THE ROYAL INSTITUTION OF NAVAL ARCHITECTS

AUSTRALIAN DIVISION

"MODERN SUBMARINES - SHIPBUILDING ASPECTS"

by

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Presented at Sydney

Tuesday, 5th July

1983

MODERN SUBMARINES - SHIPBUILDING ASPECTS

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SUMMARY

The last quarter century has seen the largest ever quantum step in submarine technology. Nuclear fuelled propulsion plant and improved life support systems have produced the true submarine, capable of long-period self-sustained submerged operations, limited only by crew endurance. The resultant vehicle provides a fast, deep-diving platform with unique maritime capability.

Such vessels, whilst playing a vital role in several major Navies, are none-the-less expensive to build, operate and maintain. Thus the conventional (ie diesel-electric) patrol submarine remains a less expensive and widely used alternative in many world Navies. Its configuration has not only been influenced advantageously by the advent of "true submarine" technology but, importantly, by such developments as the fuel cell and the closed cycle diesel which, in the not-too-distant future, will narrow the gap still further.

This paper addresses the changes necessary to adapt traditional shipbuilding methods to meet the demands of the highest levels of modern submarine construction technology.

1. THE SHIPBUILDER'S DESIGN TASK

1.1 Design partnership

Although for many years UK Shipbuilders have capably performed as prime contractors, with full design and commissioning responsibility, to meet the requirements of Overseas Navies, warship design for the Royal Navy was usually the province of MOD(N). However, with the complexity of the modern large submarine, the RN design task became more akin to a partnership.

The way in which the Shipbuilder fulfills his role is illustrated in Fig 1. Shipbuilder designers, engineers and draughtsmen assist MOD(N) during the earliest stages of developing the design. In this way construction expertise is brought to bear on design feasibility, and the Shipbuilder begins to acquire detailed knowledge of the project. In later stages, more and more tasks are placed with the Shipbuilder, in the form of Project Orders, within the framework of an 'umbrella' involvement contract. Over a period of two to three years, design guidance information, long lead ordering, planning, models, equipment development and other facets of the project are 'hardened up' into a firm contract definition. This enables the Shipbuilder to submit a construction tender based on well-founded information.

The complexity of Fleet and Polaris submarines demanded an extremely high level of discipline from the submarine designer, as well as from those responsible for the design of machinery and equipment and the selection of materials. This increase in complexity, coupled with the large increase in workload on MOD design staff, led to the adoption of the previously mentioned relationship, involving a greater, and most welcome, degree of participation by the Shipbuilder.

1.2 Effort

The total shipbuilder effort expended in the modern submarine design task can be divided into three packages:

Design assistance to MOD(N)
Design development
Working drawings

involving approx 1000 man years over a 7-year period.

In addition to the traditional Naval Architects and associated skills, the large submarine requires specialised departments: Weight Control, Ventilation and Air Conditioning, Mock-ups (later Modelling), and Project Design Offices (to deal with specific problems, eg noise attenuation). The Polaris Weapons system required a completely new Weapons Department, peaking up to 160 people. Hull, Electrical and Marine Engineering Drawing Offices were expanded from about 150 draughtsmen to 500.

In the period 1955 to 1966, the number of employees at Vickers Barrow Shipyard rose from 4000 to 7300 (Fig 2). This growth took place in a series of steps - firstly to match the needs

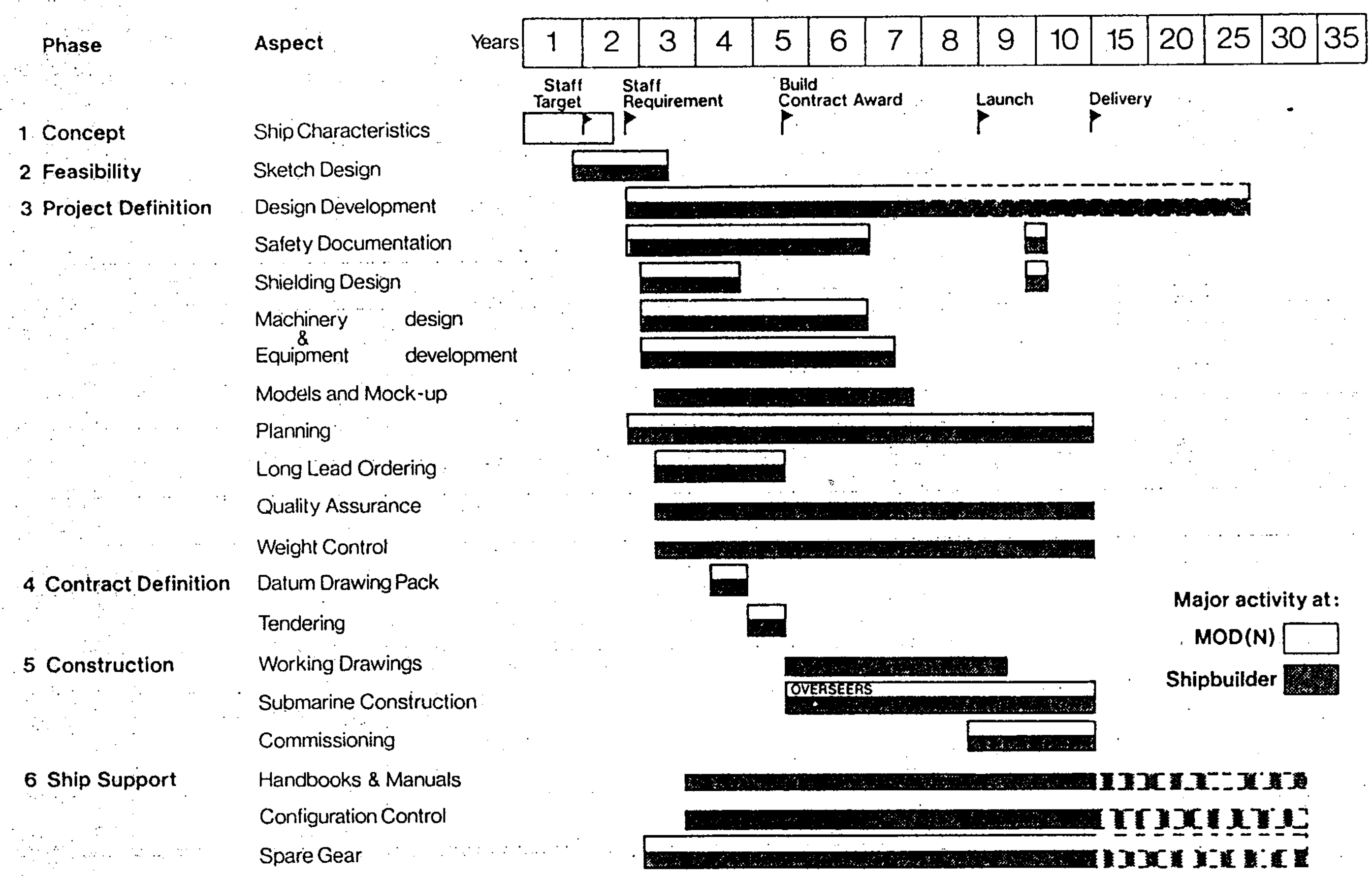


Fig 1 The Shipbuilder's Role

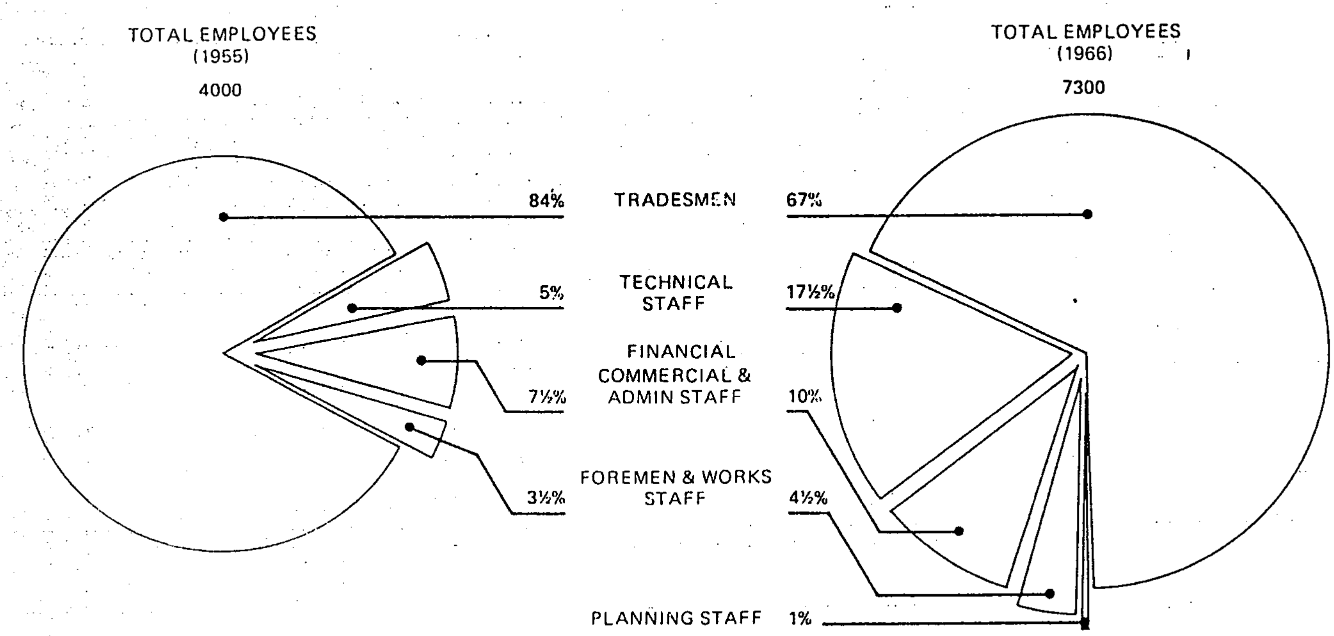


Fig 2 Changes in Shipbuilders Organisation

of DREADNOUGHT (for which American hull form and machinery were used), then for the all-British VALIANT design, followed by the POLARIS boats.

In this period the number of technical staff rose from 200 (5% of total) to almost 1300 (17½%).

The cost of the full range of design and support-to-build tasks is equal to about one third of the construction costs of the First-of-Class submarine.

1.3 Advantages

The effort expended in this work, and the strong links forged between MOD, the Shipbuilder and the suppliers of specialised equipments and materials, are key factors in the technical success of UK submarine enterprise, as well as in its excellent record for avoiding cost and programme overruns. Good preparation pays substantial dividends.

To a large degree the partnership method has also been adopted for RN First-of-Class surface warships.

2. PREPARATIONS

Vickers specialisation in submarine production at Barrow goes back to the earliest days of the Company. Indeed, the 297th submarine was 'in hand' as the DREADNOUGHT contract was signed. DREADNOUGHT was the harbinger of great changes in organisation, staffing, skills, facilities and management of the Shipyard.

