DEVELOPED TO TIME

THE GAS MANAGEMENT PLANT PROJECT

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ABSTRACT

The VANGUARD Class required an alternative method of disposing of the Hydrogen produced by the electrolyser rather than discharging it to the sea. The development of a suitable equipment, the Gas Management Plant, was successfully achieved to a tight programme, albeit with some cost escalation. The development project is described, with some comments on the problems of control of time and cost.

Background

The electrolyser is an excellent plant for supplying oxygen to a nuclear submarine but has the disadvantage that it produces twice as much hydrogen as oxygen. The Gas Management Plant (GMP) is the MOD answer to the problem.

The Start of the Project (late 1982)

A variety of methods requiring minimal development were considered, none of which met the requirements, including storing hydrogen on board in bottles or as metal hydrides. The best that could be achieved in an acceptable space was 48 hours' storage. We will ignore the suggestion that sufficient oxygen candles should be carried to produce oxygen to combine with the hydrogen.

The U.S. Navy had developed a suitable equipment and approaches were made to buy the licence to build it in the U.K. using U.K. components where possible. This proposal was rejected by the U.S. Navy.

In 1983, therefore, the MOD placed a small (about £10,000) contract with CJB Developments (CJBD) to study the commercial processes available and recommend the most suitable for R.N. development. CJBD had a long history of development of chemical plant for submarine air purification. They designed the High Pressure Electrolyser using an alkaline electrolyte in the early 1960s and in 1983 were near the end of development of an electrolyser based on a solid polymer electrolyte called the Low Pressure Electrolyser (LPE) which entered service in 1986. They had also developed the Freon Removal Unit for the SSBNs and the Temperature Swing Molecular Adsorber (TSMA) for carbon dioxide removal in the TRAFALGAR Class.

Their study concluded that the ICI low pressure methanol process had no serious competitors (which was the same conclusion that the U.S. had come to since their equipment relied on the process).

The basic reaction is:

$$3H_2 + CO_2 \rightarrow CH_3OH + H_2O$$

The CO_2 would come from the amine scrubbers and the reaction has the great advantage over the Bosch process that ratio of hydrogen to CO_2 is favourable. For each molecule of oxygen used by the human body, about 0.9 molecules of CO_2 are expelled. So every 3 molecules of hydrogen corresponds to 1.5 molecules of oxygen produced and 1.35 molecules of CO_2. As only one molecule of CO_2 is needed, there is a 35% excess of CO_2

available so that all the hydrogen can always be consumed. In the Bosch process

$$2H_2 + CO_2 \rightarrow C + 2H_2O$$

there is a 10% deficiency of CO_2 on average.

Following the study, the MOD decided to develop the GMP using the methanol process. Discussions with the U.S. had continued so there was a fallback position of buying the U.S. equipment off the shelf. The U.S. price however was high enough to make the development look very cost-effective (especially at the dollar/pound exchange rate of 1.1:1 in 1984)

The Development Plan (1983)

CJBD put forward a detailed proposal and Development Cost Plan (DCP) in December 1983. The first part of the programme covered design, build and test of a process demonstrator as a 'breadboard' plant, that is a plant which would have all the essential components of a naval plant of the right size but there would be no attempt to meet the space constraints of a submarine or the shock and environmental standards. The demonstrator would be followed by a navalized prototype plant which would meet all the space, weight, environmental and other requirements of a production unit. The deadline for the project overall was to deliver two production units for installation in H.M.S. *Vanguard* in June 1989. The initial programme is shown in FIG. 1.

Some features of this very tight programme are:

(*a*) Ordering of components for the demonstrator had to begin very early in the design.

(*b*) Design of the navalized prototype had to begin at the end of commissioning the demonstrator, before any trials.

(*c*) Design of the prototype would barely complete before the end of build.

(*d*) Procurement of the production units was programmed to start before prototype trials.

