The ±250kV d.c. Submarine Power-cable Interconnection

for the Benmore-Haywards h.v.d.c. transmission scheme

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The submarine power cables across Cook Strait are a part of the ±250 kV 600 MW d.c. transmission system from Benmore, in the South Island of New Zealand, to Haywards in North Island. Two 24-mile single-core gas-filled submarine cables convey the power from Fighting Bay in South Island to Oteranga Bay in North Island, and a third cable serves as a spare. The paper describes the cable route and site conditions and then deals with the cable design, manufacture, and proving. Novel features are the use of a bend-restricting construction where the cable is laid on a rocky sea bed, and short-circuiting studs between sheath and armour to limit overvoltages developed across the anticorrosion serving. Because the water depth necessitates an internal gas pressure of 425 lb/in², the sealing ends are so designed that the pressure porcelain is not in tension. The cable-laying equipment and methods are explained, and the repair of the fault which occurred during the laying of one of the cables is described.

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1. INTRODUCTION

THE installation of three 250 kV d.c. submarine power cables across the Cook Strait, linking the North and South Islands of New Zealand, was completed in May 1965.

Two cables, each operating at 250 kV (positive and negative to earth), form a 600 MW circuit, while the third cable has been installed as a spare.

The cable system forms part of an inter-island transmission to convey power from a hydro-electric station at Benmore on the Waitaki river in the south of South Island to Haywards substation on North Island (Fig. 1).

The power is rectified at Benmore and is transmitted by overhead line some 335 miles to Fighting Bay, then by 24 route miles of submarine cables across Cook Strait to Oteranga Bay and, finally, by 25 miles of overhead line to Haywards substation on North Island, where the d.c. power is converted back to a.c. for feeding into the North Island power system.

In New Zealand, the major demand for electrical energy is in North Island, whereas water power is more abundant in South Island. The history of the investigational and planning work, on which the decision to provide the inter-island electrical-power link was taken, has already been published (1), and the present paper deals solely with the submarine power-cable system, since the other parts of the link are the subject of separate publications.

The decision to use 250 kV d.c. was based on the fact that it showed a marked economic advantage over an all a.c. or a mixed a.c./d.c. scheme, while the development of the d.c. equipment and plant was such as to justify the adoption of the 250 kV d.c. system. For an a.c. transmission, using cables of the same physical size, it would have been necessary to install 11 cables, i.e. three circuits plus two spare cables.

The initial investigational work into the design and development of the cable was begun in 1956. The cables concerned are of the gas-filled single-core type, and the paper describes the design, manufacture and installation of the complete cable system.

2. SUBMARINE-CABLE ROUTE

Data from existing hydrographic surveys, supplemented by information obtained from *ad hoc* surveys for the project, led to the choice of a short route between Oteranga Bay on North Island and Fighting Bay on South Island (Fig. 2).

2.1. Marine and Other Conditions

2.1.1. *Sea Bed*

The central region of the Strait is composed of sedimentary material up to 5,000 ft deep, so that there is no possibility of protrusion of the underlying greywacke rock.

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For a distance of about nine miles from Oteranga Bay, the sedimentary layer thins to allow exposure of rocky ridges, while towards the shore, there are cobbles a few inches in diameter, occasional large boulders and rock outcrops. The history of small, relatively light telegraph cables shows that abrasion can occur if cables move on the rocky sea bed.

On the South Island side, the sea bed consists of progressively smaller pebbles and fines until, approaching Fighting Bay, there is a good sandy bottom right into the shore line.

2.1.2. *Depth of Water and Sea-bed Contour*

There is a zone between the Islands, about seven miles wide, where the maximum depth is not more than 140 fathoms. To allow for an additional circuit later, the cables were laid in the northern section of this zone, where the depth increases steadily to 135 fathoms about one third of the way across from Oteranga Bay and then decreases progressively to Fighting Bay. The sea-bed gradient does not exceed 1 in 5, and there are no precipitious cliffs or crevices.

2.1.3. *Tidal Currents*

The current through the Strait is predominantly south-going, and surface currents up to 4½ knots have been observed. Measurements have shown that the bottom current may be one third of that at the surface. Tidal rips and overfalls occur, but the selected route is outside the well known Terawhiti and Karori rips.

2.1.4. *Chemical and Biological Conditions*

No sign of chemical corrosion has been found on telegraph cables in the area and the possibility of sulphate-reducing bacteria is remote. Teredo action has been found on the hulls of wrecks (2), and evidence of gastropod boring was found on a trial power cable installed in 1958.

2.1.5. *Weather*

The Strait is subject to frequent high winds and storms, and records show that settled good weather over periods of three days is of infrequent occurrence. Sea swells of sufficient magnitude to prevent cable landing or jointing operations frequently continue for several days after the southerly storms producing them have subsided.

2.1.6. *Earthquake Fault Lines*

There is only one fault line (inactive) in the area considered, and a layer of sediment covers it. The risks from this cause are probably a good deal less than those accepted on land in various parts of the world.

2.1.7. *Magnetic Effects*

The route is practically due east-west and the magnetic effects of the d.c. cable currents will not affect ship navigation by compass.

2.1.8. *Interference by Surface Vessels*

Hazards due to anchors or trawls are extremely limited. Ships do not normally anchor, or even stay, in these parts of the Strait because of weather and inshore navigation hazards, and, in any case, anchors are not generally used in the water depths which constitute the major proportion of the route.

Fishing by trawls is not extensively practised in the Strait, and submarine-telegraph-cable experience confirms that this hazard is extremely small.

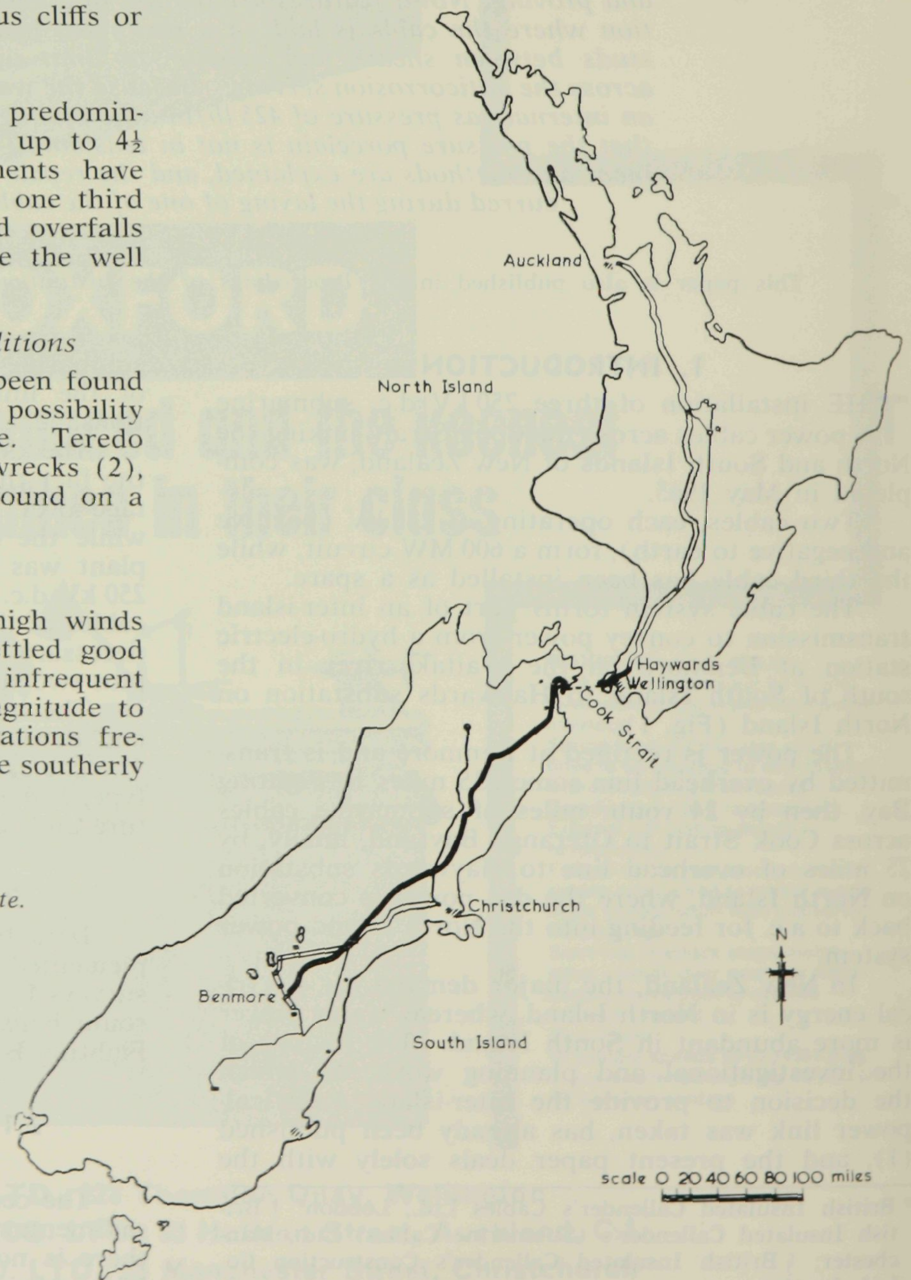

Fig. 1: Benmore-Haywards d.c. transmission route.

——— 220 kV a.c. lines (existing or proposed).

▬▬ ±250 kV d.c. line.

- - - - ±250 kV d.c. submarine line.