2.1 New Departments

The traditional organisational structure for conventional naval shipbuilding was in simple functional groupings covering the mainstream operations of steelworking and outfitting, supported by appropriate technical, commercial and administrative planning resources, in a low-overhead setting. There were few, if any, formal written procedures and, as in shipbuilding generally, tenuous lines of communication, with the Ship Manager as a key figure organising the construction of the hull and, later, its outfitting. Fig 3 indicates this traditional type of organisation.

Fig 4 shows the substantial enlargement of the Shipyard organisation required to cope with Fleet and, later, Polaris submarines. The increased demand inherent in the construction of large submarines applied as much to production management as to design and technical functions. It required a much strengthened support service, most particularly in planning, procurement, quality assurance, testing and commissioning and modification control. One example was the complete transfer of the marine installation task and personnel from Vickers Engineering Company to the Shipyard.

2.2 Recruitment and Training

Recruitment of a small number of specialist staff, and shipyard training began with the nuclear submarine programme in the late 1950s, as preparation for building DREADNOUGHT. Selected senior management were indoctrinated in the new technology. Substantial additional training was also undertaken in the leading USA submarine shipyard at Groton, Connecticut, and in the US specialist contractors' works. The shortest visit/training course was four days and the longest one year. Approx 100 staff were involved: the total effort amounted to some 18 man-years and saw Vickers well into the construction of their first two nuclear-powered Fleet submarines.

The Polaris programme produced an even larger challenge: to integrate the complex Polaris weapons system. A systematic analysis of the extra resources required to embrace the Polaris weapons system led to further massive recruitment across a wide range of personnel, together with an equally substantial indoctrination and training effort. Vickers again sent their senior and middle management to a series of courses in the USA; principally to the leading Polaris builder, to specialist weapons contractors and to associated bodies. A large number of senior and middle management personnel were also streamed through technology training at Greenwich, under the tutelage of Dr J Edwards. The shortest course was two days, the longest 6½ months, and the total effort amounted to some 30 man-years.

Vickers, as the lead Polaris builder in the UK, then set up a recruitment and training programme for Cammell Laird, who were also to construct the vessels.

It is believed that the scale of these operations was without precedent in UK shipbuilding. Interestingly enough, old ties were renewed between Vickers and 'The Electric Boat Co.' (now part of General Dynamics) - as 'Vickers Sons and Maxim' and 'The Holland Torpedo Boat Company' the two had collaborated in 1901 to build that 'damned un-English weapon'(1) the first submarine for the Royal Navy, Holland 1, at a cost of £35,000.

2.3 New and Extended Facilities

Considerable improvements to facilities at Vickers Barrow Shipyard were necessary. Most urgent was the rapid expansion of office space to accommodate increased numbers of staff and new technical departments. In production areas, plant to manufacture, weld and radiograph the heavier section frames and pressure hull plating was uprated. The assembly area was enlarged and, to cope with the very much heavier hull sections, a large heavy transporter, reinforced concrete floors, roads, and a building berth were constructed. The deeper draught of DREADNOUGHT required regular dredging of the launch area and it was necessary to dredge a

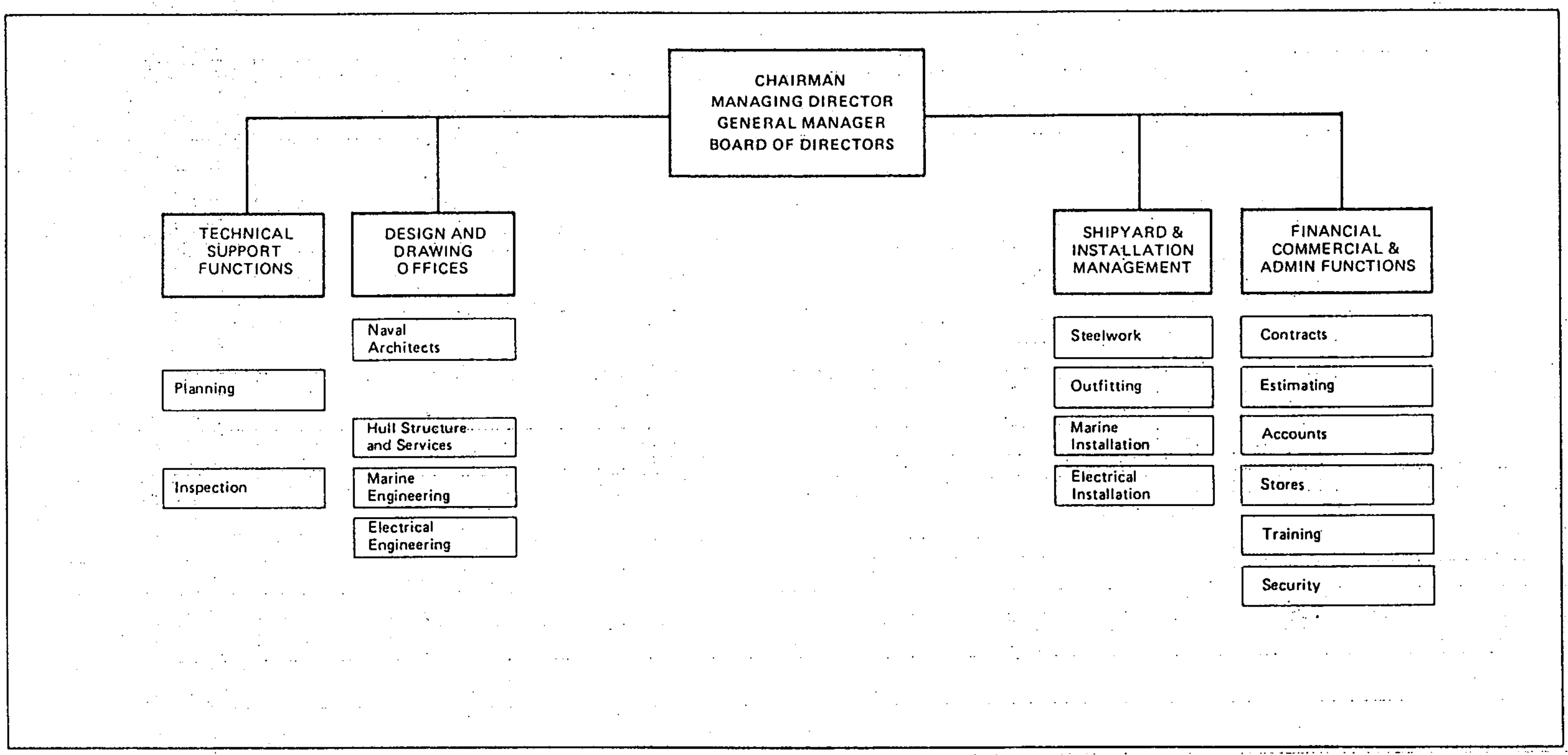


Fig 3 Traditional Shipbuilding Organisation

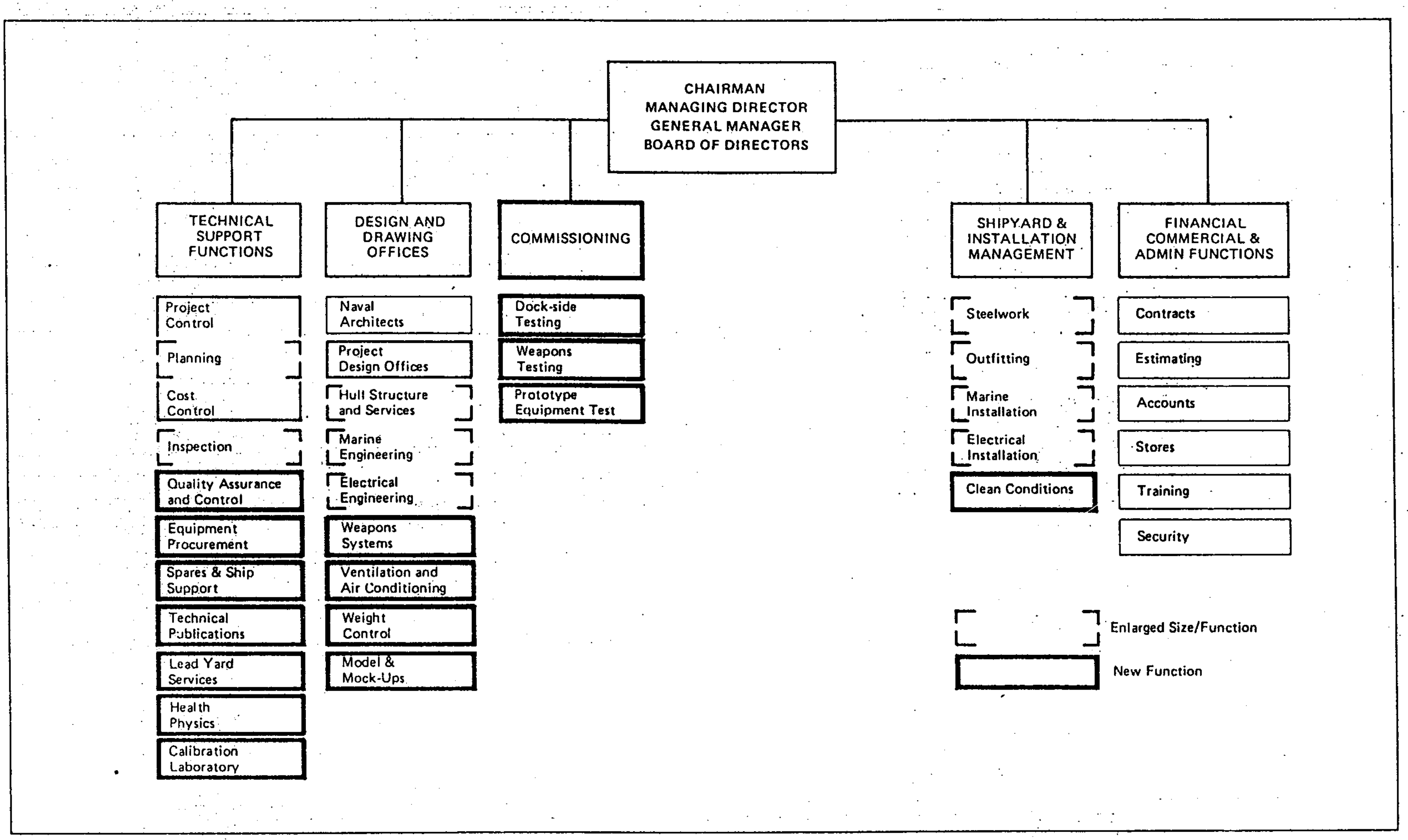


Fig 4 Shipbuilders Organisation for New Generation Submarines

deep hole to facilitate docking and to accommodate trim and incline experiments and other dived tests and trials. A specially-designed Admiralty Floating Dock (AFD) was also dedicated to the programme.

A health physics laboratory, a facilities barge, a steam raising barge, a Submarine Machinery Test Establishment and other specialised facilities were also additions required to deal with the new technology. Clean conditions for certain areas and for pipe-work systems became a new way of life in the shipyard. A Weapons Department building, including a Calibration Laboratory to NPL standards, was included in the special facilities added for Polaris during the early 1960s.

