# ENGINEERING INSIGHTS

21 case studies by practising engineers.

ICI

Editors' note

The casebook articles have been
selected to reflect the range of ICI
Australia's engineering activities which
involve chemical, mechanical, civil,
electrical instrument and mining
engineering. The emphasis is on
mechanical and chemical engineering as
more than 70% of ICI Australia's 350
professional engineers come from these
two disciplines.

In order to help provide some insights
into what engineers actually do the
authors were encouraged to write about
their particular role in a project or venture
in their own way rather than attempt a
text book coverage of each subject. As a
result you will notice some difference in
style.

The articles represent the views of their
authors and not necessarily those of the
company or other groups within it.

We hope you find the booklet interesting
and informative. ICI Australia would like
to build on its contacts with universities
and research institutions and readers are
encouraged to initiate their own contacts
with authors or group engineering
managers.

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Engineering Insights Contents

Foreword

Australia has a long history of successful engineering innovation. Ridley's stripper in wheat harvesting, Michell's thrust bearing in ship propulsion, and Sarich's orbital engine are a few examples that come to mind. Yet to the man in the street, the ordinary citizen, the profession of engineering is unknown and mysterious, and the engineer an anonymous backroom worker whose contribution to society is unhonoured and vexing.

This Casebook is an attempt to redress the balance. Here engineers working in a major manufacturing company write about their work, talking to us through the medium of the printed page. Gradually the reader builds up a picture of the duties and responsibilities of professional engineers, of the intellectual challenges which spur them on and the sense of achievement they gain from successfully meeting these challenges.

The scene is the process industry where the company, in this instance ICI Australia, manufactures and distributes an incredibly wide range of plastics, chemicals and petrochemicals. It is technology on a large scale; the economics of production dictate high outputs and long production runs. But people — many people from many different backgrounds with many different skills — are the lynch-pin of the enterprise. The role of the engineer is especially critical: the design, construction, commissioning and operation of chemical process plants demand engineering talents of the highest order.

Many of these talents are exhibited in the case histories which comprise this book.

The histories are written by professional engineers who draw on their personal experience to describe tasks they have performed during the course of their employment. Much of the work is concerned with the development of plant and equipment to improve efficiency, reduce energy consumption, and above all to contain costs in a time of continuous inflation and rapidly developing international competition.

Understanding and appreciating the case histories requires some technical knowledge on the part of the reader, but certainly not more than that possessed by an engineering student recently embarked on tertiary studies.

Australia is not a large country. To maintain and enhance our position in the world, we must attract the most intelligent and perceptive of our young people to productive roles in industry. The editors of the ICI Australia engineering casebook have assembled a comprehensive set of case histories to open up new intellectual horizons for young people and reveal the fascinating challenges offered by engineering careers in industry.

I commend the editors for the task they have so ably performed and extend to all young readers my best wishes for happy and fulfilling careers.

W. P. LEWIS,
Chairman,
Department of Mechanical and
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University of Melbourne.

September 1983.

DEVELOPMENT

Trends That Show the Need for Change

Some innovations simply happen, but most of them are consciously aimed at. How can we improve our ability to select the best areas for reflection and experiment — whether as academics, working engineers, holders of purse-strings, or whole organisations? How can we refine our technological targeting?

INELEGANCIES

A ready indicator that improvement is called for is inelegancy — of the chemical route, the enabling technology of the engineering as a whole. Many multi-stage processes in organic chemistry, for instance, involve four, five or six stages. Even with 85% conversion per stage, the overall yield after five stages is only 44% — see fig. 1. Moreover, such processes often use high-cost materials, require considerable intermediate storage using large working capital (a particularly insidious form of low capital utilisation) and produce a disproportionately high volume of effluent which is wasteful both intrinsically and in disposal costs. Such obvious inelegancy is a prima-facie indication that multi-stage processes may be prime technological targets.

Our experience with paraquat bears recalling. When this highly effective herbicide was discovered in 1959, the only way to produce it in quantity was to scale up the laboratory method — which used hot sodium. This gave a yield of about 40%, which was tolerable initially when the product was new and tonnages were small, but was too hazardous for further scaling up.

Seven years later, after developing a magnesium process, we moved back to sodium, but now at –25°C. This dramatically increased the yield to 96% and seemed the near-perfect answer.

But the low-temperature sodium route is only practical on a large scale and conflicts with our present plans to disperse manufacture. We are making good progress with alternative routes giving good yields on a smaller scale. But the journey has been both protracted and 'inelegantly' circuitous — see fig. 2.
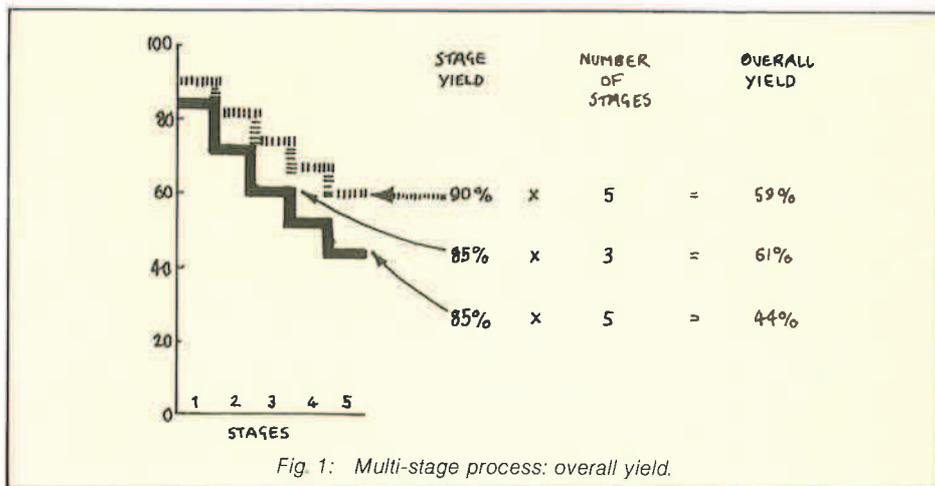

Fig. 1: Multi-stage process: overall yield.

	Stage Yield	Number of Stages		Overall Yield
	90%	×	5 =	59%
	85%	×	3 =	61%
	85%	×	5 =	44%

1959	1963	1966
50 t/yr	800 t/yr	3500 t/yr
batch	batch	continuous
Sodium dispersion in pyridine	Magnesium solution in pyridine	Sodium/liquid NH_3 diglyme solvent
90°C	155–0°C	–25°C
40% yield	55% yield	96% yield

Fig. 2: Paraquat process — dimerisation of pyridine.

Increasing stage-yields obviously leads to huge benefits. But technological targeting might lead us to aim rather at reducing the number of stages. The latter might prove quicker and cheaper if the target were identified early enough.

It is not only the routes to more complex chemicals and their processes that exhibit inelegance. Some simpler conversions still lack chemical specificity. Yields of ethylene oxide (see fig. 3) have improved greatly over the years and are improving further through better catalysts. But ethylene oxide, propylene oxide and phenol processes all progressed through discarding the use of chlorine. Excellent chemical though it is, chlorine is absent from the final molecule of the products. It has been used simply as a chemical crutch and (if the metaphor holds) was eventually destined to be thrown aside. Technological targeting might lead us to identify such crutches at an earlier stage and to discard them at the earliest possible moment.

THE PLANT-AFTER-NEXT

To describe hard-won achievements as 'inelegant' seems ungenerous — a combination of back-seat driving and arguing from hindsight. Similarly, to advocate the plant-after-next concept may seem blatantly unfair to those who are grappling with the plant that we need straight away. Yet the two are creatively linked.

Preparing the case for a major new plant or process is an exercise in compromise.
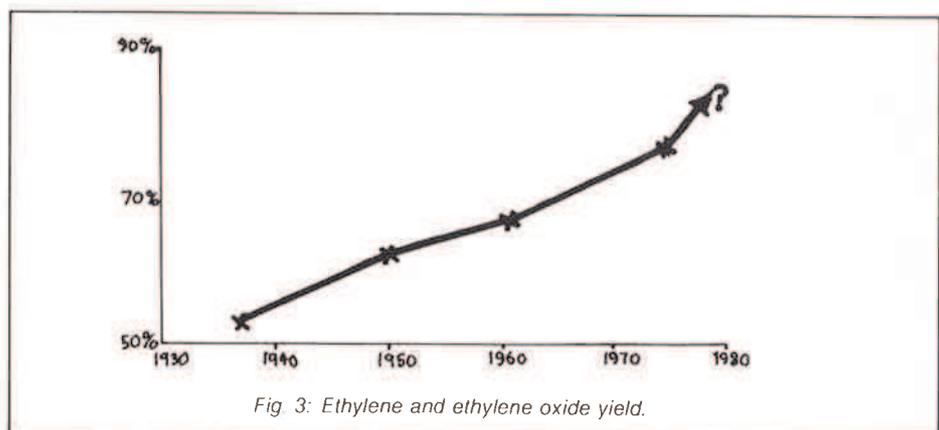
Fig. 3: Ethylene and ethylene oxide yield.
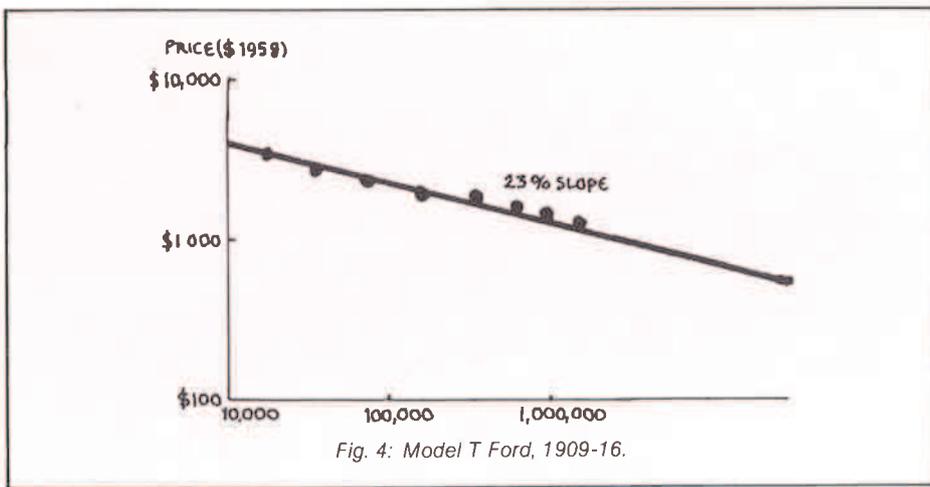
Fig. 4: Model T Ford, 1909-16.

Theoretical options are whittled down to practical options. The desirable is weighed against cost and time factors, and always loses to some extent. We reach a decision and devote our resources, both physically and mentally, to its execution.

But for technological targeting the plant that we need straight away is already a lost cause. The fundamental technical options for it were closed 18 months before it was approved. The perception of fresh options was effectively deadlined several years before that.

Yet the time we decide about *this* plant is psychologically the critical time for targeting the *next* plant. The inelegancies, the compromises, the 'not now' opportunities, are vividly clear in the mind. If

$$D \times V \times P \rightarrow Change$$

(where   D = dissatisfaction
         V = vision
         P = practical first steps)

there is no richer moment for settling on targets for innovative effort than when working pressures make them uncomfortable to admit. The plant-after-next concept is as psychologically difficult as it is practically essential for our future success.

BOSTON EXPERIENCE CURVES

In a competitive world our most constant need is to reduce product costs. Attention to learning curves can help us to achieve this. The Boston Consultancy Group have established that (other things being equal) the real cost of a product falls by 20-25% as its output doubles (figures must be inflation-adjusted). This ratio hold for a remarkably wide variety of products; so, prima-facie, if a particular product or process gives a different reading, a new approach to process or manufacture is probably overdue.

Figures 4, 5 and 6 show examples of learning curves from other industries.

Figures 7 and 8 show that although it is necessary to 'de-bottleneck' existing assets to optimise their use, this is an end in itself and not an alternative to the development of fundamental changes of route or process.

The dotted line in Figure 9 was a projection of prices and costs. The management embarked on a vigorous program of
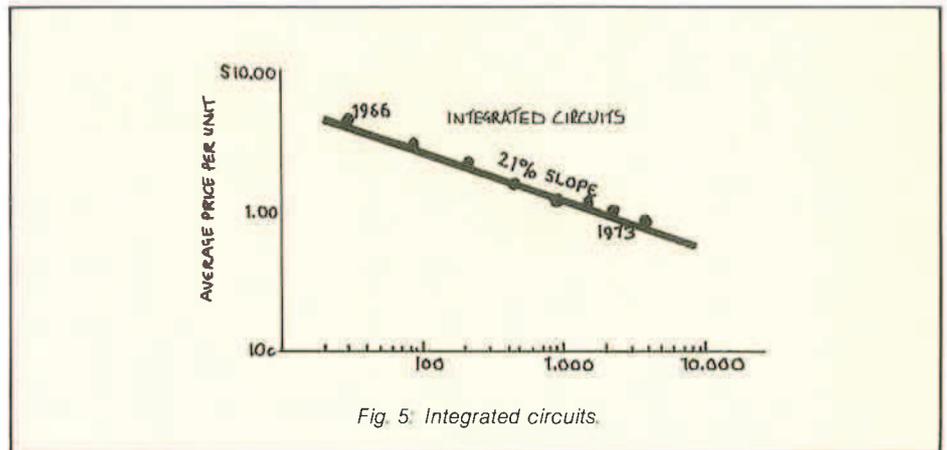
Fig. 5: Integrated circuits.
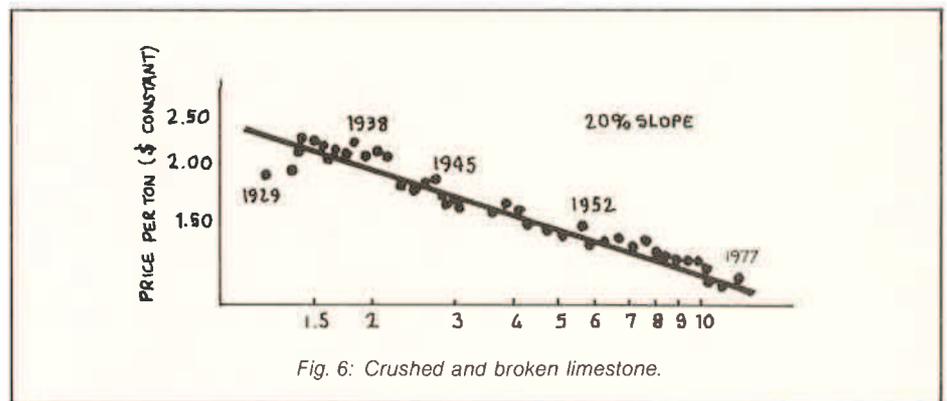
Fig. 6: Crushed and broken limestone.
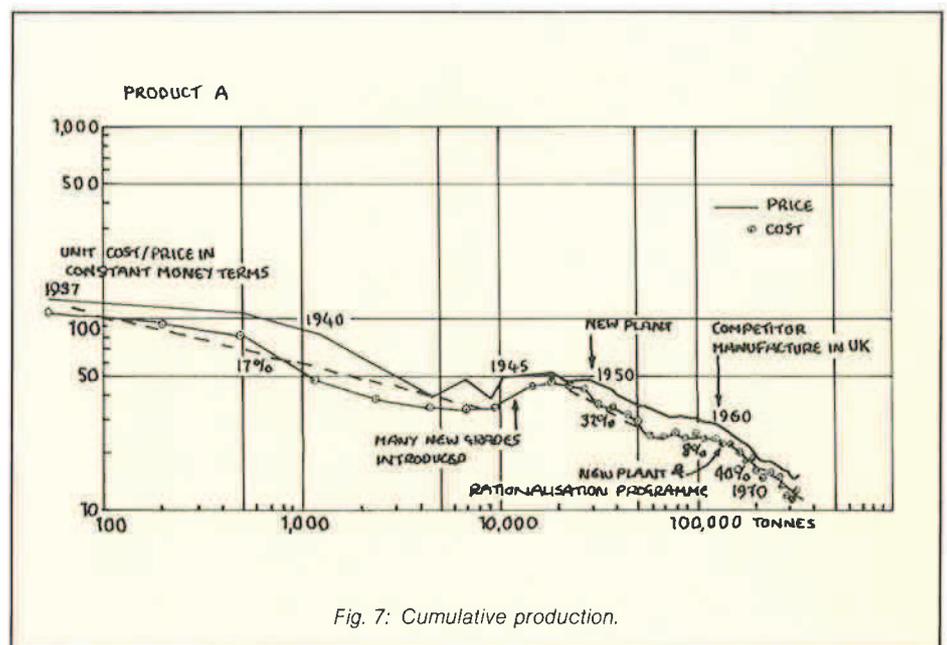
Fig. 7: Cumulative production.

innovation to keep driving costs down and has since had satisfactory results.

The Boston curve for ethylene (*see fig. 10*) reflects OPEC price increases. It also identifies the fixed costs as falling dramatically — thus highlighting the question: will the curve now resume its 30% decline after the sudden kink upwards, or is other technological action required?

There is no simple way to success. Chance innovations will continue to help us as individuals and groups experience flashes of insight. But targeted innovation must receive more attention, and aids are at hand as we formulate such targets. Experience curves provide a yardstick and a signal. Inelegancies and the plant-after-next concept are good working resources for pin-pointing practical first steps.
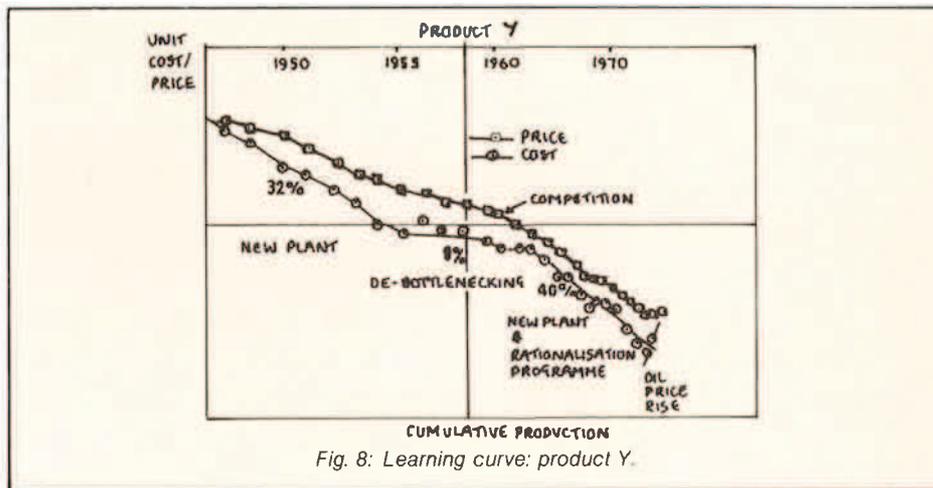
Fig. 8: Learning curve: product Y
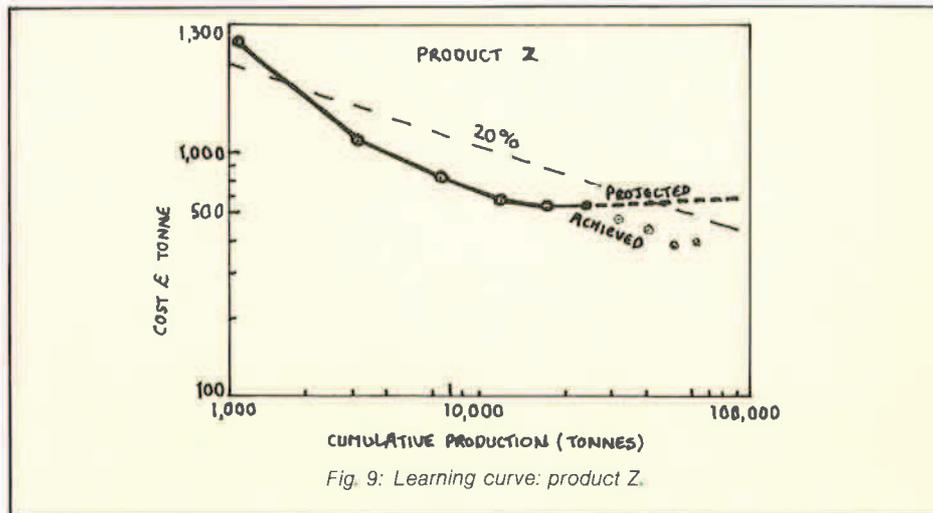
Fig. 9: Learning curve: product Z
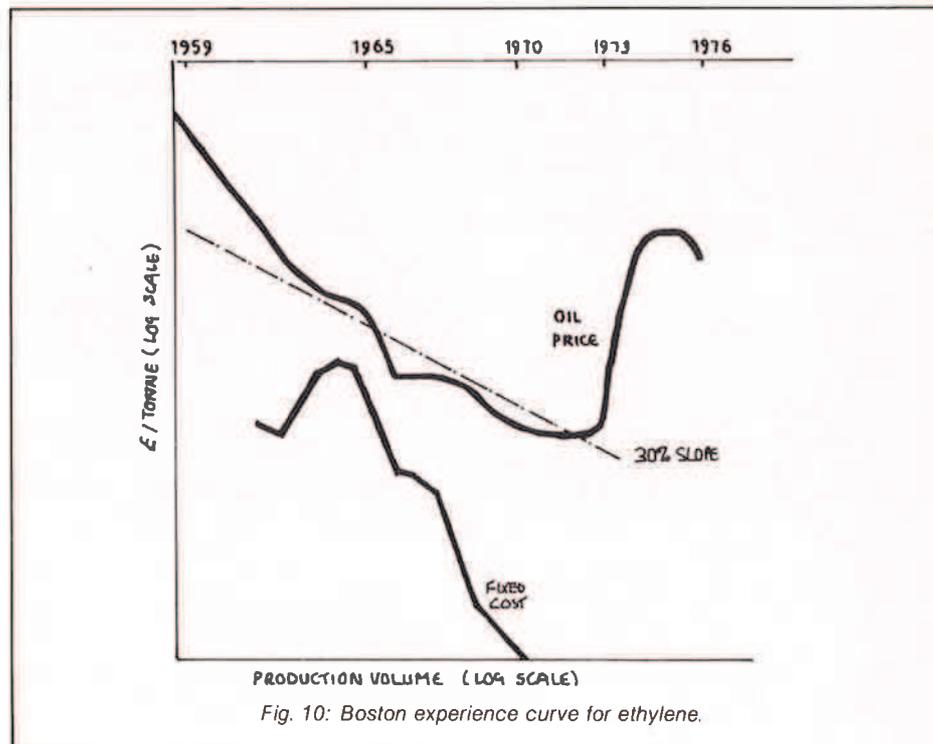
Fig. 10: Boston experience curve for ethylene.

Multi-phase Reactor Design

Investigation of gas-liquid reaction rates and of the design of stirred vessels for more efficient mixing.

More than half of ICI's most important processes involve reactions in the liquid phase in which one of the reactants is introduced as a gas. Very often a particulate solid is also present as intermediate, product, or catalyst.

The equipment chosen for these reactions is almost invariably a bubble-column or a stirred tank. The choice is often based as much on tradition as on the needs of the chemistry. A great many interacting physical and chemical phenomena are concerned (for example, bubble formation and flow, mass transfer between gas and liquid, liquid mixing, the reaction rate itself, and possibly mass transfer between solid and liquid). Often we do not have the data on the rate-governing mechanism. This, coupled with inadequate understanding of the fundamental mechanisms, makes it almost impossible to be confident that our designs are as good as they could be.

Various groups within ICI are working to develop sound design techniques, and thus more appropriate reactors, to enable us to take full advantage of the inherent speed of the reactions themselves.

To investigate the reaction mechanism we need apparatus for measuring reaction rates, unhampered by mixing or inter-phase mass transfer effects.

Our approach is mainly based on rapid mixing of the liquids by turbulent jets meeting at a T-junction. Mixing occurs within a few pipe diameters of the meeting point, and we can then monitor the reaction by techniques such as temperature measurement or infra-red spectroscopy as it proceeds further downstream — see fig. 1. The unit runs in a steady state, so that we have a wide range of analytical methods at our disposal.

This is more flexible than the stopped-flow technique (which we also use) in which a valve at C on Figure 2 is turned off and we then 'watch' the reaction as it occurs in the body of the cell during the next few seconds.

There is an alternative approach which is to mix the reactants at such a low temperature that the reaction rate is negligible and then suddenly raise the
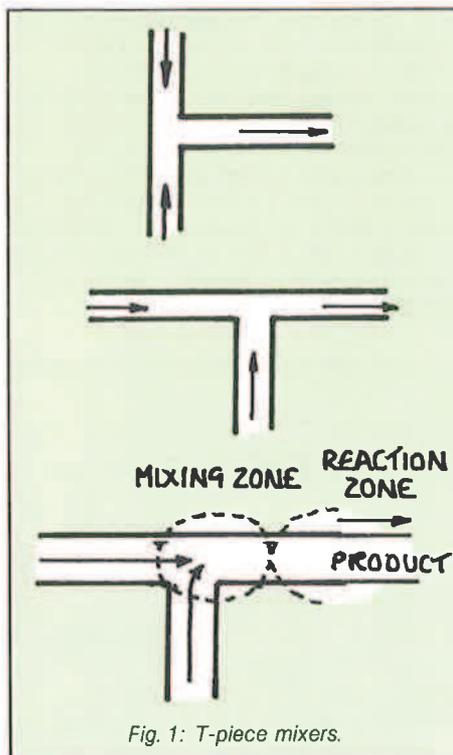
Fig. 1: T-piece mixers.

temperature with a laser, for example, and observe the reaction as it occurs.

If a gas is involved in the reaction then it is pre-dissolved in one of the liquids, usually at high pressure. Sometimes we cannot dissolve enough gas using this technique, and we need lab-scale devices to give very rapid mass transfer between gas and liquid in such cases.
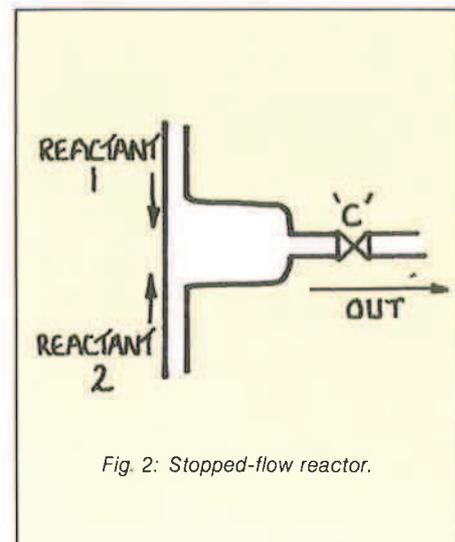
Fig. 2: Stopped-flow reactor.

The reaction itself is often rapid, and the overall performance of the reactor is then governed by the mass transfer rate between gas and liquid. It is not possible to predict or scale up this rate, especially in stirred reactors, because of a lack of large-scale experimentation in the previous research work.
A number of large-scale measurements have been made and related to the hydrodynamics in the vessel. The work is still in progress, but it indicates that the power input per unit reacting volume is an important correlating factor. The problem is that this cannot be predicted adequately for plant-scale vessels containing liquid systems through which
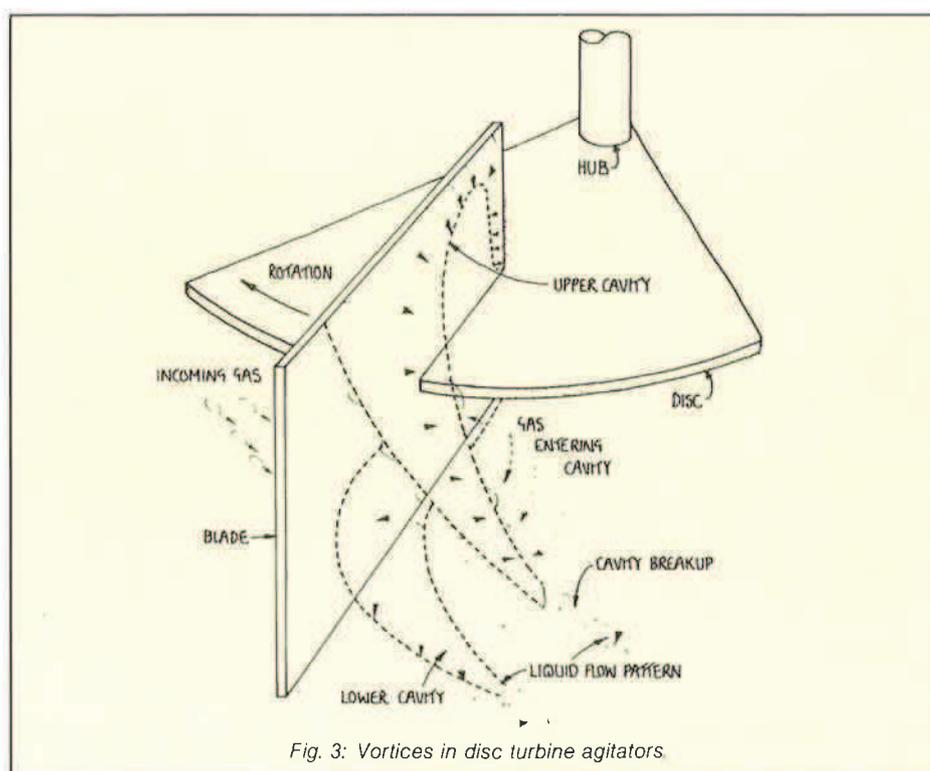
Fig. 3: Vortices in disc turbine agitators.

a gas is bubbling. With the usual disc turbine agitators, increased gas rate renders the agitator less able to transmit power to the liquid.

To overcome these problems the funda-mental behaviour of agitator blades in gas-liquid mixtures has been studied. Flow visualisation has been used to determine the gas break-up mechanism and has revealed that the gas is drawn into the blade vortices, gathering there in 'cavities' which 'streamline' the blades and obstruct their 'pumping' ability: this in turn reduces the effectiveness of the agitator in dispersing gas, mixing the liquid, encouraging heat transfer, suspending particles, etc. — see fig. 3.

High-speed photography shows that no bubbles are 'chopped' by the agitator blade, and that most enter the cavity from 'downstream' (moving against the prevail-ing flow direction). The fine bubbles are generated by the random break-up of the 'tail' of the cavity. Measurements of velocity and flow pattern from these films have been used to back up detailed theoretical analysis of flows in agitated vessels.

The magnitude of these effects cannot yet be predicted reliably for full-scale vessels, so there is an incentive to reduce the uncertainty in design (and also to use installed power more effectively) by finding an agitator with a 'flatter' power vs gas rate characteristic — see fig. 4.

To bring together kinetics, mass transfer and flow interactions in reactors the circulation loops in a vessel have been modelled on a computer. The loop is represented as a series of linked cells in each of which there is mass transfer and reaction — see fig. 5.

We are also seeking plant-scale devices with dramatically increased mass transfer capabilities to help us remove this physical restraint from the chemical action desired. Then we should be able to reduce the size and capital cost of plant items. As indicated above, this would probably involve absorbing much more power per unit volume, and this could possibly be achieved, for example, by using a pump, with some kind of high-pressure-drop turbulent flow device in a two-phase tubular reactor.

Fig. 4: Power consumed in agitators.

Fig. 5: Gas and liquid flows in a stirred reactor using the 'mixed zones in loops' model.
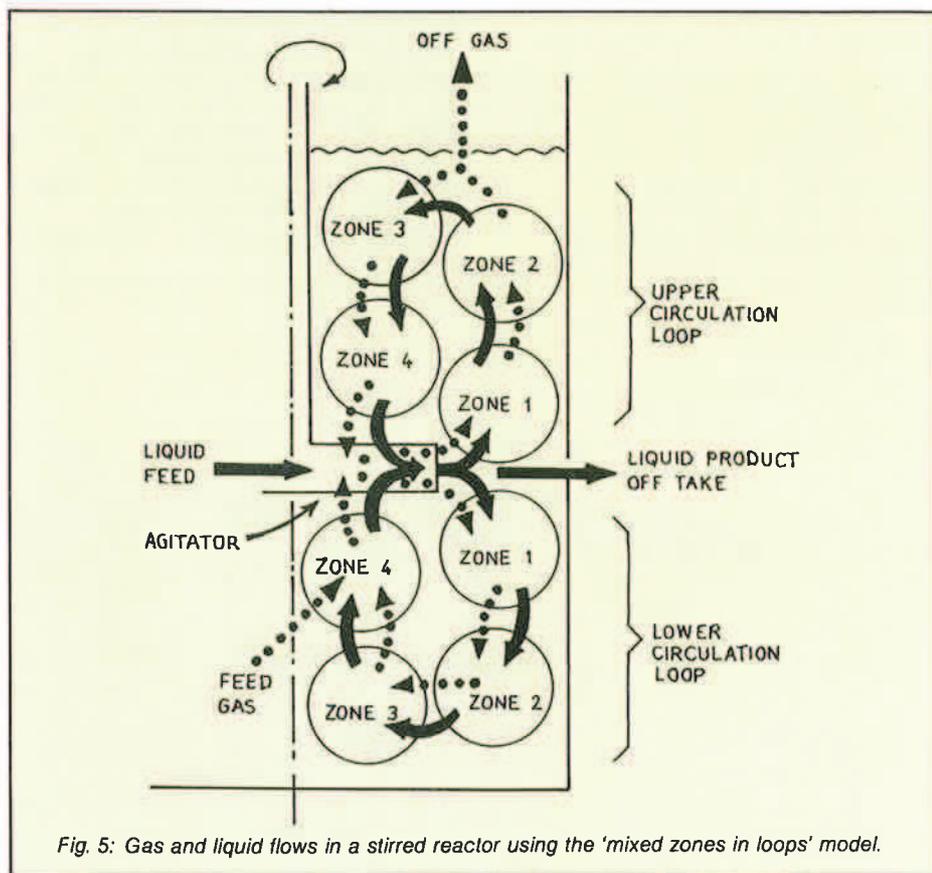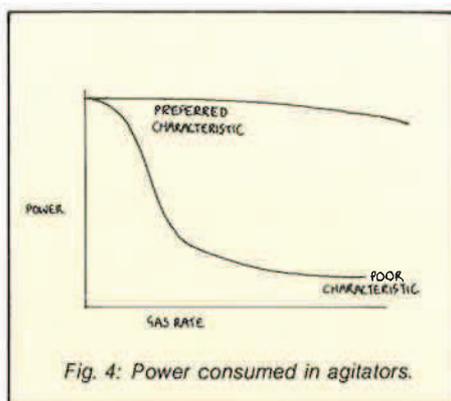
Continuous PVC Stripper
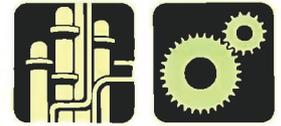
Development of a continous PVC slurry stripper from laboratory experiments to full scale plant operation.

INTRODUCTION

In 1974 Vinyl Chloride Monomer (VCM), the monomer of Polyvinyl Chloride (PVC), was classed as a carcinogen. As a result, an Australian Vinyl Chloride Code of Safe Practice was promulgated and the industry adopted standards of low VCM concentrations in PVC to be used in the food industry. A particularly difficult problem was to reduce the residual VCM in the water slurry of PVC before drying so that the dried PVC would easily meet these standards. The existing batch stripping process caused product degradation when pushed towards the very low VCM levels required and also adversely affected the process economics. The solution adopted by ICI Australia involved research, which started in 1976, advanced through co-operative research/process design and led to a continuous stripping plant which was commissioned at Botany, NSW, in September 1978.

RESEARCH WORK

In conventional tray-with-downcomer stripping columns PVC particles typically have a wide residence time distribution resulting in incomplete stripping of the short duration particles and thermal degradation of the long duration particles. A research programme was started to develop a continuous stripping column aiming for a narrow residence time distribution as the critical parameter for assessing suitability of design.

Initially we used a single sieve plate in a 15 cm diameter glass column. Steam was injected into the bottom of the column at a rate sufficiently high to prevent slurry 'weeping' through the holes. The slurry was analysed for VCM content at specified time intervals and it was deduced from various steam rates and plate configurations that the rate of VCM removal from PVC particles was controlled by diffusion. Experiments were then run using a 13-plate 15 cm diameter column without downcomers, followed by a 19-plate 15 cm diameter column installed on the plant to obtain a continuous supply of slurry under plant conditions.

The results of this work agreed closely with prediction. Because of wall effects in a small column, the hydraulic perform-ance of larger columns was studied

before increasing the scale of operation. Two 4-plate units of 30 and 60 cm diameter were constructed and operated over a wide range, producing hydraulic data which were used for the design of the final column. This work on the larger columns also confirmed the optimum spacing of the plates.

The research work confirmed that a narrow residence time distribution could be obtained and very low levels of residual VCM in the PVC could be expected. It was decided that a full scale stripping plant could be designed without recourse to a pilot scale investigation.

PROCESS DESIGN

Several process design parameters could be varied, particularly:
1. Operating pressure and temperature.
2. Number of plates.
3. Plate spacing.

