BTX	0.0	3.4	8.8	14.3	12.3	10.5	11.0
	Subtotal	81.4	65.6	66.0	61.9	60.6	58.8	54.2
	C_4 : S	4.8	2.0	4.2	3.9	5.3	6.8	4.5
	Gasoline	0.2	4.2	6.5	11.1	14.4	17.4	9.6
	Subtotal	5.0	6.2	10.7	15.0	19.7	24.2	14.1
	Fuel gas	13.6	28.2	20.0	17.6	16.0	14.5	11.7
	Fuel oil	0.0	0.0	3.3	5.5	3.7	2.5	20.0
	Subtotal	13.6	28.2	23.3	23.1	19.7	17.0	31.7
	Total feed	100.0	100.0	100.0	100.0	100.0	100.0	100.0

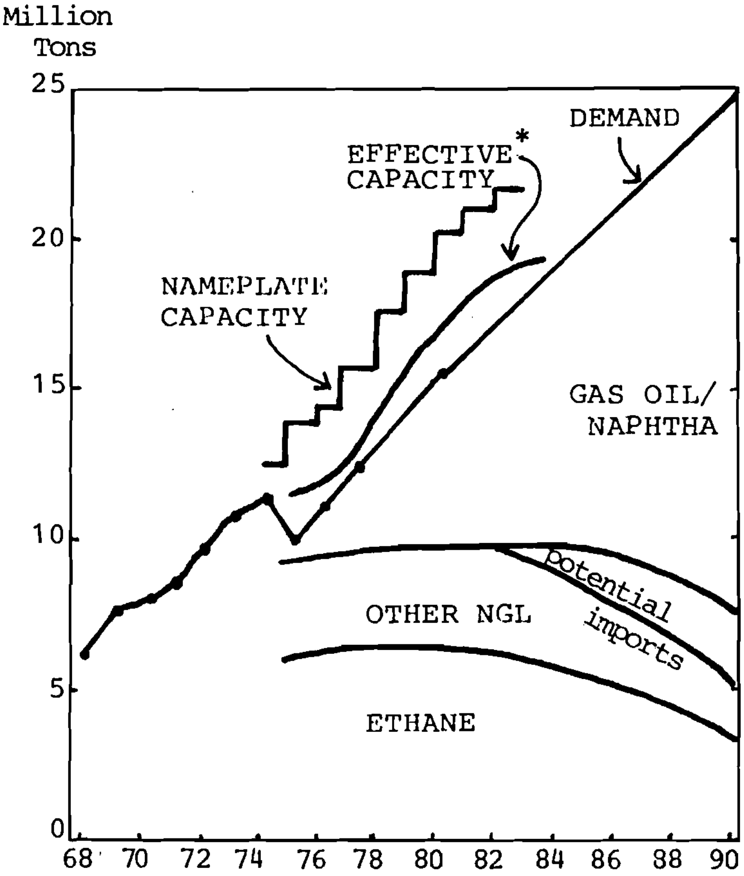
Source: Becdelievre and Kaiser (1978).

Feedstock is thus the primary determinant of the range of outputs of an olefins plant. Increasingly, planners and designers are seeking to build in flexibility from the start. Liquid feedstocks give greater flexibility, as they allow considerable controlled variation of outputs by adjusting the operating conditions or "cracking severity" of the pyrolysis process. Also, when liquid feedstocks are used, the by-products are liquids easily transported as bulky materials. (Liquid ethylene and propylene can be shipped, in special tankers). A Shell forecast of the U.S. ethylene supply/demand picture shows the expected change in future feedstock patterns in the U.S. (Figure 1).

To respond to the varying demands for the products of a petrochemical complex, the ethylene plant must be able to process several feedstocks at different severities, and some operators have recently been investing heavily to increase the flexibility of their plants (e.g., Shell in U.K., see Chemical Marketing Reporter 1977 [referred to after this as CMR]).

In times of possible feedstock shortage, the most fundamental need, however, is to have a dependable source of supply. This gives the major oil companies a fundamental advantage over chemical companies in the petrochemicals sector; an advantage reinforced by their generally greater financial resources, which the escalating capital costs of plant have very much required. For example, feedstock problems caused naphtha's price on the Rotterdam spot market to rise from \$120/ton in January 1978 to \$200/ton in January 1979. Given other costs and co-product prices, this was reckoned to add \$126/ton to the price of ethylene; and the price of polyethylene consequently rose from \$570/ton in December 1978 to almost \$1,000/ton at the beginning of March 1979 (The Economist 1979a, 1979c).

Slow economic growth has contributed to excess plant capacity, however, so that although the reduction of Iranian supplies or similar shocks may cause violent fluctuations in feedstock prices, a more chronic problem likely to persist for the next few years is excess plant capacity. The following section briefly describes the main elements of an olefin plant.



*Forecast operating rate = 75-80%

Source: Shell Chemical Co., in Wett (1978a)

Figure 1. Forecast of U.S. Ethylene Supply/Demand and Feedstock Mix.

3 OLEFIN PLANTS, SCALE AND PETROCHEMICAL COMPLEXES

3.1 Basic Technology of Plants

Woodhouse et al. (1974) give a good summary of the historical development of ethylene technology:

> In the 1930s and during the war years, ethylene was produced in small amounts by a variety of routes. These included the dehydration of ethanol and the hydrogenation of acetylene, as well as the recovery of ethylene from coke-oven gas.
>
> As the demand for ethylene as a petrochemical feedstock started to increase, plants were built based on the thermal cracking of petroleum fractions. In the U.S., plants were based on ethane cracking. In 1942, British Celanese built a plant to crack gas oil under vacuum to provide ethylene for further conversion to ethanol and acetic acid.
>
> The tremendous increase in demand for ethylene over the last 20 years has brought with it big changes in technology and even bigger changes in the size of plants. Early plants based on thermal cracking of petroleum distillates had capacities of about 30,000 tons/yr of ethylene.
>
> After about 1965, many companies that traditionally had been ethylene suppliers started to invest in downstream units and became producers of ethylene-based derivatives: conversely, many consumer companies started to build their own plants to satisfy captive needs. Along with these developments, ethylene pipelines were built in areas such as th Gulf Coast of Texas, linking producer and consumer plants.
>
> In the early 1960s, capacities had risen to 100,000 tons, and present-day plants have capacities as high as 500,000 tons/yr. This capacity will probably not be exceeded because the economies of scale stop at about this point for a number of factors: for example, some of the major items of equipment reach a size that require field fabrication.
>
> These events combined to shape the industry in the U.S., Japan and Western Europe into what

exists today, i.e., large plants of 300,000-500,000 ton/yr capacities, feeding either downstream units located on adjacent sites, or pipeline systems.

Figure 2 outlines the common basic process scheme in ethylene plants, and the main stages are described here.