Some of these facilities have also been used in developing first-of-class surface warships such as SHEFFIELD and INVINCIBLE, in addition to SWIFTSURE and TRAFALGAR Class submarines.

3. PRODUCTION

3.1 Skills and Technology

The new technologies involved plant, equipment, materials, processes, management aspects, and extensive training of people in new skills. Some were introduced at the start of the nuclear programme and others evolved as knowledge of the product and experience accumulated.

The configuration and scantlings of the large submarine hull require a completely new approach from steelmaker and shipbuilder. The steel was to be high-yield, low-alloy, fine grain, fully killed, quenched and tempered. Thicker, heavier plates were needed for the pressure hull. Frame scantlings were several times heavier than the rolled 'T' sections built into earlier submarines. Non-destructive testing techniques (ie ultrasonic, radiographic, etc) had to be developed and the latest practice is to ultrasonically search the plates for faults, prior to working them. Pressure hull and pressure vessel welding must conform to an extremely high radiographic standard and requires initial and regular repeat qualification testing of Grade A welders. Frame bending and plate rolling skills, and control of metallurgical and dimensional parameters, must be to a consistent high standard. Exacting quality standards of workmanship, and high-grade clean conditions apply to much of the work.

Design as well as fabrication of pipework has demanded an all-round investment. Whether forming part of the Polaris launch system, the propulsion steam system, or whether full of sea-water at full diving depth pressure, piping systems, in a wide range of steels and alloys, must be to the highest standards of integrity, for reasons of safety as well as operational requirements.

Technology was particularly tested when an attempt was made to encourage British Industry to produce large nickel-aluminium bronze castings for high-pressure services (eg sea-water cooling) which, for safety reasons, required full radiographic and/or ultrasonic standards. Ultimately, the Shipbuilder was obliged to specialise, and became practically the sole source of major castings to this specification.

As the completed boats are 'set-to-work' prior to sea trials, a four-party testing and commissioning team is brought to bear. The Shipyard's Dockside Test Organisation (DTO) is joined by the MOD overseer; the relevant members of the RN ship's staff; and, in certain areas, the equipment contractor. This close-knit partnership of technology and skills prepares the written test documentation, and then undertakes the many hundreds of tests necessary to commission firstly sub-systems, and then full systems, to ensure that all are well-proven before the submarine is taken to sea for trials.

3.2 Changes in Methods and Processes

An outline of the methods and processes used to build a fleet submarine will serve to give scale to the operation and illustrate certain of the unusual and novel aspects involved.

3.2.1 Hull Construction

The construction of the hull (Figure 5a) commences with the manufacture of bulkheads and heavy-section frames. For early vessels, these frames were produced by trammel-burning the webs and welding them to strip-cut tables. Later, frames were formed from cold-bent extrusions. To maintain the stringent requirements for circularity and boost the production rate, some 20-plus pressure hull 'hoops', over 30 feet in diameter and about 10 feet in length, are assembled in jigs (Fig 5b). Within these jigs, frame circularity is maintained by radial struts. Frames are supported horizontally at the required spacing, whilst segments of pressure hull plating, pre-shaped by cold-rolling, are 'wrapped' round the jigged framing. The pressure hull plates are butt-welded to each other, then welded to the frames.

Bulkheads are completely prefabricated before being built into the hoops at the relevant frame positions. Still lying on end (Fig 5c), hoops are transferred to a turntable for butt edge preparation, using a bevelled flame cutter. This ensures the precise limits necessary to obviate adjustment when aligning neighbouring hoops. Three or more hoops (Fig 5d) are then erected on to a mandrel, with their axes horizontal, and are rotated for submerged-arc fuse melt welding of the butt joints between hoops, under a fixed automatic welding head. In this way, eight major pressure hull units are constructed. The radial struts are retained until internal deck and seating structure is added. Initial

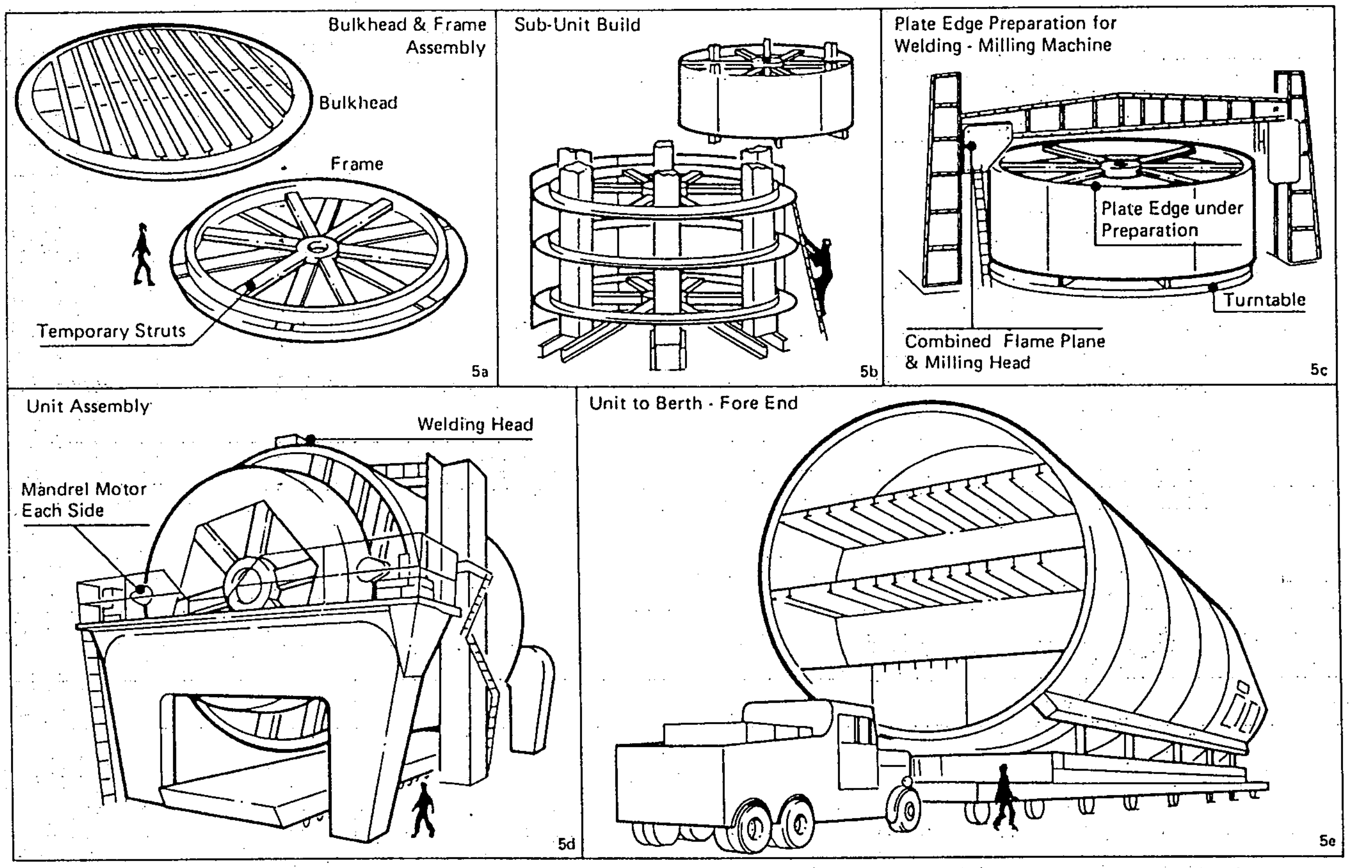


Fig 5 Hull Construction

outfitting, eg penetrations and fittings, is commenced in the shop before each unit is loaded onto a heavy transporter (Fig 5e) and, at a weight of up to 500 tons, is moved to the building berth. The procedure is significantly different from that used for the lighter scantlings of earlier submarines, which were built up from large fore and-aft plates erected onto standing frames in the style of traditional shipbuilding. Indeed, the procedure is now more in the nature of precise production engineering. Probably the largest development in the hull sector embraced the metallurgy of both steel-making and welding.(2) Dreadnought's specification called for full penetration welds for all major tee-joints, where previously fillet welds had sufficed: furthermore, the low-alloy, high yield, quenched and tempered QT35 hull steel was of much heavier scantlings.

Many metallurgical and welding technology problems were encountered and overcome. Plate composition for the mechanical properties required in a given steel is the principal factor in considering weldability. The formulation of the welding procedure takes account of alloy content by the application of a proven Carbon Equivalent (CE) formula where

$$CE = C + \frac{Mn}{6} + \frac{Si}{24} + \frac{Ni}{40} + \frac{Cr}{5} + \frac{Mo}{4}$$

and the limiting value of this is 0.70 for QT 35 and 0.85 for Q1(N). Weldability decreases with increasing CE. The CE is, in essence, an index of Heat Affected Zone (HAZ) hardening and is related to the maximum rate of cooling which can occur during welding. Thus, for a given value of CE there is a thermal conductivity balance, which requires certain preheat temperatures in order to avoid HAZ cold cracking. It is, therefore, necessary to correlate CE, preheat temperature and plate thickness when welding this type of material.

Increased residual stress at tee junctions, coupled with insufficient 'through-thickness' ductility, led to an incidence of lamellar tearing in early submarines. Weld 'buttering' techniques, peening, and under-matching of weld metal were devices employed to overcome this problem. In the interim, the steelmaker applied intensive efforts towards producing 'cleaner' steel, to improve 'through-thickness' ductility and reduce tearing. This material was used for the first three vessels, and then there was a swing towards use of American HY 80 steel, until Q1(N), the latest British high-yield material, came into production.

Hull welding processes include submerged arc for rotated butt welds and manual metal arc for static seams and butts, with Manual Inert Gas (MIG) welding of frames to pressure hull. All weld processes are of the low hydrogen type, with electrical pre-heating of parent plate to a predetermined temperature (checked by Tempilstik methods prior to welding) and pre-baking (following oven-storage) of manual electrodes.

All pressure hull butt and seam welds are to Class I standard, determined by radiographic and ultrasonic inspection. Frame welds to pressure hull are inspected by ultrasonic probe, coupled with magnetic surface crack detection and visual checks.

