Operation Pluto*

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The code name "Pluto", coined from the initial letters of "Pipe Line Under The Ocean", was chosen for the operation of laying submarine pipe lines across the English Channel and supplying petrol to the Allied Armies of Liberation for their advance across France and Belgium into Germany.

In this lecture I will describe how the urgent operational need for pipe lines came to be clearly stated and how an oil company, a submarine cable company, and a steel company developed, for the Petroleum Warfare Department, two novel methods which, as a result of collaboration between many rival commercial firms, Government Departments, and the Services, were used to deliver more than 1,000,000 gallons of petrol a day across the Channel.

A system of petrol pumping stations with pipe lines eventually 1,000 miles long was being constructed in 1942 across England to supply petrol, discharged from tankers in the relatively safe ports of the Bristol Channel and in the Mersey, to the London, South Coast, and East Coast areas.

Pipe lines had been proved essential for maintaining the vast supplies of petrol required by fully mechanized armies in Egypt and North Africa; and bolted tanks, Victaulic-jointed pipe lines, and pumps were being ordered in great quantities for erection by the Royal Engineers across Europe after the projected invasion. Special Companies of the Royal Army Service Corps were being trained for handling petrol in bulk. Admiral Mountbatten, Chief of Combined Operations, was developing all means for putting troops and supplies across the Channel and for their maintenance and support in the advance. Initial supplies of petrol would be in 4-gallon tins and in "Jerricans" carried across the beaches, but he knew that bulk supplies would be necessary at the earliest possible moment. He could not rely upon capturing a port with complete oil storage and discharge facilities for ocean-going tankers, and he was therefore developing means for pulling out short pipe lines from the beaches to a sufficient depth of water to allow small coastal tankers to discharge into cylindrical or bolted tanks to be erected on or near the sand dunes.

Experiments were made at Westward Ho! where sea conditions were similar to those on the French Coast and, by the beginning of April 1942, Lord Louis became convinced that there would be grave risk of supplies being interrupted by the hazards of weather when tankers were discharging on a lee shore, and that they would be sitting targets for enemy sea and air attack. He therefore decided that a petrol pipe line across the Channel was necessary if supplies were to be assured at all times, and he asked Mr. Geoffrey Lloyd, the Secretary for Petroleum, who was responsible for the English pipe line system, if he could carry that system across to feed the land lines which I have said would be put down by the Royal Engineers as the armies advanced.

Mr. Lloyd referred this clearly stated and urgent operational requirement to the experts in his Department, and to those who were advising them on the construction of the English system. He was advised that tidal conditions and depth of water would make it a long operation requiring heavy moorings and large flotillas of craft if any of the known methods of laying submarine oil lines were used, and that even in peace time, weather conditions would make it an extremely hazardous operation. In war time, the need to stop to make joints would render enemy interference by sea, air, and by the guns on Cap Gris Nez so easy that even given good weather, known methods were clearly impossible.

I will now describe how the requirement was eventually met by the use of two novel types of oil pipe, dealing first with the Hais (Hartley Anglo-Iranian Siemens) cable and then with the Hamel (Hammick Ellis) steel pipe.

I was told of the requirement when I visited the Petroleum Department on 15th April 1942, and at first agreed with the views of the experts, but when the urgent need for a solution of the problem was repeatedly emphasized I suggested the only chance of success would be to make a pipe in one complete length, so as to lay it across without stopping and at sufficient speed to get across the strong tidal currents. This would mean using a small-diameter pipe owing to the bulk and weight, but I then thought of the way in which a difficult pumping problem through hilly country in Iran had been solved. The unusually small internal diameter of 3 inches had been chosen; and by working at the very high pressure of 1,500 lb. per sq. in., more than 100,000 gallons, or the equivalent of 25,000 Jerricans a day were being delivered a distance of 40 miles from pumping station to pumping station. I realized how valuable such a line would be and that, if one, many could be laid.

I was immediately encouraged to develop my idea, and I thought of submarine telephone and power cable practice.

Sir William Fraser, C.B.E., Chairman of the Anglo-Iranian Oil Company, Ltd., and Honorary Petroleum Adviser to the War Office, that night offered the fullest support, and I saw Dr. H. R. Wright, Managing Director of Messrs. Siemens Brothers and Company, Ltd., the next morning. He received my idea with enthusiasm and at once agreed to make a trial length of cable armoured with steel tape and wire, but without the communicating wires, and conducting insulation, and it would start with the usual lead covering, as an inner lead pipe impervious to petrol. It would be prevented from bursting by the steel tapes and would be held together longitudinally by the steel wires.

Even at this early stage it was realized that secrecy would be essential and it was decided to use the word cable rather than pipe, and the code name Hais was chosen.

