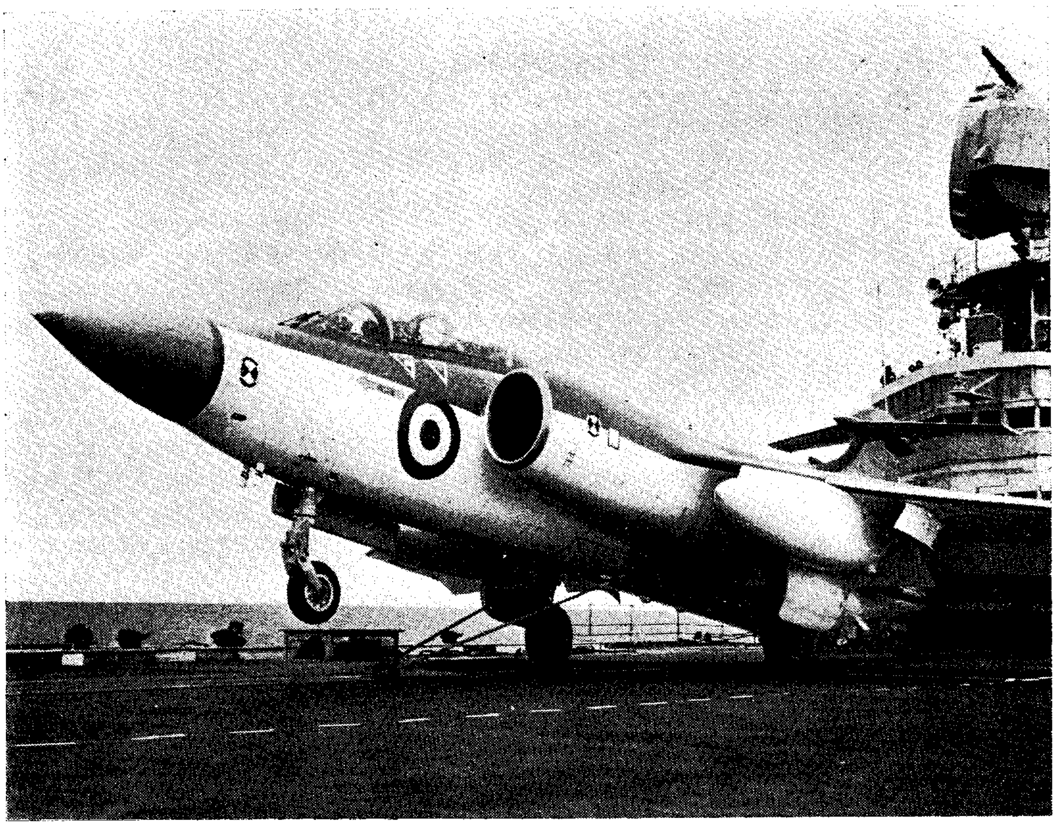


FIG. 1—A BUCCANEER ABOUT TO BE LAUNCHED FROM H.M.S. 'HERMES'

DEVELOPMENT OF THE STEAM CATAPULT

BY

LIEUTENANT-COMMANDER T. A. RITCHIE, R.N., C.ENG., AND F. D. SKELTON

In 1957, an article in Vol. 10, No. 2 of this *Journal* covered the description of the first B.S.4 steam catapult as installed in H.M.S. *Ark Royal* during her 1954–55 refit and also the behaviour of this equipment during the first six months of operational use.

Now that the end of the 'fixed-wing' carrier is in sight, it is perhaps opportune to review the problems and improvements associated with the development of the steam catapult over the last ten years or so, and also to give a glimpse of the design intended for the new carrier before it was cancelled in February, 1966.

In retrospect it is interesting to note the word of warning offered by the Author of the above quoted article in that *Ark Royal*'s catapults were nearly flat out when launching a D.H.110 (Sea Vixen) at about three-quarters of its, then, operational weight. Since those early *Ark Royal* days of operating Sea Hawks at about 16,000 lb take-off weight, the heavier jet aircraft have entered ship-borne squadrons and as is always inevitable their capabilities have been exploited and operational weights have continued to increase. To meet these increases it has been necessary to develop the steam catapult to match these

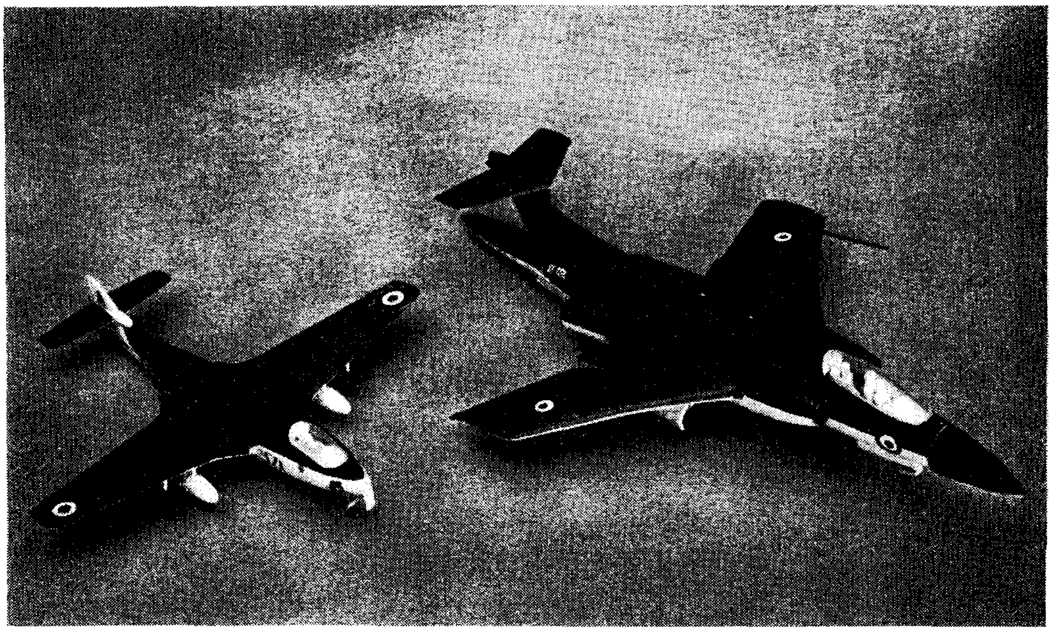


FIG. 2—COMPARISON BETWEEN A SEA HAWK AND A BUCCANEER

aircraft and today Sea Vixens and Buccaneers are launched from the same basic design at weights of up to 46,000 and 50,000 lb respectively.

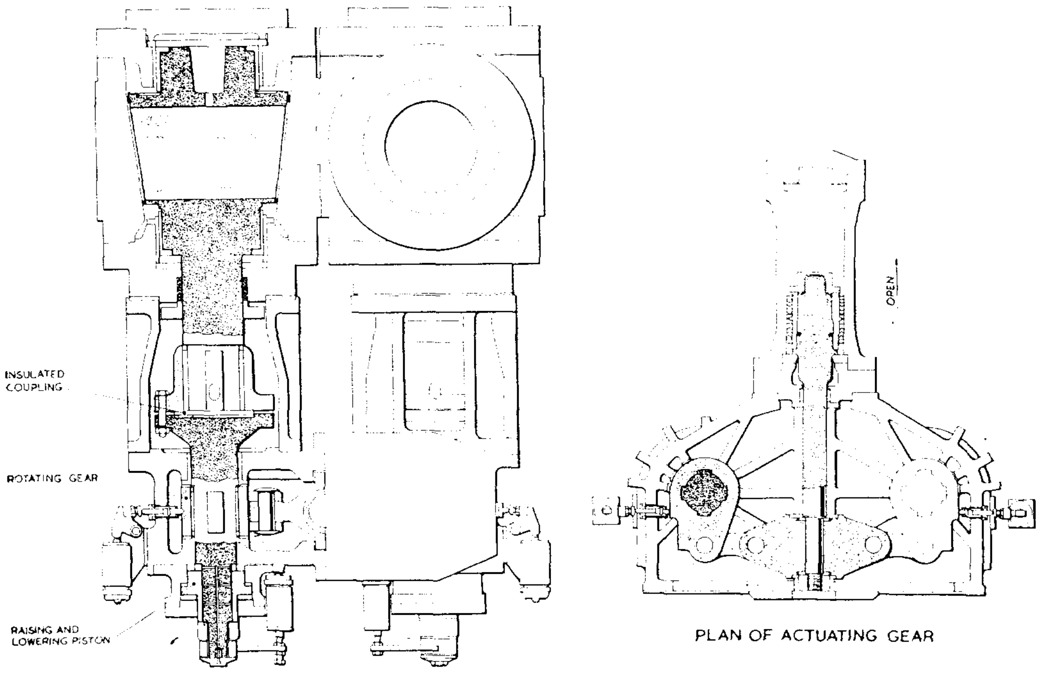
At about the time *Ark Royal*'s catapults were being installed, experience with the prototype catapult fitted in H.M.S. *Perseus* pointed the way to a number of possible and highly desirable improvements to components of the catapult installation. The fields in which most gains could be expected appeared at that time to be in:

(*a*) Reduction of steam consumption
(*b*) Increase in performance for the same initial boiler steam pressure
(*c*) Reduction in weight of moving components
(*d*) Retention of the launching bridle on completion of each launch
(*e*) Reduction of retardation loads on ship's structure.

Note: With regard to (*a*), reduction of steam consumption became lower in development priorities because of the prospect of increased performance for the same quantity of steam; (*c*) became less important because of the increased breakaway shot speeds which would result from the lower weights. It will be appreciated that the higher the speed, the higher the retardation 'g' and hence the more difficult to design to a lower weight. So far as major development is concerned, this article is confined therefore to (*b*), (*d*) and (*e*).