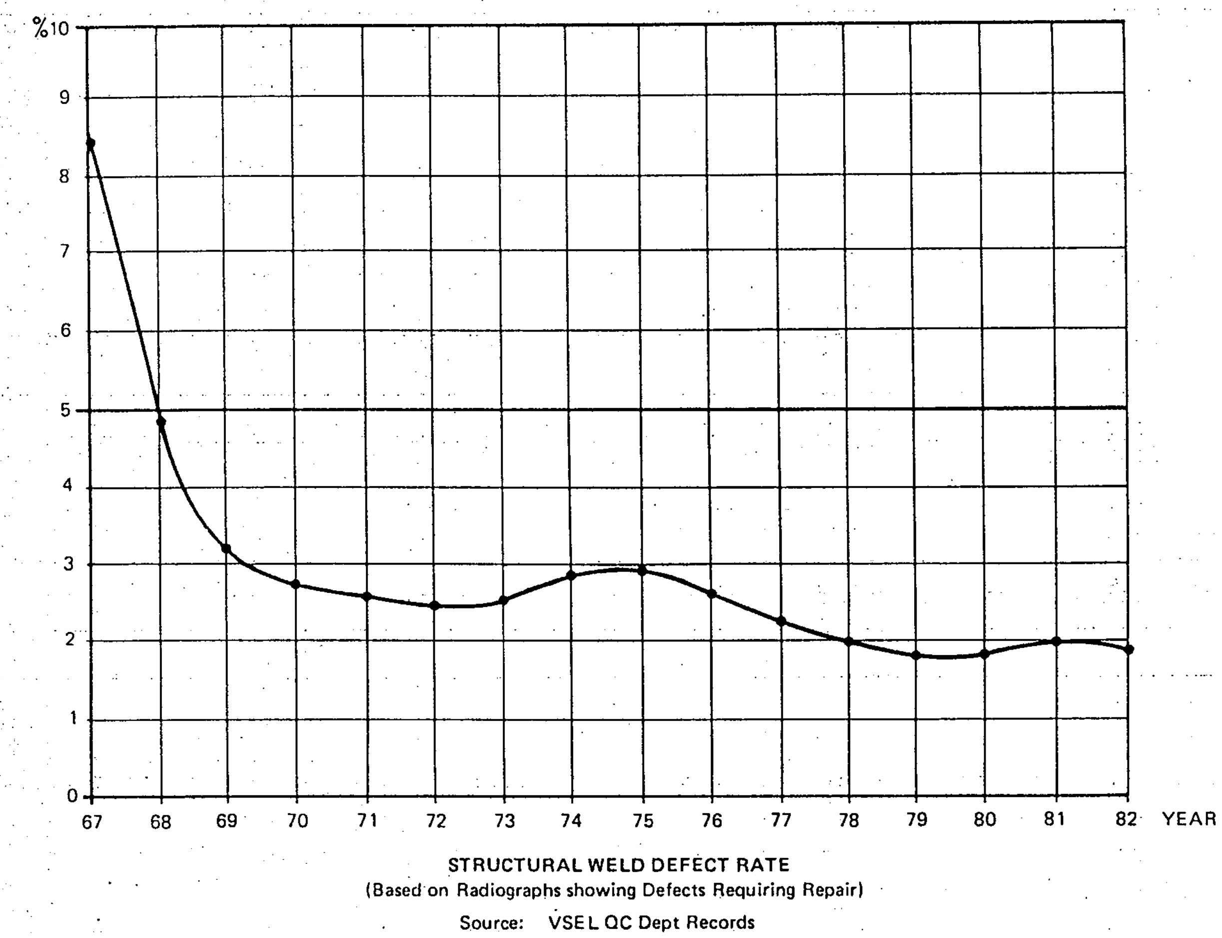


Fig 6 Structural Weld Defect Rate

In 1963, and after having employed outside consultancy ad hoc, the Shipbuilding Company established its own metallurgical capability, maintaining close links with the Welding Institute; Admiralty Research Establishments; British Ship Research Association, and the technical departments of welding process suppliers.

By virtue of continuous application, the incidence of repairable hull weld defects arising from the introduction of new alloy steels and heavy scantlings has been considerably reduced and has now levelled out at the low percentage (less than 2%) illustrated in Fig 6.

3.2.2 Hull Outfit

In recent years the shipbuilder's outfitting operations have been transformed. The array of propulsion, weapons, navigation, communication, sensors, life support and other equipment carried on board a modern submarine, together with associated power and control systems, adds up to a considerable and complex installation task (See Plate 1). Submarine safety standards have always been onerous, but with the advent of the nuclear submarine the most stringent safeguards against nuclear hazards were added. This experience has brought substantial changes in the field of mechanical engineeering.[3] New procedures and processes have been introduced to ensure structural and pressure-tight integrity as well as the cleanliness of piping systems.

Material history is stringently recorded and inspection, handling, quarantining, allocation and cleanliness are rigidly controlled to ensure complete confidence in specification and quality.

The ability of the Shipbuilder to produce pipework to exacting service standards, configured within very restrictive space envelopes and in the quantities necessary, is one of the most demanding parameters of a submarine programme. Traditionally, pipe runs were outlined on drawings, worked out in detail on board the first-of-class, and wire templates and/or tradesman sketches were made, from which pipes were fabricated ashore. Pipes were often sand or resin-filled and 'fire'-bent or hand-manipulated to shape. Most joints were made with massive and heavy mechanical couplings or, occasionally, were brazed or welded. A great deal of work had to be carried out on board.

By contrast, today, the draughtsman and the modeller produce a 1/5th scale three-dimensional model of each compartment, with all relevant structure, equipment, piping and cabling represented. Production information is obtained via a 'Computer Design from Engineering Models' (CODEM) system. The model is transferred to a reference table and, by using high-accuracy sighting telescopes, the pipe configuration is automatically mapped, relative to ship datums.

This and other information is entered into a computer to produce isometric pipe production drawings and parts schedules, which provide the tradesman with manufacturing information. Experiments are being carried out to automate bending and checking operations. Apart from hand-manipulated small bore pipes, CODEM information enables some 72% of piping systems to be pre-manufactured in the workshop. This radically reduces the amount of on-board work necessary in making templates and sketches.

Again, welding is a primary factor in both integrity and containment requirements. Materials welded include Q1N, HY80, mild steel, chrome molybdenum and stainless steels; 70/30 and 90/10 copper nickel; copper and monel. Welding specifications are Class 1 (nuclear quality) and subject to MOD acceptance standards. The majority of welds employ a Tungsten Inert Gas (TIG) process, the remainder being manual metal arc welding. Throughout manufacture, welding processes are subject to 100% inspection using radiographic, ultrasonic and other non-destructive testing techniques.

Reduced radius bending, the use of induction heating, extrusion-formed jointing, a range of cryogenic fittings and other techniques make their contribution. Overall, the aim is to produce high integrity systems and reduce on-board operations, at the same time improving efficiency and restraining costs.

The electrical outfit for an advanced submarine has to service the complexities of the propulsion systems, as well as a greatly increased electrical demand for dc and ac systems in a variety of voltages and frequencies to suit control, instrumentation, communication, navigation, weapons and life-support systems. The old-style wiring-up of electrical equipment initially involved pulling large continuous cables through the boat at an early stage of assembly; connecting up proceeded at a later stage, as surrounding structure was completed and as equipment progressively became available from suppliers.

Improved techniques and methods have had two aims: to complete more work early in the construction programme and to increase the volume of work undertaken in the workshop rather than in the cramped confines of the submarine. In the new procedure, bulkhead connectors allow 'in-line' jointing of cables each side of bulkheads and cable ends are 'made off' to space frame jigs simulating the actual equipments; final connections are then made by plug and socket. On the earlier submarines a great deal of outfitting remained to be completed after launch. However, design and production techniques have progressively improved. The other vital ingredient has been the detailed planning of the many outfit sequences in order to provide logical and orderly progression of installation work. Now, virtually all major equipment is on board at launch and up to 70% of all other installation work has been carried out.

Following the 1962 Nassau Agreement, the decision to construct British Nuclear Ballistic Missile System submarines to carry Polaris, further tested the technology and skills of two British Shipyards. The Polaris Weapons Command and Control system was, in the opinion of American experts, the greatest challenge which would confront the UK Shipbuilders. It embraced the interfacing of UK and USA equipments into a common system. It required the shipyard to set up, inter alia, a Weapons Systems Team; a Polaris drawing office; a calibration facility; a shore training unit (which reproduced one missile tube with all its controls, etc) and an organisation to deal with major US suppliers of command and control equipment, together with the associated hardware, software and interfacing. In the event, the organisation worked well, and indeed was able to equal, if not better, the completion time achieved by US builders.

Thus, in the last quarter-century there has been substantial progress in production methods and skills, which required a competent planning service and resolute management.

4. MANAGEMENT

The modern submarine is as great a challenge to the manager as to the technologist.

In their own inimitable style, the Americans had added a great deal of science to the art of management during their very determined NAUTILUS and POLARIS programmes. In common with their technology, this new scientific management was applied to the UK programmes, with substantial contribution to its success. Much has now become standard MOD practice on procurement contracts.

4.1 Planning

Growth in the size and number of departments; the time and effort taken to develop the design; and the new techniques and skills to be brought to bear on large submarine and surface vessel projects, call for the following crucial elements in planning (Fig 7):

- knowledge of the 'cardinal' dates (start production: keel laid: launch etc);

- a forward analysis of equipment: particularly those with long lead times;

- details concerning the availability of production drawings and information;

- exhaustive lists of materials, equipment and components necessary for the task, who is supplying them and what the supply position is;

- preparation for and execution of testing and commissioning programme;

- provision of adequate labour resources;

- methods of monitoring and analysis of performance for management purposes.

The Cardinal Date Programme (CDP) is the 1st Level Programme, carrying some 500 standard events, or milestones. 2nd Level planning is expanded from the CDP to cover:

- drawings, specifications, model and other design information;

- 'bought-out' equipment and materials;

- hull construction;

- electrical, piping, engineering, weapons and other outfitting operations;

- testing and commissioning;

- sea trials

A Critical Path Network of approx 1000 events is updated monthly, through the computer, to evaluate progress.

2nd Level programmes are detailed still further to a 3rd Level to ensure proper planning and control of each area of activity contributing to the project. Coverage is as follows:

- Design Programmes

- Drawings Control System
  MOD(N)
  Suppliers
  Shipbuilder Drawing Offices (3)

- Equipment and Material Programme
  MOD(N) - supplied items
  Shipbuilder purchases

- Models/Mock-ups

- Component Production
  Internal (see COMPARTS)
  External

- Hull Construction
  Steelwork production
  control system

- Outfit
  Compartment Programmes
  COMPARTS Computerised scheduling
  system (See below)

- Testing and Commissioning
  Test Forms
  Test Schedules
  'Plan-of-the-Day' Minutes

- Ship Support Documentation

- Plant Modification (when necessary)

- Labour budgeting

The computer has been used since 1964 to schedule submarine outfit operations. There follows a description of the current method.

COMPARTS (Fig 8) splits the installation task down into a complete list (perhaps a million items) of all the components required to identify WHO is to do WHAT, AND WHEN. For certain systems this includes information for manufacture prior to installation. The core of 'COMPARTS' is a computer file listing all components, classified into categories which require similar treatment for manufacture and/or installation purposes. Classifications include:

- outfit equipment;

- ventilation trunking;

- electrical equipment;

- engineering equipment;

- pipes, valves, fittings etc.

For each line item within 'COMPARTS', a ticket is computer-produced, together with tabulations informing departments what is expected of them and when.

To minimise the clerical work of each department in the chain, completion/availability is signalled by a tear-off portion of each line item ticket. In this way, the whole system is quickly updated to provide production control information, progress statistics, and graphs (Fig 9).