The first 200 yards were ready for test in a week and withstood test pressures of up to 700 lb. per sq. in. before failing at the plumbed ends. It was only 2 inches in diameter and designed for a working pressure of 500 lb. per sq. in. It would only deliver about 30,000 gallons a day across the 20 nautical miles then visualized, but when it had been handled in and out of a Post Office Cable Ship and again been tested satisfactorily, samples were shown by Mr. Lloyd to the Service Chiefs and to Mr. Churchill, then Prime Minister. Instructions were received to proceed with its development with all speed.

The Post Office, the Admiralty, Combined Operations, the War Office, and the Anglo-Iranian Oil Company were called together at the Petroleum Division to arrange the manufacture of further lengths and prepare a complete test programme. The Anglo-Iranian then undertook, as agents of the Petroleum Division, to develop, order, progress, and supervise the whole of the pipe, pipe joints, pumping installations, etc., required. Messrs. Siemens Brothers, without waiting for official orders or priorities, quickly produced more cable. A length was laid by the Post Office Telegraph Ship *Alert* as a loop in the Medway at Chatham, on 10th May 1942, and a pumping test was started with pumps borrowed from the Manchester Ship Canal Company, which they were keeping for the emergency operation of lock gates in case of "blitz" damage.

Failures occurred on this length after two days' pumping, and the faulty portions were recovered and examined by the Post Office, by Siemens, and by Henleys, who had, at Messrs. Siemens' suggestion, been brought in to provide more manu-

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facturing capacity. It was soon evident that the chief reason for the failure was the extrusion of the lead through gaps which had been left in the spiral steel tape armouring due to the upper layers of tape having come back directly over the lower instead of breaking joints in certain places along the cable.

A striking example of the way in which the various interests combined all their resources even at this stage to get over difficulties was then provided by Siemens and Henleys combining their Research and Design facilities and together with the Post Office and the National Physical Laboratory, who had also been brought in, helping us to prepare a new specification within two days of the failure. Further lengths of 2-inch (internal) diameter cable were ordered from both cable makers with four layers of steel tape instead of two, to reduce risk of lead extrusion and to enable a higher working pressure to be used.

This was calculated to be 750 lb. per sq. in., on the basis that, allowing for the gaps in the spirals, only three out of the four tapes would be effective and that each would be stressed to half the yield point of the steel.

The lays of the tapes and of the wires were designed for right- and left-hand lay respectively to balance each other so that the cable would not twist under the influence of internal pressure.

The construction of the cable is shown in Fig. 1 which, however, illustrates the later 3 inches cable.

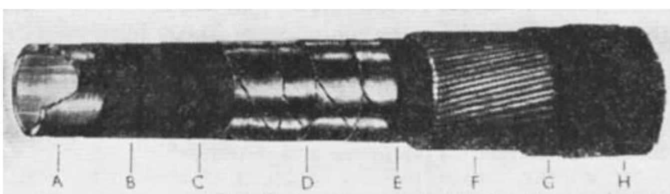

Fig. 1. Hais Cable

A Lead tube, coated with compound.
B Two layers of prepared tape, impregnated with compound (left-hand lay).
C One layer of bitumen-prepared cotton tape (left-hand lay).
D Four layers of uncoated planished mild steel strip (right-hand lay).
E One serving of 12 lb. gas-tarred jute yarn (right-hand lay).
F Galvanized steel wires, each coated with compound (left-hand lay).
G One serving of 12 lb. gas-tarred jute yarn (right-hand lay).
H One serving of 12 lb. gas-tarred jute yarn (left-hand lay).

Differences in the method of manufacture of lead sheath normally used by the various cable makers had meanwhile been under discussion, and Messrs. Siemens Brothers took the view that their technique, using a vertical press and involving a longitudinal seam, while entirely satisfactory for extruding lead sheath on ordinary cable, might need some development to make it equally satisfactory for making pipe. Rather than run the slightest risk or delay, they agreed to use lead made in presses which avoid a longitudinal seam. Messrs. Pirelli's lead, made in their continuous extrusion machine, was tested, but before it could be adopted, their works were damaged by enemy action. Messrs. Henleys' lead, made in their "Judge" straight-through presses, had already been proved suitable, and this type of press provided all the lead pipe used until the capacity of further cable companies had to be brought in to produce the large quantities of cable eventually required. Lead pipe made both by Messrs. Pirelli's continuous presses and by vertical presses both here and in the U.S.A. was later used with complete success.

Test lengths of both firms' manufacture were laid by the Post Office Telegraph Ship *Iris* in deep water off the Clyde. Messrs. Siemens's length was laid first under the severest possible conditions, being laid over the bow and filled with air under only atmospheric pressure. On test, after recovery from the depth of about 200 feet where the external pressure on the cable was 90 lb. per sq. in., it appeared at first to be leaking because the applied internal test pressure would not remain steady after the cable had been filled with water, and because water appeared in places through the outer jute serving. These places were stripped, and the lead pipe was found to have been pressed in on itself into a kidney shape (Fig. 2, Plate 1) by the external water pressure, and some water was found to have been trapped in the space thus formed between the lead pipe and its armouring. Under application of the test pressure, the lead pipe began to resume its circular shape and push the trapped water through the outer armouring, giving the impression of leaks.

