I.O.S.

OPERATIONAL EXPERIENCES WITH WAVERIDER BUOYS AND THEIR MOORINGS

J D HUMPHERY

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NATURAL ENVIRONMENT RESEARCH COUNCIL

INSTITUTE OF OCEANOGRAPHIC SCIENCES

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FIGURE CAPTIONS

1. INTRODUCTION

The first IOS Waverider was deployed at the Eddystone site on 25 June 1973. Since then a total of 10,241 buoy-days on site have been logged up to 31 December 1981. This approximates to 28 buoy-years on site, and during this time, considerable experience has been gained on the performance of the buoys and their moorings. This report sets out to list some of those experiences, and to describe the latest improvements in mooring design.

2. THE INSTALLATIONS

Seven areas of the UK coastline have been instrumented directly by IOS with Waverider buoys. Of these, four areas have been served by more than one installation, usually to compare results obtained at more than one point. Thus a total of 15 sites have been instrumented, of which five were current at 31 December 1981.

Table I lists all the sites which have been instrumented. Other information shows:

Start	- the date of the first deployment
Finish	- the date of the last recovery, or the date that the last buoy at the site went adrift, or the 31 December 1981, ie the site was still operational on that date.
Days possible	- the number of days between the Start and Finish dates.
Days on site	- the number of days that a buoy was actually on site.
$\frac{b}{a}$ x 100%	- gives the ratio of Days on site: days possible as a percentage.
Adrift	- the number of times that a mooring failed and the buoy went adrift on that site.

From the table it may be calculated that 65 deployments have been made at the fifteen sites, yielding 10,241 buoy-days service out of a maximum possible of 11,312. This gives an in-service percentage of 90.53%, and the average duration of each buoy deployment is 157.5 days, ranging between 18 days at the Eddystone in the early days when satisfactory moorings had not been perfected, to 417 days at the South Uist Inshore I site.

Of course, this does not mean that 10,241 days-worth of good data have been achieved. By far the biggest reasons for data loss are malfunction in the receiving station and the data-logging equipment, and heavy radio interference.

It is not within the scope of this report to describe these faults. However valid data-returns of between 80 and 90% of the maximum possible are common for present installations (they have occasionally exceeded 95%), while valid returns of less than 70% are considered poor. A small proportion of lost data is however, directly attributable to Waverider buoy malfunction, and we shall have a closer look at the causes in the next section. (Data loss due to mooring failures will be discussed in the section on moorings.)

3. WAVERIDER BUOY FAULTS

(Note: Most of the faults described in this section have been observed in Waveriders owned by IOS. However, the author has been asked to investigate Waverider malfunctions in equipment owned and operated by commercial companies and other authorities. Some of the faults described have been observed during these consultancies.

Also, it is assumed that the reader is reasonably familiar with the construction of the Waverider buoy, and will recognise the components from the descriptions given.) Figure 1 shows the layout of the buoy.

The faults are described according to the components effected.

a) Aerial faults:

i) Broken transmission aerial: only one case has been observed, when some 45 cm of an old style (hollow) whip aerial was broken during a deployment, presumably by human interference. There was no noticeable effect on the data return (transmission distance 20.4 km).

ii) Annular notch round base of fibreglass: Waverider transmission aerials suffer much whipping motion due to pitch-roll motions of the buoy. If the aerial works loose in its socket, the aerial is constrained mainly by the aerial top-nut, which during a long deployment, can start to cut into the fibreglass just above the brass base. This was particularly so when the top-nuts were of stainless steel: with the current nylon (thicker) top-nuts, the problem is much less common. About four serious cases have been noted.

iii) Fibreglass whip loose in brass aerial-base: the whip aerial should be fully tightened in the aerial socket prior to deployment otherwise the whipping motions mentioned above can fracture the cement used to bond the fibreglass to the brass aerial base. If this happens aerial contact is lost and poor radiation results, and the fibreglass part can even work its way out of the base and be lost completely, (one occurrence recorded). Three occasions have been recorded when the whip became loose in its base, but the fault has been seen perhaps six times.

b) Faults with the aerial spring and top-nut:

i) Overtightening the top-nut can cause the nylon threads to jump if they are worn for any reason. This effect has been noted on one occasion.

ii) Overtightening the top-nut in very cold conditions can cause the top-nut to fracture between the threaded, lower part and the more solid upper part. Excessive force should not be used, and the top-nuts should only be tightened by hand. Three fracture cases have been noted.

iii) Whip aerial base loose in aerial spring sockets: if the whip aerial is not fully tightened in its socket prior to deployment, lateral movement due to aerial whipping can cause severe wear of the brass threads between the two parts, leading to aerial 'slop' and poor electrical connection. If this occurs, the roofhatch top-plate with aerial spring and socket, and the aerial, should be replaced. This fault has occurred on three occasions.

c) Roofhatch faults:

i) Crevice corrosion: this is an effect produced by the action of sea water on stainless steel. At places where the oxygen concentration in sea water becomes depleted (eg in O-ring grooves or between two plates of stainless steel clamped together), the effective electrochemical potential of the metal is raised, and the metal thus becomes subject to corrosion. The effect is also noted particularly at weld-points, where impurities introduced by the welding process cause local electrolytic action, and at stress-points caused by machining (eg around the pins on stainless steel shackles). The corrosion produces deep pits in the metal, which is reduced to a dense, grey friable material, and can ultimately lead to a thin skin of metal enclosing only corrosion products (this is particularly so with stainless steel nuts, and the effect can be catrastrophic and even dangerous). Crevice corrosion is found to be particularly severe when the buoy is operated in waters which are subject to heavy industrial pollution.

In the Waverider roofhatch two areas are mainly at risk: the O-ring grooves taking the seals between the glass and the stainless steel plates of the roofhatch, and the area of the sphere-sealing plate which is in contact with the flange on the buoy hull. Whenever the glass is removed from a roofhatch at IOS, the O-ring grooves are filled with Vaseline petroleum jelly prior to re-assembly, and the roofhatch O-ring groove and the sealing faces are liberally smeared with Vaseline when the buoy is energised and sealed prior to deployment. This excludes water from the critical areas and reduces the effects of crevice corrosion.

Crevice corrosion leading to condensation forming inside the glass of roofhatches has been detected on three occasions. In severe cases, the major metal parts have to be replaced.

ii) Bent aerial spring and/or top plate: Waveriders which are recovered in rough conditions can suffer bent aerial-springs if the buoy is knocked hard against the hull of the recovery boat by wave action. The springs can also be bent if the buoy goes adrift and comes ashore on rocks. About four occurrences have been noted.