Micro-computers and on-line terminals hold great promise for further refinement of this type of planning and data system. Many of the planning lessons learned during the nuclear submarine programme have been incorporated into MOD(N) Specification DG Ships 113A 'Planning Programming and Scheduling the Building of Naval Vessels,' January 1972.[4]

4.2 Cost Control

Firm discipline is essential if programme and cost overruns are to be avoided in large high-technology projects. The fact that the last 25 years of sustained submarine production has attracted no significant public controversy over cost problems says a great deal for the care taken to plan in detail and to monitor progress and expenditure realistically.

Effective cost control begins with appropriate contractual arrangements.

Where a warship project includes elements of development beyond the shipbuilders' recent past experience, the contract has been placed on a basis of cost incurred plus a profit fee, for early technical development and construction, with the proviso that the builder would quote a fixed price prior to completion of the vessel: this would be at that stage where information

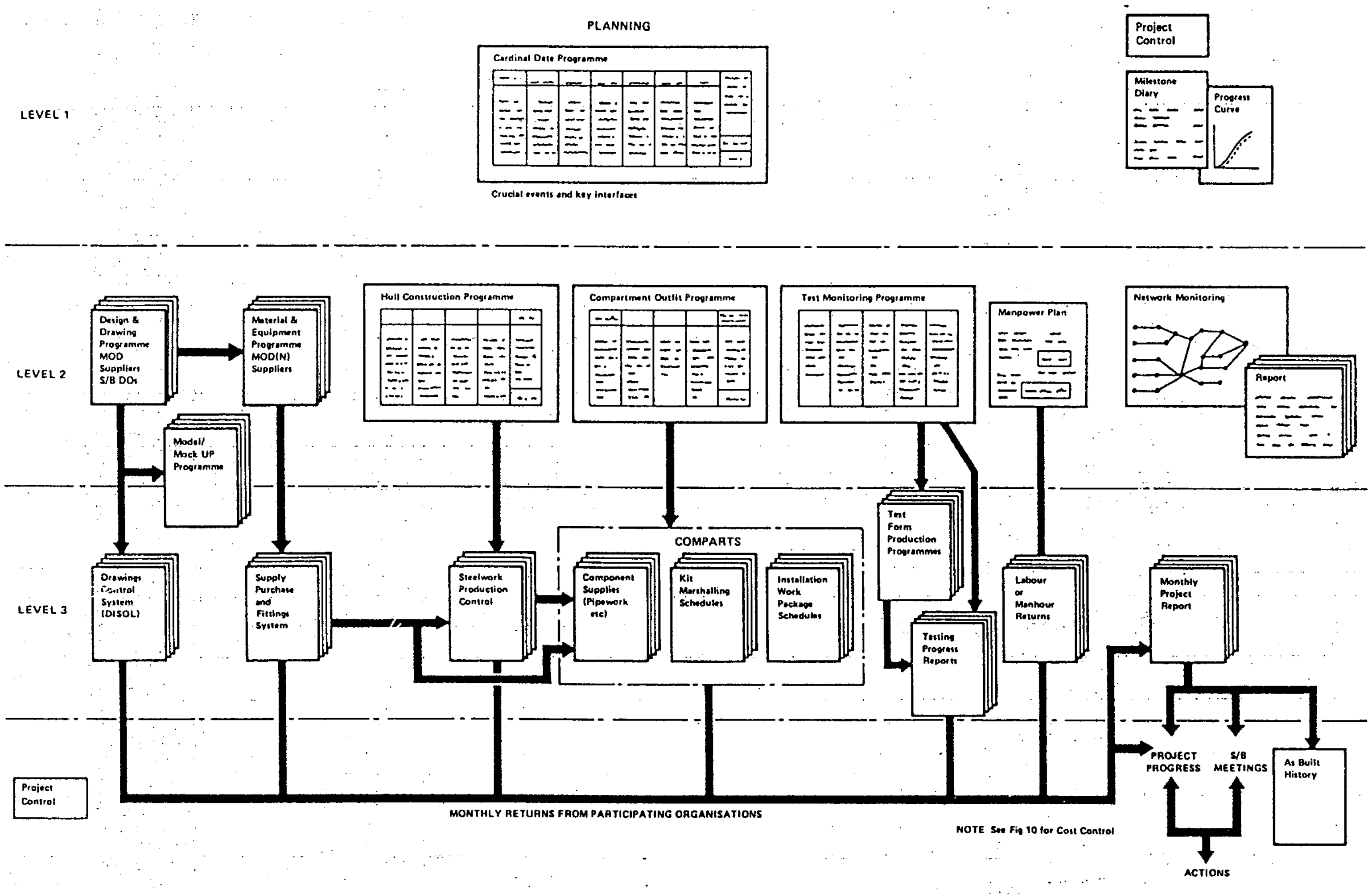


Fig 7 Planning and Project Control System

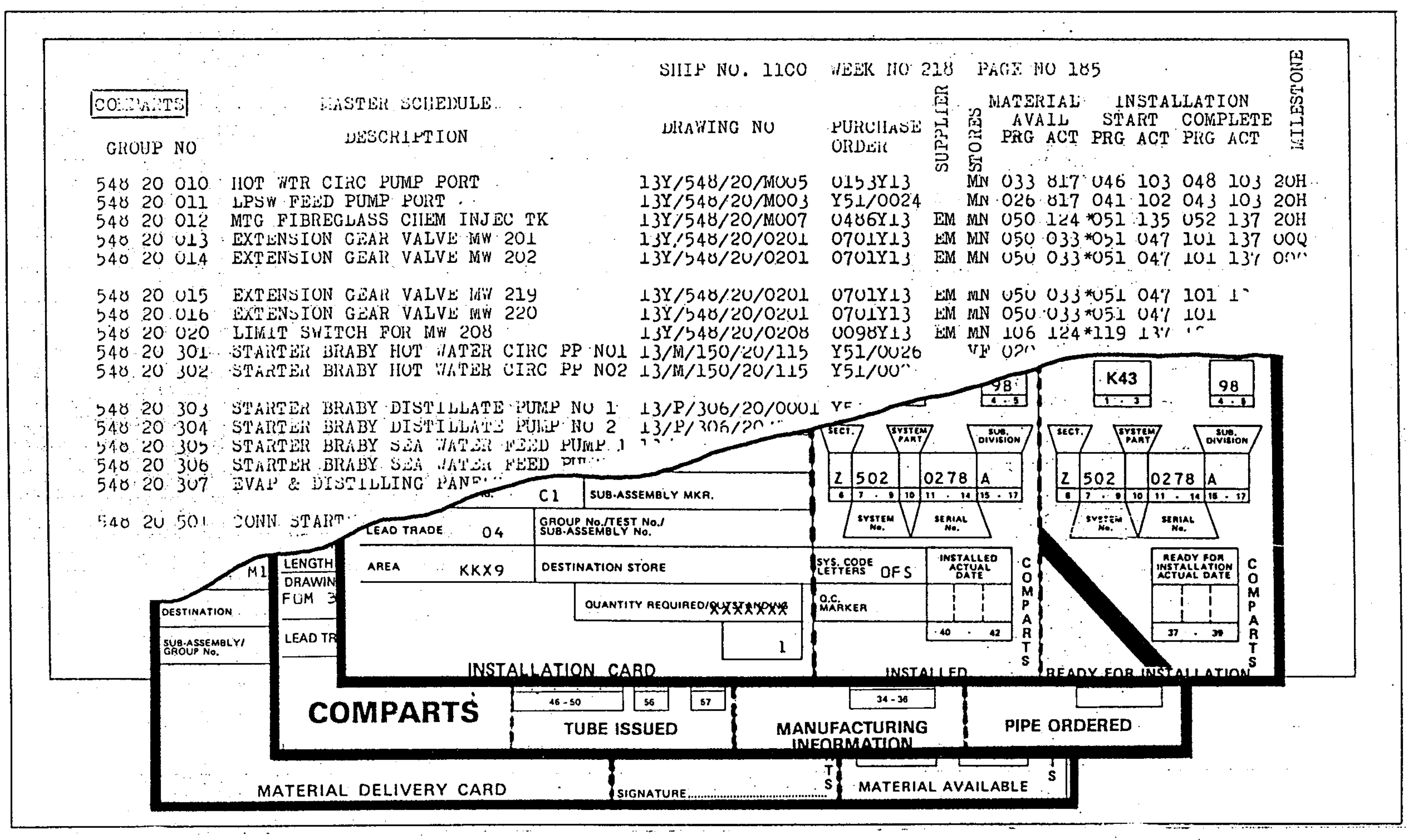
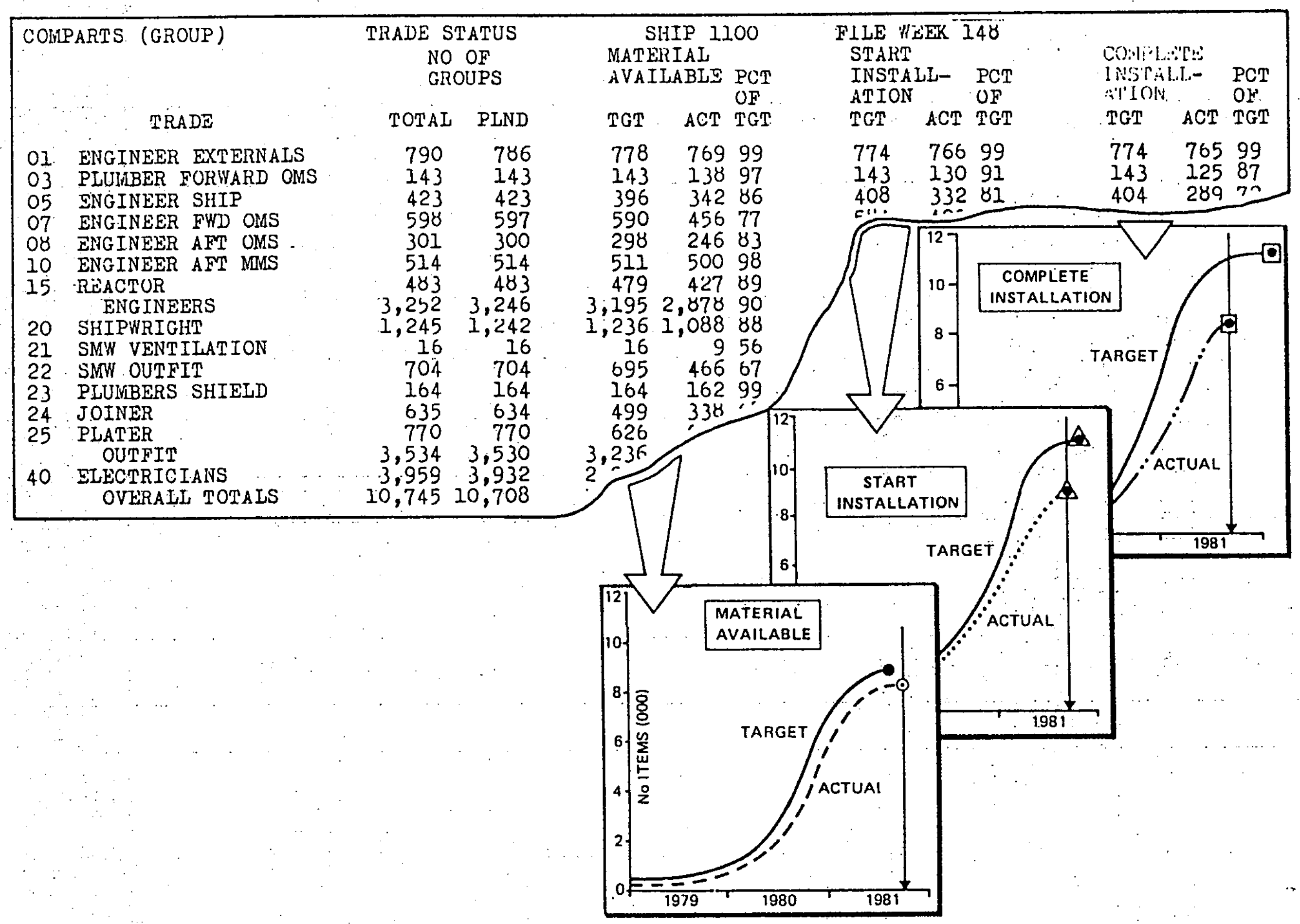


