UPHOLDER CLASS SUBMARINE WEAPON DISCHARGE SYSTEM

THE LONG CLIMB BACK

BY

R.A.D. HARRIS CENG FIMARE
(*Director General Underwater Weapons*)

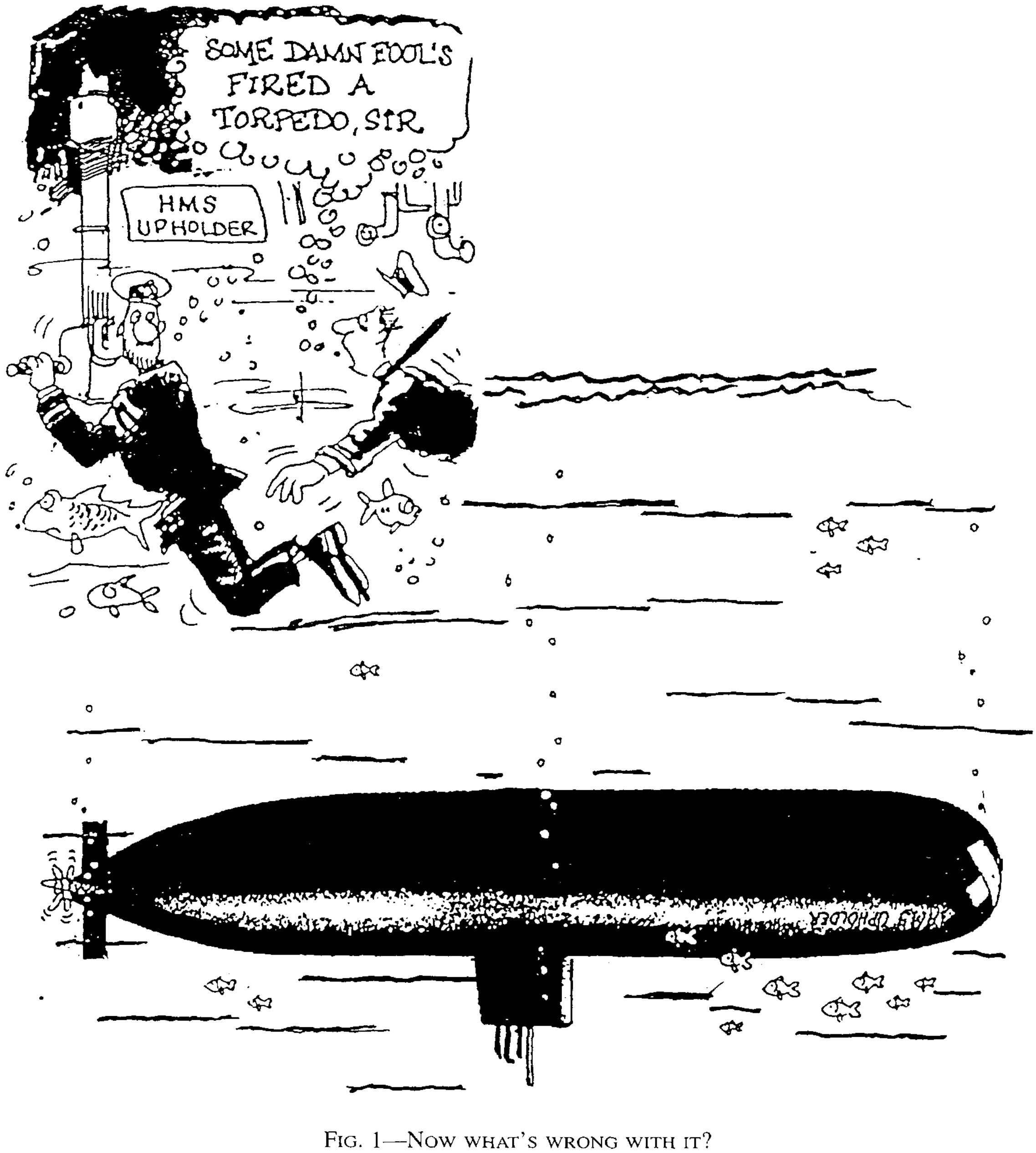

FIG. 1—NOW WHAT'S WRONG WITH IT?

ABSTRACT

This article outlines the problems experienced with the UPHOLDER class weapon discharge hydraulic system, how the modifications were evolved and tested, the problems solved and the design finally certified for safety. Starting during the early days of setting to work in H.M.S. *Upholder* with the emergence of the problems, the article outlines the measures that were put in place to allow sea trials to continue whilst seeking a solution to the problem. The evolution of the design changes is covered together with the testing of the final chosen option and some of the major problems encountered during testing.

The sea—the truth must be confessed—has no generosity. No display of manly qualities—courage, hardihood, endurance, faithfulness,—has ever been known to touch its irresponsible consciousness of power.

Joseph Conrad.

Introduction

There can be few who have not read or heard about the problems which beset the torpedo tubes fitted to the UPHOLDER class and the systems unwillingness to allow the tubes to remain sealed from the sea. The press cuttings are numerous and the technical problems have all been described in many wonderful and various ways, including a few cartoons (FIG. 1). It is sometimes difficult to see the humorous side, when 'friends' phone you up just to remind you that they have seen the cartoon! It is also quite daunting when you realise that, as the equipment project manager, you have inherited ownership of some of the largest holes in the submarine hull! This is quite evident in the photograph taken during construction (FIG. 2). The six torpedo tubes, their apertures and the hydraulic system of interlocks and motive power to control the system are unlike any other previous submarine discharge systems.[1] As a result of the siting of the sonar array in the position traditionally reserved for the torpedo tubes of all previous submarines

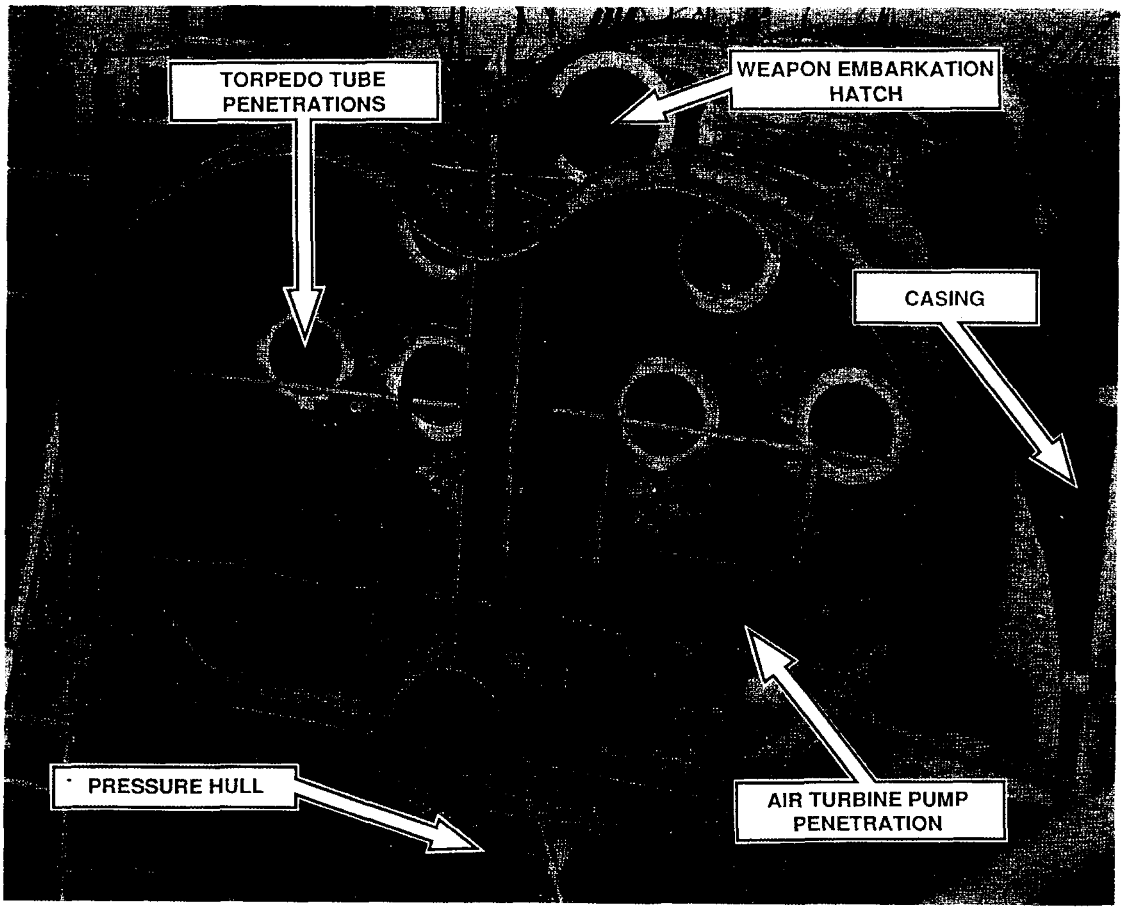

FIG. 2—VIEW OF BOW DOME OF H.M.S. 'UPHOLDER' DURING CONSTRUCTION

and the decision to fit six tubes instead of five, the space left to fit the system was restricted to the upper third of the submarine. Three major departures from previous designs were:

(1) The choice of an air turbine pump,[2] in place of the bulky water ram system to act as the prime mover for discharging the weapon.