The top plate can also be bent by the buoy bumping severely on the rocks (one occurrence at IOS) or if the buoy is dropped accidently off a lorry(!) (one occurrence). Where the spring or top plate is bent seriously, the whole top-plate assembly must be replaced.

iii) Flashing light failure: One occurrence has been noted of flash light failure due to a short-circuit in the HF auto-transformer (T4), mounted on the flash tube assembly within the roofhatch glass. The whole assembly was replaced. It should be noted that flash light performance has been much degraded by the incorporation of a yellow filter (as stipulated by IMCO for "special marks").

d) Faults with the top pcb:

i) Corrosion due to sea water leakage: Only one occurrence has been noted, and can be attributed directly to an assembly error. The roofhatch glass and roofhatch support columns had been removed to check on condensation. When the roofhatch was reassembled the nuts and sealing washers under the top pcb were not tightened sufficiently, and leaked during the next deployment. Small amounts of salt water produced considerable corrosion of the printed circuit, leading eventually to transmitter failure. The buoy was recovered, one sealing washer and the top pcb were replaced, and the nuts were re-tightened. The batteries, which had been flattened by a salt water short circuit, had to be renewed. No other damage was caused, and the buoy has been re-used.

ii) Transmissions on wrong frequency: caused by operator error - the wrong crystals were fitted prior to deployment. Two occurrences have been noted.

iii) Transmitter output power variations during deployment. Five occurrences have been noted. One was due to insufficient length of a brass sleeve fitted over the roofhatch dome support rod. The sleeve presses against the component surface of the top pcb, giving an earthing contact underneath the circuit board. In the case noted, the transmitter earth only made contact intermittently, giving large variations in output power. Datawell have since modified the sleeve disign to reduce the possibility of this fault.

Of the other four cases (transmissions stopped entirely in one case) nothing is known of the causes (ie no reason could be found on buoy recovery). However in all cases the buoys were either operating in high current locations and were possibly being pulled under, or they were found to be off-station at recovery (ie the anchors had dragged, possibly due to fishing activity). It should be noted that the bases of the aerials are insulated with silicone grease prior to deployment, and that a sea-water short circuit is unlikely.

e) Battery faults: No serious battery fault has occurred in the IOS experience. One set became completely exhausted during deployment, but the buoy had simply been left on site too long, and the batteries were not new when the buoy had been installed anyway. Except on one occasion, IOS has always used the cells recommended by Datawell, ie Leclanche cells made at Yverdon, Switzerland. They have never been known to distort or leak in use. Battery life is given as greater than nine months by Datawell in their publicity sheets, but on at least three occasions, IOS has operated Waveriders continuously for periods of between 12 and 14 months with no detectable reduction in data quality.

f) Accelerometer faults: (Figure 2 shows a diagrammatic representation of the accelerometer assembly). The accelerometer is at once the heart and the Achilles' heel of the Waverider system. It is a passive instrument of considerable sensitivity which draws very little current, but is damaged very easily by spinning about a vertical axis. The accelerometer is decoupled from horizontal accelerations by mounting it on a plate in a fluid-filled sphere, in such a way that the whole becomes a long-period pendulum. This requires a very light suspension which in practice has very little torsional rigidity about the vertical axis. Spinning the buoy produces twists, kinks, or even loops in the suspension, which hold the accelerometer platform away from the horizontal, and thus the sensor becomes sensitive to horizontal accelerations which contaminate the wave records with a long period mean-line variation.

i) Mean line variation due to twisted suspensions: Five cases have been encountered at IOS, and three commercial companies have sent buoys to IOS for correction of this type of fault. Correction to an acceptable standard has been possible in four cases altogether. Correction involves clearing the buoy to accelerometer level and gaining access to the inner accelerometer sphere by removing the small sealing cap. A piece of wire, suitably bent and sterilized, is lowered into the inner sphere and through one of the holes in the accelerometer platform. If the wire is bent so that it does not fall completely into the inner sphere, and so that it can pass under the vertical gimbal ring, then spinning the inner sphere in the correct sense about the support tube will untwist the suspension. Obviously the sense of the original twists must be determined beforehand; this is difficult from outside the outer sphere. The suspension wires are very fine and can barely be seen using a mirror and inspection lamp. (Remember also that a mirror produces an inverted image!) IOS uses an endoscope and a bench light source coupled by a flexible light guide. This instrument is expensive, but pays for itself even if only one buoy is saved. (Broken accelerometers cannot be replaced.)

The accelerometer and its platform are very nearly neutrally buoyant in the accelerometer fluid (which is mainly a mixture of glycerine and water.) If the suspension is twisted many times the platform can lift since its effective weight is very small. In this case a kink or loop can form in the suspension wires, and this can be very difficult to remove.

In all cases when suspensions are untwisted, the accelerometer platform must end up horizontal so that the sensor experiences only vertical accelerations (otherwise mean line variation will contaminate the wave records.) It is necessary to perform a tilt test (see the Waverider handbook) to determine platform horizontality after untwisting a suspension. At IOS, a Waverider is also calibrated after this operation.

ii) Mean line variation due to broken gimbals: The inner accelerometer sphere is maintained in position with respect to the outer sphere by two gimbals. On one occasion, one of the pins joining the two gimbals together dropped out, allowing the inner sphere to drop. It was thus not stabilized, allowing buoy motions to produce turbulence inside the inner sphere, which produced mean line variation on the wave records. No repair was possible.

iii) Unusual wave shapes being recorded: On two recorded occasions Warep chart records displayed unusual wave-shapes (square topped waves.) Accelerometer checks on the relevant buoys revealed no obvious fault. On the second occasion, simultaneous chart and digital data logger records were taken however, and the digital records were completely normal. A check on the chart recorders showed that the pen-arms had been bent when inserting new labyrinth pens and that friction was limiting pen-movement. Normal operation was restored by carefully bending the pen-arms straight again.

iv) Ageing: IOS experience shows that buoys are subject to a definite ageing process. Buoys are more prone to mean line variation as they get older and this appears to be only partly due to the cumulative effects of buoy-spinning. Datawell have introduced two modifications which have improved old buoy performance, viz a stabilizing chain is now fitted directly below the buoy which reduces pitch-roll motions and therefore any work-hardening effects on the platform suspension wires, and very thin insulation is now used on the suspension itself making it much more flexible. The accelerometer platform is thus able to remain more stable, extending effective buoy life.

v) Transmission normal, but no wave record produced: Only one example has been noted. A new 90 cm buoy started producing increasingly wild mean line variations after only 10 days in the water. Eventually, no frequency modulation of the 259 Hz tone was produced at all, producing locked, straightline records. Tests were performed in the laboratory and the accelerometer current was found to be very high. The buoy was returned to Datawell who removed the accelerometer, and found that a short circuit had developed within the accelerometer. (The equatorial fender was missing at recovery, so possibly the buoy had been in collision with a boat.) The buoy was thus written off after providing only 10 days data.