Desirable objectives for incorporation in the process design philosophy were:
1. Maximum turndown ratio and con-stant performance at all rates.

2. Ease of stripping VCM from a wide range of PVC slurries having different characteristics.

3. Minimum steam usage.

4. Minimum operator involvement.

5. Potential for greater throughput in the future.

Performance, ease of plant operation and energy economy were to be given priority.

Process design was the responsibility of the Project Manager who sought active co-operation from the research team in defining design criteria. This collaboration was successful in the fixing of many options. For example, the rate of stripping increases markedly with temperature but the risk of thermal degradation increases even faster. Similarly steam usage, capital cost and flexibility of operation have conflicting influence on the number of plates. In all such cases optimisation was an essential feature of the process design, shown in outline in Figure 1.

Fig. 1: Continuous PVC Stripping Plant
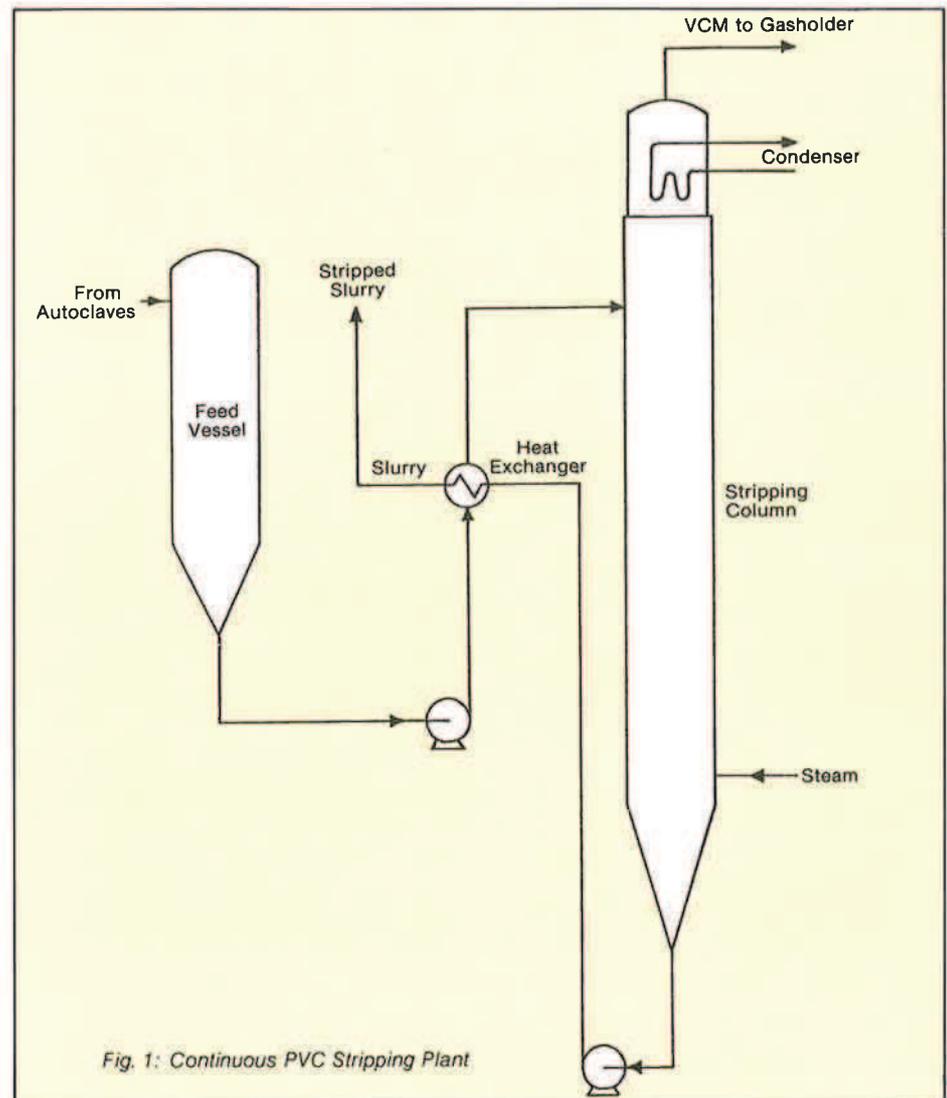
Fig. 2: Continuous PVC Slurry Stripping Column.

PLANT DESIGN

The Project Manager was also responsible for plant design and thus there was no strict demarcation between process and plant design.

Many of the design features of the stripping plant were in response to the handling of slurry (35% solids) and to processing a product (PVC) liable to thermal degradation. Thus all piping and plant items were designed to ensure that the slurry velocities were adequate at all times to prevent settling of the PVC particles, yet avoiding both excessive pressure drops at high flow rates and pumping of unnecessary quanitities of slurry.

The possibility of thermal degradation and contamination was reduced to negligible proportions by limiting the time that the stripped slurry remains at column temperatures before cooling and also by a very detailed approach to column design including the fit of the plates to the column walls and elimination of all ledges and crevices.

Advanced instrument control and automation including the use of microprocessors reduced the operator involvement virtually to setting throughput rates and selecting the mode of opera-

tion. All abnormal events automatically initiate either the SHUTDOWN sequence of a STAND-BY sequence, each designed to facilitate a return to stripping operations quickly and with the minimum of operator attention.

Other features of plant design were the use of spiral heat exchangers for slurry/slurry heat exchange and for the stripping column condenser. The slurry exchanger gives the required rapid cooling of stripped slurry while effecting steam economies through pre-heating the column feed. Mounting the condenser directly to the top of the column eliminated the need for condensate collection and pumping facilities and so reduced the capital cost. The column was designed in sections allowing the option of adding a future section if required for throughput or quality reasons.

PERFORMANCE

The stripping plant (*see Fig. 2*) was commissioned in September 1978 and from the outset its performance exceeded design expectations in throughput, quality, running costs, and reliability and ease of operation.

The production rate has been increased to 150% of design maximum producing slurry containing 1 ppm on the dry basis compared with the design of 5 ppm.

A number of residence time distributions

have been determined using radioactive sodium 24 in sodium chloride solution as a tracer, and these studies confirm the narrow residence time distribution predicted in early research work and sought in the process design (*ref. Fig. 3*).

Patents have been applied for in fourteen countries and to date have been granted in Australia, Belgium, New Zealand, Spain and the United Kingdom.

DEVELOPMENTS

The process and plant design have been studied by overseas companies and the principles used for stripping plants in South Africa and the USA. ICI Australia has designed a complete stripping plant for a PVC project in Argentina and a second stripping plant was commissioned at Botany in April 1982.

Fig. 3: Residence Time Distribution.

Modelling of a Thermal Cracking Furnace

Mathematical modelling and computer simulation used to increase vinyl chloride reactor output.

Vinyl Chloride Monomer (VCM) is manufactured by the thermal cracking of Ethylene Dichloride (EDC) in a tubular reactor. The reactor is situated in a combustion chamber, fired at the walls. In the ICI Australia VCM plant at Botany, the EDC cracking furnace had long been one of the major limitations to increasing the VCM production capacity. The basic problem was one of increasing the heat flux without exceeding the metallurgical temperature limits for cracker tubes. A redistribution of the heat flux pattern was expected to provide a marginal increase in capacity, but the actual capacity increase and the optimum heat release patterns could be established only by mathematical modelling and computer simulation of the firebox-reactor system. The existing conditions were first simulated to verify the validity of the model. The computer model was then run for a number of different burner arrangements. An optimum pattern was selected for the actual uprate. A 10% increase in capacity was achieved with no increase to tube wall temperature. Good verification of the model predictions was obtained from tube wall temperature measurements using an infra-red pistol thermometer.

For purposes of modelling, the combustion side and the process side of the furnace are treated separately, while maintaining the interaction between them.

FIRE BOX MODEL

The furnace is rectangular in cross-section, fired at the walls and has a double row of tubes centered in the combustion chamber. The radiative heat transfer calculations are performed using the zoning technique of Hottel and co-workers. The gas space is divided into rectangular volumes as illustrated in Figure 1. The furnace has a plane of symmetry through the tubes and therefore the analysis is restricted to one half of the furnace. The tubular reactor is treated as a planar sink in the centre of the radiant chamber. The tubes are fired by four rows of burners located on the refractory wall opposite to the tubes. The tube plane is divided into four equal length vertical zones, each corresponding to one burner row. The refractory surfaces and the gas space between the tube and refractory wall are divided into

the same number of lengths. The floor of the furnace forms an additional refractory zone.

The sloping wall at the top of the radiant chamber is transposed into an equivalent rectangular configuration. It is assumed that each zone, the refractory, gas volume and sink is isothermal at its respective temperature level.

The combustion gas is assumed to consist of one gray component and one clear component. Using the composition of combustion gases in the chamber, the absorptivity and emissivity of the gray component are correlated as a function of temperature and a characteristic length (smallest edge of the rectangular parallelopiped).

The basic equations governing the system are the total energy balances for each zone:

For a surface zone —

Radiant energy received from all surface zones	+	Radiant energy received from all gas zones
+ Convective energy received from all neighbouring gas zones	−	Radiant energy emitted from surface
− Energy losses to ambient	=	Net heat input to the surface (1)

The right hand side term, net heat input is non-zero for all sink surfaces (the endothermic reaction heat), but zero for all refractory surfaces.

For a gas zone:

Radiant energy received from all surface zones	+	Radiant energy received from all gas zones
Net enthalpy flux into the gas + zone across its boundaries	+	Convective energy received from all neighbouring surface zones
− Radiant energy emitted from the gas zone	=	Combustion heat liberated in the gas zone (negative) (2)

REACTOR MODEL

The process side of the cracker is modelled as a plug flow tubular reactor with no axial or radial diffusion. The main pyrolysis reaction is —

$$CH_2Cl - CH_2Cl \xrightarrow{\text{Heat}} CH_2 = CHCl + HCl$$
$$\text{(EDC)} \qquad\qquad \text{(VCM)}$$

The overall reaction is first order with respect to EDC. The basic reactor equations are —

$$u \frac{dc}{dz} - k_1 c = 0 \qquad \text{(mass)} \quad (3)$$

$$C_p G \frac{dT}{dz} - \frac{4 \dot{Q} D_o}{D_i^2} + k_1 c (\Delta H) = 0 \qquad \text{(energy)} \quad (4)$$

In the above equations, u is the velocity, c the concentration of EDC, k_1 first order rate constant, C_p heat capacity, G mass velocity, T temperature, $\dot{Q}$ heat flux on the tube, ΔH endothermic heat of reaction, z the axial distance and D_o and D_i are the outside and inside diameters of tube.

The initial conditions are —

$$\text{At} \quad z = 0, \ T = T_{in}, \ p = p_{in}, \ C = C_{in} \quad (5)$$

In addition to the mass and energy continuity equations, the pressure drop equation needs to be integrated along the reactor length because of the increase in the

1-5 Heat transfer zones defined for modelling purposes

Fig. 1: Furnace and reactor tube geometry.

number of moles as reaction proceeds.

$$-\frac{dp}{dz} = \frac{2 f P u^2}{D_i} \qquad (6)$$

where f is the Fanning friction factor, P is the density of the mixture and p is the pressure. Additional pressure drop due to tube bends should be included at the appropriate lengths.

The overall heat transfer coefficient at the wall of the reactor tube is obtained from —

$$\frac{1}{U} = \frac{1}{h_i} + R_c + R_w \qquad (7)$$

where h_i is the inside coefficient calculated from standard correlations for turbulent gas flow, R_c is the resistance due to a deposit of coke layer and R_w is the wall resistance. The coke layer is never uniform in real situations, but assumed uniform for the sake of the model.

The average wall temperature is:

$$T_{w_{average}} = T + \frac{Q}{U} \qquad (8)$$

The circumferential heat flux around the tube is not uniform, and a value is obtained for the ratio of maximum to average heat flux, based on the tube diameter and tube arrangement. The maximum attainable tube wall temperature is —

$$T_{w_{maximum}} = T + \frac{R\dot{Q}}{U} \qquad (9)$$

where $R = \dfrac{\text{maximum heat flux}}{\text{average heat flux}} \qquad (10)$

SOLUTION OF THE EQUATIONS

The fire box model is first solved for an assumed tube surface temperature and an estimate of the heat flux distribution is obtained. Since the radiative heat transfer terms contain temperatures as T^4 and the convective terms are linear in temperature, the zone energy balance equations are non-linear. They are solved by an iterative procedure, one zone at a time, keeping all other temperatures constant, until convergence is reached.

Using the heat fluxes obtained, the reactor equations are integrated using a fourth order Runge-Kutta method to obtain a fresh estimate of the surface temperatures, which are again used in the fire box model. Three iterations were sufficient for convergence. A flow chart is shown in Figure 2.

RESULTS

The model was run with six different heat release patterns by choosing various burner arrangements. Three of the cases are shown in Table 1.

Table 1: Heat Release Patterns

Case	% of Total Heat Release				
	Gas Zone				
	1	2	3	4	
1	23.8	23.8	28.6	23.8	Before uprate
2	25	25	25	25	Uniform
3	20.8	20.8	29.2	29.2	

For case 3 where there is greater heat release in the top two burner rows (gas zones 3 and 4), the gas temperatures and refractory surface temperatures became more uniform.

The maximum tube wall temperature profiles as a function of the dimensionless reactor length are shown in Figure 3. It can be seen that the maximum temperature becomes more uniform for case 3.

Figure 4 shows a comparison of the average tube wall temperature profiles for the following conditions:

1. Production rate of VCM and burner arrangement prior to uprate (case 1).
2. 12.5% increase in VCM production rate — uprate top two burner rows (case 3).

It is clear from the comparison that an increase of 12.5% in the capacity can be achieved without significantly increasing the maximum tube wall temperature, an important factor from the standpoint of both furnace tube life and by-product formation.

Measurements of tube wall temperatures at several points were made after the cracker uprate using an infra-red non-contact pistol thermometer. The temperatures predicted by the computer model were in close agreement with the measured temperatures.

The main limitation of the model is the assumption of a single constant gas temperature in a gas zone, whereas in actual practice, significant temperature gradients exist between the refractory and the tube plane. Any further extention of the model will have to take into account the flow patterns of the gas in the fire box and gas recirculation. Considering the remarkably good agreement between measured and predicted temperatures, such sophistication is not warranted. This exercise has highlighted the usefulness of modelling and simulation for problems involving minor plant extensions.
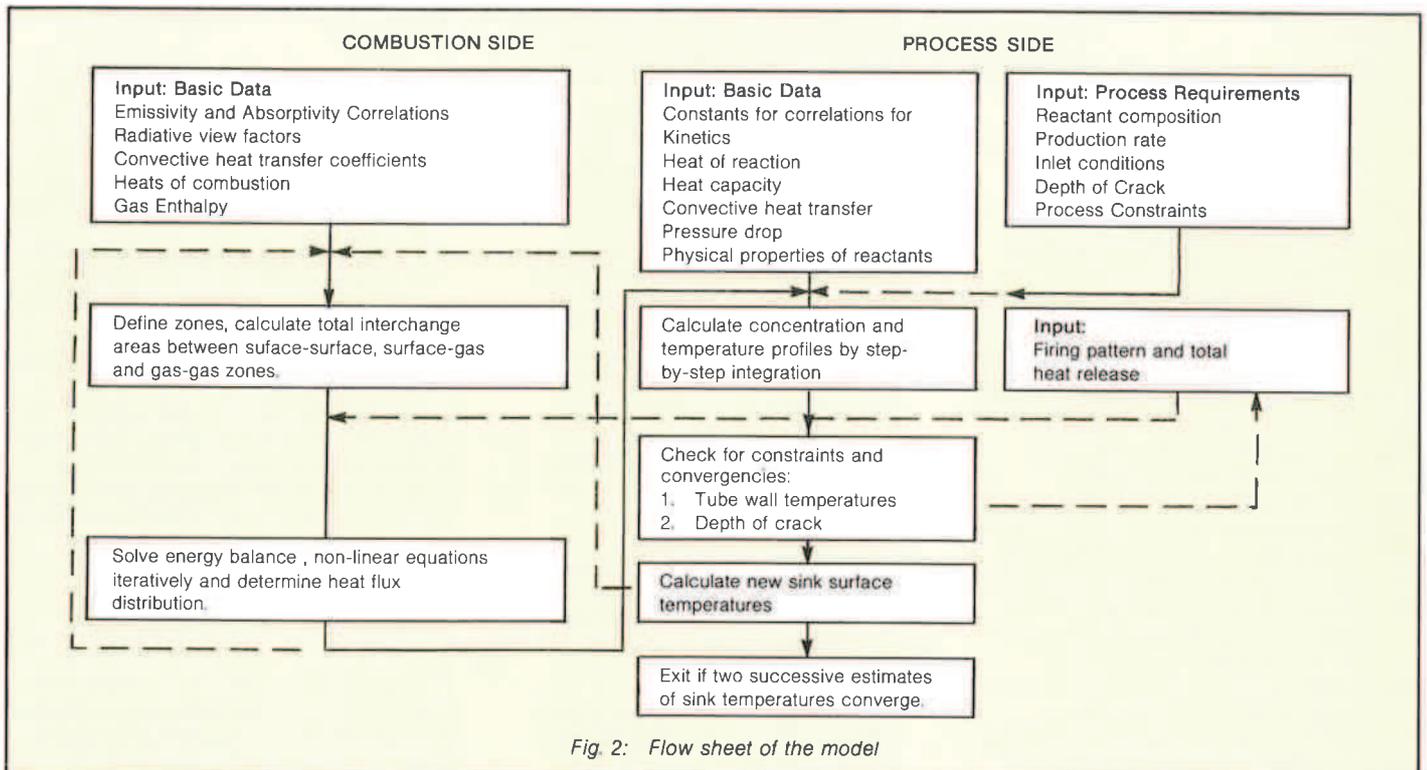
Fig. 2: Flow sheet of the model

COMBUSTION SIDE   PROCESS SIDE

Input: Basic Data
Emissivity and Absorptivity Correlations
Radiative view factors
Convective heat transfer coefficients
Heats of combustion
Gas Enthalpy

Input: Basic Data
Constants for correlations for
Kinetics
Heat of reaction
Heat capacity
Convective heat transfer
Pressure drop
Physical properties of reactants

Input: Process Requirements
Reactant composition
Production rate
Inlet conditions
Depth of Crack
Process Constraints

Define zones, calculate total interchange areas between suface-surface, surface-gas and gas-gas zones.

Calculate concentration and temperature profiles by step-by-step integration

Input:
Firing pattern and total heat release

Check for constraints and convergencies:
1. Tube wall temperatures
2. Depth of crack

Solve energy balance, non-linear equations iteratively and determine heat flux distribution.

Calculate new sink surface temperatures

Exit if two successive estimates of sink temperatures converge.

Fig. 3: Maximum tube wall temperature profiles.

Fig. 4: Mean tube wall temperature profiles.

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Chemical Process Energy Targeting

Heat exchanger network analysis can lead to big savings in energy and capital.

Chemical processes in general, operate at temperature levels widely differing from ambient and together with their heats of reaction require heat to be supplied and removed by hot and cold utilities. Most chemical processing operations therefore, are likely to benefit greatly by optimising the integration of the exchange of heat between process streams. Conservation of energy will result.

The application of energy conservation methods and procedures of heat exchange network analysis to existing and new processes is likely to have a major impact on operating costs. The largest cost impact, however, will be obtained by applying the procedures at the design stage of new processes because this could result in capital as well as operating cost savings.

IDENTIFICATION

Process flowsheets with basic layout considerations form the basis of heat utilisation and recovery studies. Process streams may be classified into either hot or cold streams. Hot streams are those which, for process reasons, need to be cooled, and cold streams are those which need to be heated. Process hot streams therefore are eligible to transfer heat to process cold streams. In reality there are often physical and process constraints which prevent the interchange of heat between some hot and cold streams. If we consider an unconstrained interchange of heat between hot and cold process streams then the minimum possible requirement for hot and cold utilities can be determined. Such a review of the process will highlight the cost penalty of placing constraints on interchange between some of the process streams.

Figure 1 sets out a process flowsheet for a Byproduct process as a simplified example. The process requirements for heat transfer are as follows:

(i) stream 1 needs to be cooled to 40°C before mixing with stream 2;

(ii) stream 3 needs to be heated to 180°C before reaction;

(iii) the product, stream 4, needs to be cooled to 40°C before catalyst removal and final storage;

Fig. 1: Byproduct process flowsheet.

STREAM No.	1	1A	1B	2	3	3A	4	5	5A
FLOW kg hr	325	325	325	250	575	575	575	540	540
TEMP °C	300/220	220/140	140/40	40	40/100	100/180	200/40	140/180	180/280
HEAT LOAD kW	24	24	30		24	32	72	24	60
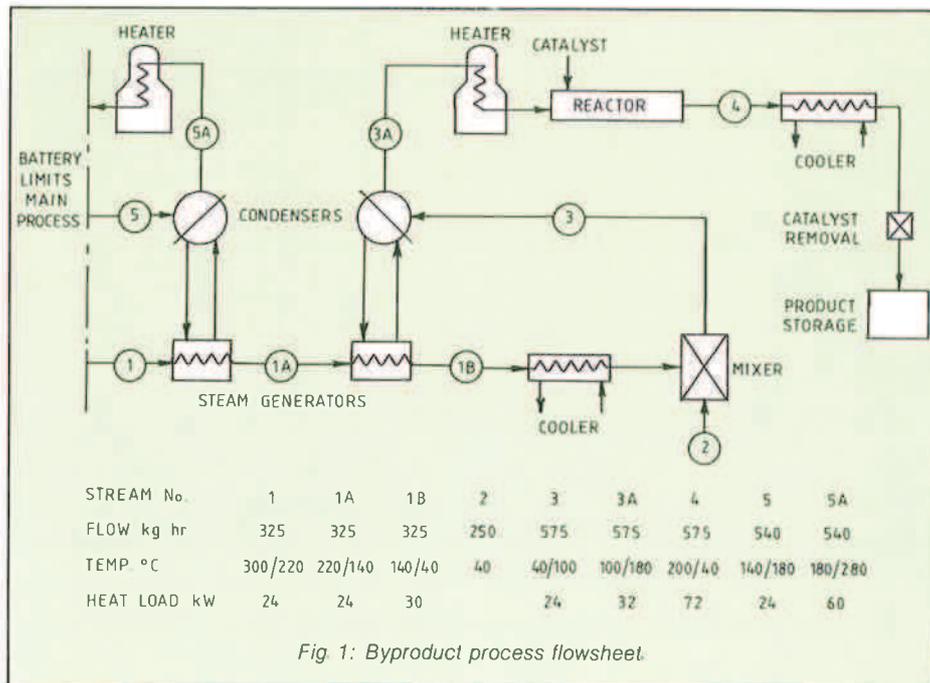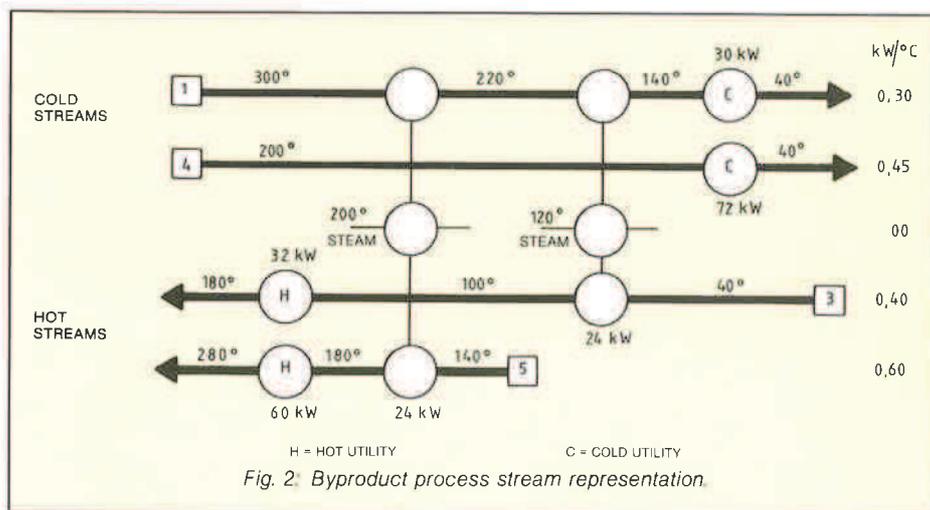
Fig. 2 Byproduct process stream representation.

(iv) stream 5 needs to be heated to 280°C.

Streams 1 and 4 are then classified as hot streams and stream 3 and 5 as cold streams.

In Figure 2 the process is represented as a heat exchange network which shows how heat is exchanged between process streams and utilities. In this case there are two 'matches' or exchanges of heat between process streams where steam has been used as an intermediary heat medium. The use of steam in this context turned out to be a non-essential feature and was included in the design as a nice idea mainly because the process had enough heat in it to generate steam. The fact that you loose potential temperature driving force had not been considered. The minimum approach temperature, i.e. the minimum temperature difference between two streams exchanging heat

was then taken as 20°C.
The utility requirements for the process as shown are:—

hot utility	92 kW
cold utility	102 kW

MAXIMUM ENERGY RECOVERY

ICI has developed a systematic method which, with the aid of a computer program, can be used to determine the heat exchange network for Maximum Energy Recovery (MER).

Figure 3 shows the heat exchange network for MER for the Byproduct process with a minimum approach temperature of 20°C. The hot utility has been reduced to 40 kW and the cold utility to 50 kW. For this process it is not possible to get below these figures. The number of exchangers has increased to seven.
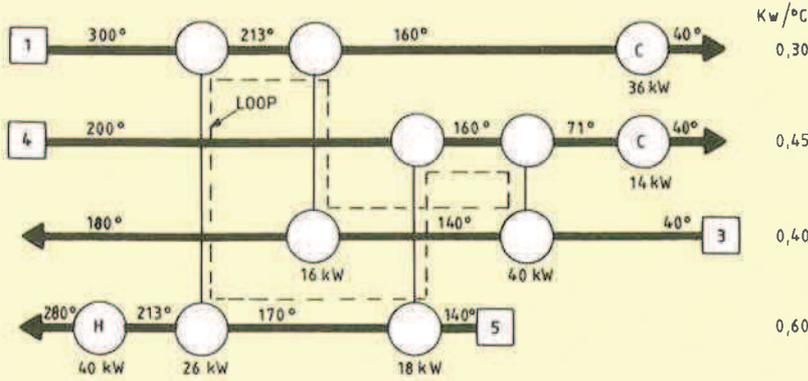
Fig. 3: Process stream representation for maximum energy recovery.
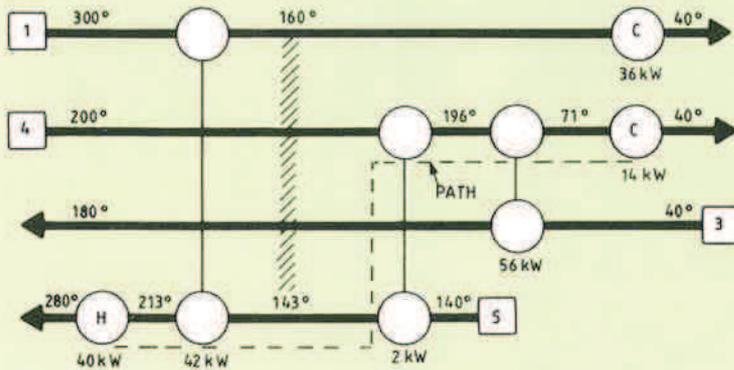
Fig. 4: Process stream representation after loop breaking.
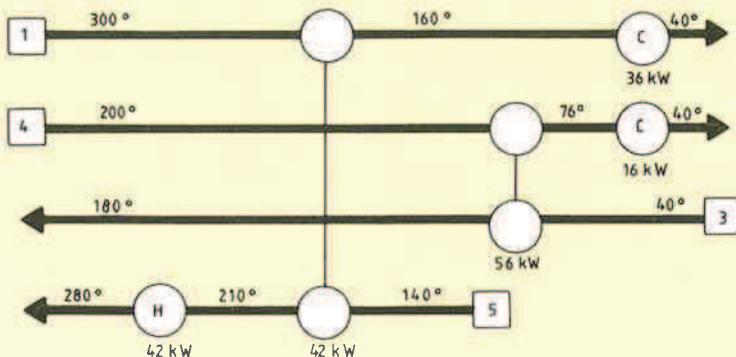
Fig. 5: Process stream representation after Δ T is restored by relaxing along a path

MINIMUM NUMBER OF HEAT EXCHANGERS

It can be shown that the minimum number of exchangers is always equal to the number of process streams plus the number of utilities minus one. In this case there are four process streams and two utilities. The minimum number of units is then five.

There are a number of methods for reducing the number of heat exchangers from that for MER and loop breaking is the first. In Figure 3 a closed loop has been drawn connecting a number of exchangers in the network. If we break the loop by removing the 16 kW exchanger, the effect can be compensated for by changing the heat loads on the other exchangers in the loop. Figure 4 shows the effect of removing the 16 kW exchanger. The hot and cold utilities have been left untouched but we have created a violation of approach temperature between streams 1 and 5 from 20 to 17°C.

The approach temperature can be restored by a technique called 'relaxing along a path'. As shown in Figure 4 a path is identified between hot and cold utilities via the affected exchanger. By increasing the utility requirements and adjusting the duties of other exchangers along the path the approach temperature can be restored. Figure 5 shows the resulting network. The hot and cold utility requirements have increased by 2 kW each, and as it turns out, the heat exchanger between streams 4 and 5 is not required and drops out.

The net result of 'loop breaking' and 'relaxing along a path' has been an increase in hot and cold utilities of 5% for a capital saving associated with two heat exchangers.

On the basis that this reduction of units is desirable the target utilities are:—

hot utility .... 42 kW
cold utility .... 52 kW

which are approximately 50% of the original process. Figure 6 shows the revised flowsheet.

OTHER STUDIES

Similar studies have been carried out on a number of major processes and substantial operating and capital cost savings have been identified (see Fig. 7). A trade-off between capital and energy forms an important part of the overall study to optimise energy recovery and capital investment.

STREAM No.	1	1A	2	3	4	4A	5	5A
FLOW kg/h	325	325	250	575	575	575	540	540
TEMP °C	300/160	160/40	40	40/180	200/76	76/40	140/210	210/280
HEAT LOAD kW	42	36		56	56	16	42	42
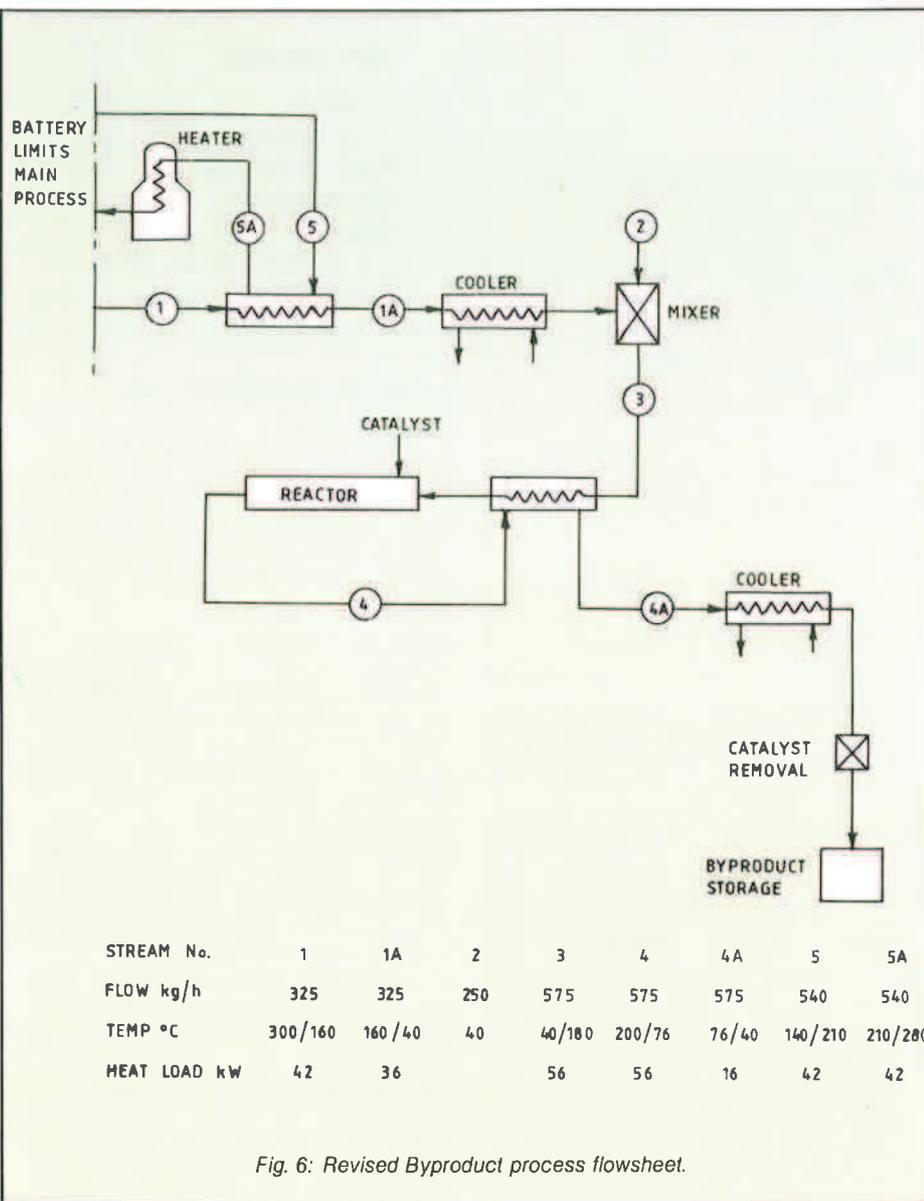
Fig. 6: Revised Byproduct process flowsheet.

Study	Process	New Process or Modification of Existing Plant	Energy Savings Available ($ p.a.)	Capital Cost Expenditure $ or Savings
1	Organic Bulk Chemical	New	800,000	800,000
2	Bulk Acid	New	80,000	140,000
3	Petrochemical	Mod	2 Million	4 Million
4	Crude Unit	Mod	500,000	Savings
5	Inorganic Bulk Chemical	New	300,000	Savings
6	General Chemical	New	360,000	Unclear
7	Power House	Mod	Phase 1 70,000	12 months payback
			Phase 2 300,000	24 months payback
8	Petrochemical	Mod	Phase 1 200,000	200,000
			Phase 2 340,000	600,000
9	Petrochemical	Mod	Phase 1 1 Million	600,000
			Phase 2 1 Million	1 Million

Fig. 7: Summary of Case Studies

Solar Saltfield Development

Seepage losses are a major consideration in the design and operation of solar saltfields.

Salt is a commonplace substance that usually receives little attention, but it is a very important raw material, used for the manufacture of alkalies and chlorine which are in turn major basic chemicals.

Salt, as a raw material for chemical manufacture must be produced in large quantities and to rigid quality specifications. Australia is a large salt producer, making about 5 million tonnes per year by the solar process, and exporting to countries around the Pacific as well as supplying its own needs.

Solar saltmaking is based on the evaporation of water from seawater or other naturally occurring brines. Fractional crystallisation of salt from the concentrated brine is used to separate it from the impurities that make up about 25% of the solids dissolved in seawater and brines of natural origin.

The salt water is made to flow through a series of ponds from which water is evaporated by solar heat absorbed at the water surface. The evaporation rate is influenced by wind and other transport effects.

The saltmaking capacity of a saltfield is largely determined by the local evaporation rate and rainfall. Brine levels and pond areas are controlled so that the brine is concentrated to the salt crystallising concentration just as it leaves the concentrating ponds and enters the crystallising ponds. The crystallising ponds are specially designed with flat floors where the salt forms a thick continuous deposit and is reclaimed periodically by special-purpose harvesting machines. The spent mother-liquor or 'bitterns' is removed from the downstream end of the crystallising ponds before excess concentrations of unwanted impurities are crystallised with the salt.

SITE SELECTION
The site for solar saltfields must be selected with care and specialists from a number of fields participate, e.g. surveying, civil engineering, meteorology, hydrogeology, soil mechanics, chemistry and biology.

The site must have sufficient area to receive the solar heat required to produce the annual salt output. Topography must be such that the costs of pumping brines and of building pond walls are minimised. There must be an adequate and reliable source of seawater or other brine nearby. The climate must not only be 'dry', i.e. with a large excess of evaporation over rainfall, but it must also be stable and reliable from year to year. The area should be free from flood problems. The permeability of the soil in the area must be uniformly low. There must be an outlet for disposal of bitterns, and finally, there should be access to high-volume, low-cost transport, to take the salt to the point of usage

DESIGN
Salt production follows the basic pattern of Salt Solution ⟶ Concentrating ⟶ Crystallising ⟶ Salt Removal. The design must take into account all the local variables and practical requirements which will affect the performance of the saltfield.

Pumping and flow-channel capacities must be designed for the maximum rate of evaporation that will be experienced, and the passage of brine through the system should be essentially plug-flow to achieve efficient evaporation and close control.