Before this explanation had been found, however, the decision had been taken to lay Henleys cable under the easiest possible conditions owing to the increasing urgency for the cross-Channel lines. It was laid over the bow of H.M.T.S. *Iris*, but with the ship going astern to simulate the easier over-the-stern laying condition; and it was laid full of water under 100 lb. per sq. in. internal pressure, to balance the external sea pressure.

The complete success of this lay and the knowledge that the Siemens cable, far from failing under the severe conditions of its lay, had, in fact, been proved capable of withstanding much rough handling, resulted in the decision to start manufacture of six operational lengths, 2 inches in internal diameter, and of 30 statute miles each, and to use one length for a full-scale trial in the Bristol Channel where conditions of tide and depth of water were more severe than those in the English Channel.

Consideration had meanwhile been given to the methods to be adopted for laying the cable in actual operation, and it was early realized that special cable ships would have to be equipped to carry a sufficient length of this unusually heavy cable, and there still remained the problem of dealing with the shore ends in the shallow water, into which the cable ship could not approach.

The Admiralty and the Ministry of War Transport made available the S.S. *London*, a coaster of 1,500 tons, and she was fitted out and renamed H.M.S. *Holdfast* under the direction of the Director of Naval Construction with Johnson and Phillips' cable gear lent by the Post Office.

In Fig. 3, Plate 1, H.M.S. *Holdfast* is loading cable into the tank with the cable-handling gear.

In the earliest tests on the cable, failures had occurred at or near the fittings provided at the ends for holding the pressure, and the great importance of designing suitable fittings for joining the shore ends to the main lengths was early realized. The efforts of the Anglo-Iranian Research Laboratory, the Admiralty Research Laboratory, and of many commercial firms were later combined and concentrated at Siemens Brothers, and resulted in the preparation of the design of the joint shown in Fig. 4, and

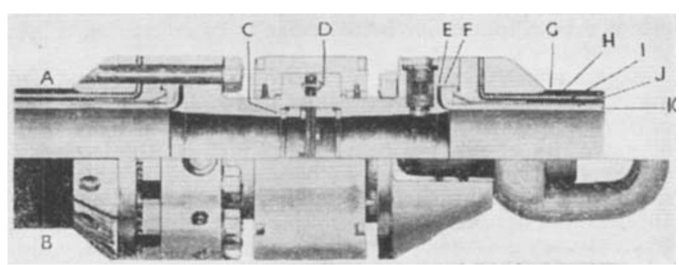

Fig. 4. The Hais Cable Coupling

A Method of coupling two cable ends by means of the split muff.
B Coupling end with swivel yoke end attached for hauling.
C Bursting disk assembly.
D U-joint rings.
E "Hat" joint.
F Flanged lead pipe.
G Outer jute servings.
H Armour wires.
I Inner jute serving.
J Steel tape.
K Lead pipe.

its manufacture by them. Bursting disks of thin copper sheet were incorporated in the joint to hold the water pressure, up to 200 lb. per sq. in., which had been found desirable during handling, storing, and laying, but were so designed as to burst under the operating pressures. Although about three or four hours were required for fitting the joint to the end of the cable, two lengths already fitted could be coupled together at sea in about 20 minutes by using the specially designed split muff coupling without the need for using any bolts. The diameter of the coupling was sufficiently reduced and faired into the cable to allow it to be handled by the cable ship's machinery.

The final design, as shown in Fig. 4, allowed the steel wires and tapes to be gripped securely and for the joints to be made petrol-tight with petrol-resisting rubber-moulded rings against the lead pipe while at the same time preventing the lead from being distorted or extruded. The steel rings locking the two half-muffs together could not be put into position unless the ends of the joints were correctly in line and the muff was fully home, thus making inaccurate assembly impossible.

Static tests on lengths of cable were continued at the makers' works, and pressures in excess of 3,000 lb. per sq. in. were maintained for many months. In addition, routine tests, in which a sample of cable was bent without pressure six times round a 6-foot diameter drum, each time in a reversed direction, gave in all cases an average bursting pressure of between 3,500 and 4,000 lb. per sq. in. It was thus obvious that the fourth tape and also the steel wires, which had been neglected in calculating the working pressure of 750 lb. per sq. in., were in fact contributing largely to the strength; and it was decided that the cables should be operated at 1,500 lb. per sq. in. The static tests showed that the lays of the steel tapes and wires were correctly balanced, as there was no tendency for the cable to rotate under the influence of internal pressure until the yield point of the tapes was reached at about 2,500 lb. per sq. in.

Throughout the autumn of 1942, Combined Operations conducted handling tests with cable on drums at the experimental establishment at Westward Ho! in an endeavour to find ways of handling the shore ends with craft which would automatically be available on the beaches on D-Day. The most promising method devised was to mount two-cable drums with about 1,000 yards of cable on horizontal axles in "L.C.T.'s" (landing craft–tanks) with a view to paying the cable out over the bow ramp which was lowered with the craft going astern.