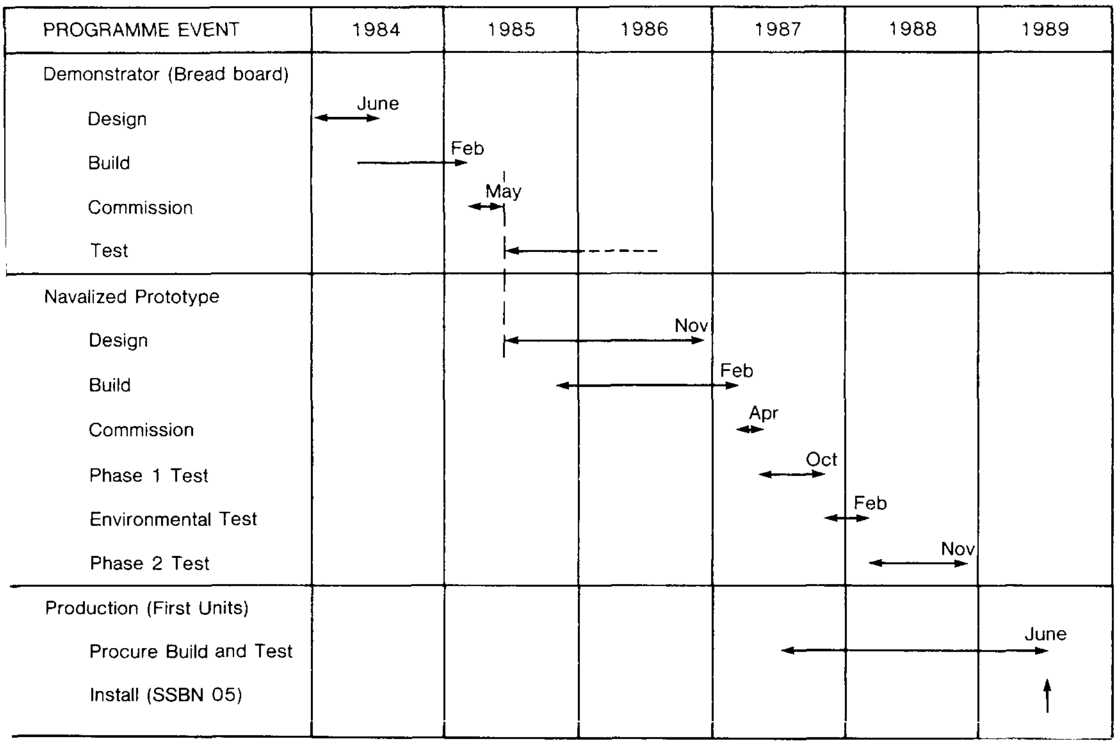

FIG. 1—INITIAL PROGRAMME (1984)

These overlaps meant there would be no clear time to review the progress and problems of one stage before much of the next stage of the project was committed. Also, the feasibility study had been small and CJBD had to assume that the ICI information on the process would be sufficient to home in quickly on the final process parameters.

Meanwhile, Johnson Matthey had put forward a competing proposal based on their work on methanol fuel cells. As the methanol reaction can work either way depending on plant conditions, the MOD accepted that Johnson Matthey had sufficient knowledge of the chemistry of the plant to be worth placing a second contract on them for a demonstrator. In the event, the electro-mechanical design of the Johnson Matthey team was not of adequate quality and the project was stopped in late 1984.

Demonstrator Design (1984)

ICI supplied information on their commercial plants and access to their mathematical model of the process which gave initial values of temperature, pressures, flow rates and conversion rates within the plant.

