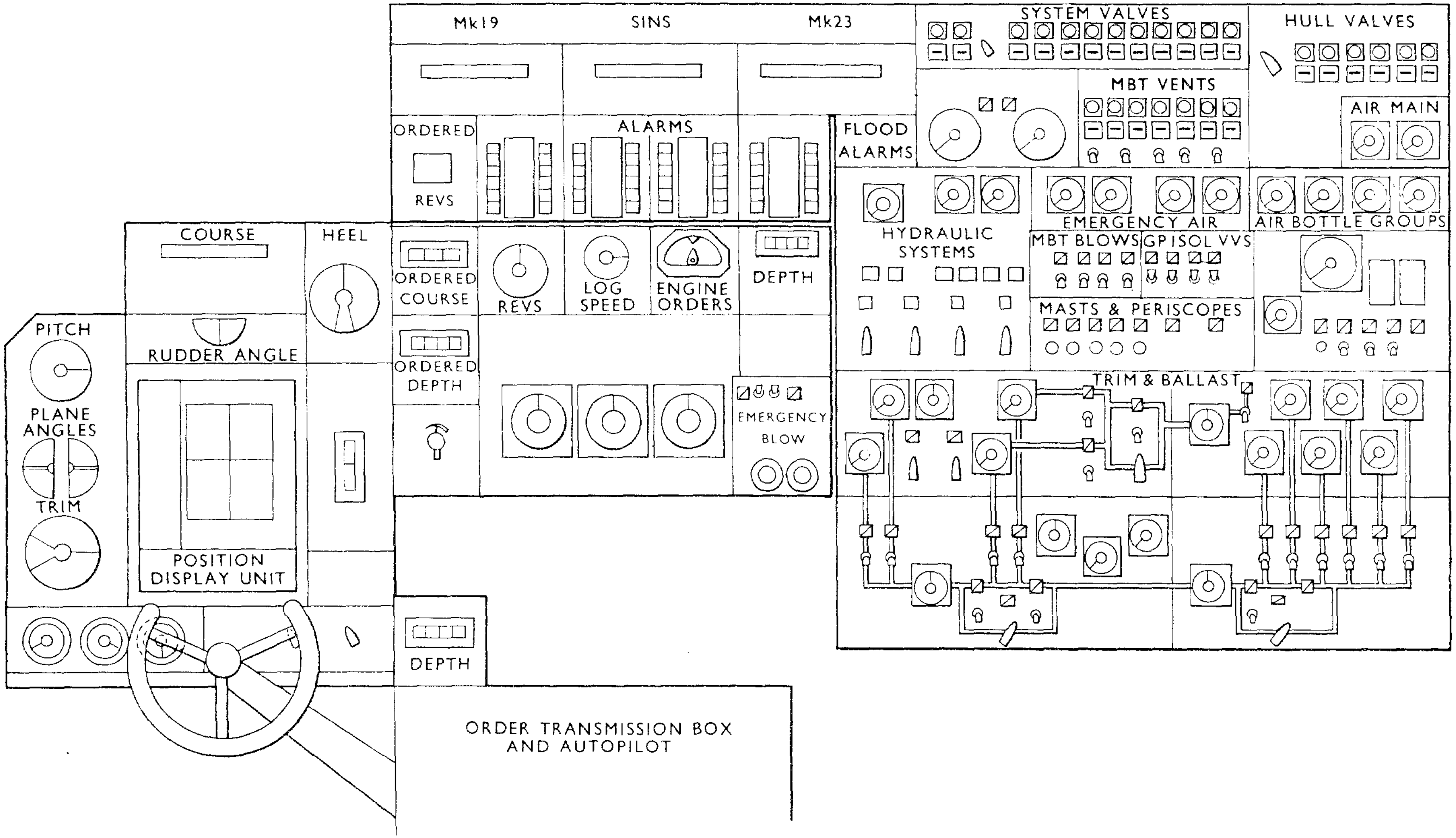

FIG. 1—MANOEUVRING AND SYSTEMS CONTROL CONSOLES

SUBMARINE CONTROL SYSTEMS

BY

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Introduction

Submarine control involves the balancing of both static and dynamic forces acting upon the hull.

The static forces of weight and buoyancy are balanced and adjusted by means of the trim and ballast systems and by the HP and LP air systems.

The dynamic response is primarily dependant on the speed and attitude of the submarine and on the control forces exerted by the after hydroplanes and rudder. The forward hydroplanes are most effective in controlling depth at low speed, but are also important for controlling pitch at higher speed in the event of an after planes malfunction.

It is the responsiveness of a submarine at high speed, as much as the desire for reduced manning levels, which dictates the need for centralized, remote operation of the ship control systems, particularly in emergency modes. In R.N. submarines the remote operation of these systems in their normal modes is entirely dependant on a secure 24 volt d.c. system and on the hydraulic servos and actuators which are controlled by it. In contrast the emergency operation of vital control systems is facilitated by high pressure air, which is generally regarded as the most secure source of readily available energy in the submarine.