A steering committee, which was formed in 1950 in conjunction with the development of steam catapults, had been given the task of investigating various sources of power for catapults. The possibility of using such propelling media as steam from a special high-pressure boiler, gas from mono-propellants, internal combustion, compressed air and liquid oxidants were discussed and analysed. In comparison with these various alternatives steam from the ship's main boilers, although having many disadvantages from a point of view of pure catapulting, was thought to be the best solution when considering the problem related to installing the catapult plant in existing carriers. For this reason then steam from ships' boilers, stored in dry receivers, was selected for the source of power for B.S.4 catapults.

Also arising from the above investigations came a proposal for storing the energy in a wet accumulator rather than in a dry receiver. From a 'first order'



PLAN OF ACTUATING GEAR

FIG. 3—12-INCH BORE ROTO-VALVES

look at this proposal such an arrangement appeared to offer considerable advantages over the dry receiver not only in performance but in the weight and space reduction for the same amount of energy stored.

In June, 1952, a brief trial was carried out in H.M.S. *Perseus* using one of the dry receiver drums modified in a simple manner to act as a wet accumulator, and the results, though not completely conclusive, were sufficiently encouraging to justify development also in this field. In 1955, therefore, broad lines along which catapult development should go had been established.

It will be appreciated that the development work associated with the novel equipment of the steam catapult covered a very wide field, particularly in respect of the numerous minor, but important, components which were involved in the early teething troubles. No article as general as this, therefore, could do justice to the valuable contribution made by the Naval Air Department of the Royal Aircraft Establishment, Bedford, to the solution of a multitude of problems in addition to the more impressive development projects dealt with in this article. The major developments were as follows:

Roto-Valves

The original launch valves were a pair of skirted lift type globe valves each operated by a double-acting hydraulic piston. To synchronize the valves they were linked by a cross shaft which also operated the 'carrot' of a control valve assembly. The carrot moved into a choke ring with the movement of the valves and in so doing increased the restriction to the flow of hydraulic fluid being exhausted from the double-acting pistons, thereby controlling the rate of opening of the main valves. While this design of valve and control proved to be effective, any form of lift valve is at a disadvantage from the point of view of pressure drop and for this reason roto-valves have been developed and fitted in their place.

These are paired rotary type plug valves, which impose as little as 5 lb/sq in. pressure drop for a steam flow rate of 500 lb/sec. Each of the two plugs is mechanically linked and turned through 90 degrees by a horizontal hydraulic operating cylinder. Hydraulic raising and lowering jacks are also fitted to

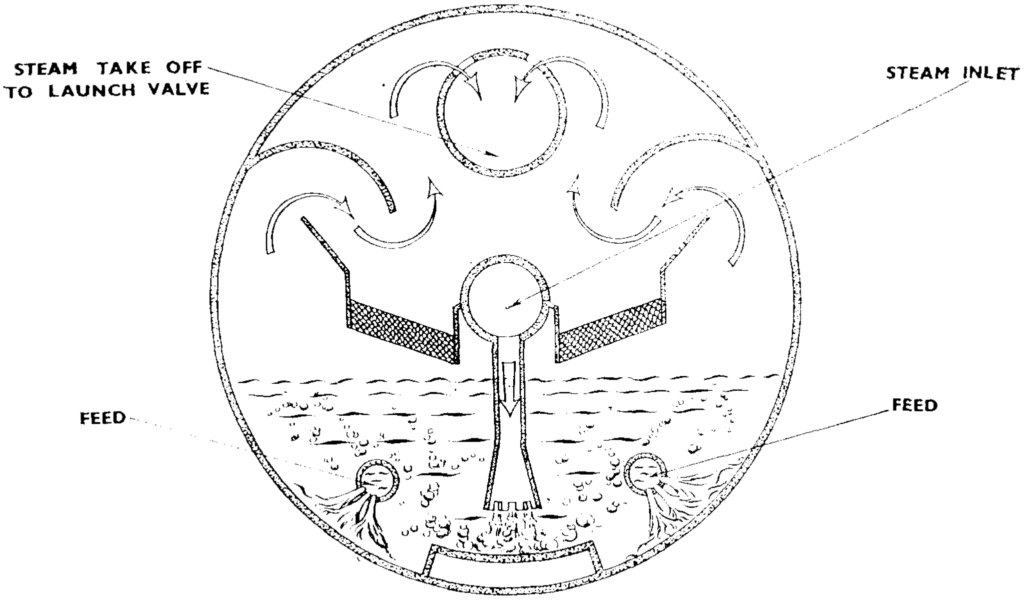


FIG. 4—ILLUSTRATING WET ACCUMULATOR INTERNALS

spindles extended from each plug and the hydraulic system which operates them is interlocked so that fluid cannot enter the turning cylinder until each jack has lifted each plug clear of its seat. Whereas in the lift-type valves the rate of opening, which is critical to the acceleration of the catapult stroke, was controlled by the carrot, the rate of opening of the roto-valves is controlled by a number of orifices which restrict the rate of flow of hydraulic fluid leaving the turning cylinder although the kinematics of the linkages give the required basic shape of the area/time diagram. Three orifices are fitted in a valve block on the turning cylinder cover, one 'fixed' and two capable of being shut off. The sizes of all three orifices are selected by trial and a combination of the three can provide the desired rate of opening of the valves to match the maximum allowable acceleration for the particular aircraft being launched.

Wet Accumulators

As already mentioned, the dry steam receivers originally installed were kept drained of condensation and charged with steam prior to the launch. On opening the launch valves steam from the receivers expanded approximately adiabatically as the pistons moved down the cylinders.

In the case of wet accumulators the receivers are fitted with suitable baffles and filled to about one-third full of water. This water is kept at saturation temperature by bubbling the charging steam through it, via a number of nozzles, when the accumulator is being charged before each launch. During the launch, as the pressure drops, some of the water flashes off into steam which tends to maintain the cylinder pressure level and hence the accelerating force applied to the pistons. Internal collector pipes, and separator assemblies, are fitted to reduce the amount of water carried over, the maximum allowable being of the order of 5 per cent. The optimum working water level is determined by trial. It will be appreciated that as the height of water above the optimum level is increased so will the carry-over be increased, and this will adversely affect the prediction of the end-speed obtained. On the other hand if the water level is decreased below the optimum level the amount of energy available is reduced and performance will start to fall off.

All operational carriers in the Royal Navy have now been fitted with wet accumulators and roto-valves and the gain from this combination has been

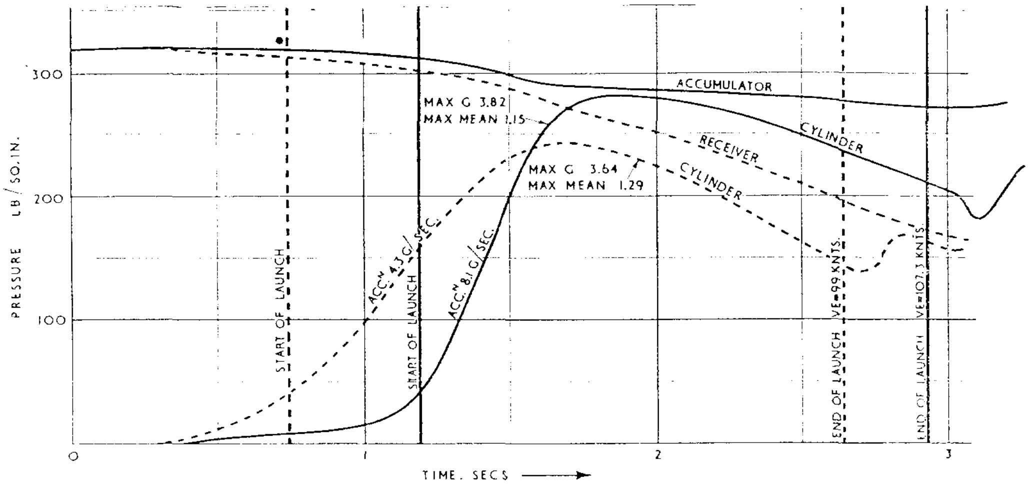


FIG. 5—PERFORMANCE CURVES OF SIMILAR LAUNCHES ILLUSTRATING THE DIFFERENCES IN PRESSURES OBTAINED BETWEEN WET ACCUMULATOR AND ROTO-VALVES, AND DRY RECEIVERS AND LIFT VALVES

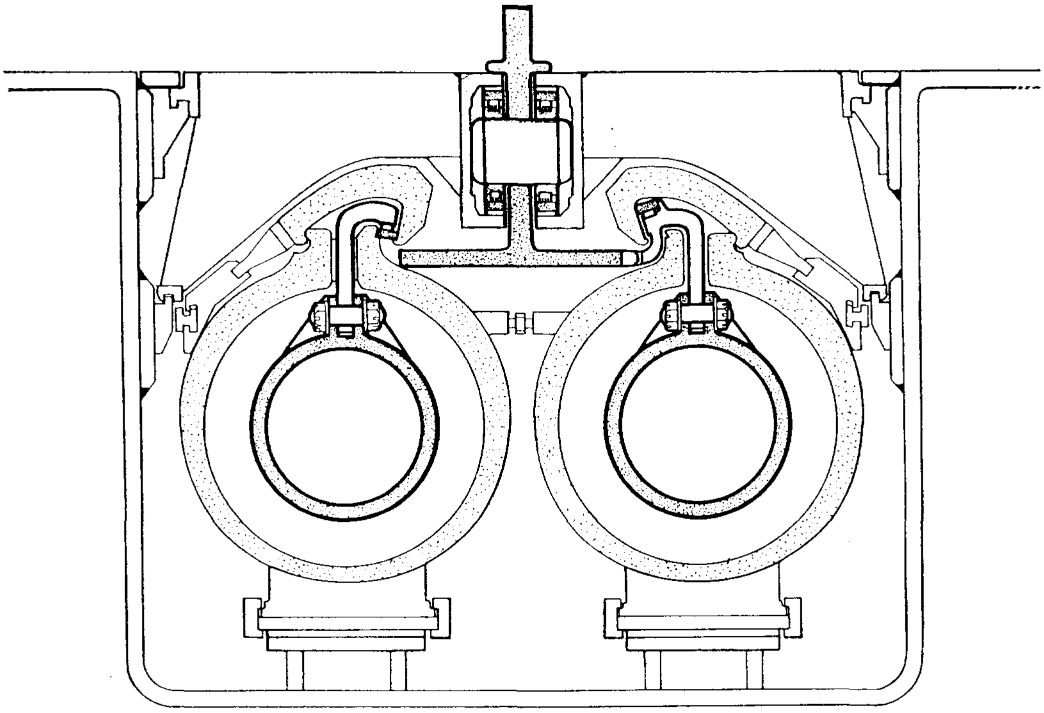


FIG. 6—CROSS-SECTION OF TROUGH SHOWING A B.S.4 CANTILEVER TRACK

of the order of 8–10 knots increase in end-speed over the weight range or, alternatively, an increase of about 6,000 lb in aircraft fuel or pay load for the same end speed.