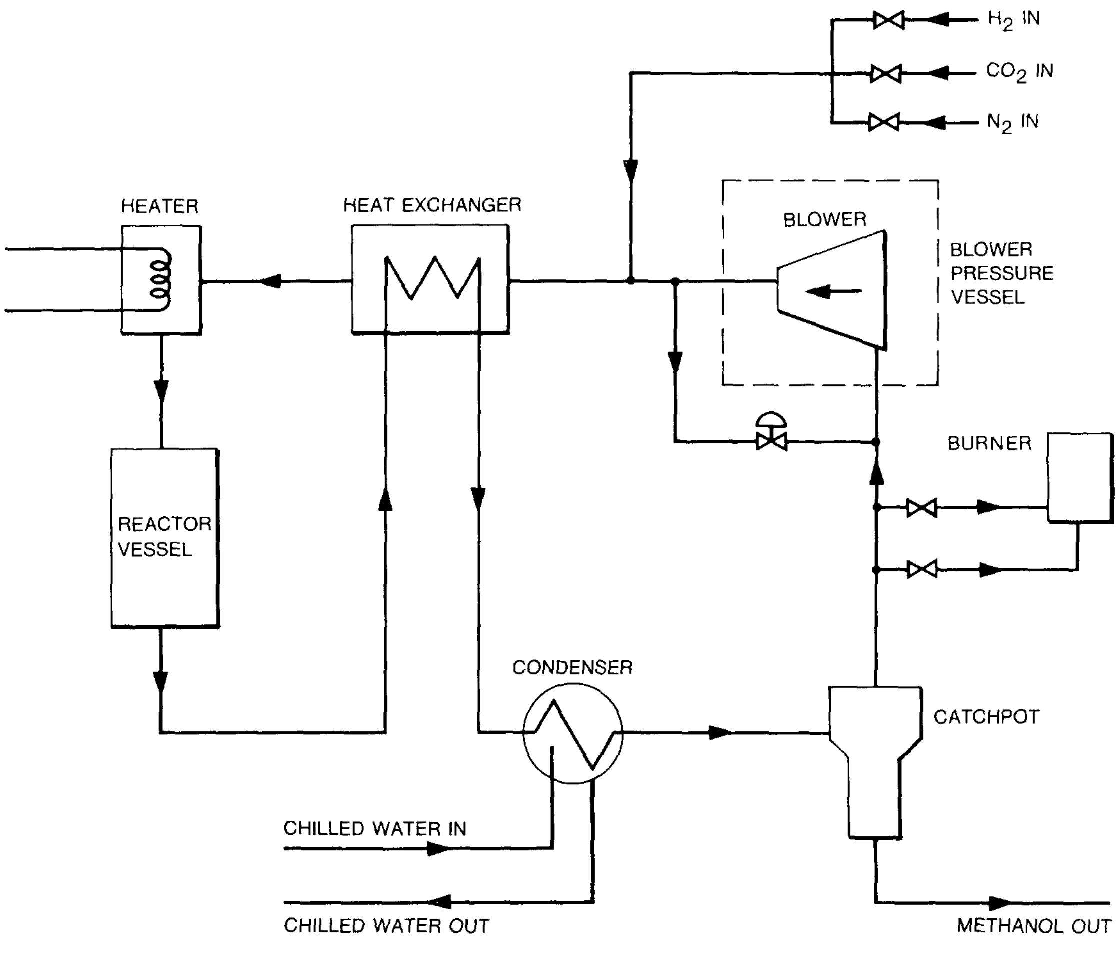

FIG. 2—GAS MANAGEMENT PLANT: FLOW DIAGRAM

The process loop is shown in FIG. 2. Carbon dioxide and hydrogen are fed into the plant at a ratio of approximately 1:3. The mixture is heated in a back-to-back heat exchanger and then by pre-heaters; it enters the reactor vessel where the ICI patented catalyst converts about 10% of the mixture to methanol at each pass; the reaction is exothermic and the hotter gases now pass through the other side of the heat exchanger to a condenser where the methanol becomes liquid; the liquid methanol is captured in a catchpot and discharged at intervals, the discharge being driven by the internal plant pressure; the unreacted gases return through a blower to pass again round the plant, taking in fresh hydrogen and CO_2 on the way.

There is a nitrogen purge to clear the plant at start up and shut down and a gas bleed after the catchpot which supplies a sample to the CO_2 analyser and also continuously removes a small amount of process gas which eliminates, in time, any nitrogen or other non-reacting gases. This bleed gas is led to a burner where it burns at about the size of the pilot flame of a domestic central heating boiler. The main use of the burner is on plant shut-down when all the process gas remaining in the plant is burnt.

The process control has 3 main feedback loops:

(*a*) Process gas composition is controlled by measuring the CO_2 content of the loop and altering the CO_2 feed to maintain a constant percentage of CO_2.

(*b*) The pre-heaters are controlled by a 3-term controller to maintain the catalyst bed temperature.

(*c*) The methanol discharge is controlled by level switches which open/close the discharge valve when the catchpot is full/empty.

The plant is at high pressure (between 30 and 55 bar) and contains inflammable and/or toxic gases (hydrogen, carbon monoxide, carbon dioxide and methanol). The process control therefore contains a large number of alarms and interlocks for plant safety.