Fig 8 COMPARTS Printout and Cards


COMPARTS (GROUP) — TRADE STATUS — SHIP 1100 — FILE WEEK 148

	TRADE	NO OF GROUPS TOTAL	PLND	MATERIAL AVAILABLE TGT	ACT	PCT OF TGT	START INSTALL-ATION TGT	ACT	PCT OF TGT	COMPLETE INSTALL-ATION TGT	ACT	PCT OF TGT
01	ENGINEER EXTERNALS	790	786	778	769	99	774	766	99	774	765	99
03	PLUMBER FORWARD OMS	143	143	143	138	97	143	130	91	143	125	87
05	ENGINEER SHIP	423	423	396	342	86	408	332	81	404	289	[illegible]
07	ENGINEER FWD OMS	598	597	590	456	77						
08	ENGINEER AFT OMS	301	300	298	246	83						
10	ENGINEER AFT MMS	514	514	511	500	98						
15	REACTOR	483	483	479	427	89						
	ENGINEERS	3,252	3,246	3,195	2,878	90						
20	SHIPWRIGHT	1,245	1,242	1,236	1,088	88						
21	SMW VENTILATION	16	16	16	9	56						
22	SMW OUTFIT	704	704	695	466	67						
23	PLUMBERS SHIELD	164	164	164	162	99						
24	JOINER	635	634	499	338							
25	PLATER	770	770	626								
	OUTFIT	3,534	3,530	3,236								
40	ELECTRICIANS	3,959	3,932	[illegible]								
	OVERALL TOTALS	10,745	10,708									

Fig 9 COMPARTS Trade Status Printout and Performance Trend Graphs

and experience on the project were sufficient to allow a reasonably accurate estimate of the total cost to be made. Within the fixed price eventually determined there remained a number of exclusions which, because of the 'First-of-Class' nature of the submarine, could not be estimated with any degree of accuracy. For succeeding submarines the fixed price contract applied, again with a certain number of exclusions in 'grey' areas. As experience and the estimating databank grew, so the exclusions were reduced, and in all recent contracts a 'target cost incentive-fee' type of contract has been the order of the day.

In this type of contract, a target cost is agreed by both parties on the basis of carefully estimated figures. A sharing arrangement is negotiated around this target whereby the shipbuilder's profit is increased by a proportion of any cost savings and, conversely, if the target cost is exceeded, the profit is reduced by a proportion of the cost overrun, up to a certain level above which the shipbuilder bears the whole of the excess cost.

The percentage profit applied to 'non-competitive' contracts such as these (whether on a 'risk' or 'non-risk' basis) is determined by a formula which was first agreed by the Government and the CBI in 1968, and which is reviewed every three years. Its aim is to give defence contractors a return on capital broadly equal to that of a wide spectrum of UK Industry. The profit formula for risk contracts currently allows 14% on capital, plus 4% on cost which, on a typical 'cost of production to capital employed' ratio of 2.25 to 1, gives 23% return on capital. The shipbuilder's ability to achieve such return depends, of course, upon his actual performance in terms of time and cost, related to those of the estimate upon which his contract is based. The formula for non-risk contracts allows a little over half of the return permitted for risk contracts, for obvious reasons.

For First-of-Class submarine contracts, many design and technical tasks are carried out prior to the main contract, in the form of pre-contract 'Project Orders'. As previously defined, there may be 8 to 12 such Orders, each of which forms a separate small contract, normally dealt with on a strictly-budgeted basis and which could, therefore, be classed as cost plus a profit fee.

In all cases where a price cannot be fixed for the contracts, strict budgeting procedures are carried out, with monthly monitoring to keep close control of cost against predetermined targets.

The Shipbuilder has built up a Cost Control department which, in addition to discharging the Company's contractual budgetary control duties, is now an integral part of the management function.

Department manhours and cost budgets, are extracted from the estimates (Fig 10). These are related to project programmes to derive Production Cost Plans. Returns are analysed monthly to provide cost reports to departments, to Company management and (on non-competitive contracts) to MOD. In addition to assessing the current status, the anticipated final out-turn is also forecast monthly. Each three months, a cost report on labour, materials and sub-contracts serves to record changes in tendered (or target) sums, as project definition improves. An annual (or as necessary) review of overall cost plans follows. The systematic breakdown of estimates and plans has paid dividends in terms of controlling manpower, of measuring changes in productivity levels, and in financial control.

4.3 Project Management

The essential principle of Project Management is that undivided attention is given to a particular enterprise. It took some years to learn how to integrate the traditional shipyard line management, responsible for control of resources contributing to the total shipyard programme, with 'project style' management, in which each project manager has responsibility for co-ordinating all the elements of one project only.

However, in any multi-project organisation, each project must compete for resources and services. Inevitably this limits, to a certain degree, the freedom of individual project managers to take action.

Project Management structures are, therefore, superimposed on the responsibilities of functional management, to form a matrix-style organisation. Fig 11 shows a typical Project Management Team working alongside, and integrated with, Line Management.

The principles adopted are:

Each major project has a Project Director. He must represent the interests of 'his' project at the highest level within the Company; represent the Company's interests to the Customer, and act as the Customer's senior point of contact with the Company.

Under each Project Director there is a Project Manager whose main terms of reference are 'to co-ordinate all aspects of the project, and any supplementary Project Orders, to ensure that the Company's overall commitments can be met in a timely and profitable manner'.
A Project Officer and a Cost Control Officer work closely with the Project Manager. Their main functions are contract strategic planning, progress and cost monitoring, and reporting to the Company and the Customer on a 'shared information' basis. Other departmental project leaders are assigned as appropriate, as indicated in Fig 11.
The whole Project Management team, including Planning and Cost Control, adds about 2% to the contract price. But this service is cost-effective, not only because it provides a practical planning service but also because close monitoring ensures that departures from plan are exposed at the earliest possible stage, thus allowing timely corrective action to be taken.

5. QUALITY ASSURANCE

The Quality Assurance organisation set up for building nuclear submarines has been described in a previous RINA paper[5]; the salient points are:

(a) the identification of areas critical to the safety of the submarine and its systems.

(b) arrangements for provision of assurance of quality in material and manufacture in those areas;

(c) a Quality Control department, independent of the production organisation;

(d) the transfer of responsibility to the contractor for his own and his subcontractors' products;

(e) the introduction of Shipyard Test Groups.

In the early 70's, new Defence Standards of Quality Assurance (Def Stan) coupled with a system of MOD Contractor assessment were introduced throughout the British Defence industry. By this assessment, firms are formally examined/assessed for competence to a level of quality necessary for the particular product which they supply. The new Defence Standards require a total quality assurance system, as distinct from the inspection-orientated quality control system previously employed.

5.1 Effects on the Shipyard[6]

Tighter disciplines were required, involving:

assessment by MOD(N) at 2-yearly intervals of the Shipbuilder's QA capability and performance;

compilation and observance by the Shipbuilder of written 'Work Instructions' for all operations/processes requiring such treatment;

introduction of QA into ship design functions;

control of subcontractor material;

calibration of test equipment, whether used by Shipbuilder or his subcontractors.