The full measure of this gain was appreciated when the carrier's sphere of operations changed from temperate climates to those obtaining East of Suez. Under tropical conditions the effective take-off thrust developed by jet aircraft falls appreciably. This adverse effect, combined with the reduction in lift due to the less dense atmosphere and the absence of natural wind, demanded enhanced catapult end-speeds to launch aircraft of similar weights.

Centre Rail Track

The catapult shuttle, which transfers the accelerating forces of the pistons

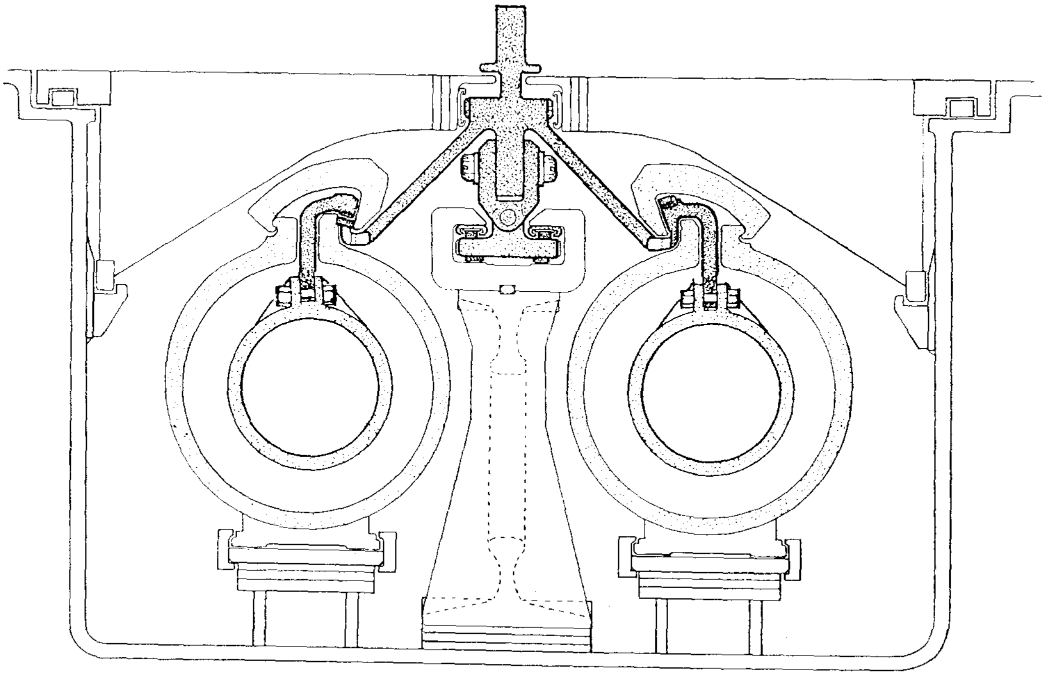


FIG. 7—CROSS-SECTION OF TROUGH SHOWING A B.S.5 CANTILEVER TRACK

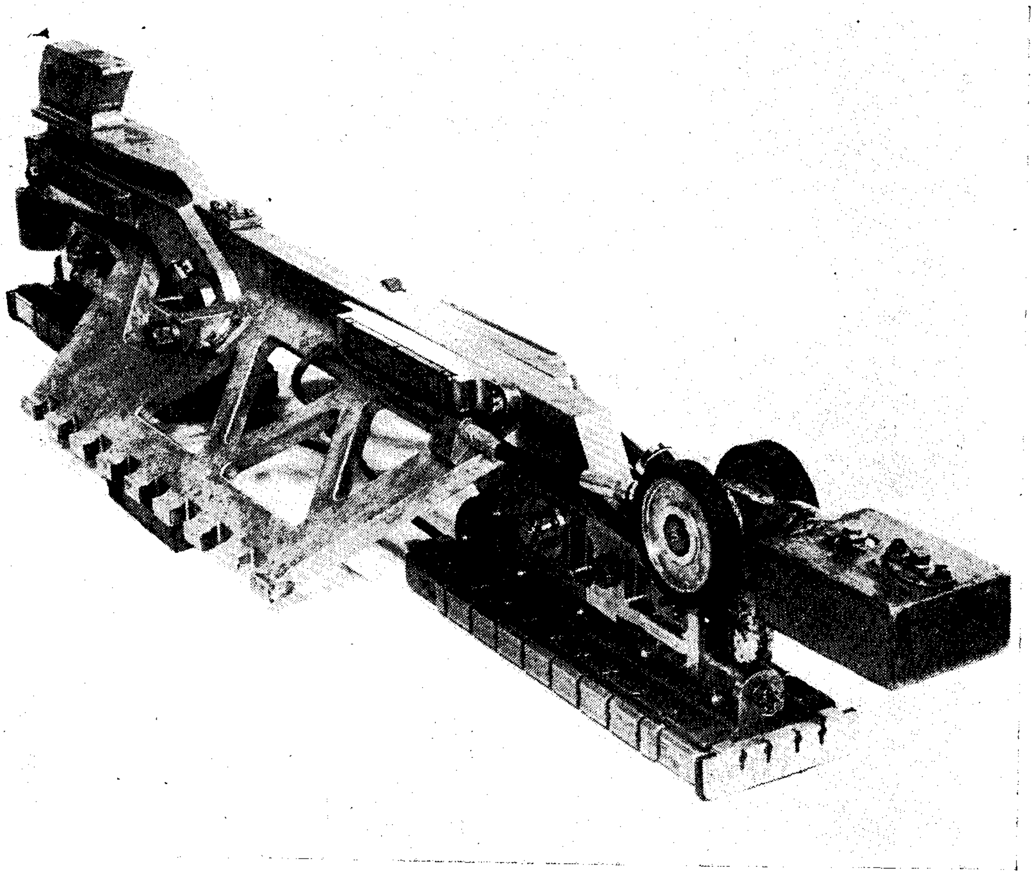


FIG. 8—A B.S.5 CENTRE RAIL SHUTTLE ASSEMBLY

to the aircraft via the towing bridle, runs on four pairs of rollers in channels which form part of the B.S.4 track covers. The latter are fixed to the catapult trough sides by upper and lower support bars so that the vertical component of the towing force is taken by the track covers on a cantilever principle. It will be appreciated that such an arrangement has limitations due to the combined deflections of the track covers and trough sides if the accelerating force, and therefore the vertical component acting on the track covers, becomes excessive. In this respect, when considering the use of higher steam pressures for catapulting, static tests were carried out in *Victorious* and *Centaur* and it was found that the maximum initial steam pressure that could be used with the existing B.S.4 design with reasonable certainty was of the order of 600 lb/sq in.

In order to apply the loads more directly to the ships' structure, a design known as the B.S.5 catapult was developed. Also, although no catastrophic failure had occurred in a ship, it was thought that conditions were being reached which would impose a very limited life on shuttle rollers. In the B.S.5 design the shuttle, instead of running on rollers, runs on slipper pads against two bearing strips in a centre rail which is supported on an 'I' beam tied directly to the ships' structure. The slipper pads are of the Michell principle hydrodynamically lubricated by oil on a once-through, total-loss, system from a gear-wheel pump mounted on the shuttle and driven by wheels in contact with the underside of the track covers. The first ship-borne B.S.5 C.R.T. catapults were fitted in the French carriers *Clemenceau* and *Foch* and have since been installed in H.M.S. *Eagle* and to date they have proved very satisfactory in service. One problem associated with the use of the slipper pad shuttle is that when the aircraft breaks out at the commencement of the launch the shuttle moves several feet before hydrodynamic lubrication of the slippers becomes effective and until this point has been reached the slipper pads are subjected to a 'dry' start with the consequent scuffing of the bearing strip and wear of the slipper pad material. So far this factor has not presented a serious problem but trials carried out at the Naval Air Department, Bedford, at launching weights not much higher than those now in service, have pointed to yet another aspect for which development and re-design is required.

Increased Steam Pressure

By the early 'sixties, the stage of catapult development had been reached where the Staff Requirement Buccaneer aircraft at 39,000 lb all-up weight could be launched from all carriers fitted with wet accumulators and roto-valves in nil-wind, tropical conditions although it was appreciated that the lack of launching stroke in naval catapults was becoming a severe limitation in performance capability. However, since the Buccaneer was still capable of being uprated to about 46/48,000 lb it was decided to investigate the possibility of increasing the catapult performance by increasing the available steam pressure. Several methods were investigated but only the following two were considered possibilities so far as existing ships were concerned.

Auxiliary Boiler

To supply the catapult independent of the ship's boilers, an auxilairy boiler was designed and developed and is, in fact, installed at the Naval Air Department, Bedford, and has given very satisfactory service in supplying steam to the experimental land-based catapults. This is a La Mont, forced circulation boiler of 110,000 lb/hr evaporation rate and variable working pressure up to 1,025 lb/sq in. saturated steam. It is fully automatic in the pressure range 550–1,000 lb/sq in. burning Diesel fuel through eight 'keyhole' type combustors.