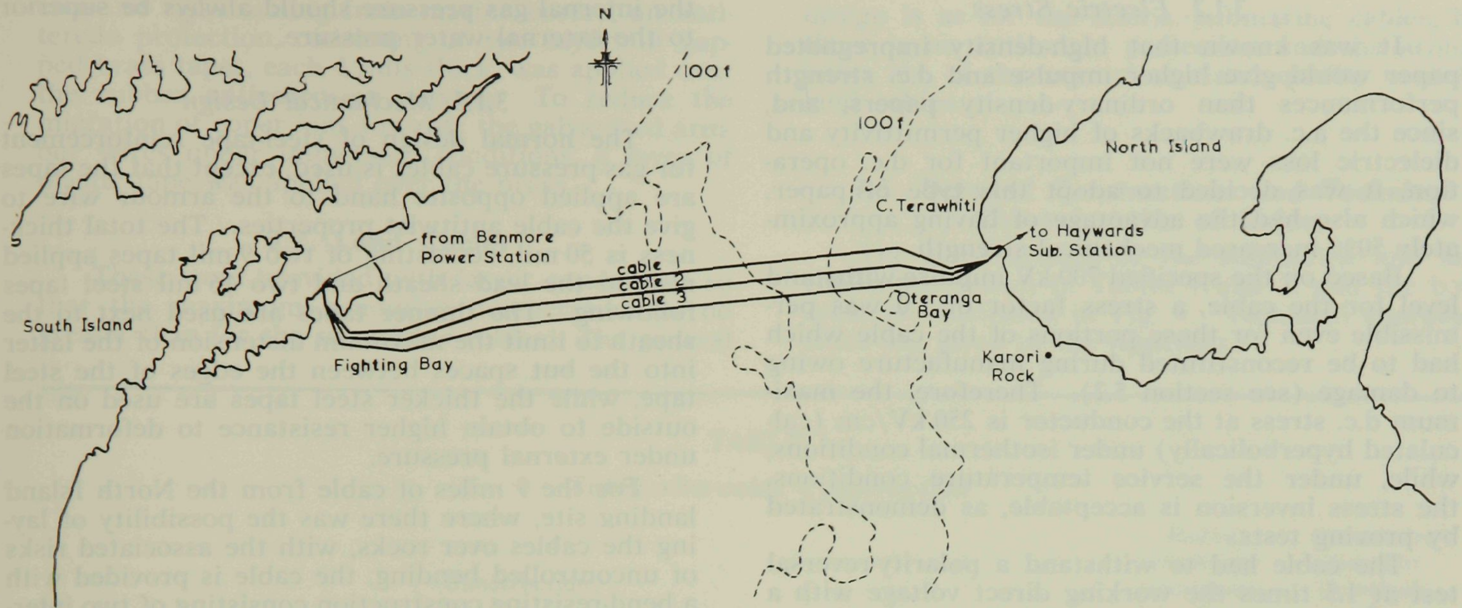

Fig. 2: Submarine-cable route; route length approximately 24 miles, main spacing 1,000 yd.

2.1.9. *Landing Sites*

The chosen landing sites were deemed to be suitable as regards marine navigation and degree of shelter from wind and weather; conditions generally were acceptable in relation to the cable design and installation. Consideration of the currents and tidal streams indicated that laying the cable from the North Island to the South Island was preferable, as the laying vessel would be moving to progressively more favourable sea conditions as it approached the South Island.

On both sites, waves and breakers of up to 20 ft have been recorded, necessitating protection of the shore ends of the cables.

The distance from the high-water mark to the cable terminations is 100 to 200 yd, and, to limit the conductor temperature in relation to the thermal characteristics of the soil where the cable is trenched in the shore, it was necessary to use land cables with a large conductor size, with joints at the high-water mark between the submarine and these land cables.

2.2. Site Factors Affecting the Cable Design

These can be briefly enumerated as follows: (a) abrasion arising from cable movement on the sea bed; (b) sea-bed rocks with the possibility of bending damage to the cable; (c) external water pressure in relation to cable deformation and ingress of water to the cable in the case of a fault; (d) marine borers; (e) wave and breaker action at the shore ends causing cable movement and abrasion; (f) weather conditions in relation to cable installation and, particularly, jointing operations at sea; (g) the length of route in relation to voltages generated across the anticorrosion sheath between the reinforced lead sheath and the armour by travelling waves on the conductor (3).

The effects of these factors on the design of the cable are dealt with in the next section.

3. CABLE DESIGN AND CONSTRUCTION

3.1. Design of Submarine Cable

3.1.1. *General Considerations*

The decision to use single-core gas-filled cable, with preimpregnated paper insulation, was based on the same reasons as for the Vancouver 138 kV a.c. submarine cables (4), which have given excellent service since 1956. Briefly, the reasons are as follows:

(a) The cable can be made in continuous lengths.

(b) Because the paper dielectric needs to contain no free impregnating compound and is under gas pressure, there are no detectable changes in dielectric quality during life. Furthermore, no mechanical problems arise with lead-sheath distension during thermal cycling.

(c) The metal tapes which reinforce the lead sheath against the internal gas pressure also serve as "antitwist" tapes, which are judged highly desirable with any heavy armoured cable laid in deep water, and also support the cable against deformation under external water pressure.

(d) Gas pressure, preventing water entry, can be maintained if the lead sheath is damaged, or during repair operations.

(e) The gas pressure brings about a significant increase in electric strength, particularly when compared with a mass-impregnated cable after prolonged service.

With solid-type cable, a serious limitation in conductor temperature is imposed by drainage of impregnating compound and the consequent uncertain electrical behaviour of the dielectric. No such limitation exists with the gas-filled cable. Oil-filled cable is ruled out on account of the oil-pressure transients on the length involved.

3.1.2. *Electric Stress*

It was known that high-density impregnated paper would give higher impulse and d.c. strength performances than ordinary-density papers, and, since the a.c. drawbacks of higher permittivity and dielectric loss were not important for d.c. operation, it was decided to adopt this type of paper, which also had the advantage of having approximately 50% increased mechanical strength.

Based on the specified 700 kV impulse-withstand level for the cable, a stress factor of 1.0 was permissible even for those portions of the cable which had to be reconstituted during manufacture owing to damage (see section 5.2). Therefore, the maximum d.c. stress at the conductor is 250 kV/cm (calculated hyperbolically) under isothermal conditions, while, under the service temperature conditions, the stress inversion is acceptable, as demonstrated by proving tests.

The cable had to withstand a polarity-reversal test at 1.5 times the working direct voltage with a circuit time constant of 5 to 10 ms, applied during the heating cycles of the stability tests. It was found that this aspect was covered by the impulse requirements for the design.

Samples of the cable tested at atmospheric pressure and ambient temperature gave values of 900 kV d.c. without breakdown, and 1,000 kV can be taken as the minimum breakdown value. Tests at ambient temperature on preimpregnated cable models and cables have indicated that nitrogen pressures of 200 to 300 lb/in^2 increase the d.c. breakdown value by 50%; so the value for the contract cable, under gas pressure, can be assumed to be 1,500 kV d.c. at ambient temperature. This value would be reduced to 800 to 900 kV with the conductor at 70° C and the corresponding thermal gradient across the dielectric.

It should be noted that the specified impulse-withstand level at 65° C conductor temperature controls the stress design. Even if this level had been lowered, the reversed polarity test at 65°C would still control the d.c. design stress. Purely on d.c., the stress rating could have been substantially increased.

3.1.3. *Temperature Rating*

The maximum conductor temperature is designed to be 60° C, corresponding to a maximum difference between conductor and sheath of 27.5 degC for the cable as laid on the sea bed. These temperature values limit mechanical stress, arising from the differential thermal expansion between conductor and sheath, to a relatively low value.

3.1.4. *Internal Gas Pressure*

This is designed to be 425 lb/in^2 referred to 15° C. The maximum external water pressure at a depth of 133 fathoms (the actual depth recorded during laying) is 356 lb/in^2. Allowing for a pneumatic head in the cable of 12 lb/in^2 at 425 lb/in^2, the margin of excess gas pressure over the external water pressure is 80 lb/in^2. This adequately covers any error in the recorded water depth, any variation due to tides, sea-water temperatures down to 5° C, and any pressure-gauge inaccuracies, so that the internal gas pressure should always be superior to the external water pressure.

3.1.5. *Mechanical Design*

The normal design of steel-tape reinforcement for gas-pressure cables is used, except that the tapes are applied opposite hand to the armour wire to give the cable antitwist properties. The total thickness is 50 mil, consisting of two 9 mil tapes applied next to the lead sheath and two 16 mil steel tapes following. The thinner tapes are used next to the sheath to limit the maximum distension of the latter into the but spaces between the edges of the steel tape, while the thicker steel tapes are used on the outside to obtain higher resistance to deformation under external pressure.

For the 9 miles of cable from the North Island landing site, where there was the possibility of laying the cables over rocks, with the associated risks of uncontrolled bending, the cable is provided with a bend-resisting construction consisting of two interlocking layers of longitudinally corrugated steel tapes, bound down by a plain steel keeper tape. This type of cable (b.r.a.) was tested by suspending it over a 1 in diameter metal bar at a height 20 ft from the ground in air (equivalent to 28 ft in sea water) without damage due to excessive bending. The rest of the cable (n.b.r.a.) is without this extra protection, and, owing to the smaller diameter, the number of armour wires is reduced. The transition from the b.r.a. to the n.b.r.a. cable was carried out over a distance of 150 yd in order to eliminate sudden changes in mechanical characteristics.

The tendency of a cable to move on the sea bed, and hence to abrade, depends on the value of the transverse component of the water current relative to the square root of the immersed-weight/diameter ratio of the cable. In view of experience with telegraph cables in the same region, this ratio was carefully checked on both types of cable, in relation to the bottom currents, and extensive experimental work was carried out in the Manchester University hydraulics laboratory. All this work indicated that the cables should not move under the conditions normally to be expected.