Pond banks must be impervious to through-flow of brines, and stable against weather and storm waves. Adequate access must be provided to all parts of the field, especially to the crystalliser ponds where large and heavy harvesting machines must be moved about without delay.

ECONOMIC CONSIDERATIONS
The amount of solar heat used in making salt is enormous; about 50 tonnes of sea water, plus a like amount of rain water must be evaporated to produce one tonne of salt. The energy available from the sun, at the pond surface at midday on a perfect summer's day, is only of the order of one kilowatt per square metre; the average flux is much less. Therefore, very large areas of pondage, between 2.5 and 12 hectares per thousand tonnes of salt per year are required, depending on local climatic and other conditions.

Salt, on the other hand, is a low-cost raw material, and if a saltfield is to be economic its total cost of production must be a very few dollars per tonne. Therefore, as a result, the allowable expenditure per hectare, in building a saltfield is very small indeed, and the pond floors and walls must be made from local soils with a minimum of earth-moving. The floors of concentrating ponds should consist of local terrain with vegetation, fences and natural rugosities left undisturbed. Pond walls must be high enough to enable most (but frequently not all) of the pond floor to be covered with water. They should be made from local soil or in cases where the local soil is unsuitable, from soil carried in from no more than two kilometres away. Walls need to be protected from wave-wash with stone roughly spread on their sloping flanks and on the seaward side of boundary walls by a natural growth of mangroves where these will grow. Crystalliser ponds must be placed where the ground is nearly level so that flat floors may be fashioned with a minimum of work. Concrete is rarely used except for pipes, flow-control structures, and pump foundations.

CORROSION
We might expect corrosion to present major problems in handling large amounts of impure brines in a wide range of concentrations. While the problems could be severe if left unsolved, their solutions are simple. The soils from which the greater part of the installation is made are not subject to corrosion. Key machine parts such as pump impellers are made from suitable alloys and give excellent service. The corrosivity of salt solutions increases with increasing salt concentration up to 3% NaCl, then falls away again so that the corrosivity of saturated brine to iron and steel is compatible to that of tap water; this fall-off is due to a decreasing oxygen solubility. Thus the corrosion of immersed metal, especially at the saturated end of the saltfield where most of the mechanical equipment is used, is not a major problem. Brine splash on unimmersed metal is hygroscopic, and can increase corrosion rates by keeping the metal damp, but this effect is eliminated by regular washing and the use of a suitable paint system.

Measurements have shown that the salt spray downwind does not have any measurable corrosive effect beyond a distance of 350 metres. Because the brines are highly conductive, care must be exercised in the design of machines to avoid galvanic couples between pairs of metals either of which, alone, would resist corrosion.

SEEPAGE

(a) **Design**
The necessarily simple and cheap construction of the ponds, together with their large area, makes seepage of brine out of the ponds a major problem, especially where the brine is highly concentrated and a small loss of brine causes a relatively large loss of salt. The absolute seepage loss rate from a pond, measured in m^3 of brine per m^2 of pond area per hour, is of less direct concern than the ratio between the absolute seepage rate and the absolute evaporation rate from the same pond. If

Fig. 1: Water hoses dissolving salt at ICI's Dry Creek field for transport by pipelines to the Osborne Soda Ash works.
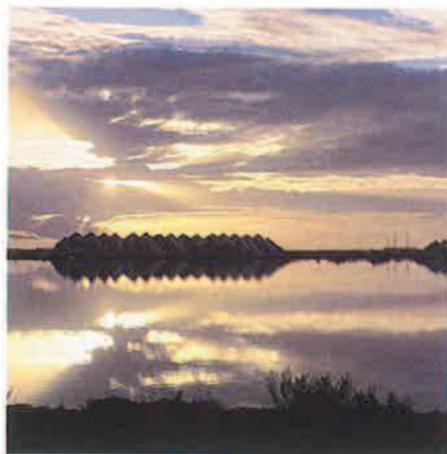
Fig. 2: Sunset on the salt fields.

Fig. 3: Harvesting solar salt at Dry Creek.

this is too high, salt will be lost faster than it is made, and that particular pond will be worse than useless. This can and does happen in at least some of the ponds in many saltfields when they are first commissioned. More seepage can be tolerated in places where the evaporation rates are high than where they are low.

All soils are permeable to brines, to a greater or lesser degree. Flow through them is governed by D'Arcy's Law:

$$V = \frac{H\,A\,P\,g\,\rho}{L\,\mu}$$

where V = volume flow rate
H = differential head across the flow path
L = length of flow path
P = permeability of soil
A = flow cross-sectional area
g = the gravitational constant
ρ = density of brine
μ = viscosity of brine

If the whole body of soil in which the seepage flow occurs is homogeneous and anisotropic, it is possible to derive mathematical expressions to predict the volume and path of the flow for geometrically simple situations. These equations may be found in text-books of hydrogeology; they are often valid and very useful in situations such as wells and sumps in large aquifers. Where the geometry of the situation is more complicated, very good approximations to the real flow situation may be determined by graphical methods. However, within a typical saltfield the nature and properties of the soil vary markedly and it is difficult to predict seepage rates.

Ideally, solar saltfields should be sited on a thick uniform bed of clay, which has a very low permeability. Athough clay has a lower permeability than most other soils, its capacity to absorb and desorb water and brines is greater. This can lead to unwanted transient effects, especially in crystalliser pond floors where operation

involves a cycle of wet and dry conditions. Some, or all of a clay area which shows very low permeability in laboratory test of the clay substance can be, in fact, riddled with worm-holes or holes left by the rotting of plant roots. In addition, clay beds are traversed by old streambeds filled with more permeable sands or gravels.

The engineer can control these imperfections in two ways: by careful attention to detail and supervision in the construction of a saltfield, and by optimising the field design within the natural constraints. In the control of construction, permeable areas must be identified by detailed attention to the nature of the ground, especially in regard to the construction of banks from this material, and any deficiencies must be rectified as far as possible. This can be done, where highly permeable paths occur, by blanketing, i.e. coating at the surface, or by coring, i.e. providing a trench backfilled with impervious material, usually clay, although plastic films can also be used. To achieve the best results every metre of pond wall must be closely supervised during its construction.

Optimisation of design against the constraints is not easy, and the methods used could be further developed.

At and just under a pond wall, the flow path length in the D'Arcy equation is at its smallest and high values of permeability can give high local intensity of seepage flow. Therefore it is very common for people who work in solar saltfields to think of this seepage loss through, or under, the walls as the only significant seepage mechanism, and to think of reduction in permeability in the walls as the only cure for seepage. In fact it is seldom as simple as this. The area of the pond floor is vastly greater than that in the walls, and if the permeability in and under the floor is not very low indeed, and if the pond is deep and therefore the differential head is high, very significant losses can flow through the floor.

Control of permeability is by no means the only way to reduce seepage flow through the walls. Reduction in the pond depth is sometimes possible, the flow path length can be increased by widening the wall, and the cross-sectional area of the flow path can be significantly reduced by avoiding the common practice of taking the wall material from right beside the wall,

Fig. 4: Clearing drains for removal of unwanted moisture from the salt mass.

Fig. 5: Crystallising ponds after harvesting. The harvested salt is stored in heaps (see background).

leaving a ditch immediately below it. Ditches may need to be dug outside the saltfield proper, and down to the water-table, to control the flow of seepage brines into adjacent farmland or forest where it could kill the vegetation, but where land is available at a low enough price these should be some distance from the pond walls to reduce wall seepage. Where permeability of the pond floors is high, the pond depth can be reduced by arranging a series of very shallow parallel ponds with separating walls following the original contour lines of the ground. The separating walls need only be of very cheap and permeable construction. All of these techniques cost money of course and their use requires optimisation. Therefore there is a great unfilled need for a cheap way of identifying and measuring the detailed permeability pattern of the area before designing a saltfield.

In designing a saltfield it is essential to make an adequate allowance for the effects of seepage losses on saltmaking capacity, when determining the area of evaporation surface required to achieve the capacity that is needed.

(b) **Operation**
Where brine seepage is a problem in existing ponds, it is often possible to take action to improve if not to cure the situation. Bad spots in or near pond walls may be fixed if they can be identified, by blanketing or coring with impervious material.

Leaky ponds sometimes improve with age. This may be due to plugging of porous material by suspended clay particles or organic material that grows in or is pumped into the pond, or by the gypsum which crystallises from the brine at the downstream end of concentrating ponds. The flow through the concentrating ponds may be reversed for a few years, with the object of moving the gypsum precipitation to ponds at the other end of the series, thereby reducing their seepage losses. In some saltfields with highly permeable floors, growth of algae has been encouraged by the addition of fertilisers to the brine, and this has led to the formation of low-permeability layers of organic matter on pond floors and walls which has reduced the seepage losses. On the other hand, uncontrolled growths of algae in other saltfields, where high concentrations of nutrients occur in the feed brines, have raised brine viscosity and reduced its evaporation rate, and have interfered seriously with crystallisation and separation of salt from its mother liquor.

Modern solar saltmaking is clearly science-based, but particularly in the area of pond design and construction there remains a large proportion of art which still presents a challenge to the engineer and scientist.

Engineering the Blast at a Surface Mine

Mining operations benefit from computer aided prediction of rock blasting performance.

Blasting is an explosives/rock interaction and has been regarded in the past as an art rather than a science. However, the increasing application of scientific principles is accelerating the art to science transition and dramatic improvements are now being made in blast performance.

Optimum blasting can be described simply as placing the designed amount and type of explosives in pre-determined positions in accurately located and drilled blast holes and firing the holes in a carefully designed initiation sequence so as to break and displace a calculated quantity of rock safely and economically.

We have developed a mathematical model which is based on the generally accepted mechanisms of rock blasting. This model incorporates rock and explosive properties and with the aid of a computer programme, it is possible to simulate blasts relatively easily. In developing such a mathematical model an understanding of the mechanism of rock blasting is essential.

ROCK BREAKAGE MECHANISMS

Consider a single explosive charge which completely fills a blasthole. Such a configuration may be likened to a thick-walled cylinder.

When the explosive is detonated, it changes very rapidly into very hot, high pressure gases occupying the same volume as the original explosive, i.e. the blasthole volume. This sudden application of the sustained explosion pressure (1 to 10 GPa) causes the blasthole itself to expand and thus generate an intense strain in the surrounding rock. The strain rate is between 250 and 500 mm/mm.s As the hole expands, the gas pressure falls until equilibrium is reached.

The cylindrically-expanding strain wave generated by the explosion pressure often exceeds the 'Hugoniot' elastic limit of the softer rocks. Fracture occurs, as the rock is compressed, due to the collapse of the intercrystalline or inter-grain structure. The rock immediately surrounding the blasthole is virtually crushed. The extent of this crushed zone increases with both the explosion pressure of the charge and the ratio of the cross-sectional area of the explosive


1-5 POSITIONS OF THE OUTBOUND COMPRESSION WAVE

Fig. 1: Plan view of Stage 1.

1-3 POSITION OF OUTBOUND COMPRESSION WAVE.
4-5 POSITION OF REFLECTED TENSION WAVE.
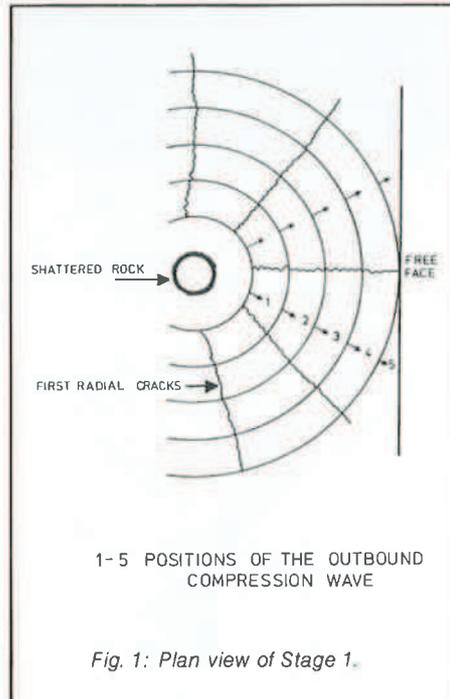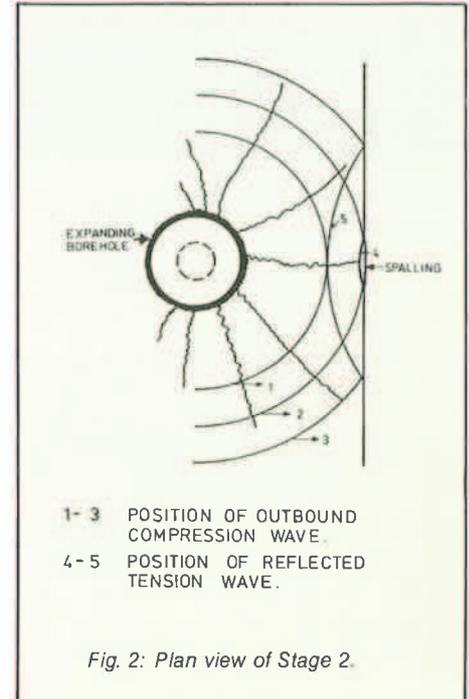
Fig. 2: Plan view of Stage 2.
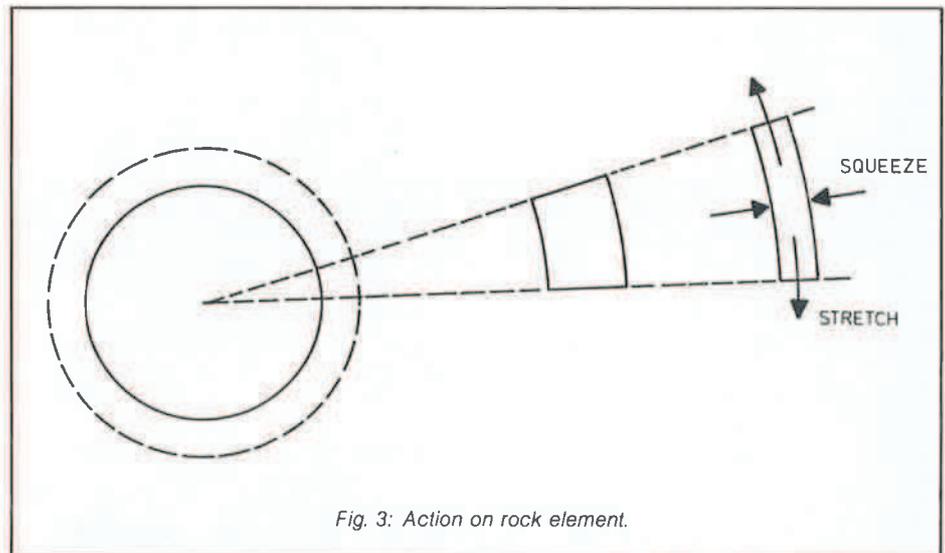
Fig. 3: Action on rock element.

charge to that of the blasthole (coupling). It also varies with the properties of both the rock and the explosive and the material between the charge and the blasthole wall (*see Fig. 1*).

As the strain wave extends into the rock (at 3,000 to 5,000 m/s) it sets up tangential stresses that create radial cracks. The first of these cracks develops in 1 to 2 ms. Figures 1 and 2 illustrate these actions. In Figure 3, the effect of compressive and tensile stresses on a particular element of rock is shown. The contraction and expansion can be described by the laws of elasticity.

During the formation of the radial cracks, the strain wave is reflected from the free surface and can interact with the cracks

originally formed and now growing. Two reflected waves, one tensile and one shear, are generated. If the tensile wave is sufficiently strong, 'spalling' (reflection breakage) occurs progressively from any effective free face back towards the blasthole (*see Fig. 2*).

All these processes occur in less than 5 ms and the gases in the blasthole are still at a very high pressure and stream into the blast-induced and natural fractures. Thus the rock is further strained and the cracks pointing towards the free face are extended.

At about this time a steady state exists as the blasthole (gases) pressure is balanced by the stresses at the boundary of the crushed zone. As gases escape through the radial cracks and stemming,

Fig. 4: Plan view of Stage 3.

→ UNLOADING, THE ROCK BREAKS UNDER TENSION.

→ DETACHED, BROKEN MASS MOVES FORWARD.
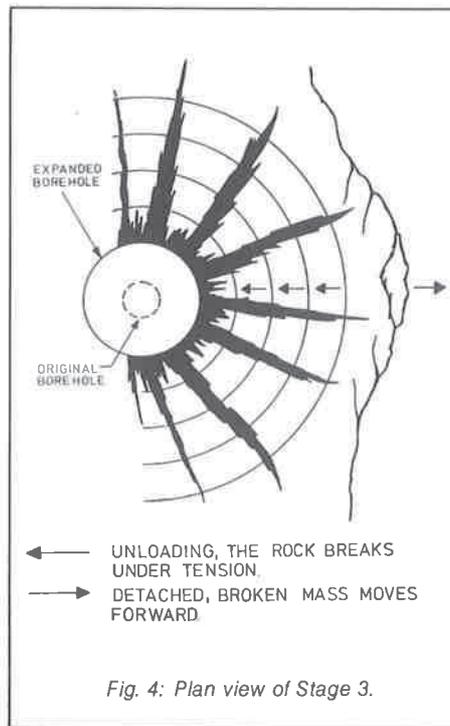
the strain energy transferred to the rock during its initial compression is released. Concentric shells of rock have undergone radial expansion after the initial compression and then tangential release-of-load fractures occur in the immediate vicinity of the blasthole.

High speed photography has shown that fracturing by 'flexural' rupture due to longitudinal bending can occur. This bending takes place after completion of the stage of radial cracking.

Other failure mechanisms are of lesser account but all interact to cause the rock to reach the stage shown in Figure 4.

In going from single hole to multiple hole blasting, a much larger rock mass is affected and it is possible to imagine that the explosive/rock interactions have reached such a stage that the rock mass has yielded and moved forward. It is then accelerated forwards and upwards by the action of the explosive gases. The pressure of these gases acting over the area bounded by the effective spacing and the face height causes the

fragmented rock mass to be displaced (or heaved) into a shape which depends upon the properties of the explosive and the rock. Figure 5 shows the simplified relationship between the starting points (explosive and rock) and the end results for multiple hole blasting.

COMPUTER SIMULATION

From a knowledge of the rock and explosive properties, the process of blasting can be modelled; i.e. a computer programme can be so designed as to simulate the explosion (and its effects) at each blasthole.

Initially the fragmentation resulting from an explosion in a single hole can be determined. Normally, production blasting consists of a number of holes fired in a particular sequence. Therefore, the interaction between holes fired in one or more sequences has to be modelled. To model actual blasts, the hole co-ordinates are first specified and fed into the computer. A crack pattern is then laid out around each hole to simulate either instantaneous or delay blasting. In addition to the blast induced cracks, naturally occurring fractures can be incorporated into the model. The material (air, water, mineral, etc) in the joint is very important as it determines whether or not a blast-induced crack will be stopped by an existing crack.

The crack pattern is normally presented in a graphical form. The basic output from the model is a size distribution curve of the fragments at virtually any point in the blast. The heave velocity can also be calculated for virtually any point on the free face.

FIELD EXAMPLE

Consider a dry granite quarry which is required to produce blasted rock with a maximum fragment size of 1.2 m. Computer blast modelling will be used to determine the optimum blasthole pattern size.

Blast parameters —

face height	15 m
hole diameter	75 mm

Explosive properties —

type	Ammonium Nitrate/Fuel Oil
density	0.8 g/cm³

Rock properties —

|	
density	2.59 g/cm³
Young's modulus	37.5 GPa
Poisson's ratio	0.23
Uniaxial compressive strength	120 MPa
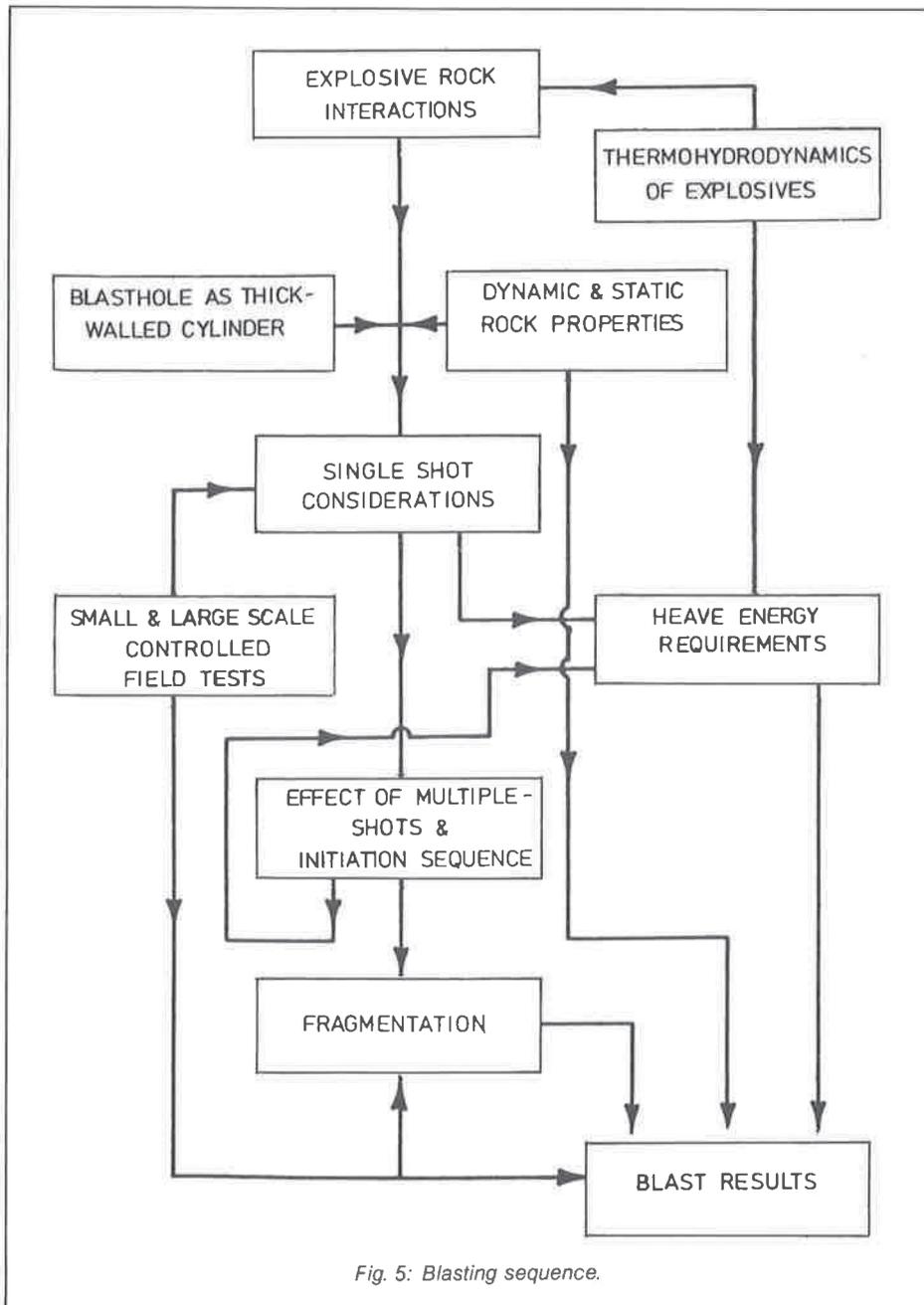
Fig. 5: Blasting sequence.

A summary of the results obtained from computer blast simulation for a range of pattern sizes is shown in Table 1.

From Table 1, the optimum blasthole pattern size to achieve a 1.2 m maximum fragmentation sizing is 1.9 m × 2.2 m. The computer graphical printout of the fragmentation crack pattern for this pattern size is shown in Figure 6.

In an actual case, the next step is to determine the effect of using other types of explosvives. As soon as the most effective explosive type has been determined, modelling is used to find the optimum initiation sequence required. This optimisation is iterative.

CONCLUSIONS

Blasting effectiveness is measured by optimum unit operating costs which are made up of a number of individual unit costs — drilling, blasting, loading, hauling and crushing. Each of the operations following drilling and blasting is influenced by fragmentation (size and distribution) and heave. With the aid of the Blasting Model, it is possible to determine how variations in blast design can affect fragmentation and heave and hence total unit production costs. In such a fashion, blasting at an existing operation (or at a green fields site) can be optimised relatively cheaply. Though highly scientific and geared to large mining operations at present, knowledge of the principles involved can be of tremendous value in helping quarry operators to obtain better value from their drilling and blasting expenditure.

Table 1: Computer Blast Simulations for 120 MPa UCS Granite

Blasthole Pattern (m)	Maximum Fragment Size (m)	Proportion Passing (%)			
		0.4 m	0.8 m	1.0 m	1.2 m
1.8 × 2.0	0.80	80.6	100.0	100.0	100.0
1.9 × 2.2	1.20	73.4	99.0	99.4	100.0
2.0 × 2.3	1.40	66.7	96.5	97.6	99.1
2.2 × 2.5	1.50	51.6	85.2	94.4	96.6
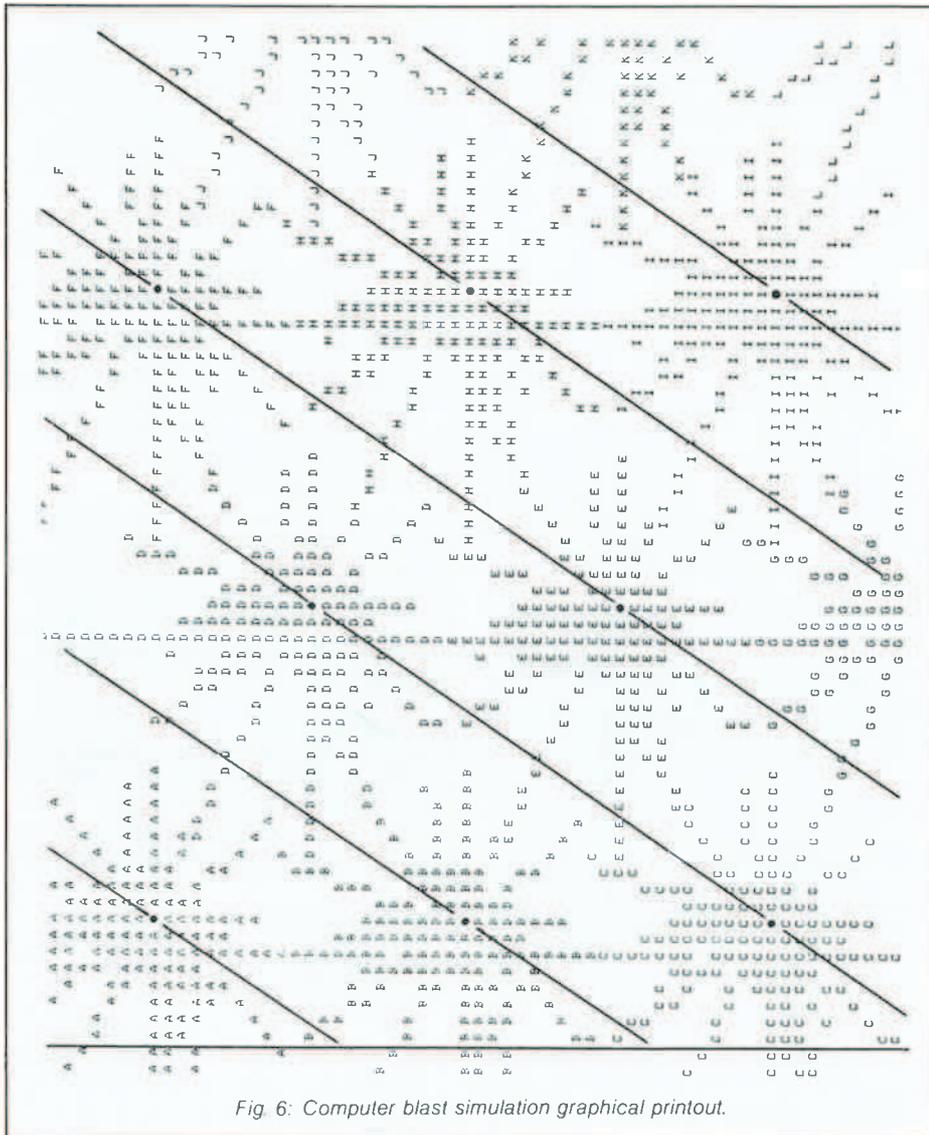
Fig. 6: Computer blast simulation graphical printout.

PROJECT

Hazard and Operability Studies

Safety should be incorporated into the design of a plant from the outset rather than added on later if the basic design has been found to be inadequate.

Safety studies are an integral part of ICI's planning, design, construction, commissioning and operation of new plants. They are undertaken to fulfil three types of requirements: legal, commercial and ethical.

During the design phase of a new project there are generally three stages of safety study:

1. When a project is first conceived, its inherent hazards are identified and broad design safety guidelines and constraints defined.

2. When flowsheets have been received, the probability and severity of any possible hazardous incident is assessed, compared with a quantified safety target and detailed design requirements defined.

3. On completion of process and instrumentation design, a Hazard and Operability Study is undertaken to audit the ability of the design to cope with abnormal and normal operating conditions and to define resulting design modifications or operating requirements.

DEFINITION OF SAFETY TARGETS

Broadly speaking, risk is the annual rate of loss, where the loss is usually money, injury or fatality. For plant safety analysis losses are usually measured in fatalities with the risk unit being the probability of death per year.

Risk is the product of the severity and the frequency of an incident. For example, if an incident has a 10% chance of killing someone, and the frequency of the incident is calculated as once per thousand years, then that person is exposed to a risk of:

$$\text{Risk} = 0.1 \times \frac{1}{1000} = \frac{1}{10000} \text{ or } 10^{-4} \text{ per annum.}$$

Public risk may be classified as voluntary or involuntary. Voluntary risks are often higher than involuntary risks, as we may engage in an activity, keenly aware of the risks, because of some benefit. High risk sports are a good example. On the other hand, if an activity of no direct benefit to us exposes us to a risk, that risk will need to be very small or we will complain.

A variety of voluntary and involuntary

risks have been evaluated. A selection is given in Table 1.

Table 1: Voluntary and Involuntary Risks

Voluntary Activity	Risk per year $\times 10^{-6}$
Smoking (20 cigarettes/day)	5000
Drinking (1 bottle wine/day)	75
Taking contraceptive pills	20

Involuntary Activity	Risk per year $\times 10^{-6}$
Run over by road vehicle (USA)	50
Run over by road vehicle (UK)	60
Floods (USA)	2.2
Lightning (UK)	0.1
Leukaemia	200
Bites of venomous creatures (UK)	0.2
All causes, males aged 35-39 (Australia)	1970

While many industrial operations have the *potential* to cause large numbers of fatalities or severe property damage, in practice this is rarely realised. For example, it is reported from the United Kingdom that in the decade 1968-1977, in which there were 191,942 fatalities from all accidental causes, not one member of the public was killed due to an incident at a chemical plant.

In practice, the general community accepts some degree of risk from industrial activity in return for the benefits of industrial production. By review of risks commonly accepted without concern by the community, a target level of risk for individual members of the public due to the company's plants has been defined.

Employee safety has been approached a little differently. The procedure followed by ICI Australia to ensure safety targets are met in new installations is outlined below. The risks to ICI employees are low compared with those faced in a range of other kinds of employment (Table 2).

Table 2: Employee Risks —
Fatalities per 100 million exposed hours
(Fatal accident frequency rate)

ICI Australia	**4**
Agriculture (UK)	10
Chemical Industry (UK)	4
Clothing & Footwear (UK)	0.15
Metal Manufacture, Shipbuilding (UK)	8
Railway Shunters (UK)	45
Timber, Furniture (UK)	3
Vehicle Manufacture (UK)	1.3
Construction (UK)	63

The company's safety performance, in relation to both fatalities and injuries, has been widely regarded as good. A target fatal accident frequency rate (FAFR) has been defined for all new plants such that the company's overall FAFR, which is already at the low end of the industrial spectrum, will continue to improve.

Stage 1: PROJECT CONCEPTION

Identification of Possible Hazards

The possible hazards inherent in the process or the materials to be used can be broadly identified at a very early stage of preliminary design. This is usually done by checking each process material and each plant section against a checklist of possible hazards compiled from a study of chemical plant incidents.

Potential hazards include:
- Toxic Escape (gas, other)
- Explosion (internal, external vapour, dust, other)
- "BLEVE" or fireball
- Fire
- Long term exposure to toxic material or noise.

(While care is taken from the outset to identify possible hazards due to long term exposure to toxic materials and to design and manage to minimise such risks, this field is one for Occupational Hygienists and is not, for a variety of reasons, included in formal risk quantification.)

Broad Design Guidelines

Once the types of potential incident have been identified, it is possible to define a safety target for each to be aimed for during design, and to define broad guidelines which, if followed by the design team, should result in the required safety being achieved.

High intrinsic safety is the prime goal at this early stage of design. This includes selection of the process, and limitation of inventories, flows, temperatures, pressures, etc, in the process chosen.

Buffer Zones

Even at a very preliminary stage of design it is appropriate to start considering the extent (if any) of buffer zones needed between the proposed plant and existing plants, offices, workshops and the public. A buffer zone minimises the impact on adjacent areas should an incident occur.

Stage 2: COMPLETION OF FLOWSHEETS

Assessment of Severity of Incidents

This may be illustrated by example. The most widely publicised accident is the Flixborough disaster in the UK, where a quantity of cyclohexane vapour (similar to petrol) escaped and exploded in the open

air, killing 29 people of whom all but 2 were killed when a building collapsed on them. No member of the public outside the plant boundary was killed, though there were injuries and substantial property damage. The plant was largely destroyed, partly by the explosion and partly by the fires which normally follow such an explosion.

The quantity of vapour involved is variously estimated to have been between 25 and 50 tonnes.

To predict the severity of a vapour cloud explosion it is first necessary to calculate the likely size of the vapour cloud which could result from escape of flammable material.

Next, one converts the mass of hydrocarbon in the cloud into an equivalent mass of TNT, taking into account the heat of combustion of the hydrocarbon and its explosion efficiency relative to TNT. By referring to a well-tested graph for TNT, the blast overpressure at various distances can be calculated. The effects of these overpressures on people and buildings have been evaluated by military authorities, so the risk to people and structures from the vapour cloud explosion can be determined.

A similar approach is taken for estimating the severity of other possible hazards such as toxic gas escapes, major fires and BLEVES. (A BLEVE is the widely publicised fireball which results from rupture of a pressurised container of a liquefied flammable gas, typically by being exposed to fire.)

Estimation of Frequency of Incidents
To illustrate the method using a simple example, a boiler will burst as a result of overpressure if *both* the pressure control system fails and the relief valves are faulty. The logic in such an incident can be quite simple (as in the boiler case given) or of varying degrees of complexity as in the case of multiple control or protective systems as are used in aircraft, nuclear power stations and some chemical plants. The logic of this type of incident requires analysis using a logic diagram or 'fault tree'. Once the logic has been clarified, the fault tree can be quantified using historical or other data about the frequency of events such as failures of particular types of plant equipment and instrumentation.

The frequency of each incident can be multiplied by the risk to individuals per occasion to find the total risk to individuals per year (public) or per 100 million exposed hours (employees).

Action Arising from Risk Assessment
When the assessed risk is above the target risk, several options are open including —

● reduction of the potential seriousness of the incident in relation to employees or the public; eg, reduction of the size of the potential explosion by such means as lower inventories, pressures, pipe diameters, temperatures, installation of automatic isolation valves, etc, or by reducing its impact by providing greater

separation between the plant and other plants or the public.

● reduction of the frequency of the potential explosion by such means as more robust design to minimise leaks and better protective systems to detect leaks and isolate them quickly.

These options can be expensive if proposed when the plant design is far advanced. This is why it is preferable to adopt a programme of safety studies from the outset of a project to guide the direction of the design as it develops.

Stage 3:
HAZARD AND OPERABILITY STUDIES
On completion of process and instrumentation design, a Hazard and Operability Study is usually undertaken, with the following objectives:

1. To identify any potentially hazardous activities or procedures, and through design modifications or management action, to eliminate or minimise them.

2. To facilitate smooth, safe and timely commissioning of new plant without extensive last-minute modifications, and to ensure safe, efficient and maintenance free operation of plant.

Hazard and operability studies basically comprise a series of studies and examinations of the design, line by line, by a group of senior representatives from design, project and operating staff using a comprehensive checklist of guide-words or questions about possible plant problems. These studies facilitate recognition, before design is hardened, of a large number of potential hazards or operational problems which can be avoided by mainly minor redesign or

suitable operating procedures. The studies also provide an excellent medium for teaching operating staff.

At the outset of the analysis of a section of plant, a design engineer with in-depth knowledge of the process depicted on the flow diagram (for example, see Fig. 1) explains to the study team the purpose of the plant or process. One particular line in the beginning of the process is selected for study and is marked intermittently with a coloured felt pen to highlight it. The design engineer details the equipment contained within this line.