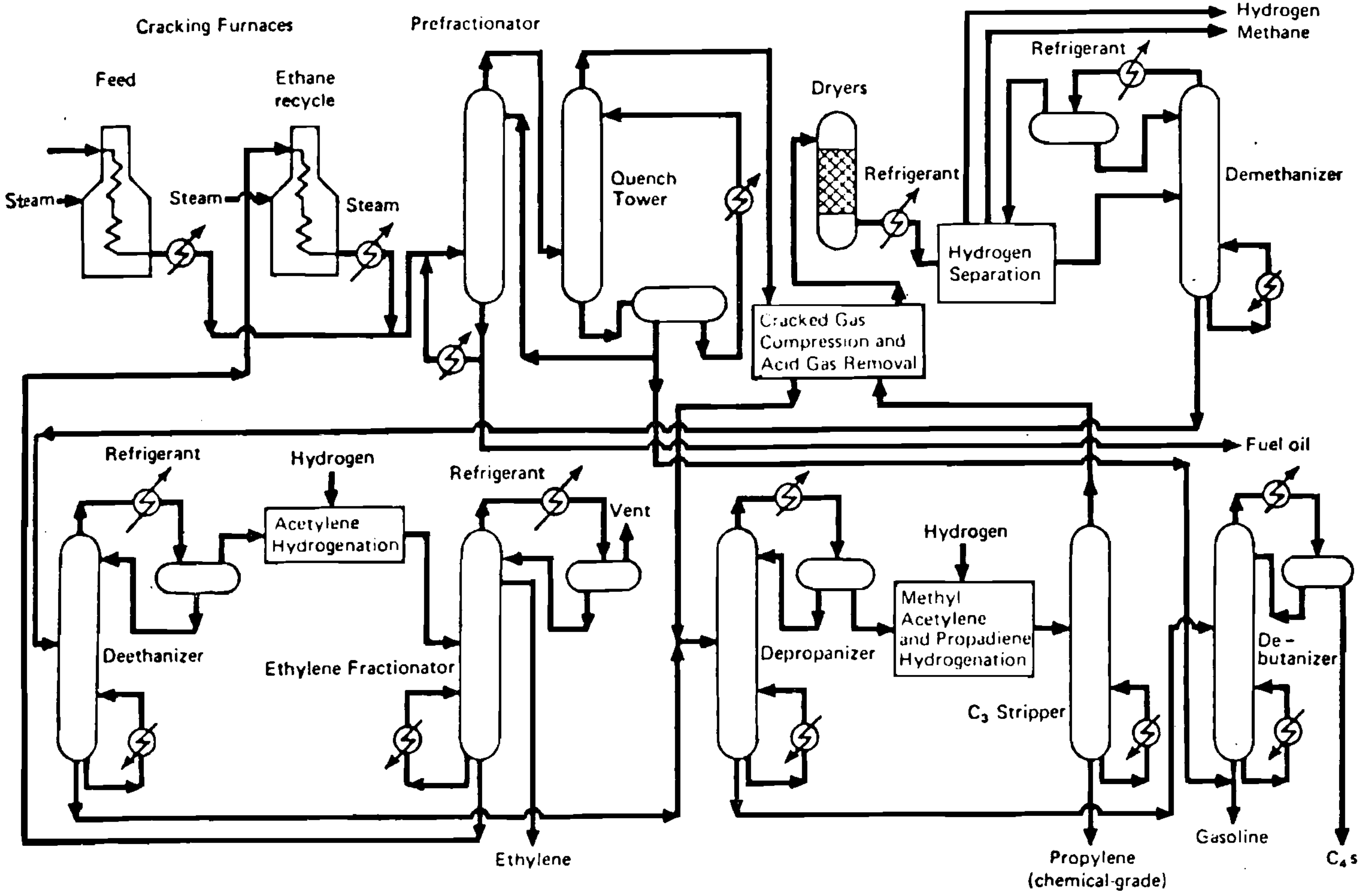
The feedstock is mixed with steam, preheated, and undergoes pyrolysis in the radiant coils of the cracking furnaces: passing the mixture rapidly through high pressure, high temperature conditions under which various chemical breakdowns and changes occur. A large plant might have 14 to 18 furnaces. The pyrolysis conditions, referred to as "cracking severity", are of critical importance in determining the mix of resulting products. In addition to the original input of feedstock, re-cycled ethane may be returned for cracking, and the outputs added to the primary stream. The mixture of cracked gas and steam is cooled in a quench exchanger (not shown), the heat removed generating high pressure steam. The cooled gas then passes to the prefractionator, where it is cooled by circulating oil streams to remove the heavy fuel oil and gas oil fractions. Further cooling in the quench tower condenses the steam and most of the gasoline product.

The cracked gas is then compressed and cooled in four or five stages, with condensate stripping between stages, and caustic washing removes the acid gases (carbon dioxide, hydrogen sulphide) which cannot be tolerated in the final product. After drying (which is essential to avoid icing problems in the following stages), a hydrogen-rich stream is removed in the demethanizer feed circuit. This enhances separation of methane from ethylene and heavier hydrocarbons in the demethanizer tower.

The demethanizer tower, operating at temperatures around -75 c, pressure 35 kg/cm2 (500 p.s.i.), is the dominant physical unit of the plant: a recently installed Gulf Coast unit was 61 meters high, 5 meters in diameter, and weighed 500 tons.

The demethanizer bottoms (i.e., those products in liquid phase under these conditions) are passed to the de-ethanizer, whose overhead stream contains an ethane-ethylene mixture, and some acetylene, which is catalytically hydrogenated to become ethane or ethylene. The ethylene fractionator splits the mixture to yield ethylene overhead, with ethane being drawn off for fuel or re-cycled.

The deethanizer bottoms are sent to the depropanizer, which produces an overhead stream rich in propylene; after further hydrogenation, this is saleable as chemical-grade propylene. (Polymer grade propylene requires further fractionation.) The bottoms stream from the depropanizer is debutanized to yield a mixed-C4 stream suitable for butadiene



Source: Woodhouse et al. (1974).

Figure 2. A Common Process Scheme in Ethylene Plants

extraction, and the bottoms stream from the debutanizer is merged with the pyrolysis gasoline to yield a stream suitable for blending into gasoline, and from which after further treatment the aromatics can be extracted.

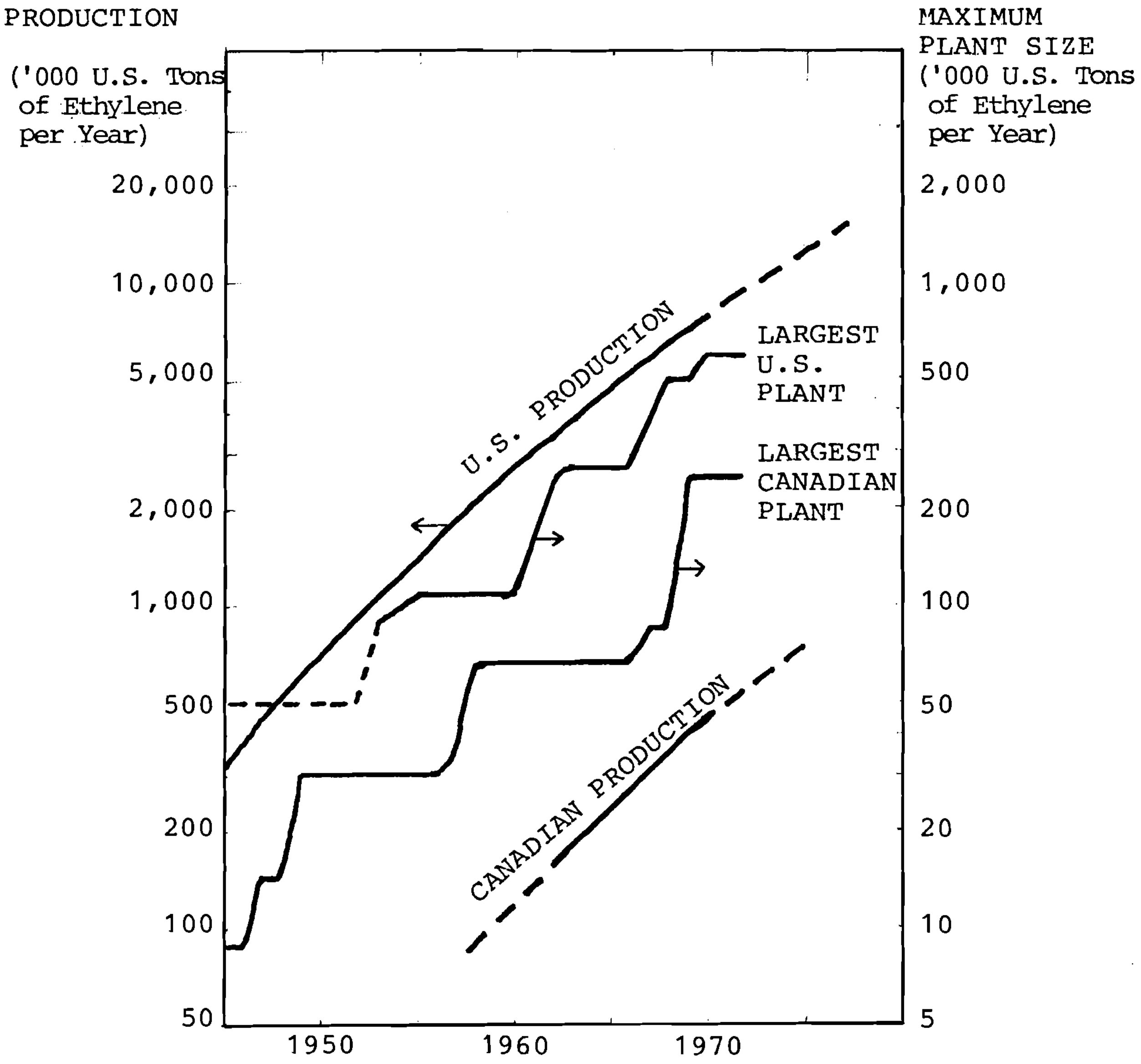
The utilities systems associated with the processing are complex, involving large amounts of refrigeration, fuel, cooling water and steam. Woodhouse et al. (1974) list the following equipment for a typical 500,000 tons/year naphtha-based cracker:

Equipment	Quantity
Cracking furnaces	16-18
Other furnaces	2-3
Reactors and drivers	11
Drums	105
Fractionating towers	12
Tanks	6
Pumps and motors	110
Compressors and drivers	3
Heat exchangers	200
Miscellaneous (filters, etc.)	100
Piping	4000 tons

The associated instrumentation and control systems are correspondingly complex, and to implement the range of alternative operating patterns which circumstances may call for, extensive computer-based on-line control systems are a necessity. Computer simulation is of course extensively used at the design stage (Bergen and Asgari 1978, Goossens et al. 1978).