This method was used when the full-scale trial was made on 29th December 1942, starting from Swansea. Although the main length was successfully laid at about 5 knots by H.M.S. *Holdfast* under the command of Commander Treby-Heale, O.B.E., R.N.R., who had been in command of Siemens famous cable-layer *Faraday*, great difficulty was experienced in laying the shore ends owing to the lack of manoeuvrability of the L.C.T.'s when going astern with heavy cable over the bow.

As a result of a conference at Combined Operations Headquarters in January 1943, it was agreed it would be necessary to adopt the method used commercially of coiling sufficient cable horizontally in the hold of a self-propelling barge specially fitted for paying it out over the stern through hand-controlled compressor gear. Although this involved allotting very precious Thames barges and their crews for this sole purpose, they were made available and the shore ends were completed in a few days' work at the end of March 1943.

Fig. 5, Plate 1, shows the main length and shore end being connected.

The National Oil Refineries at Swansea, with the Royal Engineers, and the Royal Army Service Corps' specially trained Bulk Petroleum Companies, had meanwhile erected a pumping station on the sea wall at Queen's Dock and connected it to their petrol tanks; and the R.E., working with Combined Operations and the R.A.S.C., had, with the help of the Petroleum Board, erected a receiving terminal with tanks, pumps, and loading racks in Watermouth Bay, near Ilfracombe.

After satisfactorily testing with water, the first petrol ever to be pumped through such a long sea line reached Watermouth on 4th April 1943. Mr. Lloyd saw the petrol arriving a few days later, and took a sample to Mr. Churchill.

It had been intended that the vulnerability of the cable to bombing or depth charges and the possibilities of repairs, should it be dragged by a ship's anchor, should be investigated. A German raid on Swansea proved that the cable was not damaged by a bomb within 100 feet, and, during a gale, a ship at the Mumbles anchorage dragged the cable with her anchor. H.M.S. *Holdfast* had no difficulty in locating the cable, cutting out the damaged portion, and running in a new length. We were thus saved, by the enemy and the weather, from the need for making our own experiments!

In order to prove the reliability of the cable and pumps, and to train the R.E. and R.A.S.C. personnel who would be responsible for the actual operation, pumping continued night and day, first at the original design pressure of 750 lb. per sq. in. and later at 1,500 lb. per sq. in., when 56,000 gallons were pumped to Watermouth each day and delivered by the Petroleum Board in Devon and Cornwall.

After many months at this rate, the Petroleum Board preferred to receive only about 25,000 gallons a day. It was arranged that the line should continue to be operated at full pressure but only for the time necessary to deliver the required quantity. This meant that during the shut-down periods the line would be under external pressure due to the difference in specific gravity of sea water and petrol, and would therefore be subjected to a daily reversal of pressure. It withstood this severe test with complete success.

The Quartermaster-General to the Forces, Sir Thomas Riddell-Webster, visited Watermouth during Easter 1943, and the cable makers' Works the following week, but before describing the action he took to press the work forward, I will recount the development and manufacture of 3-inch Hais cable and also of the Hamel pipe.

While the manufacture and testing of 2-inch internal diameter cable had been proceeding, experiments were made with larger diameters, and it was proved that one cable 3 inches in internal diameter and 4½ inches in external diameter could be made with existing facilities and could be handled by the ship's machinery with only minor modifications. A 3-inch cable would deliver about 2¾ times more petrol than a 2-inch cable, and it was therefore decided to stop the manufacture of the 2-inch and concentrate on the 3-inch. I will now give you the specification and describe the method of manufacture.

Of the 570 nautical miles of lead sheath used in the United Kingdom 463 were made on the Henley straight-through presses by Messrs. Henley and the Telegraph Construction and Maintenance Company, and 87 nautical miles on the Pirelli continuous extrusion machine by Messrs. Pirelli, Johnson and Phillips, the Standard Telephone Company, and the Edison Swan Electric Company, the balance being supplied by Messrs. Glover's on their "Farmer" press. The lead sheath has an internal bore of 3·05 inches with a minimum lead thickness of 0·175 inch, and was manufactured in 700-yard drum lengths. The drums of lead sheath were placed behind the armouring machines and each individual length was joined by lead burning to the continuous length being armoured. The cable was armoured, and a pressure of 25 lb. per sq. in. was maintained to prevent collapse.