The armour wires are of the 60 to 70 ton quality (instead of the usual 25 to 32 ton), in order to give the highest abrasion resistance in case movement should occur occasionally under extreme conditions.

3.1.6. *Protective Coverings*

The anticorrosion serving over the metallic reinforcement constitutes an insulation between the reinforced sheath and armour, and voltage transients or travelling waves on the conductor will produce voltages between sheath and armour. These values increase with the length of the cable, and, to limit them to values below the electric strength of the anti-corrosion sheath, an investigation was carried out to determine the maximum permissible distance between short-circuiting electrical connections from sheath to armour (5). This distance was found to be 3.6 miles, and watertight stainless-steel conections, as illustrated in Fig. 3, are applied between the sheath and armour at these positions. Because of risks arising from marine borers, an antiteredo protection, consisting of two layers of gapped brass tapes, each 4 mils thick, was applied over the rubber anticorrosion serving. To reduce the migration of coper ions towards the galvanised armour wires under immersion conditions, a layer of plastic tape was applied over the brass.

3.2. Land Cables

These were provided with larger conductors so that the maximum conductor temperature is no greater than for the submarine cables. The general design is as for the n.b.r.a. submarine cables, but there is no antiteredo protection and the armour wires are of the normal size and quality used for land cables.

3.3. Detailed Constructions and Technical Characteristics of Cables

The constructions of the submarine and land cables are shown in Tables 1 and 2, and the b.r.a. cable is illustrated in Fig. 4. Technical characteristics are given in the Appendix.

TABLE 1

Submarine-cable Construction

Construction	*Radial thickness (minimum)* R (in)	*Cumulative diameter (nominal)* D (in)		
Hollow duct. Steel strip spiral	0.040	0.530		
Copper conductor. 40/0.122 + 78/0.085 in wires	—	1.318		
Conductor screen. Three metallised papers	0.0105	1.339		
Dielectric. Preimpregnated paper tapes	0.560	2.489		
Dielectric screen. Copper tape	0.003	2.497		
Lead sheath. Alloy E	0.140	2.797		
Reinforcement bedding. Copper woven-fabric tape	0.012	2.833		
Reinforcement. Four layers steel tapes	0.050	2.933		
	B.R.A. type		N.B.R.A. type	
	R	*D*	*R*	*D*
Bend-restricting construction bedding. Cotton tape	0.012	2.963	—	—
Bend-restricting construction[*]. Two layers corrugated steel strip + two layers flat steel strip	0.315	3.593		
Anticorrosion serving. Cotton tape, proof tape, four layers rubber tape, cotton tape	0.149	3.963	0.149	3.303
Antiteredo protection. Two layers brass tape, Melinex tape, cotton tape	0.021	4.012	0.021	3.352
Armour bedding. Jute string	0.050	4.132	0.050	3.472
Armour. 0.232 in galvanised steel wires (52 on b.r.a., 45 on n.b.r.a.)	0.232	4.556	0.232	3.896
Serving. Proof tape, cotton tape, two layers jute strings	0.177	5.016	0.177	4.366

[*] This consists of two 40 mil steel tapes, 1.75 in wide, longitudinally corrugated to a depth of 0.210 in and pitch of 0.500 in applied interlocked and with approximately 50% registration, and finally bound down by a 40 mil plain steel tape.

(The only basic differences from the Vancouver cables (4) are the high-density paper dielectric, the bend-resisting construction and the antiteredo protection.)

TABLE 2

Land-cable Construction

Construction	*Radial thickness (minimum)* R (in)	*Cumulative diameter (nominal)* D (in)
Hollow duct. Steel strip spiral	0.030	0.530
Copper conductor. 150/0.105 in wires	—	1.580
Conductor screen. Three metallised papers	0.0105	1.601
Dielectric. Preimpregnated paper tapes	0.560	2.751
Dielectric screen. Copper tape	0.003	2.759
Lead sheath. Alloy E	0.105	2.935
Reinforcement bedding. Copper woven-fabric tape	0.012	3.009
Reinforcement. Four layers steel tapes	0.056	3.121
Anticorrosive serving. Cotton tape, proof tape, two layers rubber tape, cotton tape	0.099	3.371
Armour bedding. Jute string	0.050	3.491
Armour. 79/0.128 in galvanised steel wires	0.128	3.727
Serving. Two layers hessian tape	0.050	3.927

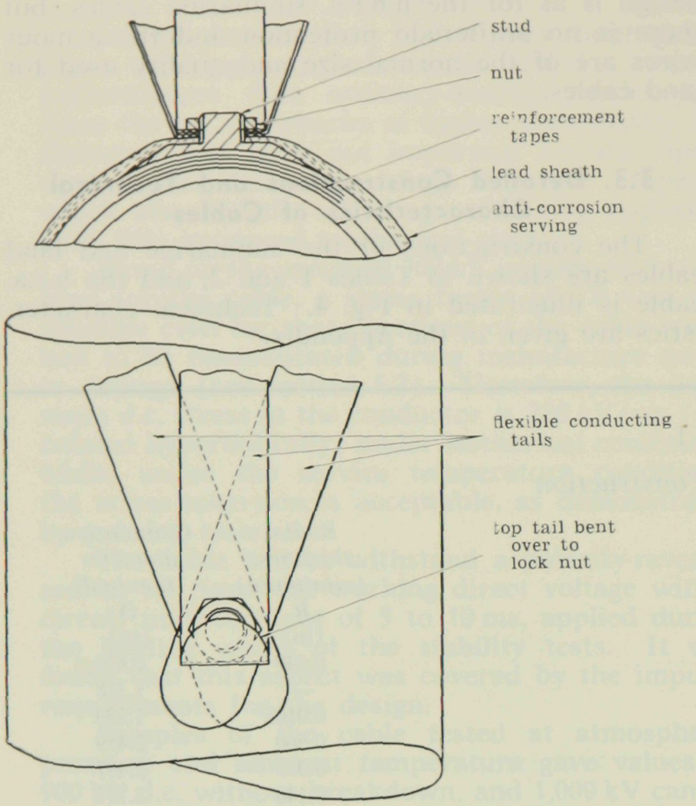

Fig. 3: Short-circuiting stud, lead sheath-armour.

4. ACCESSORIES, DESIGN AND CONSTRUCTION

4.1. Sealing Ends

A few fractures of shedded porcelain insulators of sealing ends have occurred after several years of operation at pressures up to 300 lb/in^2. The fractures have been explained, and the remedial measures appear to be effective, but, since the Cook Strait sealing ends were to operate at 425 lb/in^2 very serious consideration was given to the design.

The decision was taken to use a bushing type of design, in which the gas pressure is sealed off by external application to a plain porcelain under compression, with both surfaces immersed in oil. The absence of sheds on the porcelain is advantageous in terms of quality and uniformity. The shedded weather porcelain is unstressed as regards gas pressure, instead of being in tension as in earlier designs.

The principle is shown schematically in Fig. 5. The sealing end consists, fundamentally, of a copper tube insulated with oil-impregnated paper and clamped between an upper weather-shedded and a lower plain pressure-resisting porcelain. An oil-impermeable joint is made between the cable and the bottom end of the copper tube, within an oil-filled pressure sleeve.

Gas is fed to the copper tube at the top of the sealing end through a small-bore porcelain tube immersed in oil at atmospheric pressure within a second weather-shedded porcelain close to the sealing end. The gas passes into the cable duct from the lower end of the copper tube within the pressure sleeve, in which the oil is maintained under the same pressure as the cable in order to avoid differential pressures across the joint insulation.

The gas-feed porcelain tube is subjected internally to the cable gas pressure, but, owing to its small bore, the tensile stress in the porcelain is very low. In addition, its thermal duty is low because it is not subjected to heating from a current-carrying conductor, while it is also shielded from outside temperature variations by the surrounding oil-filled outer porcelain. The tube is of uniform cross-section and is extruded, and hence is likely to be uniform in quality; 28 such small-bore porcelains have given faultless service in Vancouver over a period of nine years at 300 lb/in^2.

The creepage distance of the weather-shedded insulators is 500 in, i.e. 2 in/kV, of which over 50% is protected.

4.2. Submarine-to-land and Submarine Repair Joints

Except for the mechanical reinforcement of the submarine repair joints, the two types of joint are similar to each other and to those designed for the Vancouver installation.

Figure 6 outlines the submarine repair joint, including the external girder frame to give strength during laying from the ship, and also shows the articulated cable protectors which were applied for a short distance over the cable adjacent to the joint to prevent excessive bending during installation. The weight load applied to the protected cable was limited by the use of cable stoppers to take part of the weight of the cable suspended to the sea bed.

The submarine-to-land joints and the submarine cables are anchored in a concrete joint pit embedded in the beach.

4.3. Cable Protection at Shore Ends

The submarine cables leaving the joint pit are protected against wave and surf action by cast-iron interlocked protectors. These are in two halves, with ball-and-socket ends, and were fitted around the cables and bolted together after installation. They are anchored to the joint and extend seaward up to 200 yd.