The primary and emergency ship control systems, which are under the supervision of the officer of the watch in the submarine control room, are the subject of this article. These systems are operated and monitored at the manoeuvring control and systems control consoles (FIG.1).

Safety Considerations

Safety has, for obvious reasons, always been a dominant factor in the submarine community. Satisfactory standards have, in the past, been maintained by a continuity of experienced personnel able to exercise 'good submarine practice' at all levels of design, construction, operation, and refit. The increased complexity of systems, combined with greater mobility of personnel, have tended to dilute the experience upon which safety was traditionally based; but the introduction of nuclear propulsion brought with it a disciplined approach to safety, including stringent documentary procedures which formed the basis for the introduction of stricter disciplines in non-nuclear areas.

Historical perspective is provided in FIG.2 which illustrates the number of submarines that have been lost in peacetime in each decade of this century. The total of declared losses—and there are obvious omissions in the records of Soviet and Eastern Bloc navies—amounts to 97. Of these some 38 per cent. resulted from collisions, usually with surface ships; 29 per cent. were caused by failure or mismanagement of hull openings; and 15 per cent. were lost as a result of foundering or explosion. The remainder were lost for unknown reasons, mostly in deep water. In fact it is somewhat disturbing to note that almost half the sinkings which have occurred during the last three decades have been for unaccountable reasons.

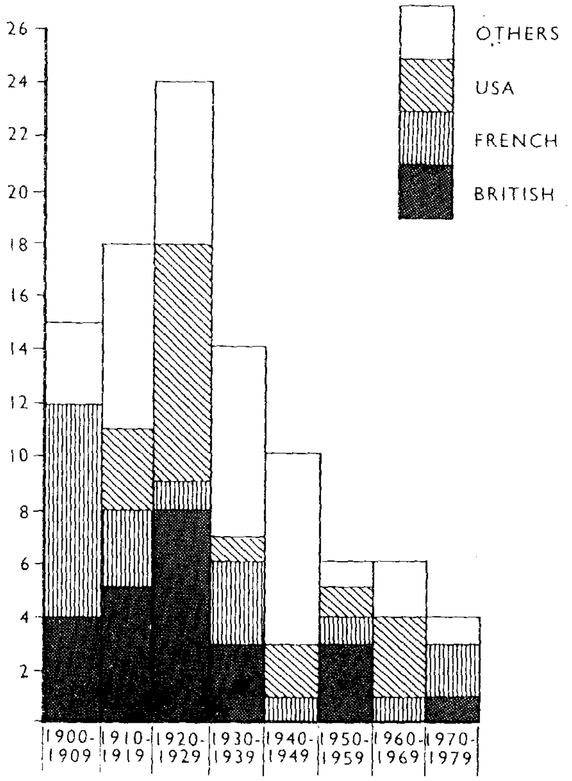

FIG. 2—RECORDED PEACETIME SUBMARINE LOSSES

Following the first reported loss of a nuclear submarine, U.S.S. *Thresher*, on 10 April 1963, the Congressional Joint Committee on Atomic Energy concluded that, although the specified cause of the *Thresher* loss was not known:

> Investigations revealed that in parts of the ship, practices, conditions and standards existing at the time were short of those required to insure safe operation of the *Thresher*. Basically, the ship was built to two standards. The standards of design and construction for the nuclear power plant were more stringent than for the rest of the ship. Of particular note is the technical specification requirements were not greatly different, but that adherence to them was far more strict for the nuclear power plant than for the rest of the ship.
>
> It is also obvious that while nuclear power was revolutionizing the submarine as a weapons system during the past 10 years, the more conventional aspects of the submarine and its safety devices were not keeping pace with the more stringent performance requirements of greater endurance, higher speed, and deeper submergence. For example, the design and limited blowing capability of the deballasting system which might have been adequate for World War II and post-war conventional submarines were inadequate as an emergency system for the large, deeper diving, higher performance nuclear submarines.

The loss of *Thresher* gave rise to a comprehensive review of submarine design standards and construction procedures in the R.N., and to the establishment of a standing Submarine Safety Working Party (SSWP) of which the author is currently chairman. It so happened that our second generation of nuclear submarines, the SWIFTSURE Class, was at the sketch design stage during these investigations so that many of the recommendations and new ideas were readily injected into the design.

The establishment of formal quality assurance procedures in the building shipyards and refitting dockyards was recommended by the SSWP and subsequently adopted on a selective basis for work designated 'first level'. A first level system or equipment was defined, for this purpose, as one in which a single failure could, under particular accident conditions, prevent the submarine from surfacing. The quality assurance of first level components requires documentary evidence of all aspects of manufacture, including material identity from stockyard to scrapyard, process control, workmen's qualification, inspection, and tests. It also requires the maintenance of a unique identity for all finished components to which the documentary evidence may be related.