When general understanding is reached, the chairman starts the critique by reference to the first of the check words in the series aimed at logical questioning of the safety, operability and maintainability of the equipment contained within the line. Table 3 is a partial list of these checks, the left hand column showing the different 'conditions' to be examined, and the right hand column, some of the 'causes'.

The first words 'High Flow–High Level' prompt a discussion on what events may

Table 3: List of Abnormal Conditions to be considered.

Condition	Possible Causes
High Flow–High Level	Pump over-speed, delivery vessel pressure lost, suction pressurised, scale dislodged, leak in heat exchanger, loss of auto control, operator error, failure of pipe or vessel, etc.
Low Flow–Low Level.........	Pump failure, partial blockage, low suction, valve jammed . . . joint failure, etc.
Zero Flow–Empty	Pump failure, gaslocking, blockage, suction loss . . . pipe failure, etc.
Reverse Flow	Pump failure, pump reversed, poor isolation . . . pipe failure, etc.
High Pressure	Boiling, cavitation, freezing . . . weather conditions.
Low Pressure	Boiling, cavitation, freezing . . . weather conditions.
High Temperature	Boiling, cavitation, chemical reaction, zero flow . . . external fire.
Low Temperature	Boiling, freezing, chemical reaction . . . weather conditions.
Impurities — Gaseous — Liquid — Solid Change in composition Change in concentration Two-phase flow	
Testing — Equipment — Product	How do we know they are OK. Vacuum and Pressure testing with harmless material.
Plant Items — Operable — Maintainable	Access, isolation, purging, drying, cooling . . . . Special equipment, techniques, skills . . . .
Instruments	Sufficient for control? Too many? Correct location? — Control valve action on air or power loss?

Table 4: Example of High Flow Deliberations from Figure 1.

High Flow Through	Possible Cause	Effect(s)	Possible Action
Unfiltered Storage Tank	Pump delivery greater than make up to tank.	Tank may run dry — interrupts flow pattern.	Instal low level alarm on tank. Instal level control in tank acting to limit pump flow.
Pumps	Low delivery pressure (a) Broken delivery line.	Safety. Loss of product. Poor filtration.	Instal flow meter with alarm on high flow.
	(b) Channelling through sand filter.	Contaminated product. Sand in filtered liquid storage tank. Pump cavitation.	
Sand Filter	High inlet pressure (a) due to increased pump speed	Overpressure vessel — distortion or failure of internals and/or the shell.	Monitor pressure differential across the filter. Alarm high inlet pressure.
	(b) two pumps running in parallel		Have indicator lights to show pumps running.
	Channelling through sand	Poor filtration.	See action under 'Pumps' above.

In this instance, the study team decided it would be safer, economic and improve operability to instal:—

1. Low level alarm on Unfiltered Liquid Storage Tank.
2. Indicator lamps to show which pump is on line.
3. High pressure alarm on inlet to Sand Filter.

Table 5: Hazard & Operability Study No. 2 — Minutes
22 August 1978, Botany, Demin Plant — Present: LCK, DHC, PTE, JTY, HMT, GR.

No.	Problem	Action	Person Responsible for Action
1.	Does PLC check that air flow/pressure is established before proceeding with sequence during generation?	Check with designers.	DHC
2.	Can reverse flow of water enter blowers?	check design of N.R. valve with supplier.	LCK
3.	With one blower on line the other may run backwards.	Instal check valve in each blower line.	DHC
4.	Does water getting into air pressure regulator matter?	Check with supplier — delete V84 if not required.	PTE
5.	Continuous pressure in degassed water line to HCL ejector for cation regen.	Fit air operated spring close valve to open during cation regen.	GR
6.	Unknown function of V115, V114 (caustic to anion regeneration)	Check purpose with supplier.	PTE
7.	Unknown function of V123, V124, V125.	Check purpose with supplier.	PTE
8.	Alfloc dosing pump may feed into dead line.	Interlock starters of dosing and de-aerator feed pumps.	LCK
9.	How does salt dissolve in caustic brine tank?	Add stirrer to design.	JTY
10.	How are effluent sump discharge valve V149, and closing valves V140, 141 and V143, 144 controlled by pH?	Query supplier re operation and ensure automatic sequencing from PLC including pH control.	PTE

lead to high flow in the line or to high level, and what the consequences of these conditions are. A typical set of considerations with the decisions on 'High Flow' with respect to Fig. 1 are shown in Table 4. As additions or deletions are agreed they are marked up in red pen on the flow diagram for future inclusion on the master drawing.

The team then proceeds to the next check words 'Low Flow–Low Level' and repeats the questioning noting decisions or items for further investigation. One such latter item may be for a nominated team member to check the manufacturer's data concerning pump net positive suction head and to specify the safe level for installation of the low level alarm on the unfiltered Liquid Storage Tank. Actions such as this are minuted as shown in Table 5.

All check words down to and including 'Instruments' on Table 3 are considered in a similar manner. When this is done the line under consideration is marked as complete by overmarking the intermittent colouring with full colouring. The second line is then brought forward for examination, and so on through the full process design.

The amended flow diagram in Figure 1 shows how the original line may be modified after completion of that stage of the hazard and operability study. When all individual lines have been studied, often check words are used in an overview of the total section of plant.

The above summary description and tables are for one line, considered at one stage of the overall hazard and operability study. Depending upon the project, the complete study can be most extensive — one recent project analysis by ICI involved eight professionals in 99 half-day meetings and resulted in 1310 specific design modifications, or operational recommendations.

Safety, operability and reliability are inter-related. Apart from their value in helping to design and operate to meet safety objectives, hazard and operability studies have substantial financial and operational benefits because they lead to more reliable and more efficient plants.
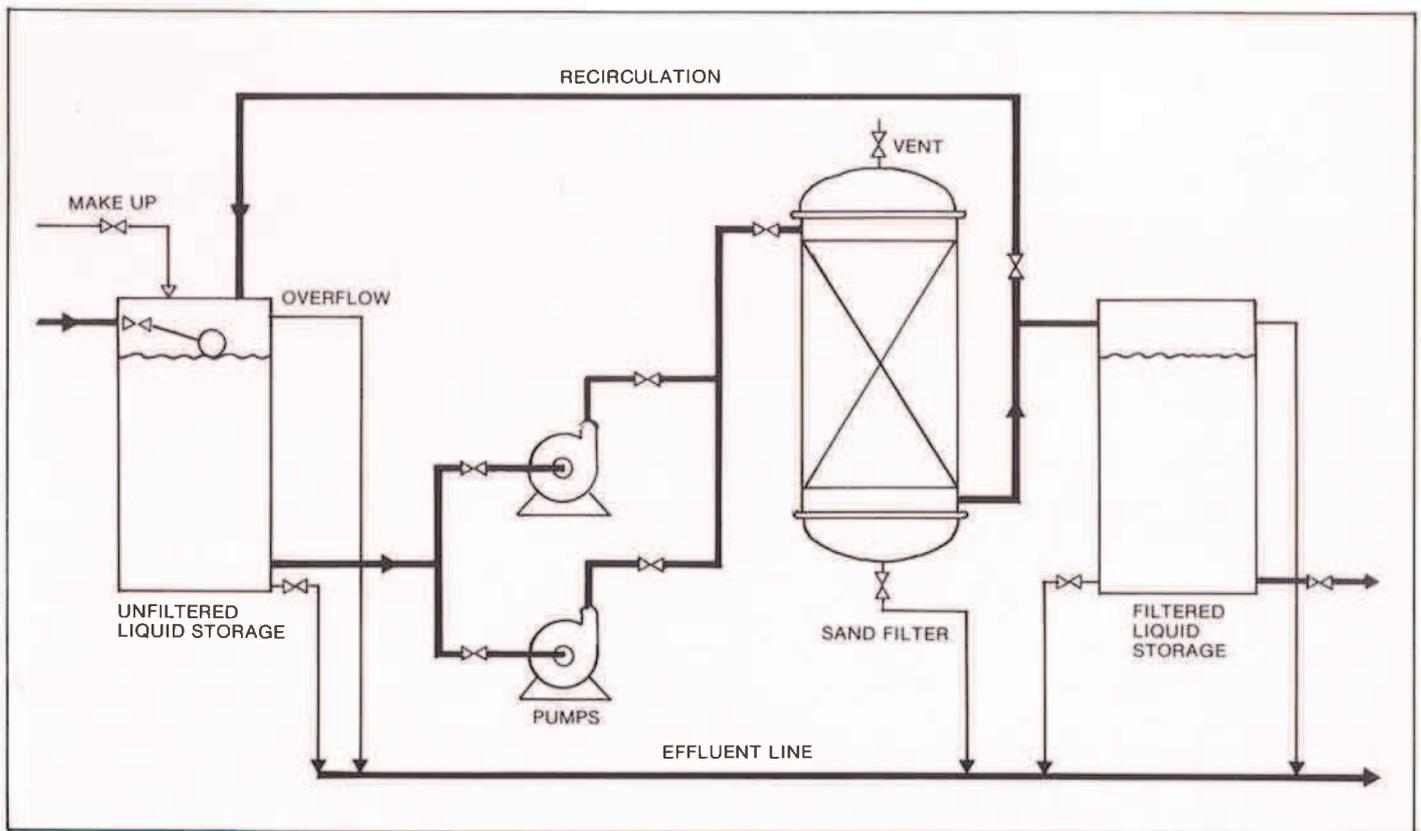
(a) Original flow diagram.
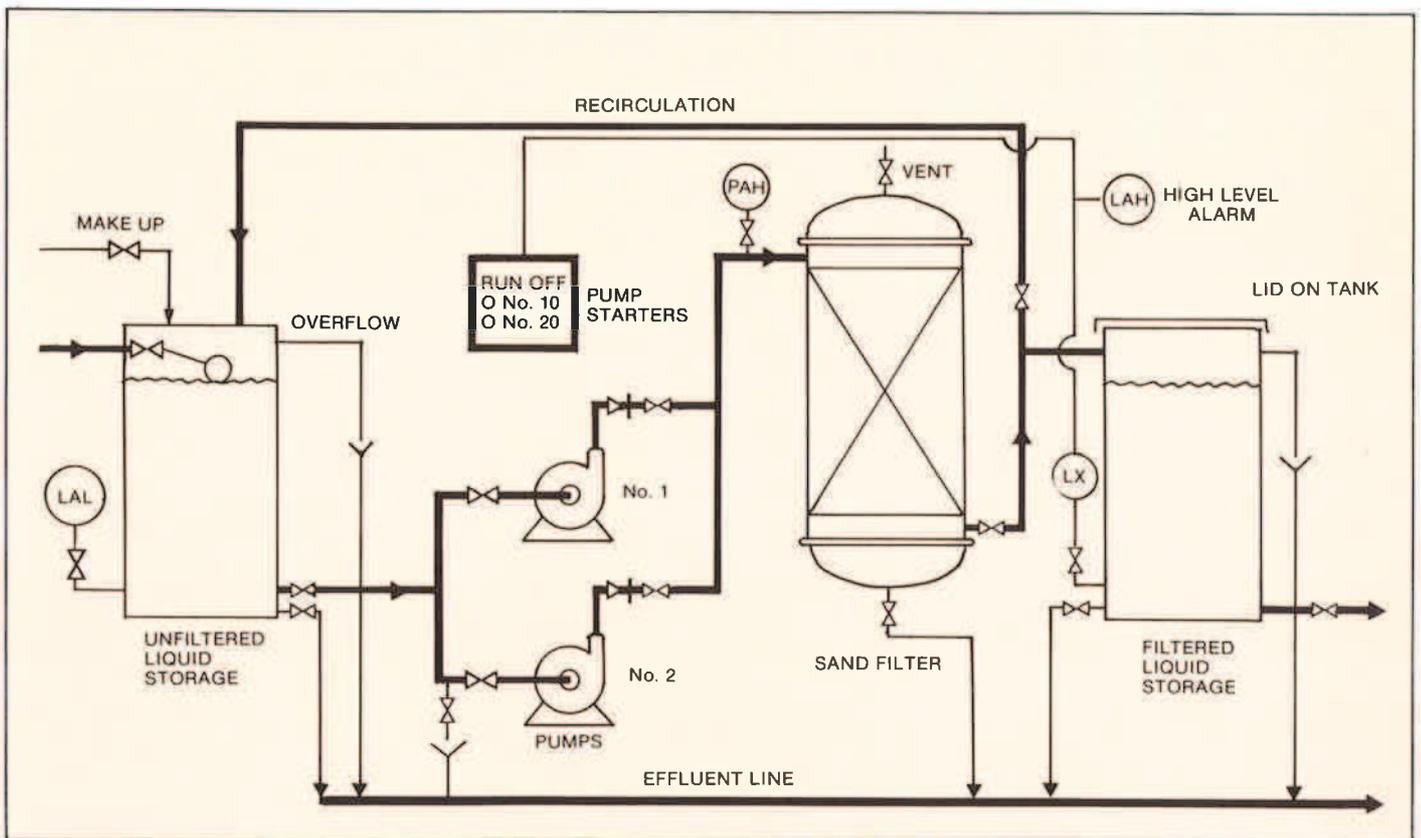
(b) Amended flow diagram after completion of hazard and operability analysis.

Fig. 1: A flow diagram before and after hazard and operability analysis.

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Building a Polythene Plant — A Project Manager's Perspective

Of the many ingredients necessary for a successful project, the most important is the human one.

GETTING STARTED

It was August 1978, and I was one of a small team of ICI Australia Engineering (ICIAE) expatriates putting the finishing touches to a methyl methacrylate plant in tropical Kaohsiung. We had been in Taiwan for about 2 years, and with the project almost complete we were looking forward to the cooler climate of Australia.

At the same time and unknown to me, another group of ICIAE specialists were in Copenhagen, sowing the seeds for a new project in Australia which would soon involve me and many others for the next 3 years or so.

The engineers in Denmark were assessing whether parts of a recently shutdown polythene plant could be salvaged and shipped to ICI Australia's Botany, NSW plant to be incorporated into a proposed major extension of that plant. The Danish operation was no longer viable in an era of larger production units and market over-supply, but the process used ICI technology similar to that at Botany and the plant was of useful capacity for Australia.

Moreover, the well-maintained reciprocating hypercompressors could be stripped, shipped and re-assembled in Australia for a much lower cost and in about half the time of new machines. Thus, the prospect of cost savings and having a new production facility on stream 12 months earlier than an all-new alternative was a very attractive one.

When I returned to Australia from the Taiwan project, senior members of the company were recommending that we proceed with the Danish plant proposal, and that I should form part of a team to investigate in detail the economic viability, timing and other practical considerations which could bring the proposal to fruition.

And so began the Major Development Investigation (MDI) — the earliest phase of any project where a wide range of company expertise is applied to agree the principal project parameters such as process route, production rate, product range (there are over 50 different grades of low density polyethylene produced in Australia), plant on-line time factors and basic locations and layouts. Usually, there are several options open to conceptual designers at this stage, and each must be carefully studied to determine the most cost-effective in terms of maximising the return on capital investment. ICIAE planners and estimators determined the cost and time factors for a number of alternatives, and discounted cash flow (DCF) studies were undertaken to determine the most profitable.

By mid-1979 we had reached general agreement on the nature of the new polythene plant, when a revolutionary new process became available. We were faced with quite a dilemma — the new process seemed promising but would take more time to develop into a live project than the familiar technology of the high pressure process. The Danes could not wait forever for us to purchase their plant and they were reportedly receiving interested enquiries from other competitors.

The solution was to take out an option on the future purchase of the Danish equipment (naturally for a fee) whilst the alternative process was evaluated.

After about 6 months, it was decided to proceed with the original high-pressure proposal, and work resumed on the preparation of process flowsheets, conceptual layouts, electrical single line diagrams and the development of an instrument control philosophy.

SANCTION

ICIAE and representatives from the existing polythene factory at Botany at last reached agreement on the scope of the project, issued the 200-page plant definition document, and on Christmas Eve 1979, the project, known mysteriously as "Polythene Stage 6E Extensions, Botany" was sanctioned by the ICI Australia Board.

ICIAE as the engineering arm of ICI Australia were then commissioned to design, procure and construct the multi-million 6E extensions and to have the new facility ready for commissioning by March 1982. I was asked to lead this part of the project as engineering project manager and in early 1980 we set out to build a team of engineers, draftsmen, procurement officers, erectors, supervisors, inspectors and all the support staff necessary to implement this major "in-house" project.

There were two major phases in the Polythene 6E project — the design phase took place at our Head Office in Melbourne over a period of some 18 months, and the construction phase at the Sydney suburban site which also lasted about 18 months. Efficient scheduling of operations led to an overlap of these phases which meant a total of 26 months were to elapse between sanction and the production of polythene.

DESIGN PHASE

Design work started in January 1980, and the prime objective of the design groups was to fully specify all plant equipment and materials for purchase locally or internationally, and then prepare "construction packages" which would enable contractors to build the plant under the general direction of ICIAE staff on site.

In the early design stages, chemical engineers developed from the plant definition documents more accurate process flowsheets in which mass and energy flow balances were refined. Mechanical and instrument engineers then began to develop piping and instrument diagrams (P & ID's) which addressed the mechanical and process control functions of the plant. Close co-operation with the Polythene Factory staff was essential at this stage, since the P & ID's would gradually evolve into a very complete description of the process plant — sort of circuit diagram popularly known as ELD's (engineering line diagrams).

This evolution of thought is at the very heart of the project — for example a particular ethylene flow rate determines the most economical pipeline size, the attendant flow control valve and pipework determine the system pressure drop and consequently the type and size of ethylene compressor can be selected. From this, detailed layouts can be developed, and support foundations, electric motor drive and control actions designed as part of an iterative procedure involving all disciplines.

There was, of course, an ever present danger of designing a plant which on paper was the last word in engineering excellence, but which might have been difficult to operate, caused environmental interference or was just too expensive to construct in days of high-cost capital and energy. So a clear statement of the overall project objectives was agreed with the operating group and early in the design phase, a series of critical reviews was undertaken to ensure that these were being met.

Hazard and operability studies were important early reviews in which each vessel, pipeline, valve, pump, instrument, etc, on each ELD were studied exhaustively for safe operability under normal and emergency conditions. Modifications ensued which improved the control of the process, reduced the risk of injury and damage to vanishingly small levels and minimised nuisance or harmful environmental effects.
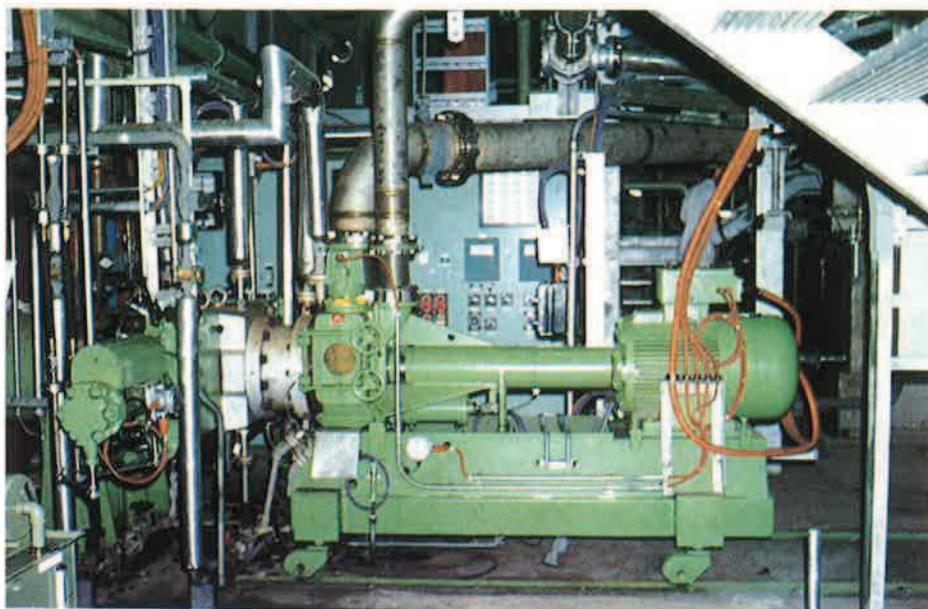
Fig. 1: New polymer extruder die face cutter where extruded molten polythene is cut into granules.

Time is important too — it costs money — so, all predictable activities were chained together by a logic which defined the activities to be completed before others could start, and milestone dates were set in the resulting master program which became firmly imprinted in all our minds.

A major milestone was reached in February 1981 when the last of the 44 ELD's was approved by the Factory engineers and each of the key ICIAE engineers — the essential design of the plant was complete, and now the "production-line" work could begin.

EQUIPMENT PURCHASE

Another dimension of many projects is the need to identify long-delivery items and be able to place orders early enough to achieve optimum project duration. The polymer extruder package was one such order, but there were others such as the high pressure reaction vessel, thick-walled pipe and fittings, the Danish equipment itself, complex instruments and so on. Thus the logical pace of development of design work had to be forced in these areas, adding to the constraints and complexities of the overall task.

As design proceeded, firm specifications were developed for main plant items, electrical equipment, instruments and civil work and from these, the procurement engineers commenced the protracted task of issuing enquiries for quotation, reviewing bids and selecting the supplier, placing orders, following up making payments, etc — in accordance with standard procedures designed to spend the company's money wisely.

Pumps, tanks, heat exchangers, compressors, motor control centres, etc, formed the basis of 450 separate orders on a wide range of suppliers across Australia, America, Europe and Japan. Another 600 orders were placed for the multitude of jobs and services required on site during the construction phase.

CONSTRUCTION PACKAGES

Once the equipment design is firm, design of support structures, buildings, foundations, pipework, ductwork, cable ladders, walkways, roads, switchboards, control panels and the myriad of other items which go to make up the complete plant proceeded. The culmination of this work was the issue of seven "construction packages" — a vast pile of documents, specifications and drawings which described the plant in sufficient detail for construction contractors to build it under fixed lump-sum price contracts.

The work was split this way to enable the most suitable contractors to tender, recognising the limits of their resources and their commitment to other projects, both within ICI and elsewhere.

Some statistics:

No. of drawings produced	=	3100
No. of main plant items	=	270
km of piping	=	20
No. of electric motor drives	=	101
No. of instr. loops	=	550

THE NEED FOR PROJECT MANAGEMENT

I have tried to sketch briefly the major aspects of designing our polythene plant extensions, and to illustrate the complexities of the activities of a multi-discipline team. With this as background and before continuing with a description of the construction phase (for which the management principles are essentially the same), we may reflect on how the activities are planned, co-ordinated and controlled — or managed.

It might be evident that the ICIAE management philosophy is to break the total job down into a number of smaller and therefore more easily controllable tasks which are then allocated to the specialist engineers. In turn, the responsible engineer may further subdivide the tasks into quantifiable elements such as stress calculations, material specifying, drafting or requisition-ing, and allocate this work according to the skills and needs of his team. Each

key team member is then given the responsibility of managing the affairs of his section, with the task of achieving previously agreed objectives of cost, quality and time.

At the front-end stage of 6E, the small team of project engineers, designers and factory developlent staff, through their experience developed the broad scale time program, defined the main plant parameters, and using new and historical data estimated the capital cost of the plant.

After sanction, the program was sub-divided into control programs for each discipline, and the estimate subdivided and re-arranged to form control estimates or budgets for each responsibility area. This subdivision work is directed by Cost Engineers, but fully involves each responsible engineer, thereby gaining his agreement and commitment to achieving the time/cost/quality objectives.

Once a week, we would hold co-ordination meetings at which each responsible engineer would report work progress against program and cost performance against budget, and indicate what corrective action was planned to recover. These meetings were also a forum for talking about factors or problems in one discipline which might effect other discip-lines. More detailed co-ordination then took place at the drawing board after the meetings.

Having decided to split the work into disciplines, a major task was to get the members of each group to talk to each other, thereby bringing together the sometimes disparate views into an acceptable overall proposal, and this responsibility fell mainly on to the shoulders of the two project engineers who alternately chaired the meetings.

As the project manager, a major concern for me was the predicted final project cost, and each month, a full review of the current and expected future status of each job or order was undertaken, engineering staffing estimates and their associated cost were reviewed, and the resulting data fed to the computer-assisted cost reporting system. The reports highlighted areas of under-expenditure (often caused by lateness in

ordering) or over-expenditure (usually brought about by unwitting scope extensions) and thereby enabled appropriate control actions to be taken.

INTO TOP GEAR

In June 1980, construction work got underway. Batteries of field offices, huts, workshops and amenities blocks rapidly appeared. Excavators, trucks, graders, pile drivers, cranes and the full armoury of construction machinery were brought to bear on the installation of roads, underground drains, foundations, cable trenches, air supply ducts, pits, firewater mains and the like. For months, holes were dug, then re-filled with concrete or underground equipment, but despite the feverish activity there seemed to be little progress.

However, in January 1981, with underground work substantially complete, the form of the plant then developed rapidly. The big compressors went in, tanks, heat exchangers, pumps, silos, blowers and structural steelwork arrived on site, and at its peak some 270 contractors were involved in the plant erection.

The high pressure pipe fabrication shop became operational and started to turn out the precision spools and fittings which had to be made with machine-shop precision (and later tested to pressures of up to 2800 kg/cm²). Refurbishing of the Danish equipment commenced, electricians laid and terminated thousands of cables; pipes and valves were installed, control panels were erected, instruments fitted and the appearance of the plant became more and more complex.

The expensive reactor vessel arrived intact from Sheffield (UK), the extruder package in 32 large crates came in from Germany, high voltage switchgear, transformers and other large equipment were installed.

Despite the frustrations, it was an exciting time, and the construction staff accepted the challenges with alacrity and drive — often working long hours to solve a problem which if left, would halt the progress of dozens of men.

We planned to complete construction just before Christmas 1981, a target acknowledged to be very difficult, but which if achieved would result in polythene being produced towards early March 1982. This was 3 months earlier than our original plan and would save significant capital, as well as getting our new homogenised product on to the market ahead of schedule. As frequently happens though, in large projects, a "black snake" slithers late on to the scene and strikes a devastating blow to the program. We were already running about 4 weeks behind our pre-Christmas completion

Fig. 2: High pressure reactory bay showing reactor (background right-hand side) and ancilliary equipment.

target when on the night of 20 January 1982, a small process fire broke out on the existing plant and burned through 37 multi-core control cables which ran from the 6E plant to the central control room.

The vital link with the nerve centre had been destroyed, and all commissioning work was temporarily halted. The cables were special instrument grades and replacement stocks were expected to be hard to find.

A magnificent rescue operation was mounted across Australia — the thousands of metres of cable were located in out of the way stores in city and country centres, and dozens of contractors worked around the clock to reinstal them (via new underground routes). Finally, the work was completed, and the final trials on the extruder and reaction equipment resumed.

On 19 February 1982, in spite of the fire and well ahead of the original schedule, the first polythene from the new line was

produced, and would soon be on its way to our customers throughout the country.

CONCLUSIONS

The most important ingredient of a successful project is the human one: the skill, experience, motivation and energy of all those involved. Few of the features demanded of the engineer on a project are learned during his basic university course. He has to acquire them on the job, first on small projects under close supervision and then on progressively larger ones and with greater freedom and responsibility. As his technical skills develop in dealing with line diagrams, plant layouts, planning, cost control, hazard studies, value analysis, etc, so do his human skills of leadership, team working, communicating and motivating his subordinates. By building on his own strengths and those of his team he will play his part in providing continuity for the technological strength of the company, and if the company sanctions the right projects, the economy of the country.

Fig. 3: Main control panel for new plant.

Planning the Preparation and Start-Up of New Plants
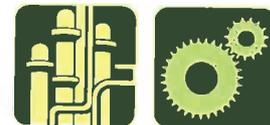
Most chemical plants can be divided into a number of process systems which if constructed and commissioned in a carefully phased sequence will lead to a smooth and early start-up.

INTRODUCTION

To be chosen for the commissioning team of a new plant is to be one of the lucky ones. This is the opportunity to use one's training and intelligence to the full and the chance to gain in a few months the equivalent of years of experience on a running plant.

At no extra charge the status symbols of tension, frustration and overwork will also be acquired, but the effort must be worthwhile. Most people involved in a properly organised start-up say afterwards "When is the next one?" The report given below concerns planning the commissioning of the Plastics (PVC) Factory at Laverton, Victoria. This project gave enormous job satisfaction to the participants.

A 52,000 tpa PVC plant was built on a green fields site. It made top quality product from the initial batch and achieved close to full capacity production within four weeks of start-up.

SUMMARY

Planning was used at Laverton to co-ordinate the activities of the factory team and to influence the construction of the plant to suit a program developed from a commissioning viewpoint to give beneficial operation at the earliest possible date.

The principles and assumptions quoted were adopted by the factory team from the word 'go'. Subsequent events reinforced our belief in these principles.

PRINCIPLES

1. The commissioning team had to define their objectives clearly.

2. The factory had to be built and handed over to the commissioning team to suit a phased commissioning plan and therefore the concept of a single "Ready for Commissioning" date for the whole plant was not meaningful.

3. The overall plan had to overlap the final stages of construction when erection activities have a direct bearing on plant preparation, eg piping should be flushed before hydrostatic testing, vessels must be passed by the commissioning team before boxing up and so on. All the possible jobs, methods of preparation and views on commissioning had to be assessed and incorporated in the plan.

4. Systems and their methods of preparation and commissioning had to be as independent as possible of one another. This approach allows flexibility in planning and can absorb delays and alterations to the programme.

5. Every piece of equipment, machinery, pump, compressor, etc, had to be examined closely before starting; every line cleaned out and leak tested, and every instrument loop checked by instrument people and then proved by process. In other words, every item on the factory floor had to be considered, its ideal treatment decided and then the treatment carried out with great care.

6. All office work had to be completed by the factory team in time to free them for plant inspection, equipment checks and so on.

7. The factory team had to be full time on site as soon as erection started in earnest, ie when vessels, pumps, etc, were being piped up. The team had to assist construction in any possible way, ie by helping to prepare and witness hydrostatic tests, flushing pipework, check pump alignments, etc. The most important assistance the team had to offer was in augmenting the construction inspection group. In practice, as systems neared completion, the factory team took over punch listing of faults and reservation checks.

8. The factory team had to be fully responsible for all cleaning, preparation and commissioning.

9. The factory team had to be fully involved in the making and the operation of all their plans.

10. Each system had to be given 'dummy runs', ie operated on non-hazardous materials at or near design conditions to prove equipment, instruments and to train operators.

11. Each system or block of systems had to be proved on process materials before being married into the full plant start-up.

12. Safe methods had to be agreed which would allow sections of the plant to be prepared and commissioned in areas under construction control where construction was still heavily engaged.

OBJECTIVES

The following objectives were set as soon as the management team was assembled:

- To achieve beneficial operation as soon as possible.
- To make maximum output in the first six months of operation.
- To make consistent first quality PVC.

Note: Any delay at Laverton not only meant a large loss of profit to the company but jeopardised the future PVC market due to forecast shortfall by October 1979. This would have meant imports subsequently difficult to stop. "Opening the flood-gates" was the favourite expression. The need to come on line smoothly and rapidly justified thinking big in terms of manpower, start-up equipment, materials. etc. In the event, it was a "damn close-run thing".

It is worth stressing that the target was to make first quality product at a good rate in a properly run factory. The normal shift teams were trained to operate the plant from the beginning. A lot of attention was given to safety, housekeeping, routine maintenance, amenities and so on.

WHY A PHASED HANDOVER?

Most of the groups involved in a new plant may appear to have different objectives, but the only reason for a new plant is to make money. This happens when the plant is in beneficial operation, ie churning out lots of saleable product. Therefore you need, not the quickest mechanical completion of the whole plant, but the quickest start-up of the plant. There is an inexorable logic about most of the sequences leading to start-up. For example, at Laverton the polymerisation reaction in an autoclave is controlled by heating and cooling the water which circulates through the autoclave jacket. To heat the jacket you need steam which entails commissioning Towns Water — Filtered Water — Demin Water (coupled with Effluent Treatment and Liquid Chemical Storage) — Boilers — Steam and Condensate Distribution, and Instrument Air and other services. To cool the jacket you cannot try out the cooling system until the heating system has been brought on line to give the refrigeration machines a load. All this adds up to a lot of time. The average for preparing and commissioning a system is about three weeks. A good team can cope with about 10 systems at a time and there are about 100 systems in a plant. Rapid mental arithmetic tells us that the whole thing will take six to seven months which is consistent with previous experience.

If you start the commissioning programme only when the plant is mechanically complete then start-up will follow 6-7 months later. The more commissioning overlaps with construction, the shorter will be the overall project time. First system handover six months before plant

mechanical completion should be the aim. If the factory team is disciplined, it doesn't interfere significantly with construction and can even help by augmenting the construction inspection group and assisting with hydrostatic tests, flushing pipework, checking pump alignments, etc.

SYSTEMS

The whole plant and factory were divided into systems. These were sections, which could usefully be prepared and commissioned as separate entities.

For example, the instrument air compressors, drier and piping local to the station was an obvious system which was brought on line as soon as possible. The instrument air distribution piping for the rest of the plant was commissioned in stages as needed. This required additional flanges to be installed in the pipework to allow positive isolation, by slipplates, of 'live' equipment from piping not yet complete.

The office block needed to house the first members of the factory team was a system. The division of the plant into systems and their size and shape will evolve from the commissioning plan and the realities of the plant. The erection program will in turn affect the systems and the commissioning plan.

There were over 100 systems, defined initially in writing and subsequently by marking up Engineering Line Diagrams, as these became available. The definitions were unequivocal, *all* equipment and piping required were marked and instruments were given two priorities; those needed at handover to enable preparation to begin and the remaining instruments which were needed to make the system fully operational. For example, the only instruments needed for the cooling water systems at handover were the pump delivery pressure gauges. Pond level control, temperature measurement and control, and so on, were not needed for another four weeks when the system had been flushed, chemically cleaned, leak tested and proved on circulation.

The system at handover was not always that defined months previously. The actual system was shown on a drawing agreed between the project and construction engineers and the factory commissioning officer responsible. This drawing was part of the handover documents.

BROAD SCALE PLAN

This took about six weeks to prepare, in conjunction with the factory manager, start-up manager, both plant managers, the factory engineer and the personnel manager (he had a process background). We should have had the factory

instrument and electrical engineer but he could not be recruited until much later. We did involve the computer expert in his bit of the plan.

The plan was a broad scale program with activities of not less than one week's duration but this plan was a precis of a great deal of detailed discussion. At the finish we knew what we had to do to commission the factory together with the sequence in which systems would be needed from the construction team

The broad scale plan never really altered, systems were handed over in almost the desired sequence and the time taken to bring a system into operation was about as forecast.
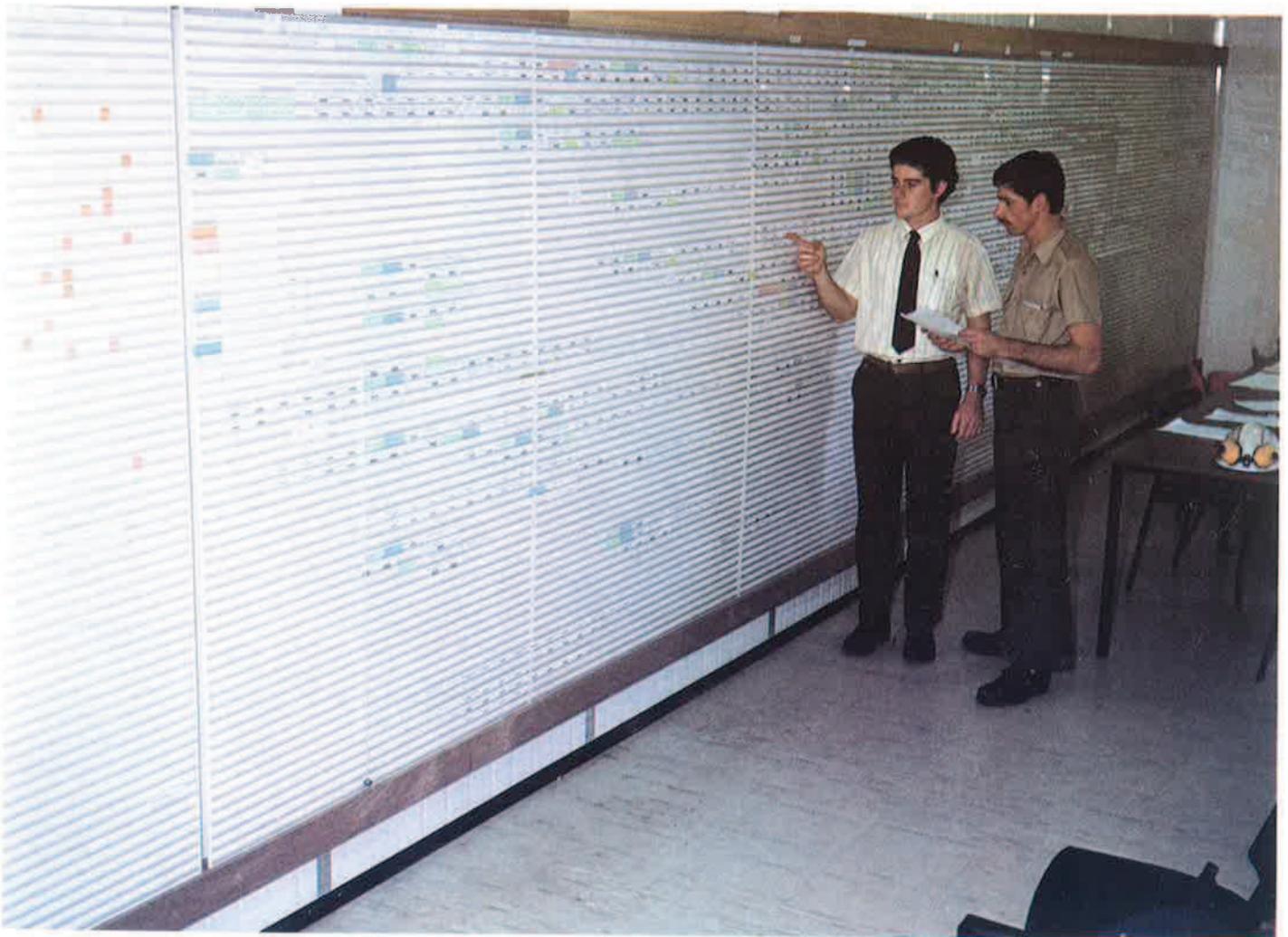

Fig. 1:   A wall in the planning hut in which the time allocation and sequence of all commissioning operations is recorded.