3.2 The Growth and Limitations of Plant Scale

From the early 1950s to the late 1960s, the increase in scale of ethylene plants was remarkable, maintaining a fairly steady relationship with the growth of the total market. Simmonds (1969) summarized the data as shown in Figure 3. This shows the maximum size of U.S. plant reaching 550,000 (metric) tons of ethylene per year, against a total U.S. market size approaching 9 million tons in the early 1970s. Growth rates of total market have since slowed because of both the general slackening of industrial growth in the 1970s, and more specifically because of the rising cost of feedstocks; but U.S. output in 1978 had reached approximately 13.5 million tons, while the maximum plant size is now 635,000 tons/year (e.g., Shell's Deer Park, Texas plant) and a 680,000 tons/year plant is under construction (Shell's Norco, Louisiana plant) (The Oil and Gas Journal 1978 [referred to after this as OGJ]).



Source: Simmonds (1969)

Figure 3. Growth in Scale of Ethylene Production and Maximum Plant Size, U.S. and Canada

The reasons for the growth of scale have been conventional economies of scale, in both capital cost of construction and labor productivity. An October 1973 estimate by Shell staff (European Chemical News 1973 [referred to after this as ECN]) showed the following scale economy:

Capacity (tons/year)	Total cost £/ton of ethylene production
100,000	58
200,000	48
300,000	42
400,000	39
500,000	37

though these figures are identical with, and presumably drawn from, Walley and Robinson (1972), who described them as "1975 basis".

Simmonds (1969) drew attention to the problems faced by smaller producer countries (such as Canada) when the pursuit of these economies of scale was leading to plants of a size large in relation to the total national market, and this is illustrated by the Canadian data in Figure 3. The financial and flexibility implications for companies could also be serious, when their entire capacity might become less than the output of the latest, largest plant. It was therefore with some relief that Coquillette (1974) could at that time report the levelling off of maximum scale at 450,000 tons/year. Coquillette pointed out that this size became standard in 1965, when total U.S. production was 4.3 million tons/year and the market was expanding at 500,000 tons/year, so that a new plant represented 10% of demand. With 1974 production estimated at 11 million tons/year and growth 900,000 tons/year, a new plant would represent only 4% of total demand, and thus such additional increments of capacity no longer resulted in major supply/demand imbalance.

An important and critical article was published by Walley and Robinson of Shell Chemicals U.K. in 1972, pointing out that the type of calculation leading to the figures quoted above "has been repeated so many times, that it has attained a sort of sanctity which is difficult to challenge. The conclusion is always that the larger the plant, the lower the costs, and by implication the larger the profit. However, as a means of optimizing an investment decision it is completely wrong." They point to the unrealistic assumption of full-capacity operation, and the neglect of the three-year build-up to maximum utlization. Even more important, "the most significant factor determining the optimum capacity of a plant is the demand for its products". Particularly in the European environment, and even on the 1972 forecast growth rates, only four large new plants per year would be required; but there were 30 olefin producers in Europe. They conclude that "it is unlikely that very large plants will be economic, other than in a few areas of high petrochemical activity and demand...much of what has been, and stll is being written about the advantages of very large plants is seriously misleading, if not completely wrong." The authors did not rule out further giant plants - given Shell's Deer Park and Norco plants, it would be embarrassing if they had - but foresaw correctly the trend towards co-operation between enterprises.

However, the levelling off in plant physical scale did not arrest the growth in scale of financial commitment, driven not only by inflation but by a change of technology in the move towards heavier feedstocks, with implications for necessary investment in downstream processing.

Kearney (1975) gave the following data in a paper drawing attention to the exhaustion of plant scale economies (data converted to metric):

> In 1967, a 230,000 tons/year plant cost about $25 million for a unit capital cost of $110/ton/year. By 1972-73, the cost of the 230,000 tons/year plant would have increased to $37.5 million, or a unit capital cost of $160/ton/year. By going to the 450,000 tons/year plant, for a cost of about $60 million, the company could produce ethylene at a unit cost of $130/ton/year. The larger plant permitted a reduction in unit capital cost almost enough to offset the effects of inflation.

Kearney estimates the 1978-80 capital cost for a 450,000 tons/year plant as $120 million based on ethane, or $200 million based on naphtha; raising unit costs for ethylene to $440/ton/year (after allowing for by-product credits from the naphtha plant), i.e., four times the 1967 level. U.K. estimates at the same date were much higher: £120 million for a 500,000 tons/year ethylene plant, plus £480 million for accompanying downstream investment (ECN 1975).

A more carefully presented analysis of the same vintage was that by Hansen (1975) who could draw on the experience of the six ethylene plants constructed over many years at Wesseling in West Germany. This is summarized in Table 2, for both the historic plants and a hypothetical future plant to open in 1982.

Hansen points to the decline in costs/ton of ethylene produced, falling to its lowest in the 1968 plant; the reasons being the economies from large-scale operation, coupled with big advances in conversion efficiency. But plant G6 represented a landmark, in that unit costs rose, in spite of the growth in scale, because of a 40% (DM) rise in costs of construction and equipment between 1968 and 1972. For reasons of flexibility and risks of naphtha shortages in the future, plant G7 will

Table 2. Economic and Technical Data for Six Existing and One Projected Ethylene Plants in West Germany

Plant:	G1	G2	G3	G4	G5	G6	G7
Economic data							
Year of start-up	1955	1959	1961	1966	1968	1972	1982
Design capacity ('000 tons/year)	10	30	75	200	320	450	450
Investment cost (U.S. $ million)	6.5	17	27.5	40	50	100	256
Cost/ton of installed ethylene capacity ($)	650	565	365	200	150	225	570
Cost/ton of ethylene produced at full load ($)	500/335	325	225	175	150	175	750 (with naphtha at $350/ton) 600 (with naphtha at $250/ton)
Technical data							
Feedstock	Refinery gas	Light naphtha	Light/full-range naphtha	Light/full-range naphtha	Full-range naphtha	Full-range naphtha	
Ethylene yield (weight %)	39	22	27	28	30	29	
Design contractor	Linde	Kellogg	C.F. Braun	C.F. Braun	Linde	Linde	
Number of furnaces	3	3	10 + 2	18 + 2	12 + 2	16	
Furnace capacity (ton/d feed)	60	160	140/60	120/70	288/164	397	
Number of compressors	16	7	6	3	3	3	
Type of compressor	Piston	Piston	Turbo	Turbo	Turbo	Turbo	
Number of operators	63/43	44	48	53	57	62	

Note: For consistency with the rest of the paper, all Hansen's cost data have been converted to U.S.$ at DM2/$.

The underlying assumptions for the cost figures are: (1) 25 percent of the capital cost is included to reflect the depreciation-charge and profit elements; (2) the cost/ton of ethylene includes only elements specifically related to the ethylene plant (overhead costs relating to general facilities have been excluded); (3) a constant naphtha price of DM 100/ton has been assumed throughout for G2 to G6, until the beginning of 1973; (4) by-products are valued on average at about the same as the naphtha price.

Source: Hansen (1975)

probably be a mixed gasoil/naphtha cracker; but supposing it were a replica of G6, the costs/ton of installed capacity will have tripled from 1972 to 1982. Hansen concludes:

> There is no possibility of offsetting this cost by further economies of scale: increases in the size of ethylene plants are technically feasible but would lead to only marginal reductions in cost/ton. The two main factors which in the past helped cut the cost of producing ethylene (improvements in technology and a larger scale operation) are likely to be less important in the future than two new ones - feedstock costs and the cost of building or constructing the plant.