g) Mean line displacement:- One case has been recorded of the mean modulation frequency changing during buoy operation, resulting in a mean line considerably displaced to one side of the chart. Small padding capacitors in the voltage to frequency converter circuit were changed to bring the mean frequency back to 259 Hz, and no further trouble was experienced. Note that the design of the modulator pcb has been changed, and it might not now suffer from this fault.

h) The Hull: The hull has to protect the working parts against all the abuse experienced by the buoy both in normal use and sometimes in abnormal circumstances. Further, it must maintain its watertight integrity for long periods in a corrosive medium. It is constructed of 316 stainless steel which is strong but heavy, and is subject to corrosion in some circumstances. To reduce the wetted area to a minimum, IOS Waveriders are painted with zinc phosphate epoxy priming paint, which adheres to the clean hull particularly well. Few corrosion problems have been encountered since its use was introduced in about 1975.

i) Dents, scratches, etc. Serious dents and scratches are usually only found in buoys which have come ashore on rocks after breaking adrift from their moorings. Dents do not usually impair the working of the buoy and serious scratches can be touched up, or the complete buoy can be repainted. Five serious cases have been recorded at IOS.

ii) Missing fenders: These are usually a sign of interference by boats during deployment. About four cases have been noted; on one occasion the fender was found to have dropped below the buoy and been held by the mooring.

iii) Crevice corrosion: This was described earlier, and attacks Waverider hulls particularly when they are not painted at all, or when painted with a brittle, flaky paint. In the latter case particularly, scallop-shaped corrosion pits radiating outward from paint scratches can be found working under the paint. The epoxy paint mentioned above is slightly flexible and reduces this effect to a minumum.

Another prime site for crevice corrosion on unprotected hulls is at the edges of the rubber equatorial fender, where deep corrosion pits (even to the point of hull penetration) can form (one consultancy case noted). Fenders are removed prior to painting IOS buoys.

Weld points are also particularly susceptible, especially round the mooring eye at the bottom, and round the lifting handles. Careful painting is essential in these areas.

A deep local corrosion pit, probably caused at the site of a high concentration of impurity, was detected on one unpainted IOS buoy. Although over 1 mm deep, further corrosion in the hole was arrested completely when the buoy was painted for the first time.

Corrosion did produce a hole which penetrated the hull completely near the mooring loop of one IOS buoy. Corrosion probably started at the site of a undetected flaw in the paintwork. Attempts to weld up the hole were unsuccessful; the heat of welding distorted the perspex of the accelerometer sphere, impeding the free movement of the gimbals. The buoy was scrapped.

In areas where corrosion is a particular problem eg where the water is warm and contains industrial effluent, Waveriders with cupro-nickel hulls can be deployed. This option can be supplied by Datawell, but IOS has no experience of these buoys.

iv) Accident: On one occasion, an IOS buoy was accidentally dropped from a lorry and suffered considerable superficial damage. However a check calibration after replacement of the roofhatch glass and aerial spring showed the buoy to be free of major defect.

v) Mooring loop wear: Until the present design of mooring loop was adopted by Datawell, wear of the mooring loop induced by considerable mooring tension when operating in high tidal-current areas was a problem. Bushes made of hard nylon were used by IOS to reduce the effects of wear; these have been made obsolete by the latest mooring loop design.

4. WAVERIDER MOORINGS NOW USED BY IOS

The first IOS Waverider was deployed at the Eddystone Rocks in June 1973. The buoy was recovered for checking after four months service, and immediately re-deployed. During the next five months, the buoy went adrift three times for different reasons; it was considered that the mooring system suggested by Datawell was inappropriate to the Eddystone site. Accordingly, a sub-surface float

(SSF) mooring system was devised and installed; a dramatic improvement in mooring performance was thenceforth achieved. The early history of the Eddystone site, and the development of the SSF mooring system is described elsewhere (Humphery, 1975).

The SSF system devised for the Eddystone was modified slightly for use at the Offshore site, S Uist, Outer Hebrides. The first buoy and mooring were installed early in 1976.

The main mooring components were (starting at the bottom):

- 1 tonne chain anchor clump;
- chain strop to bind the anchor clump together;
- riser chain to restrain the sub-surface float;
- sub-surface float (with swivel at the top);
- nylon covered steel wire (NS wire) strop;
- rubbercord (15 m);
- stabilizing chain;
- Waverider buoy.

After 18 months' continuous service at the S Uist site, there were three successive failures of the moorings over a period of one year. In each case the NS strop was found to have failed. A modification was introduced which replaced the NS strop with a buoyed polypropylene rope strop, and at the same time the swivel on the SSF was replaced with a fixed eye (which simplified construction considerably).

Other mooring configurations have been developed for specific sites. A heavy rope mooring (basically similar to the Datawell standard system) has been developed for the S Uist Deepwater site (100 m depth). A "buoyant chain" mooring has been used successfully at the three inshore sites off S Uist, and uses galvanised chain which is buoyed by trawlfloats as the major mooring element.

There are thus four main types of mooring used for Waveriders by IOS. Before describing them in detail, it is probably worth restating the major design considerations of a mooring used for a wave-following buoy:

1) The mooring must keep the buoy in one position for a period approaching or exceeding the operational life of the buoy (say one year).

2) The mooring must be compliant, and have sufficient accumulation to allow the buoy to follow the water surface accurately under all conditions of tidal flow, and tidal and wave height. This second consideration is usually achieved by giving the mooring considerable length and by using a compliant component (the rubbercord).

3) The mooring system used should be chosen with the bottom nature of the site taken into consideration, ie rope moorings should not be used on rocky bottoms etc.

4.1 The standard mooring (see Fig 3)

This is a slightly modified version of the mooring recommended by Datawell and is only used where the bottom is of sand or mud, and environmental conditions are not too severe.

Starting at the bottom, the mooring comprises:

- 30 kg Meon (digger) anchor
- 10 m of 20-25 mm chain
- 10 m of 9 or 10 mm galvanised long-link chain
- 12 mm braided polypropylene rope, of length equal to twice the water depth at high tide, minus 15 m. (In very shallow waters, this rope is always kept longer than the maximum water depth, to ease recovery.) The ends are fitted with hardeye thimbles, and the lower end is buoyed with one or two 275 mm diameter central-hole trawlfloats. Datawell p-rope terminations have not been used for some years (they make winch recovery difficult).
- 15 m rubbercord (supplied by Datawell), fitted with hard nylon bushes in the terminations to reduce abrasion effects and electrolytic action. The lower end is fitted with one 200 mm or two 125 mm trawlfloats.
- stabilizing chain (supplied by Datawell).

The Waverider, stabilizing chain and rubbercord are all shackled with 12.5 mm stainless steel shackles which are either moused (ie the pins are secured) with nylon twine after being tightened, or the pins are secured with a nut and stainless split-pin. All other mooring components are joined by galvanised shackles of 11 mm pin diameter or larger. Galvanised shackles are greased with graphite grease, and moused with galvanised wire after being tightened fully.