A Failure Mode, Effect and Criticality Analysis (FMECA) was carried out early in the design when all the failures that could be conceived were examined and suitable safety features designed.

These technical details show that the GMP is a reasonably complex chemical plant. It requires a good degree of electro-mechanical expertise to achieve safe and efficient operation in a small space with adequate maintenance access.

Demonstrator Build and Trials (1985/86)

Given the complexity of the plant, there were remarkably few problems with the demonstrator unit. There were some difficulties with finding suitable instruments to measure the low flow rate high pressure water-saturated gases that were being fed to the plant. The process itself however turned out to be benign as the gas composition could vary fairly widely ($\pm 2\%$) without much affecting the catalytic reaction and hence the plant temperatures. The main problem area was the design of the blower bearings which repeatedly failed in the CO_2 and methanol laden atmosphere. Eventually a grease was found which had been developed to cope with the CO_2 circulating blowers in Magnox and AGR power stations and this, coupled with stainless steel ball bearings, allowed the blower to run for over 2000 hours without failure.

There was some slippage in the programme—in particular commissioning was not completed until September 1985 compared with a due date of May. However there was sufficient confidence in the plant for the design of the navalized prototype to start nearly on time.

The demonstrator ran for 3000 hours on the main programme and then a further 1100 hours were added to demonstrate that the GMP would run just as well when supplied with CO_2 from the MPT scrubber as when it was supplied from bottled CO_2. The main significance of this test was to show that the CO_2 from the scrubber was pure enough, as the GMP catalyst can be poisoned by a variety of substances, notably halogens (e.g. freons) and sulphur compounds. The LPE/MPT/GMP trial ended with Freon 12 and Freon 114 being injected into the MPT air intake. No freons were detected in the CO_2 output.