PEOPLE PLAN

This also took about six weeks to produce but it was monitored and modified continually. It never really stopped, going on into training programs, fire and safety plans and so on. Thrashing out the people plans made us think properly about who we needed, what we wanted operators to do, what paperwork needed to be written (and what a lot it was), and what the organisation should be. In fact, it could be argued that this was the most important plan. It determined the timing of recruitment and ensured the completion of training material for the new starters. Because the paperwork was broken down into small portions, progress could be monitored weekly and people nagged into keeping up.

The computer people were very reluctant to make a work plan because they said the work was too esoteric to be defined and programmed and also because everything was under control. When anyone says that — get out the rubber hoses. It might be hard to programme discoveries in theoretical physics but all jobs on a start-up can and must be planned. By November 1978 the key dates given by the computer team had slipped three months and then a plan was produced. This was met reasonably well and the tested software was available when required.

DETAILED PLAN

This was prepared in discussions with the people responsible for commissioning each system (the commissioning officer, mechanical engineer, instrument and electrical representatives and the ICIAE project engineer for that system). We thrashed out exactly how a vessel should be cleaned, a silo calibrated, a system leak tested or a dummy run carried out. All the activities were shown on cards displayed on planning boards. Thus we had a comprehensive plan showing daily activities and covering the whole period of preparation, commissioning and start-up, spanning seven months.

The plan produced was not as important as its making. Most people, unless they've done a particular job before, are not really sure how to go about it and even when they do, their colleagues' perceptions are not the same. When we finished the plan for any system, the commissioning officer was firmly decided how to prepare it, the engineer knew what fitments had to be made, the instrument expert knew which instruments to get ready and for what purpose, and so on. Perfect communication would prevent a lot of problems; we should try to recruit telepaths more often.

After the plan was on the board, people went away and did a lot more planning themselves, writing preparation instructions, dummy runs, etc.

DAILY MEETINGS

The planning boards were displayed around the walls of a large hut. Meetings were held (every morning from February 1979 onwards) to which most of the factory team came. Attendance ranged from supervisors to factory manager, with representatives from ICIAE, construction and anyone else involved. The object of the meetings was to ensure that everyone knew the current position, to press the immediate and important jobs and to indicate the longer term program. People reported their progress against the plan, highlighted problems and aired grievances. In fact, this meeting was an essential means of communication.

There is a theory that the most rapid way of conducting affairs is to report by exception, ie only bring up problems and assume that anything not mentioned is proceeding satisfactorily. This is a delusion; people can be evasive, forgetful or be doing something else which they consider more important. The Laverton meetings were prompt, after some nagging, and brief (twenty to thirty minutes).

DUMMY RUNS

Whenever possible each system or section was subjected to a run using non-hazardous materials. This was absolutely vital, enabling us to train operators, gain operating experience and eliminate faults. It is the faults that are most important. Every system at Laverton had problems, some of them difficult ones, not revealed until the systems were operated.

Some Examples:

Tankers of water were solemnly offloaded at the VCM offloading station. The articulated arms couldn't be manipulated, the knuckle joints couldn't be made leak tight and a lot of the safety instrumentation didn't work.

The autoclaves were deliberately over-pressured when filled with water to see what happened to the discharge from the bursting discs. A lot of it came in to the operating floor, which would be rather

Fig. 2: Section of detailed commissioning located on walls of commissioning hut.

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irritating with VCM in the autoclave. We had to seal off the lift shaft, modify the eaves and box over the ladder entries. The whole reaction was water proved and it took many weeks to get it right, but it was well worth it. The actual production of PVC was an anti-climax. Even on the Werribee plains VCM polymerises and there was only one thing left to prove; did our chefs have the right recipe? They did.

PROCESS RUNS

However successfully one proves out systems on their own and on safe materials, ultimately, to run the plant the systems have to be made 'live' and interdependent. One can remove a lot of unknowns by making limited areas or sections live as soon as possible.

Two Examples:

Poor quality PVC was brought into the factory, slurried in the autoclaves, pumped to the drying plant, dried, pneumatically conveyed to the silos and finally bagged and palletised on the packing line. It was possible to solve most problems during repeated runs. When our own product was made the downstream sections could handle it.

A recycle line was installed between the VCM still product line and the autoclaves' VCM charge line. We were able to prove VCM evaporation from sweetening of the autoclaves, handling, storage, compression and liquefaction of gaseous VCM. Distillation of VCM dislodged residual rust from the column and this rust was trapped in an autoclave from which it could be safely removed. We got a clean, proved system.

The real principle involved here is to do everything a bit at a time and build up absolutely solid foundations. If this is properly done the start-up is not exciting; nor should it be.

SAFETY

Phased handover is of course an intrinsically dangerous way of working. It means that contractors' men will be engaged in areas where the process team will want to blow out lines, make steam systems 'live' and ultimately introduce hazardous chemicals. To carry out these operations safely throws an extra burden on the commissioning team but safe working is possible.

Before any system was handed over it was positively isolated from other systems and areas under construction by slipplating, physical disconnection with blanks, or if appropriate, valves chained and locked shut. The segregation points were clearly identified by labels. The slip-plates and blanks were painted with yellow and black stripes. All plates and blanks were made to the correct code for the piping and their insertion and removal were controlled by means of a register. All equipment and lines, before being pressurised, were marked with "Danger — Line Under Pressure" labels at frequent intervals. Where necessary areas were barricaded off, notices displayed and sentries posted. All blowing was done during contractors' breaks or at night, and hazardous materials were only brought in when areas could be cleared and kept cleared of non-ICI people.

From the time of handover, all work on a system, including completion of reservations by the contractors, was carried out under full factory clearance procedures.

No one was injured by any of the preparation and commissioning activities.

Civil Engineering for a New Chemical Plant

Engineering design for projects is an ongoing process, and early issue of construction drawings defines the scope of the work for the contractors.

The ICI Australia PVC plant at Laverton, Victoria, supplies a major fraction of a growing Australian market. Work on the plant was completed early in 1979 following a year of construction. Capital cost of civil works alone amounted to ten million dollars.

In addition to being personally resposible for a considerable amount of the design work, ICI Civil Engineers had the task of exercising cost control and co-ordinating detail design work in contractor's offices. Within ICI Australia Engineering (ICIAE) itself it was necessary to maintain a continual flow of information between different disciplines.

Engineering design for projects is an ongoing process with drawings having to be reviewed and upgraded as more information becomes available from other disciplines. For the Laverton project this was complicated by the fact that construction drawings were issued as early as possible so as to allow contractors to commence work on site.

This involved having to define the scope of the work for the contractors, and transmitting to them all the necessary information such as site layout and plans and elevations of buildings. Such drawings usually locate the columns, main beams and bays where bracing could be placed. Information conveyed to the consultants verbally was recorded as the Minutes of regular meetings.

During the construction of concrete structures, a Civil Design Engineer was employed on site in an administrative capacity to check quantities and negotiate with the contractor. Overall, supervising and liaising with the contractors and consultants required 15% of ICIAE's design time.

INITIAL SITE SURVEY AND SOIL INVESTIGATION

An existing site survey plan prepared in 1962 was used for a preliminary layout of buildings, roads and drainage. A preliminary soil investigation of the site was carried out in December 1973. The results of this investigation were applied to preliminary designs for estimating purposes. All the preliminary footings were designed as bearing pads as was recommended in the soils report.

A site visit is considered to be essential and should be conducted before the final estimate is prepared. The site visit highlighted a number of points, eg. based on the presence of flood marks and debris, an approximate flood level was established for the creek which crossed the property. This creek was subsequently relocated along the western edge of the site. (See plan of site.)

CAPITAL & OVERHEADS ESTIMATE

Before estimating was started, the following items were prepared:

1. Site layouts, showing the extent of roads, paved areas, underground drains, pipe bridges and the location of buildings, plant structures and plant and equipment items.

2. Floor layouts and elevations of all buildings, eg. administration, amenities, services and plant.

3. Preliminary structural design for all buildings and the foundation design for plant and equipment items.

FINAL SITE SURVEY AND SOIL INVESTIGATION

The final site survey and soil investigation was not started until mid-May 1977, after the site layout had been completed.

The area was generally used for agriculture, with loose stones gathered into various heaps. Examination of the underlying features by pits and bores revealed an upper layer of basalt covering approximately half the site followed by a layer of clay and a weathered lower basalt layer 6 m deep.
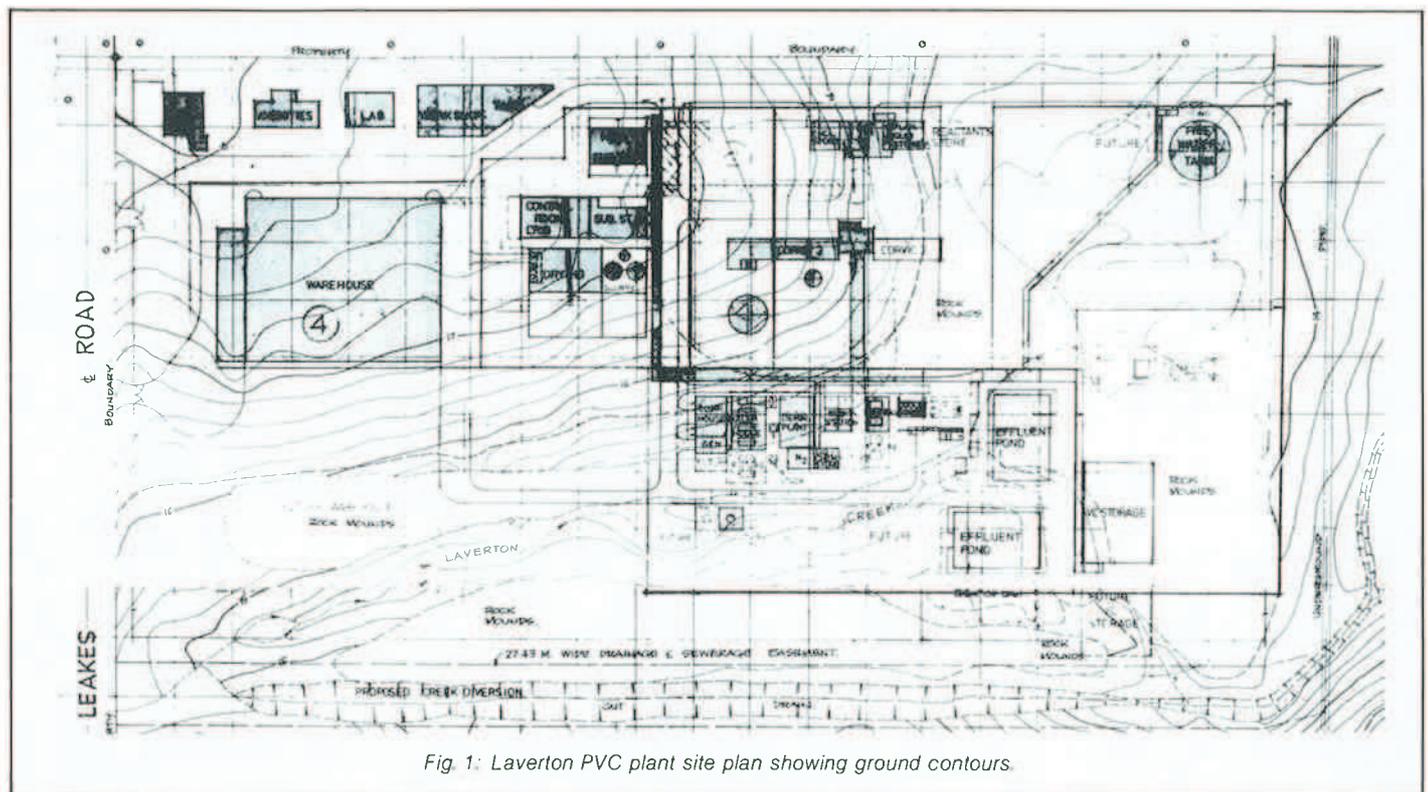

Fig. 1: Laverton PVC plant site plan showing ground contours.

The black soil which is formed by the decomposition of basalt is subject to swelling and shrinking as its moisture content varies. This property meant that care had to be taken with shallow foundations. The varying ground conditions caused concern where heavy loads were carried because of the possibility of differential or excessive settlement. It was decided to carry all heavy loads on piled foundations founded on the lower basalt layer.

Shallow foundations were designed as spread footings at least 1 m below the surface. The 1 m depth was considered necessary to reach soil with a moisture content that would not vary significantly.

DESIGN PROGRAM AND MANNING ORGANISATION

The first activity of the design stage was to prepare a detailed civil design and manning program. This showed that a peak of ten engineers and ten draughtsmen would be required. The decision was made to have part of the work done by consultants and/or contractors. This eased the problem of recruiting and supervising new personnel and providing them with office accommodation and facilities.

The work was allocated as follows:
1. Process facilities to be designed by ICIAE.

These were the Reaction/Additive building, dryer building, slurry tanks, reactant store, and VC storage area. ICIAE prepared the basic concept of floor layouts and elevations and the detail design of these steel structures was done by the contractor.

This decision gave the ICIAE civil design team the time to concentrate on the foundation design in above-mentioned areas and on co-ordinating the flow of information.

2. Supporting facilities to be designed by consultants and/or contractors.

The scope of work for this section was defined. The information could be readily transmitted by means of drawings which had been prepared by ICIAE. These drawings showed the plans and elevations of the Office, Workshop, Laboratory and Warehouse. The contractor undertook the architectural and structural design. Similarly the site layout had been prepared by ICIAE and showed the location of the roads and storm-water drains, so that detail design of roads, drains and cable trenches could be done elsewhere.

CONTROL CENTRE BUILDING

Having particular regard to the disastrous explosion at Flixborough (UK) some years ago, special and novel precautions were taken to ensure that the control centre building, which houses most of the operating staff, should provide the maximum of protection. Because action to close down the plant in an emergency requires electric power to operate valves and control gear, the two sub-stations are built to the same standard.

The design philosophy for these buildings is that they should not collapse under a blast load of 70 kPa applied for 20 milliseconds. Also, the buildings are of materials which will not shatter and cause further damage. With this in mind,

the control room was designed without windows, and the entry door is on the side furthest from the plant (see Fig. 2).

The concrete roof slab is supported on a steel frame. The walls were made of precast concrete T-sections which were placed on a ground beam, the concrete floor then had an edge beam 700 mm deep, and the T-section bears against this edge beam. The roof was cast over the top of the T-section and there was also an edge beam cast into the roof which bears against the inside of the T-beam. A 200 mm deep sill was then poured against the toe of the T-section.

PILE FOUNDATIONS

The piling was carried out using two crane-mounted drills, which cut a 600 mm diameter core. The bit is a circle with a hardened cutting edge which removes a circle of rock approximately 25 mm wide. Where a rock layer is cut through, the core is removed by lifting the drill clear of the hole and unscrewing the drill tip. Where a pile had to be socketed into the basalt, the drilling was carried out to the estimated required depth and by rocking

EAST ELEVATION
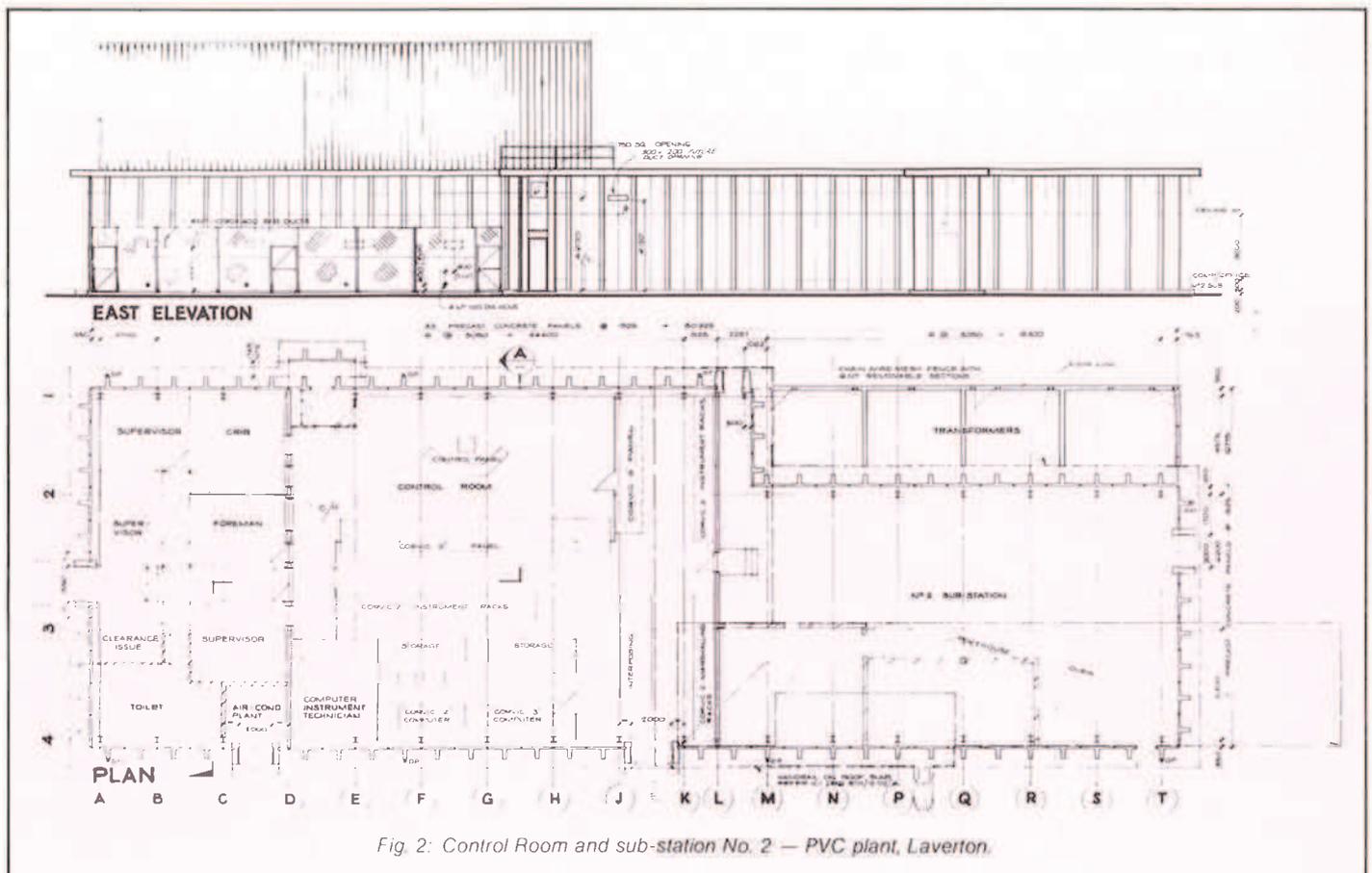
PLAN

Fig. 2: Control Room and sub-station No. 2 — PVC plant, Laverton.

the drill sideways the core was broken off and recovered.

Each core was examined for signs of weathering, cracks and faults. On the basis of this examination, and a knowledge of the loads applied to the pile, a decision was made as to whether or not the depth of the socket was adequate.

The maximum likely uplift of any foundation could be as high as 650 kN and the maximum downward load 2400 kN.

An unexpected problem was encountered with the clay layer between two basalt layers. The clay proved to be water logged and soft. After drilling the pile hole, a sleeve was placed in the hole, the

reinforcement cage was positioned, and the concrete placed by mechanical compaction as the sleeve was withdrawn. The pile caps were poured so that the horizontal components of the load were transferred to the sound rock in the upper basalt layer or to the ground by means of ground beams where the upper basalt had weathered to boulders (see Figs. 3 & 4).
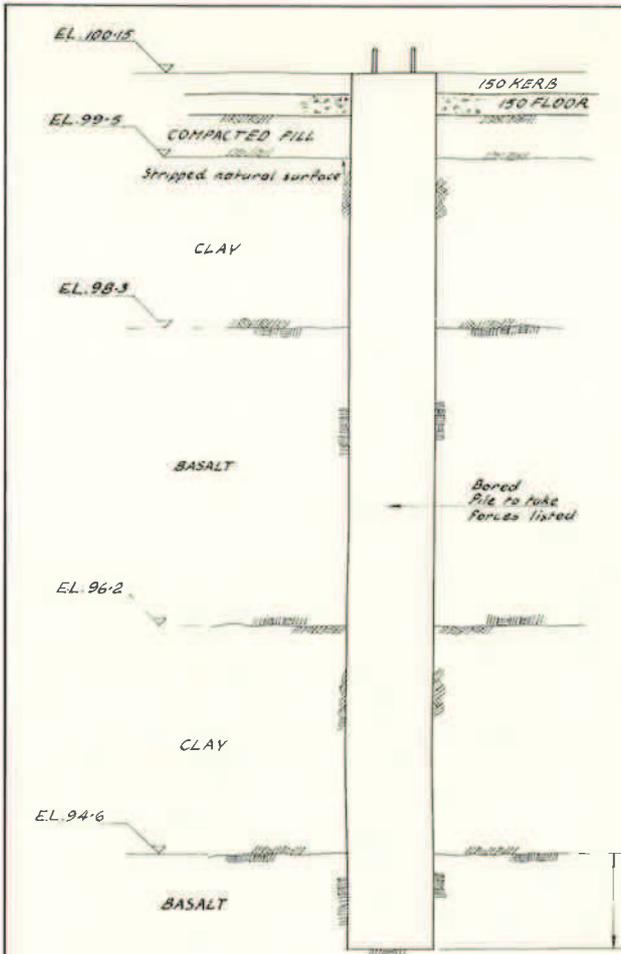
Fig. 3: Elevation and part section of single beam with the sleeve withdrawn, in upper basalt layer.
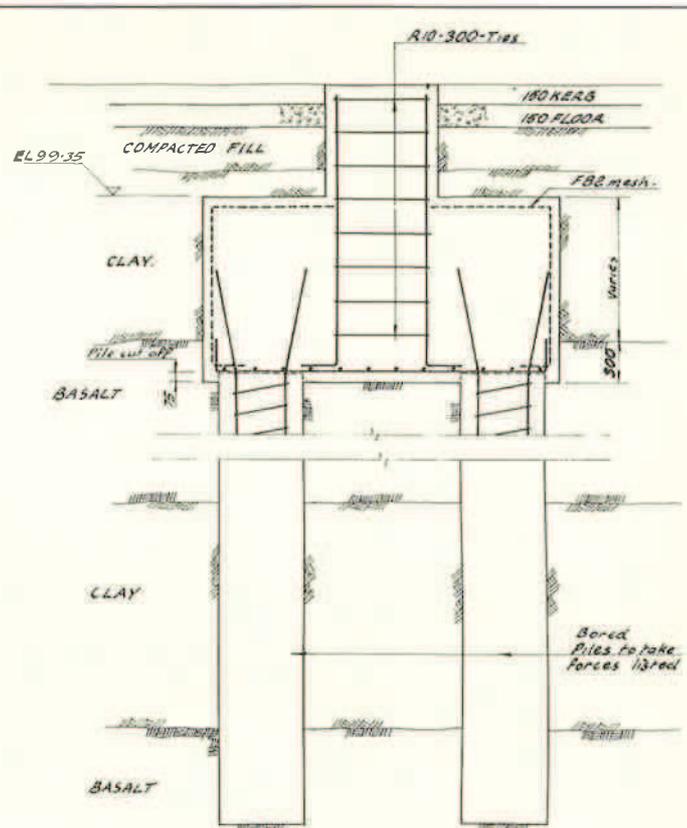
Fig. 4: Bored piles to take forces listed — elevations and part section of double beams.

Fig. 5: A 'bird's-eye' view of the Laverton complex.

(Photo courtesy Val Foreman)

Thermodynamics of Multi-Stage Compression

Temperature-entropy diagrams are a useful tool for analysing ethylene compression close to its critical point.

The ICI high-pressure polyethylene process requires ethylene pressures up to 2000 Bar or more. The supply pressure to the plant is around 33 Bar, further compression being effected in a 2-stage "primary" reciprocating compressor followed by a 2-stage "secondary" compressor of special design. Intercooling is provided between stages.

The operation of multi-stage compressors is quite sensitive to suction temperatures. In particular, a significant increase in throughput can be obtained without a corresponding increase in driving power, if these temperatures can be reduced. As part of a design study to up-rate existing plant, the precise thermodynamics of a primary compressor were investigated using the Temperature-Entropy (T-S) diagram for ethylene (Fig. 1).

Because compression takes place fairly close to the critical point (282.6°K, 50.6 Bar), the "perfect" gas laws do not apply even approximately, and it is therefore not possible to use the usual formulae such as:

$$T_2 = T_1 \left(\frac{P_2}{P_1}\right)^{\gamma - 1/\gamma}$$

Instead a graphical construction based on the T-S diagram must be used.

A typical set of pressure and temperature readings from a compressor prior to up-rating is shown in red on Fig. 1. Some of the desired new conditions were known:—

1st stage suction		
	temperature	25°C (298°K)
	pressure	33.8 Bar
2nd stage delivery		
	pressure	250 Bar.

It was necessary to determine the 1st stage delivery pressure and the 2nd stage delivery temperature for a range of 2nd stage suction temperatures, so that the need for additional intercooling could be assessed. The graphical construction to obtain this information is shown in black (see Fig. 1).

The point representing 1st stage suction can be defined at once from the known data, and a compression line can be drawn through this at the same slope as
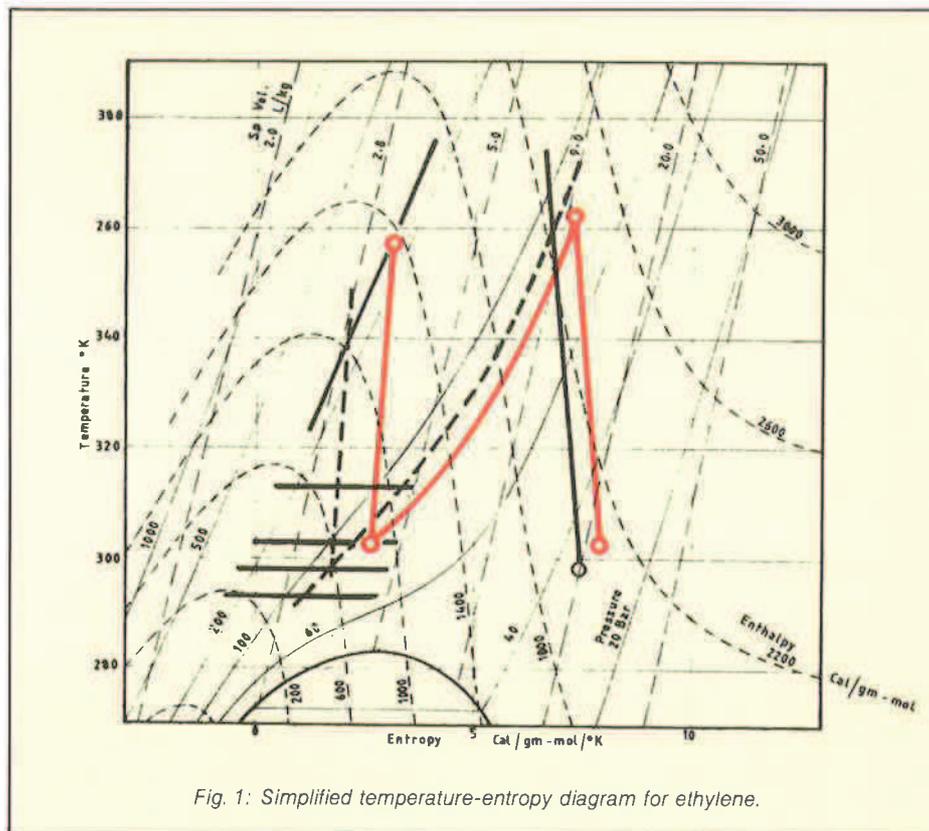

Fig. 1: Simplified temperature-entropy diagram for ethylene.

for the existing conditions (red line), ie the same isentropic efficiency is assumed, which is reasonable. It is then necessary to assume an interstage pressure (dotted black line). The intercooler pressure drop is relatively very small and can be neglected. A second-stage suction temperature is also assumed.

The second stage compression line can then be drawn as before, intersecting the known 2nd stage delivery pressure line. All points are then provisionally defined, though only the 1st stage suction point is "firm". Values of ethylene specific volume can be read off the chart for each point. (A logarithmic interpolation is rather tedious, but necessary.)

The gas throughput per revolution can then be calculated separately for each stage, from the cylinder dimensions and clearance volumes:—

$$\text{Mass flow} = \frac{\text{Piston Displacement} + \text{Clearance Vol.}}{\text{Suction Specific Volume}}$$
$$- \frac{\text{Clearance Volume}}{\text{Delivery Specific Volume}}$$

noting that the compressor is double-acting, and that allowance must be made for the crank-end piston rod area, which is by no means negligible for the second stage.

The mass flows thus calculated are unlikely to be equal for each stage,

unless the assumed figure for interstage pressure happened to be correct. The procedure is therefore repeated for several other insterstage pressures, giving two lines whose intersection is the correct pressure (Fig. 2).

The whole series of operations is then repeated for various second-stage suction temperatures. It is then possible to cross-plot the results as a function of 2nd stage suction temperature (Fig. 3). Interestingly, the compressor manufacturer's recommended limits for both the interstage pressure and the 2nd stage delivery temperatures are reached at a 2nd stage suction temperature of 33°C. Since this can be attained by the use of plant cooling water at 28°C, there is no need to provide expensive facilities for water chilling. The design study was therefore worthwhile.

Although not required for the study, it is also possible to determine the theoretical compression powers for each stage, by reference to the lines of constant enthalpy. The sharply-curved configuration of these lines mean that required compression power for the later stages of compression is substantially less than might at first sight be supposed. For this reason it is always prudent to plot compression (or expansion) events on a T-S chart rather than to rely on formulae.
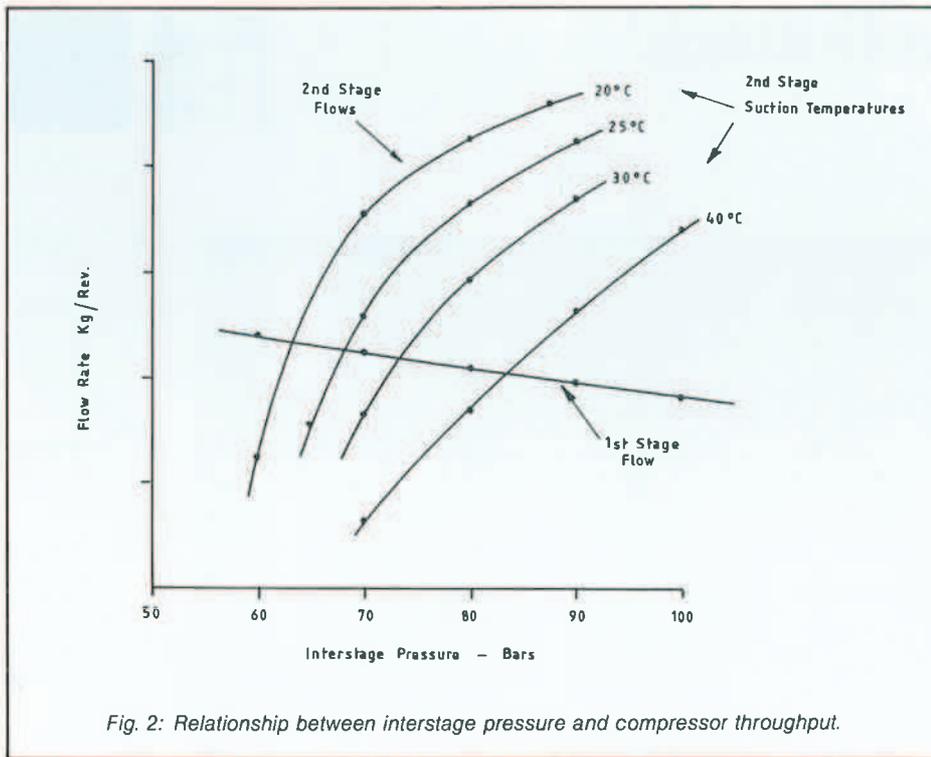
Fig. 2: Relationship between interstage pressure and compressor throughput.
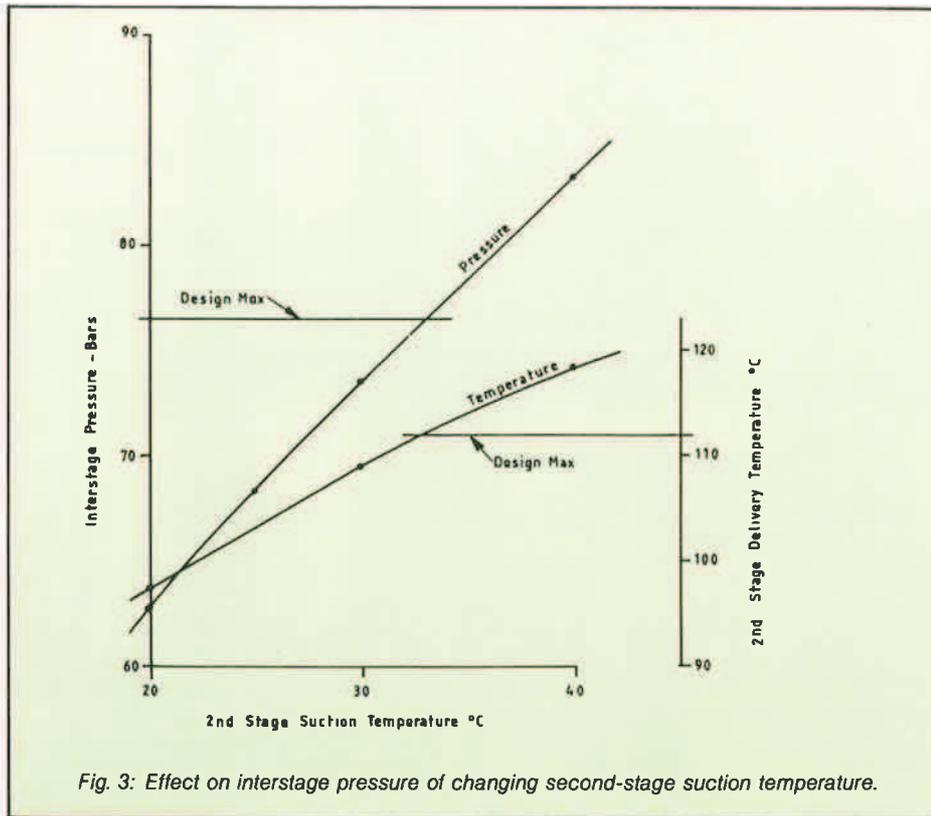
Fig. 3: Effect on interstage pressure of changing second-stage suction temperature.

Engineering in the Outback
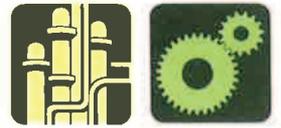
Explosives plants need to be of rugged and reliable design for operation at mine sites in remote parts of Australia.

Modern engineering practice requires large quantities of explosive to fragment ore or overburden before removal to benefication or other treatments.

Individual mines within Australia use up to 20 000 tonnes of explosive each year and explosives suppliers have had to develop methods by which explosives are supplied in bulk to load mine blastholes which might require in excess of 1 tonne of explosive in each and up to 300 tonnes in a single blast.

Development of these bulk explosives systems has involved a team of chemists and engineers over the past 10-15 years; chemists developing new explosives and engineers developing plant and mobile units for their manufacture.

A continuing effort is required to adapt explosives technology to meet the changing needs of mining throughout Australia and the world.