4.2 The heavy standard mooring

This mooring only differs from the standard mooring in detail. The anchor and heavy chain are the same but the intermediate chain is uprated to 12.5 mm. The polypropylene rope is uprated to 8-plait 16 mm multiplait rope with spliced eyes at the ends; galvanised hard eyes are whipped in place and the bights are protected by heat shrink sleeving placed over the rope prior to splicing, but shrunk afterwards. The lower end is supported by two 275 mm central hole trawl floats, set onto a separate short length and held in place by a barrel stopper knot which is sewn together with twine. The splices used are square splices, the ends of which are whipped in place (see Fig 4).

All galvanised shackles have a 16 mm minimum pin diameter. The mooring is used where the bottom conditions are reasonably sympathetic, but where environmental conditions are extreme. It has been used with success at the S Uist Deepwater site, where the first Waverider to be deployed gave 12 months unattended service. A similar mooring is to be used on a site some 26 km west of St Mary's, Isles of Scilly.

4.3 The sub-surface float mooring (see Fig 5)

This mooring was originally developed in response to poor mooring performance with the standard mooring at the Eddystone site, but has been modified in detail since the original was first installed.

The mooring now comprises:

- anchor clump, ½-1 tonne of 2 m lengths approximately of heavy chain
- anchor strop - a three metre length approximately 12.5 mm long link galvanised chain, used to hold the anchor clump together. It may be protected by a sacrificial anode, (see Fig 6). Note: the second D-shackle on the strop attaches a 13 mm wire lowering - cable to the chain strop; the clump is lowered to the bottom, and the cable is cut when there is no danger of the cut end fouling the SSF or upper part of the mooring.
- riser chain - of 9.5 mm galvanised long link chain. The length is cut so that the sub-surface float is 10-20 m below the surface after installation, depending on the wave heights and tidal ranges anticipated at that site. Note: if the water depth is so great that the weight of chain gives the sub-surface float insufficient buoyancy reserve, the chain could be replaced by a suitably protected and terminated wire; IOS has no operational experience of

this method, however.

- Sub-surface float - a steel sphere 865 mm in diameter, with a lug at the bottom and an eye at the top. Fabricated from 8 mm steel, it is pressure tested for leaks prior to acceptance, and an oval sacrificial anode is welded, point down, on the lower hemisphere. It is painted with Waxoyl to prevent corrosion during storage only. See Fig 7.
- Rope strop - a 16 mm multiplait polypropylene rope strop 10-20 m long depending on the depth of the SSF. Galvanised thimbles are whipped and square-spliced into the ends, and a 275 mm central hole trawl float is con-trained by a barrel stopper knot some 2 m above the SSF. (This reduces the chance of chafe between the rope and SSF.) See Fig 8. Note that the rope bight round the thimble is now protected by sleeving shrunk around it after splicing.
- Rubbercord - the standard 15 m rubbercord supplied by Datawell. It is fitted with two 125 or 200 mm trawlfloats depending on whether neutral or positive buoyancy is required (there should be no chance of the rope strop being pulled to a depth where it can foul the SSF). The rubbercord end fittings are fitted with hard nylon bushes, (see Fig 4), to reduce abrasion effects and electrolytic action.
- Stabilizing chain - as supplied by Datawell (see Fig 9). The Waverider, stabilizing chain and rubbercord are shackled together with 12.5 mm stainless steel shackles (which are <u>not</u> greased, and are moused with nylon twine); all other components are shackled with 16 mm minimum galvanised shackles, which are greased and moused with wire.

The SSF is an expensive mooring; once deployed it cannot be recovered easily. Until early 1981, IOS recovered only as far down as the SSF: a diver would cut through the riser chain with a hacksaw. A heavy recovery grapnel has now been developed, (see Fig 10); it is deployed on a 13 mm wire (10 tonne breaking strain) which is usually shackled onto a trawl-warp. The grapnel has to catch the riser chain between the anchor clump and SSF if mooring recovery is to succeed safely. The grapnel is usually lowered to the bottom and the ship steams round the mooring paying out cable. Cable is then hauled from one side, dragging the grapnel past the riser chain. Two Hebrides moorings have been recovered in this way; however an attempt at a similar recovery at the Eddystone failed when the grapnel became fast on the bottom, and the cable had to be cut. In all cases, the Waverider is removed first and the mooring marked with a large surface marker buoy.

4.4 The buoyant chain mooring

During 1979 a requirement was stated for a Waverider to be deployed in about 15 m water to the west of S Uist. Bottom nature was likely to be sand-filled rocky gullies with the possibility of the odd pinnacle.

This is a very difficult water depth in which to moor a Waverider as the lower end of the rubbercord can bounce on the bottom at low tides or in big waves. It is also not deep enough for a SSF mooring - wave action could move the SSF through large arcs, and the mooring could be subject to large breaking waves. No rope mooring could reasonably be expected to last given the site conditions.

Accordingly, a mooring was devised to work in these conditions, and despite early forebodings, it has performed reasonably well. Both the top and the bottom are similar to the standard mooring; however the light anchor chain and polypropylene rope are replaced by a 50 m length of 12.5 mm long-link galvanised chain. About half the chain is always on the bottom and hence there is no chance of the anchor dragging. (The anchor itself is a 50 kg fisherman's type.) The Waverider has insufficient buoyancy reserve to carry this amount of chain; the upper end is buoyed with approximately 30-200 mm trawl floats linked to the chain as shown in Fig 11. This is sufficient to lift the chain to the surface. The floats should be at close intervals, just sufficient to ensure that they do not hit together when deployed; on the first of these moorings, the chain hung in a series of bights between buoys and the whole of the buoyed length tangled into a single mass during the deployment period. The mooring did not fail, but it was very difficult to recover. The buoyed chain is simply shackled to the lower end of the rubbercord with a 16 mm galvanised shackle.

Although the Inshore site at the Hebrides has been moved into 25 m of water, this mooring configuration has been retained.

5. MOORING FAILURES

An analysis of mooring failures and component faults has been made and is summarised as follows:

a) Rubbercord

- Pulling out of end-fittings: This is known to have happened on four occasions, and all occurred either during deployment or retrieval. Stretching the rubbercord reduces its diameter and it becomes loose in its securing wedges. Failures occurred when:

i) A buoy was towed by its mooring from a powerful military craft after accidentally breaking adrift from the ship's side.

ii) Buoys were being exchanged on an existing mooring with the anchor still on the bottom. The rubbercord was secured to the ship by a rope tied to its end fitting; the ship drifted off station in the strong tide. A crewman who was helping to change the buoy suffered injury to his hand when the rubbercord pulled out of the top end-fitting.

iii) A buoy had been lifted out of the water during recovery, while the anchor was still on the bottom. The ship drifted off station and the rubbercord pulled out of its end fitting, allowing the buoy to swing as a pendulum. It struck a crewman and threw him forward violently, causing serious injury.

iv) A transmitter aerial had failed during deployment and was replaced while the buoy was lifted from the water with the anchor still on the bottom. Although the buoy pulled back strongly when released due to contraction of the rubbercord, it washed up on the beach two days later; the lower end fitting had failed. The mooring, (a "buoyant chain" type) was later recovered using Decca Navigator information recorded at the time of deployment.