A factor in rising capital costs has been the rise in construction period, although Kearney (1975) emphasizes that no significantly new technical problems are encountered; at the 450,000 tons/year level, the two largest towers for LPG plants have already to be field-fabricated, because of their diameters. Field fabrication "requires some extra construction time and field coordination in getting the total plant built because of the added activities at the site." Woodhouse et al. (1974) make explicit estimates for the time-lag from an October 1973 decision to date of start-up for hypothetical plants of various capacities:

Capacity, tons/year	Duration
300,000	30 months
450,000	36 months
900,000	42 months

A similar estimate, 33 to 40 months, was given by Van Dalen in March 1975, in a speech referring to the increased number of critical delivery items, the increasing difficulty of obtaining standard units for very large plant, the problems of site fabrication and the general trend of inflation of unpredictable magnitude (Greek, 1975). Van Dalen estimated 350,000 tons/year of ethylene as a lower limit of viability for capacity, 600,000 tons/year as the upper limit.

The combination of increased construction time, increased capital cost and rapid inflation, as foreseen by Hansen (1975), has led to increased financial problems for producers, who have had difficulty in obtaining the price levels necessary to fund large new investments, particularly in a situation of excess capacity. Disenchantment with economies of scale was expressed by ICI Director J. Harvey-Jones in October 1976 (OGJ 1976b):

> ...feels the economies of scale have been largely explored. A trend away from very large plants has appeared. Only a few years ago, he said, ICI was considering the probability of building a 1-million ton/year ethylene plant. Investment decisions now are heading toward the 350,000 ton area.

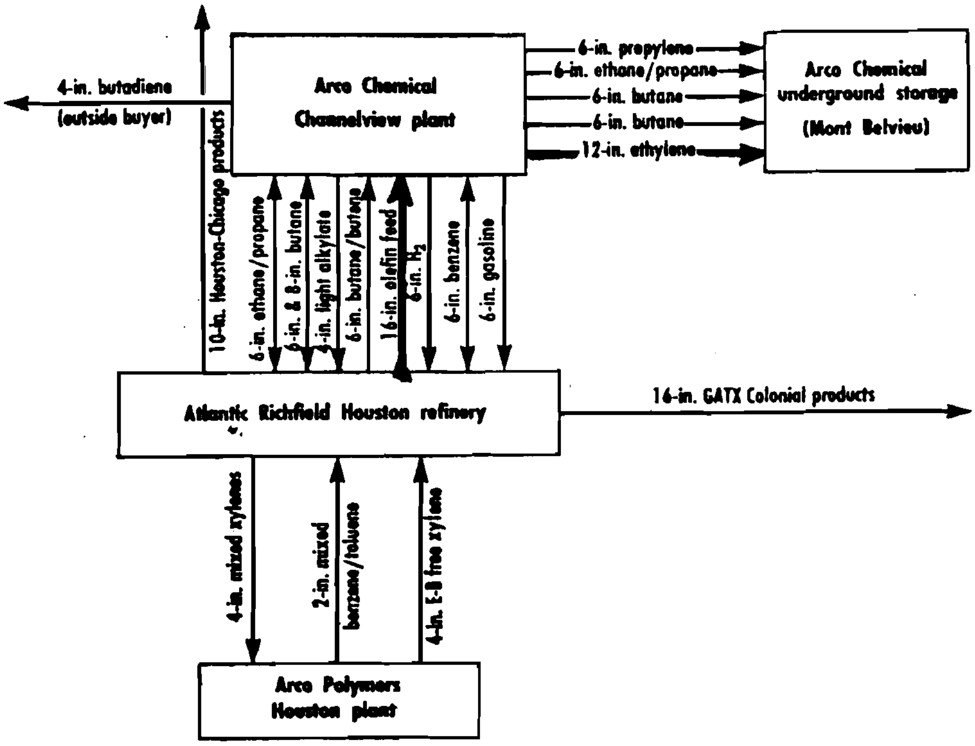
We return in the final section, on "Issues", to the rethinking of plant design concepts which is now taking place.

3.3 Petrochemical Complexes

The development of bulk markets for ethylene coproducts and derivatives, and the economies of scale in these plants have encouraged the development of massive, integrated industrial complexes. In these, transport costs and delays can be minimized, and inter-process stocks of intermediate products reduced to the smallest levels sufficient to cover short-term fluctuations. In 1975, Nahas of C-E Lummus (reported by Greek, 1975) envisaged a plant to crack crude oil directly to petrochemicals; giving more efficient use of raw materials; minimal loss of products to fuel, by recycling them to other units; and maximum thermal efficiency through a central utilities system. He estimated the cost of a 700,000 tons/year (ethylene) plant on the Gulf Coast, using a light Arabian crude oil, as $750 million.

Developments since have confirmed these forecasts, both for the closer integration of olefin plants with refineries, and the downstream integration to derivative products. Some of the recent moves in this direction are described below.

Atlantic Richfield Company (ARCO)'s long-established Houston refinery (Texas) has been expanded (August 1976) to supply a giant olefins complex ten miles away at Arco Chemical's Channelview plant, which comprises two 500,000 tons/year ethylene crackers. These went on line in 1976 and 1977 (Aalund 1978, Wett 1978b). An example of the many synergistic links between the plants is the return from the olefins plant of the pyrolysis gasoline, which will be important in helping the refinery to meet the growing demand for unleaded gasoline. The refinery can supply basically four types of feedstocks to the olefin plant (ranging from light naphtha to light vacuum gas oil), the amount of each depending on economics each month. As with many European complexes, naphtha can be diverted to the olefin plant from the refinery's catalytic reformer if a temporary surplus of motor gasoline develops. A summary diagram of the ARCO complex is shown in Figure 4. Further integration downstream is also typical of oil-company moves. Ethylene and propylene from ARCO will be used by Oxirane, a joint venture with Halcon International, to produce propylene oxide, ethylene oxide, and styrene: and by ARCO Polymers for polyethylene.



Source: Aalund (1978).

Figure 4. The ARCO Houston-Channelview Refinery-Petrochemicals Complex

The financial scale and market ramifications of such complexes have encouraged the formation of consortia or joint ventures, as in the following examples.

Petrosar in Ontario, Canada, is owned 60% by Polysar Ltd., 20% by Du Pont of Canada Ltd., and 20% by Union Carbide Canada Ltd. Starting with crude oil, it produces 450,000 tons/year of ethylene, as well as the usual range of co-products associated with a naphtha feedstock. Petrosar will feed ethylene and benzene to Polysar's new ethylbenzene/styrene plant.

One of the largest ethylene plants currently under construction is Shell's 680,000 tons/year plant, based on heavy liquids, which is being added to its complex at Norco, Louisiana. The existing complex includes a 240,000 b/d refinery and two other major olefin plants with a total ethylene capacity of 700,000 tons/year. While not a consortium, the scale of production is based substantially on long-term contracts with customers for the outputs.

Continental Oil and Monsanto, an oil and a chemical major, have agreed on a joint project to make a major expanson of

Monsanto's existing petrochemical complex at Chocolate Bayou, Texas, while Conoco construct a complementary feedstock-manufacturing unit at their Lake Charles, Louisiana, refinery. A similar joint venture is under way between Champlin Petroleum Co., ICI Americas and Solex Polymer Corp., at Corpus Christi, Texas.

These ventures combine a determination to obtain the benefits of large-scale integration with a desire to limit the exposure on massive single investments by some of the companies involved. The complexity of operating and controlling the plants appears to be satisfactorily solved by current computing and software capabilities. The greater risks remain in the external environment, affecting feedstock availability or end-product demand, and in the co-ordination of long, complex construction projects. Problems have been encountered where one element in a complex is delayed - e.g., oilfield gas had to be flared because of hold-ups in the construction of an ethylene cracker at Tobolsk, and a similar delay at the Lisichansk project meant that downstream chemical plants were starved of ethylene (The Economist, 1979b).

Some of the risks of co-ordination problems may be resoluble by yet further integration and proximity between independent operators, through the development of joint-use pipeline and storage networks such as Union Carbide has constructed to support its ethylene purchasing strategy in the Gulf Coast area (Wett, 1978a).

4 CURRENT WORLD SITUATION

4.1 Current Capacity and Locations

Under the heading "Ethylene market faces overcapacity future", The Oil and Gas Journal (Wett 1978c) last year reported worldwide ethylene capacity as well in excess of demand, with expected additional capacity currently under construction likely to maintain this situation well into the 1980s. The journal listed all the plants on stream in the Western world, and the figures are summarized in Table 3.