4.4. Gas Equipment

At each terminal site and on each cable, gas-pressure gauges are provided with electrical contacts to give warning of a fall in pressure. Gas-feed control equipment is also installed, so that, in the case of the severest leak, the cable gas pressures are automatically maintained above the minimum value to prevent water ingress to the cables. In addition, there are 36 gas cylinders (6,400 ft^3) at each site, and gas-leak location panels and equipment. It is estimated that, even in the improbable case of a cable being completely severed and gas being fed in at the maximum controlled rate continuously, the cable gas pressure can be maintained at a safe value over a period of three weeks from the two terminal reservoirs. When such a leak has been approximately located, the gas feeds from each end can be manually reduced to lower values than the automatic maximum, thus extending the endurance time of the reservoirs. Actually, owing to the robust character of the cable, it is extremely difficult to produce by mechanical action, apart from sawing

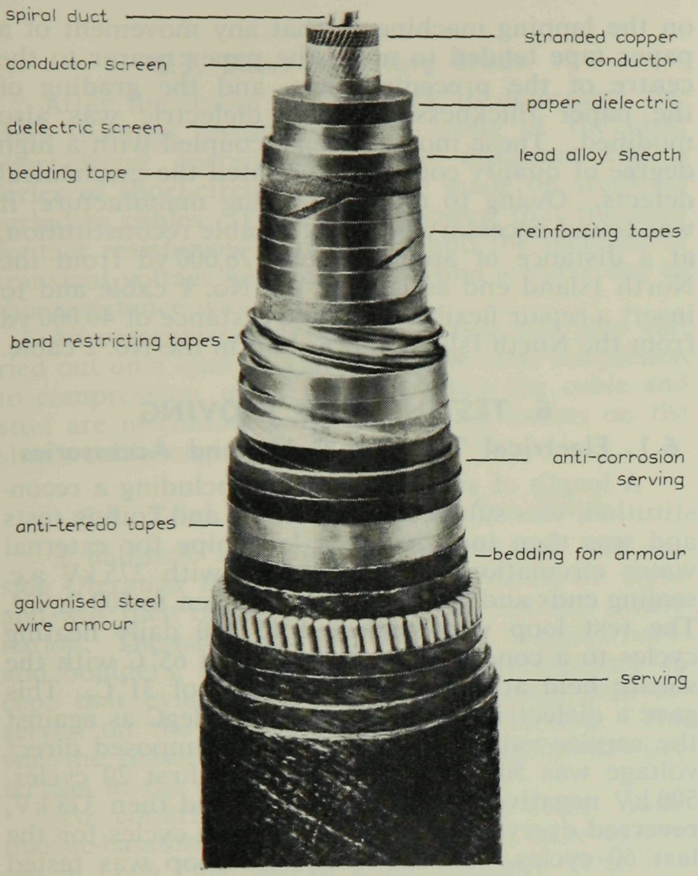

Fig. 4: Bend-restricting-construction cable.

or the use of an explosive grapnel, cable damage so severe that the pneumatic resistance of the leak itself does not limit the gas-flow rate.

Gas control feeding rates have been evaluated to ensure that, even in the case of a severe cable leak occurring at the maximum rated temperature with the current loading being removed, water cannot obtain ingress to the cable during the cooling period when the cable gas volume will be contracting and reducing in pressure.

4.5. General

All accessories, where subjected to the 425 lb/in^2 pressure in service, were tested hydraulically at 1,350 lb/in^2, followed by 675 lb/in^2 gas pressure.

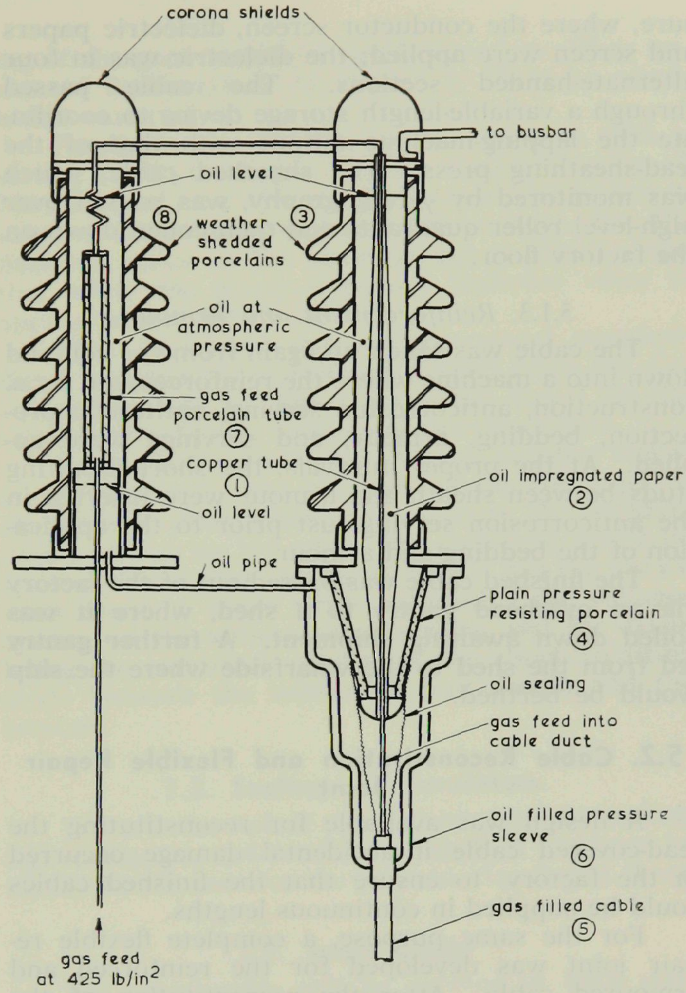

Fig. 5: Schematic of cable sealing end.

5. CABLE MANUFACTURE

5.1. Procedure

The 24-mile lengths of cable were made in three stages.

5.1.1. *Conductor*

The spiral gas duct was fed in jointed lengths into the back of a stranding machine, where the four layers of copper wire were applied. The finished conductor was wound down onto a 47 ft diameter turntable.

5.1.2. *Dielectric and Lead Sheath*

Conductor was fed from the turntable through the lapping machine in an air-conditioned enclo-

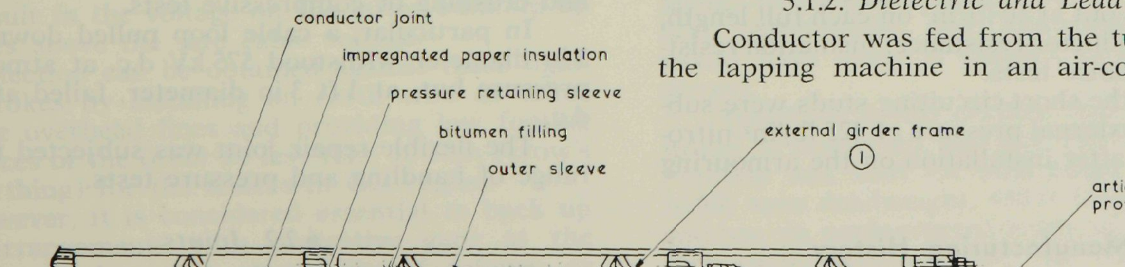

Fig. 6: Submarine repair joint.

sure, where the conductor screen, dielectric papers and screen were applied; the dielectric was in four alternate-handed sections. The cable passed through a variable-length storage device to coordinate the lapping-machine output with that of the lead-sheathing press. The sheathed cable, which was monitored by γ radiography, was passed over high-level roller quadrants and then coiled down on the factory floor.

5.1.3. *Reinforcement and Armour*

The cable was taken up again from the coil and down into a machine where the reinforcement, b.r.a. construction, anticorrosion serving, antiteredo protection, bedding, armour, and servings were applied. At the proper intervals, the short-circuiting studs between sheath and armour were inserted in the anticorrosion serving just prior to the application of the bedding and armour.

The finished cable was passed out of the factory via an overhead gantry to a shed, where it was coiled down awaiting shipment. A further gantry led from the shed to the wharfside where the ship would be berthed.

5.2. Cable Reconstitution and Flexible Repair Joint

A design was available for reconstituting the lead-covered cable if accidental damage occurred in the factory, to ensure that the finished cables could be supplied in continuous lengths.

For the same purpose, a complete flexible repair joint was developed for the reinforced and armoured cable. After the reconstitution of the lead-covered cable, the reinforcing tapes were reapplied, the cut ends of corresponding wires being joined by right- and left-hand turnbuckles screwed on to the threaded ends of the wires so that they could be pulled tight.

5.3. Routine Testing

At the start and finish of each manufacturing length, in the lead-covered and finished states, sample lengths were cut off for examination and test. The full lengths of lead-covered and armoured cable were subjected to electrical tests of 525 kV d.c. between conductor and sheath for 30 min, at atmospheric pressure. Internal-gas-pressure tests were also carried out at 50 lb/in^2 on each full length, together with conductor-resistance, insulation-resistance, and capacitance tests.

In addition, the short-circuiting studs were subjected to a local external pressure of 425 lb/in^2 nitrogen immediately after installation on the armouring machine.

5.4. Manufacturing History

Trial lengths of cable were manufactured before the commencement of the contract proper, and these were subjected to accelerated-type tests.

After some initial difficulties, owing to collapse wrinkling and deformation of the cable dielectric when coiled down in the lead-covered state, adjustments were made to the widths of the gaps between paper edges, the registration value was increased on the lapping machine so that any movement of a paper tape tended to move the paper nearer to the centre of the preceding tape, and the grading of the paper thicknesses in the dielectric was also modified. These modifications, coupled with a high degree of quality control, eliminated the mechanical defects. Owing to mishaps during manufacture, it was found necessary to insert a cable reconstitution, at a distance of approximately 26,000 yd from the North Island end as laid, in the No. 1 cable and to insert a repair flexible joint at a distance of 40,000 yd from the North Island end as laid in the No. 2 cable.