The lead sheath was first coated with a layer of petroleum residue compound, followed by two layers of compounded paper tape with a width of 2½ inches and a thickness of 0·010 inch, applied left-hand lay with a gap of approximately $\frac{1}{10}$ inch. This wrapping is then followed by one layer of compounded cotton tape about 3 inches wide, having an overlap of ⅛ inch, these materials being applied to give a bedding for the steel tape and also to increase flexibility. Then follow four layers of steel tape 2 inches wide, with a thickness of 0·022 inch, made from steel with a minimum tensile strength of 25 tons per sq. in., a minimum yield of 20 tons per sq. in., and an elongation of 10 per cent in a length of 10 inches. These steel tapes are applied right-hand lay with a gap of 0·15 inch, breaking joint about "60/40". The individual tapes are joined together by cutting at 30 deg. to the length of the tape and lap spot welding. The diameter of the cable over these tapes is about 3·72 inches.

There then follows a petroleum residue compounded coating with a first serving of single-ply jute bedding, right-hand lay, and a further coating of compound applied at the armouring die, to provide a flexible bedding for the armouring wires. There are 57 galvanized steel wires each ~~0·92~~ inch in diameter, having a tensile strength of 25–30 tons per sq. in. with elongation of 12 per cent minimum in a length of 10 inches, and they are applied left-hand at about 30 inches lay, with an approximate diameter over the wires of 4·19 inches. The wires are applied from a rotating carriage having floating bobbins to eliminate twist of the wire, and each individual length is joined by butt welding. A second serving of single-ply jute is put on right-hand lay with a petroleum residue compound over the jute. A third serving of three-ply jute is now added and is applied left-hand lay, after which there is a layer of compound followed by a final coat of whitewash solution.

The finished cable, full of water, weighs 63 tons per nautical mile, and was made in continuous lengths of 35 nautical miles, coiled direct from the armouring machine into special storage sites to await loading on to the ship. Fig. 6, Plate 1, shows a 35-nautical mile length being loaded from the factory coiling site; the diameter of the coil is approximately 60 feet.

At the commencement of the manufacture of 3-inch Hais cable it became necessary to obtain much greater manufacturing capacity; and therefore additional machines were brought into operation at Messrs. Callender's, Glover's, and Pirelli's. In the case of Messrs. Callender's, four machines were finally brought into production, and an overhead gantry 45 feet high by 1,600 feet long with supporting towers every 70 feet, was constructed to carry cable from their armouring shop to an adjacent deep-water jetty. Eight 60-foot diameter coiling sites were situated between the supporting towers to facilitate continuous manufacture and loading; and these sites were covered by a continuous light-framed steel building which had to be erected due to blackout regulations. A similar arrangement was made for two armouring machines at Messrs. Glover's and for storage and loading at the Manchester Ship Canal.

In February 1944, I visited the United States to arrange the manufacture of cable at four works there, to meet the increased requirements.

Messrs. Phelps-Dodge erected a plant alongside deep water at Yonkers, New Jersey, in which they installed two armouring machines delivering cables to a specially designed coiling site which had additional facilities for receiving 3½-mile lengths of cable, delivered coiled down on groups of four freight cars from Messrs. General Electric and Okonite-Callenders. These lengths were spliced into continuous lengths at the site. Messrs. General Cables Corporation manufactured a length of cable at their Perth Amboy works which are adjacent to deep water. The cable was delivered to the United Kingdom in merchant ships specially fitted with cable tanks.

A total of 710 nautical miles of Hais cable was produced for Operation Pluto, of which 140 miles came from the United States.

The second novel proposal came at the end of April 1942 from Mr. B. J. Ellis, O.B.E., chief oilfields engineer of the Burmah Oil Company, and Mr. H. A. Hammick, O.B.E., chief engineer of the Iraq Petroleum Company, both of whom were at that time seconded by their Companies to the Petroleum Department. They were dealing with the Hais cable, and when they saw how flexible it was in a long length, although extremely stiff in a short length, they suggested that steel pipe, which they had also seen to be very flexible, when handled in long lengths in the oilfields, might also be used for making long lengths of line required in one piece.

With the assistance of Messrs. Stewarts and Lloyds, Messrs. J. and E. Hall, of Dartford, and Messrs. A. I. Welding, they quickly proved that 3-inch steel pipe could be bent round a wheel 30 feet in diameter, could be pulled off again relatively straight without kinking, and could be flash-welded to provide any required length. They realized that it could not be handled like cable in horizontal stationary coils in a cable ship because this involves a complete twist in each turn while coiling down, and its removal while uncoiling for laying. Mr. Ellis therefore suggested, first, the use of a large wheel mounted on trunnions on the deck of a hopper barge with its lower portion protruding into the sea through the hopper doors, and later a floating drum like a gigantic cotton bobbin capable of carrying any quantity of pipe likely to be required.

Model tests of the floating drum—H.M.S. *Conundrum* or "Conun", as it came to be called—were made at the National Physical Laboratory in their Froude tank and confirmed that such a vessel could be towed at sufficient speed without yawing.