It should be noted that the energy release consequent upon the failure of an end-fitting under extreme tension is quite sufficient to cause severe injury and even death. Extreme care should be exercised if this situation can possibly arise; it is preferable, if possible, to recover the Waverider and rubbercord using a small boat, marking the mooring with a large float for recovery later by the mother ship.

- Damaged rubber. Rubbercords buoyed close to the surface can suffer damage due to boats passing over them, in which case the propellor frequently causes a series of cuts along the length of the rubber. The rubbercord is always replaced if damaged in this way; failure of the rubbercord when under tension is progressive and rapid from any cut. Three cases have been noted.
- Crevice corrosion. Usually occurs on the surface of the stainless steel bobbin forming part of the rubbercord terminal, underneath the rubber. Severe pitting can be caused, leading to abrasion of the rubber. Deep pitting can also occur at weld-points. About 10 or 12 end-fittings have been replaced due to corrosion problems.

b) Polypropylene Rope (standard mooring only)
Failures have been caused as follows:

i) One failure was almost certainly due to a fish or squid bite. Close to the bottom (below human interference), two very limited areas of chafe, separated by some 25 cm, were caused, the lower one severing the rope completely.

ii) Two failures were caused by chafe on the bottom.

iii) One failure was caused by human interference, ie the rope was cut deliberately, probably in the hope of financial reward.

iv) The rope parted on recovery on one occasion.

c) Anchor and mooring chain (standard moorings only)
i) Fouled anchors. Three cases have been recorded of the anchor chain fouling the anchor. In one case where a Meon anchor was used, fouling was so bad that the anchor was prevented from digging into the soft bottom and the mooring dragged 1.5 km in a month.

ii) Corrosion of ground tackle. Different grades of steel are used for anchors and chains, and sometimes for different chain sizes. This can lead to electolytic action and hence corrosion. Two serious cases have been recorded; one led to mooring failure and the buoy went adrift.

d) Nylon-covered steel wire strop (used in early SSF moorings only)
i) Three failures were recorded which resulted in buoys going adrift. In one, the bulldog grip termination failed, allowing the end to pull free. In the other cases, mooring entanglement resulted in chafe and consequent corrosion and abrasion.

ii) In one case, the nylon-steel strop was tangled round the riser chain, but the mooring was serviced before failure occurred, (ie all mooring components above the SSF were replaced by divers).

e) 16 mm polypropylene rope strop (SSF moorings only)
These have replaced the nylon covered steel wire strop mentioned above.
No Waverider has yet been lost during deployment due to failure of this component. However, two have failed during recovery while supporting the weight of the anchor clump, before heavy grapnels were used in recovery.

f) Sub-surface floats

No mooring failure due to SSF malfunction has been noted. However, when they were fitted with swivels, they had sacrificial anodes screwed to them, and these could be lost due to unscrewing; (2 occurrences noted). Anodes are now welded to the lower hemisphere.

The SSF's used to be painted with zinc phosphate epoxy for protection both before and after deployment. It was noted that the paint was always severely blistered on buoy recovery, but that the metal was still bright underneath. Both effects have been attributed to the action of the sacrificial anodes; hence the buoys are now treated only with Waxoyl, purely for storage protection.

g) Riser chain and anchor strop (SSF moorings only)

Two mooring failures have been noted which were due to corrosion either of the lower end of the riser chain or of the chain strop round the anchor. In one other case, failure was only prevented by mooring replacement after advanced corrosion was detected by divers.

Chain protection can be achieved by fitting sacrificial anodes; there is however the difficulty of clamping the anodes tightly to the chain.

h) Shackles

These are used for joining all major mooring components together. Galvanised shackles are greased with a heavy graphited grease, fully tightened with an adjustable spanner and moused with galvanised wire prior to deployment. Stainless steel shackles are never greased (crevice corrosion effects can be exacerbated by grease) and are moused with nylon twine; galvanised wire would introduce electrolytic action.

Only one mooring loss has been attributed to shackle failure.

i) Crevice corrosion in stainless steel shackles

No mooring failure is attributed to this cause. However, serious cases have been noted, particularly in areas which are subject to industrial pollution and high sediment load, eg the Dunwich and Sizewell Banks. No serious case has been reported from the Hebrides.

j) Human error

Two cases of early mooring failure are attributed to assembly errors; the buoy went adrift after only a few minutes deployment. It was recovered and redeployed.

k) Causes unknown

Five moorings have failed due to unknown causes.

ACKNOWLEDGEMENTS

The Waverider programme at IOS has enjoyed considerable success. Thanks are due to the Design Section at IOS Wormley for their considerable help and support in the programme and to engineers in the Instrument Engineering Group at IOS Taunton for help in instrument preparation and deployment, and in particular to Mr B M Norman who will be taking the Waverider programme over from me from now on.

REFERENCES

HUMPHERY, J D, 1975. Waverider Moorings and their modification at IOS. Pp 42-46 in Technology of buoy mooring systems. London: Society for Underwater Technology, 111 pp.

TABLE I

SITE	START	FINISH*	DAYS POSS. a	DAYS ON SITE b	$\frac{b}{a} \times 100\%$	DEPLOY-MENTS	ADRIFT	COMMENTS
S Uist O/S	28.02.76	31.12.81	2133	1982	92.92	12	3	SSF mooring
S Uist I/S I	25.06.78	16.08.79	417	417	100	1	0	Buoyant chain
S Uist I/S II	16.08.79	20.01.81	666	469	70.42	3	2	Buoyant chain
S Uist I/S III	01.03.81	31.12.81	305	305	100	2	0	Buoyant chain
S Uist D/W	10.08.80	31.12.81	508	508	100	2	0	Heavy standard mooring
Start Bay I	23.01.74	05.08.74	192	192	100	2	0	Standard mooring
Start Bay II	25.09.75	26.03.76	177	177	100	2	1	Standard mooring
Start Bay III	06.02.77	13.11.80	1376	1218	88.52	7	2	Standard mooring
Scarweather	21.06.74	12.05.78	1417	1332	94.00	8	2	1 buoy lost Run down? Standard mooring
Prawle Pt	28.04.75	10.07.75	73	73	100	1	0	SSF mooring
Size/Dun O/S	21.07.77	24.5.79	672	613	91.22	4	1	Standard mooring
Size/Dun I/S	26.10.78	25.05.79	211	211	100	1	0	Standard mooring
CLV	19.10.80	12.11.80	24	24	100	1	0	Standard mooring
Eddystone	25.06.73	31.12.81	3111	2690	86.47	18	5	Adrift 3 times Nov 73-Mar 74 Development site. Initially standard mooring. After 24.10.74 SSF mooring.
Eddystone D/W	01.12.81	31.12.81	30 TOTAL 11312	30 TOTAL 10241	100 AVERAGE 90.53	1 TOTAL 65	0	Standard mooring

* 31.12.81 = existing installation.