6. TESTING AND PROVING

6.1. Electrical Tests on Cable and Accessories

A length of submarine cable, including a reconstitution, was subjected to bending and coiling tests and was then installed in a lead pipe for external water circulation and terminated with 275 kV a.c. sealing ends and charged with nitrogen to 300 lb/in^2. The test loop was subjected to 100 daily heating cycles to a conductor temperature of 65° C with the sheath held at a mean temperature of 31° C. This gave a dielectric thermal drop of 34 degC as against the service value of 27.5 degC. The imposed direct voltage was 500 kV positive for the first 20 cycles, 500 kV negative for the second 20, and then 375 kV, reversed every 2 h during the heating cycles for the last 60 cycles. Subsequently, the loop was tested with the conductor at 60° C and the sheath at 28° C at 575 kV d.c. positive for 30 min, and then, with the conductor at 65° C and sheath at 31° C, was impulse-tested, with 10 positive and 10 negative shots at each step, at 700, 725, 750, 775, and 800 kV, at which level breakdown occurred in the reconstitution.

Similar tests were carried out on the land cable, submarine-to-land joint, submarine joint, and contract sealing ends, using the design gas-pressure value.

6.2. Mechanical Tests

6.2.1. *Cable and Flexible Repair Joint*

Tests included coiling, bending under tension, tensile and twisting tests up to 15 ton loading, internal gas pressure, external water pressure, handling and coiling under 450 lb/in^2 internal pressure, and crushing or compressive tests.

In particular, a cable loop pulled down to 3 ft 3 in diameter withstood 575 kV d.c. at atmospheric pressure but, at 1 ft 3 in diameter, failed at 330 kV d.c.

The flexible repair joint was subjected to a full range of handling and pressure tests.

6.2.2. *Joints*

These were internally and externally pressure and electrically tested after being subjected to bending under limited tension and under straight heavy tensile testing.

6.2.3. *Articulated Cable Protectors*

Mechanical tests, exaggerated in relation to the expected service duty, were carried out.

6.3. Short-circuiting Studs

After the initial E.R.A. work to determine the stud spacings, estimates were made of the stud short-circuit currents and their duration, and a series of short-circuit tests were made on studs inserted in cables. These tests showed that the stud contact resistances were stable, and the increase of transient voltage between sheath and armour due to this resistance was negligible.

An external-gas-pressure-type test was also carried out on a stud in a cable sample after subjection to compression, as in the case when the cable and stud are in contact with the fleeting knives on the ship's cable engine during installation.

6.4. Trial Installation and Sea Trials

A half-mile length of b.r.a. cable was laid outside Oteranga Bay in 1958 in 15 fathoms of water and was then recovered in 1960 for test and examination. The cable was laid over and between rocks and boulders, but the results were satisfactory except that evidence of gastrapod borings was observed on the rubber anticorrosion serving. This was the reason for the inclusion of antiteredo protection in the contract cables.

To confirm the design of the cable under marine-handling conditions, sea trials were carried out in Loch Fyne and in Largs Channel. The trial cables incorporated reconstitutions and flexible repair joints (see section 9).

7. OVERVOLTAGE PROTECTION

7.1. Cable System Generally

Owing to the long length of leakage path required, the insulation level of the 250 kV d.c. overhead-line insulators is in excess of 1,000 kV, especially near the coastal region where there is increased creepage length in view of salt pollution.

For travelling voltage waves coming from, say, a mile or two from the cable termination, a peak value of 935 kV would be refracted down to a safe value in the cable, even allowing for the d.c. standing voltage wave.

However, if a lightning stroke occurs within less than a mile of the cable termination, successive reflections from the point of stroke to the cable may result in the voltage on the latter building up to values above the safe cable voltage.

Protection can be obtained against these lightning strokes by installing an earth wire or wires over the overhead lines and providing low footing resistances of the order of less than 10 ohm (crow's foot earthing) for the towers in this region.

However, it is considered essential to back up these arrangements with protective gaps at the cable terminations as a second line of defence, or to cover any deterioration of the protective arrangements. The settings of these gaps have to be above the level of occasional a.c. or d.c. transients from the d.c. equipment.

Initially, a proposal was made to use large sphere (1 m) gaps in order to give as low an impulse ratio as possible, but, as well as worries of possible salt pollution and maintaining the sphere surfaces in good condition, it was felt that the spacing of the gaps would be small enough to allow unwanted flashovers to be caused by birds or windborne material.

Finally, it was decided to use rod gaps with a setting of 32½ in to give a 100% flashover value of 700 kV based on a 15% margin from a 50% flashover value of 610 kV on a negative 0.02 μs wave. The 0% flashover value on the same margin is 520 kV negative, while the power-frequency flashover value is approximately 400 kV peak.

It is considered that any occasional transient direct or alternating voltages arising from the d.c. equipment will not affect the cable, based on the values given by the equipment manufacturers.

A travelling wave of 950 kV peak negative would be necessary to cause flashover of the rod gaps on the positive cable, taking into account the standing direct voltage on the cable. The dielectric would be subjected to a peak voltage of 700 kV, but the 950 kV value must be taken when calculating the voltages arising on the anticorrosion serving and for calculating the maximum spacing of the short-circuiting studs between the reinforced lead sheath and the armour.

7.2. Sealing-end Insulators

There is the risk of salt pollution on the sealing-end insulators, and washing equipment has been installed by the user for the periodic cleaning of them.

7.3. Spare Cable

The spare cable will be earthed at both ends and the gas pressure will be the only monitoring device. It is proposed to change over the spare cable with one of the active cables after a reasonable period of service, and the future changeover arrangements will depend on experience.

8. VESSELS

8.1. M.V. "Photinia"

Because of the mechanical characteristics of the cable, the minimum supported bending diameter which could be tolerated around wheels was 12½ ft and the minimum coiling diameter 22½ ft. No existing cable-laying ship had sheaves and cable-laying machinery big enough to comply with the first requirement, and limitations in hold sizes would have made it difficult to comply with the second.

Therefore it was decided that a suitable vessel would be converted, and m.v. *Photinia* was selected. *Photinia* was built for bulk cargo carrying. She is 10,000 tons deadweight, 480 ft long, and 60 ft beam, and has six unobstructed holds, of which four could each easily accommodate one complete length of cable. Manoeuvrability was improved by installing a bow propeller giving a 10 ton thrust.

An outline sketch of the vessel is given in Fig. 7. Holds 3, 4, and 5 were adapted for carrying the cables, while hold 6 was used for providing living accommodation for extra men. Hold 1 accommodated the prime movers (totalling about 1,600 hp)) to drive the bow propeller and the cable engine, while hold 2 was used to store and handle the numerous additional items which would be required.

Above each of the cable holds was installed a gantry carrying a 16 ft sheave hydraulically driven from a diesel engine mounted on the deck. The purpose of these sheaves was to lift the cable from the hold during laying and deliver it, via a roller train which ran along the ship on the port side, to a back-tension sheave which immediately preceded the cable-engine drum. The cable-engine drum was driven hydraulically from a diesel engine in No. 1 hold, and the back-tension sheave was coupled to it by an adjustable clutch, so that the cable would be presented to the cable engine at a controllable known tension. The cable engine could operate at speeds up to 8 knots and could sustain a tension up to 50 ton at low speed. The cable engine was fitted with fleeting knives, the design of which was the result of theoretical study and model experiments so that, under all conditions of cable laying or recovery, the pressures on the cable would be well within tolerable limits. On leaving the cable engine, the cable passed along rollers at high level to a free-running bow sheave. Below the bow sheave was mounted a bellmouth, so designed that the bending of the cable would be controlled, whatever the angle at which it left the ship. The forward half of the bellmouth was hinged so that it could be opened if it were necessary to pass repair joints through it.

A second bow sheave was installed on the starboard side, to be used in conjunction with a 30 ton diesel-driven winch in case it should be necessary to carry out repair operations.

For control of the cable-handling equipment, a cabin was installed just forward of the cable engine and above it.

A system of indicating and recording instruments was installed so that measurements of cable tension, speed and length, fleeting-knife pressure etc. could be made. The main centre of instrumentation was a control room, in the centre castle of the ship, with repeaters in the cable-engine control cabin and elsewhere. Main engine controls were fitted at the bow, so that the ship could be handled from that position if necessary; controls for the bow propeller were installed at the bow and on the bridge.

8.2. M.V. "Arran Firth"

This ship is a small coaster of 750 tons. She had a triple function: (a) to convey to New Zealand the mooring gear which would be installed in both Bays, and numerous other items; (b) to lay the moorings in the Bays, for which she was specially equipped; (c) to act as tender to m.v. *Photinia* during all operations.

8.3. Auxiliary Vessels

Two robust 50 hp boats were provided, primarily for the handling of mooring lines. In addition, there were two inflated rubber Z craft for working in very shallow water.

8.4. Special Craft

As an essential part of the laying operations, three special vessels were provided. There were:

(a) Two "float riggers", one for use in each Bay. These were in the form of rafts with suitable superstructure, so that floats of special design could be readily placed under the cable during the landing of the starting and finishing ends. The details of the floating process are described later.

(b) A "floating head", for use in landing the finished end of cable. This consisted of a large freely rotating drum, mounted between two pontoons, and served as a floating extension of the ship's bow sheave. The floating head could be hauled towards shore by a winch on the beach, and it was so designed that it could move up the beach until the required length of cable had been landed. (Again, details of the process are given later.)

9. SEA TRIALS

The special equipment in *Photinia* was first fitted early in 1962, and sea trials were carried out in Scotland later in the same year. Loch Fyne was selected for deep-water exercises, and Largs Channel was chosen for rehearsals of shore-end landing procedures.