Preliminary work had thus proved that the pipe could be bent and pulled off straight, that it could be welded with absolute reliability, and that it could be carried and laid by either the wheel and barge or the Conuns, but there was no previous experience as to how bare steel pipe would lie and behave on the bottom of the sea. It was felt, however, that it would have at least a six-weeks' life, and on this basis of life, and as it was by no means certain there would be sufficient supplies of lead available to produce all the Hais cable required, it was decided to proceed with all speed with a factory at Tilbury to weld, store, and wind Hamel pipe and with the conversion of a hopper barge—later called H.M.S. *Persephone*—and with the construction of six Conuns.

Messrs. Stewarts and Lloyds undertook, in addition to making the steel pipe, to act as agents of the Petroleum Division for the design, construction, and subsequently the operation, of the Tilbury factory; and the Director of Naval Construction fitted out *Persephone*, designed the Conun, and supervised their construction by Messrs. Orthostyle.

Each Conun was 90 feet long, with a diameter of 40 feet and a length of 60 feet between the flanges. Each flange was 52 feet in diameter, having teeth on the periphery for rotating the Conun in the winding operations by a chain drive. It could carry up to 70 miles of 3-inch steel pipe at a time, and weighed with this length of pipe 1,600 tons. The hollow steel trunnions, 10¼ inches in diameter, had Timken roller bearings in cylindrical cast steel housings having pairs of vertical trunnion pins 4 inches in diameter, to which two towing lines would be attached. The housings were closed at each end by cast steel covers, each of which carried a special arrangement of grease seals. Each pair of bearings was designed to withstand a breaking load of 130 tons on the tow rope, as well as a 40-ton thrust load due to the angular pull of the tow ropes.

Two factories with storage sites were erected at Tilbury, each having seven lines of machines consisting of a flash-welding machine, a Taylors pipe-cutter, and a traversing machine. The standard 40-foot lengths of pipe were welded one by one with "A.I" flash-welding machines to form lengths of 4,000 feet.

Low-carbon mild steel was used to facilitate the welding, and the pipe was made 3½ inches in external diameter, with a wall thickness of 0·212 inch and a weight of 20·21 tons a nautical mile.

Beads standing about ¼ inch proud of the pipe were produced by the flash-welding process, and they were machined down to about $\frac{1}{32}$ inch internally by a rotating cutter and air-blast brushes on long spears, and externally by a Taylor cutter.

The traversing machines had top and bottom tracks which gripped the pipe with spring-loaded pads and pushed it along the 4,000-foot long conveyor channels as each new length of pipe was welded on. Storage space was provided below the conveyors, and when each length was completed a few yards were lifted off at one end, and the whole length then threw itself off, due to its weight and elasticity, at about 120 m.p.h. Fig. 7, Plate 2, shows the storage racks with the winding site in the background.

A welding machine was provided there for joining the 4,000-foot lengths into the continuous length required; and a specially designed hydraulically loaded machine, similar to the snubbing gear used on oil wells, was provided for maintaining the steady back-pull on the pipe of about 2 tons, which was necessary for bending it round the Conun during winding.

Hinged arms were provided at the end of the jetty to hold the Conun in position by its trunnions (Fig. 8, Plate 2), and means were provided to ballast it with water when light to minimize wind effect. The pipe was guided on to the Conun through a traversing cab to ensure neat winding; and spring spacers were clipped on to the pipe as it was wound, to maintain passages between adjacent pipes through which water, trapped as the Conun rotated during the lay, could escape. It was thought that without this means of escape, sufficient water might be picked up to cause excessive braking effect and increase the pull necessary during the lay.

Pending completion of the Tilbury factory, some miles of 3-inch steel pipe were hand-welded at Portsmouth Dockyard and wound on *Persephone's* wheel for preliminary trials which were, to the admitted astonishment of most of the spectators, entirely successful. This was early in April 1943, so both the Hais cable and Hamel pipe had been brought successfully through their full-scale trials, and production on a considerable scale had been organized by the Petroleum Division and Chief of Combined Operations before they handed on responsibility for the Operational Stage respectively to the Petroleum Warfare

Department under its Director-General, Major-General Sir Donald Banks, K.C.B., D.S.O., M.C., T.D., and to Force Pluto specially organized by the Admiralty under the command of Captain J. F. Hutchings, C.B.E., D.S.O., R.N.

Thus, after visiting Watermouth on 24th April 1943, and seeing the Hais cable in actual operation, the Quartermaster-General was able, on the 29th April, to visit the Hamel factory at Tilbury, to see Hais cable in production at both Henleys at Gravesend and at Siemens's at Woolwich, where he also saw H.M.S. *Holdfast* loading cable. He decided that further lengths should be ordered at once.

During June and July 1943, recommendations were made by the Quartermaster-General's Petroleum Committee, and confirmed by the Chiefs of Staff Committee, who awarded a high priority, that the English pipe-line system should be extended to Dungeness and to the Isle of Wight and that pumping stations of 3,500 and 3,000 tons a day capacity, respectively, should be erected at these places.