Although a reasonably compact self-contained unit, it was not as small as was hoped and the evaporation rate required to meet a cycle time of 30 seconds was about twice that possible from the boiler. A boiler twice the size, sited in its own boiler room complete with full auxiliaries, was considered to be too great a penalty in space and weight for back fitting into existing carriers. No further consideration was given therefore in this direction.

Steam Compressor

The second alternative, and that recommended for development, was for a steam-driven steam compressor supplied from the ship's boilers, at 375 lb/sq in. (460–700 degrees F.) inlet and 400–685 lb/sq in. with slight superheat at the outlet. A development contract was placed for the design and manufacture of a prototype steam compressor. This consisted essentially of a single unit turbo-compressor with a four-stage turbine and a two-stage compressor on a common shaft; the shaft being mounted on two plain bearings and designed to run at 19,000 r.p.m. full speed, the whole speed range for charging being above the first critical. It was intended to enclose the rotor within an unsplit casing and assemble it axially so that the final outlet flange would be the only bolted flange subjected to the high steam pressure. The exhaust steam from the turbine would be condensed in a surface condenser at atmospheric pressure and mounted axially with the turbo-compressor unit.

After about two years, when the design had reached about 90 per cent completion, it was considered that a complete re-appraisal of the whole project from aspects of both cost and installation should be made.

Firstly, the original estimate of cost for the prototype machine had doubled and, although not prohibitive in itself, it was by no means the final price and it seemed more than likely to increase still further before the project would be complete. Secondly, the further the design progressed, the more it became obvious that many ship installation problems were presenting themselves as major factors.

Like the auxiliary boiler, the original concept of 'just fitting a steam compressor' was quickly developing into a large installation with its attendant auxiliaries. Not least of the problems would have been the routeing of eight-inch bore high-pressure pipes (about 18 inches over lagging) from the vicinity of the boiler rooms to forward just below the flight deck, in already congested ships. The installation was considered in two stages; the first involving only the fitting of the steam compressor installation which, for all ships except *Eagle*, would have limited the compressor operating pressure to about 600 lb/sq in. due to the limitation of the B.S.4 design of cantilever track cover. To take full advantage of the steam compressor therefore, the second stage would have involved the fitting in all ships, of a centre rail track in addition to the steam compressor. In view of the considerable installation costs, in addition to the costs of supplying the compressor, CRT catapults and other high pressure components, the continuance of this project could not be justified. Furthermore, these modifications would have necessitated each carrier being non-operational for about two years and this was unacceptable to the Naval Staff.

Several other problems were foreseen, among which was the inability to shore-test the compressor at its full rated conditions thus necessitating the use of an operational carrier as a test vehicle. The steam consumption of the compressor would have been some 240,000 lb/hr, which represents a large percentage of the boiler output for some ships. Another problem was the possibility that the continual use of high power cylinder pressures would seriously affect the stability of the power cylinders. A final doubt concerning its use was introduced by the fact that the Buccaneer aircraft probably could not be strengthened sufficiently to take the increased accelerating loads that would be imposed by using higher pressure in the power cylinders in the

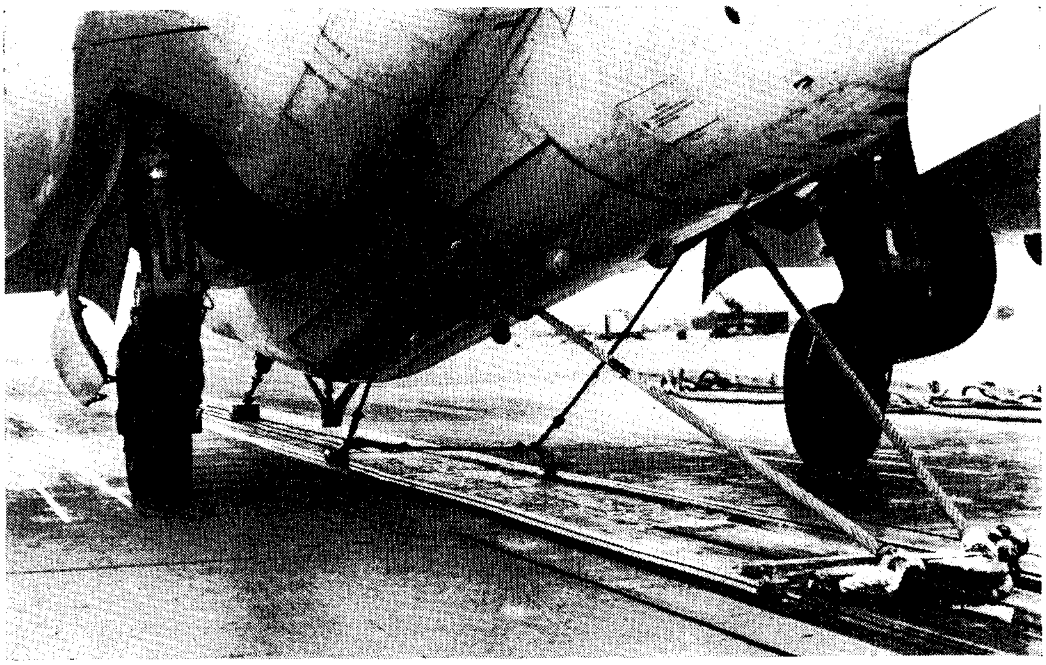


FIG. 9—BRIDLE ARRESTER—NYLON LANYARDS CONNECTING A BUCCANEER BRIDLE TO THE SLIDERS OF A VAN ZELM ARRESTING GEAR

relatively short naval catapults. All these factors weighed heavily against the continuance of the steam compressor project and it was finally abandoned in 1962.

It is understood that the U.S. Navy have recently decided to introduce steam compressors into those carriers where lower steam pressures are used. This project will therefore be followed with much interest.

Bridle Arresters

Since the inception of launching aircraft with an expendable bridle, it has always been recognized that a means of retaining the bridle is highly desirable. A bridle for a modern aircraft is manufactured from approximately 25 feet of 4½-inch steel wire rope at a cost of approximately twelve pounds and, while this cost is negligible when compared with the cost of launching the aircraft, the logistic support of bridles is of much more concern and a greater reason for their retention and repeated use. It will be appreciated that it is of paramount importance that any form of bridle arrester, which must catch a steel wire of varying attitude weighing about 150 lb and travelling at about 100/120 knots, must not damage the aircraft or external stores or prejudice the safety of the launch in any way. Several methods of arresting bridles have been tried, some with partial success. These have usually been based on the principle that the K.E. of the bridle is absorbed by 'undrawn' nylon but to date no R.N. design has been entirely successful. The U.S. Navy have been more successful in this field and have produced a design, commonly known as the 'Van Zelm', but officially designated Mark 2, Mod. 2, Bridle Arrester, which is now in service with U.S. carriers. In this design the bridle is attached to 'sliders', which run in tracks mounted on the track covers about three feet apart, by two nylon rope lanyards and two nylon rope grommets. The tracks run the whole length of the catapult and continue on to a 'boom' projecting from the round-down at the forward end ahead of the catapult. One of the sliders is attached to a 400 ft long steel tape, having a cross-section 3 in. × 0·05 in. the back end of which is attached to a 'braking engine' sited immediately under the flight deck at the after end of the catapult. As the bridle is towed forward during the launch the steel tape is allowed to run out until the aircraft starts to leave the bridle, at which point brakes are applied and the bridle is gradually brought to rest on the boom. The 'engine' then retracts the bridle back to the battery position where the bridle is inspected and made ready for the succeeding launch. This design of arrester, having been installed at Bedford, and its compatibility with most operational R.N. aircraft established, is now planned to be fitted in R.N. carriers.

Retardation

Retardation development has continued over many years at Bedford, and has been aimed at improving the performance of the gear, reducing the loads on the piston assembly and retardation structure, and getting a better theoretical understanding of the problems. It must be remembered that, whereas the operating conditions of the catapult entail launching speeds of up to 150 knots, failure of the link between the aircraft and shuttle, not only could involve the loss of an aircraft but also cause very high entry speeds of the piston assembly into the retardation system. These entry speeds could be as high as 400 knots depending on the weight of the moving parts. However, in view of the extremely rare possibility of a 'break-away' shot occurring (that is at the point of maximum acceleration during the launch), it has been usual to design for a no-damage condition for the 'run-away' shot case (bridle shedding at the commencement of a launch, that is, a very fast 'light shot') and a minimum of damage to moving parts with no damage to the retardation structure for the 'break-away' shot case.

For the proposed B.S.6 catapult, this involved the retardation of a piston assembly weight up to 9,500 lb at 'run-away' shot speeds up to 275 knots and 'break-away' shot speeds up to 350 knots. In the latter case, the load on the ship's structure would be of the order of 4,500 tons, the retardation acting on the piston and shuttle components of the order of 1,600 g and a maximum pressure in the retardation cylinders of about 80,000 lb/sq in. with a duration of only about 0·025 seconds.

Early design of retardation rams did not take care of all the various factors and the profile was based on the assumption that water was an incompressible fluid. This theory has since been modified and in later designs account is taken of the involved problem of delay in the 'bucket effect' during retardation. It must be appreciated that the impingement of the water from the retardation cylinder on to the bucket of the ram represents some 25 per cent of the total energy absorption of the system.

Problems of bucket flare, choke ring design, skeleton cylinder deformation and structural support in this area resulting from in-service experience have been largely resolved at the Naval Air Department, Bedford.

In-Service Problems

In parallel with the development of catapults there has been a fairly constant requirement to overcome troubles thrown up by sea experience, and it is proposed to mention here only those which have given most cause for concern.

Guide Pistons

While we were able to reap the benefit of higher catapult performances by launching heavier aircraft, this in itself created its own problem.