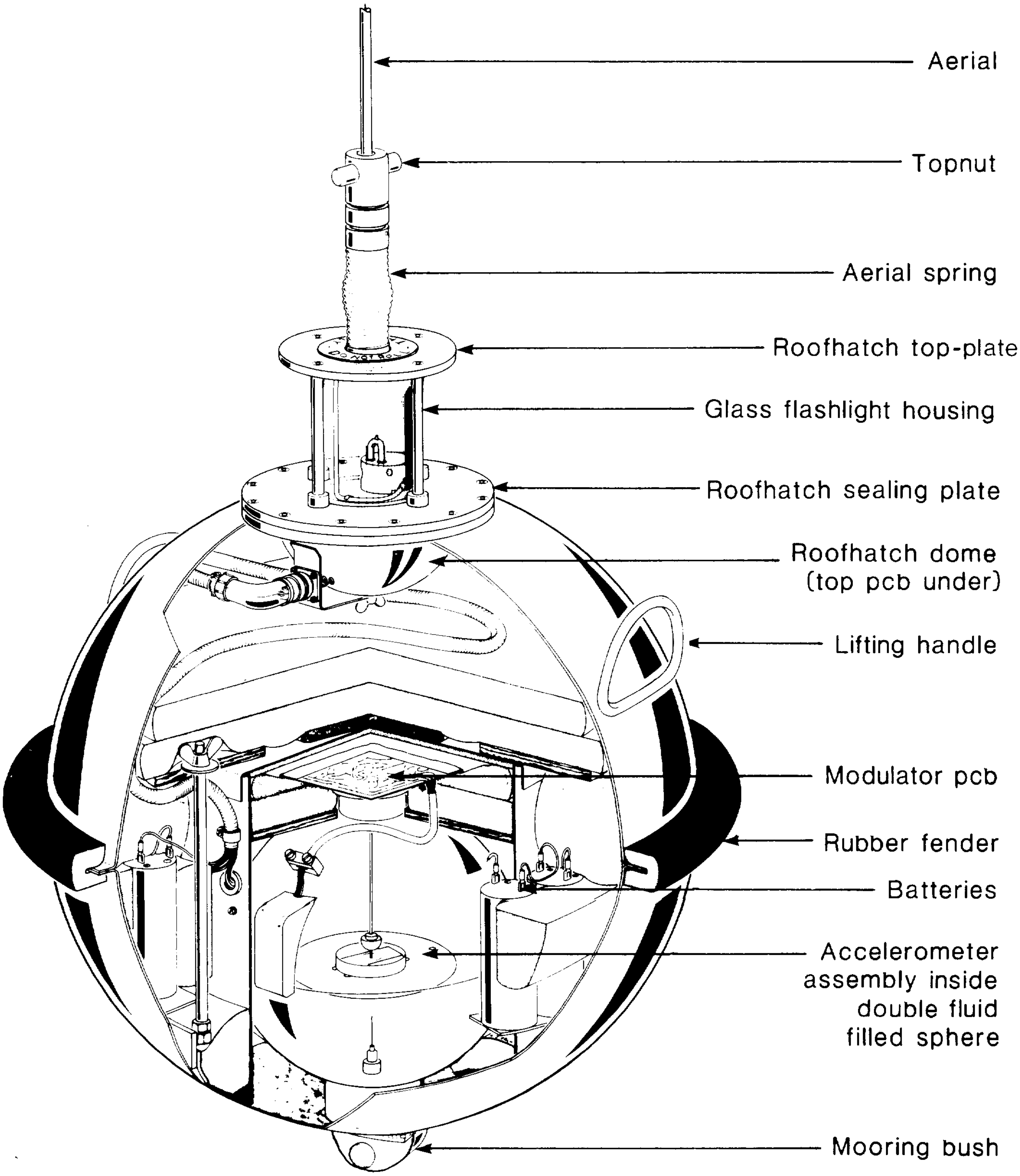

Fig 1 Waverider buoy.