This requirement for bulk explosives has been met by constructing explosive production facilities adjacent to major mines and mining centres. ICI explosive plants are located throughout Australia. Their locations range from Savage River in Tasmania to Groote Eylandt in the North, from Shay Gap in Western Australia to German Creek in Queensland. Designing, constructing and maintaining these plants and their associated bulk manufacturing and delivery equipment is truly 'Engineering in the Outback'.

Modern bulk explosives produced by ICI Australia are manufactured using mobile units which transport the ingredients to the mine bench and mix the explosive as it is loaded into the blasthole. Two explosive types are used — ANFO (ammonium nitrate fuel oil mixtures) for use in dry blastholes and Watergels (sometimes called slurry explosives) for use in wet blastholes. These mobile units deliver up to 15 tonnes of explosives at rates up to 500 kg/minute directly into the mine blastholes in quantities specified by the mine.

'Engineering in the Outback' has special problems and challenges for the engineer involved in these areas.

1. Reliability of equipment is essential if we are to give the level of service mines require. Operating conditions range from

Fig. 1: 2 × 100-tonne capacity bulk ammonium nitrate bins and mobile bulk ANFO unit located at Gregory Mine site, central Queensland.

extreme cold and continuously wet (below 0°C — 3300 mm pa), to extreme heat and dusty (45°C — 125 mm pa). Mobile equipment must perform in rugged off-road situations under this range of conditions.

2. Simplicity of design is essential because the plants are operated by a small team of 1 to 4 men who do not have sophisticated technical back-up close at hand.

3. Safety is of paramount importance and is built into the plant engineering.

4. The plant design is tailored to meet the blasting practices of the particular mine or group of mines. Blastholes loaded at existing sites range from 3 m deep and 120 mm diameter to 45 m deep and 380 mm diameter.

The explosive plant which must be engineered to meet these general

specifications will take in the order of 7 to 9 months to design and construct.

Projects of this nature dictate that a small close-knit engineering team is required. The team is responsible for design, construction and ongoing maintenance of the facility. Feedback of design oversights or faults from the operating facilities allows continual improvements in plant and methods. The small team approach allows each engineer within the team to gain exposure in other engineering disciplines and put these into practice in circumstances where individual achievement is readily measurable.

Earlier we stated that the plants are designed to supply a range of explosives to mines in a variety of conditions. Let us look at these designs to see what range of problems are encountered.

1. THE BASE FACILITY
The basic facility is essentially a storage area where raw materials are stored and, in the case of bulk watergels, intermediates are manufactured. In general a stock cover of about 1 month is maintained on each site but may range from two weeks to three months, depending on the distance of the site from supplies.

The building design and layout is simple and location for ease of materials handling is the prime consideration.

Ammonium nitrate, the major ingredient used in all commercial primary explosives, is supplied in a porous prill about 2 mm in diameter. It is supplied in this manner so that it can absorb diesel oil with which it forms an explosive mixture. Ammonium nitrate is an unusual material. It is hygroscopic if relative humidity exceeds 50-60%. It undergoes a crystal phase change at 32°C which involves a 4% change in volume which causes internal stress within the individual crystal and prill. The prill is comparatively weak and can be crushed if subjected to excessive mechanical handling or phase change. The prills will bond together if allowed to stand undisturbed under low pressures for periods in excess of 48 hours. In addition, ammonium nitrate if wet is a strong oxidising agent and corrodes steel, copper, electrical wiring and reacts with concrete to weaken it to the point of destruction.

Our engineering team has not overcome all the problems of working with bulk ammonium nitrate prill, but have developed practical methods which are now in daily operation. These methods encompass:

(a) Storage in overhead storage silos fed by bucket elevators which discharge by gravity into bulk mixing and delivery units. Bin sizes range from 30 to 100 tonnes capacity and are successfully used where high throughput rates are maintained.

(b) Storage in sheds constructed like large squash courts with total capacity of 400 to 1000 tonnes. Materials handling into

and out of store may be via bucket elevators, augers or conveyors to suit the site. A front-end loader is used within the shed to move ammonium nitrate from the bay.

Continuous engineering development is overcoming the limitations of the storages and to reduce the cost of construction. Research investigations commissioned by ICI at the University of Newcastle have resulted in design changes in silo shape and bin angles to achieve mass flow conditions, addition of effective humidity control and automatic recycling systems on bin contents.

Input from most engineering disciplines, civil, electrical and mechanical is required to successfully design, construct and maintain these facilities.

2. MOBILE MIXING AND DELIVERY UNITS
Two types of truck-mounted units are required — one for the production of ANFO explosives and one for the production of watergel explosives.

ANFO is manufactured by adding distillate or fuel to a special absorbent explosive grade ammonium nitrate prill. The result is a low cost, effective, safe explosive which can be initiated with a primer provided it is not used in wet blastholes. ANFO is the major explosive used throughout Australia and the world. It is not technologically difficult to manufacture and engineering problems associated with its use relate to the design of truck-mounted manufacturing units which load large quantities of explosive in minimum time.

Watergels are a range of explosive products which can be used in either wet or dry blastholes. Manufacture is complex, requiring admixtures of up to 12 separate ingredients ranging down to trace quantities. Most technological development of primary explosives is occurring in this area and significant engineering input is required to develop these new explosive systems. The existing units meter and mix up to four liquid flows and two dry flows and pump the resultant explosive into the mine blasthole.

Design of truck-mounted units involves some unusual engineering problems:

(a) The unit must operate reliably in rough, off-road conditions under adverse climatic conditions.

(b) The design must be such that manufacturers (and statutory) axle loadings should not be exceeded. This is exceptionally difficult for watergel units where the loading varies with the type of product manufactured.

(c) Dynamic stress/fatigue situations are encountered due to racking and twisting of the unit and acceleration/ braking effects while in transit.

(d) The unit must be capable of high speed travel between base facility and mine (travel distances within mines are from 5-12 km round trip), yet have low gearing to reach points of difficult access.

All this would be easy if unlimited money were available, but unfortunately, this is not so. Care is required to achieve the design objectives while minimising cost.

In practice, this means selecting a suitable chassis unit to which the equipment can be fitted. Currently, 8 x 4 chassis (4 axles, 2 axles driven with twin steering axles) are used on the larger units and will carry payloads of 10-15 tonnes.

Each type of truck, ANFO or Watergel, uses auger and pumps to meter dry feeds to the point of mixing. These are driven

Fig. 2: Mobile bulk Watergel mixing and delivery unit located at Liddell, New South Wales.

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hydraulically but activated by an electric control circuit via a system of interlocks which ensure that the explosive blown (ANFO) or pumped (Watergel) is of good quality.

The construction of mobile units is done in Melbourne workshops and supervised by one of the engineering team. Problems encountered during construction are normal. Access to suppliers for parts overlooked or specialist help is as near as the telephone or a few kilometres by car or taxi.

Construction of the base facility and commissioning of the total facility is not quite so easy. The nearest town is 100 km away. You can't get the overlooked or faulty part there anyway. The supplier is 700 or 1000 km away. You have to wait two days while the part or specialist is airfreighted to the site. This is when the true need for 'Engineering in the Outback' is realised because good design, good planning and good co-operation within the explosives engineering team is the way such problems are minimised.

Fig. 3: 400-tonne capacity bulk ammonium nitrate storage shed erected at German Creek mine in central Queensland. This facility and associated equipment is designed to supply bulk ANFO and bulk Watergel explosives to the German Creek mine.

Another 55 kiloamps of Chlorine Production

The installation of an additional transformer/ rectifier set boosted the DC current feed capacity at the Botany Chlorine Plant by 55 kiloamps.

INTRODUCTION
Some engineering projects are far more interesting than others from the point of view of an electrical engineer; the most interesting include steam and power plants, aluminium smelters and chlorine-caustic soda plants. The recent uprating of a chlorine cell bank of ICI Australia Operations' chlorine-caustic soda plant was one such project.

THE PROCESS
Chlorine and caustic soda are produced at Botany by electrolysing sodium chloride in mercury cells.

Each cell consists of a steel baseplate, over which mercury flows. Brine is pumped over the mercury. A rigid perforated metal plate is suspended a few millimeters above the mercury in the brine, and acts as the anode. Chlorine bubbles off the anode and is drawn away. The mercury acts as the cathode and sodium comes out of solution forming a mercury-sodium amalgam. At the end of the cell, the mercury is pumped through a 'denuder' which just washes the mercury-sodium amalgam in clean water in the presence of graphite. The sodium comes out of the amalgam, and reacts with water to form caustic soda, releasing hydrogen gas.

There are a number of fittings on the cells, including equipment to adjust the anode to cathode gap and cell-shorting switches which can take a cell out of service simply by bypassing the current through it.

The recent uprating of the cells boosted the current through the cells to well over 150 kiloamps at between 100 and 130 total voltage drop across the cells. To provide this current, transformer-rectifier sets are used, each consisting of an on-load tap changer, an HV/LV transformer, banks of silicon diodes and an automatic current controller.

ADDITIONAL RECTIFIER
A transformer/rectifier set (second-hand) was acquired to feed additional current to the cells in parallel with three existing rectifiers. This unit has a rating of 60 kiloamps DC.

The whole transformer/rectifier set consisted of one 11 kV on-load tap changer autotransformer, three rectifier transformers, six diode cubicles with sixty 400 amps silicon diodes each, plus the control cubicle and miscellaneous bus ducting to connect the transformers to the diode cubicles.

The diode cubicles and the controls were badly corroded, but the transformers were in perfect condition, apart from a couple of minor oil leaks.

DESIGN AND INSTALLATION
Usually with a rectifier project, the rectifier is the last thing to arrive on site. Instead, it was available on site before we had decided exactly how and where it was to be installed.

Following completion of design, the civil work started almost immediately. A building to house the diode cubicles was erected while we were still working out how to run the DC busbars.

Mechanical work was minor — a heat exchanger and two pumps for the water cooled diode cubicles.

The diode cubicles were completely disassembled, cleaned and painted, and the more corroded diodes were replaced.

The control system was rebuilt. During commissioning we learnt the hard way that we should have thrown out more of the various components than we did. We had not done this because we weren't sure how they worked. The first time we tried the automatic current controller on line for a brief period the cells got 20 kA or so more than ever before, until I manually tripped the HT circuit breaker. Fortunately the cells weren't adversely affected by this brief current surge.

BUSBARS
To carry 55 kiloamps away from the rectifier requires substantial busbars which we constructed from $22,000 worth of copper plates and $70,000 worth of aluminium plates and slabs.

We used 250 × 7 mm cross-section copper plates in parallel per diode cubicle on each of the positive and
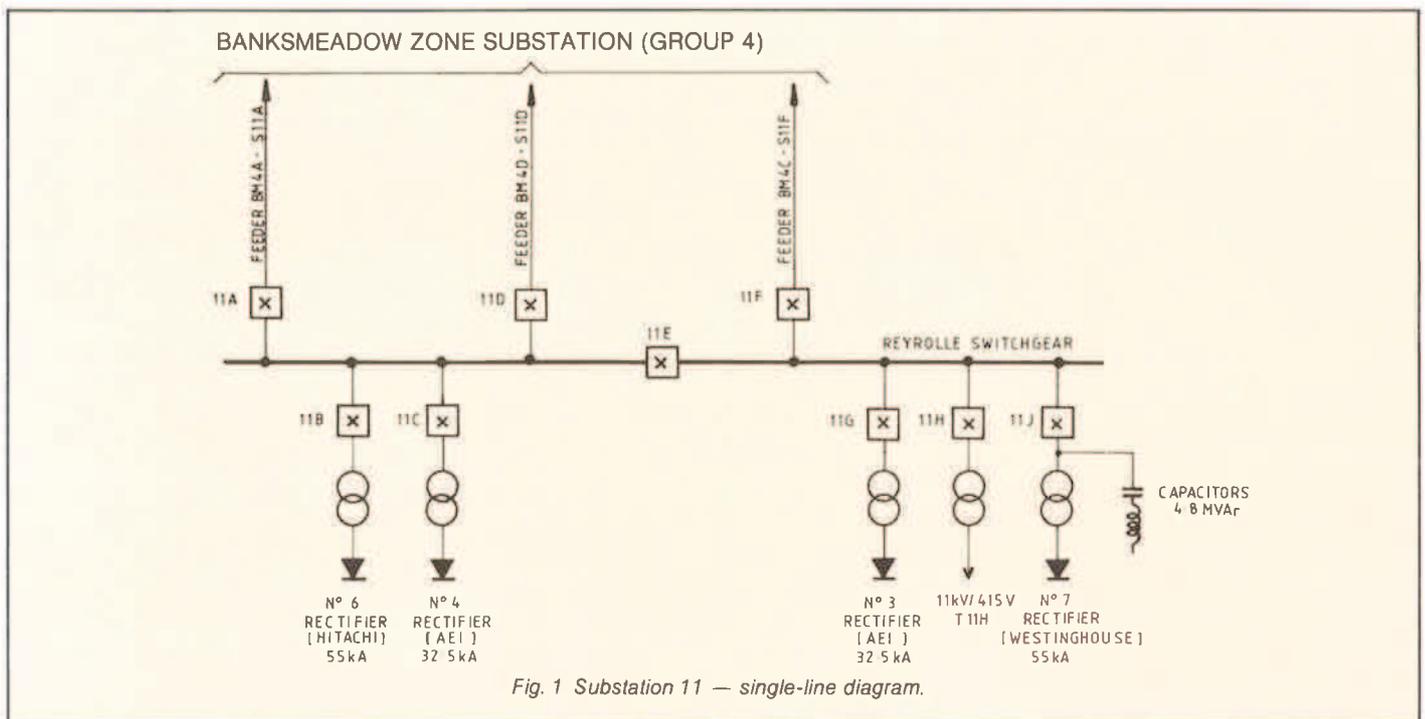
Fig. 1 Substation 11 — single-line diagram.

negative sides, inside the building. Several plates (laminations) in parallel rather than a single slab were used to minimise skin effect and allow for convection cooling, since the copper runs fairly warm.

Aluminium plates 570 × 13 mm cross-section were used from the cell side of the DC isolating switches to the connection with the existing busbars from the other rectifiers. Again, several parallel plates were used spaced apart to give improved heat dissipation.

The negative return busbar from the far end of the cells was uprated by adding a series of aluminium slabs 508 × 140 mm, in parallel with the existing similar slabs.

It was necessary to allow for thermal expansion. We made flexible connections to the busbars using aluminium rope welded at both ends. Some bends were put in the laminated busbars to provide some flexibility for thermal expansion and we also put in some sliding supports made from PTFE sheets to further facilitate thermal expansion.

Considerable care was taken with the joints, since they were the most critical part of the busbars. Effective welded joints were used throughout the aluminium busbars and copper busbar joints were thoroughly cleaned (to remove oxide film), smeared with petroleum jelly, and bolted using high tensile bolts.

To save time and money, standard cell shorting switches were used for DC isolating switches. These disconnect the rectifiers from the cells to facilitate safe maintenance.

POWER SUPPLY
About 22 megawatts is drawn by the cells being uprated. Supply is taken at 33 kV directly from the ECNSW/SCC terminal station at the old Bunnerong Power Station, which is now a major switching station. ICI's own feeder cables start at the circuit breakers at Bunnerong. These feeder cables, except for the two most recent, terminate at 33/11 kV transformers at ICI's 'Banksmeadow' zone sub-station on Botany site. 11 kV feeders run from Banksmeadow to sub-stations in the various factories. Five cables now feed the sub-station which is dedicated to the cells.

When the extra rectifier was installed, it was necessary to uprate the supply to this sub-station. This was done by providing the fifth feeder cable. The cable route had to be chosen to keep it away from the other cables so that there was no loss of rating due to mutual heating.

To further uprate the supply to the sub-station four 1.2MVA capacitor banks were restored and recommissioned. They had gone out of service when the control switches failed some years previously. We connected all of them in parallel with the extra rectifier.

The net power factor of the sub-station is now very close to unity, so we are making the best use of megawatt carrying capacity of the feeder cables.

OTHER UPRATING WORK
To enable the cells to take the increased current, some other uprating work was done. This included careful reduction of the resistance of joints and additional cell shorting switches. This was engineered by the factory on a cell-by-cell basis as they were taken off line in turn. This uprating work is continuing and, as production is further increased, new bottlenecks in the whole system are found and overcome.

Key Words:

Mercury cells
Transformer
Busbar
Rectifier
Kiloamps
Uprating
Refurbish
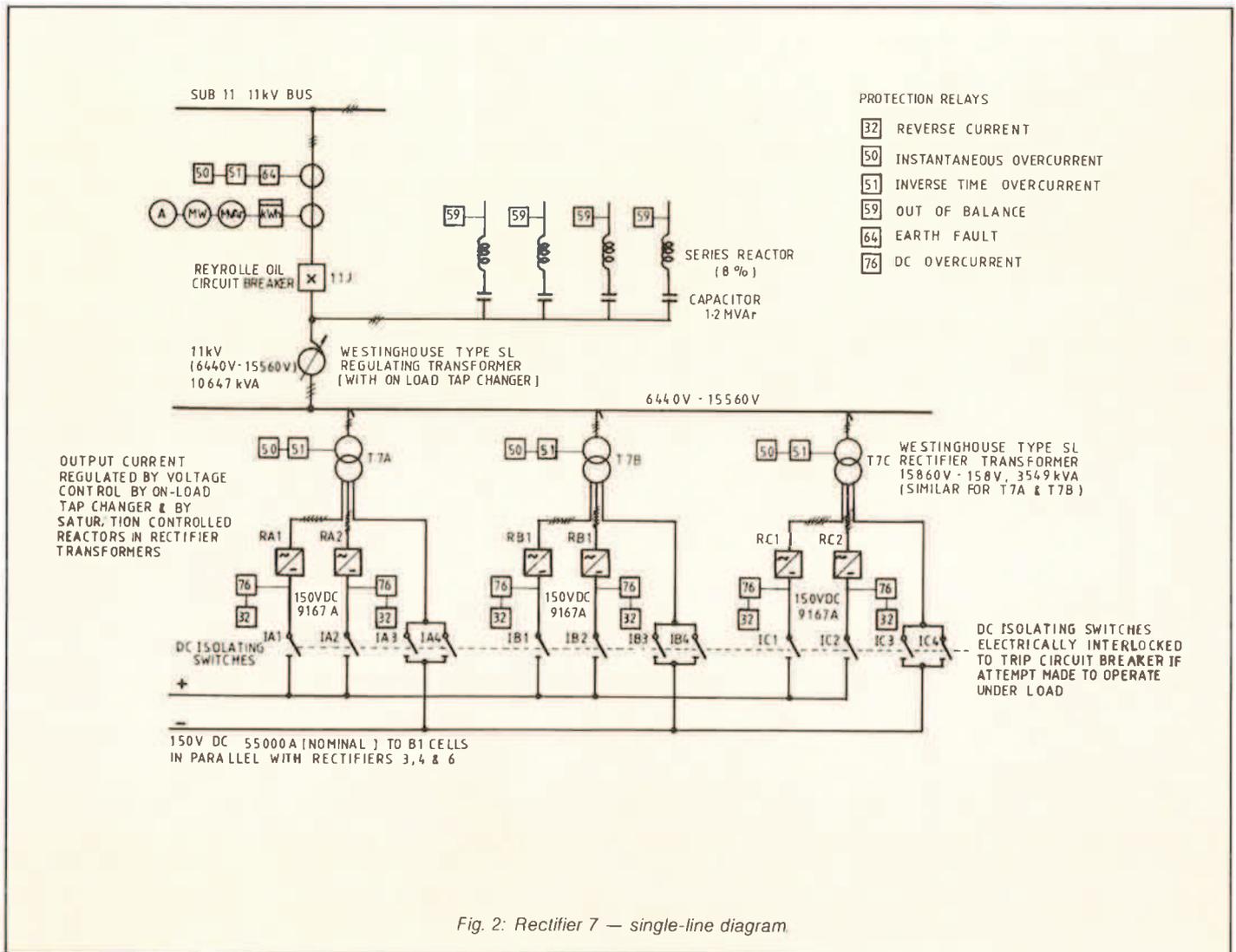
*Fig. 2: Rectifier 7 — single-line diagram*

Fig. 3: The rectifier building showing the three rectifier transformers.

Fig. 4: Inside the rectifier building. On the left are the diode cubicles. The DC busbars are on the right. Some of the copper busbars are visible at the top.
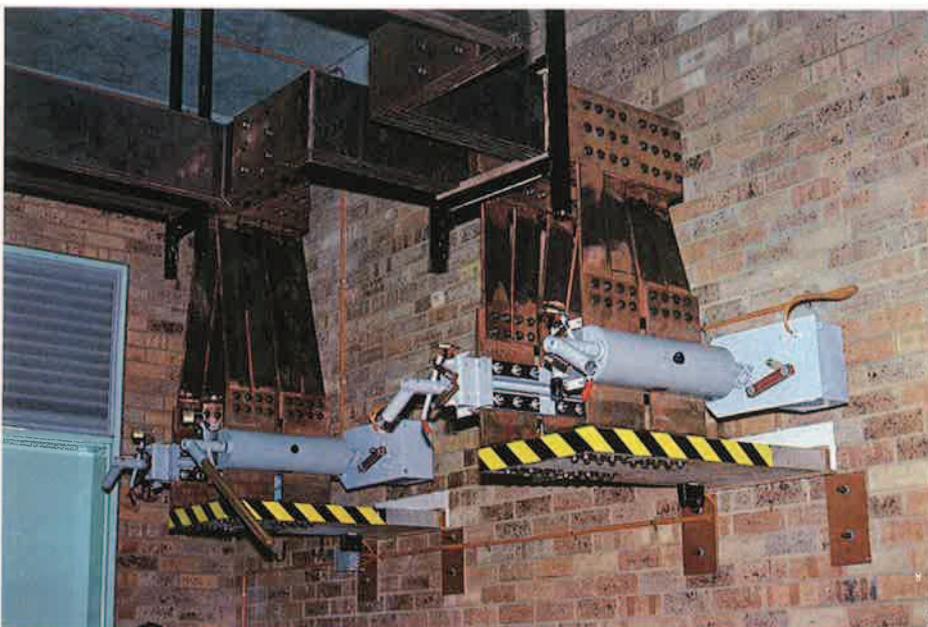

Fig. 5: Close-up of 4 DC isolating switches, each carrying 9200 amps, also showing some of the copper busbars.

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OPERATIONS

The Value of Clarity

Clear diagrams and manuals can greatly help engineers to communicate, and savings are sometimes dramatic.

One might suppose that only fools would willingly communicate by means of puzzles; but very often an engineering drawing is no easier to solve than a crossword. Most engineers may take it for granted that the people they deal with can follow engineering drawings; having mastered technical drawing at university, they may pride themselves on being able to read plans, elevations, wiring diagrams and flow charts. Yet you can hear remarks such as 'Yes, this linkage must penetrate through here,' or 'It's this dotted line on this view', or 'Does this connect that pump to the overflow spill-pot here?'

So why does this puzzle-drawing continue? There are many reasons.

1. An engineering drawing shows dimensions, surface finishes, machining tolerances, and other data. A flow chart shows control-loops, instrumentation, and flows. These formats are a very compact means of showing a great deal, even if they are confusing.

2. It is seldom possible to say how much money a clearer drawing or an easier-to-read manual would save.

3. Isometric views, perspective cutaways, or exploded diagrams are clearer to many people, but few are well-versed in the techniques of drawing them.

4. Technical illustration is sometimes divorced from the needs of the user. In addition to clear drawings, one may need overlays, captions, decision-trees, cartoons, text, index, contents, trouble-shooting procedures, etc. If a package is not well designed it will be largely wasted.

5. It is widely thought that the cost of a well-designed package is prohibitive.

6. Suppliers often lack the skill to produce good maintenance manuals. They are also concerned with the commercial implications: secrecy, legal liability, loss of service business, and fear that a customer may make mistakes.

7. Many people have never encountered easy-to-read representational diagrams, so they don't consider drawing them.

8. Some people seem to take pride in producing work that other people cannot easily understand.
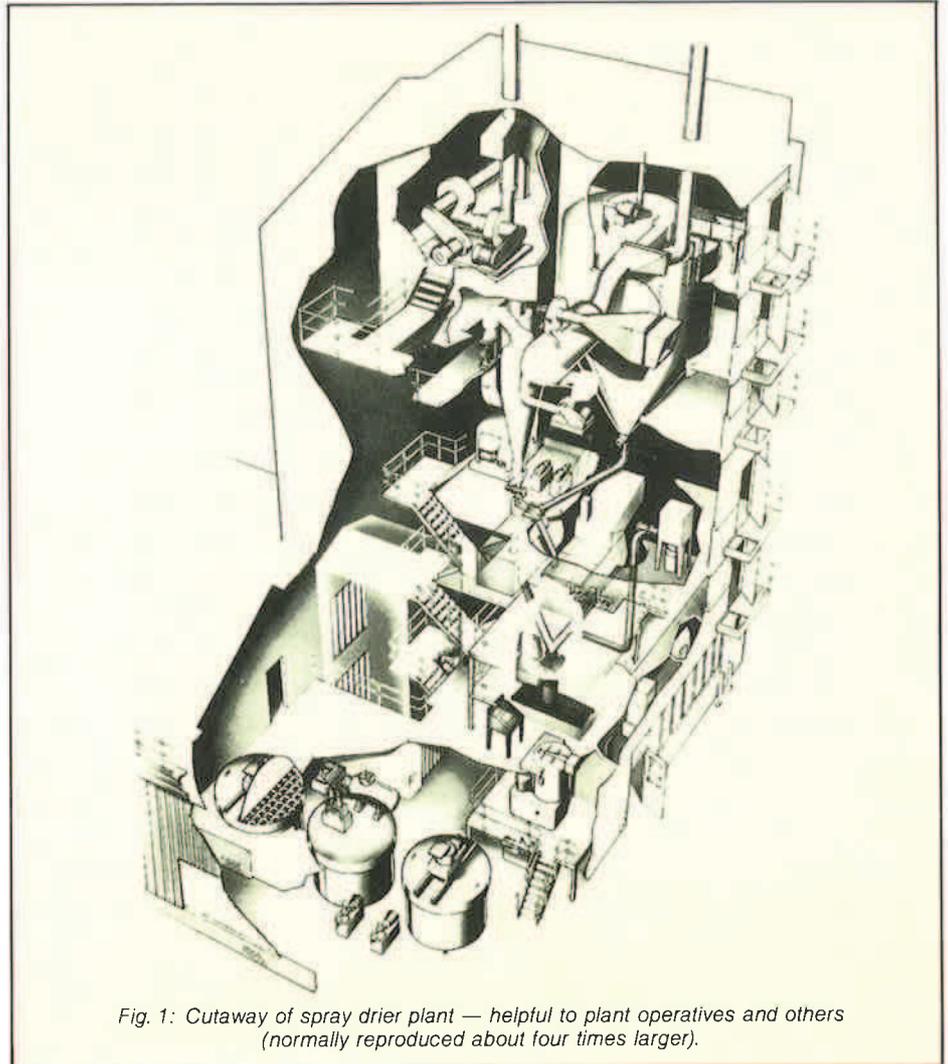
Fig. 1: Cutaway of spray drier plant — helpful to plant operatives and others (normally reproduced about four times larger).

The cost of good diagrams is high, and this is the main reason why they are rare. However, a drawing such as that in Figure 1 is of great help in explaining a proposed modification or a new safety system. It is particularly valuable when talking to government officials or worker representatives, or for training and familiarisation. A model, though ideal, costs far more; and if one exists it may not be portable.

Consider another instance. When a chemical plant breaks down there may be a costly loss of production or an unacceptable increase in hazard. Simple cutaway diagrams such as Figure 2 may help operators much more than a maintenance manual.

A recent task at the ICI 'Visqueen' Polythene Film Factory is one example of the benefits to be gained from clear documentation and presentation.

Technical and presentation skills were required to alleviate some operating problems with the refrigeration plant at the factory (see Fig. 3). The refrigeration plant comprises three 55 kW reciprocating compressors and uses R22 as the refrigerant. On compression, the refrigerant and lubricating oil mixture passes through an oil separation system, and then the gaseous refrigerant is liquefied at constant pressure in a condenser.

This liquid is expanded through an evaporator and the cold gas returned to the compressor suction. In the evaporator, heat is transferred from the circulating water glycol mixture returning from the factory. This mixture is water with 30% ethylene glycol and circulates around the factory providing process cooling.

The plant was custom designed by the manufacturer many years ago before the current plant engineers had joined the factory. The plant suffered recently from one major failure, the seizing and crankcase cracking of one of the three compressors, and several other system malfunctions. $17,000 was spent on maintenance in the last nine-month period. Due to inadequate documentation

STUFFING BOX ASSEMBLY FOR 8/9000 GALLON VESSELS
*Fig. 2: Annotated cutaway for maintenance
(normally reproduced about four times larger).*

*Fig. 3: VisQueen factory refrigeration plant, Deer Park, Victoria.*
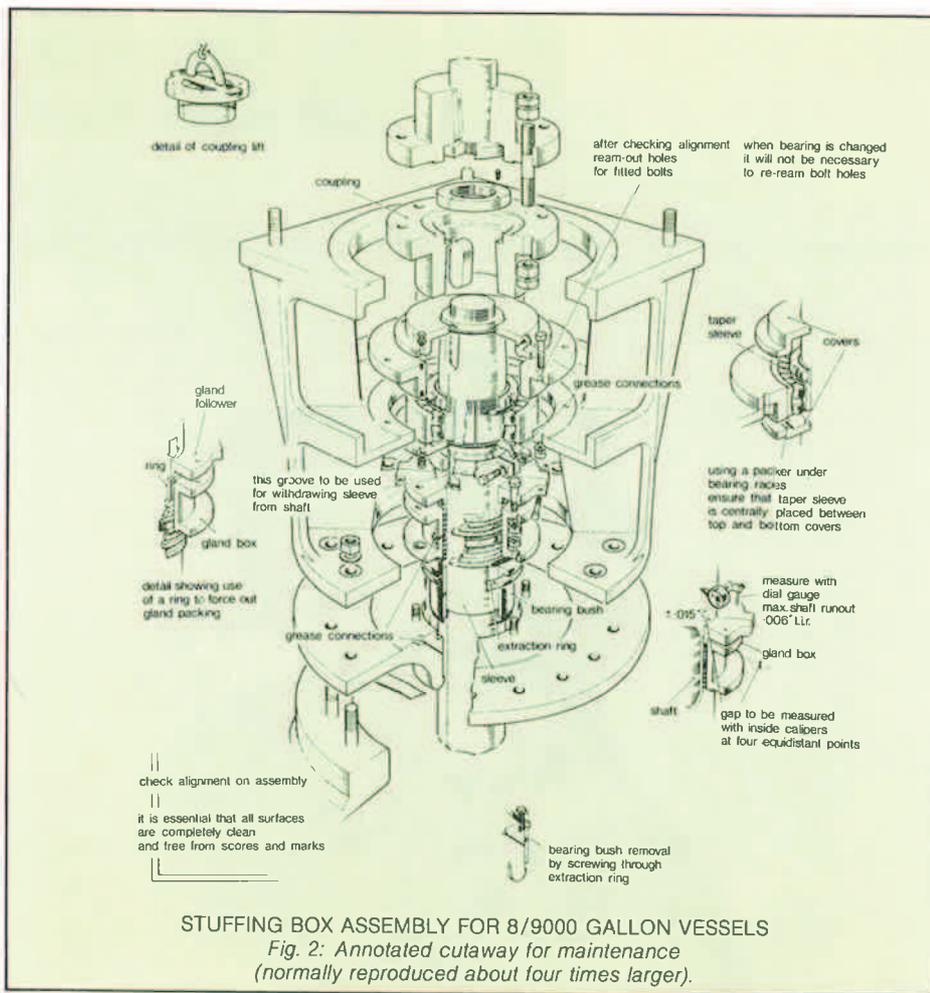
the plant engineers and the manufacturer's serviceman had limited understanding of the unit's principles of operation, and the process foreman's operational knowledge was minimal due to lack of training.

Two flowsheets were prepared; an engineering line diagram giving full system details, and a pictorial flowsheet, duly illustrated and coloured showing principles of operation (*see Fig. 4*). This pictorial was used for training, and a copy is on display near the unit for reference. A set of operating instructions and a trouble-shooting guide were prepared. All are incorporated in a plant manual. Two log sheets are in use — one for process on which entries are made once per shift, and the second for engineering, on which entries are made by the maintenance foreman once per week.

The process readings cover items that are affected by changes in factory load, ambient temperature, and sudden changes that could cause failure. The engineering readings cover longer term changes in load, slow deterioration and leaks, and instabilities of control system. For clarity, all gauges on the refrigeration plant are labelled and carry an identifying letter, which also appears on the pictorial flowsheet and log sheets.

This work has led to the increased reliability of the unit, better monitoring and control which has reduced the likelihood of catastrophic failure, and reduced fault finding and total maintenance time.
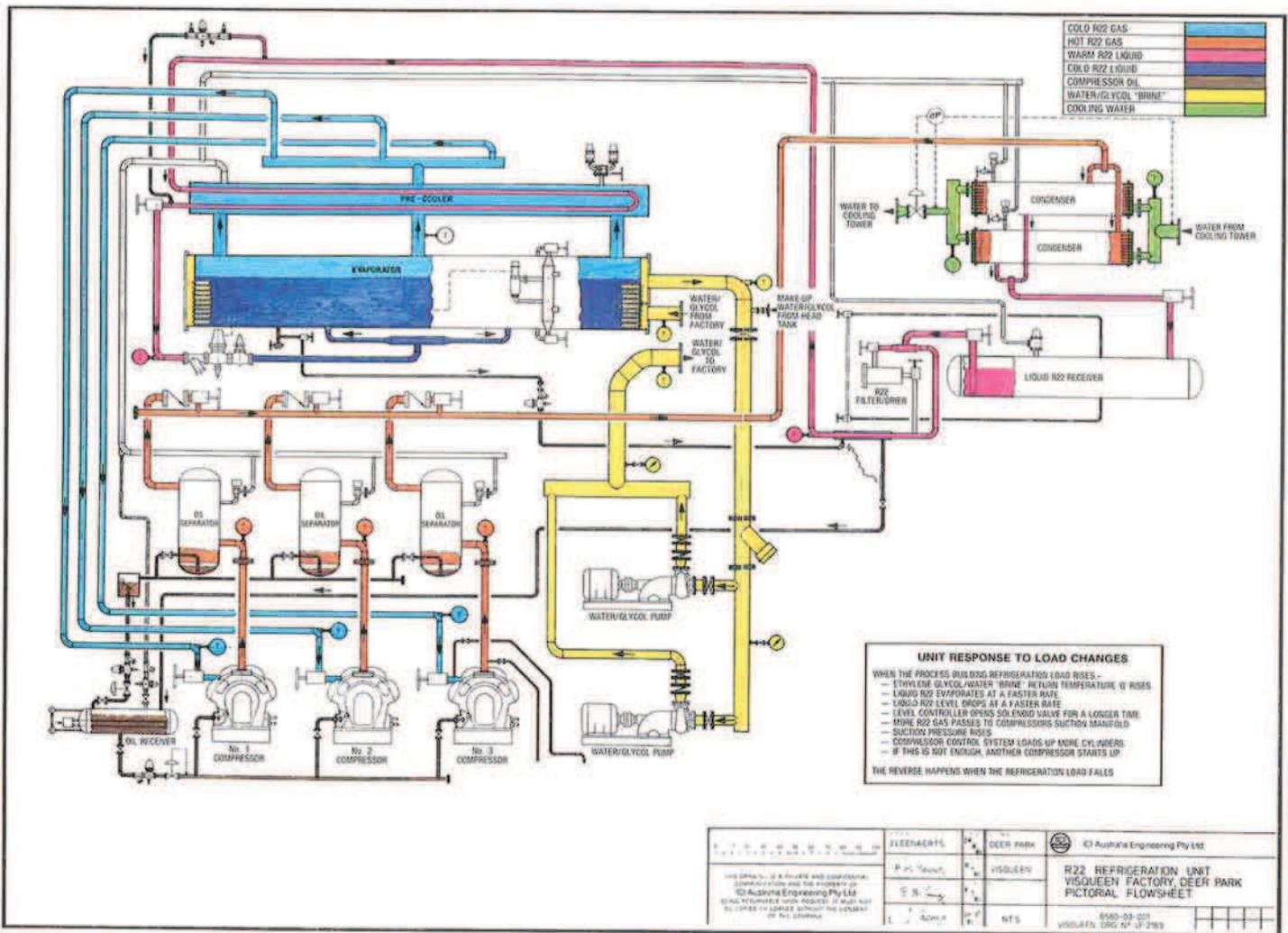
Fig. 4: Refrigeration plant pictorial flow-sheet.

Improved Process Control with Microcomputers
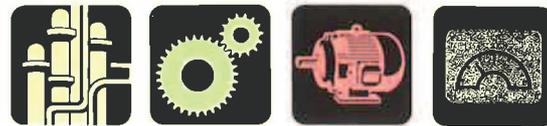
Micro-computers make routine decisions on how to run process plants more efficiently, and provide centralised information to operators.