The mechanics of the catapult is relatively simple in concept and the piston assembly can be roughly illustrated as a pair of dumb-bells forced along the cylinders by steam pressure towing the aircraft, via a shuttle, by a steel wire bridle at about 20–30 degrees to the horizontal. The after part of the dumb-bell

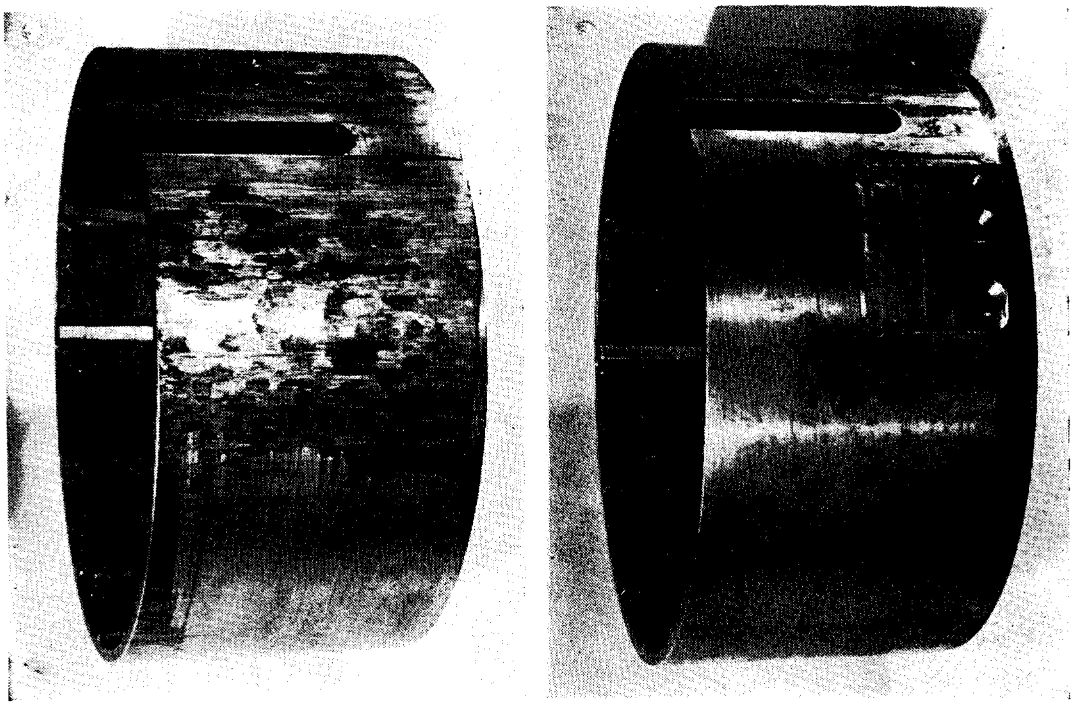


FIG. 10—GUIDE PISTONS; LEFT, THE ORIGINAL DESIGN SHOWING SEVERE WEAR AND RIGHT, DESIGN MODIFIED WITH STEAM POCKETS

comprises the main piston and the forward the guide piston. The horizontal component of the bridle tension causes a couple to be applied to the dumb-bells via the shuttle dogs, the reaction against which is taken by the upper surfaces of the forward aluminium bronze guide pistons against the steel cylinders.

In 1960 the operational weights of the heavier jet aircraft in service had reached 35,000–36,000 lb and in consequence the accelerating forces necessary to launch aircraft at these weights in low natural wind conditions increased considerably with the result that the wear rate of the aluminium bronze guide pistons rose to alarming proportions. The life of the pistons, which had been well over 1,500 launches, rapidly dropped to below 100 and operational carriers were faced with the prospect of doing a one-and-a-half to two-day piston change every three or four days, an operation not normally carried out at sea. Needless to say, strong representations were made by the Fleet at having to operate carriers with the prospect of such serious limitations.

Urgent research was therefore necessary. The short-term possible solution appeared to be in improved guide piston materials, consistent with the steel cylinders, and better lubrication. But for the long-term answer an articulated piston assembly which would allow a greater bearing surface, was already being developed although unfortunately the first designs had failed structurally on trials. Meanwhile, to combat the immediate problem, a proposal, which was originally considered in the *Perseus* prototype, was approved. This entailed drilling holes in the top of the guide pistons to allow the driving steam to enter areas recessed on the outside of the guide pistons, thereby forming a steam cushion between the piston and cylinder. This design, known as the steam pocketed piston, is self-compensating in that the greater the force required to drive the piston the greater the force opposing the couple. This design has, to date, been successful and has brought the life of guide pistons back to acceptable limits.

Shuttle Dogs

Associated with the problem of guide piston wear was an indication that dog locking could occur between the engaging dogs of the piston assembly and the shuttle thereby tending to increase the turning moment applied to the piston assembly. This would, of course, aggravate the guide piston wear. It was therefore decided to increase the design clearance between the dogs from 0·002 in. to 0·008 in., but this resulted in the clearance opening up still further and at a disturbing rate. One ship reached a 'rattling good fit' of 0·030 in. This is perhaps not surprising when one realizes that approximately two tons of moving parts travelling at about 100 knots are brought to rest in five feet, all parts being subjected to a maximum retardation of the order of 200 g.

It was decided therefore to revert to the existing design clearance of 0·002 in. and since steam pocketing the guide pistons had solved the guide piston wear problem it seemed prudent to let sleeping dogs lie!

Gap Opening

It is probably well known that the steam catapult was designed by Mr. C. C. Mitchell of Messrs. Brown Bros. and Co. Ltd., and there is little doubt that the biggest single feature contributing to its success is the very successful design of the slotted cylinder which is required to flex under pressure for sealing purposes and at the same time be stiff enough to maintain a stable shape when the pressure is released. From the cross-sectional illustrations it will be seen that the sealing strip, after it has been ironed down into place by the passing piston assembly, acts as a strut between the cylinder and cylinder cover thereby effectively sealing the cylinder. To date, this design has successfully withstood working pressures of 700–800 lb/sq in. without deformation although without a sealing strip in place permanent distortion would occur at pressures below 30 lb/sq in.

It will be appreciated that during a launch, failure to seat the sealing strip in its proper place, and therefore failure to seal the cylinder, will cause a loss in steam pressure behind the piston assembly with the result that an aircraft will almost certainly be lost. It is of importance therefore that the gap in the cylinder slot must remain constant. If the gap closes in, the strip will fall out or if the gap opens out, the strip will not seat in its place; either way resulting in disastrous consequences.

Until 1962 there appeared to be a difference in experience between the R.N. and U.S.N. over cylinder gaps, thought to be due to the different attitudes towards cylinder lubrication. Whereas we had found that gaps tended to close in service, the U.S.N. found that after about 3,000 launches the gaps had opened out to the limit of the design and in consequence the cylinders were removed for 'peening'.

Because of the uncertain state of cylinder gaps in R.N. service and the fact that in one ship a strip bar was damaged due to the shuttle jamming, much more interest was focussed on cylinder gaps and in 1962 full particulars on the U.S.N. peening procedure were obtained and also the criteria to which they were working. Subsequently a critical examination of the cylinder gaps in H.M.S. *Ark Royal* and *Victorious* revealed that, as had been the case with U.S.N. ships, cylinder gaps in R.N. ships had now started to open out, and, by their standards, outside the limits laid down for safe launching. It was decided, therefore, to seek further information from the U.S.N. on the know-how and techniques required to peen cylinders and, under the initial guidance of the U.S., cylinders in *Ark Royal* and *Victorious* were peened and restored to their design dimensions.

Briefly, peening cylinders involves 'windy-hammering' the outside surfaces of the undersides of the cylinders so that the surface metal is stretched circumferentially. This results in the gap closing. In some cases, it was also found that the cylinder bars had slightly bowed longitudinally, that is, the gaps were wider in the centre than at the flanges. It was possible to retrieve some such cylinders by peening, to close the gaps in the centre, and then applying thin welding runs on the flange edges to open out the gaps at the flanges to nullify the effects of the peening.

Peening has now become a standard practice in the reclamation of catapult power cylinders.

It is an interesting phenomenon experienced in U.S.N. ships that peening has been found necessary after about 2,000 launches and again when 5,000 and 17,000 launches have been reached; but after this cylinders appear to become virtually stable and require no further peening throughout their lives. It is understood that they have now reached a total of 30,000 since the third peening and the gaps are still within their limits.

B.S. 6 Catapult

As long ago as 1952, thought was being given to the catapults to be fitted in a new carrier. Four installations based on B.S.4 design were envisaged, two were to be capable of launching 70,000 lb at 120 knots with a maximum acceleration of 4·5 g, and two launching 30,000 lb at 150 knots with a 6 g limitation. Steam pressure of 550 lb/sq in. was considered adequate especially as a working stroke of over 300 ft was thought possible.

Due to numerous factors, by 1960 the requirements had changed for CVA 01. Two catapults only were required having the ability to launch aircraft by conventional and nosewheel-tow methods. They were to be designed to launch 60,000 lb aircraft at 150 knots at an acceleration not exceeding 4·7 g. Catapults 250 ft long could meet this requirement.

In conjunction with a design study to ascertain how best the Staff Requirements could be met, a review of various proposals concerning the sources of power for catapults resulted in the decision to continue the development of the steam catapult using a maximum wet accumulator pressure of 750 lb/sq in. A new catapult known as the B.S.6 would be developed for the new carrier since it was not possible to meet the Staff Requirement solely by an extension of the length of either B.S.4 or B.S.5 designs. The main difference between B.S.6 design and current catapult installations are briefly described below.

Power Cylinders—To eliminate the maintenance load and unserviceability associated with the need to peen cylinders as mentioned earlier, a more stable design of cylinder was necessary. Tests at the Naval Air Department, Bedford, have gone some way towards achieving this and have resulted in a cylinder 6 ft long with increased top bar width and flange radial thickness with no gap adjusting gear.