A breakdown by continent from the same article, including the 1977 figures, shows a 21% increase in capacity from 1977 to 1978 (Table 4).

Figure 5 shows the size distribution of the plants listed in the Oil and Gas Journal article; those above 550,000 tons/year are probably all multi-unit, rather than single-train, plants.

During the early 1970s, ethylene demand surged ahead and projects proliferated. Following the rise in energy costs and worldwide economic slowdown, utilization levels have fallen as new capacity came on stream, and current projects will add 3.9

Table 3. Ethylene Capacity by Countries, as of 30 June 1978

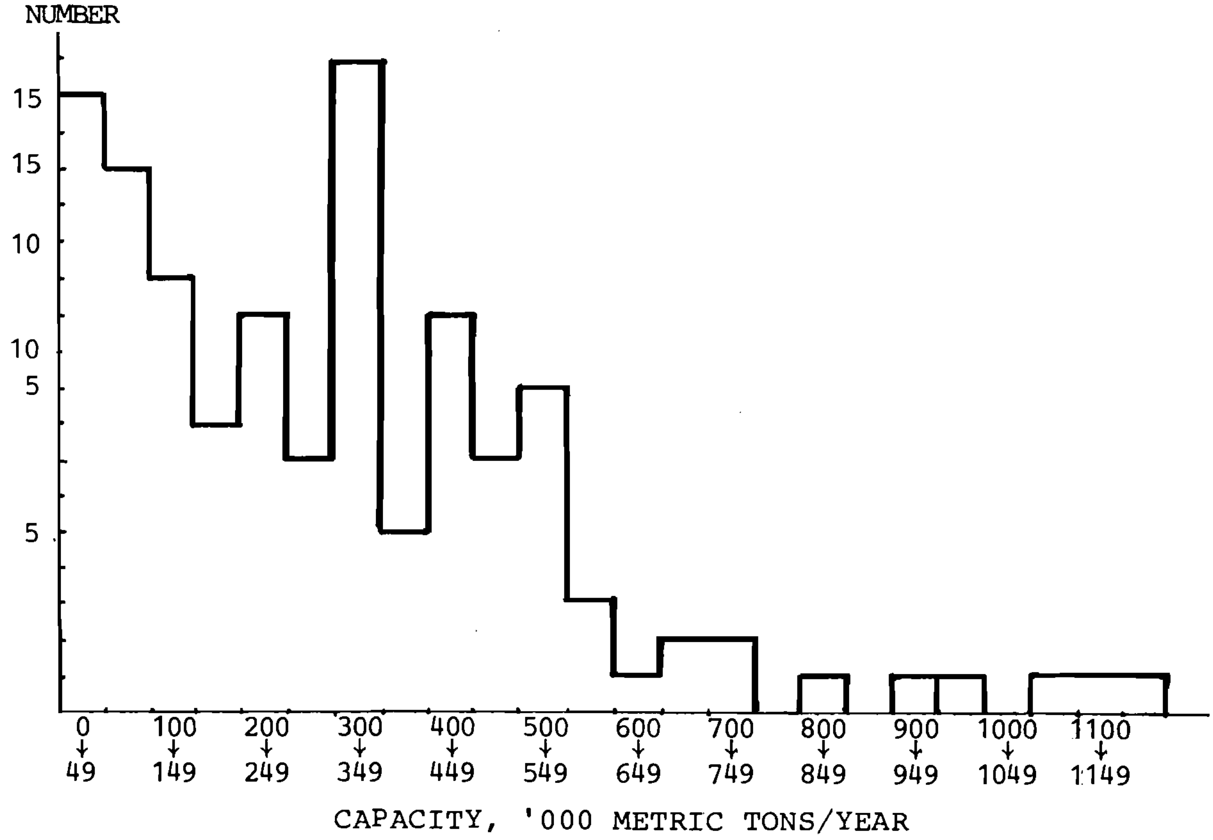
Country	Number of Plants	Capacity ('000 tons/year ethylene)
United States	34	13,680
Argentina	3	150
Australia	3	255
Austria	1	105
Belgium	1	520
Brazil	2	718
Canada	5	1,249
Chile	1	60
Colombia	1	16
Denmark	1 (shut down)	(43)
Finland	1	165
France	8	2,220
Germany (FRG)	12	4,405
Greece	1	15
India	4	214
Iran	1	26
Israel	1	24
Italy	9	1,853
Japan	17	5,580
Korea (S.)	1	155
Mexico	5	445
Netherlands	6	5,190
Norway	1	300
Puerto Rico	2	905
Qatar	1	280
South Africa	1	150
Spain	3	656
Sweden	1	350
Taiwan	1	515
Turkey	1	55
United Kingdom	5	1,675
Venezuela	1	200
TOTAL (Exc. Socialist Countries)	135	42,130

Source: Wett (1978c)

Table 4. Ethylene Capacity by World Regions, as of 30 June 1978

Area	1977 ('000 metric	1978 tons/year)	% increase
North America	13,478.76	14,929.47	10.8
Latin America	1,889.8	2,493.8	32.0
Asia/Pacific	5,716	6,718	17.5
Western Europe	13,514	17,439	29.0
Others	244	550	25.4
Total (exc. socialist countries)	34,842.56	42,130.27	20.9

Source: Wett (1978c).



Source: Based on Wett (1978c)

Figure 5. Ethylene Plant Size Distribution as of 30 June 1978

million tons (28%) to U.S. capacity by 1980, barring closures of older (smaller) plants. Many of the new projects are 450,000-550,000 ton plants, at the top end of the size range, while closures are concentrated at the bottom end.

In Western Europe (EEC plus Austria, Spain and Scandinavia), the overcapacity situation looks more serious, according to the December 1977 forecast by the European Council of Chemical Manufacturers' Federations (Cefic 1977). This is summarized in Table 5.

4.2 Factors of Change in Market Structure

We defer to sections 5.2 and 5.4 the questions of technical change in plant design, but note here some of the major dynamic influences currently affecting the world market position for ethylene.

First of all, the bringing on stream of the large new plants is almost invariably accompanied by closure of old units. A dramatic example is provided by Dow Chemical (U.S.A.), who in September 1978 announced the closure of their San Francisco plant (70,000 tons/year). The local manager was quoted (Midland Daily 1978) as follows:

> The 20-year-old plant was unable to compete with newer plants six times its size which can be run by about the same number of employees. This plant is only a sixth as big as world scale, which is a billion pounds of ethylene produced per year. Dow has 14 petrochemical plants in the world. Half of them are small, like the Bay City plant, and the rest are world scale. The small plants will all be shutting down by the end of next month because they aren't economical.

A feature which has marked the development of the ethylene industry over recent years has been the expansion downstream by the oil companies, whose capital spending has been significantly disproportionate to their sales representation (CMR 1976). This has not been the result of aggressive diversification, however, but the logic of the switch towards heavier feedstocks, itself a necessary result of the decline (in the U.S.) of natural gas liquids since 1972. The oil companies, as refiners, control the availability of these heavier feedstocks, and can moreover market the significant fuel by-products which result from their use. As the Economist reported (1979a) "Companies which do not have their own production of base chemicals are being squeezed out of some markets - like Monsanto, Union Carbide and Conoco last year."

As pointed out in 2.2, Europe and Japan have been users of naphtha or gas oil for many years, and therefore this pattern of oil-petrochemical integration has for long been standard in

Table 5. 1971-76 Actual and 1977-81 Forecast Ethylene Capacity and Production in Western Europe

	'000 tons						Forecast				
	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981
Effective Capacity	7,471	9,194	10,864	12,156	12,695	12,998	13,710	13,915	16,430	16,840	16,965
Production/ Consumption*	6,561	8,037	9,654	10,468	7,967	10,340	10,370	10,900	11,450	12,000	12,600
Utilization	87.8	87.4	88.8	86.1	62.8	79.6	75.6	73.1	69.7	71.3	74.3
% growth in capacity		23.1	18.2	11.9	4.4	2.4	5.5	8.8	10.2	2.5	0.7
% growth in production		22.5	20.1	8.4	-23.9	19.8	0.3	5.1	5.0	4.8	5.0

*For total Western Europe, production and consumption were within 1% of one another; forecast 1977 onwards is for consumption, but "utilization" is calculated as though production = consumption.