Hydraulic Oil Systems

System Growth

The hydraulic oil system, known to generations of diesel submariners as the telemotor system, is of crucial importance to the safe, centralized control of a modern high-speed submarine. While the primary functions of the hydraulic system remain largely unchanged, the considerable number of additional equipments fitted in a nuclear submarine have caused a growth in system size and complexity which is indicated in TABLE I by comparing the hydraulic services in the A Class submarine of 1943 with those in our first generation nuclear submarines of the VALIANT Class.

TABLE I—*Hydraulic Oil Services*

A Class	*Additional services in Valiant Class*
Torpedo tube bow caps	Main ballast tank blow valves
Torpedo lifting press	Air bottle group isolating valves
Foreplane housing gear	Watertight door actuators
Foreplane tilting gear	Trim, bilge and ballast system valves
Capstans	Gash compactor and can crusher
EW mast hoist	Diesel exhaust mast
Periscope hoists	Communications mast
Snort mast ram	Radar mast
Snort hull valve	Bridge fin shutters
Main ballast tank vents	Ventilation exhaust valve
Engine clutch	Diesel exhaust and muffler valves
Steering gear	Containment valves
Hydroplane gear	Main engine turning gear
	Sea water system valves
	Steam system valves
	Feed water system valves
	Secondary propulsion gear
	Thrustmeter and resonance changer
	Torpedo handling winches
	Anchor windlass
	Communications buoy handling gear
	Aerial deployment system

Centralized Control

In a diesel electric submarine, even one such as the A Class which represented the accumulated experience of forty years' submarine design and two world wars, the hydraulic system, although vital to manoeuvring control of the submarine, was not particularly complex. The centralized operation of ship control systems such as manoeuvring control, buoyancy control, and trim control was achieved by running these systems to the control room and distributing from that central location through valve manifold chests.

The advent of nuclear power resulted in a quantum jump in submarine performance, an increase in the number of systems, and additional safety requirements associated with the reactor. Higher submerged speeds of extended duration have demanded significant increases in the power capacity and integrity of hydroplane and rudder control systems (TABLE II) so that the distribution of power hydraulics from the control room is no longer a practicable proposition.

TABLE II—*Systems for Hydroplane and Rudder Control*

	A Class	*Valiant*
Pressure	1150–1500 p.s.i.	2550–3000 p.s.i.
Piping	$1\frac{1}{2}$ inch copper	$2\frac{1}{2}$ inch Cu Ni
Pumps	2 × $6\frac{1}{2}$ gal./min.	3 × 25 gal./min.
Accumulators	21 gallons	21 gallons
Replenishment tank	75 gallons	210 gallons

One of the penalties of high s.h.p. steam propulsion is that a number of large bore cooling water systems are continuously exposed to diving depth pressure. This is in marked to a diesel submarine in which the sea-connected systems are of relatively small diameter. Since only a small proportion of the main ballast water can be blown when deeply submerged the presence of these large diameter sea-connected systems in nuclear boats constitutes a potential hazard of significant proportions. In the event of a sea water system failure when the submarine is deep, particularly at slow speed, it is essential for the hull valves to be shut, and the main ballast tanks to be blown, very rapidly indeed. This can only be achieved by providing centralized control of all the large hull valves and of the HP air blowing systems. Centralized control of propulsion systems is also essential to ensure safety and to minimize watchkeeping load.

Only hydraulic power can provide the necessary degree of precision and reliability for the operation of vital hull valves and system valves. However, FIG. 3 illustrates the price which we pay in complexity for centralized control of systems and remote control of equipment. This, as much as the additional hydraulic equipment listed in TABLE I, is responsible for the proliferation of hydraulic system pipework in nuclear submarines (FIG. 4).