(2) A re-designed valve, to replace the flap valve, that allows the water from the pump to enter the selected tube. The flap valve from previous classes which requires space to allow it to swing open was replaced by a slide valve, which when installed (FIG. 3), requires very little additional space to allow it to function.

(3) In an effort to conserve space, the extensive use of externally mounted hydraulic interlocks was employed to ensure safety rather than, as had previously been the custom of mounting the interlocks inboard with a direct mechanical link to the device they were protecting.

These fundamental departures from previous practices were a cause for concern, and the system was subjected to rigorous testing at the design authority's (Strachan and Henshaw, (S&H)) works in Bristol. However, although interfaces with the remainder of the submarine's systems were agreed, their possible effects on the discharge system were not fully explored. Time was also tight, and it was realised at an early stage that there would have to be considerable overlap between development and production if the submarine fit dates were to be met.

Design evolution

The Naval Staff Requirement (NSR) required a system that, under micro-processor control, could discharge selected weapons in a salvo or single shot mode from the control room. This was to be achieved in a submarine less than half the size of a nuclear boat and in a space only a third as large as previous systems. A significant omission from the NSR was any clear statement for safety. Work started in 1980 and the Director General Underwater Weapons (Naval) (DGUW (N)), (then DUWP), remained the Design Authority (DA) until 1986 when full system DA was transferred to S&H. By this time the design was frozen and production was underway. The design process was monitored mainly by DUWP, S&H and the Submarine Safety Working Party (SSWP). Various safety studies were carried out by S&H in 1982, and again in 1983, which recommended that some form of latch should be fitted to prevent inadvertent opening of the bow cap and slide valve. This suggestion was rejected by the Project and the SSWP, since it was argued that the probability of an occurrence where a latch would be required was of such low order that it was not warranted. Had the many failure modes that eventually defeated the system been recognized at the time, then it is highly probable that latches would have been fitted from the outset.

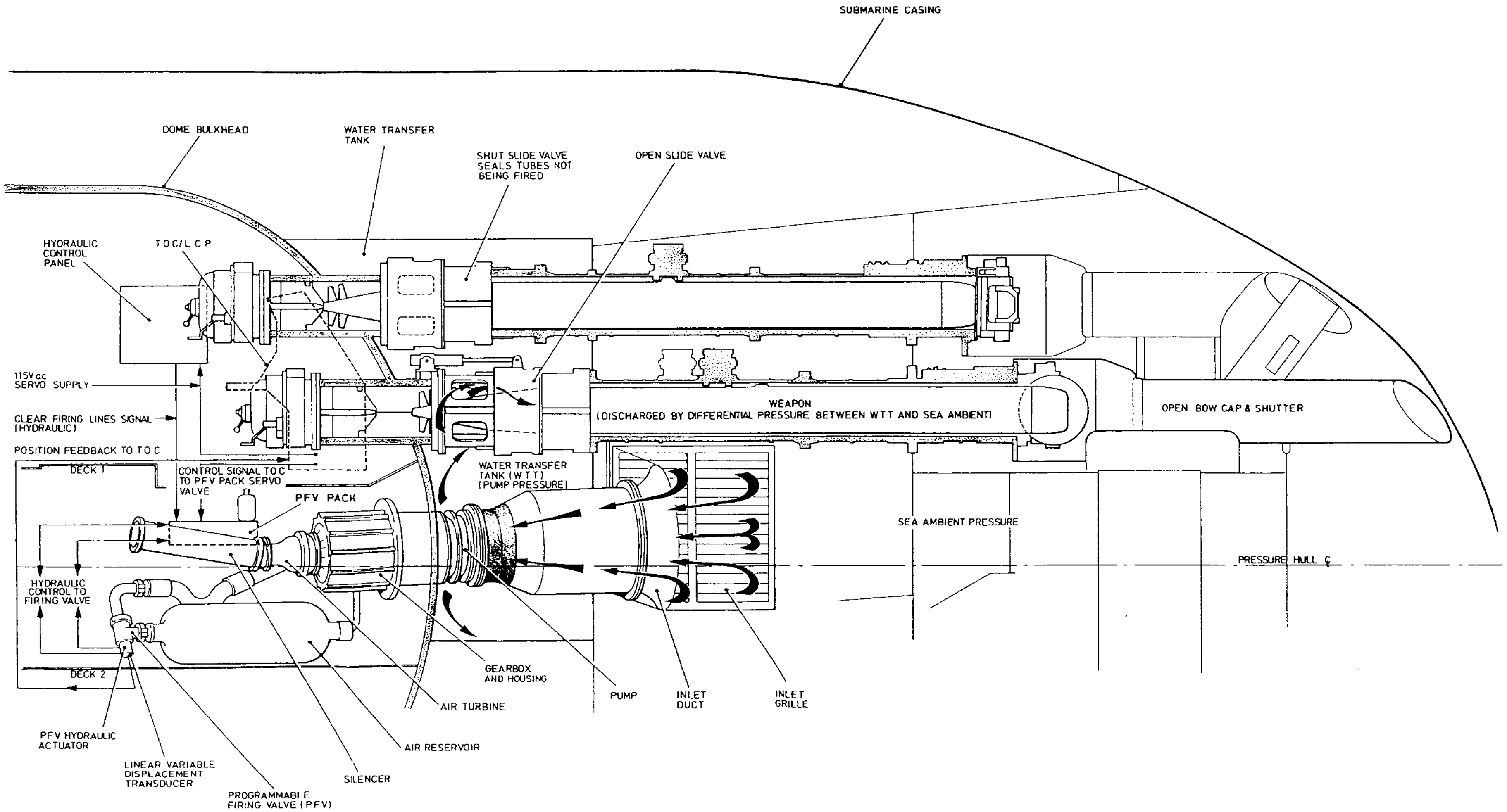

FIG. 3—DISCHARGE SYSTEM SCHEMATIC DIAGRAM

The original design concept

All the actuators and the Top Stop (a device for holding the weapon in the tube until the moment of firing) were of the regenerative type i.e. external pressure is constantly fed onto the smaller area holding the actuator in the shut position. Opening is achieved by applying the same pressure to the larger area whilst at the same time allowing the volume of oil from the smaller area to assist the flow of oil to the opening side (FIG. 4). This arrangement has the advantages of:

(*a*) High speed of opening.
(*b*) Circuit simplification.
(*c*) Accumulator efficiency.