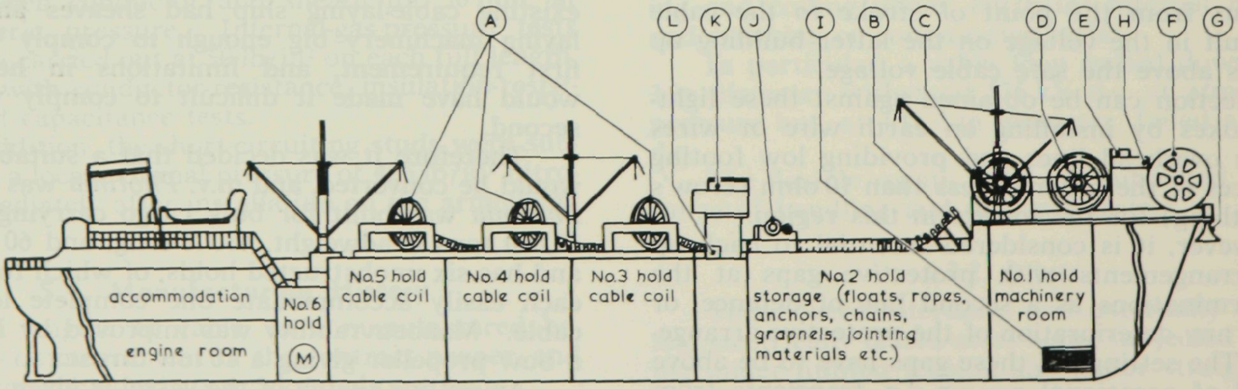

Fig. 7: M.V. Photinia.

A *Hatch sheaves (angled towards port side)*
B *Roller train (port side)*
C *Back-tension sheave*
D *Cable engine*
E *Cable-laying machinery controls*
F *Bowsheaves*
G *Bellmouth*
H *Jointing enclosure*
I *Bow-propeller tunnel*
J *30 ton winch (starboard side)*
K *Upper bridge*
L *Cable-laying control room*
M *Accommodation (40 men)*

The trials in Loch Fyne covered the laying and recovery of 2,000 yd lengths of cable, the deeper conditions of Cook Strait being simulated by increasing the cable-laying tension appropriately. Also, the method which had been developed for cutting cable on the sea bed in deep water, by means of a grapnel fitted with an explosive charge, was proved.

In Largs Channel, the landing and recovery of starting and finishing ends of cable, and the approach to and departure from moorings laying cable, were rehearsed.

These trials proved the equipment to be generally sound but indicated numerous features which could be improved. Therefore, immediately before the ship was due to load the contract cable in 1964, a further trial was carried out in Loch Fyne. For this, 10,000 yd of cable was provided, and this enabled laying rehearsals to be carried out at the nominal laying speed of 3 to 4 knots, with overspeed tests up to nearly 6 knots. The longer length of cable also permitted more prolonged recovery trials, the doubtful point here having been the ability to recoil cable continuously back into the hold; it was found that, provided a sufficient labour force was available, a recovery speed up to 1,200 yd/h could be maintained. Experiments were also made in mooring the ship in about 40 fathoms of water and making and laying repair joints.

The results were judged satisfactory, and *Photinia* then proceeded to load the contract cable.

10. LAND WORK

As soon as *Arran Firth* reached New Zealand in the spring of 1964, cable work commenced. The land cables were first laid, loops being provided so that surplus cable would be available for repairs if necessary, and this was followed by the construction of the sealing ends and the gas-feed arrangements. As soon as they were completed, the land cables and sealing ends were pneumatically tested at 600 lb/in^2 to ensure that they were leaktight.

11. MARINE WORK

11.1. Shore-end Moorings

The moorings consisted of strategically placed anchors (the embedment of them being checked by divers) followed by lengths of chain, then steel wires to clumps, to which were attached conventional cylindrical mooring buoys. In both cases, the moorings were about 1,000 yd from the beach.

11.2. Navigation Aids

To ensure information on the position of *Photinia* at all times, a Decca Hi-Fix system was installed. The master station was on the hills above Fighting Bay, and slave stations were erected at Cloudy Bay, south of Fighting Bay, and at Oteranga Bay. The position of the receiving aerial on *Photinia* could be pinpointed to within 1 yd.

11.3. Communications

Radiocommunications were set up between all land stations and both ships. In addition, walkie-talkie radios and flag signals were arranged between the beaches, *Photinia*, and other craft while working close inshore.

11.4. Weather Forecasts

Special arrangements were set up with the N.Z. Meteorological Department so that 36 h forecasts were issued to *Photinia* and *Arran Firth* every few hours. Although it is difficult to prepare accurate forecasts for Cook Strait because of the variability of conditions and the absence of sufficient weather stations, the forecasts proved to be highly dependable.

11.5. General Cable-laying Procedure

It had been estimated that the three phases of landing the starting end, laying the main length, and landing the finishing end would each occupy about 6 h when due allowance was made for awaiting the right tidal conditions before sailing from Oteranga Bay. When *Photinia* reached New Zealand, a period of about 10 days was spent in dummy runs and rehearsals and in training local labour, and all was ready for commencing contract work by 6 November 1964, at which time of the year the total hours of daylight were only about 16. Therefore, some part of the operation had to be performed in darkness. The safest plan was judged to be that the departure from Oteranga Bay should be timed so that *Photinia* reached Fighting Bay as late as possible in the evening, to lie at moorings overnight and to begin the landing of the finishing end at first light the following morning. Temporary navigation lights were installed at Fighting Bay so that entry in the dark could be made. Because of the experience gained in laying the first two cables, which showed that it was undesirable to moor even in Fighting Bay for more than the minimum essential time, the plan was modified for the last cable laid, and the finishing end was landed in darkness without difficulty. The cables were numbered 1, 2, and 3, from north to south. As the current in Cook Strait is predominantly southgoing, with the consequent risk of the ship being forced to the south during laying, the cables were laid in reverse order, cable 3 (the southernmost) being laid first and cable 1 (the northernmost) last. Actually, no significant deviations from course occurred.

The procedure was for both vessels to anchor in a base established in Port Underwood, a few miles south of Fighting Bay. When the weather forecast offered even the slightest chance of laying cable, they both crossed the Strait to Oteranga Bay. *Arran Firth*, carrying the two work boats, entered the Bay to examine and report on conditions, while *Photinia* waited outside. When weather and tidal conditions were right, *Arran Firth* put the work boats in the water at the moorings and cleared the Bay, and *Photinia* entered and moored. For the mooring lines, plaited polypropylene ropes, 6½ in in circumference, were used. These had the advantages that they were light and flexible, so that they were easily handled by the work boats and, because they floated, were easily seen. The position of the bow was adjusted by taking a distance line to the bow mooring, so that the proper cable separation would be obtained.

11.5.1. *Landing the Starting End*

The leading end of cable was brought up from the hold and taken through the cable-laying machinery to the bow; to it was attached a polypropylene rope to a winch installed on shore near the joint pit. A float rigger was secured beneath the bow and the cable end drawn through it. Then, strings of floats which had been previously assembled in No. 2 hold were lowered to the float rigger and placed under the cable.

The floats were rectangular and were made of rubberised fabric in pairs so that the cable rested between them. Individual pairs were tied together at a spacing of 3 yd. All the floats on one side of the cable were fitted with plugs attached together by a continuous light floating line. Then, when all of the required length of cable had been floated ashore, one of the work boats patrolled the route, starting from the shore, recovering the line and pulling out the plugs one by one. As the air escaped from the floats on one side of the cable, the cable was lowered gently onto the sea bed; the still inflated floats on the other side then brought all of the floats back to the surface for easy recovery. In shallow water inshore, where the floats might be trapped by the cable, single floats were used so that they could be removed easily. While the cable was being sunk to the bottom, extra cable was paid out from *Photinia* to maintain the correct tension.

The work boats then towed the strings of floats back to *Photinia*, and they were returned to No. 2 hold.

11.5.2. *Laying of Main Length*

Photinia cast off moorings and manoeuvred on to the correct course, while cable handling was controlled by an officer at the bow. As soon as the ship's course and speed were properly adjusted (after about half a mile), all cable control was taken over by the control room, the staff of which issued instructions direct to the engineer operating the cable-laying machinery controls. Cable tension was adjusted in relation to water depth and speed according to a schedule which had been prepared from earlier depth surveys and corrected from the information obtained during the dummy runs which had been carried out. The "residual tension", that is to say, the tension in the cable as it reached the sea bed (6) was 1 ton.

For each cable route, a course had been drawn on the automatic course plotter, which was an integral part of the Decca system, and this was continuously observed by an officer on the bridge who gave the appropriate instructions to the helmsman. The cables were laid 1,000 yd apart (except when they converged at the landing points).

As soon as *Photinia* left Oteranga Bay, the work boats cleared up the lines in the bay and were then picked up by *Arran Firth*, which sailed to arrive in Fighting Bay sufficiently far in advance of *Photinia* to be able to examine conditions and report by radio, lower the work boats into the water and depart to leave the way clear for *Photinia*.

When *Photinia* entered Fighting Bay, the control of the ship remained with the captain on the bridge but, at the last moment before mooring, cable control was taken over by an officer at the bow to make sure that the cable lead was correctly maintained and tension was not lost.

11.5.3. *Landing the Finishing End*

The position of the bow was set by distance line, and a float rigger and the floating head (which was moored in Fighting Bay) were brought into position.

The floating head, attached to a shore winch by a polypropylene rope, was positioned under the cable beneath the bow, and it was then hauled towards the shore, cable being paid out from the ship and lowered round the floating head to the sea bed. When the loop of cable between the bow and the floating head was just above water, strings of floats were placed under the cable from the float rigger, as in landing the starting end. Movement of the floating head towards the beach proceeded, and, as the floats drifted clear of the cable on reaching the floating head, they were recovered by the work boats and returned to *Photinia*.

When the floating head reached the estimated halfway position, range-finder checks were made and the cable was cut and capped in the hold. It was tailed with a floating rope and the floating head was hauled towards and up the beach until the whole cable had been landed.