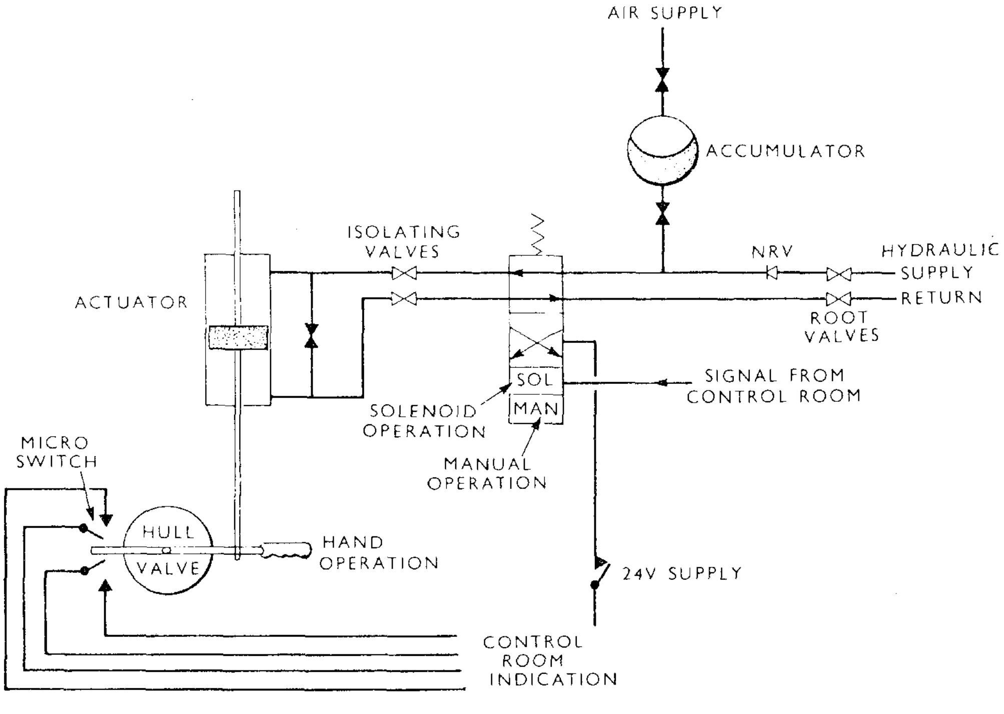

FIG. 3—OPERATING SYSTEM FOR A TYPICAL HULL VALVE

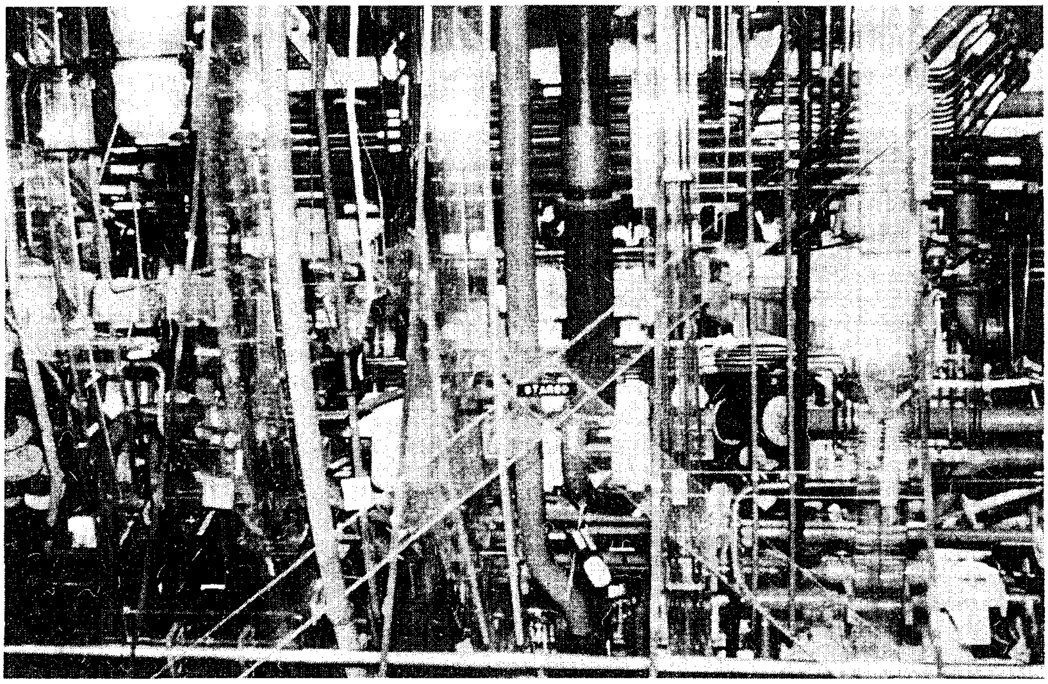

Fig. 4—Pipework in Trafalgar Class main machinery space, seen from starboard in a one-fifth scale model

Valiant Class System Concept

The general arrangement of the Valiant system is shown in Fig. 5. The central power plant supplies two separate headers known as the Main and Vital systems. These 2½ inch (64 mm.) diameter pipes, together with their return lines, run the entire length of the pressure hull. The Vital system is