The tests at Bedford included burning cordite in a rig comprising three cylinder lengths and a simulated piston and key-iron assembly so that only half of the rig was pressurized. During these tests it was observed that the cylinder slot closed in rapidly with successive charges. Detailed investigation into the cause of this closure tended to suggest the view that this was a result of the high thermal stress set up in the cylinder wall when suddenly brought into contact with the hot gas.

Temperature measurement on the BXS.5 (Flush) catapult at Bedford and theoretical study suggest that the same phenomenon to a lesser degree will be present on in-service steam catapults although this tendency for closure is probably compensated by the cold working of the cylinder bore by the

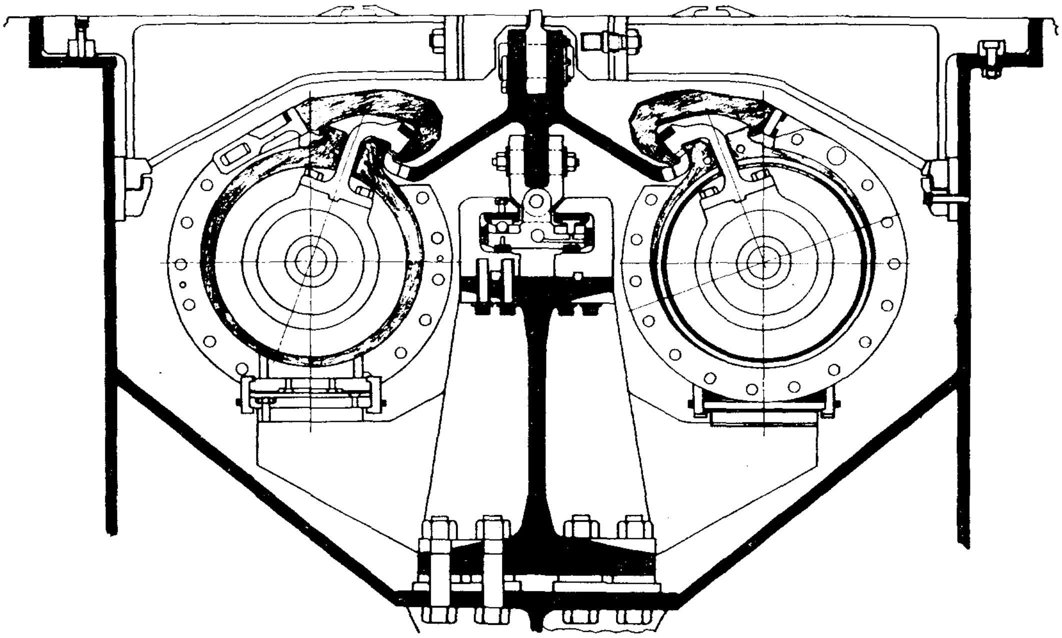


FIG. 11—CROSS-SECTION OF A B.S.6 TROUGH SHOWING CENTRE RAIL AND CYLINDERS SUPPORTED FROM THE CENTRE 'I' BEAM

piston which tends to open the slot and to predominate over any tendency to closure. With the higher steam pressures and temperatures envisaged for the new catapult, however, there appeared to be the possibility that the thermal effect would become the major one and in that case slot closure with the associated seizures would occur. It was decided therefore to electrically preheat the cylinders externally to reduce thermal shock to a low level. It was envisaged that this would be achieved by enclosing the cylinders as far as possible in lagged heating elements. A possibility that the variation of the preheat temperature and consequent variation of the degree of thermal shock would enable the slot opening and closing tendencies to be balanced indefinitely, thus maintaining a constant slot width.

Centre Rail Stool Design—For ease of installation and maintenance of alignment, the power cylinder feet support stools were carried by the centre rail track stool instead of being independent as in the B.S.5 design. With such a design the assembly of adjacent units could be done on the shop floor and alignment guaranteed before installation on board. It was also intended that this centre stool, after installation, would be the datum for aligning track cover support bars.

Catapult Trough—From considerations of both strength and accessibility, the conventional trough gave way to one of novel design. It comprised two continuous longitudinal bulkheads 6 ft 6 in. apart and extending the length of the catapult. For ease of maintenance it was increased in width to nearly 8 ft in way of the retardation and skeleton cylinders at the forward end, and the roto-valves and first 8 ft of the catapult stroke at the after end. Athwartships diaphragms which transmitted the load from the centre track to the longitudinals were sited every 3 to 4 ft along the length of the catapult and below the power cylinders. The height between the track covers and the in-trough space was 11 ft 6 in. which enabled the maintainer to stand upright in the trough with comparatively unrestricted access to the cylinders above.

Retraction System—To meet the Staff Requirement cycle time it was necessary for the grab to travel forward in 8 seconds and retract a much heavier piston assembly in 12 seconds which meant retraction speeds of about 30 ft/sec had

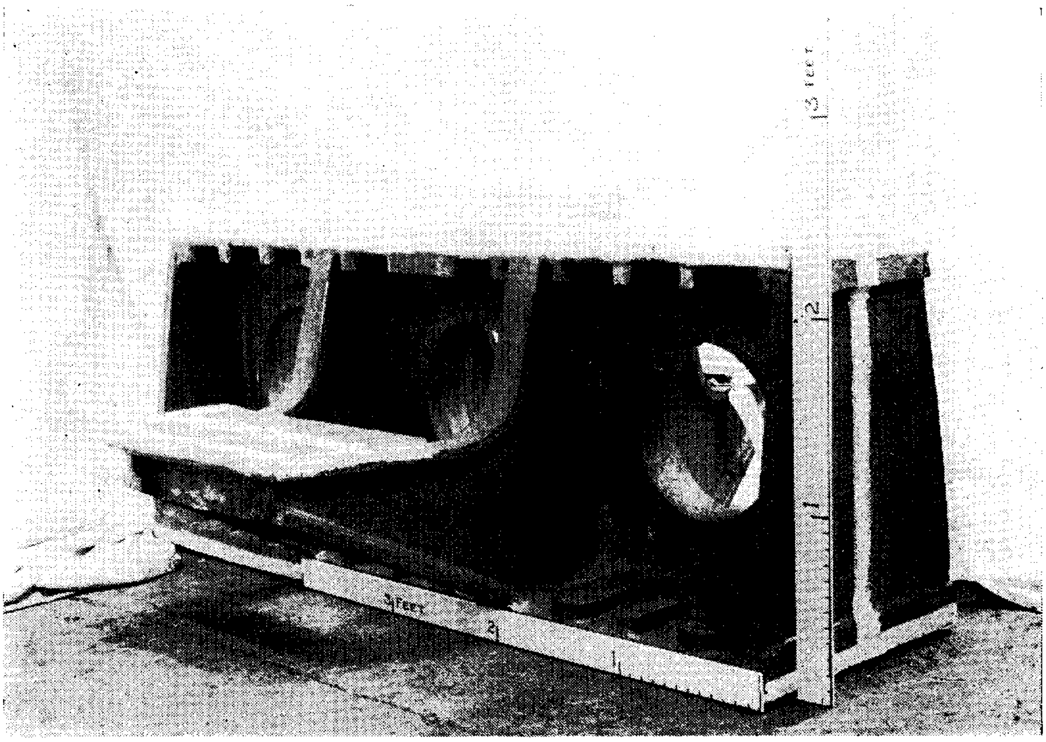


FIG. 12—A 6-FT SECTION OF A B.S.6 CENTRE RAIL 'I' BEAM AND STOOL

to be attained. It was decided therefore to use a design of hydraulic winch. Such a duty with a conventional hydraulic jigger system would have involved a considerable penalty in weight, space and power demand, in fact, as far back as 1955 the U.S.N. were advised to investigate winch retraction when it was obvious that hydraulic jiggers for their 250 ft catapults were becoming too large and heavy. Basically, single forward and aft grab ropes are wound on to a winch drum so that as one rope is pulled in by the rotation of the drum the other is payed out. The drum is driven via a simple gearbox by two hydraulic motors supplied by two electric driven swash-plate type hydraulic pumps. Control is effected by variation of the swash angle. Forward tensioning of the aircraft would be effected by a direct-acting hydraulic ram sited between the aftermost power cylinders, the winch controls being arranged to permit the winch drum to 'free-wheel' during the forward movement of the shuttle and grab.

Piston Assemblies—These were designed to enable all wearing components to be replaced *in situ* and so obviate the time delay currently involved in removing the assemblies from the trough. To eliminate fastening problems, the power piston, distance piece and retard ram were forged as a single unit. Similarly the driving key and driving iron were integral.

Wearing segments were designed to replace the conventional guide pistons which made for easier and more economic replacement. Trials to reduce the effective area of the steam pockets, to improve the wear on the lower half of the piston now being experienced in present ships, are being continued in order to reduce still further the present frequency of piston changing.

Steam Systems

Steam pipes fitted between the wet steam accumulator and the roto-valves and the entire exhaust system were being increased to 18-inch bore. Throughout all systems, flanged joints were to be reduced in number to those required to remove maintainable components, the larger components being fitted with seal-welded flanged joints.