12. INSTALLATION TIMETABLE AND TESTING

12.1. Timetable

The weather and sea conditions were generally bad. Although the ships were ready on 6 November, the laying of cable 3 could not be started until 12 November. Cable-laying operations commenced at 12.20 p.m. *Photinia* left Oteranga Bay at 5.16 p.m., to moor in Fighting Bay at 11.35 p.m., and operations were resumed at first light at 4.15 a.m. the following morning. The finishing end of cable was landed at noon, 13 November.

Then followed 10 days of unsuitable conditions, and the laying of cable 2 commenced at 1.25 p.m., 23 November, to finish at 11 a.m., 24 November. An even longer interval elapsed before cable 1 was laid, commencing at 12.15 p.m., 11 December, and finishing at 4.35 a.m. on 12 December.

12.2. Testing

After each cable was laid, it was immediately manoeuvred into the joint pits at both ends and the submarine-to-land joints were made, these processes taking about three days. Nitrogen gas at approximately 100 lb/in^2 was introduced from the Oteranga Bay end, and, after some seven or eight hours, gas pressure appeared at the remote end. The pressure was then slowly raised from Oteranga Bay until the nominal operating pressure of 425 lb/in^2 had been uniformly established. The electrical test of 520 kV d.c. was then applied. The cable pressure was next raised to the overpressure value of 600 lb/in^2 for four days to ensure that the system was pneumatically sound. Pressure was then lowered to 425 lb/in^2, at which each cable contained approximately 30,000 ft^3 of gas at atmospheric pressure.

Cable 3 successfully passed the high-voltage test on 29 November, and its overpressure test was completed on 8 December. The corresponding dates for cable 2 were 6 and 15 December. However, when cable 1 was subjected to the high-voltage test on 23 December, a fault occurred at 320 kV, and this was subsequently located to a position 26,280 yd from the Oteranga Bay joint, that is to say, at about nine miles from Fighting Bay in 52 fathoms of water.

13. REPAIR OF THE FAULT IN CABLE 1

13.1. General

Initially, the reason for the fault was a mystery, because none of the observers on the ship had noticed any incident. The location gave a position very close to that of the reconstitution which was made in the factory because of an accident during production and which was estimated by factory measurement to be 26,360 yd from the Oteranga Bay joint. It was at first supposed, therefore, that something had gone wrong with this reconstitution, even though the low voltage of the failure was inexplicable.

The sea bed in the fault area was of sand and shingle, giving a good holding power for anchors. The first stage in any method of repair is to cut out the faulty cable*, and it was believed that this could be followed by a "conventional" repair, i.e. the insertion of a new length of cable and two rigid repair joints. Plans for the repair were made accordingly.

The plan was to lay a box of six moorings around the fault, so that the eastern four could be used for work on the Oteranga Bay end of cable and the western four for work at the Fighting Bay end. *Photinia* would first grapple the cable on the Oteranga Bay side (i.e. that leading to deeper water) and lift it a fathom or two off the sea bed so that no water would enter when *Arran Firth*, working as a free ship within the mooring box, cut the cable explosively. *Photinia* was then to lift the Oteranga Bay end, clear the fault, seal the end and relay it on the sea bed. She would then warp to the Fighting Bay end, grapple and lift the cable and clear the damaged portion, make a straight-through joint to the new cable in the hold, lay towards and pick up the Oteranga Bay end, and finally make and lay a closing joint.

13.2. First Attempt

A box of moorings was laid around the fault position on 9 and 10 January 1965. Each mooring consisted of a heavy Danforth-type anchor, a length of chain, and then 3½ in wire rope to a surface buoy. The anchors were placed approximately 800 yd from cable 1 in order to give sufficient scope to develop high holding power.

On 11 January, *Photinia* moored south of the cable, ready to begin the grappling operations, in such a position that wire ropes from the anchors were inboard at the stern, while, at the bow, scope was increased by 6½ in polypropylene rope.

When *Photinia* had been moored for only two hours, before any cable handling had commenced, the southgoing current increased, and one of the stern mooring wires parted without warning; the movement which immediately occurred put very heavy strain on the other stern mooring. In an attempt to alleviate the position, the bow propeller was used, but one of the polypropylene ropes at the bow formed a loop on the surface which was swept by the current into the bow-propeller tunnel, and some hundreds of feet of tail rope which had been coiled on the deck were wound up into the bow-propeller blades within a few seconds. Further work had to be abandoned until *Photinia* could be dry-docked for removing the tangled mass of polypropylene rope and inspecting the bow-propeller blades.

The current was not measured when this accident occurred, but it was estimated to be approaching 4 knots, which was considerably greater than had been expected in the area. While *Photinia* was undergoing repair, *Arran Firth*, equipped with Decca apparatus, was used as a log ship to make a thorough survey of conditions, and it was found that the fault lay in a localised area of high currents which were predominantly southgoing, reaching a speed of 3.5 knots. This knowledge suggested an alternative explanation of the fault and made necessary a reappraisal of the mooring methods which it had been proposed to use.

Considering first the cause of the fault, the laying speed approaching the position had been 4.4 knots, but the ship was deliberately slowed down so that the cable reconstitution made in the factory would pass the machinery at a speed not greater than 3 knots. A careful study of the laying records revealed that, for a period of less than 1 min, the residual laying tension had fallen to zero and that this had been followed immediately by a rapid correction of tension. Under these circumstances, excess cable could have been laid on the sea bed and then snatched into a kink; a calculation based on this assumption showed that the cable could have ben severely damaged 26,290 yd from the Oteranga Bay joint, a figure which agreed precisely with the electrical location. During the short period while this loss of tension occurred, the cable-laying speed was 3 knots, and it must be assumed that, on entering an unexpected zone of high current, the speed of the ship over the ground had temporarily fallen to a lower value. There was no direct evidence for this, because the log, which measured the speed of the ship through the water, did not fall below 3 knots. However, there was now good reason to suppose that the fault was due to a kink, which would explain the very low level of the voltage breakdown.

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* Considerable energy is released at the fault position on electrical breakdown, and there is a probability that the lead sheath will be perforated and a possibility that the anticorrosion serving will also be damaged. Water entry to the dielectric, and thence to the hollow conductor, can be prevented with certainty only by maintaining the internal gas pressure. The making of a repair joint can be carried out only with cable at atmospheric pressure, and, if the risk of spoiling a long length of cable is to be minimised, the damaged portion must be removed first.

Concerning the design of moorings, it was assumed that allowance must be made for winds up to 30 knots and simultaneous currents up to 4 knots in the same direction. Calculations were made and the mooring arrangements redesigned on this basis; an important factor was the inclusion of extra resilience to absorb surges. Some delay arose in obtaining extra equipment which was needed, and work at sea was not resumed until early in February.

13.3. Fault Clearance

Because of bad weather and sea conditions, and the frequent entanglement of buoys and surface lines by vast masses of floating kelp, *Photinia* did not moor to the easterly moorings until 23 February. A 36 h mooring trial was then conducted, during which the wind reached 28 knots and the current 3 knots, and the mooring performance was studied. The highest tension recorded in any mooring was 12½ ton, which was in accordance with calculations and well within the capacity of the 5,000 lb Danforth anchors and 3½ in steel-wire rope. A disconcerting feature was that the bow movement was excessive, and there were excursions up to 100 yd owing to the stretch of the polypropylene ropes used to extend the scope of the bow moorings. It was decided to proceed with the clearing of the fault and then to proceed with jointing, or defer it, in the light of experience.

Photinia grappled the cable on the Oteranga Bay side of the fault on 26 February, and *Arran Firth* cut the cable on the sea bed with an explosive grapnel. The length of cable containing the fault was recovered, the fault being confirmed to be a straightened kink exactly in the predicted position. The sound Oteranga Bay end of cable was relaid on the sea bed and buoyed.

Bad conditions delayed the grappling and clearing of the Fighting Bay end until the following day, when preparations were made for starting the first joint. During the night, however, when the current was high and the wind gusting to 35 knots, the ship was forced over the cable, with the probability that fresh damage had been caused at the bottom of the suspended length; this was confirmed by recovering more cable. Because the weather forecast predicted strong southerly winds, the new damage was cut out and the sound cable sealed and relaid, these operations being completed just before dark in rapidly roughening seas. *Photinia* left the moorings.

The overall position was then that:

(a) A 950 yd length of cable, including the fault, had been removed and two good cable ends relaid.

(b) *Photinia* had been successfully held in the moorings for six days.

(c) Excessive bow movement made further progress with the original plan impossible. The excessive movement was undoubtedly caused by the long lengths of polypropylene rope which were necessary to tie *Photinia* to the mooring wires in a mooring arrangement which must allow for grappling, warping, and jointing. Calculations showed that the extension of the rope which would be expected under the tensile loading corresponded closely to the movement experienced.

Therefore, the plan was changed to an alternative method which had been developed and practised in the 1962 sea trial in case such a situation should arise. This was to recover the whole of the Fighting Bay end of cable, to lengthen it by joining to it 2,000 yd of new cable by means of a flexible joint, to place around the Oteranga Bay end a "rigid" mooring box containing no polypropylene rope except that inserted for surge absorption, to make only one joint at sea, and then finally to relay the cable into Fighting Bay.

The moorings which had been used during the removal of the fault were picked up to clear the way for this method.

13.4. Completion of Repair

The moorings in Fighting Bay were inspected by divers and found to be in good order. The gas pressure in the cable was reduced to atmospheric, the cable was cut at the seaward end of the Fighting Bay joint pit, and both cut ends were resealed[°]. The seaward end of the cable was moved away from the joint pit so that the floating head could move over it without any risk of damage to cable 2.

The recovery operation commenced at 7 a.m. on 25 March, with *Photinia* moored in Fighting Bay and a polypropylene rope from the cable engine taken to the beach, around the floating head and attached to a pulling eye on the end of the cable. Back tension was maintained on the floating head by a shore winch. A float rigger was positioned just outside the surf line, in about one fathom of water, with the polypropylene rope passing through it.