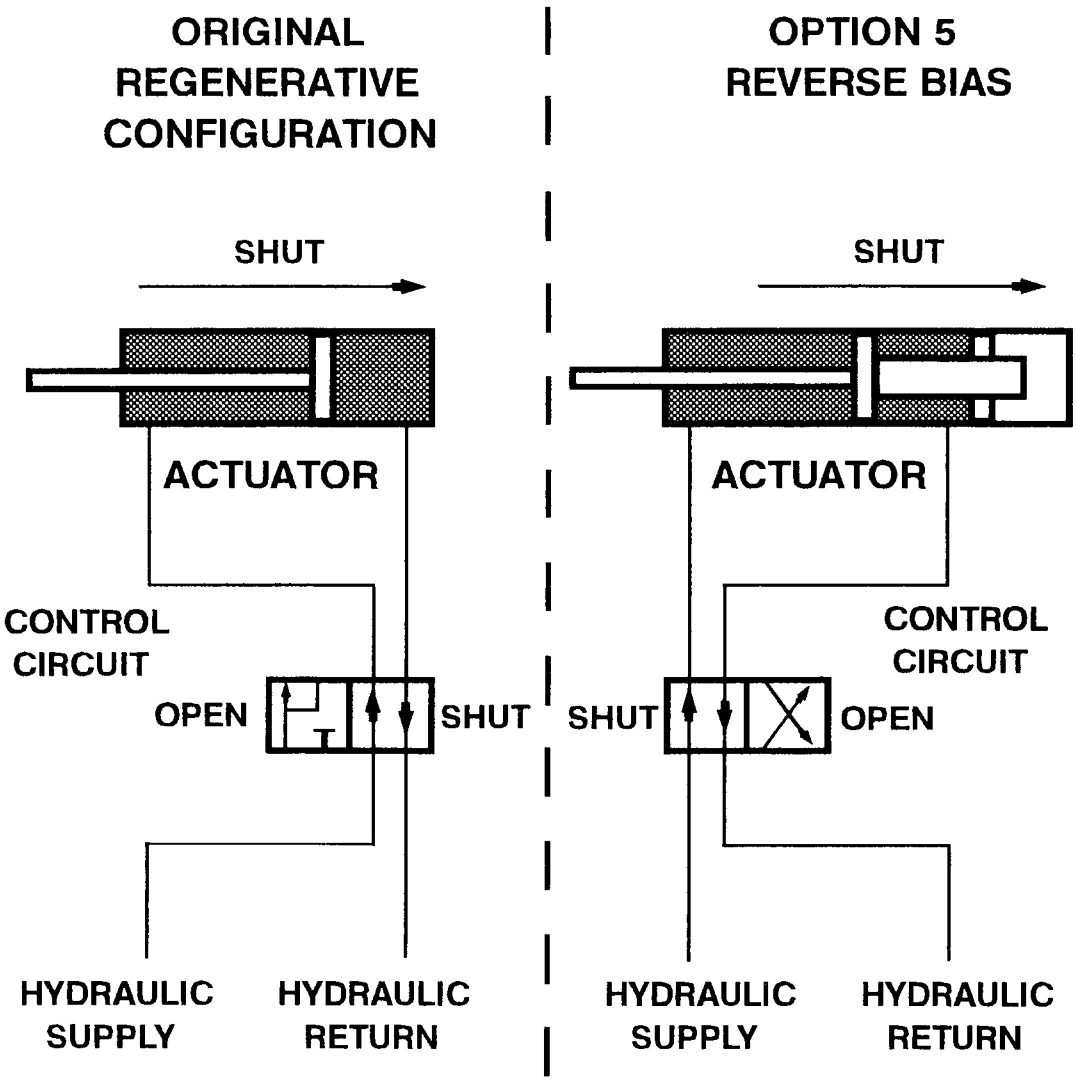

FIG. 4—HYDRAULIC SUPPLY TO ACTUATORS

It's major drawback is that when shut, the actuator's large opening area is directly connected to the submarine hydraulic return system. The return system would not normally experience pressures higher than 5% of the supply pressure. However due to area bias of the actuator, if the return pressure is allowed to rise in the return system to approximately 43–70% (dependent on the actual actuator) of the supply pressure, then the actuator will move towards the opening position. The risk of an inadvertent opening is further increased if hydraulic power should fail since, by design, the shutting pressure quickly dissipates once the accumulators are flattened by leakage flow through the numerous cartridge valves, leaving the larger opening area to react to any pressure variations that may occur in the return system. The actuators can therefore be described as biased to open. This potential to open is further aggravated by the introduction of the slide valve, which by virtue of its design, receives little assistance from hydrostatic pressure to remain shut. This is further compounded by the siting of the torpedo tubes in the upper part of the hull, where in normal surface trim the two upper tubes are only half submerged.

Emergence of the problems

In 1989, Vickers Shipbuilding and Engineering Ltd reported two separate incidents on H.M.S. *Upholder* during the setting to work phase:

- January when three tubes became inadvertently flooded. This was caused by unauthorized re-pressurization of the system after fitting flushing cartridges.
- April when two tubes were flooded. This came about when an abnormally large quantity of oil was dumped into the hydraulic return line whilst the relief valve in this line was inoperative, causing high back pressures to act upon the larger opening side of the actuators.

In both these instances it was the slide valves that partially opened. Subsequently there were other instances of inadvertent tube flooding during the construction of H.M.S. *Unseen* and *Ursula* at Cammell Lairds. One was confirmed as direct contravention of valve line ups, and another unexplained. Now that the dynamic performance of the system is understood, it is almost certain that the unexplained event was caused by one of these dynamic failure modes and covered later in this article.

The palliative fix

To ensure that the relevant interested parties were fully informed and part of the decision making process, an extraordinary group of the SSWP was set up and consisted of:

Director General Submarines (DGSM).
DGUW(N).
Director Naval Architecture (DNA) (then CNA).
Flag Officer Submarines (FOSM).
Director Submarines 1 (SM1).
DA.
The weapon engineer officers of the class when available.

Since it was apparent that the long term means of preventing further incidents was not going to happen overnight, some short term measures were implemented that at least would allow the submarines to proceed on sea trials in safety. These measures known as the 'palliatives' also allowed setting to work to continue (albeit with rigorous procedures) and consisted of:

(1) Maintenance of clear hydraulic return lines at all times by locking open all relevant valves.
(2) Fitting additional relief and non return valves in the return lines.
(3) Fitting of hydraulic low pressure alarms.
(4) Improving hull valve accessibility.

To allow the tubes to be loaded at depth, as part of the sea trials, the bow caps and slide valves were gagged shut. These measures proved successful in allowing the shipbuilders programme to continue without any further incidents.

The safety criteria

During the formation of the palliative measures it was clearly obvious that robust safety criteria would be required to ensure that any redesign would considerably improve the existing safety levels. The generation of these criteria fell to CNA's department. The requirement for a safety standard applicable to equipment that has the capability to cause the loss of a submarine, now seems so obvious. However safety had previously been almost taken for granted, due to the safe track record of proven designs and by virtue of no reported incidents. The situation for the UPHOLDER class was however very different.

The final agreement by all parties to the safety criteria was obtained in February 1989 and only after numerous iterations! These criteria contained:

(*a*) The CNA requirements for watertight integrity.

(*b*) The DGUW(N) requirements for safeguarding against inadvertent weapon release within the tube and firing into an obstruction i.e. bow cap or shutter.

The top level requirements of the criteria state that:

(*a*) For the loss of the submarine, at least three independent and unlikely fault conditions are to exist simultaneously.

(*b*) For firing into an obstruction or the inadvertent release of a weapon, at least two independent and unlikely fault conditions are to exist simultaneously.

It was agreed from the outset that in applying the criteria, the aim would be that there should be only one operator error in the three faults and that operator error should be classed as unlikely. The original criteria only covered safety at sea i.e. whilst fully manned. It was later recognized that an equally dangerous, if not more so, situation arose whilst alongside and not fully manned. For this reason the 'alongside' safety criteria were generated in 1993. These 'alongside' criteria differed from the 'at sea' version mainly in the amount of water that could be taken on board due to the larger reserves of buoyancy whilst alongside. The generation of the 'at sea' criteria evolved ahead of DEF STAN 00–56, but it is now interesting to look back and compare the many similarities between the two documents and how they are applied. The management of the safety case warrants an article in it's own right and it is hoped that this will be produced in mid 1994.

The design solution

A contract was placed with S&H in September 1988 to produce four designs schemes with timescales for implementation and costs. These four schemes, known as Options 1 to 4, had to take note of the safety criteria that was evolving and were vastly different in their approach, ranging from a complete re-think to minimum change. DGUW(N) contracted Cambridge Consultants to act as independent auditors. After the design reviews it was obvious that some of the schemes, although having considerable merit, would:

- Entail almost a complete strip of the fore ends.
- The drilling of additional hull penetrations to allow the passage of extended actuator rods.
- The manufacture of new hydraulic manifolds.

Throughout, a costly and very time consuming task.