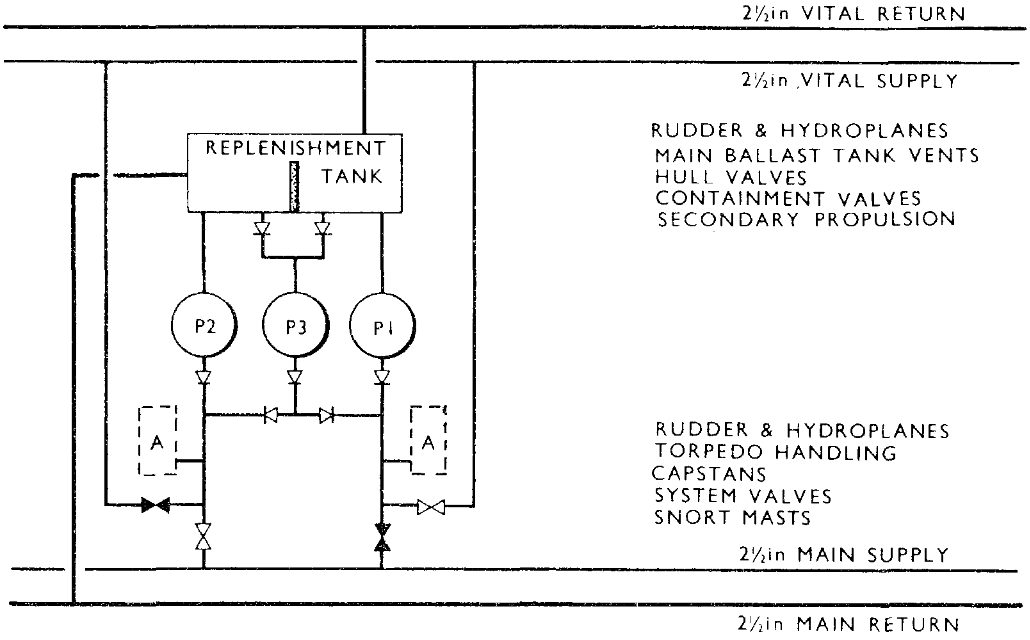

Fig. 5—Valiant Class hydraulic system

regarded as a protected system which supplies only those equipments which are essential in securing the ultimate safety of the submarine. The Main system serves general hull equipment and provides the normal source of energy to operate the rudder and hydroplanes. The systems are of the constant pressure type and are normally operated with the common pump (P3) continuously running to supply both Main and Vital demands. Additional demand in either circuit can be met initially from the accumulator but, when pressure drops to 2550 p.s.i.(176 bar), the appropriate dedicated pump will start. The pumps are of fixed displacement radial piston type.

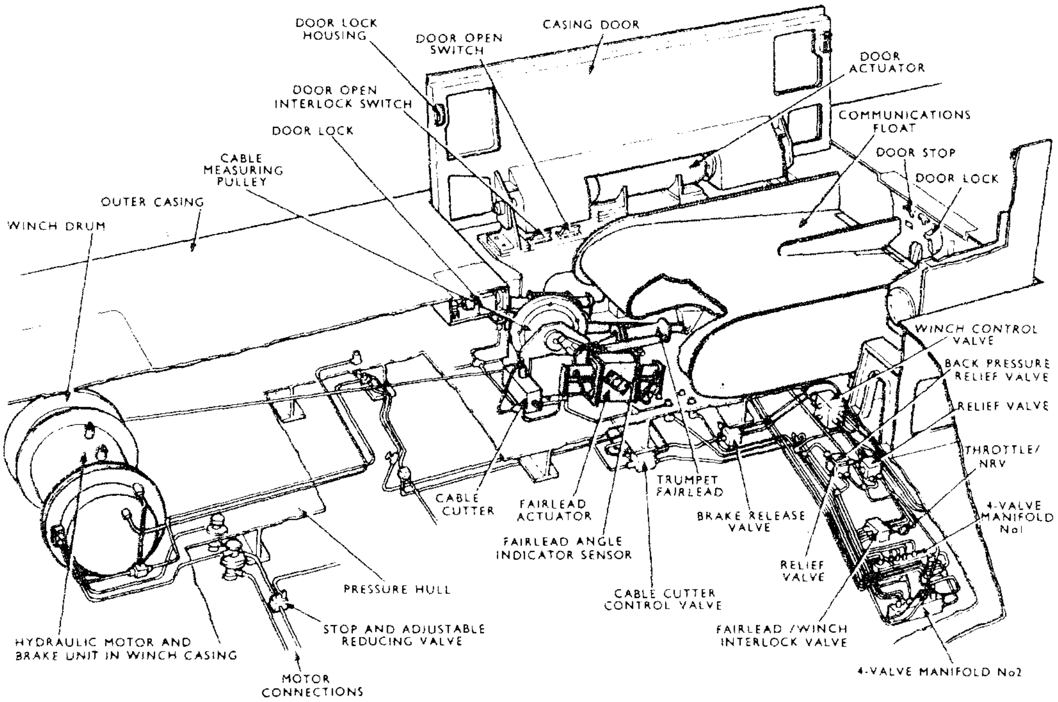

FIG. 6—TYPICAL EXTERNAL EQUIPMENT, OPERATED HYDRAULICALLY

Swiftsure Class System Concept

In reviewing the design philosophy of hydraulic systems in VALIANT, the SWIFTSURE design team made a number of observations in relation to safety:

(*a*) Despite the massive investment in copper nickel pipe only the control surfaces are provided with duplicated supplies from both Main and Vital headers.

(*b*) The very size of the system, with its large number of pipe connections and fittings, tends to compromise its integrity.

(*c*) The pumps, sited side by side, are somewhat vulnerable to fire or flood which could put them all out of action and , furthermore, they are about 70 feet (20 m.) from the largest and most essential service—the rudder and hydroplane actuators.

Consideration was given to fitting distributed power packs in order to improve the integrity of vital supplies but, due to the diversity factor on equipment use, this option was found to be uneconomic and to make disproportionate demands on weight and space budgets.

The compromise arrangement finally adopted for the SWIFTSURE Class was to site a power plant at the after end of the pressure hull, dedicated solely to powering the after control surfaces, and to supply all other internal equipment from a single, through-ship, distribution system. The integrity of the more essential supplies on the ship system is assured by local accumulators of one or two gallon capacity which are arranged to serve groups of similar valves. Cross connection of the Aft and Main hydraulic systems is, of course, possible in the event of power plant failure.