The Isle of Wight to Cherbourg crossing, then considered for the first time, involved a sea crossing of about 70 nautical miles instead of the 20 or so originally visualized, and made necessary the provision of larger cable ships and the use of the Conun loaded down till the axles were awash. Following a successful lay with 3-inch Hais cable, S.N.O. Pluto obtained three more ships to be converted and fitted with cable gear by the Director of Naval Construction, one, H.M.S. *Algerian* to carry 30 miles of 3-inch cable, and the other two, H.M.S. *Latimer* (Fig. 9, Plate 2), and H.M.S. *Sancroft*, to carry 100 miles of 3-inch cable weighing about 6,400 tons. Six Thames barges were equipped to handle the shore ends and a large number of auxiliary vessels were added to the Force, whose personnel numbered 100 officers and 1,000 men.

Further tests with a model Conun at the National Physical Laboratory showed it could be handled when loaded with 70 miles of pipe, provided two of the largest class of ocean rescue tugs were used ahead, with a smaller tug astern for steering.

The Isle of Wight pumping installation at Sandown consisted of sixteen reciprocating and two centrifugal pumps, and at Shanklin, eight reciprocating and two centrifugal pumps, these stations being cross-connected by two Hamel line loops laid out to sea and in again. Thus if either of the installations at Sandown or Shanklin had been "blitzed" the other could have taken over.

At Dungeness, thirty reciprocating and four centrifugal pumps, designed for 1,500 lb. per sq. in. pressure, were installed at three well-dispersed sites along the coast and were fed from the land-line system.

The reciprocating pumps were manufactured by Messrs. Frank Pearn, Ltd., and delivered approximately 40 Imperial gallons of gasoline per minute, when running at a speed of 45 r.p.m. They were driven by V-ropes by 60 h.p. "Caterpillar" engines. The centrifugal pumps were manufactured by Messrs. Mather and Platt, Ltd., and delivered 214 Imperial gallons of gasoline a minute, and were driven by 500 h.p. motors.

The Anglo-Iranian undertook the supervision of the erection of the pumping terminals and tankage by civilian contractors and R.E., R.A.S.C., and Pioneers.

The Petroleum Board constructed the land lines and S.N.O. Pluto laid a large number of Hais and Hamel lines across the Solent, both to provide the link across to the Isle of Wight, and also, at the same time, to train its large new Force and develop and try out its ships and gear. During these operations it was found that the cable and pipe would withstand all reasonable end-pulls, but that both would be severely kinked and damaged if allowed to hang vertically from the laying vessel, or if run back upon.

Full-scale trials were made with the Conun in the Thames in February 1944, and in Bournemouth Bay in April 1944, during which the technique for towing at speeds up to 7 knots was developed. The decision was also taken to moor the Conun at the beginning of her run and haul in the shore length of pipe by means of a warp pulled in by a plough traction engine, the farther end being laid parallel with the shore and subsequently pulled in.

It was the decision to lay Pluto lines to Cherbourg which had made necessary much larger supplies of Hais cable and Hamel pipe; and, in addition to increasing the British manufacture of Hais cable as much as possible, and starting production in the U.S.A., the decision was taken to duplicate the Tilbury facilities for welding and winding Hamel pipe.

I will now refer briefly to an American scheme which had been developed for laying cross-Channel lines by welding lengths of about 6 miles of 6-inch steel pipe on shore and towing them out to sea under Radar guidance in the hope that the ends might be connected below water by means of extremely ingenious "grasshopper" swivel joints. When it was seen how far Hais and Hamel had been developed and that no joints were required in the main lays, and realizing the difficulties divers would encounter while making joints in the tidal currents of the English Channel, General Eisenhower decided to abandon the American scheme in December 1943, and to give us all possible help in making Hais cable and in providing pumping equipment, etc.

I have reserved a reference to one aspect of the whole operation until now in order to emphasize its extreme importance. I refer to security and camouflage. Unlike many war secrets, Pluto could have been given away by a single phrase, for instance: "A petrol pipe like a hollow submarine cable across the Channel", and pumping stations and both types of sea lines could easily have been attacked.

The pumping station construction was under the supervision of a camouflage officer; all plant which might be seen from the air was moved into position at night; and existing buildings such as bungalows, garages, ice cream factories, etc., were used as pump houses. Control photographs were taken at regular intervals by the R.A.F., and the complete success of all the precautions, often expensive and irksome, was proved by the lack of any known attempt by the enemy to interfere at any time.

All was ready to carry out Operation Pluto some weeks before D-Day, but it could not begin till 12th August 1944, because of the delay in capturing Cherbourg and in clearing sea mines. Two Hais cables and two Hamel pipes were laid during the next few weeks and difficulties were encountered which provided valuable experience for the future lays.

Petrol was pumped across to Cherbourg, but the Allied Armies' rapid advance along the French Coast made it necessary to concentrate all efforts on the Dungeness crossing, and the Cherbourg lines were shut down.