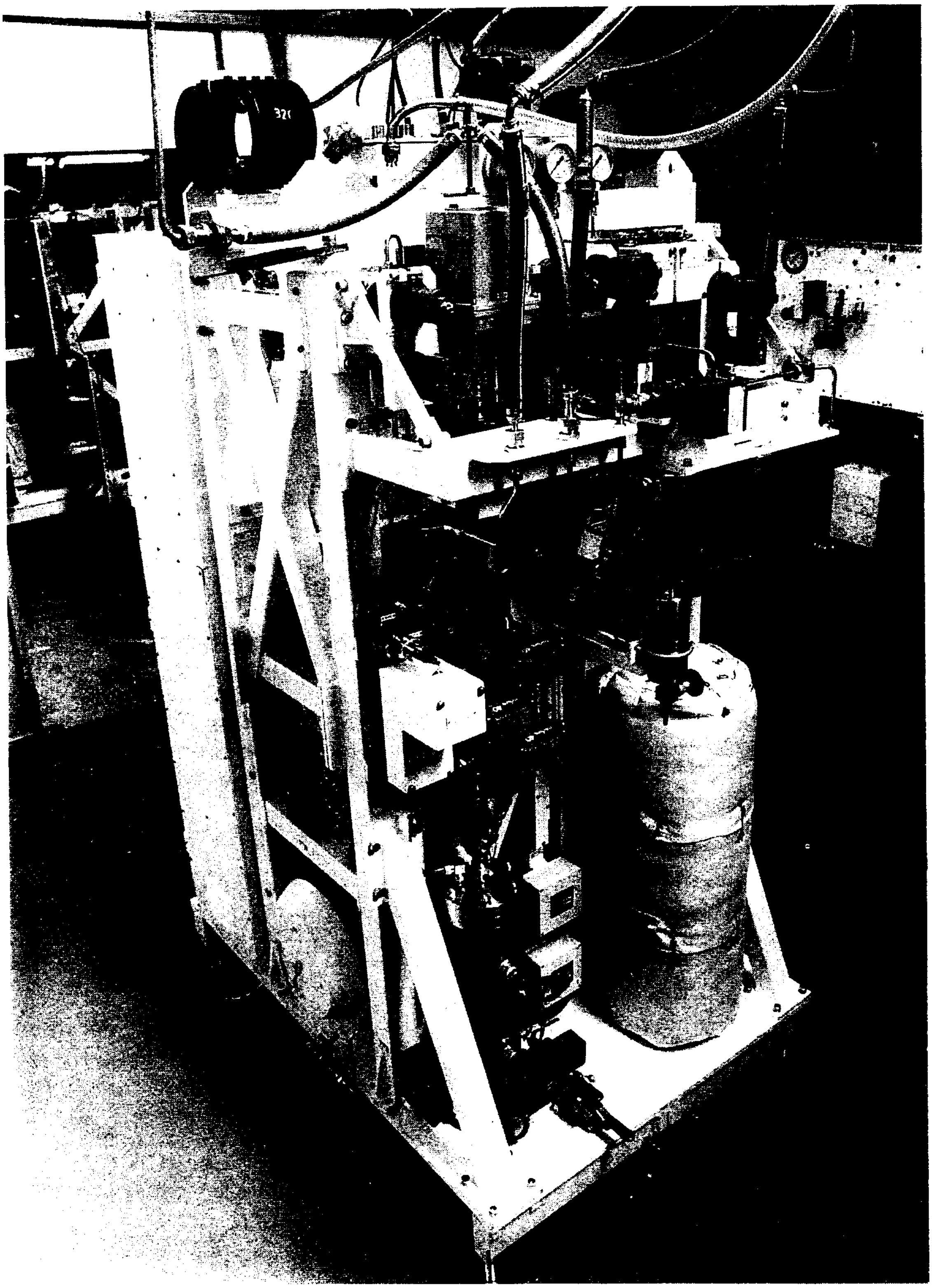

FIG. 3—GAS MANAGEMENT PLANT PROTOTYPE: REAR/SIDE VIEW

Navalized Prototype (1986 to 1988)

The great achievement of this navalized prototype design (FIG. 3) was to compress the components of the demonstrator into about one third of the volume while retaining adequate maintenance access and a plant that could be broken down to pass through a standard submarine hatch. The detailed design of many of the major components, such as the reactor vessel, was changed but the design concepts were virtually unaltered.

The one large change was the addition of a 'hold' plant state which CJBD were requested to design following discussions between the MOD and the U.S. Navy in early 1986. The plant operating states are now:

Normal operation — plant producing methanol.

Standby — plant not taking in feed gases but maintained at temperature and pressure with the plant running.

Hold — plant sealed with a full charge of process gas but heaters and blower not operating.

Shut Down — plant emptied of process gas and filled with nitrogen at atmospheric pressure

There were some large conflicts in priority in the CJBD Design Office with the GMP design, design of another MOD equipment and the normal work-load for the MOD, especially with the entry into service of the LPE. The programme was maintained by the use of contract draughtsmen, which is an acceptable solution in principle but, in a cost plus contract, there should have been much more detailed discussion with the MOD.

Procurement problems were acute at certain stages, particularly when sub-contractors failed to meet their deliveries or had quality deficiencies. These various problems led to a two month delay compared with the original programme, and this extended to nearly four months (nominally) at the end of commissioning. Most of this was drawn back in the Phase 1 testing as Commissioning had eliminated virtually all the usual test problems.

The Phase 1 endurance trial was programmed to achieve 2500 hours running. In the event, some 1950 hours were recorded before the plant had to be transported to RAE (West Drayton) for environmental trials. In the last week before shipment, VSEL carried out an Upkeep Evaluation. As a result, a number of changes were made to the maintenance procedures but the modifications to the hardware were minimal. The environmental trials went smoothly and the only fault of any consequence was a failure to meet the full electro-magnetic compatability (EMC) requirements. Shock testing was delayed until September 1988 because the 2 tonne shock machine was being repaired, but the GMP passed this test successfully.

Phase 2 trials completed the full 5000 hours running overall with no significant problems except that the blower bearings failed at 2300 hours running when liquid methanol was carried over into the blower casing and washed out all the grease. Prior to this, there had been no signs of distress from the blower so that bearing problem can be said to be solved.

Production Units (1988/89)

CJBD had reconsidered the production timescales and concluded that a production lead time of 16 months would be adequate, that is a contract could be placed in February 1988 to meet a June 1989 delivery. Sufficient data was made available in November 1987 to define the plant adequately for contract purposes in the form:

(*a*) A base pack of production drawings.