It was therefore decided to take what were considered to be the best design and safety features from the schemes and to amalgamate them into one system that had the best chance of meeting the criteria, and which could be manufactured, tested and installed with minimum cost and delay. This design became known as

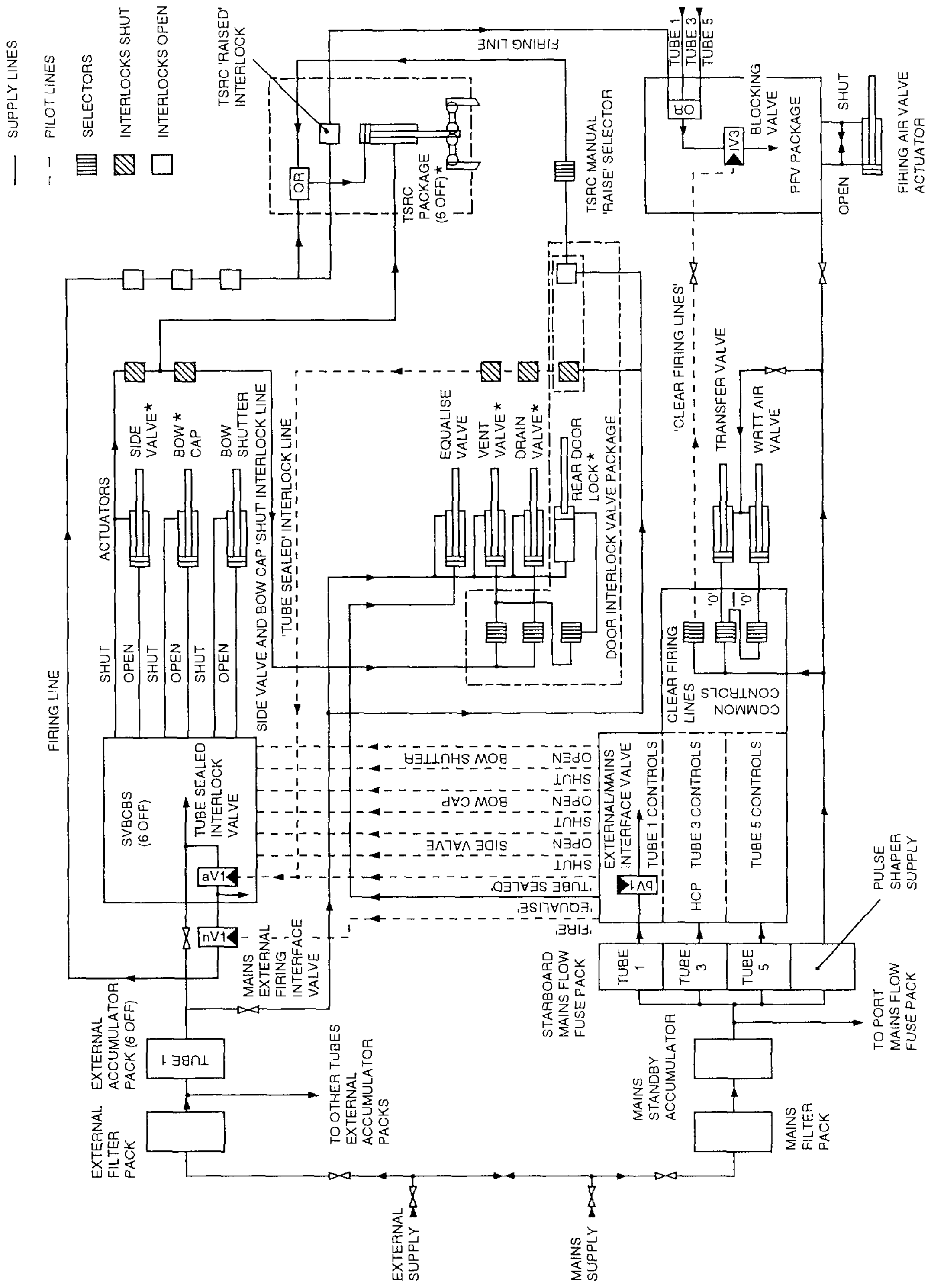

FIG. 5—WEAPON DISCHARGE HYDRAULIC CIRCUIT SIMPLIFIED BLOCK SCHEMATIC BEFORE MODIFICATION

Option 5 and it sought to address all the then known weaknesses in the original design as follows:

(1) To reverse the unsafe bias of all actuators which have a safety implication, both inboard and outboard, to safe bias (see FIG. 4), including the Top Stop for weapon retention in the tube. The extent of the actuators modified to safe bias can be seen in (FIG. 5).

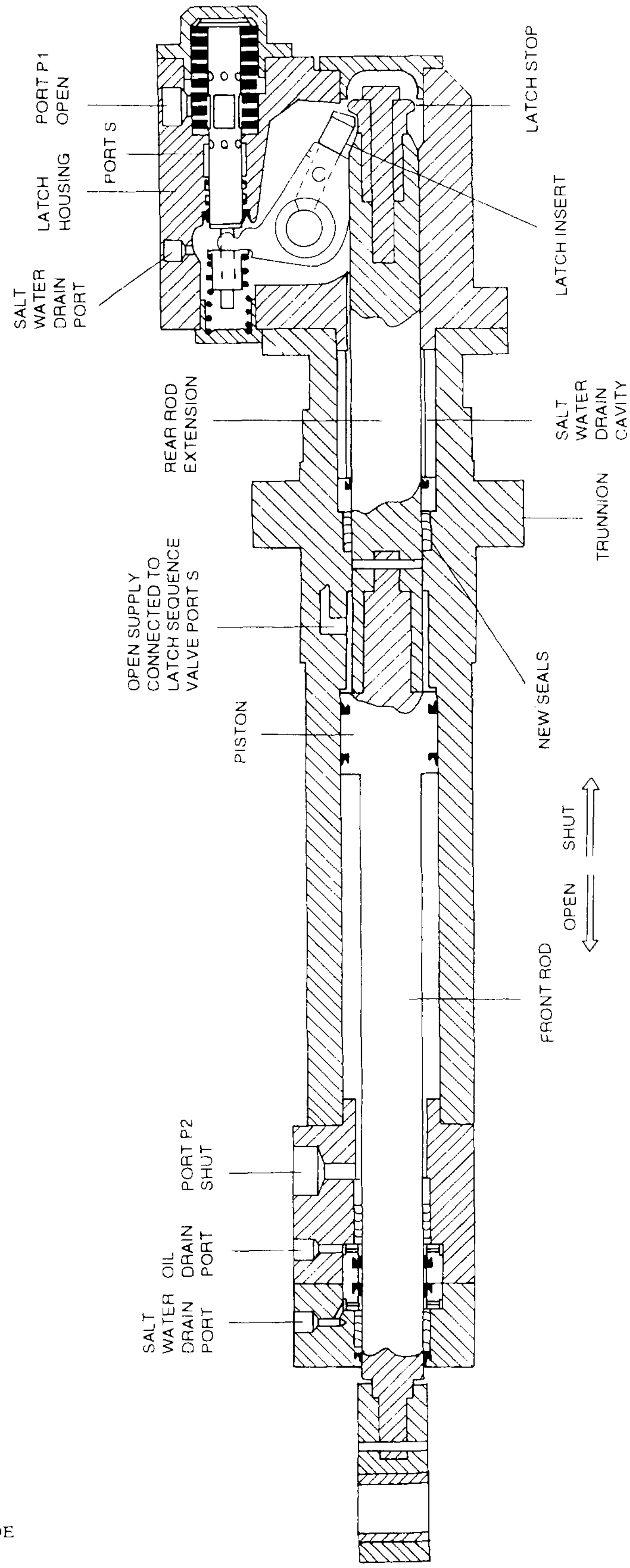

FIG. 6—OPTION 5—REVERSE BIAS SLIDE VALVE ACTUATOR

(2) To remove the leakage paths which prevented the creation of a hydraulic lock being achieved on the slide valve actuators.

(3) To provide some form of mechanical latching to both the slide valve and bow cap actuators (FIG. 6).

(4) To provide an automatic means of generating a hydraulic lock in the slide valve and bow cap actuators, to retain these apertures shut in the event of a hydraulic supply failure.

All these were to be achieved:

(*a*) Without the need for additional hull penetrations.

(*b*) Maintaining the operator interface.

(*c*) Without degrading to any great extent the performance characteristics.

It was agreed that, because of the tight timescales, the risks of running the testing programme in parallel with production were acceptable. This was based on a programme for testing where it was assumed that the design changes introduced would not adversely affect the remainder of the unmodified system, also that the remainder of the system would meet the safety criteria without modification. The proposed way ahead was presented to a wide ranging audience in December 1988. It was agreed that representatives from DGSM; DNA; FOSM; together with DGUW(N) and the DA would form the core of the safety group in assessing the design. DGUW(N) realised the amount of work that lay ahead, and in May 1989 placed a contract with Frazer Nash Consultancy to provide a full time safety consultant attached to the project. The initial contract was for a year, in the final event it lasted nearly five years, but has proven its worth time and time again by allowing the project manager to concentrate on managing the safety case and the remainder of the project.