To avoid unreliability problems associated with sea water contamination of vital equipment acuators and control valves, an entirely separate power plant and External distribution system was provided to serve the numerous actuators sited external to the pressure hull (FIG. 6). Although it is common practice to use double seals with external drains on external equipment shafts, there is an occasional risk of sea water ingress when seals fail or drain lines are inadvertently shut off. OX-30, a water emulsifying oil able to tolerate up to 10 per cent. water contamination, is therefore used in this system and also, for logistics reasons, in the Aft and Main hydraulic systems.

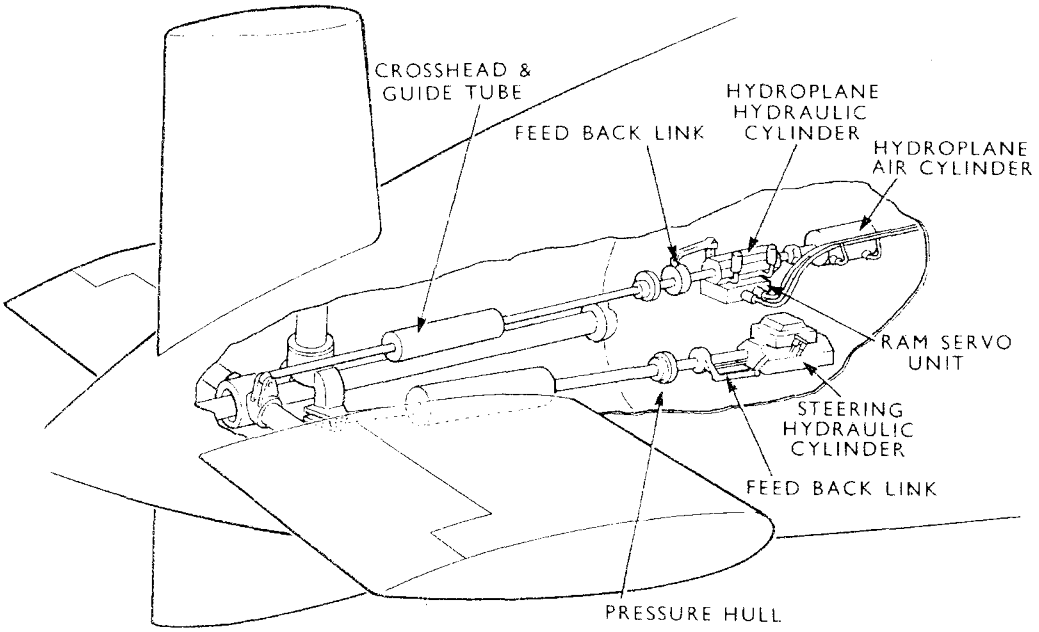

FIG. 7—RUDDER AND HYDROPLANE OPERATING GEAR

Fire Hazard

While the integrity of vital equipment could be still further improved by the elimination of elastomeric seals from pipe couplings, it is the fire risk associated with hydraulic systems in general, and pipe couplings in particular, which has been the subject of more recent safety reviews and improvement effort. Three major submarine fires during the past decade have been attributed to oil leakage, or spray, from pipe couplings, and considerable effort has been expended in the search for alternative couplings which may be utilized when butt welding of pipework is deemed to be impracticable. Hydraulic systems are generally routed clear of designated fire risk areas but, where this is not feasible, it is standard practice to fit oil collecting muffs round breakable couplings and to shield nearby absorbent surfaces, such as pipe lagging, with stainless steel cladding. Remotely operated stop valves have been introduced to enable power plant accumulators to be isolated in the event of a system failure or fire.

Fire-resistant fluids have been shown to provide significant protection against certain types of fire but their introduction, particularly in existing systems, could pose problems of material compatibility and wear. Of the various fire-resistant fluids which have been tested, the water polyglycols appear to be the most promising and long-term tests are being undertaken to evaluate the performance and reliability of typical equipment[1].

Manoeuvring Control

Order Transmission System

The rudder and hydroplanes are operated, via robust linkages, by hydraulic actuators sited within the pressure hull. The ram servo unit (RSU), which translates the helmsman's demands into hydraulic power, is mounted directly on the ram (FIG. 7). The helmsman sits at the manoeuvring console in the control room and operates the control surfaces by means of an aircraft type control column mounted on the order transmission box (OTB). The OTB is a mechanical unit, with electrical and hydraulic interfaces for converting stick movement into an analogue signal which is transmitted to the RSU.

It may be of interest to note that, whereas the aircraft industry has only recently adopted 'fly by wire' techniques, R.N. submarines have, for more than 20 years, relied upon electrical synchros for the primary mode of signal transmission. The secondary order transmission mode, in our current submarines, is provided by an 'oleo' hydraulic system which is automatically engaged if the synchros become misaligned. Both the primary and secondary signal transmission systems provide position control of the rudder and hydroplanes since the servo loop is closed by a feedback linkage between the ram and the RSU.