The floating head was moved down the beach and picked up the cable end, and floats, brought ashore by the work boats, were attached to the cable. When the floating head was afloat, the float rigger was moved back to it, and the two were secured together. From then onwards, strings of floats were taken to the float rigger and placed under the cable in the usual manner. The shore end of cable was completely recovered into the ship by 3 p.m., and *Photinia* then released moorings and moved slowly out of the bay recovering cable. Recovery proceeded smoothly, and the only difficulty was in controlling the attitude of the ship in the moderately strong currents which were experienced early in the operation. The ship was controlled from the bow, and her course was dictated by the cable lead, but position was checked by the Hi-Fix system. During the whole of the recovery, the bow was maintained about 50 yd to the side of the cable route, this being judged the safest position if it should prove impossible to prevent the ship overrunning the cable. A maximum recovery speed of about 1,300 yd/h was attained, the limiting factor being the rate at which the cable could be coiled,

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[°] At the time the cable was high-voltage tested the pressure was 425 lb/in^2. When the depth at the fault was known, the pressure was reduced to 200 lb/in^2, both to reduce the violence of gas escape when the cable was cut and to reduce the time needed to let out the gas for jointing operations. When the ends cut at sea were recapped and relaid, a gas pressure a little in excess of the external water pressure at the ends was restored.

and the seaward end of the cable was reached at 4.20 a.m. on 26 March. A high-voltabe test set was erected in the hold, and the 15,000 yd (approx.) length of recovered cable successfully passed a 525 kV d.c. atmospheric-pressure-withstand test on 28 March; the cable appeared to have suffered no damage whatsoever during the recovery.

The flexible joint was then made in the hold (taking 19 days), and the whole cable and joint were retested electrically. The cable was recoiled in the careful manner which is necessary to ensure free running when laying at speed, and all was ready on 22 April for the final operation.

There were several days of bad weather while new moorings were being laid around the Oteranga Bay end of the cable, and some of the better weather which occurred had to be used in repairing surface equipment which was damaged as a result. It was not until the afternoon of 5 May that the Oteranga Bay end of cable could be picked up and the ship moored. Jointing work started at 1 a.m. on 6 May and was completed at 9 a.m. on 7 May.

The joint was lowered to the sea bed, and the ship left moorings and commenced laying cable back towards Fighting Bay. When about halfway there, unexpected southerly squalls blew up, and the sea became rough. Conditions in the Bay worsened rapidly, and it was evident that the lay could not be completed. An emergency plan for such a circumstance (which had always been envisaged) was put into operation, and, when about a mile off shore, the ship turned to the south west and the remaining cable was laid out parallel to the coast. The end was buoyed.

The following day was lost through bad weather, but lifting of the cable began at 3 a.m. on 9 May and continued until 9 a.m., when the vessel was manoeuvred back on to the laying course. When the ship moored in Fighting Bay at 10 a.m., there was still considerable swell and surf which made the handling of the floating head very difficult, but nevertheless the end was safely ashore by 5.15 p.m.

Jointing proceeded immediately, and, after the gas pressure had been raised to 425 lb/in^2, the cable passed the 520 kV d.c. test on 19 May. The overpressure test was then successfully carried out.

14. CONCLUSIONS

The project was successfully completed, but not without difficulties. These were not of a fundamental nature.

A very high standard of quality was attained by extensive preliminary testing and development and by meticulous attention to detail at all stages. In consequence, it is believed that performance will be satisfactory.

The damage to cable 1 during laying emphasises the fact that, even with the most careful planning, the unexpected may happen. In submarine power-cable schemes, it is regarded as essential that repair methods based on sound principles are available from the outset. Then, even though it is not feasible to legislate in advance for all contingencies, techniques can be adapted to meet the particular conditions encountered.

15. ACKNOWLEDGMENTS

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APPENDIX

Technical Data

Conductor area			
	Submarine cable		0.80 in^2 nominal
	Land cable		1.25 in^2 nominal
D.C. resistance of conductor at 20° C			
	Submarine cable		0.0303 ohm/1,000 yd
	Land cable		0.0185 ohm/1,000 yd
D.C. resistance of sheath at 20° C			
	Submarine cable		0.262 ohm/1,000 yd
	Land cable		0.322 ohm/1,000 yd
D.C. resistance of reinforcement at 20° C			
	Submarine cable		
		b.r.a.	0.500 ohm/1,000 yd
		n.b.r.a.	0.875 ohm/1,000 yd
D.C. resistance of armour wires at 20°C			
	Submarine	b.r.a.	0.089 ohm/1,000 yd
		n.b.r.a.	0.105 ohm/1,000 yd
	Land cables		0.195 ohm/1,000 yd
Weight in air		b.r.a.	88 lb/yd
		n.b.r.a.	69 lb/yd
Weight in seawater		b.r.a.	63 lb/yd
		n.b.r.a.	61 lb/yd
Overall diameter		b.r.a.	5.01 in
		n.b.r.a.	4.37 in
		land	3.93 in
Minimum permissible bending diameter			12.5 ft
Minimum permissible coiling-eye diameter			22.5 ft
Maximum permissible tensile load			15 ton

Torsional modulus	b.r.a.	0.21 deg/yd per ton
	n.b.r.a.	0.08 deg/yd per ton
Capacitance	Submarine	$0.287\ \mu F/1,000$ yd
Electric stress at the conductor at 15° C		250 kV/cm
Electric stress at the screen, conductor at 60° C		
	screen at 32.5° C	240 kV/cm
Gas pressure nominal at 15° C		425 lb/in^2 nitrogen
Current rating		1,200 A
Losses per cable at full load and temperature		
	Submarine	50.5 kW/1,000 yd
	Land	30.7 kW/1,000 yd

Maximum conductor operating temperature		
	in sea	60° C
	on land	60° C
Maximum sheath temperatures		
	in sea	32.5° C
	on land	45° C
Soil resistivity	on sea bed	30 thermal ohm/cm^3
	on land	120 thermal ohm/cm^3
Average ambient temperature		
	in sea	15° C
	on land	15° C

The Engineer in the Public Arena

JAMES R. KILLIAN[*]

This article was drawn from a Roy V. Wright Lecture delivered to the American Society of Mechanical Engineers. It is reprinted with permission from the Technology Review *of the Massachusetts Institute of Technology.*

IN a recent essay on science and public policy, Christopher Wright has spoken of the "science affairs community". We today witness the growth, slow to be sure, of an "engineering affairs community", the evolution of an engineering subprofession skilled in advising government in local, national, and international contexts.

Despite the growth of this engineering affairs community and its contributions in the public arena, outworn stereotypes of the engineer persist. They need to be cast aside. The quarterly publication of the Engineers' Joint Council recently pointed to one of these steoreotypes in C. P. Snow's novel, *The New Men*. In noting the absence of engineers from a meeting of scientists called to express their grave concern about the awesome danger to mankind of nuclear weapons, Snow says, in the words of a character in the novel: "It struck me that all the top scientists . . . were present but none of the engineers. As an outsider, it had taken me years to understand this rift in technical society . . . The engineers . . . who used existing knowledge to make something go, were in nine cases out of ten, conservatives in politics, acceptant of any regime in which they found themselves, interested in maikng the machine work, indifferent to long-term social guesses.

"Whereas the physicists, whose whole intellectal life was spent in seeking new truths, found it uncongenial to stop seeking when they had a look at society. They were rebellious, questioning, protestant, curious for the future and unable to resist shaping it . . ."

This incident expresses a cliché that dies hard. Even had it ever been true, it is wide of the mark today. It is an out-of-date stereotype to type engineers as not interested in seeking new truth. Engineers are working side by side with scientists in many research programmes, and more and more the education of engineers provides them with the fundamental training and the motivation to enable them to become highly successful innovators. And this kind of intensive creativity encourages independence and nonconformity. Gerard Piel has said it just right: "Engineering as the closest coupling of science to society is too widely celebrated for its utility and not enough for its creativity."

So we need to dump these stereotypes, frequently held by engineers themselves, if the engineer is to be of maximum usefulness in the public domain. Our societies need independent-minded, questioning, concerned engineers as well as scientists with these traits.

New educational programmes that are under way seek to give new dimensions to engineers so that they can perform effectively in the public arena. Not only have there been changes in the undergraduate programme giving greater emphasis to the fundamentals of science and the humanities, and a steady lengthening of engineering education by graduate and postdoctoral study; increasingly, engineers elect to study management and public administration either through electives in undergraduate school or full time at the graduate level. In a number of American universities, new programmes have rerently been started dealing with science and technology and public policy. For the past several years I have had the stimulating experience of occasionally giving a graduate seminar to engineers, scientists, and political scientists on science and technology and public policy. I have become convinced of the importance of a continuing study of the impact of technology on government and on foreign affairs and of a cross-fertilisation between engineering and political science.

Today, students, both undergraduate and graduate, occasionally come to me to inquire how they can enter the service of the Government or contribute to the public service. In general, my inclination is to tell them that they must first establish firmly in their professions, achieving a record in the practice of science and engineering. They are then in a much stronger position to make their talents effectively available in government. At the same time, however, it must be recognised that with the preparation now available in an increasing number of universities in public administration and in political science, increasing numbers of young people find it possible to move immediately into the service of the Government.

There is an impressive interest on the part of students today in public service, especially students in science and engineering. It is another manifestation of the motives and altruism which mark service in the Peace Corps and other groups serving the public welfare.

Let me note five areas of public service where the specialised skills of the engineer are increasingly in demand and where the profession is qualified to make an even larger contribution. I leave out such major but obvious

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