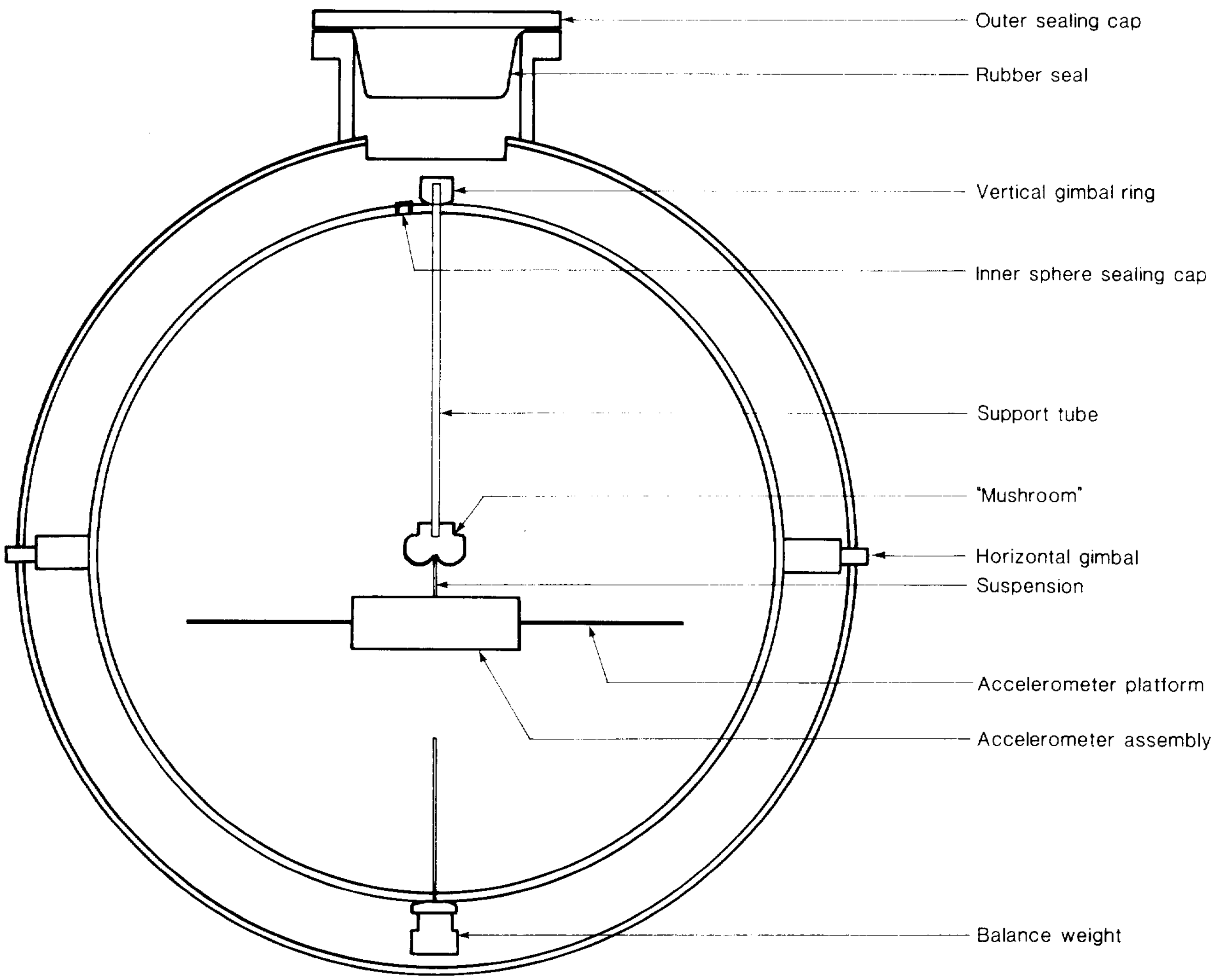

Fig 2 Diagram of Waverider accelerometer assembly.

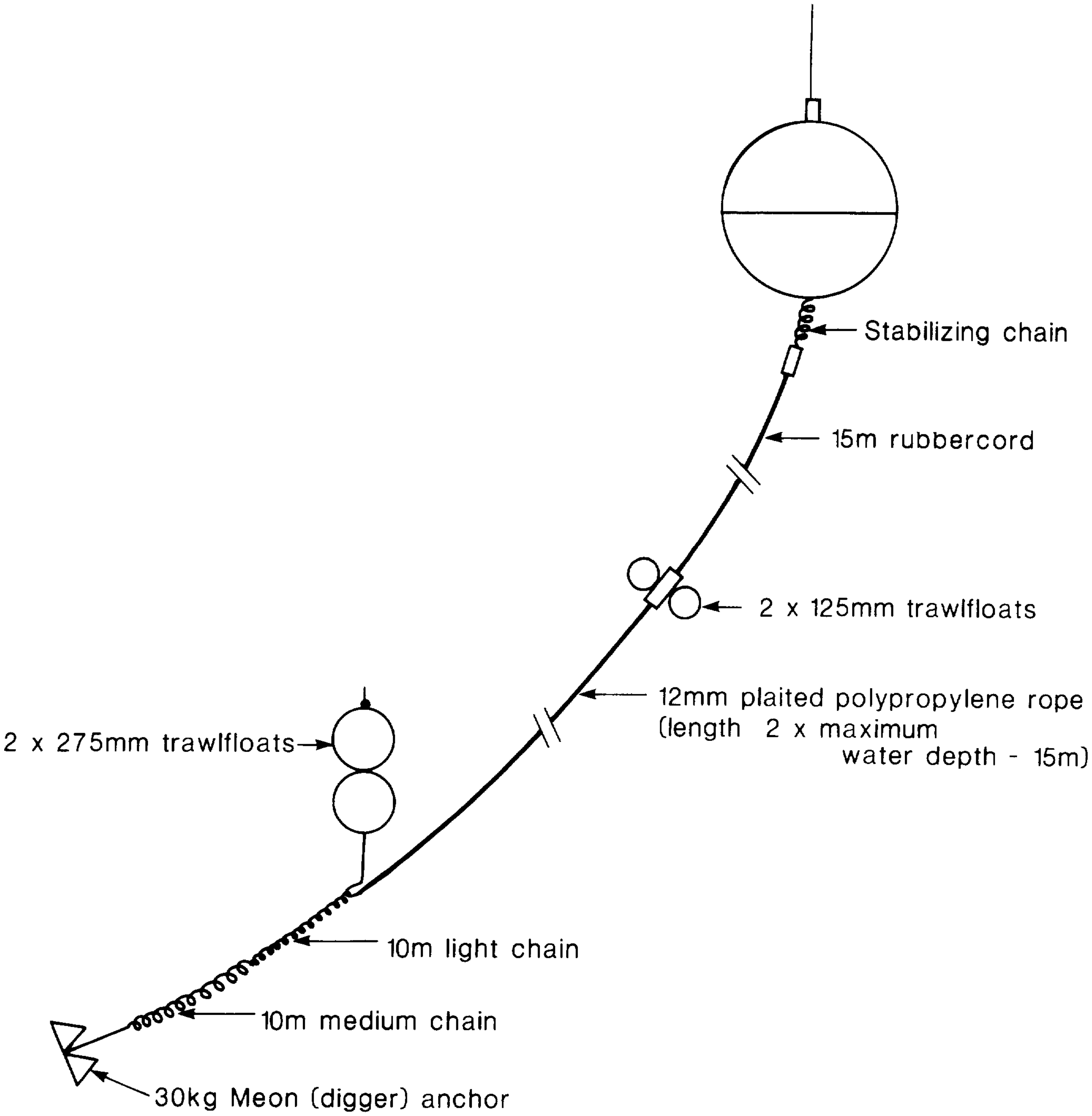

Fig 3 The "Standard" Waverider mooring.