The micro-computer industry is one of the fastest growing technologies in our world today. Its influence has spread to the process industries, with many classes of equipment now incorporating micro-processors, e.g. measuring instruments, data loggers and monitors, process controllers, general purpose calculators and computers, etc. As with any other new products available on the market, these devices must survive a period of growing acceptance by those who would supply, use and maintain them. A number of criteria must be worked through and satisfied: cost-effectiveness, dependability of supplier, reliability of the device in practice, and so on. A successful outcome of this introductory phase would be that today's avant-garde gadgetry would become tomorrow's conventional equipment.

The new micro-computer hardware, and associated software, have made possible new levels of sophistication in control concepts. These match the increased demands today for safety (process and environment), product quality, efficiency (material and energy), and also for information, duly condensed and interpreted. Aware of these developments, ICI Australia set up a Process Control Task Force to explore potential applications of micro-processors in the control of existing process plants. One such study is described in this article.

SWITCHING OFF AIR-CONDITIONING IN A FIBRES PLANT

This application is concerned with a scheme to minimise both electrical energy usage and cost of electrical energy in a plant producing nylon and terylene yarns.

Successful yarn production is critically dependent on close control of both the temperature and relative humidity in the various manufacturing zones. To achieve climatic control of these zones a large number of air-conditioning units comprising refrigeration units and fans are employed, and these constitute a significant proportion (23%) of the total factory electrical demand of

8 megawatts. There is scope, however, for switching off ome of the air-conditioning sets for short periods to save power while still maintaining adequate process operating conditions.

POWER USAGE AND POWER COSTS

The state electricity generating authorities charge on a commodity basis (quantity) and a monthly maximum demand basis (rate of consumption), this latter charge being to cover the capital cost of the installed generating capacity.

The maximum demand (MD) in Victoria is calculated on the basis of consecutive 15 minute periods. The highest rate of power consumption in any one of those periods fixes the MD charge for that month, irrespective of when it occurs during the month.

Tariffs at present are of the order of $10/MW commodity charge and $8/kW maximum demand charge, and the maximum demand charge in this fibres plant is typically as high as 60% of the total charge. Thus the strategy for operating the factory is to preset a feasible MD target at the beginning of the month and ensure this is not exceeded during the month.

The factory currently attempts to clip anticipated power demand peaks by shedding loads at appropriate times. It is not feasible to take spinning machines off-line, but air-conditioning sets can be switched off for limited periods. There are some 43 air-conditioners which are potential candidates for this exercise, totalling 1300 kW, and they range in size from about 5 kW to over 160 kW. The selection of factory zones to be switched off, however, is a complex procedure.

MD CONTROL —
THE OPERATING TASK

We found it useful, in formulating a particular process control problem, to write down in a straightforward manner: what is the control system trying to do; within what limits must the plant work; what factors or variables are available for exercising control; what perturbations or upsets are likely to be imposed on the plant? For the fibres factory the task was formulated as follows:

Objectives:
1. Do not exceed the monthly target MD figure.
2. Minimise the total power consumption at all times.

Constraints:
1. Spinning machines cannot be stopped to shed power load.
2. Stay within the tolerable ranges of relative humidity in the various factory

zones for satisfactory yarn production (typically 70% ± 10%).
3. There is a minimum running time after start-up of a fan motor, in order to cool it back to operating temperatures.
4. Temperature levels in the various zones must be satisfactory for both operator comfort and production conditions.

Controls:
1. Whichever air-conditioning sets are on, can be switched off.

Disturbances:
1. Current total factory demand.
2. Ambient temperature and humidity.

The usual starting point is to investigate how the current control system operates, whether it is effective, easy to use and understand, and so on. We found that an essentially manual system was in operation. A recording MD meter is located in the shift superintendent's office and this instrument records the cumulative factory power consumption during each standard quarter-hour period. If the trends shown by the recorder predict a surge in demand above the target MD, then manual action is taken to shed load by shutting down selected air-conditioning sets, at one or more local control panels, for short intervals of time — typically 15 minutes.

The decision process used to select the unit(s) to be shut down is based on operational priorities current at the time, subject to the various constraints above. The factors considered include the size of the load to be shed, the relative humidity "safety margin" available in the various zones (not centrally available), the time since the particular unit was last brought on-line and operator comfort. In fact, the safety margin is even more complicated — it depends on the capacity of adjacent zone conditioners to absorb the duty of the shutdown unit, the tolerance of the particular manufacturing process to accidental excursions outside the humidity limits and the current manufacturing schedule.

In an attempt to move towards some form of automatic MD control, the factory staff have developed a practical air-conditioner cycling programme which relies on some of the constraints above to define a fixed cycling schedule. Figure 1 shows a fragment of this programme in which selected units are switched off for a quarter of the time, using simple local timers. It suffers from the obvious limitation that it is inflexible and cannot take account of relative humidity feedback, or anticipate changes due to the manufacturing schedule. Furthermore, it would not attempt to minimise the total power consumption at all times. For this a dynamic switching algorithm provided by a micro-computer is needed.
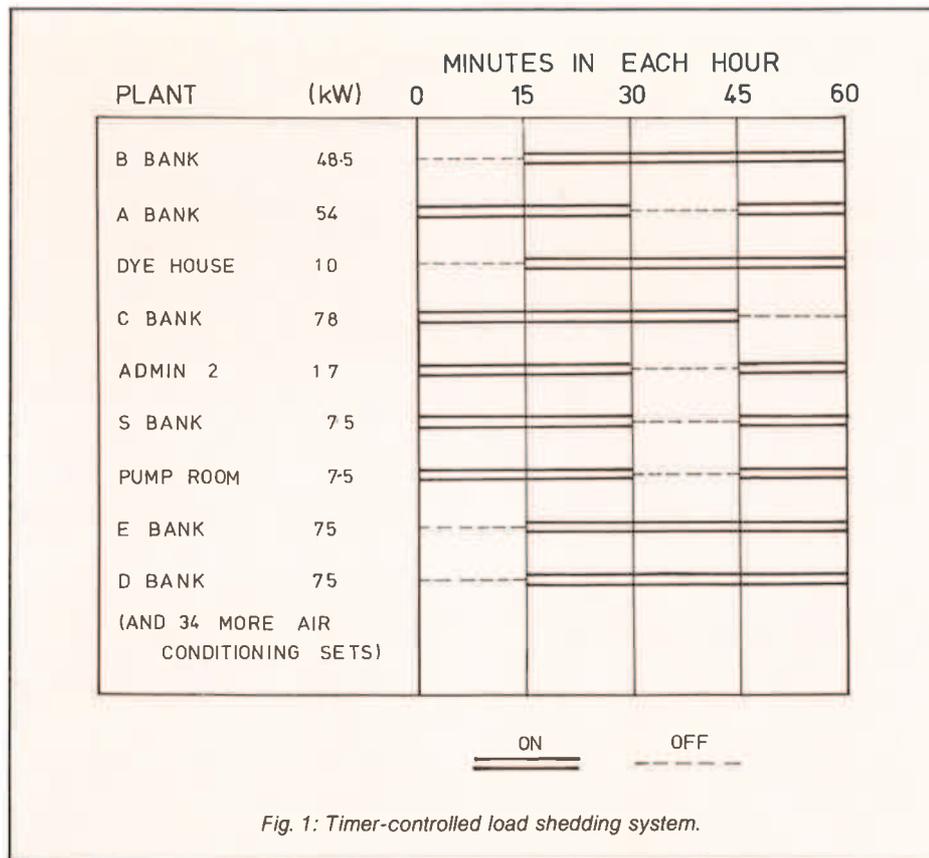
Fig. 1: Timer-controlled load shedding system.

PROPOSED MICRO-COMPUTER CONTROL SYSTEM

We proposed a micro-computer-based control system shown schematically in Fig. 2. The computer receives analogue input signals from relative humidity sensors located in the plant zones which are candidates for cycling control. It also receives an analogue input signal derived from the MD meter, and operator input through a console keyboard. It generates digital output signals which control motor status via 32 volt relays located in the remote control panels. Proving contracts on these relays are used to provide digital inputs confirming that the motor has switched on or off as desired. Standard failsafe procedures are adopted. The relays are wired so that in the event of computer failure, air-conditioning is assured under local control even if this should violate the MD target.

The operation of the system is under control of a computer programme that is "table-driven", which implies that the length of the table and the elements within it are flexible and easily altered. Initially a table of entries for each switchable air-conditioner is stored in the computer memory:

1. priority for the zone
2. actual (nameplate or equivalent) load for the unit
3. upper humidity limit
4. lower humidity limit
5. minimum on-time for the motors
6. maximum off-time for the motors
7. "exclusion factor"
8. other data, e.g. humidity tolerances.

Any or all of these entries can be altered through the operator keyboard at any time.

When the input signal from the MD meter predicts the need to shed load, the control algorithm scans the actual relative humidities in the various zones in decreasing order of operational priority (entry 1) to find the largest load it can shed (entry 2) which has the largest humidity safety margin (entries 3 & 4), a safe elapsed time since the motor was last started (entry 5), and is not temporarily excluded from consideration (entry 7). Loads are shed until the MD target is met, or there are no further feasible loads to shed.

During each scanning cycle (at intervals of, say, 1 minute), air-conditioning set motors are restarted if the humidity in a zone approaches a limit (i.e. is within the tolerance allowed), or the unit has been off for the maximum time (entry 6). The priority (entry 1), and exclusion factor (entry 7), allow the operator to inject his experience and knowledge of future operating conditions into the selection algorithm.

Obviously, dummy values could be inserted to make the system 'degenerate' to follow a simple duty cycling programme (as in *Figure 1*) by widening humidity limits such that they are ignored, and making all loads equal. A further extension would be to tune the system carefully to shed load at *any* time in a zone provided it met the relative humidity criteria, thus minimising the total power consumption. Some caution would be necessary in implementing such optimising control — because motors require a minimum running time for cooling, there may be insufficient switchable load to meet a sudden requirement for load shedding to constrain MD.
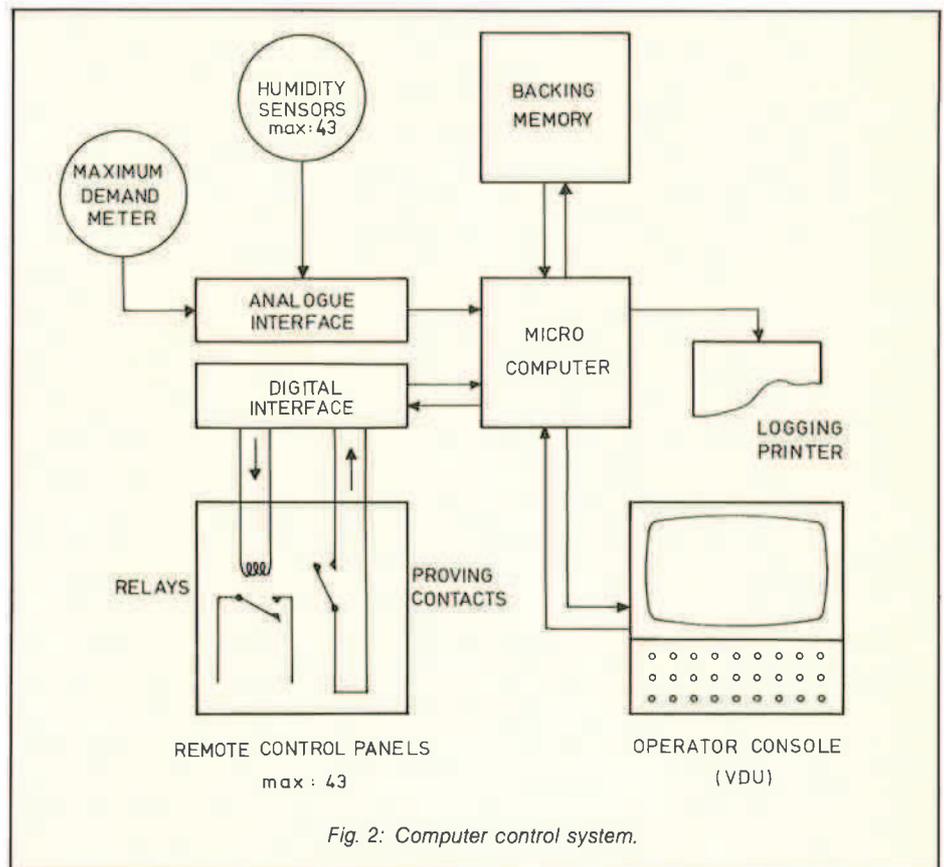

Fig. 2: Computer control system.

The proposed system provides additional spin-off benefits which include: regular and/or on-demand logs of humidity levels and motor status in all zones, and total power consumption; alarm logging of humidities; centralised remote starting/ stopping of air-conditioning sets; records of running hours of motors, for main-tenance purposes.

Since seeing is believing, we prepared a computer programme to simulate the behaviour of this aspect of the fibres plant. A subset of 15 air-conditioning sets provided the total demand and MD controls. Disturbances in spinning demand were allowed to occur randomly at 5-minute intervals. Zone relative humidities were assumed to alter linearly with time at selectable rates, the relative humidity falling when the set is off, and rising to the local controller set point when the set is on. The programme was written in interpreter BASIC, originally for the Motorola M6800, but transferred readily to Apple II for demonstration purposes, in 4K bytes (8-bit) for source text and data storage. The display showed the status of all 15 sets, the zone relative humidities and the current total demand relative to the MD target.

COSTS AND SAVINGS

All engineering projects in ICI Australia Ltd must be assessed for cost-effective-ness, and micro-computer systems are no exception. We found that the control system would cost some $50,000 and would save about $50,000 per annum, thus providing a payback of 1 year which is very reasonable. The cost includes a nominal $10,000 for the micro-computer with process interface, VDU and printer (e.g. Cromemco CS-2, with 2 floppy disc drives and 64K RAM thus allowing for considerable data storage); $20,000 for 43 humidity sensors and amplifiers, installed; $12,000 for software develop-ment and implementation (including documentation), and overall project management. The somewhat surprising point we note is how low a proportion of the cost is attributable to the computer hardware — it is the software, labour, and the field instruments and installation which dominate.

CONCLUSION

What has proven interesting about this application is the fact that its nature tended to change as we delved more deeply into the problem. It appeared at first to be a logic device to make decisions on how to avoid overshooting the factory MD target. It ended up as a process control system maintaining averaging control of humidity in 43 zones (based on the fact that excess air-conditioning capacity exists), with an accompanying objective of minimising factory power consumption charges.

Application of Computers to Site Co-ordination

Complex interactions between chemical plants on Botany Site are co-ordinated with the assistance of computer aids.

The ICI Australia Ltd Botany works is a large chemical complex comprising more than eleven plants interacting through the transfer of intermediate chemicals, steam and electricity (see *Fig. 1*). The key intermediate chemicals are ethylene, chlorine, propylene, ethylene dichloride, hydrochloric acid, and vinyl chloride monomer. Storage is available, but since capacity is limited, it is necessary to co-ordinate production rates so that stocks are within acceptable limits and all plants operate in harmony.

Efficient operation of the site depends upon effective co-ordination of steam and electricity usage. The cost of electricity at Botany is dependent on maximum overall demand taken during any half hour in each month, so action is necessary to co-ordinate usage so that all plants do not require high demands at the same time. Steam is provided at four different pressures. Most is generated at 6.2 MPa at the steam and power plant, and letdown to distribution pressure through turboalternators. Flexibility in the operation of these machines can be used to help control maximum demand for electricity.

DECISION-MAKING SYSTEM

To simplify operation of the site, the plants are organised into four groups, each with its own management and operating objectives. An attempt is made to co-ordinate these objectives by the joint development of quarterly production targets. This forms the first of three levels of co-ordination (see *Fig. 2*). The second level involves the daily co-ordination of plant operations. The third is responsible for controlling the maximum demand for electricity.

Computer aids have been developed to assist at all levels of decision-making. A linear programming model is used to help decide quarterly plans. This determines the optimum allocation of intermediate chemicals between competing users, and the cost of deviating from this plan. At the daily co-ordination level, an interactive decision-making aid has been developed to enable planners to quickly explore the repercussions of following alternative courses of action in the short term. At the lowest level, a micro-computer is used to continually monitor electricity demands
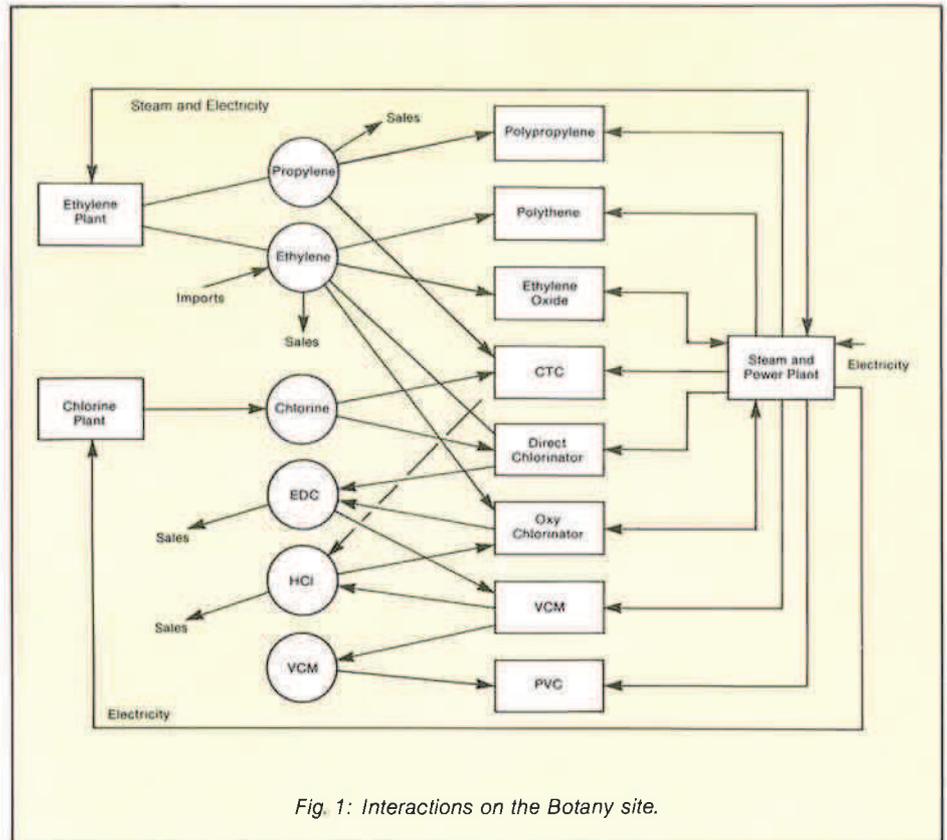

Fig. 1: Interactions on the Botany site.
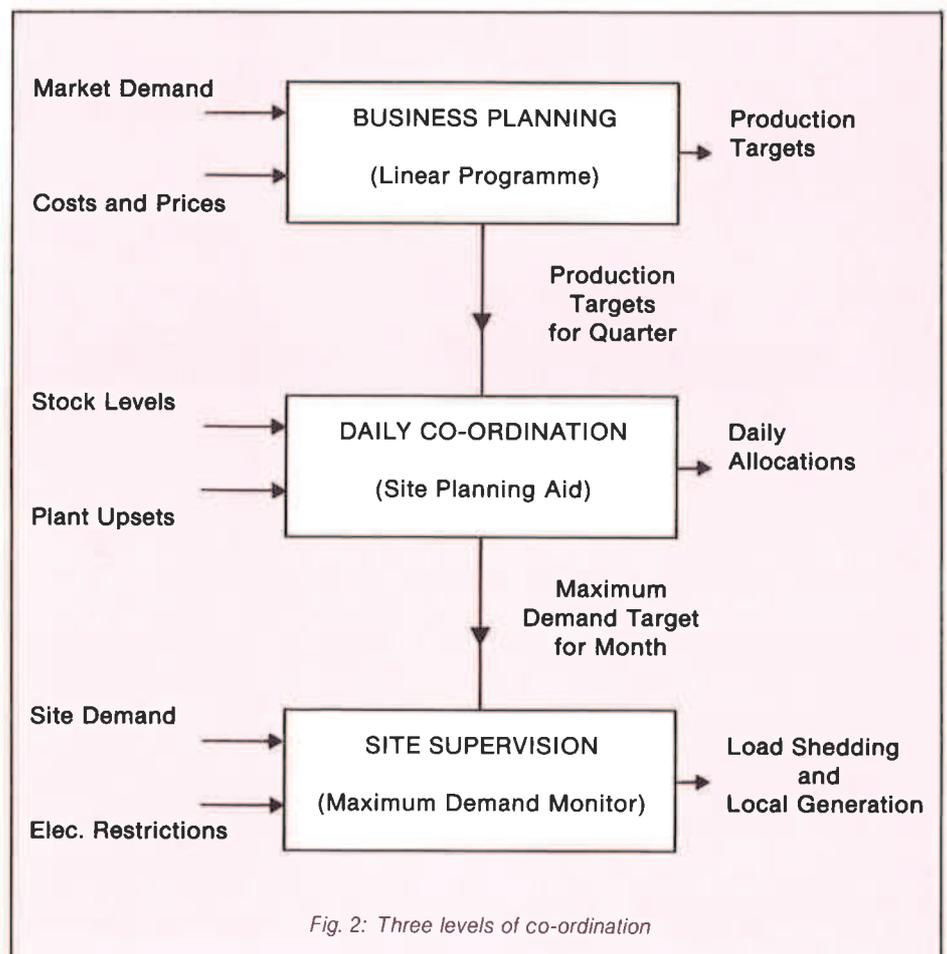
Fig. 2: Three levels of co-ordination

and display information to help control maximum demands.

BUSINESS PLANNING MODEL
The linear programming model used for medium-term business planning is operated in Melbourne on the company's IBM 370 computer. The model is continually updated so it reflects current marketing information and data on plant characteristics and shutdown plans. Considerable skill has been developed in using the model and presenting its results, so that managers automatically refer to it before making decisions which affect interactions on the site.

SITE PLANNING AID
The interactive decision-making aid used for daily co-ordination is shown in Fig. 3. This is operated on an Intecolor micro-computer which is run as a terminal to the Botany site PDP 11/70 computer. Information on the daily production plans over the next few weeks is presented on the screen of a large colour visual display unit using a simple colour code. This enables a large amount of information to be displayed, whilst still highlighting the important information. To explore the effect of changes to the plan, the site planner points to the appropriate part of the screen using a light pen. Within seconds the computer calculates the effect on stock levels, production targets and energy usage, and updates the display. This makes it easy for planners to explore several alternative courses of action and consider their complex inter-action on the site, before implementing the plans.

This computer aid incorporates the latest technology in interactive decision-making and was the earliest of its type in Australia. The system was both designed and programmed within ICI Australia.

A by-product of this planning aid is its ability to predict how electricity demands are expected to vary day by day over the next month. This helps to set a maximum demand target for the coming month, and to explore appropriate actions for avoiding demand peaks. This information is used in the Maximum Demand Monitor described below.

MAXIMUM DEMAND MONITOR
A micro-computer is used to monitor electricity demands in the same manner used by the electricity authority for calculating demand charges. It calculates the rolling half-hour average demand and compares this with the maximum so far achieved in the calendar month. This information is output on a visual display unit in the steam and power plant control room as shown in Figure 4. The graph updates the half-hour average demand changes each five minutes and shows how close it is to the previous maximum demand and target level. This visually indicates when action is required and alerts operators to act promptly.

Fig. 3: Site planning aid.

Fig. 4: Maximum demand monitor.

Plant Shutdowns

Plant shutdowns are often the most active times on a chemical plant providing engineers with the opportunity to implement plant modifications and maintenance work.

The polypropylene plant is one of a number of petrochemical plants at ICI's Botany chemical complex that receive their primary feedstock from the site Olefines plant. In October 1981, both the Polypropylene and Olefines plants shutdown primarily for their statutory pressure vessel inspection. The Polypropylene plant came off line on October 3 and re-started on October 22, a total of 20 days off line. During that period, there were 350 extra people on the factory site. Trades represented included mechanical, electrical and instrument fitters, iron workers, welders qualified to Department of Industrial Relations (DIR) standards, laggers, riggers, scaffolders, high pressure water wash crews and cleaners.

The prime purpose of the shutdown was to inspect internally all 280 registered pressure vessels. In addition to this the opportunity was taken to implement a considerable programme of machine maintenance, both mechanical and electrical, as well as welding modifications.

PREPARATION

Initial planning for the Polypropylene plant shutdown started in 1980 with the preparation of pressure vessel, machine, electrical and instrument (E & I) workscopes. Preparation of a workscope involves: (1) the detailed breakdown of each job into specific tasks; (2) identifying the manpower and equipment requirements for each task; (3) scheduling tasks in the order that they need to be undertaken. In March 1981, final preparation began in earnest, priority being fiven to the finalisation of the E & I workscopes and generation of a workscope for process pipelines, welding modifications and repairs (line breaks).

The first task in the outstanding work for the pressure vessel shumponent consisted of preparation of a pressure vessel gasket register and the subsequent purchase of the gaskets. Upon delivery the gaskets were compiled into kit form, identified by vessel plant equipment number, and placed in the shutdown store.

In addition to the vessel gaskets, kits were prepared for the relief valve gaskets, bursting discs, slipplates, and associated slipplate gaskets. Identification was achieved by tagging the kits and the plant location to ensure correct replacement during the shutdown by contract fitters.

Workscope definition for line breaks proved to be a monumental task. Several major capital projects had to be included for plant reliability and safety. In addition, maintenance welding jobs repeatedly surfaced as October approached and these had to be scheduled in also, e.g. repair of welded-in valves and modification of lines prone to blockage. This type of last minute but necessary work, placed a considerable strain on the factory's engineering resources and created significant problems in materials supply. In fact, due to the changing priorities of the developing plan, the workscope was not finalised until the end of August.

In April, workscope and shutdown time constraint information to date was used to generate the first estimate of the daily manpower requirements (resource profile) with the aid of a computer programme.

RESOURCE PROFILE

In essence, the resource profile (*see Table 1*) was a daily list of the personnel, by trade classification, required to complete the shutdown in the alloted time. It was recognised in April that the profile would change as the final line break workscope was added, but nevertheless, it was good enough for the first approach by ICI Australia Engineering Contracts Section to look for suitable contracting firms to be the prime contractor.

The final optimisation exercise for the resource profile was done in late August. Several changes resulted from the inclusion of some additional tasks, and a change in the shutdown date to bring it forward by two weeks corresponding to a similar change in the Olefines shutdown timing. The expected profile changes in the areas of riggers, scaffolders, welders and pre-shutdown scaffolding were catered for in the remaining available time before October.

Selection of a prime contractor took several months and was based on the supply and management of:

(a) all mechanical fitting and trades assistant labour;

(b) appropriate sub-contractors for rigging, scaffolding, lagging, water wash, craneage, and transport.

Another significant factor which ultimately determined the final selection was the quality of labour available from each contractor, particularly machine fitting labour. The Polypropylene factory has a preponderance of mechnical machinery and a substantial portion was scheduled for maintenance work during the shutdown. It was essential to obtain good quality labour for the machine work to ensure a smooth and timely plant start-up and subsequent machine reliability. The problem was compounded by the drain on available resources due to the concurrent Olefines shutdown.

Provision of the site establishment was another major task undertaken by factory personnel. Using the resource profile and in consultation with the Employers' Federation concerning acceptable accommodation standards, the equipment and huts for the site establishment were finalised. There were approximately 25 huts on site which had to be located, supplied with power, drinking water and furnished.

Additional ablution facilities to that which the factory already had were also necessary. This task was placed in the hands of one person whose job it was to set up the site in the minimum time prior to the shutdown and then demobilise it as soon as possible after the shutdown.

Negotiations between the factory, Department of Industrial Relations, and Boiler Inspectors, were opened at an early date. The vessel inspection program was placed in the hands of one person. It was his responsibility to organise the daily vessel inspection program so that there was a representative of either the Department of Industrial Relations or Boiler Inspectors, plus a factory engineering representative at each and every vessel inspection. He also had to allow for any changes in the program due to changes in priorities — fortunately there were few.

It was essential that this operation went smoothly as it represented the prime justification for the shutdown. The responsible person had a total list of vessels to be inspected plus a daily list which was altered as priorities changed. He also had to liaise with process staff to ensure the smooth issuing of clearances, particularly confined space clearances, and that the necessary gear for entry was pre-prepared and waiting at the vessel site. Attention to detail in this operation paid handsome dividends in getting the job done smoothly and in public relations with the statutory and inspection representatives.

Process personnel were also heavily commited with the shutdown preparations. Once the resource profile was

finalised, all clearances for every job had to be pre-written and organisation charts had to be drawn up for the three phases of the shutdown. These were:

1. Shutdown/degassing period.
2. Maintenance period.
3. Start-up.

In addition, all equipment had to be identified by either plant equipment number, pressure relief valve tag, or line break tag.

Pre-shutdown scaffolding started in September and was executed by the rigging and scaffolding sub-contractor. Particular attention was required on this job as the plant was on line. All the scaffolding was pre-designed so that it would not interfere with the safe running of the plant.

Security of scaffolding materials was ensured by the use of a scaffolding store and special gate security measures.

ORGANISATION

The organisation chart (see Table 2) is somewhat complex, but experience has shown that it worked well. I will only

Table 1: Resource Profile showing detailed manpower breakdown required during shutdown.

Trade: Day Duration: Day No.:	3/10 Sat. 8 1	Sun 8 2	M 10 3	T 10 4	W 10 5	T 10 6	F 10 7	S 8 8	Sun 8 9	M 10 10	T 10 11	W 10 12	T 10 13	F 10 14	S 8 15	Sun 8 16	M 10 17	T 10 18	W 10 19	(22/10) T 10 20	Total Hours
Iron Worker AA-AE/AM	2	4	3	55	56	57	57	57	2	56	55	55	52	45	45	2	21	3	–	–	6,046
Iron Worker Inst. (Mech) A1	–	–	–	3	3	3	3	3	–	3	3	3	3	3	2	–	–	–	–	–	310
Iron Worker Inst. Fitter Asst. IA	–	1	–	5	5	5	5	5	–	5	5	5	5	4	3	–	1	1	–	–	532
Iron Worker Pool A	–	–	–	9	9	9	9	9	–	9	9	9	9	9	9	–	–	–	–	–	954
Iron Worker Pool A (Shift)	7 shifts 12 hrs 5 men 7am-7pm-7am					10 Night shifts 10 hours 5 men No Sunday Shift										11 shifts 12 hrs 5 men 7am-7pm-7am					1,320
Total Iron workers excl. Shift Cover	2	5	3	72	73	74	74	74	2	73	72	72	69	61	59	2	22	4	–	–	9,162
Fitter FA-FE	2	2	1	36	36	36	36	36	2	36	35	35	35	27	27	–	17	–	–	–	3,852
Fitter Inst. (Mech.) F1	–	–	–	3	3	3	3	3	–	3	3	3	3	2	2	–	–	–	–	–	300
Fitter Machine FM	–	2	2	18	18	19	19	19	–	19	19	19	16	16	16	4	4	3	–	–	2,048
Pipe Fabricator Fitter Pool F	–	–	–	9	9	9	9	9	–	9	9	9	9	9	9	–	–	–	–	–	954
Fitter Pool F (Shift)	7 shifts 12 hrs 5 men 7am-7pm-7am					10 Night shifts 10 hours 5 men No Sunday Shift										11 shifts 12 hrs 5 men 7am-7pm-7am					1,320
Total Fitters excl. Shift cover	2	4	3	66	66	67	67	67	2	67	66	66	63	54	54	4	21	3	–	–	8,474
Rigger Machine RM	–	1	1	9	9	9	9	9	–	9	9	9	9	7	7	–	5	3	–	–	1,016
Scaffolder S	–	9	15	21	21	21	21	21	–	21	21	21	21	18	18	12	19	3	–	–	2,710
Rigger R	–	–	–	20	20	20	20	20	–	20	20	20	20	9	4	–	–	–	–	–	1,882
Rigger R Shift Cover	7 shifts 12 hrs 3 men 7am-7pm-7am					10 Night Shifts 10 hrs 2 men No Sunday Shift										11 shifts 12 hrs 3 men 7am-7pm-7am					848
Lagger L	–	–	6	12	12	12	12	12	–	12	12	12	12	10	10	–	–	–	–	–	1,296
Lagger L Shift Cover	7 shifts 12 hrs 2 men 7am-7pm-7am															11 shifts 12 hrs 3 men 7am-7pm-7am					546
Painter PT	–	–	–	–	–	–	1	1	–	–	2	2	2	2	2	–	1	–	–	–	126
Contract Cleaner CL	–	5	5	16	16	16	16	16	–	16	16	16	16	10	10	–	–	–	–	–	1,678
Contract Cleaner CL (Shift cover)																11 shifts 12 hrs 2 men 7am-7pm-7am					264
TOTAL TRADES EXCL. SHIFT	4	24	33	216	217	220	220	219	4	218	218	218	212	171	164	18	68	13	–	–	10,366

Supervisors:				Additional:			GRAND TOTAL:	28,002
	General Fitting	—	5					
	Machine Fitting	—	2	(Leading hands)				
	Night Shift Fitting	—	1					
	(All Areas)			Storemen	—	2		
	Scaffolding	—	1	+ 2 Leading hands	Nippers	—	3	
	Rigging	—	1		First Aid Man	—	1	
	Lagging/painting	—	1		Safety Officer	—	1	
	Transport	—	1	(Leading hand)				
	Cleaning	—	1					

highlight some of the more important functions.

The man in the hot-seat is obviously the Shutdown Manager, and his success depends on good preparation and the competence of the people he manages. It is essential that the Manager does not get embroiled in the day-to-day prolems of the shutdown — he must be able to step back and watch. This was achieved during the shutdown with the help of the Maintenance Co-ordinator. This person was carefully selected, based on past shutdown experience, and also Botany site experience. The day-to-day problems are his responsibility and he must keep tabs on job progress and be able to deploy labour where needed. A close liaison is necessary between the Maintenance Co-ordinator and Contractor Manager to ensure job continuity.

The Planning Manager is also a very important person. Initially he was deeply involved in the setting of priorities, and his remit during the shutdown was to receive an update on the day's progress each afternoon and then feed the data back to the computer each night. The end result was a revised work programme and resource profile early each morning on the following day. Information received in the daily update from the appropriate supervisors was used to determine the shutdown progress and ensure adherence to the time schedule. Appropriate priorities were re-set whenever a problem arose.

Polypropylene factory's two mechanical foremen filled the Machine Supervisors'

positions with a contract foreman working for each. Good quality supervision plus high calibre tradesmen supplied by the prime contractor paid handsome dividends in machine reliability at and after start-up.

The line break supervisor was also a factory employee, in fact, the same person who did the spooling preparation for the shutdown. The combination of preparation and installation resulted in the line breaks being finished on time.

Two weeks before the shutdown, all supervisors, both contract and factory, started a two-week training course run by factory engineering personnel. Major points covered were: safety; plant areas and services; familiarisation with plant equipment; understanding of the computer resource profile printouts; procedures for daily updating; engineering method sheets for particular jobs — mainly machines; interaction of services, e.g. rigging, scaffolding and lagging; vessel, machine and line break workscope; site conditions; location and care of stores items; procedures for slipplates and pressure relief valve/bursting disc procedures.

These two weeks proved invaluable as each contract supervisor became familiar with his workscope and the plant in general. He was also able to make his own assessment of job preparation, tools, and equipment and make recommendations when needed.

Included in the two weeks was an address to all shutdown management regarding Industrial Relations by repre-

sentatives of the Empoyers' Federation and the ICI Australia Engineering Contracts section. The last-minute details on working conditions and pay arrangements were finalised at this meeting.

SHUTDOWN
The shutdown degassing period started on schedule. Labour allocation was found to be slightly low due to the fitters' lack of plant knowledge, however, with a small resources increase, the exercise went well and the plant was ready for the main workforce on Tuesday, October 6.

The first week went very well, in fact, we were slightly ahead of plan. Site facilities proved adequate, the vessel inspection was going well with only minor problems found in one or two vessels. The power off day on October 11, went without a hitch with power available on the following Monday. Towards the end of the first week, extra unplanned work, mainly cleaning, was starting to creep in. Problems were also becoming evident in the rigging and scaffolding camp concerning industrial relations and equipment supply.

The second week saw further good progress. There were difficult periods at the end of the shutdown when delays were experienced in testing machines and instruments. Industrial problems continued throughout the second week.