Work now concentrated on assessing the proposed design for compliance with the safety criteria. This culminated in a presentation of the watertight integrity aspects of the design to the senior professional engineers, which took place on 1 June 1990. The design was endorsed, but subject to numerous caveats, among which was that environmental, reliability, and functional testing had to carried out. It was noted that the date, purely by coincidence, was the 51st anniversary of the tragic loss of the submarine H.M.S. *Thetis*! Readers may recall that her loss was attributed to uncontrollable flooding through the torpedo tube bow cap and rear door. It is interesting to note that one of the foremost British submariners of World War 1, ADMIRAL Sir Max HORTON, was reported to have repeatedly maintained that any submarine would easily survive a single isolated accident or mistake, but that no submarine could be expected to be safe against a succession or combination of more than one misadventure.

Shore testing at H.M.S 'Dolphin'

The test rig used during development testing had been dismantled and was used to supply the majority of components for the training rig at the Royal Navy submarine school at H.M.S. *Dolphin*. This rig consists of a single torpedo tube training rig with a hydraulic tube control system virtually identical to that fitted in the submarines, however the tube control micro processor and hydraulic supplies differ from the submarine fit. It was therefore important that wherever possible the total submarine system should be replicated and to achieve this the following changes were incorporated into the rig:

(1) The addition of a second hydraulic supply pump to enable the effects of varying the mains and external pressures independently to be fully investigated.

(2) A means of controlling the pressure in the return systems, including pressure regulators capable of raising the return pressure to the maximum that would be likely to be seen in the submarine systems.

(3) Numerous additional pressure and temperature monitoring points throughout the circuit.

(4) Ensuring that all components within the system that could affect

performance were of the correct build standard and as fitted to the submarines.

The training rig at *Dolphin* was ready to commence testing in December 1990, and it was planned to complete all testing by March 1991. In the end, full testing on the final version of system design was not completed until April 1993. This delay was caused mainly by the problems experienced with areas of the system that were unmodified, but were clearly seen as not meeting the safety criteria.

SOME OF THE MAJOR PROBLEMS ENCOUNTERED DURING TESTING

The pilot race

Like so many engineering problems, once the cause or causes are understood, it all seems so basic and logical, however that is one of the factors that makes solving engineering problems so interesting. This was exactly how the pilot race problem emerged.

One of the hydraulic safety interlocks known as the Tube Sealed Line was designed to prevent any of the outboards being opened whilst any of the inboards remained open. This was achieved as shown in (FIG. 7), where as soon as the interlock chain is broken, valves 1 and 2 switch. In switching:

(*a*) Valve 1 dumps main hydraulic supply pressure from both the open and shut pilots of the Directional Control Valves (DCVs) which switch opening power to the outboard apertures.

(*b*) When valve 2 switches, it dumps the external hydraulic pressure supply to the DCVs.

The 'open' pilot to the DCV is fitted with a timing choke which is designed to provide a time delay to ensure that on re-pressurization (i.e. shutting the inboard apertures), the 'shut' pilot is always established ahead of the 'open' pilot thus maintaining the outboards shut. During system testing at *Dolphin* in February 1991, inadvertent movement of the DCVs was seen; had valve 2 suffered a failure at the same time then the potential existed for an uncontrolled flooding route into the submarine via the bow cap/slide valve and vent valve/drain valve. The inadvertent movement of the DCVs was intermittent and at first appeared to be of a random nature, however after extensive testing and analysis, the culprit was finally tracked down to air in the pilot lines. By experimentation with varying amounts of air in the pilot lines, it was possible to upset the sequence of the decay and rise times for the 'open' and 'close' pilots which resulted in inadvertent movement. Since the presence of air altered the bulk modulus of the oil by orders of magnitude, the timing choke fitted to overcome the timing problem was completely defeated. Air can find its way into hydraulic systems in many ways:

- Via a cavitating pump or leaky seal.
- When unpressurized or maintaining the system.

It was now obvious that the presence of air must be treated as a likely event and that the design must be robust against it, in any event the safety criteria requires three levels of safety for an uncontrolled flooding, the design as it stood was only one fault safe and that one fault could remain latent and therefore undetected, a sobering and frightening thought! It was only now that the dynamic effects of the system began to be understood.

The solution

After assessing numerous schemes it was finally decided to modify the control circuit (FIG. 8), so that there was a continuous supply to the shut pilots, even when the tube sealed line was broken i.e. inboard apertures open. The scheme looks fairly simple on paper, however implementing it into the hardware was a different matter. The modification was incorporated into assemblies known as the