In order to guard against failure of the order transmission systems or feedback mechanism, or total loss of hydraulic power, an air ram is fitted in tandem with the after hydroplane hydraulic ram. The air ram is controlled in open loop from the helmsman's position and, being supplied from the HP air ring main, allows for prolonged operation in the emergency mode. Following an incident in which air starvation of the air ram occurred when the main ballast tanks were blown while exercising air control of the hydroplanes, it was decided to fit a dedicated air bottle to guarantee sufficient air for emergency recovery.

Emergency control of the rudder is by open loop rate control of the hydraulic ram. In VALIANT Class this was achieved by direct control of the power hydraulics in the control room but in the SWIFTSURE's considerable reduction of pipework was achieved by adopting remote solenoid operation of the rate control valve (and by deleting hydraulic rate control of the after hydroplanes).

Ergonomics

In earlier submarines, such as the A Class, the rudder and forward and after hydroplanes were operated independently by three tapper bars, each directly controlling the flow of oil to the appropriate actuator. The helmsman controlled course keeping and the fore planesman kept depth, while the after planesman watched the 'bubble'. Separate control of the forward and after hydroplanes allowed quite accurate control of depth to be achieved at periscope depth in moderate sea states.

The adoption of one man control in the OBERON Class in the early 1960s offered the major advantage of reducing the crew by four but, since it was ergonomically impracticable for the helmsman to handle three independent controls, some loss of capability was accepted by linking the hydroplane controls. Forward movement of the stick therefore drives the after planes to a positive angle of attack and the fore planes to a negative angle of attack, causing the submarine to pitch down. The ratio of foreplane to afterplane angle may be adjusted between minus 1:4 and 1:1, by means of a knob on the OTB.

A mechanical autopilot is incorporated in this One Man Control (OMC) gear, allowing automatic depth and/or course keeping and automatic depth and/or course changing. In manual control the single helmsman is assisted in executing depth and course changes by a submarine position display unit on which Cartesian co-ordinates represent course and depth error. A cross displayed on the VDU indicates the current course and depth errors and a circle shows the predicted errors some distance ahead of the submarine. When completing a depth and course changing manoeuvre the helmsman attempts to avoid overshoot by taking off rudder and hydroplane angles at a rate sufficient to hold the circle at the origin.

System Integrity

The integrity of manoeuvring control is assured by system redundancy and by utilizing large factors of safety in the design of common failure mode components. In SWIFTSURE Class, for example, there are three separate power sources capable of driving the after hydroplanes, and three order transmission modes (TABLE III).

TABLE III—*Redundancy in Manoeuvring Control*

Power Source	*Order Transmission*
After hydraulic plant	Electric
Main hydraulic plant	Hydraulic
HP air	Air

While actuator redundancy is provided on the after hydroplane system by means of the air ram, there is no such redundancy in the steering system. On both systems it is recognized that the linkages aft of the actuators are common failure mode components in which a single failure could cause loss of control. This is accommodated by working to conservative design principles, using well proven materials and generous factors of safety and, in the case of the hydroplanes, by designing them to trail at a small angle in the event of linkage failure. If failure mode analysis were to identify components 'upstream' of the actuator, such as the RSU, in which failure could result in total loss of control then retractable stops may be fitted to the actuator to physically limit hydroplane angle when at high speed. This is already the practice in some navies but has not previously been considered necessary in the R.N.

Alternative control geometries have been devised in an attempt to extend system redundancy right down to the lifting surface. The **X** stern with four independent actuators and associated linkages is probably the most extreme example and the **Λ** stern is another. Given sophisticated control equations both these arrangements offer the additional advantage of improved depth control in a high speed turn. A third possibility for increasing system redundancy is to split each of the conventional after hydroplanes to provide independent inboard and outboard planes driven by concentric shafts. This presents the opportunity of tailoring one set of planes, with its actuator, to normal cruising demands, while sizing the second set for emergency recovery. Great care would need to be taken to ensure that the additional complexity of such arrangements did not prejudice the integrity which they are intended to enhance. There is much to be said for keeping it simple.

Forward Hydroplanes

Any observer of submarine matters will have noticed the two schools of thought which exist regarding the location of foreplanes. While the U.S.N. have, since the introduction of nuclear power, favoured the siting of foreplanes on the bridge fin most other navies have located them forward of the pressure hull where they are either fitted high up, so as not to project beyond the hull diameter, or low down with some form of housing mechanism. The internal arrangement of R.N. submarines tends to result in the bridge fin being sited proportionately further aft than in U.S. submarines so that, to exert the same pitching moment, any planes mounted thereon would need to be larger than the already sizeable U.S. planes. While there are disadvantages associated with the foreplanes wherever they are fitted, the particular problems associated with hull mounting include competition for space with weapon discharge and sensor requirements (which tends to increase the length of the submarine), possible interference with sonar at speed, the need for external hydraulics, and access problems for maintenance.