Source: Cefic (1977).

these areas. Moreover, the availability of naphtha on the Rotterdam spot market has enabled chemical firms to assume and to rely upon its continued availability. Should the recent shortages of naphtha persist, it will emphasize the importance of technologies which might permit the use of other feedstocks: direct use of crude oil, coal (via liquefaction), or biomass (plants). Kureha in Japan have for many years operated a small crude oil based ethylene plant (Greek 1975), and they and Chiyoda are reported recently (The Economist 1979d) as having done the basic development work. Thus the technological base for the current structure of the industry cannot be taken as fixed in the longer term.

The geographical distribution is also undergoing significant evolution, in ways not reflected in the static picture shown in Tables 3 and 4. Natural-resource-rich countries are naturally anxious to add maximum value at the point of origin, and are reluctant to remain solely producers of crude oil or natural gas. There are at least five distinct geographical areas in which major change is taking place.

Mexico is planning to quadruple its capacity to 1.6 million tons by 1982 (Gancia 1978).

The North Sea basin is a stimulus to the growth of oil/petrochemical based complexes in Norway, the U.K. and Northern Europe. The U.K. government has repeatedly spoken (CMR 1977, COI 1978) of its desire to see four new ethylene crackers by 1988 to restore U.K. market share of Western European supply, but so far European investment has mainly been centered on Belgium and the Netherlands. There are currently 19 ethylene projects in the planning or construction stage in Western Europe (Wett 1978c), but many of these have been delayed or deferred.

In North Africa and the Middle East, the ethylene projects listed in Table 6 were noted in the 1976 U.K. study (UKCEDC 1976).

The timing of many of these projects is, as elsewhere very uncertain. The U.K. report comments:

> The investment intentions are extremely large but to put them into perspective it is unlikely that the countries concerned will be able to produce more than 800,000 tons of ethylene in 1980 and not more than 2 million tons by 1985. It would be surprising if the totals given were achieved by the turn of the century. Nevertheless, companies will have to take the plans of Middle Eastern producers into account in assessing their own investment intentions and their feedstock sources.

Table 6. Ethylene Projects in North Africa and Middle East, March 1976, Capacities in '000 tons per year

	Firm or Fairly Firm	Under Study	Total
Algeria	420	-	420
Abu Dhabi	-	250	250
Egypt	256	300	556
Iran	360	900	1,260
Iraq	150	400	550
Kuwait	120	250	370
Libya	330	-	330
Qatar	300	-	300
Saudi Arabia	1,000	1,500	2,500
Totals	2,936	3,600	6,536

In Canada, the federal structure delegates substantial control of natural resources to the provincial governments; there may be some hyperbole in the Alberta Energy Resource Conservation Board's reported belief that (Canadian Chemical Processing 1975) "Alberta will become a major center of petrochemical production in Canada...by the end of the century some seven world-scale ethylene plants will be based in the province using a variety of feedstocks and producing various derivative products...eight new ammonia plants...six world scale methanol producing units...an integrated steel industry..." In support of this development policy, Canada's National Energy Board has been restrictive in granting export licences for ethane, propane or ethylene; and there have been protracted battles with Dow Chemical over export licences both for its planned purchases from Alberta Gas Ethylene and for its planned exports from a projected Dow-Dome Petroleum ethane cracker (Brender 1974, OGJ 1976a).

Clearly not all published statements can be taken at face value, since there are elements of gaming in the competitive situation, creating the maximum impression that one is about to add substantial capacity (to deter others), while in practice delaying as long as possible the actual commitment to build (to avoid overcapacity, underutilization and low prices).

A more immediate and tangible challenge to the Western European assumption that "consumption = production" comes from the growing exports of Eastern European chemical producers. A Kidder, Peabody report summarized in the Economist (1979b) shows Western European ethylene capacity growing from roughly 13 to 19 million tons (by 49%) over 1975-81, while Eastern European capacity grows from 2.4 to 5 million tons (by 104%). Of 16 olefins projects currently under way, five are "barter" projects in which the capital cost of the plant will be met from sales of its production on the Western markets.

A comprehensive and up-to-date review of the whole chemicals industry, in which the olefins play a major part, was recently published in the Economist (1979e).

5 KEY ISSUES IN ETHYLENE PLANTS

5.1 Introduction

The experience and the problems of the chemical industry illuminate some issues of more widespread significance. In this final section, we suggest some of these issues which merit discussion, proceeding from the more specific and technical towards the more strategic and general.

5.2 Ethylene Plants, Economies of Scale, Models of Learning and Innovation

Ethylene, or petrochemical, plants appear to be the outstanding example of a capital intensive industry, in which the capital cost economies of the "two-thirds power" law have been demonstrated and achieved, and the problems of technological scale-up for all parts of the process solved at each successive size of unit. Labor productivity improvements have been dramatic, reflecting virtually constant manning levels independent of plant size.

The concentration of expertise in plant construction in a handful of groups, and the near-stabilization since the mid-sixties on a scale of around 500,000 tons/year, should have enabled learning curve effects to take place to some degree; particularly since firms have specialized in the various plant components. There is evidence of this in the improved efficiency and product selectivity achieved in pyrolysis. However, the careful empirical study by Lau and Tamura (1972), based on 20 Japanese ethylene plants of vintages from 1958 to 1969, although supporting the clearcut capital and labor economies of scale, finds no evidence of technical progress other than that embodied in scale increase. Their key conclusions were as follows:

> We observe that the estimated scale coefficient for capital is very close to the "six-tenths" factor customarily used by engineers in cost estimation. The Scale coefficient for labor is not significantly different from zero, indicating extreme economies of scale in labor. ...once that fixed level is reached, output can be increased to *any level* by merely increasing other inputs while holding labor at a fixed level. ... Both the energy and raw materials scale coefficients are close to one, indicating constant returns. In other words, energy and raw materials are ued in fixed proportions to output. The technical change parameters are on the whole not significantly different from zero. In fact we cannot reject the hypothesis of no technical change. This implies that any technical progress that is present in the petrochemical progress must be embodied in scale rather than in capital goods of a given vintage.

It may be that "learning" attributable to repeated production (and therefore improvement) of basically identical components (if not whole plants) will have progressed significantly only since the late 1960s when plant size levelled off, in which case the Lau and Tamura data would scarcely capture it.

The issues raised by the combination of scale effects and the possibility of "learning curve" cost reduction are fundamental to the whole theory and application of learning curves, which suggest that for every doubling of cumulative output, unit costs can be reduced by a certain proportion (typically around 20%). There is not space here to do more than pose a few of the questions raised by this. First of all, is the cumulative output referred to

(a) of ethylene

(b) of ethylene plants - including all stages of design, manufacture, erection and commissioning

(c) of major components - pyrolysis furnaces, quench towers, compressors, heat exchangers, fractionation columns, etc.

One could expect experience curves to be applicable to all three of the above categories. Obviously there has been a reduction in the unit resource cost per ton of ethylene Produced - but does the experience curve include or exclude the plant scale economies to which much (or, according to Lau and Tamura, all) of this cost reduction is attributable? Such questions highlight the "black-box" nature of the learning curve model - and we share Gold et al's view (1975) of the desirability of penetrating beneath such approaches to modeling change and innovation.

In addition to the above division of learning areas into categories, one can ask whether the learning process proceeds in a worldwide parallel process, or in insulated compartments each at different points on their respective learning curves. Observation suggests a high degree of cross transfer of experience, through education, trade literature, licensing, the use of common plant designers and component suppliers; but there are examples where individual sub-sectors of the industry may obtain at least for some years some technical advantage which they will seek to maintain by secrecy and/or patent coverage. The extent to which such progress is continuous and incremental, or radical (requiring the scrapping of not-fully-depreciated old plant) could be of considerable significance in determining the pattern of evolution of the industry. Further modeling or investigation of the decisions faced and taken by the various actors in the industry, which have cumulatively led to the observed aggregate pattern, would require one "to examine possible sources of difference in the predecision environment, in the characteristics of the innovation and in the bases for making evaluations relative to each criterion as well as for combining the results into a decision." (Gold et al. 1975)

The structure suggested by Gold, Peirce and Rosegger offers a tool for analyzing the historic evolution and current situation of ethylene plant technology; it is summarized in Table 7. Different elements of this table will be of different significance at various phases of the industry's development.

5.3 Ethylene Plants and Other Industries - Similarities and Differences

Ethylene plants have some characteristics unique to petrochemicals, others common to a number of industries. Some of the respects in which its characteristics are shared with or distinct from other industries are highlighted here.