The Dungeness lines were run to a beach inside the outer harbour of Boulogne, in order to save the time required to clear the heavily mined beach at Ambleteuse which had previously been chosen. This involved a longer run and a more difficult approach, but the first was laid in October 1944 and after the technique had been perfected for laying the main lengths of Hais cable over the stern and dropping the ends to the bottom, to be picked up at a suitable state of a later tide for connecting to the shore ends in the barges, further lines were laid and commissioned with certainty and without incident.

The method of pulling in the Hamel shore ends from the Conun, however, proved difficult and involved the loss of one Conun. A solution was found by winding turns of Hais cable at the beginning and end of each length of Hamel, followed by a special floating wire. The Conun could then be handled like the cable ship, laying each end on the bottom for the barges to pick up and connect to the shore ends in the same way as for a complete Hais. This technique enabled the first Hais-Hamel line to be commissioned in January 1945.

Force Pluto were responsible for laying the line to above low water on each shore, and the R.E. and R.A.S.C. then connected the home end with steel pipe to the valves and filters provided on the pump delivery lines, and at the far end to a valve manifold.

Main and group control rooms, with telephone communication between themselves, the pump houses, and to the opposite terminal, were provided, and had diagrams on their walls on which the control officers could indicate by disks on hooks the direction of flow of oil, as well as the pumps and lines in use, etc., at any time.

Reference has been made earlier in the paper to the bursting disks fitted to the Hais cable joints to contain water under pressure in the cables while being laid and connected. When a line was ready for commissioning, a pump was started and the rate of rise of pressure was recorded. At first the rise was slow, and when a pressure of 400 lb. per sq. in. or so was reached, the first disk was broken and the pressure was seen to fall immediately, and then begin slowly to rise again. This was repeated at each disk until the arrival of liquid was at the farther end reported by direct telephone.

Each 3-inch line at Dungeness could deliver about 400 tons a day, or 120,000 gallons, and lines were laid quickly enough to keep ahead of the capacity to pump beyond Boulogne. Eventually eleven Hais and six Hais-Hamel lines were laid with a capacity of more than 4,500 tons, or 1,350,000 gallons a day; and 1,000,000 gallons a day were pumped across for many weeks.

The valve manifold system (Fig. 10, Plate 2) on the beach at Boulogne, with a tank at beach level, provided facilities for test purposes, but the flow was usually taken direct through three lines of 6-inch Victaulic-jointed pipe to tanks of 1,200 tons capacity on the cliff north of Boulogne. The petrol was then pumped to Calais, Ghent, Antwerp, Eindhoven, and across the Rhine through further 6-inch Victaulic lines (Fig. 11).

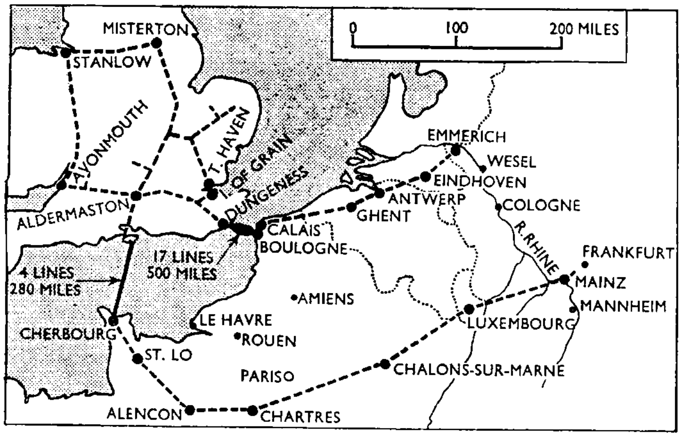

Fig. 11. Map showing Extent of Pipe-line System supplied through Operation Pluto

A duplicate system of lines was being laid right up to "V.E."-Day to provide against a possible last desperate submarine attack, and pumping was continued until the end of July 1945, to enable all available tankers to be diverted to the Far East.

In the words of the Quartermaster-General, " . . . it saved a very large tanker tonnage which was badly needed in the East. Thus Pluto had a reaction which extended all over the world".

No Hais cable which had been satisfactorily laid and commissioned failed; and a recovery operation to clear the beaches has recently shown the cable to be in good and usable condition. There is every indication that, like submarine telephone cables on which it is modelled, it will have a long life. The Hamel pipes on the other hand, while more than fulfilling the original estimate of six weeks of useful life, did fail successively in 77, 52, 55, 112, 55, and 60 days. The loss of petrol between tanks at Dungeness and at Boulogne was, however, less than 1·1 per cent for the whole operation, in spite of these failures.

The Supreme Allied Commander, General Eisenhower, described Pluto in his report as "second in daring only to the artificial harbours projects", and wrote, "This provided our main supplies of fuel during the winter and spring campaigns".

I hope I have been able to give you some idea of the really remarkable co-operation and whole-hearted effort on the part of all the varied interests involved, which was necessary to meet the operational requirement and to enable Pluto to deliver 172,000,000 gallons to the Allied Armies of Liberation with certainty and at the daily rate required.