(*b*) Modification defined and costed but not yet incorporated into the base drawings.

(*c*) A general warning that, since development was still in progress, further modifications might be required.

For a variety of reasons, the contract for the production units did not reach CJBD from Vickers until June 1988. Despite this, it is still likely that the first production units will be delivered on time, albeit without the EMC modifications, which will be incorporated later.

Project Management Review

The programme achieved (with some extrapolation to the first production units) is compared with the initial programme in FIG. 4.

As will be seen, the objective of designing, building and testing a navalized prototype by November 1988 was achieved. The small slippages in the early part of the project were compensated by the nearly trouble-free running of the endurance trials.

Some of the success can be attributed to the information supplied by ICI, the fact that the process turned out to be less critical to control than it might have been and the indefinable advantage of knowing such a plant would work as both ICI and the U.S. Navy had produced a working plant of about the same size. There remained however ample opportunity for major overruns as the overlapping programme meant that any large error at any point in the development would have been fatally compromising. It is a major tribute to CJBD that they anticipated the potential problems and designed them out.

Project control followed MOD guide lines closely. CJBD held regular design review meetings internally and produced analyses such as FMECA at the right time in the project. Progress meetings with the MOD took place every six weeks on average with formal design reviews on three separate occasions. Every six months there was a Budgetary Control Meeting.

Technically, the project went smoothly so that major decisions were rarely required except in defining any extra work essential to the success of the project, such as the 1000 hour LPE/MPT/GMP trial.

The main causes of dissension lay in the cost control. The contract was cost plus so there was no built in incentive to minimize expenditure. A sophisticated paperwork system was used where, each month, an updated DCP was produced with forecasts of the monthly spend to the end of the project. These costs were presented in 2 ways:

(*a*) By category of labour employed (engineers, draughtsmen, etc.).

(*b*) By work Activity (e.g. 'design of reactor vessel' or 'Phase 1 trials').

The Activity Costs were compared on an Activity Cost Variance Analysis and significant changes of an Activity Cost from one DCP to the rest was further clarified by breaking the change down into separate labour costs. From these financial sheets it was easy to see where the major increases had occurred and which elements had caused the increase. They could not show whether the cost escalation was justified by essential work carried out in an efficient manner. That could only be established definitely by an intimate knowledge of the workings of the company. The paperwork however enabled the MOD to challenge the cost escalations although it still took a large and substantial effort to contain them, despite the sophistication of the system.

Cost plus contracts are of course anathema in the current climate. They can be as cheap or cheaper than other forms of contract if the necessary effort is expended in house or if the contractor has a strong incentive to