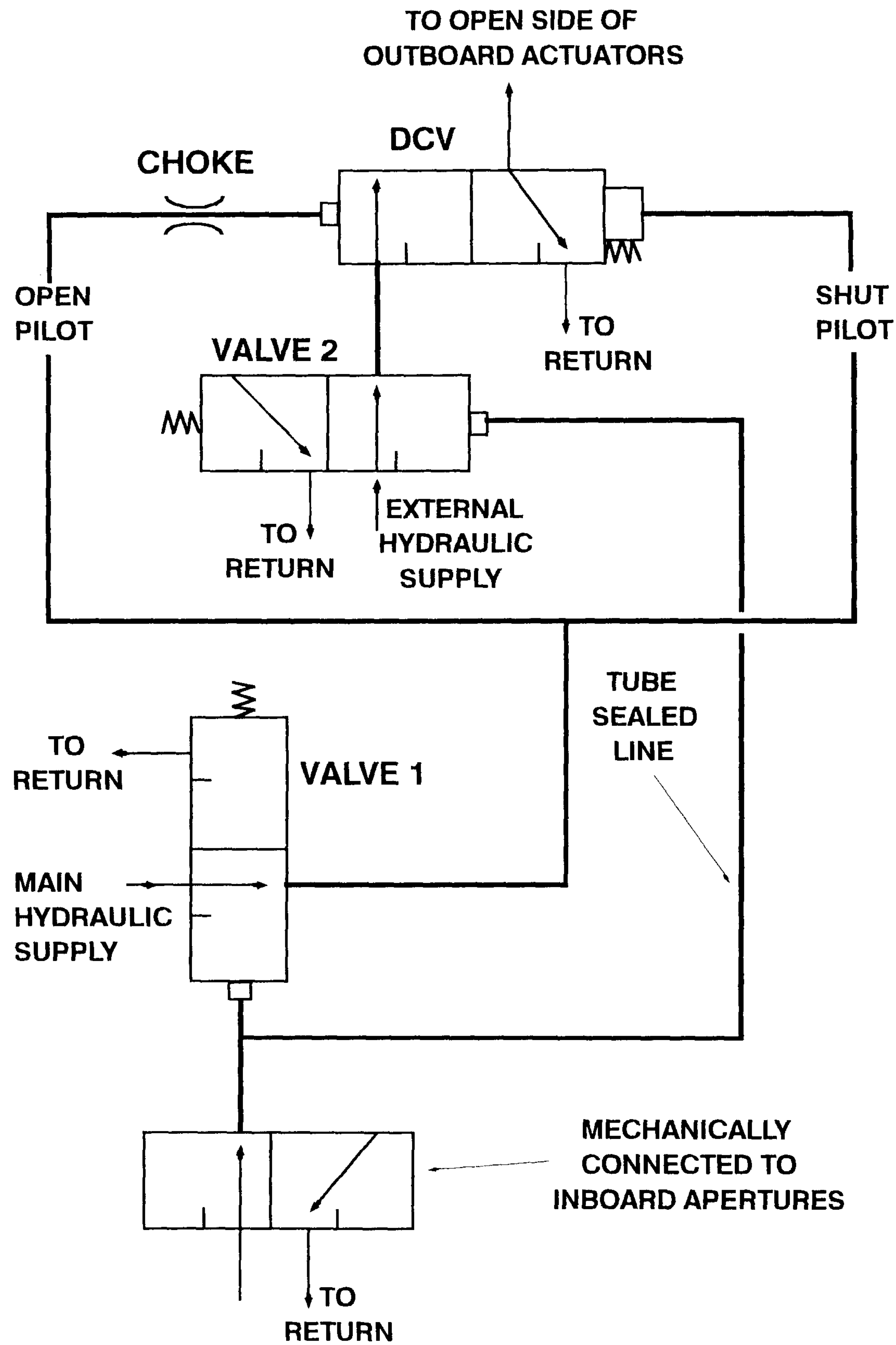

FIG. 7—SIMPLIFIED PART HYDRAULIC CIRCUIT TO ILLUSTRATE PILOT RACE—BEFORE MODIFICATION

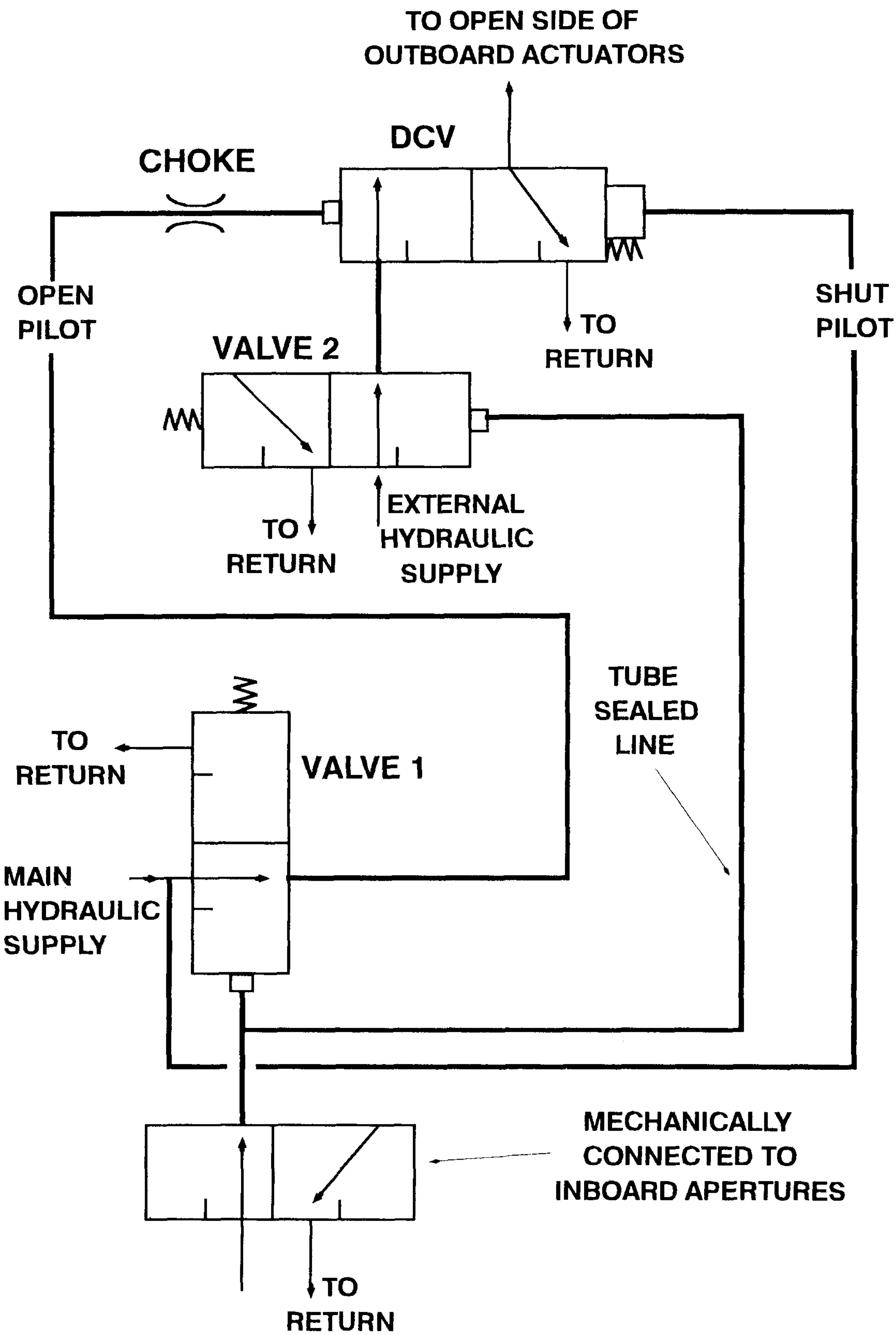

FIG. 8—SIMPLIFIED PART HYDRAULIC CIRCUIT TO ILLUSTRATE RACE—AFTER MODIFICATION

Hydraulic Control Packages which are located adjacent to the tubes, one port and one starboard, with each package serving three tubes. Luckily a complete set of boat spares was held which enabled a rolling modification programme to be initiated. The modification involved drilling and blanking within the manifold to create the revised circuitry. Some idea of the complexity of the modification can be assessed from the photograph shown in (FIG. 9) of a full scale perspex model of a similar modification to another manifold. The new drillings are identified by the green lines.

Although this modification has been completely successful in eliminating the pilot race when making and breaking the tube sealed line, it does not cater for a complete loss of main hydraulic supply pressure or its restoration. To date these have been covered by additional crew drill procedures, however a study is currently in hand to address a hardware solution that does not rely on drills.

Control valve instability on loss of main hydraulic supply

In the early days of testing and setting to work with the original design, it was considered by all parties that the safest configuration for the system was to leave external hydraulic power on, thus maintaining the outboards shut, whilst removing main hydraulic supply to prevent the possibility of an invalid pilot signal reaching any of the DCVs. How wrong this proved. Fortunately, the worst that could happen, although still highly undesirable, was that sealed tubes could inadvertently flood. It is now considered likely that this could explain some of the unresolved tube incidents during construction of the submarines at Cammell Lairds.

As already described, the DCVs (FIG. 10), switch opening hydraulic power to the outboard tube apertures. In normal operation with both pilots being supplied from the mains supply, the larger of the two pilots always ensures that the valve is in the position where the opening side of the actuator is connected to the return system. This ensures that with shutting pressure still applied, the outboards will remain shut. If as stated above, mains hydraulic pressure is deliberately removed then both pilots will drop to zero. Unfortunately, by virtue of the central drilling in the spool valve (to ensure it is always balanced), any pressure in the external return system also acts on the reverse side of both pilot pistons, where now, the larger area of the 'safe' pilot piston ensures that it becomes 'unsafe'. In some cases this results in both pilot pistons being pushed away from the control valve leaving the spool free to float. On the worst case valve, this occurred at a pressure of approximately 3 bar. This pressure is normal within the return system without any faults. With the spool now free to float, gravity, any submarine movement or vibration could cause the valve to move to allow opening pressure onto the actuator. Once again a failure mode had been identified that demonstrated that the original design could result in uncontrollable flooding with less than three faults, on the premise that loss of hydraulics and its accumulator back up is not a fault. The solution shown in FIG. 10, is the one which had already been successfully applied in aircraft landing gear, was to physically attach the spool to the small pilot piston and fit a stronger spring to the larger pilot piston. This ensured that the spool was always retained in the safe position on loss of the pilots. The implementation of the modification into the system was achieved by a simple cartridge change.

Additional modifications required to meet the safety criteria

The basic concept of the major design changes of reversing the bias of all actuators and the addition of latches and hydraulic locking valves has already been discussed. Table 1 shows the extent of additional modifications that were shown to be required to satisfy the safety criteria.