However, in spite of the last-minute problems, which it seems always arise, the start-up was on time and the plant was able to receive its full complement of feedstock once the Olefines plant was up and running.
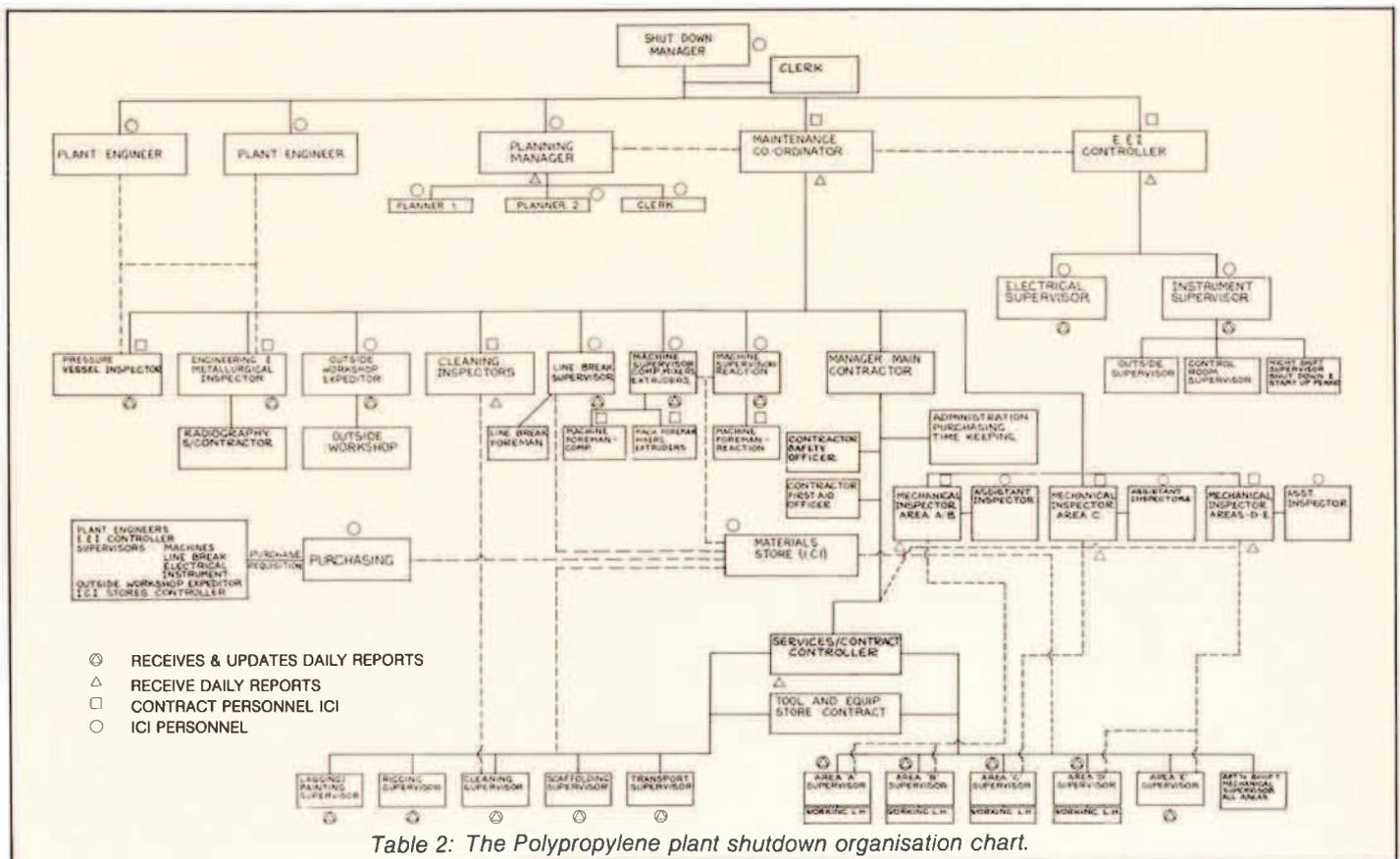
Table 2: The Polypropylene plant shutdown organisation chart.

Inspection Platforms for Large Vessels
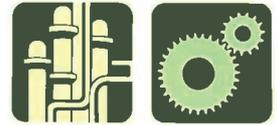
The inspection platform for a large vessel had to be designed to fit through a manhole half a metre wide.

Fig. 1: Alternative layouts for radial arms.

INTRODUCTION
ICI Australia operates a number of process vessels having the shape of a vertical cylinder. The walls are in highly-polished stainless steel, and require detailed inspection at regular intervals. The only access is via a central manhole at the top, with an internal diameter about 500 mm.

Erection and removal of fixed scaffolding to allow inspection would be very time-consuming, and would entail a considerable risk of scratching the internal walls. The interesting mechanical design problem therefore arose, of how to provide a suitable suspended, folding platform which could be lowered through the manhole and then opened out to within 75 mm or so of the walls. Clearly a structure resembling an inverted umbrella would be required.

CONCEPTUAL DESIGN
There were various quite severe geometric restraints to be considered. Apart from an obvious diameter limitation on the folded assembly, the overall height was governed by a maximum distance between manhole flange and platform lifting hoist hook of about 3500 mm. The hoist capacity of 2 tonnes was ample, but the platform itself had to be good for about 5 kg f/m² everywhere plus a point load of 115 kg anywhere plus 500 kg on the vessel centreline plus structure self-weight. Proper means of access to the platform would be required, once it had been lowered into the vessel and unfolded. The angle of tilt, assuming the 115 kg point load were applied at the platform edge, should be preferably less than 5° and certainly below 10°.

Preliminary layouts indicated that there were two key factors. Firstly, the platform suspension could not coincide with the vessel centreline, because there had to be personnel access between support rope and one side of the manhole. A minimum offset of 90 mm would be essential. Secondly, the number (n) and width of the "umbrella" radial arms would be in direct conflict. Layouts for 6, 8 and 10 arms are shown in Fig. 1, from which it will be noted that the arms plus any allowance for hinges must form (when folded) a polygon fitting entirely within the manhole circle. Also, the arms must have
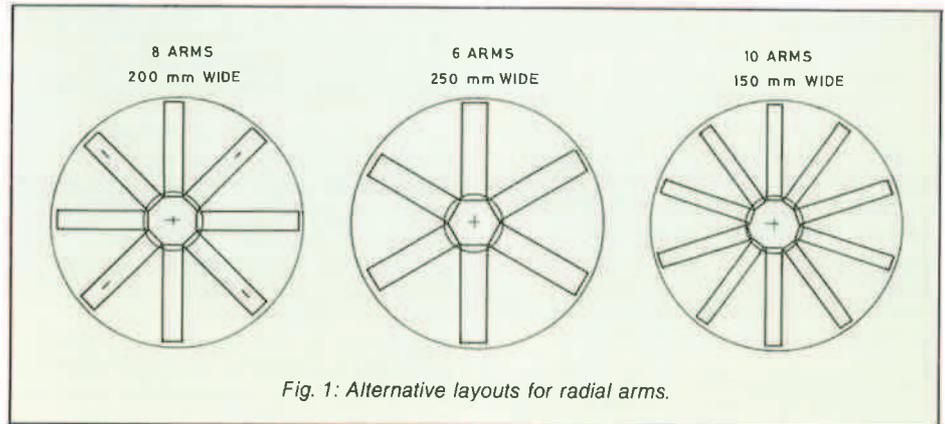
enough strength in bending to take the design load, i.e. the second moment of area of each arm section must be adequate, and in practice it would have to be accommodated between the polygon and the circle. In order to minimise the section area, it was decided to make the arms from folded stainless steel strip, 3 mm thick, for which the allowable design stress is 2.7 MPa (18 700 lb/in²).

DETAILS
Any arm must be able to support $\frac{1}{n}$ times the distributed load, plus all the point load at its far end, acting as a cantilever. More arms means a somewhat lower load per arm, but a much smaller practicable second moment of area, and vice-versa. A further complication is that the space between arms has somehow to be filled

in, with a proper load-bearing surface. A fabric as for an umbrella, however strong, would not suffice. Finally, there had to be means to ensure that the arms would fold and unfold without fail, by means controlled from outside the vessel.

It was evident from further layouts that the only feasible geometry involved 8 arms, joined by triangular hinged plates extending out to rather more than half the vessel radius. the remaining areas would have to be filled with removable plates resting on the radial arms. These could be placed in position after unfolding the main structure, which had adequate area to allow this work in reasonable safety. (Whoever did this would have to wear a normal safety harness.) Four of the plates would need to be hinged so that they could be passed through the manhole. *See Figs. 2 and 3.*
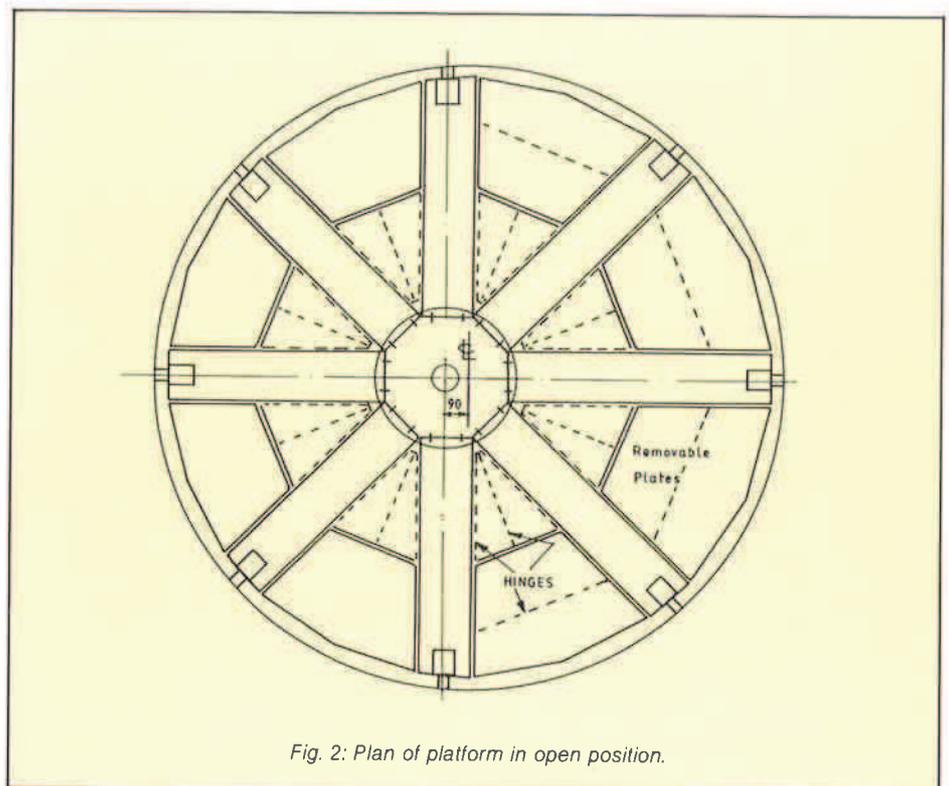

Fig. 2: Plan of platform in open position.

ACTUATION

Several devices for folding and unfolding were considered. Separate hydraulic or pneumatic cylinders for each arm were impracticable because, in the folded configuration, they did not provide a positive lock and there was hardly enough space available anyway. The final solution was a single, central pneumatic cylinder connected via 8 lenghts of chain to the outer ends of the folding triangular plates. These afford a positive folding force at all times; initial unfolding requires a fairly heavy spring at each arm, and final unfolding is assisted by gravity. The removable filler plates have tabs fitting into the triangular plates, which prevent inadvertent folding of the platform while in actual use.

Two other details should be mentioned. The structure includes a built-in ladder so that access is possible while the platform is near the top of the vessel and having its filler plates fitted or removed. Also, some means of preventing platform sway (and damage to the vessel walls) is essential. Each arm is therefore provided with a spring-loaded nylon roller at its outer end. See Fig. 4.

The platform design was considerably assisted by the making of a 1:2.5 wooden model, shown in Fig. 5; Figure 6 shows the platform itself.

Fig. 3: Section through radial arm.
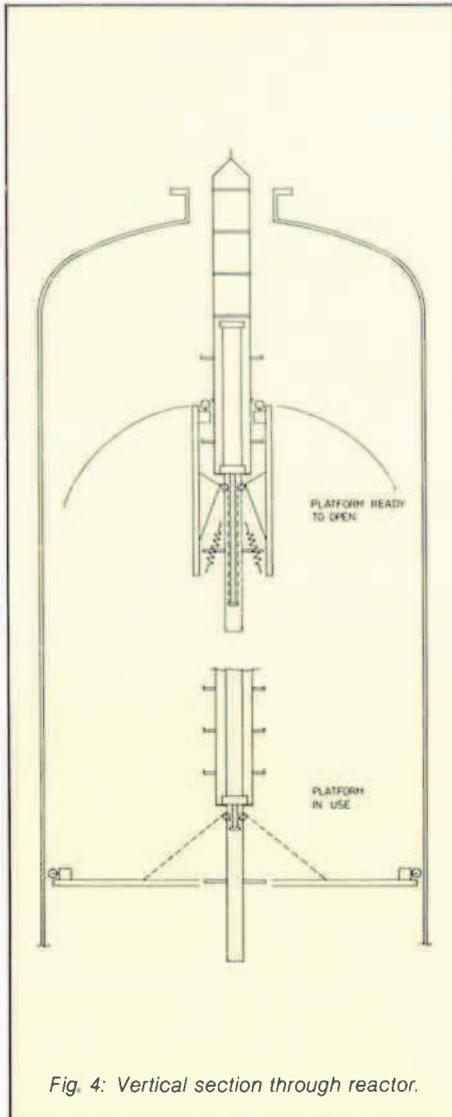
Fig. 4: Vertical section through reactor.
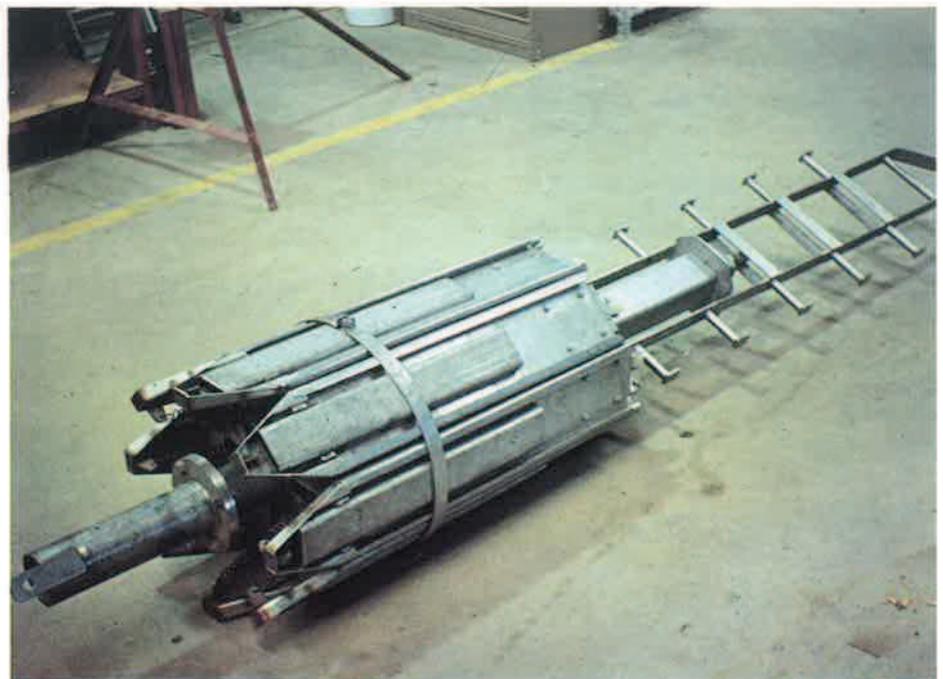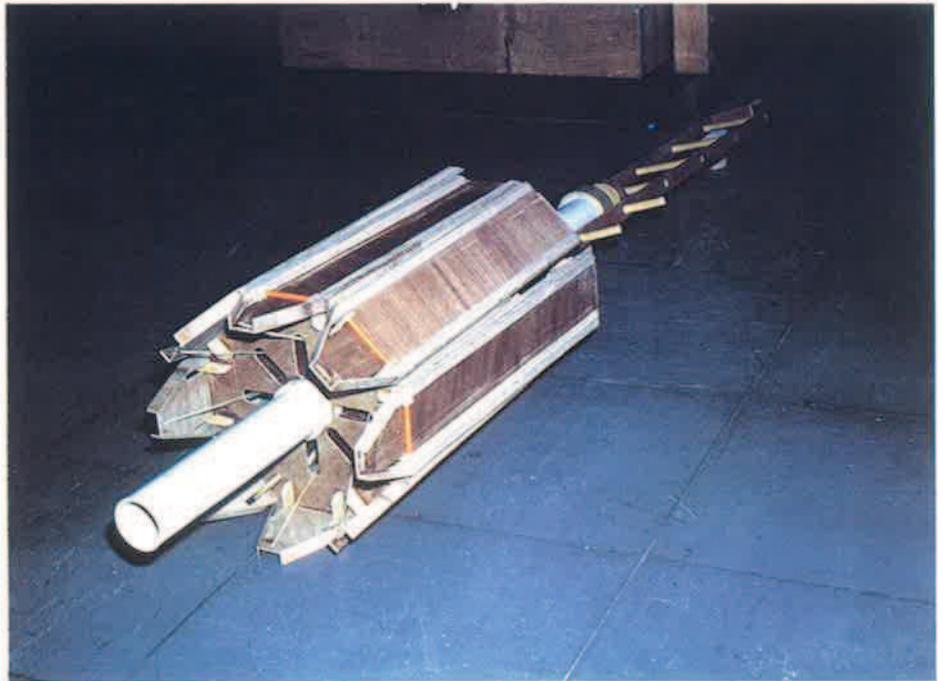
Fig. 6: The finished platform.

Compressor Malfunction Diagnosis Using Vibration and Position Monitoring

Appropriate continuous monitoring equipment is needed for checking vibration performance of major machinery on single stream petro-chemical plant.

Vibration performance of major machinery on single stream petro-chemical plants and the provision of appropriate continuous monitoring equipment is a far cry from merely checking the machine during start-up using a portable vibration meter. This was the state-of-the-art in 1966 when ICI Australia's Olefines 1 plant was built. In 1978 the machines on this plant were "retro-fitted" with fixed vibration sensing probes with control room readout at a cost of $90,000. This equipment has provided an indication of imminent trouble — in the case of the Ethylene compressor, an incorrectly installed bearing retainer, in the case of the Feed Gas gas compressor, damage to a coupling between gearbox and a compressor casing.

Potentionally, the savings by having such advance warning, by detection of small changes in machine vibration, is the time associated with fixing a simple problem or defective item instead of a significantly damaged machine; thus significant and costly plant downtime can be avoided.

For the new Olefines 2 plant, a vibration measurement system was specified as part of the machinery supplier's delivery, and associated diagnostic equipment is being purchased. Attention was also given to vendor's calculations of machine critical speeds and foundation natural frequencies. The turbines and centrifugal compressors at Olefines 2 run at speeds up to 10 000 rpm, have many rotors weighing over one tonne with bearing spans around 3 metres and in 100-200 mm diameter bearings of several different designs.

MACHINE VIBRATION

In operation, the machine casings may deform under the influence of temperature, inside pressure and movement of connecting piping. There are 'overhung' couplings with torque transmission friction. There are intermittent forces due to turbine blading, governor drives and compressor impeller vanes. Dirty oil, steam and gas can result in bearing damage and solids adhesion, corrosion or erosion to rotors. These factors, plus critical speeds, seal friction and loosened components (perhaps,
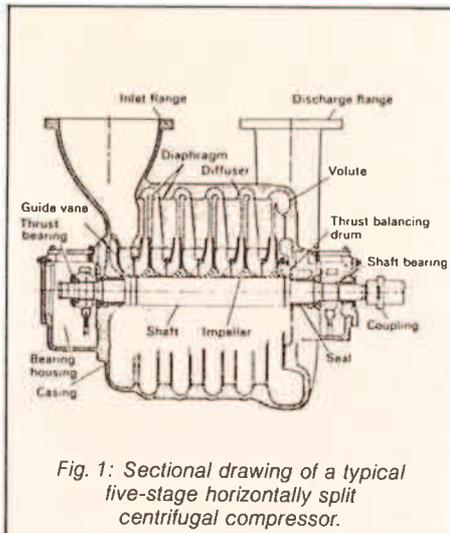
Fig. 1: Sectional drawing of a typical five-stage horizontally split centrifugal compressor.

caused by excessive vibration) all produce a pattern of vibration which can be measured.

A rotor (Fig. 1), can be represented by a number of masses on a shaft of certain stiffness (spring rate) running between bearings of known span. In a given operating speed range the above arrangement will deform elastically, the shape and frequency of change being a function of:

(i) the mass-stiffness arrangement,

(ii) the location and frequency of uncompensated applied forces.
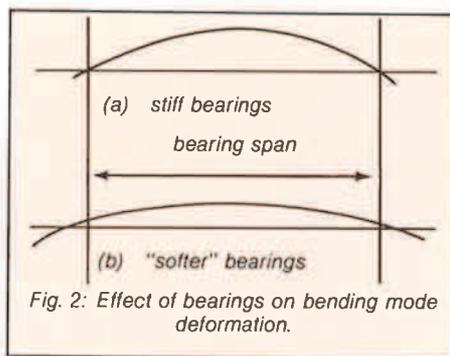

Fig. 2: Effect of bearings on bending mode deformation.

It can be shown mathematically that the simple bending mode of deformation (Fig. 2), has a specified speed where the transfer of energy between the mass and spring elements results in ever increasing bending. This 'natural frequency' of the shaft is commonly called the 'first lateral critical speed'.

Less clamping effect of the bearing shell on the shaft lowers the support spring stiffness. The oil film in the bearings (Fig. 3), acts like a shock absorber to dampen rotor eccentricity. The softer bearing decreases the critical speed of the assembly.

For the Olefines 2 plant the equipment manufacturers submitted lateral critical speed analyses for each rotor and
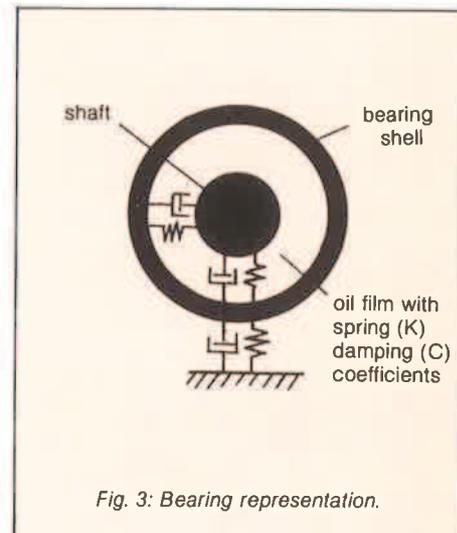

Fig. 3: Bearing representation.

torsional modal analyses for the complete units, showing compatibility of turbines with compressors and sufficient separation between critical and operating speeds.

Incremental balancing (balancing between fitting of impellers) was carried out during assembly of the rotors. Separate full speed running tests were conducted in the manufacturer's works for both installed and spare rotors (mounted in the actual machines), vibration being measured with the calibrated probes which form part of the machine supply.

MEASUREMENT OF VIBRATION

The vibration or movement of the shaft under the influence of disturbing force can be measured in several ways:

1. 'Displacement' of the shaft within its bearings, using eddy current probes mounted in the bearing housing at a set distance from the shaft. This is first hand information from the shaft, though physical and electrical properties of the round shaft can influence the measurements.

2. 'Velocity' or 'acceleration' of the 'stationary' bearing housings primarily under the influence of forces imparted by the shaft through the bearings. Velocity sensors and accelerometers are easily fitted and provide a direct measure of imparted damaging energy (velocity) or forces (acceleration); however, where rotors are substantially lighter than their casings, this 'second-hand' indication of shaft oscillation is less sensitive.

The American Petroleum Institute has combined the knowledge and experience of petroleum refineries and monitoring systems manufacturers into its Standard 670 "Non-Contacting Vibration and Axial Position Monitoring System". This is an aid to manufacturing and purchasing of the eddy current displacement probe

system of measurement, which is now in common use on petrochemical plant machinery.

SPECTRUM ANALYSIS

The measured vibration shows a range of frequencies due to continual application of a number of forces, and the proximity of the running speed frequency and its harmonics to the system lateral and torsional natural frequencies. The task is to sort out these frequencies so that the driving forces can be identified.

The 'time-domain' wave form does not permit this ready recognition and thus a range of spectrum analysers, different in their extent of resulution, has been developed which resolve the waveform into a plot of amplitude versus frequency (Fig. 4).

Fig. 4: Time-frequency domain relationship.
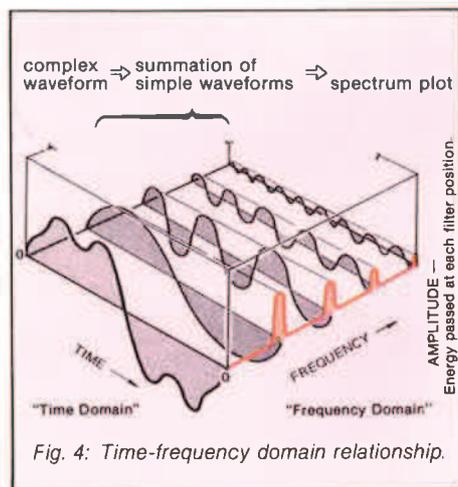
Octave and third-octave analysis filter band widths are proportional to their centre frequency (71% and 24% respectively) and accordingly resolution is lower at higher frequencies. Constant band width filters overcome this deficiency and in this category are sweeping filters, time-compression real-time analysers, and fast Fourier transform (FFT) analysers. The sweeping or scanning filters require constancy of signal for the duration of scanning and thus they have limited 'on-line' use, being able to provide only limited information during speed and load changes.

The real-time analysers can compute spectra from less than 1 second length of time-domain vibration waveform, with the capacity to provide continuous graphical display of the spectrum, and repeat this during the course of events such as machine run-up, load changing, etc.

RUNNING TESTS IN MANUFACTURER'S WORKS

The purpose of testing Olefines 2 equipment in the manufacturer's workshop was threefold:

1. To verify that the assemblies were accurately built — i.e. when slowly turned on V-blocks total mechanical and electrical runout of the shaft at the point of vibration pick-up was of such low level that it could not be confused with vibration (Fig. 5).

2. To confirm the values of the calculated critical speeds by plotting unfiltered

vibration amplitudes against running speed during acceleration from slow roll to operation speed. Using a mark at the shaft end in conjunction with a probe (key phazor) enables the phase of the maximum vibration amplitude to be plotted, thus confirming that there is a change in the mode of vibration when the 'critical' is passed (Fig. 6).

3. To observe and record the vibration spectrum for a series of speeds — slow roll, below critical speed, above critical speed, minimum governor speed, normal running speed, overspeed. Observation was by means of an oscilloscope, showing vibration amplitude in the time domain and by printout of the spectrum determined by the Real Time Analyser (Fig. 7). Recording of signals from both probes at both bearing housings of each machine, at each speed, was affected simultaneously on a 14-channel FM tape recorder, to provide the 'new machine' base data by which machine condition can be assessed during every start-up in its lifetime.

SITE INSTALLATION

The main machine's Monitoring Console will provide information beyond the normal alarm and trip actuation based on measured maximum vibration amplitude level. It will, when complete:

1. Analyse machine vibration at several speeds during run-up by comparing with the manufacturer's test data stored on floppy discs.

2. Continuously scan vibration amplitude levels of all connected machines and automatically provide speed, amplitude, phase and spectral data when alarm levels of vibration occur.

3. Capture, on a multi-channel recorder automatically started by machine trip, the full recording of run-down vibrations to zero speed.

4. Collect and store, by intermittent operation of a tape recorder, long term machine condition data.

The installed vibration monitoring system is designed to keep plant operators fully informed of machine condition, and provide specialist engineers with the means of rapid diagnosis of changes in vibration signatures.


Fig. 5: Electrical and mechanical run-out recording.

Fig. 6: Amplitude and phase v. speed plot.
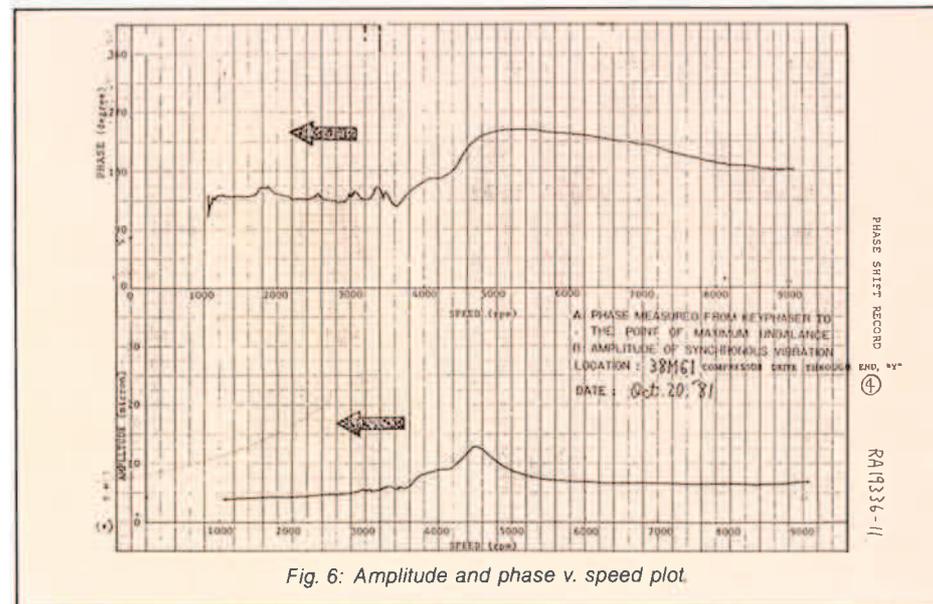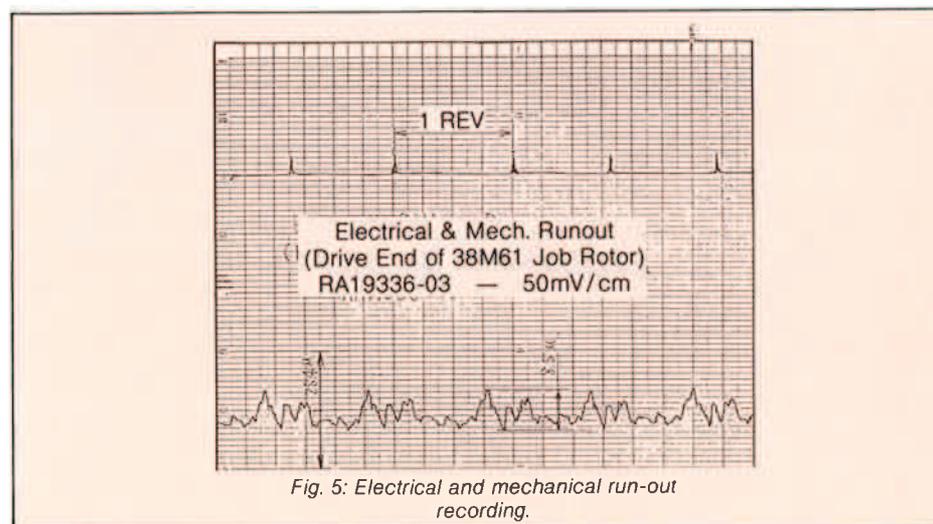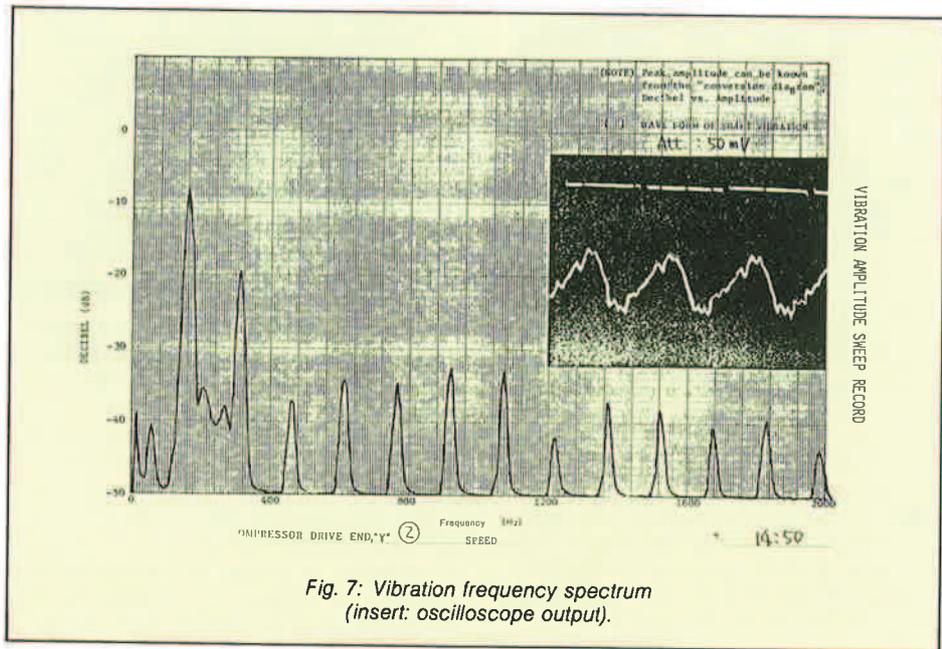
Fig. 7: Vibration frequency spectrum
(insert: oscilloscope output).

The basic business of ICI Australia

Product Class	Principal Raw Materials	Typical ICI Products	Typical Industry Served
Industrial Chemicals and Raw Materials	Salt Limestone Coke Paraffin Propylene Sand Energy (electricity, gas)	Ammonia Soda ash Chlorine Sodium silicates Caustic soda Sodium bicarbonate 'Perclean' and 'Genklene' Carbon tetrachloride Refinery catalysts Acids Swimming pool chemicals Chlorinated paraffins Fire fighting chemicals	Refrigeration Glass Paper, water treatment Soap and detergents Alumina Food Dry cleaning Aerosols and refrigerants Minerals/Oil refining Steel pickling Community and home pools Plasticisers Fire protection
Plastics and Petrochemicals	Ethylene Propylene Chlorine Urea Formaldehyde Methanol Ethylene oxide	'Corvic' PVC polymers, 'Welvic' PVC compounds and dry blends 'Alkathene' polythene 'Propathene' polypropylene 'Visqueen' polythene film and sacks Polypropylene and polyester films 'Palletwrap', 'Fortecon' concrete underlay 'Propafilm', 'Viscourse' Urea formaldehyde resins, brake fluids 'Teric' surfactants Glycols, glycol ethers, glycol ether acetates, Polyethylene glycols Ethanolamines, polyurethanes 'Daltolac' polyols and polyol blends 'Suprasec' isocyanates, 'Perspex' acrylic sheet 'Diakon' acrylic, 'Duracon' acetal 'Duranex' PBT, 'Iupilon' polycarbonate TPX 4 methyl pentene, 'Fluon' PTFE 'Takiron' PVC sheet, 'Maranyl' N66 UBE nylon 6, UBE nylon 12, polycarbonate sheet	Cable insulation and sheathing Automotive Footwear Agriculture Plumbing Packaging Building Furniture Detergents Oil and gas Paints Cosmetics Textiles Refrigeration
Industrial Explosive Systems	Nitric acid Ammonium nitrate Sodium nitrate Aluminium powder Ethylene glycol	Explosive grade AN ANFO explosives NG based explosives Slurry explosives, initiating systems Explosive accessories	Civil engineering Mining and quarrying Seismic prospecting
Rural Chemicals and Fertilizers	Chemical compounds Phosphate rock Sulphuric acid Ammonia Nitric acid	'Teric' and grass tetany medicated supplements 'Nilverm' anthelmintics, 'Tasvax' vaccines 'Promicide' tickicide, 'Uramol' feed supplements 'Gramoxone' non-residual herbicide 'Spray•Seed' cereal herbicide, 'Grenade' Insecticides, fungicides Phosphatic, nitrogenous and compound fertilizers 'Nilvax' combined anthelmintic and vaccine	Agriculture — Animal health Crop protection Pasture improvement
Fibres	Nylon polymer Polyester polymer Fibre processing aids Dyes	Nylon 'Terylene' 'Crimplene' 'Filamel' and 'Timbrelle' yarns and fibres	Automotive, civil engineering Clothing and textiles Defence, furnishing Minerals, transport
Pharmaceuticals	Formulation chemicals	'Inderal', 'Atromid'-S, 'Tenormin' heart drugs 'Savlon' and 'Hibitane' antiseptics 'Fluothane' anaesthetic 'Nolvadex' breast cancer treatment UV sun protection products	Health care
Paints and Coatings	Synthetic resins Pigments Solvents Dispersants Monomers Latex emulsions	'Dulux' enamels, 'Dulon' automotive finishes 'Durethane' finishes, 'Dulux' Acran enamels 'Wundercoat'/'Wunderprime' 'Weathershield'/'Wash-n-Wear'/ 'Weatherprime'/'Timbercolour' 'Super Enamel'/'Hi Gloss' 'Super Gloss'/'Undercover' Walpamur paints 'Powdercote' powder coatings 'Comdec' wallcoverings	Housing, construction Automotive, can Steel fabrication Household appliances Aircraft

Keywords index

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