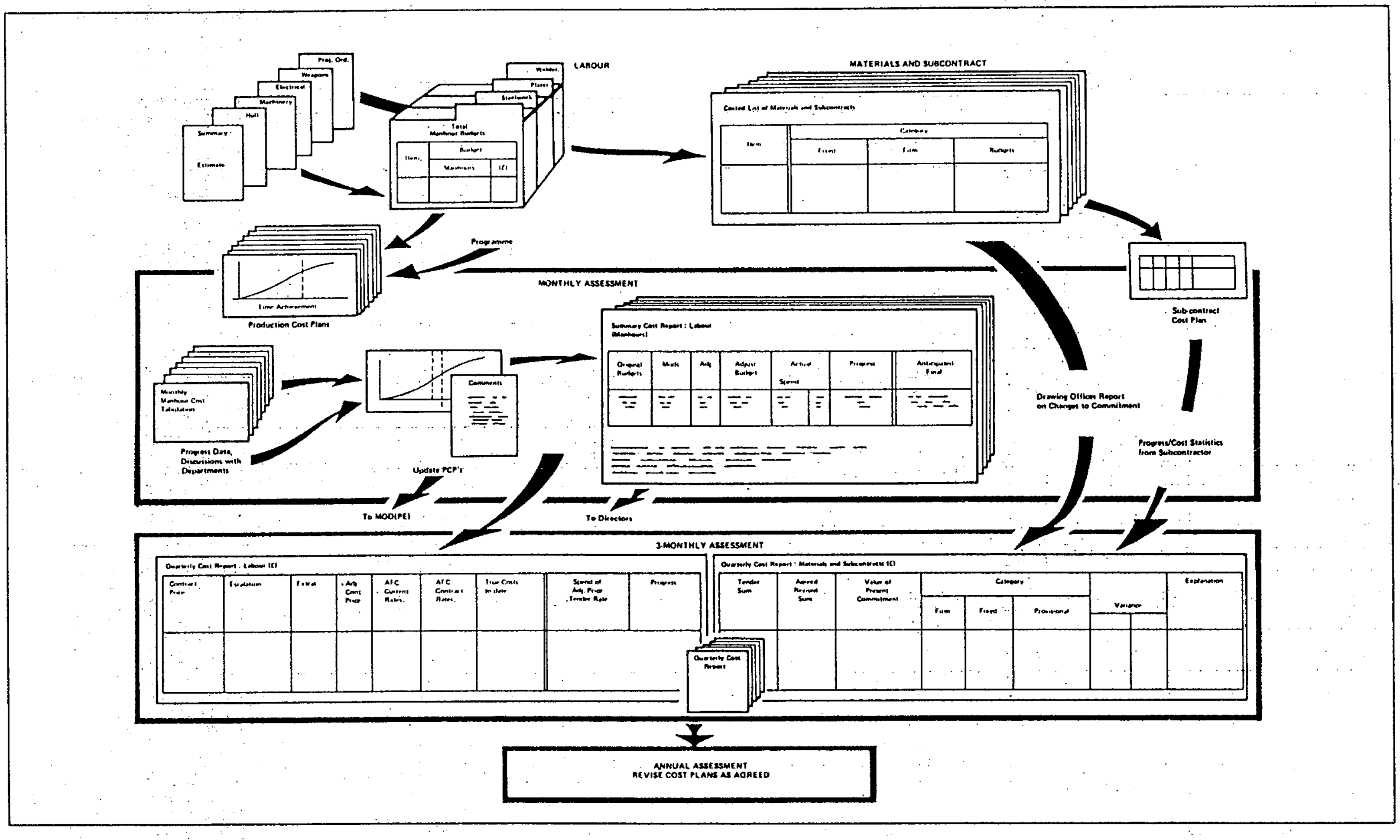


Fig 10 Estimating, Budgeting and Cost Control

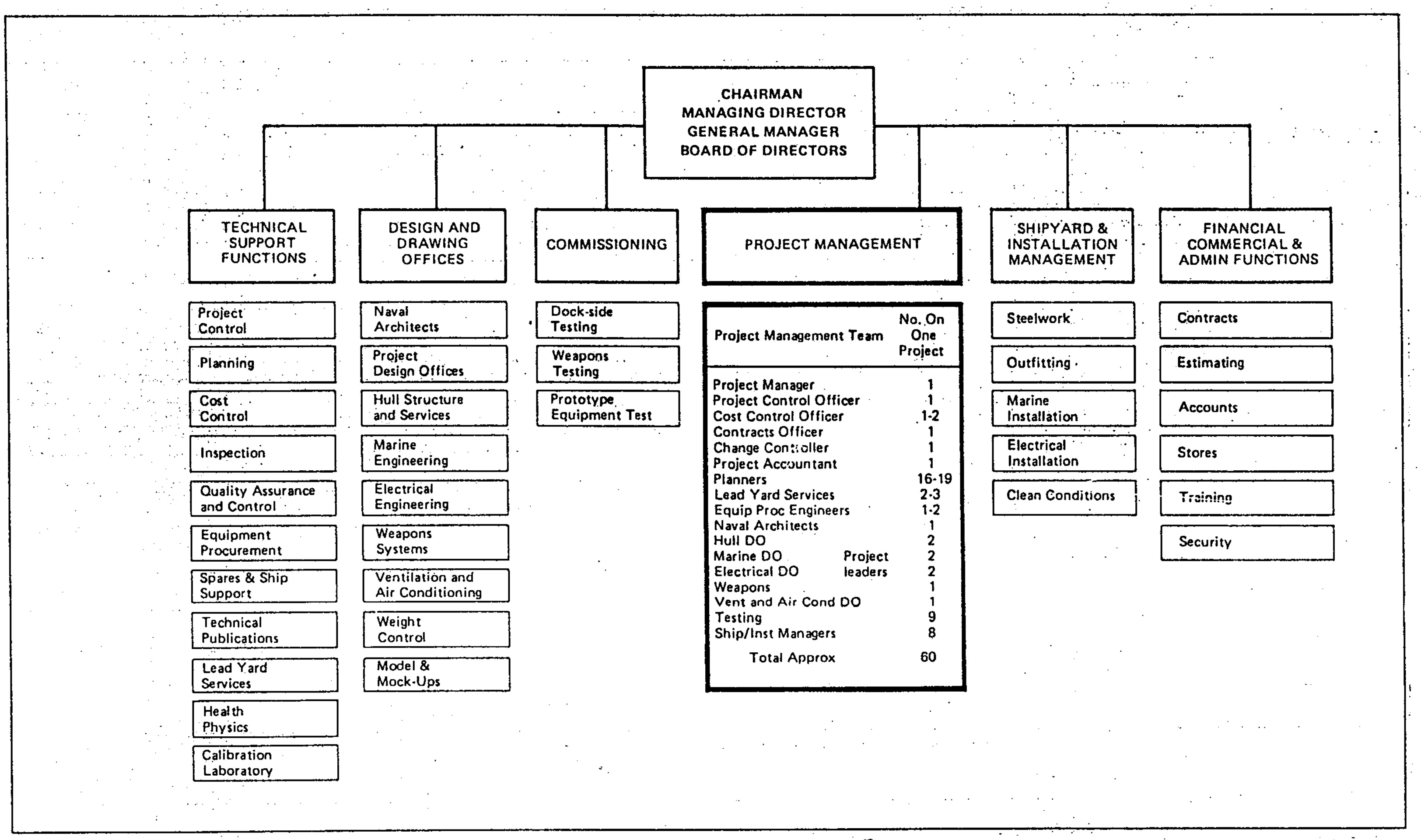
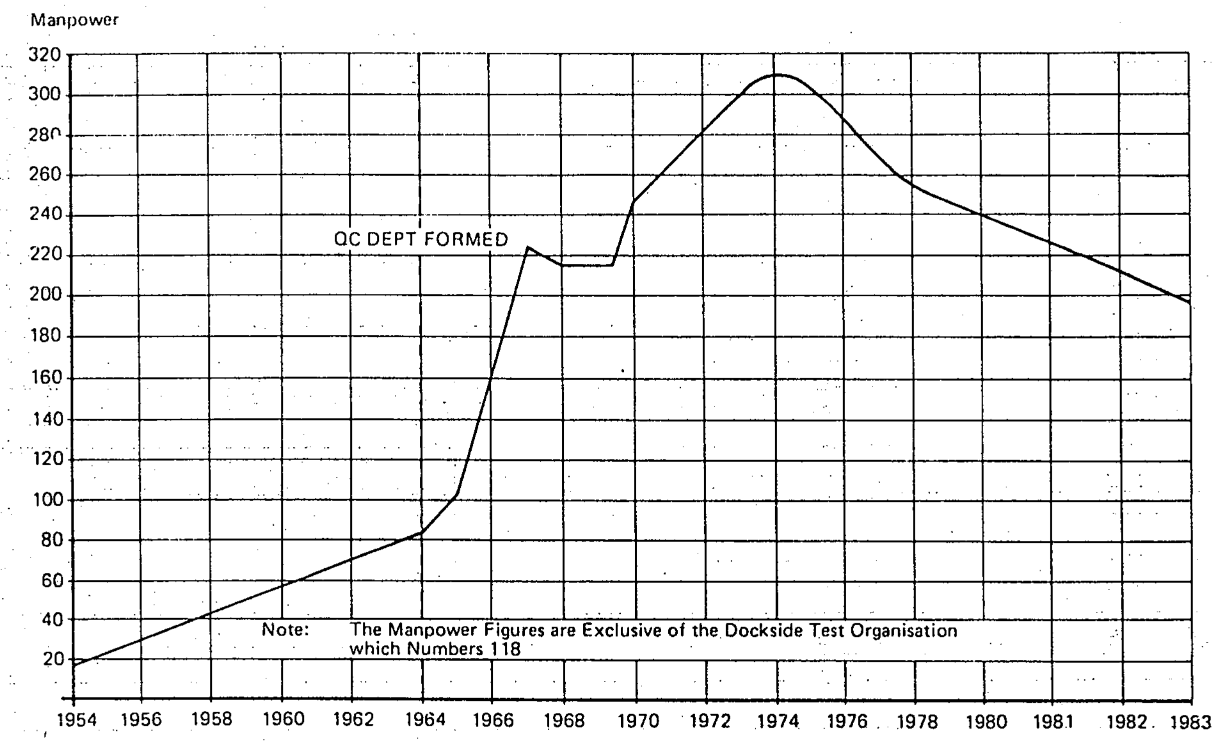


Fig 11 Project Management Organisation



THE GROWTH OF QUALITY CONTROL
Source: VSEL Records

Fig 12 The Growth of Quality Control

The build up of QA/QC personnel in Vickers to respond to the new standards is shown in Fig 12. After reaching a peak in 1974, numbers reduced to a lower 'steady state' as the new system became routine. At the same time, since the formation of Defence Quality Assurance Board (DQAB) and transference of QA responsibility to Industry, the number of Ministry Overseers and Inspectors in works and factories has reduced to less than half the original number, and is still decreasing.

5.2 Improved Links between Design and Production

From evidence available, both to the Ministry and the Shipbuilder, QA is making a significant contribution to warship construction, leading to increased effectiveness of ships and equipment in service. The most significant determinant of quality is good design: design deficiencies mean either expensive correction when the hardware is built, or that the user has to tolerate higher maintenance/sub-standard performance throughout the life of the product. Reliability prediction for essential equipments and systems is most important. The designer must increasingly take into account the implications of through-life support when deciding design options. Hence, feedback from the operator and maintainer is an essential prerequisite to progression in design, as is the matter of availability, reliability and maintenance (Section 6).

5.3 Responsibility of the Production Organisation

The original Quality Control organisations were independent of production and reported directly to Senior Management. They were responsible for the control of standards, inspection and the provision of assurance documentation. However, the attitude of the craftsmen (who considered the activities of the QC/QA Department as infringing upon their own responsibilities for craftsmanship) brought about a change of policy.

Within this policy, the Quality Assurance Department publishes required standards; audits quality performance and maintains the QA documentation: the task of attaining the desired quality performance has been returned to where it originated, ie within the Production function.

6. SHIP SUPPORT

The Shipbuilder's involvement does not end when the submarine leaves the shipyard for its 25 years' life with the Royal Navy.