The growth of scale to achieve capital cost economies is encountering certain limiting factors or countervailing tendencies. The extended construction period causes increased capital cost (through interest charges) and increased uncertainty (since plants have to be planned further ahead). The extended construction period is itself caused partly by the need for field fabrication of large units, because transport considerations determine the maximum size of unit which can be factory-built. These are factors also encountered in electricity generating units.

The highly capital intensive, continuous process flow nature of the plants has permitted and encouraged the development of sophisticated instrumentation and automatic controls. The demands on instruments, transducers and on-line computers appear to be well within the capacities of existing hardware and software. The complex short and medium-term

Table 7. Gold-Peirce-Rosegger Analysis of Predecision Environment for Technical Innovation

Four most important elements of the Predecision environment:			
I. Urgency	II. Nature of needs	III. Alternatives to technological innovation	IV. Management Preferences
Under greatest urgency: -- act sooner -- favor quick gains -- accept greater risks	1. Increase/replace capacity 2. Increase scale of operation 3. Improve product quality 4. Reduce requirements for scarce inputs 5. Decrease costs by improved yields 6. Decrease costs by lower factor prices 7. Increase sales	1. marketing 2. organizational	influenced by: 1. Source of innovation? a) firm's own staff b) external source, exclusive basis c) supplier promoting wider use 2. Nature of innovation? a) alien/familiar technology b) use new/existing channels c) to new/current customers . . .

Source: Based on Gold et al. (1975).

scheduling problems are readily soluble by mathematical programming. This controllability of a large and complex activity may be contrasted with the greater difficulties of controlling industries with similarly large concentrations of capital, but greater labor intensity: such as a steelworks, or still more an automobile factory. One might speculate on the nature of the differences which make for greater or lesser controllability in large-scale systems.

On a longer-term time scale, most petrochemical complexes and their associated facilities may have to be planned as transient, rather than permanent, entities, where the feedstocks whose location has determined the site of the complex have expected depletion periods of under three decades. Thus a government might reasonably have reservations about how far today's petrochemcals complexes should be allowed to influence tomorrow's social infrastructure. A complex without its traditional feedstock would seem less capable of conversion to alternative uses than, say, a car factory. Demountability and termination costs should therefore enter current decisions.

The intrinsically energy-intensive and volatile nature of the products processed, as with an oil refinery, makes risk analysis important at all levels from routine operating practice to strategic location.

5.4 New Philosophies in Plant Design

The limitations on the growth of plant scale, and the levelling off of further growth, have already been referred to. The plant engineers have not remained passive in this situation, and a good deal of radical re-thinking is taking place. The prospect of continued over-capacity, increasing competition, a slower rate of industry growth and the ending of further plant scale increases as the road to greater efficiency and competitiveness - such factors as these are contributing to the greater sense of urgency marked by Gold et al. as a precondition conducive to innovation (see Table 7). There are some indications in the literature of the directions that such innovation might take.

The improvements in pyrolysis conditions and coil design, the design of the downcomer trays in the fractionation columns, are typical of the many small improvements which, although not "breakthroughs", contribute to the progress down the learning curve. More radical re-thinking is indicated by Friedman (1977) of C-E Lummus. He does not fundamentally question the need for large scale.

"As the technologically difficult transition from oil to coal-based feedstock approaches, increased capital intensification will unquestionably drive industry to even larger installations in the future." He acknowledges, however, that "...evidence is beginning to be seen of size and dimensional limitations which will impose new demands on engineers and technology managers." He points to the traditional habits of designers, which tend to treat the flow-sheet diagram as a layout design of the plant, and which then encounter physical limits on heights, diameters, unsupported spans etc. of the pipes and vessels. "At what diameter is a pipe no longer a pipe, but rather a large pressure vessel of peculiar geometry? This question implies the use of a different design discipline." Emphasizing that simple scale-up of traditional designs is not a safe, conservative philosophy, Friedman points out how integration of functions can eliminate piping and solve mechanical problems, and calls for attempts deliberately to seek out the atypical and potentially novel at a very early stage of plant design. Demonstration-scale plants should be designed on paper as full-size units, and then scaled down to actual size. In ways like these, Friedman seeks to facilitate the continuing growth and scale-up of plants, while recognizing and finding ways to overcome the significant engineering problems.

Reports from ICI in June (Financial Times [referred to after this as FT] and November (The Economist) 1978 suggest that the assumption of necessary scale-up is being questioned along with the design concepts. Robert Malpas, their (then) director of engineering, foresees a revolution in chemical plant design. The following points are summarized from the FT European Energy Report (1978):

- more efficiency in energy consumption
- "plant after next" concept, by which as soon as a new plant is finished, engineers are asked to identify all "inelegancies" and put time-scales against eliminating them (it is probably too late for the "next" plant)
- use of learning curves to set cost targets
- possibility of halving the size and reducing the energy requirements of ammonia plants within 20 years
- advances in control engineering to tighten efficiency by previously too hazardous routes
- "intensification" of process technology by plants which are both smaller and have fewer stages
- rapid site assembly of prefabricated, factory-finished modules - of up to 3,000 tons (as in shipyards).

The same philosophy is repeated in the Economist report (1978), with the addition of a summary of the pressures forcing such innovation:

> The caution of many chemical companies is understandable enough. In the industry's salad days, before the 1973 oil crisis, innovation rode on the back of rapid demand-induced expansion of capacity. Now the cards are stacked against that easy strategy.
>
> Companies are facing much more slowly growing markets, higher inflation, and increased (and often subsidized) competition from eastern Europe, the Opec club and some other developing countries. They are also saddled with higher costs - thanks not only to the escalation of the prices of traditional petro-feedstocks but also to the growing array of environmental and safety regulations that investment projects must now satisfy.
>
> That's not a happy combination, especially in an industry in which economies of scale have led to bigger and bigger plant. When the competition is quoting prices based on book cost of existing plant, the decision to scrap your own old plant in favor of new is hard enough in an inflationary world; the new plant must pay off in terms of future costs. It is all the harder when, say, one typical new ICI plant could supply five years of today's sluggish British chemicals demand - and a large slice of continental Europe's, too.
>
> Yet the top management of the world's fifth largest chemical company, ICI, is coming round to the view that its future lies in big imaginative leaps in technology rather than the small evolutionary hops that have characterized its past investment and R and D strategy. Why?
>
> Primarily because the alternative is so unpalatable: passive acceptance of slow growth, one new plant every 20 years, a trimmed reseach budget and so on. If present markets for today's products are sluggish, create new ones with entirely new products. If you cannot beat subsidized, state-run companies on price on today's technology, find new, lower-cost processes the competition cannot copy. And this time ICI will not license to outsiders unless they pay through the nose, or swap equally attractive technology.

The last sentence refers to the fact that many of the world's methanol plants license ICI technology.

Oxirane, the subsidiary of Atlantic Richfield and Halcon International mentioned in 3.3 is also acquiring an innovative reputation; Robert Malpas is now with Halcon.

5.5 Flexibility, Uncertainty and the Design of Complexes

The design of petrochemical complexes raises a host of technical problems beyond the basic chemistry and engineering. Given high uncertainty about future feedstocks and final product demands over the life of the complex (or of its first major units), some balance has to be struck between cost and flexibility. Flexibility in this context has many dimensions. The ability to utilize a variety of feedstocks, and the ability to produce changeable proportions of desired outputs, have already been referred to: these have direct implications for the cost and design of specific units, particularly the pyrolysis furnaces. Product proportions and scheduling questions for both supply and dispatch will be the determinants of the mix and capacity of storage facilities at all stages.

Less obviously, the pursuit of flexibility appears to be best achieved by greater integration, as illustrated by the complexes referred to in 3.3, which combine refineries with olefin plants. Becdelievre and Kaiser (1978) argue the case for combining a naphtha/gas-oil ethylene unit with a catalytic reformer (a standard element of refinery operations, it uses special naphtha cuts rich in aromatics, and enables the aromatics: olefins product mix to be balanced). "Combining" means connecting, by pipes; and there is only the pipeline cost itself to set against the possible advantages of connecting widely separated plants. Thus at sufficient scale (or proximity), the possibility of ethylene pipeline and storage systems exists, considerably increasing the flexibility of operation of both contributory and distributory "connectees".