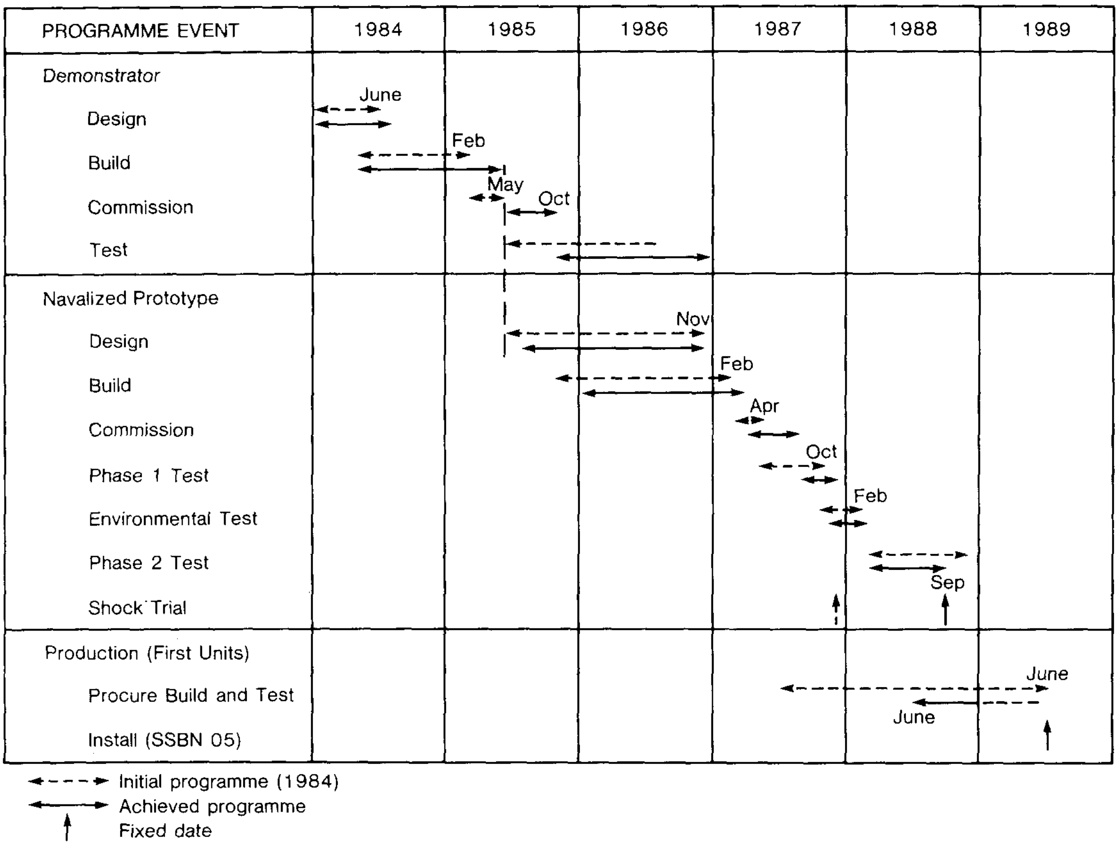

FIG. 4—ACHIEVED PROGRAMME (TO JANUARY 1989)

efficient working such as limited staff and a limited timescale. The CJBD employment of contract draughtsmen referred to above without formal authority from the MOD caused a major argument because it removed an incentive to efficiency.

Overall, the project overran its initial (1984) cost estimate by 63%. Of this, 17% is accounted for by inflation, reflected in the rise in labour and overhead rates; 23% is the result of extra work authorized by the MOD and 23% was escalation of the original cost estimates of the activities. It can be argued that this is a good result as cost plus contracts contain no explicit contingency which, for a fixed price or incentive type of contract, would probably run between 20% and 30%. Furthermore, cost plus contracts tend to be priced optimistically (as escalation will be covered) and an overlapping development/production programme such as the GMP is very vulnerable to waste as work has to be committed to the next stage before the problems of the previous stage have been identified.

In this case however drawing office costs were a large part of the contract price and were a major contributor to the escalation. Drawings have to be produced to the highest MOD (NES 722) standard for the production units when the design is fixed. In this contract, drawings were produced to this standard early in the project when, in MOD opinion, a much lower standard would have been adequate for both design and build of the prototype. Design changes, which are inevitable in a development, were very expensive as many drawings of high quality were affected each time. CJBD were within their rights under the terms of the contract and the MOD could only try and influence the interpretation of the drawing quality required. CJBD have recently installed a CAD system which should greatly reduce this problem in future contracts.

Any future contract would probably be one of the incentive type where a price and a programme are agreed; programme overruns reduce the contractors profit; early completion enhances his profit. Such a contract would greatly reduce the MOD in-house effort in monitoring the contract financially and would encourage the firm to work to the lowest adequate standards.

Despite the criticisms of the cost increases, the savings in buying the U.K. GMP rather than the U.S. version 'off the shelf' will pay for the cost of development within the first three units delivered (i.e. one and a half boat sets), using a dollar/pound exchange rate of 1.75:1.

Conclusions

The GMP project was fully successful in developing and testing a prototype unit which meets the technical requirements within the timescale originally programmed.

The final cost of the development programme escalated but will still be paid for by the savings in the first three units purchased compared with buying the U.S. equipment 'off the shelf'.

Postscript

Even fully tested chemical plants can spring surprises. While decommissioning the prototype, the catalyst is oxidized to a safe state. The reaction is exothermic. Air had been fed to the reactor vessel for nearly 2 hours with a very slow temperature rise and resulting boredom for the watchkeepers (who included MOD personnel). Then a runaway condition developed and the bed temperature rose from 60°C to 560°C in a matter of minutes. No damage was done fortunately, but the operation will not be recommended for shipboard use.