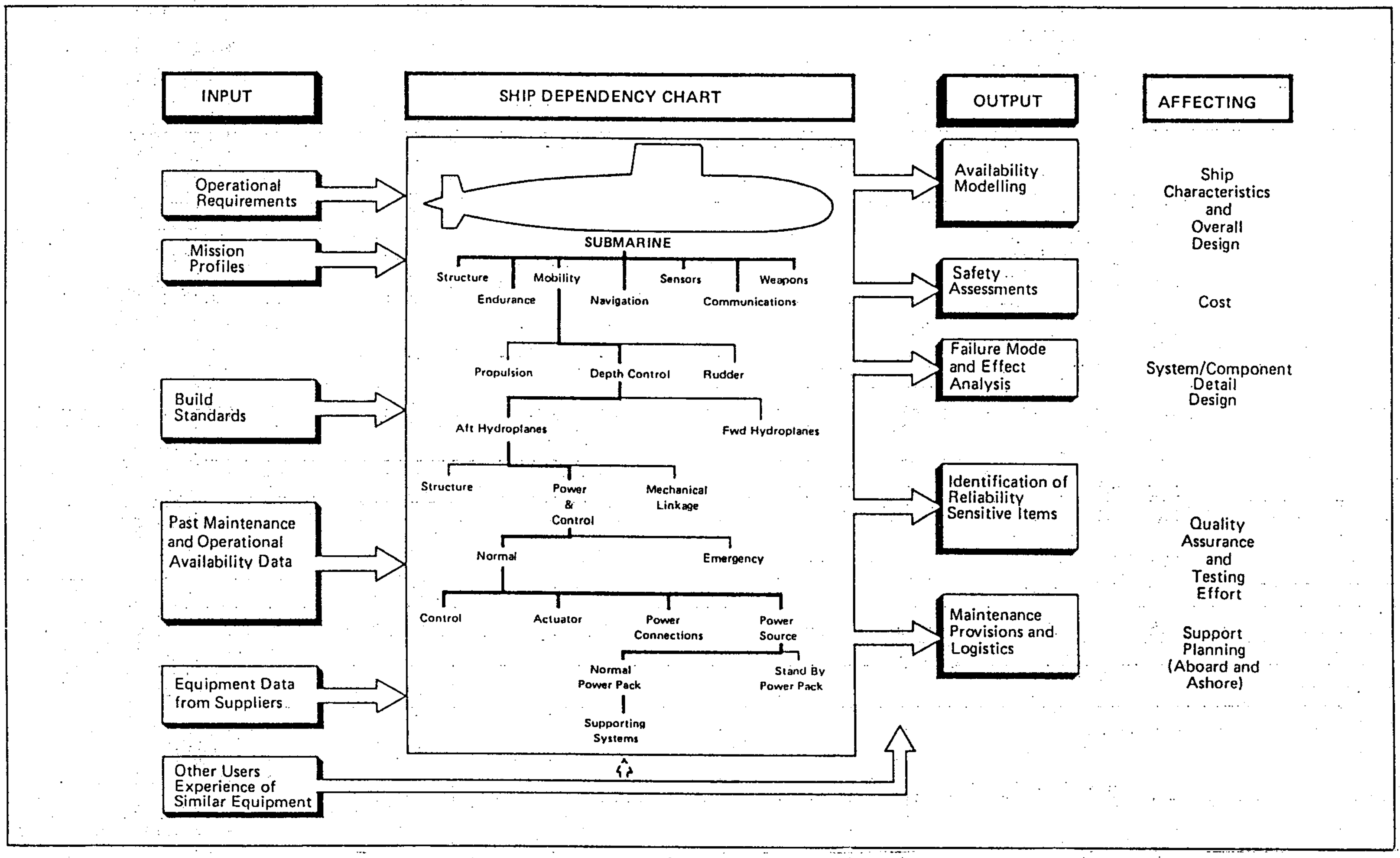


Fig 13 Availability, Reliability and Maintainability (ARM) Techniques

6.1 ARM techniques

Availability, Reliability and Maintainability are essential factors in the design of any modern warship, which must be considered at the earliest possible stage of design and modelling to assure optimum safety and service performance. The techniques employed (illustrated in Figure 13) are as follows:

(a) **Availability modelling** - a powerful analytical tool used to assess the probability of a ship achieving given mission profiles. The assessment begins by producing a Ship Dependency Diagram showing the relationship between operational characteristics and the systems/equipments which support them. Each element is then examined to determine its likely failure rate, causes and consequences (Failure Mode and Effect Analysis). The results are applied to a Ship Availability Model which produces theoretical availability data for various mission profiles. This approach is most useful in comparing the reliability of varying system proposals in the design stage, and for demonstrating that systems selected do not have an 'Achilles heel'.

(b) By the use of **models and mock-ups,** equipment maintenance envelopes and removal routes are carefully designed, checked and then verified finally at ship.

(c) Design decisions affect through-life cost, and ARM techniques coupled with systematic design reviews offer a means of achieving an acceptable balance between procurement and upkeep costs and operational targets.[7][8] The greater attention being paid by MOD(N) and the Shipbuilder to this aspect of design demands a good-quality feed back from service, so that assumptions can be verified and improved data provided for availability modelling.

Through-life costing is by no means a simple exercise but recent work suggests that the largest single element of through-life cost lies in support, ie maintenance, refit and modernisation.

The Navy must be well informed on the designed capability of its equipment and must be trained to operate and maintain it. Accurate information must readily be to hand, for training, for the rapid diagnosis of problems and for their solution. Logistic support by way of planned work schedules and spares availability is also essential.

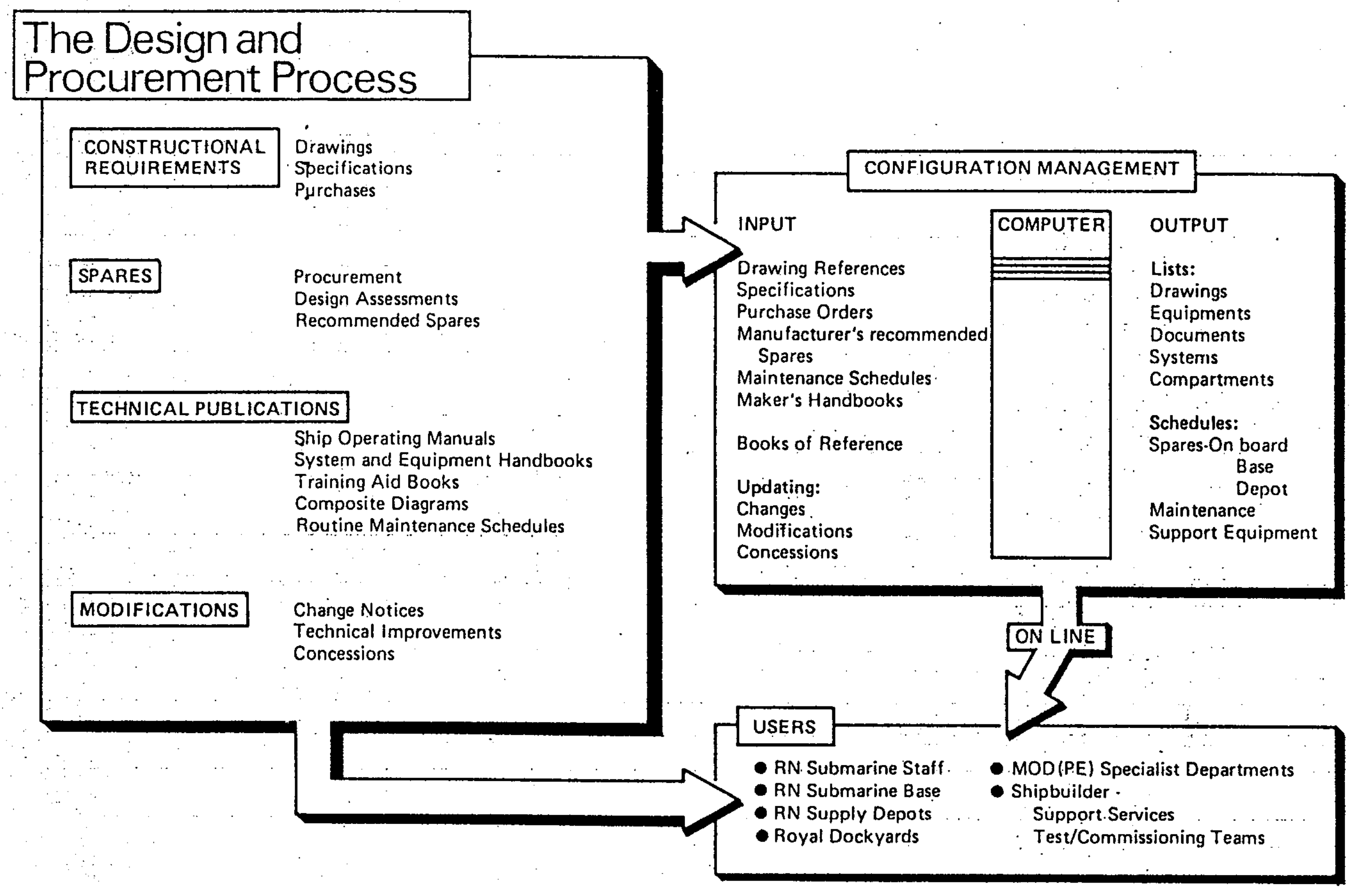


Fig 14 Ship Support

The partnership theme is again to the fore as MOD, Royal Navy establishments, the Shipbuilder and suppliers work to ensure high operational reliability and effectiveness (Fig 14).

6.2 Handbooks and Manuals

Under MOD guidance and approval, and assisted by information from suppliers, the Shipbuilder expends for each class of submarine approximately 100 man-years of effort in producing Technical Publications, including:

- the ship operating manual,
- systems and equipment handbooks,
- training aid books,
- composite diagrams,
- routine maintenance schedules.

These aids are made available to the submarine staff, to training establishments, Naval Dockyards, Support Bases, MOD specialist departments and to the Shipbuilder's testing and commissioning team.

6.3 Configuration Management

For the Submarine Base (responsible for inter-patrol maintenance), and the Royal Dockyards (major refits, repairs etc) accurate information about the configuration of the nuclear submarine is essential. The heart of this 'Configuration Management' system is a computer file, comprising a comprehensive Drawings List and an Equipment Master Record.

The Master Record is progressively expanded to define each piece of the submarine's supportable equipment, with information such as Maker's Drawing Number, RN Modification Status, NATO Stock No., Naval Stores Reference No., installation details and the like. The Drawing List and the Master Record are continually updated to take account of modifications, additions, production deviations etc, so that each individual submarine has its own high-integrity record. This accurate identification of fitted equipment ensures rapid provision of the correct spares.

6.4 Spare Gear

During the design and procurement phase, and as ship systems are developed - with identification of preferred equipment and components - suppliers are requested by the Shipbuilder to provide lists of recommended spares. The Shipbuilder then, in conformity with the Availability and Reliability process, assesses the system and its components and passes the suppliers' and his own views to MOD as recommendations. MOD then, in consultation with its Customer, the Royal Navy, finalises the submarine spares policy and catalogue.

A specialist spares section of VSEL's Procurement Department plays a major role in placing and progressing spares orders.

These three elements of Shipbuilder support - Technical Publications, Configuration Management and Spare Gear - add up to approximately 150 man-years of effort, which has made a substantial contribution to the high levels of operational availability of the RN submarine fleet.

CONCLUSIONS

Over the last 25 years, both MOD and Industry have made many changes in capability and organisation to design and build modern submarines. The size of product and the challenge of expanding technology have forged strong links between the organisations involved and those who work in them.

In the Shipbuilding sector one sees a project-oriented organisation, with a ratio of staff to industrials far higher than the average for the Industry, but essential for safety verification, for efficient management of expensive resources, and for long term product development and support. In the course of the programme there have been lapses in design, in quality and in production control: the management system adopted has ensured that these aberrations have been detected and dealt with, before they could seriously jeopardise safety or project viability.

This high-overhead type of organisation precludes the Shipbuilder from participation in other than high-technology work.

The UK submarine programme received valuable help initially from the USA, but the later nuclear programmes have been almost entirely British; the result of unremitting efforts from the MOD and industry teams involved.

Future submarine building operations will encompass the following:

- Increased statistical control of build and outfit operations.
- More precise resource planning.
- Optimisation of production engineering principles throughout.
- Reduction in unit cost.

overall, a determined drive to improve the effectiveness of the submarine and the means by which it is produced.

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