A similar function at a higher organizational level is provided by the existence of the "spot" market in Rotterdam for chemical intermediates: this offers more flexible supply/demand adjustment than could be achieved if all transactions were bilateral contracts fixed in time, date and quantity. However, the existence of a substantial proportion of tied, "contract" or captive business clearly has a stabilizing influence on a company's plans, commitments and cash flow. There may be an optimum balance which each producer needs to determine in the light of his own circumstances.

5.6 The Relationship between Enterprise Planning, State Planning and Supra-National Economic Logic

It is clear that for several related reasons the planning of new petrochemical complexes, or of substantial enlargements, is of such significance as to be likely under any political system to involve the national government. Issues of national trade policy; security of supply for the plant, and therefore for all the downstream industries and jobs which depend upon it; the scale and impact of the financial commitment; are examples of the ways in which the enterprise planning decison will have such social impact as to involve governments. The determination of governments to develop so far as possible the basis for what is seen as a modern, high growth, high-value-added industry has already been evidenced in the expansion plans referred to in section 4.2. It is also to be noticed that the desires and published statements of governments frequently run rather ahead of the firm commitments made by the enterprises.

These are features of a world industry which has moved from the "disturbed reactive" into the "turbulent field" category of organizational environment, as these terms are used by Emery and Trist (1965). Such an environemnt is characterized by a multiplicity of "actors", tightly interdependent or "connected", and by resulting instability. The actors each have the ability to affect other actors, and their joint actions affect the environment for all, often unpredictably. The "actors" unavoidably drawn into the system include suppliers, companies, governments, customers, and many aspects of public interest in many countries. Tools for the analysis and description of such multi-participant, connected systems have been developed by Fischer (1978) in Canada and at IIASA, in the contexts of natural resource management and of North Sea oil industry development and regulation.

Emery suggests (1967) that forms of response to the richly connected environment will include "attempts...to downgrade them to the less complex types of environments", i.e., perhaps to dis-connect into disjoint, smaller environments. This is clearly a possibility which has echoes of "self-reliance", or in trading terms, "protection", and Simmonds (1969) has already pointed to the connection between economies of plant scale, adjacent small and large countries, and the role of tariffs. Both co-ordination of investment plans, and protection by quotas or tariffs, are discussed within Europe (The Economist, 1978a) as solutions to the problems of over-capacity.

In the centrally planned economies, the benefits of jointly increased welfare have hitherto favoured concentration, specialization, and the pursuit of economies of scale; as in the long-range economic integration program of the Comecon countries. However, under the unanimity rule, individual participant countries retain control over decisions which affect their economies significantly; so that they can choose whether to combine efforts to achieve large-scale benefits, or retain smaller plants for local control if this is preferred.

References

Aalund, L. (1978) Refinery is cornerstone of huge olefins comples. The Oil and Gas Journal, 20 February.

Becdelievre, C. and Kaiser, V. (1978) Needs dictate olefin-plant flexibility. The Oil and Gas Journal, 3 April.

Bergen, B.M. and Asgari, M. (1978) Computer improves Czech plant. The Oil and Gas Journal, 4 September.

Brender, A. (1974) Ethylene Project Hangs On An Okay by Canada's NEB. Chemical Marketing Reporter, 1 July.

Canadian Chemical Processing (1975) May issue:14.

Cefic (1977) (European Council of Chemical Manufacturers' Federations) Survey on Olefins 1971-81: Enquiry 1977. Avenue Louise 250, Bte 71, 1050 Brussels.

Central Office of Information (1978) British Industry To-day: Chemicals. HMSO, London.

Chemical Marketing Reporter (1976) Oil Firms No 'Spoilers'? 7 June:3, 28.

Chemical Marketing Reporter (1977) Ethylene Capacity in Britain Seen Rising by 34 Percent; Production, Use Also Climb. 28 February:18.

Coquillette, R.M. (1974) Chemicals Seen Stabilized. as reported in Chemical Marketing Reporter, 25 November:3, 49.

The Economist (1978a) Chemicals: Down with competition 6 May:96.

The Economist (1978b) Chemicals: ICI believes in big discoveries. 25 November:100.

The Economist (1979a) Chemicals giants start the big push for higher prices. 20 January:75.

The Economist (1979b) Chemicals in the east explode west. 10 February:84-85.

The Economist (1979c) Petrochemicals: It's rough - downstream. 17 February:90-91.

The Economist (1979d) Chemical feedstocks: White, black or green. 24 February:90.

The Economist (1979e) Chemicals: A Survey. 7 April: after p.70.

Emery, F.E. and Trist, E.L. (1965) The causal texture of organizational environments. Human Relations, vol. 18:21-23. Reprinted (1969) in Emery, F.E. (ed.) Systems Thinking, Penguin Modern Management Readings, Penguin Books; pp. 241-257. There is a summary of the concepts referred to in Cantley, M.F. and Glagolev, V.N. (1978) "Problems of Scale" - The Case for IIASA Research, IIASA Research Memorandum 78-47:47-53.

Emery, F.E. (1967) The Next Thirty Years: Concepts, Methods and Anticipations. Human Relations, Vol.20: 199-235.

European Chemical News (1973) Shell paper examines chemical feedstock problems. 20 October:4.

European Chemical News (1975) Petrochemicals first in line for new U.K. planning agreements. 28 November:4.

Financial Times European Energy Report (1978) "Plant-After-Next" will use much less energy. 20 June:4-5.

Fischer, D.W. and Keith, R.F. (1977) Assessing the Development Decision-Making Process. The American Journal of Economics and Sociology 36:1 pp. 1-17.

Friedman, G. (1977) Large petrochemical plants are using tomorrow's concepts. The Oil and Gas Journal, 12 December, pp 80-84.

Gancia, L.H. (1978) La petroquima de base en Mexico 1977-82. Ing. quim 10, No.107:45-49.

Gold, B., Peirce, W.S., and Rosegger, G. (1975) Difussion of Major Technological Innovations, Section F: Towards a Broader Analytical Framework, Sub-section 2: The Decision Model. In Gold, B., ed. (1975) Technological Change: Economics, Management and Environment. pp. 142-146.

Goossens, A.G., Dente, M., and Ranzi, E. (1978) Simulation program predicts olefin-furnace performance The Oil and Gas Journal, 4 September:89-104.

Greek, B.F. (1975) Feedstock shift would change olefin economics. Report of speeches by J.D. van Dalen, of Shell, and by R.S. Nahas, of C-E Lummus. Chemical and Engineering News, 31 March.

Hansen, F.H. (1975) Trends in the cost of ethylene production: A producer's view. Chemistry and Industry, 6 December: 1005-1008.

Kearney, D.B. (1975) Ethylene Plant Size Limitations. Chemical Engineering Progress 71:11 November: 68-70.

Lau, L.J. and Tamura, S., (1972) Economies of Scale, Technical Progress, and the Nonhomothetic Leontief Production Function: An Application to the Japanese Petrochemical Processing Industry. Journal of Political Economy 80:6 pp.1168-1187.

Midland Daily (1978) Bay City plant closing down due to economics - Dow. 9 February.

The Oil and Gas Journal (1976a) Canada permits Dow to export ethylene to U.S. 14 June, p.46.

The Oil and Gas Journal (1976b) Higher petroleum investment returns seen needed, report of speech by ICI director J. Harvey-Jones. 11 October:95.

The Oil and Gas Journal (1978) Shell:U.S ethylene capacity surplus to vanish in 5 years. 30 January:105.

Simmonds, W.H.C. (1969) Stepwise Expansion and Profitability. Chemistry in Canada, September. The Canada:U.S. Scale Problem. Chemistry in Canada, October.

U.K. Chemicals Economic Development Committee (1976) U.K. Chemicals 1975-85. U.K. National Economic Development Office, London.

Walley, K.H., and Robinson, S.J.Q. (1972) Effects of scale on the economics of olefin production - theory and reality. Paper delivered at a 1972 symposium on olefins production, organized by the Economic Commission for Europe, in Bratislava. Subsequently printed in Petroleum Review, November: 328-332.

Wett, T. (1978a) The refiner's role in petrochemicals is growing. The Oil and Gas Journal, 3 April:65-67.

Wett, T. (1978b) Refinery/olefins integration helps productivity of both. The Oil and Gas Journal, 3 April: 68-71.

Wett, T. (1978c) Ethylene market faces overcapacity future. The Oil and Gas Journal, 4 September:63-68.

Woodhouse, G., Samols, D., and Newman, J. (1974) The Economics and Technology of Large Ethylene Projects. Chemical Engineering, 18 March:72-85