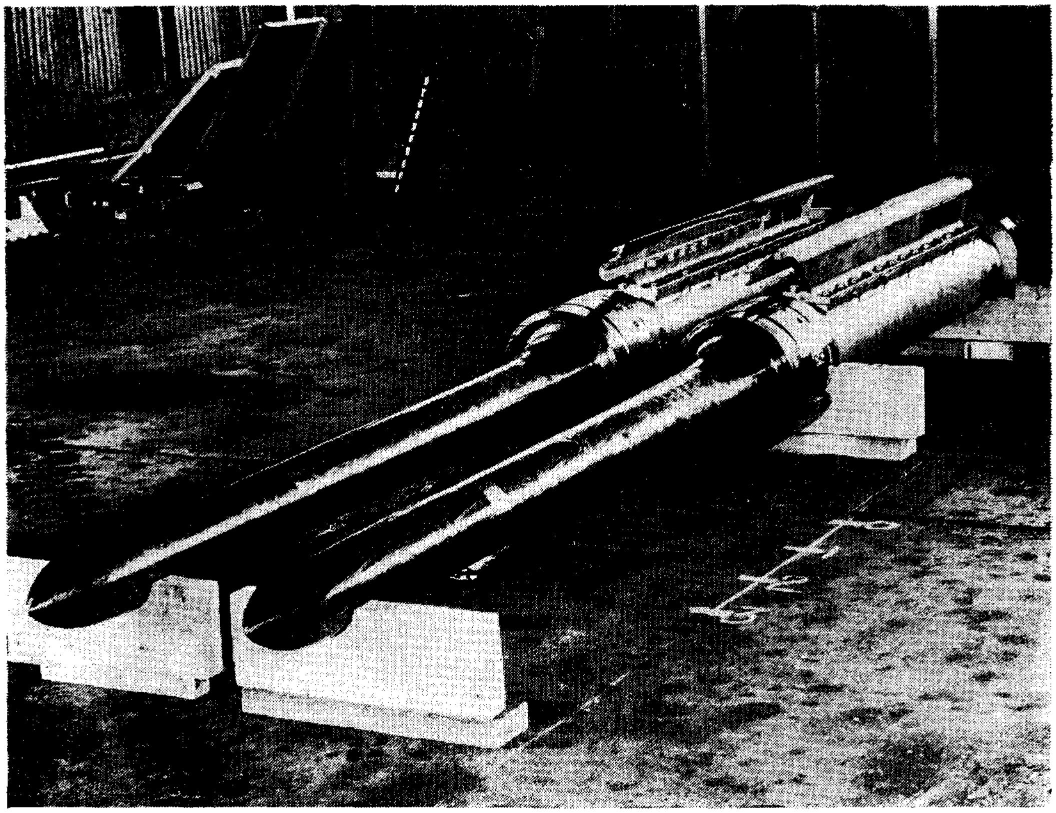


FIG. 13—A B.S.6 PISTON ASSEMBLY

Hydraulic Systems

Two separate systems using Houghto-Safe 271 hydraulic fluid were envisaged: one for catapult general service and the other for the retraction winch. All pumps in the installation were to be electrically driven.

Catapult Control

The Flyco, Flight Deck Officer, Howdah and Console concept was to have been retained in CVA 01, the howdah being air-conditioned and sound-proofed and designed to house the operator and the Catapult F.D.E.O. at appropriate control positions. For emergency operation, controls in the howdah were duplicated at the console in the main catapult machinery compartment sited in an air-conditioned control room. The normal stations of the operator (POM(E)) the diagnostician (ERA) and the machinery room watchkeepers (LM(E)s) and (M(E)s) were to be at appropriate 'consolised' positions in the control room.

Flying programme details were to be promulgated by television, receivers being fitted in the F.D.E.O.'s office, ready rooms, howdahs and control rooms. Launching information between Flyco, howdahs and catapult control rooms was designed to be transmitted by electro-writers.

In order to meet a 45-second launching cycle, the majority of catapult functions, after the initial push-button activation, were automatic. For example, after pushing the fire push in a full cycle operation all subsequent catapult functions, up to the stage where the next aircraft required tensioning, were fully automatic (with the exception of raising the jet blast deflectors). It is of interest to recall that the original console for *Perseus* was designed and built for automatic sequence control although at that time 'automation' gave way to well-tried principles of a less spectacular form. Since then, of course,

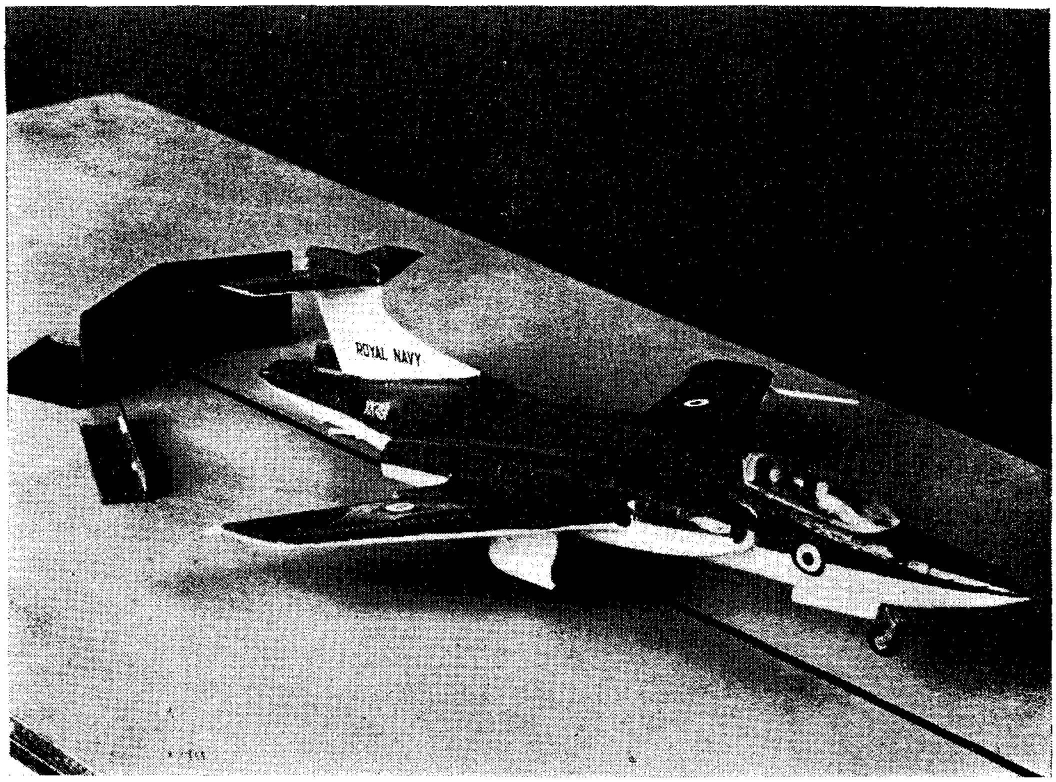


FIG. 14—MODEL OF NEW JET BLAST DEFLECTOR CONFIGURATION

control electrics have attained high standards of reliability and were to be used extensively in the control systems of the B.S.6 catapults. With bridle launched aircraft, deck crews were still required to attach the holdback and bridle although the equivalent of this equipment in nosewheel-tow launching was automatically connected.

B.S. Ancillary Equipment

Provision was made in CVA 01 for an area of the flight deck immediately aft of the catapult trough to be 'dimpled' one-foot deep to accommodate the operating equipments associated with blast deflectors, aircraft loading chocks, holdback tracks and nosewheel tow gear. The provision of this dimple not only made the concept of a flush deck a reality but provided flexibility for possible changes in the configuration of these components in meeting future generations of aircraft. However, in CVA 01 this shortcoming was rectified by the dimple deck concept.

Jet Blast Deflectors

All R.N. carriers have suffered to varying degrees many jet blast deflector failures. Basically all the failures can be attributed to the lack of adequate space below the jet blast deflectors in which to install operating equipment capable of withstanding the effects of the adverse conditions in the loading base area.

From model tests at the Naval Air Department, Bedford, it was established that the present configuration of jet blast deflectors was aerodynamically incorrect and that the ideal configuration should consist of two large upright plates set at 120 degrees to each other, the fore and aft line of the catapult passing through the apex so formed. To collect any jet efflux which tended to pass outside the forward edges of the main plates, side collector plates were positioned to deflect the exhaust on to the main plates. The effectiveness of this arrangement was demonstrated during full-scale tests with a Buccaneer at

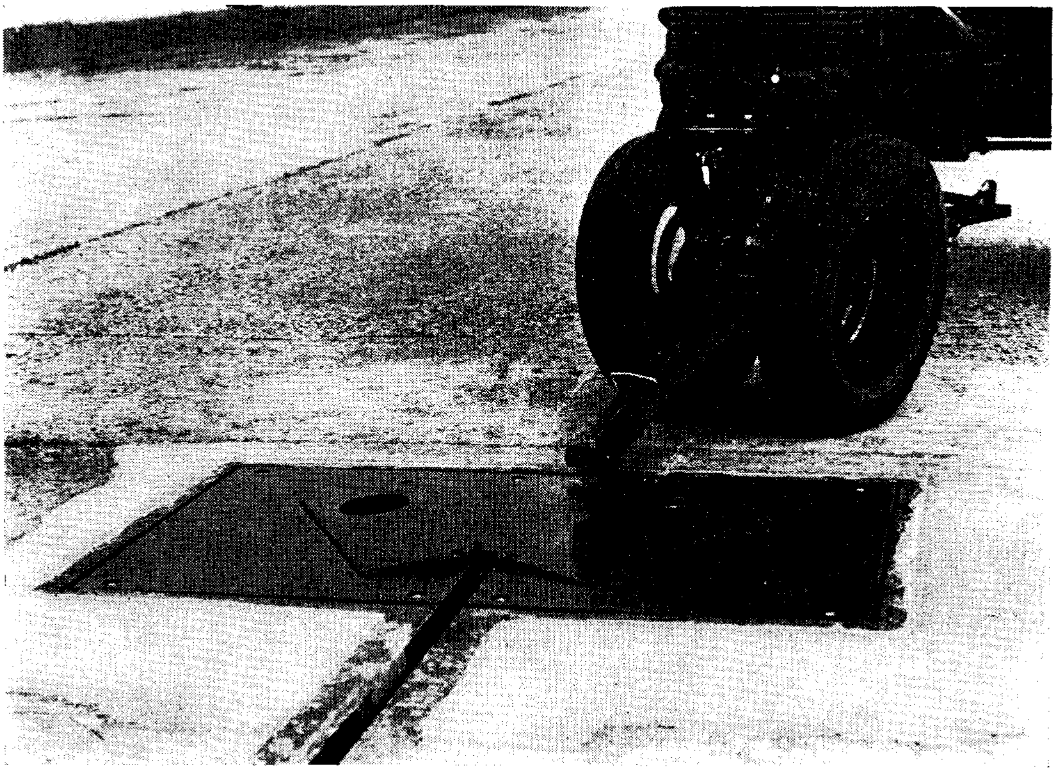


FIG. 15—MOCK-UP OF A NOSEWHEEL TOW BAR AND GUIDE

take off power when it was possible to pass immediately behind the jet blast deflector.