In SWIFTSURE Class the bow planes are located in the hydrodynamically most effective position, forward of the pressure hull at axis level, so they are correspondingly smaller than in previous designs. In order to avoid flow noise problems, and to provide a small speed advantage, the planes may be fully retracted at medium and high speed (FIG. 8). However the bow planes would make such a significant contribution to recovery if the after planes were to jam at a large angle that it is common practice, in peacetime, to leave the planes extended, except when coming alongside in harbour.

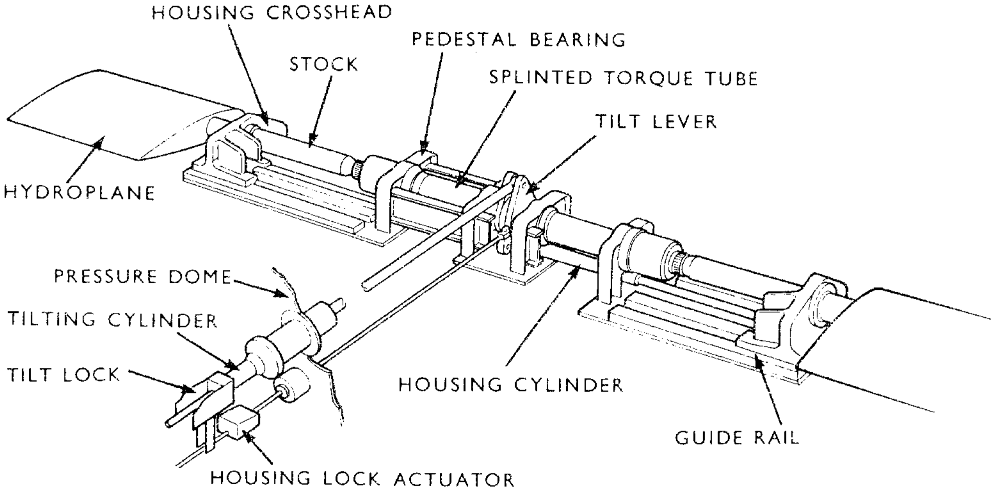

FIG. 8—RETRACTABLE FORWARD HYDROPLANES

Compressed Air Systems

System Growth

High pressure air, stored in bottles located inside or outside the pressure hull, represents the energy source of last resort in both diesel and nuclear submarines. While the primary function of this stored energy system has traditionally been to facilitate the environmental transition from sub-marine to surface, the very existence of such an extensive distribution system has proved irresistibly tempting to the designer seeking a simple and reliable energy source. For many years, therefore, it has been customary to utilize air at reduced pressures for numerous auxiliary service tanks. In nuclear submarines the compressed air systems have been further extended to satisfy additional demands associated mainly with the control of air purification equipment and with the blowing of additional service tanks. In SWIFTSURE Class for example there are approximately fifty air services demanding air at eighteen different pressures ranging from 5 p.s.i. (0.3 bar) to 4000 p.s.i. (276 bar). Typical services are listed in TABLE IV and compared with those provided in the A Class.

TABLE IV—*Compressed Air Services*

A Class	*Additional services in Swiftsure Class*
Main ballast tank blows	MBT emergency blows
Q tank direct blow	After hydroplanes actuator
Torpedo firing reservoirs	Garbage ejector
Torpedo charging	Reactor air services
Compartment blows	CO_2 absorption units
Hydraulic system accumulators	Emergency breathing system
Periscope desiccator	Shaft seal
Engine starter	Thrust block
Signal ejectors	Machinery mounts
Siren	Torpedo power loading
Gun recuperator	CO_2 scrubber control
Fuel tanks	CO_2 scrubber blow down
Fresh water tanks	Electrolyser control
Torpedo tanks	Atmosphere analyser
Torpedo tubes	Sonar cabinets
Telemotor tank	Sonar cooling system
Sewage and slop drain tank	Sonar cooling expansion tank
Trim tanks	Chilled water tank
Lubricating oil tanks	Reserve feed tanks
R compensating tank	Water transfer tank
Engine cooling water system	Precipitator drain tank
	Spent amine tank

Although steps have been taken to introduce welded pipes and cryogenic couplings, there remain, even in our latest air (and hydraulic) systems, a large number of mechanical pipe couplings incorporating nitrile rubber 'O' seals which tend to age harden and lose their resealing capability after a few years in service. The maintenance chores of renewing 'O' seals and repairing air compressors in service are a direct consequence of excessive system leakage. In the absence of that elusive component, the perfect pipe coupling, there are compelling reasons for the rationalization and simplification of air services. It is desirable not only to minimize the number of leak-prone pipe couplings and reducing stations, but also to remove services from the HP air system, particularly those which require a continuous bleed, albeit at low pressure, such as fluidics control and certain service tanks. Consideration is being given, in the Trident submarine design, to the use of a continuously running LP compressor, serving a 120 p.s.i. (8 bar) distribution system which could supply the majority of reduced pressure air requirements.