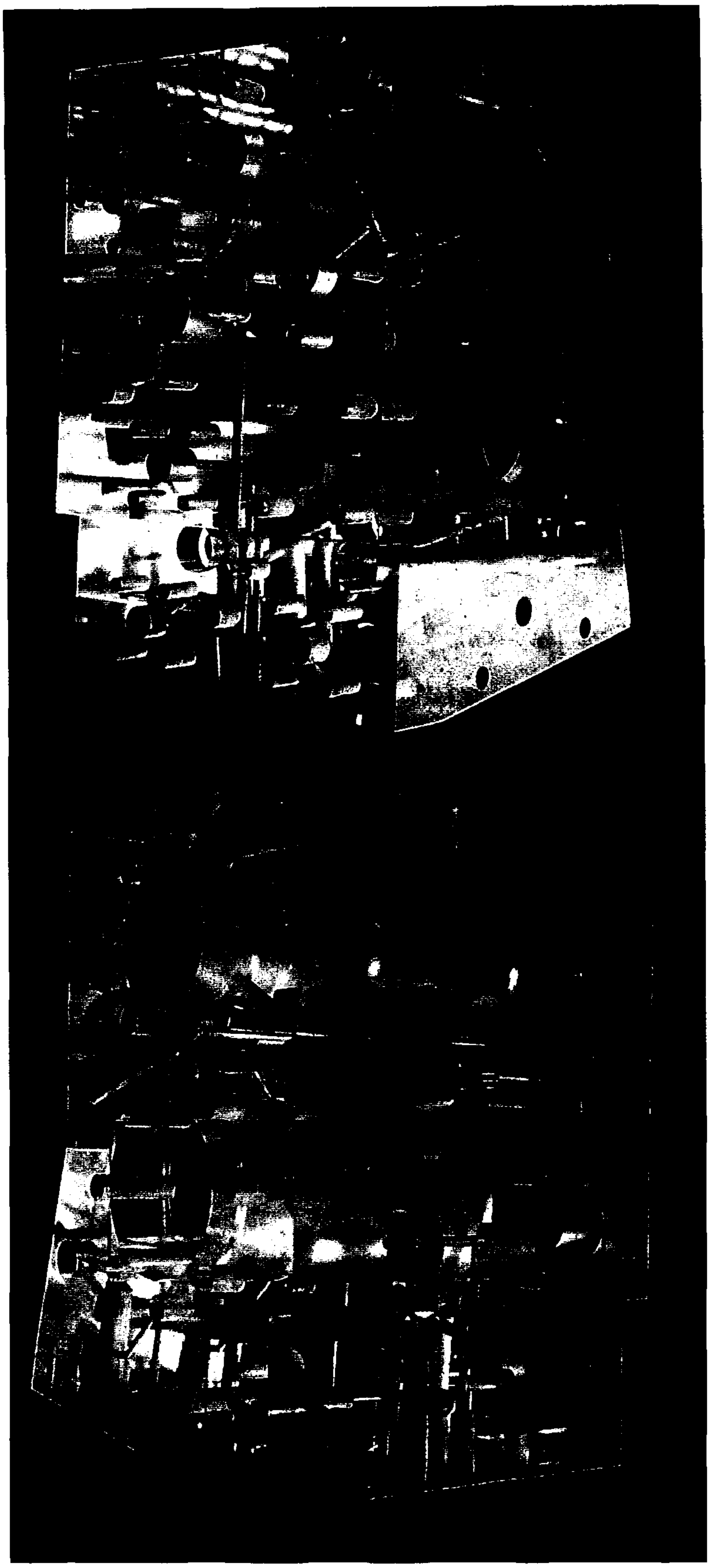

FIG. 9—HYDRAULIC MANIFOLD
NEW DRILLINGS SHOWN IN GREEN

TABLE 1—*Summary of additional modifications to meet the safety criteria*

Description	Purpose
One additional 5 bar and two 35 bar relief valves fitted in the return system.	To raise the protection level to three faults.
Valve for manually raising or lowering the Top Stop changed from twist to push button.	Dead mans switch ensures that the Top Stop is always lowered prior to weapon loading.
Additional filtration fitted to four selector valves per tube.	To protect against internally generated debris causing valves to seize.
Additional test points fitted.	To aid diagnostic and preventative maintenance.
Additional bleed points fitted.	To allow pilot lines to be bled.
Rear door plate valve aperture reduced (FIGS. 11 & 12).	To reduce aperture to less than recoverable hole size.
Drain valve aperture reduced and filter mesh fitted.	To prevent ingress of debris and possible jamming of valve at an aperture greater than recoverable hole size.
Main hydraulic control pack re-drilled and galleries plugged to alter pilot pressure flow logic.	To ensure shut pilots are always pressurized to prevent 'pilot race'.
Pressure gauges fitted to monitor functions of the outboard and inboard safety interlocks.	Mandatory checks included as part of revised drill procedures to meet the three fault criteria.
Pilot piston secured to spool valve and stronger springs fitted to certain DCVs.	To prevent spool valve float on loss of pilot pressure.
Choke fitted to the drain valve actuator shutting line.	To prevent inadvertent opening of inboards and outboards simultaneously.
Switching pressure of safety interlock valve raised.	To cater for failure of the drain valve choke fitted above.

The totality of the complete modification package was identified as Modification State Zero (MSZ) and was fully tested on the rig at H.M.S. *Dolphin* in the period between March and April 1993. In addition to the hardware modifications there were critical drill procedures which also supported the safety case, and these were incorporated into the mandatory submarine operating procedures.

The independent audit

The problem of being a project manager whose equipment is being subjected to a protracted and intensive safety programme, is that you can so easily get completely 'buried' in solving the day to day problems and keeping the programme moving. Because of these factors, and the emergence, late in the testing programme of dynamic failures, which tended to erode confidence, it was decided to undertake an independent safety audit. The work was placed with the Safety and Reliability Directorate (SRD) of AEA Technology in March 1993, for a final report to be available by the end of May 1993. The aim of the audit was to confirm that:

(1) The methodology used in the safety studies would result in identification of all failure modes.

(2) By sample audit that the method had been correctly applied.

The audit was completed on time, and recommended immediate actions to be taken prior to submission for safety endoısement, and longer term actions to follow in slower time. SRD stated that until these short term actions were