The operating equipment was substantially simplified and consisted of two jacks and two solid struts per main plate. A hinge line torque tube was introduced to assist both raising and lowering, and arrangements were made to water-cool the surface panel of the main plates.

Similar arrangements to those envisaged above are planned to be introduced into existing R.N. carriers in the near future.

Chocks

Since, after preliminary trials at sea, it was considered acceptable to centre the aircraft on to the loading base by means other than the conventional roller mats, the latter were not considered necessary for CVA 01 particularly as they were an embarrassment to the arrangement of machinery immediately below the flight deck. However, loading chocks were still required to positively locate the aircraft at its loading position. Advantage was taken to obtain the maximum accelerating stroke for each complement aircraft by fitting appropriate sets of chocks at optimum distances aft of the catapult datum. Such arrangements are now planned to be introduced into R.N. carriers in the near future.

Holdback Arrangements

As carriers have suffered too long with the above deck obstruction in the aircraft taxi-ing area caused by the holdback 'T' anchor block, a below-deck resilient loader was designed for the new installation. An off-loading facility has been incorporated in the design. A design of below-deck resilient loader will be introduced into R.N. carriers in the near future.

Nosewheel-Tow Arrangements

The many advantages associated with this method of launching, which does not require bridle or holdback handlers, are generally well known. The method

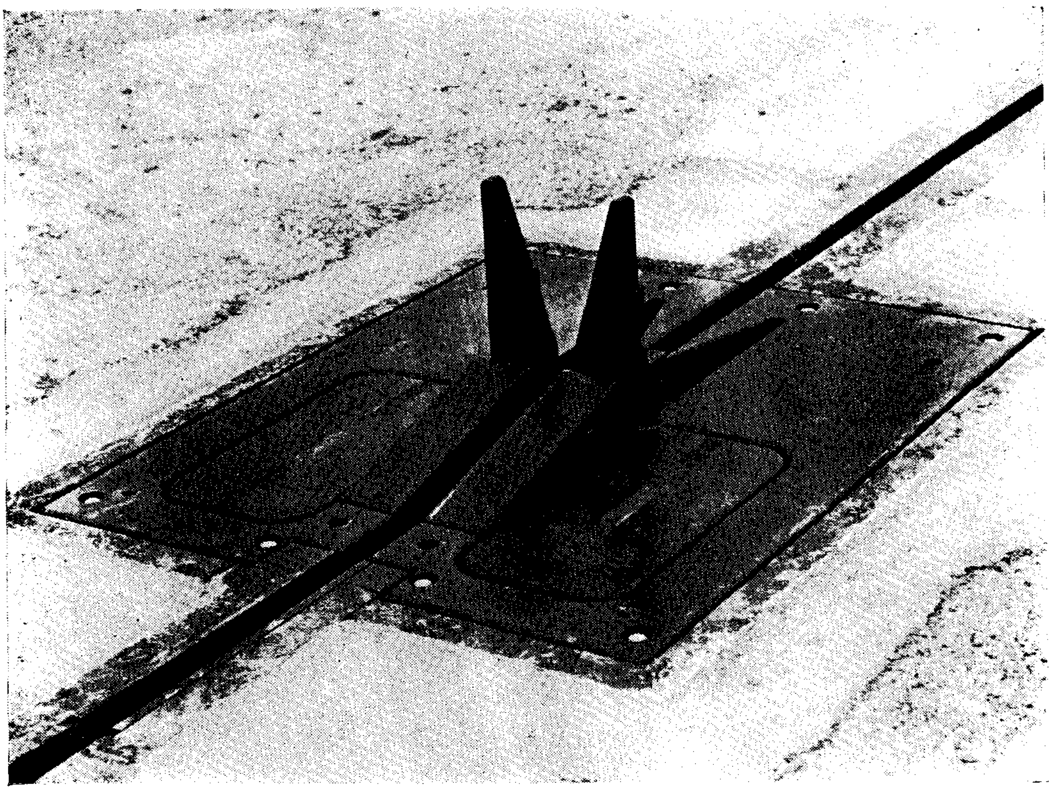


FIG. 16—TRAIL BAR TRAP FOR NOSEWHEEL-TOWED AIRCRAFT

itself requires a tow-bar and a trail-bar attached to the nosewheel gear of the aircraft. The tow-bar is engaged by the catapult shuttle spreader nose while the trail-bar, which also incorporates the holdback release unit, provides the means of stopping the aircraft at the loading position. The tow-bar incorporates a means of guiding a taxi-ing aircraft along the line of the catapult until it engages the shuttle nose while the trail-bar is automatically guided below deck level to engage a buffer. The latter also incorporates an off-loading capability.

It was the intention that the distance between the tow-bar and trail-bar would be mandatory and similar to that employed in the present U.S.N. above-deck arrangement. The actual guidance equipment was installed at Bedford and trials successfully completed.

It will be appreciated that as the catapult accelerating stroke of NWT aircraft is measured from the tensioned position of its nosewheel, this stroke will be the same for all nosewheel-towed aircraft. Also, since with nosewheel tow the tensioning stroke will be much less due to the absence of bridle and holdback 'slack', and in some cases aircraft rotation, longer acceleration strokes will be obtained.

The advantages of the nosewheel-tow system from a point of view of automatic loading, as well as reduction in manpower, has been well demonstrated in U.S.S. *Saratoga* where 57 launch and recovery cycles were completed in one hour using one catapult. The U.S.N. equipment was portable and sited above the flight deck with resulting disadvantages particularly if adopted in R.N. waist catapults, i.e., when sited in the landing area. The U.S.N. were well aware of the advantages to be gained from a below-deck arrangement and are now actively engaged in the design of one. At the time the Defence Review was published it had already been recognized by the U.S.N. that the development of R.N. below-deck NWT equipment was well ahead of their own counterpart and they have shown considerable interest in our design.

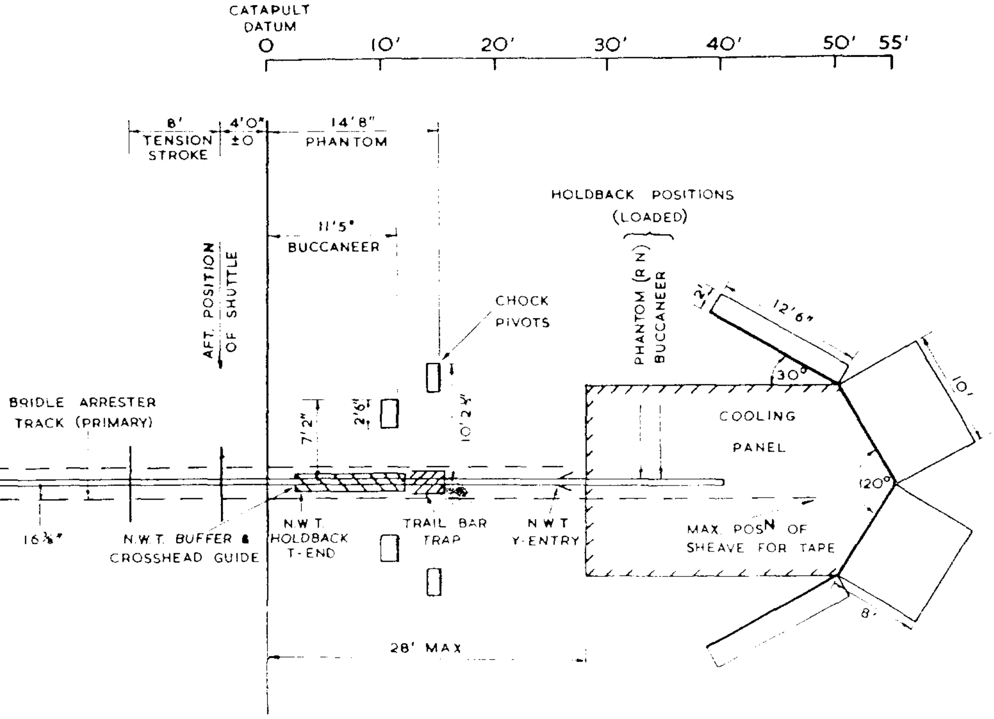


FIG. 17—B.S.6 CATAPULT LOADING AREA

Manning and Training

No article covering the wider aspects of catapult development could omit some mention of the contribution made by the Flight Deck Trials and Training Unit stationed at H.M.S. *Daedalus.* As their title suggests the Unit fulfils two separate roles: they provide a vital service in the conduct of flight deck machinery trials and they train personnel in the operation and maintenance of the machinery and in the loading base drill for launching aircraft.

Not only has the Unit coped efficiently with the many changes in both drill and maintenance techniques but their valuable user experience has been fed into many of the new designs.

To date, both the mechanical improvements and improvements to operating drills have enabled a reduction in manpower to be made without any lowering of the present high standard of safety which is the envy of other navies. A comparable installation in the U.S.N. for instance requires twice the number of catapult crew as the R.N. counterpart.

Conclusion

It may appear from this article that a very great deal of time and money has been spent on giving the Fleet just one safe piece of equipment. Nevertheless, it is worth reflecting that an operational carrier achieves around 3,000 launches per year and that on each occasion there are two lives and, in most cases, over one million pounds worth of material on the end of the launching bridle. The results of a single failure can be disastrous!