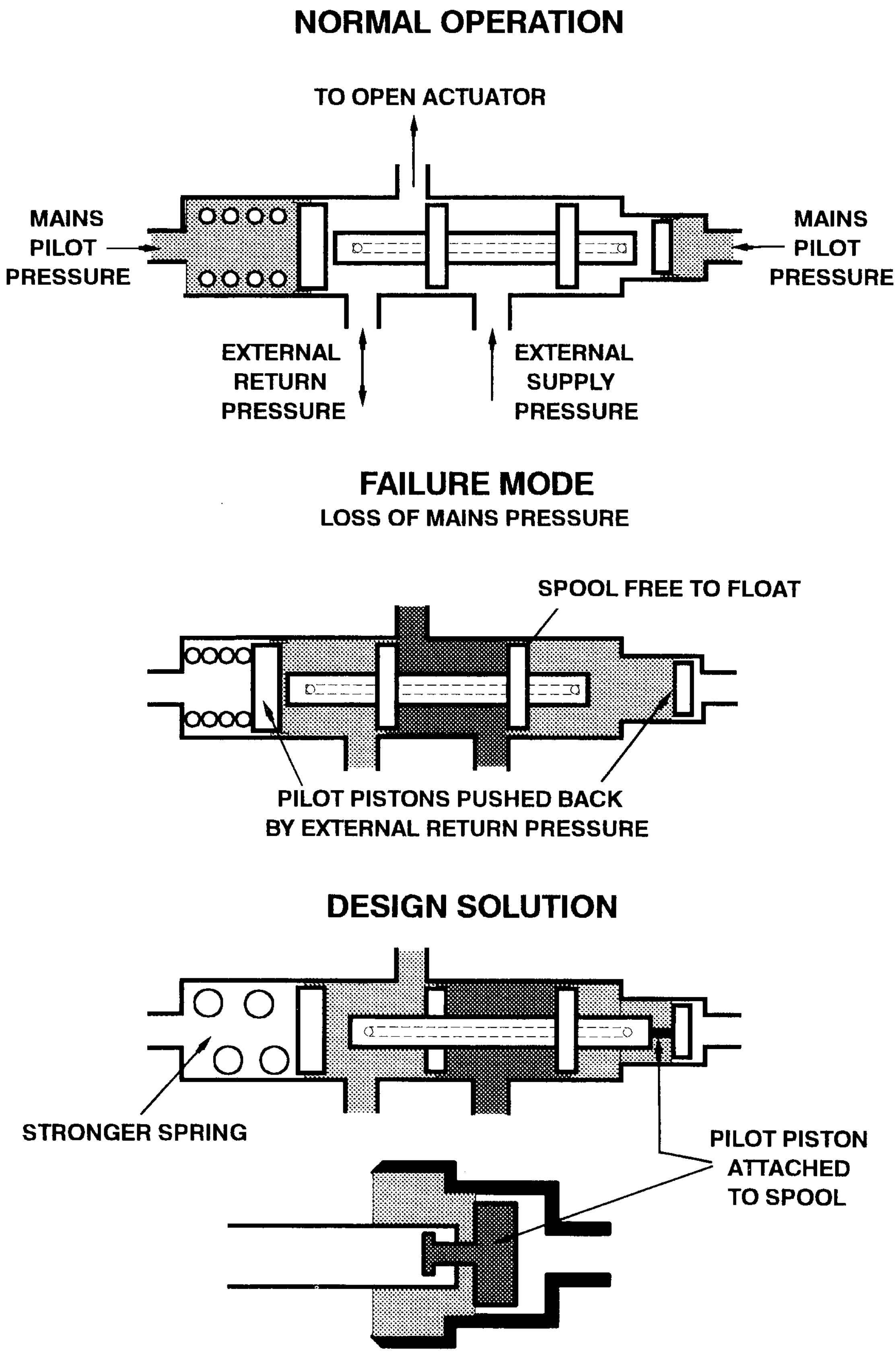

FIG. 10—TYPICAL DIRECTIONAL CONTROL VALVE

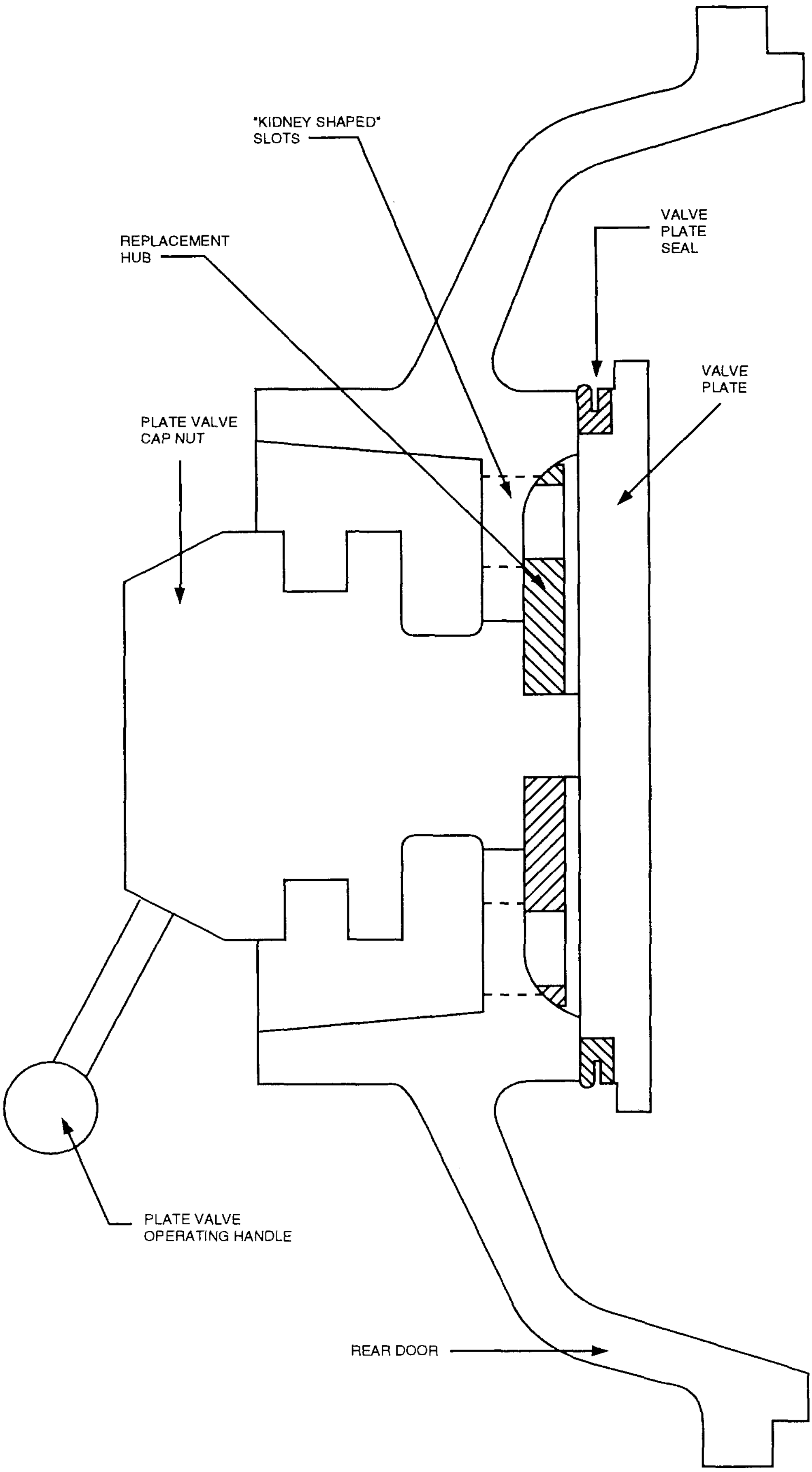

FIG. 11—REAR DOOR PLATE VALVE POSITION OF REPLACEMENT HUB

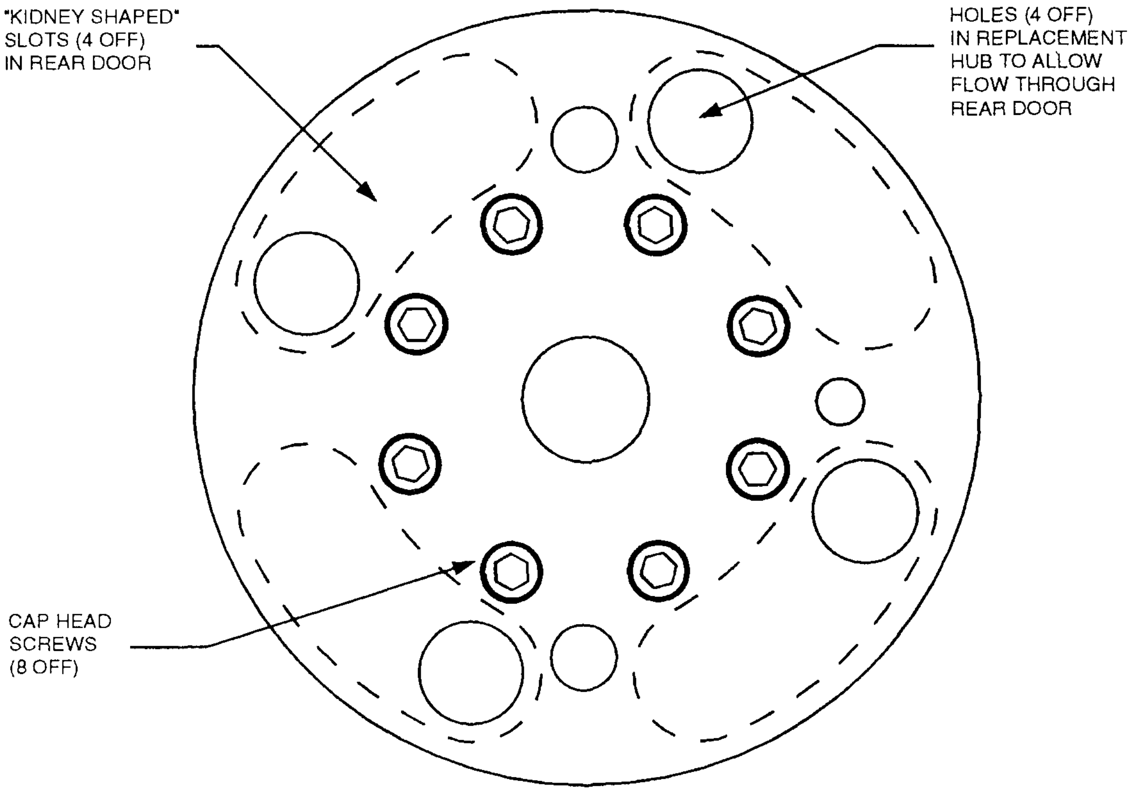

FIG. 12—REAR DOOR PLATE VALVE—REPLACEMENT HUB

completed satisfactorily they could not endorse the design. One of the deficiencies highlighted (which was actually in hand prior to the audit), was the need for latent failure testing to ensure that any fault which formed part of the three fault criteria, and was not normally tested, would not remain undetected. This one task alone proved to be far more difficult to implement than anyone at the time realised. However they were finally agreed and successfully implemented.

Final endorsement

The final Certificate of Safety of Design was signed by:

The DA.
The equipment project manager.
The platform project manager (DGSM) for the interface conditions, and FOSM for operator competence.

The relevant senior professional engineers, in this case DGUW(N) and DNA, endorsed the design for safety and DGSM the final MSZ design. The system has successfully completed a Sea Acceptance Trial (Fleet) on the AUTEC range.

Conclusions

- The safety criteria and design requirements have all been met.
- Comprehensive safety standards and criteria should be agreed and applied at an early stage for those systems which are safety critical.
- Many of the system problems arose from external interface conditions which had never been fully understood or tested.
- Safety studies gain considerable benefit from external audits.
- Never under-estimate the effect of apparently insignificant changes to a large system.

- When you think you have finished testing, then think again.
- During testing of any complex system the consequences of embedding major modifications within that system must be fully explored.
- When large interactive systems are modified it is always wise to ensure that no obscure and hitherto unpredicted change in performance has occurred as a result of the modifications.

Acknowledgements

The Author would like to thank Strachan and Henshaw and Frazer Nash Consultancy Ltd for their assistance in compiling this article and for their part in achieving a safer design.

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