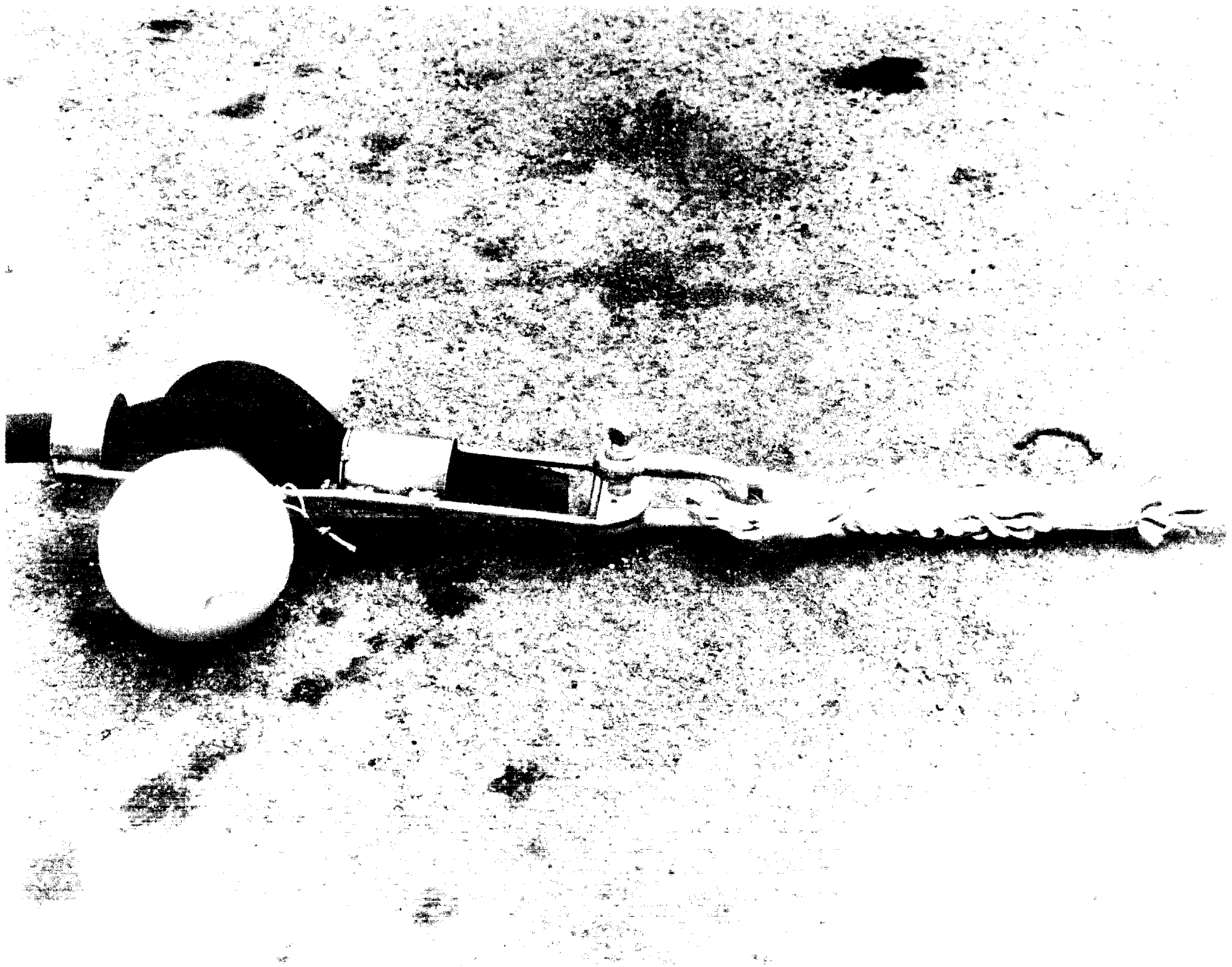

Fig 4 Lower Rubbercord Termination with trawlfloats and hard nylon bush, and 16 mm multiplait polypropylene rope with square splice.

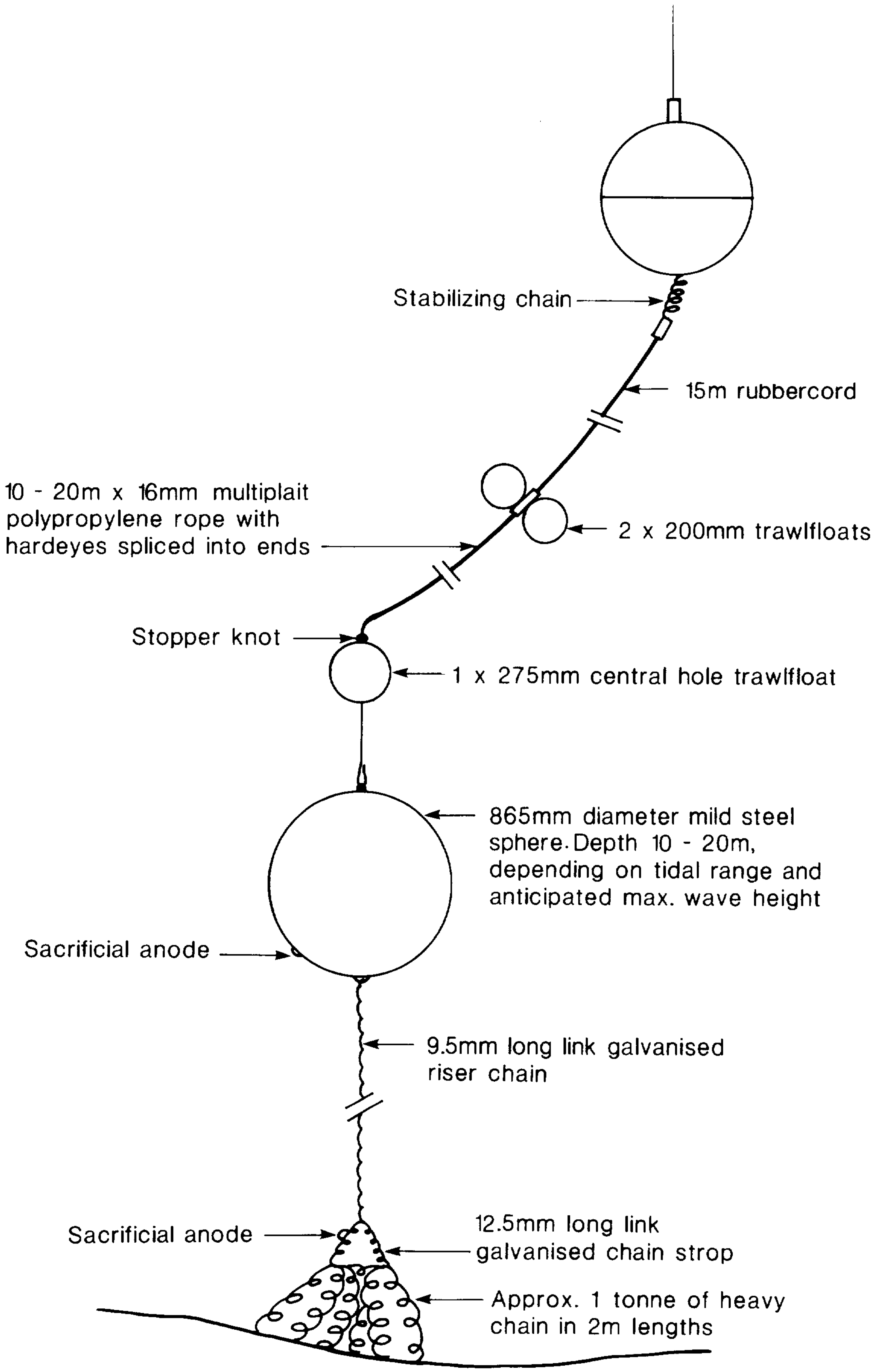

Fig 5 The sub-surface float mooring.

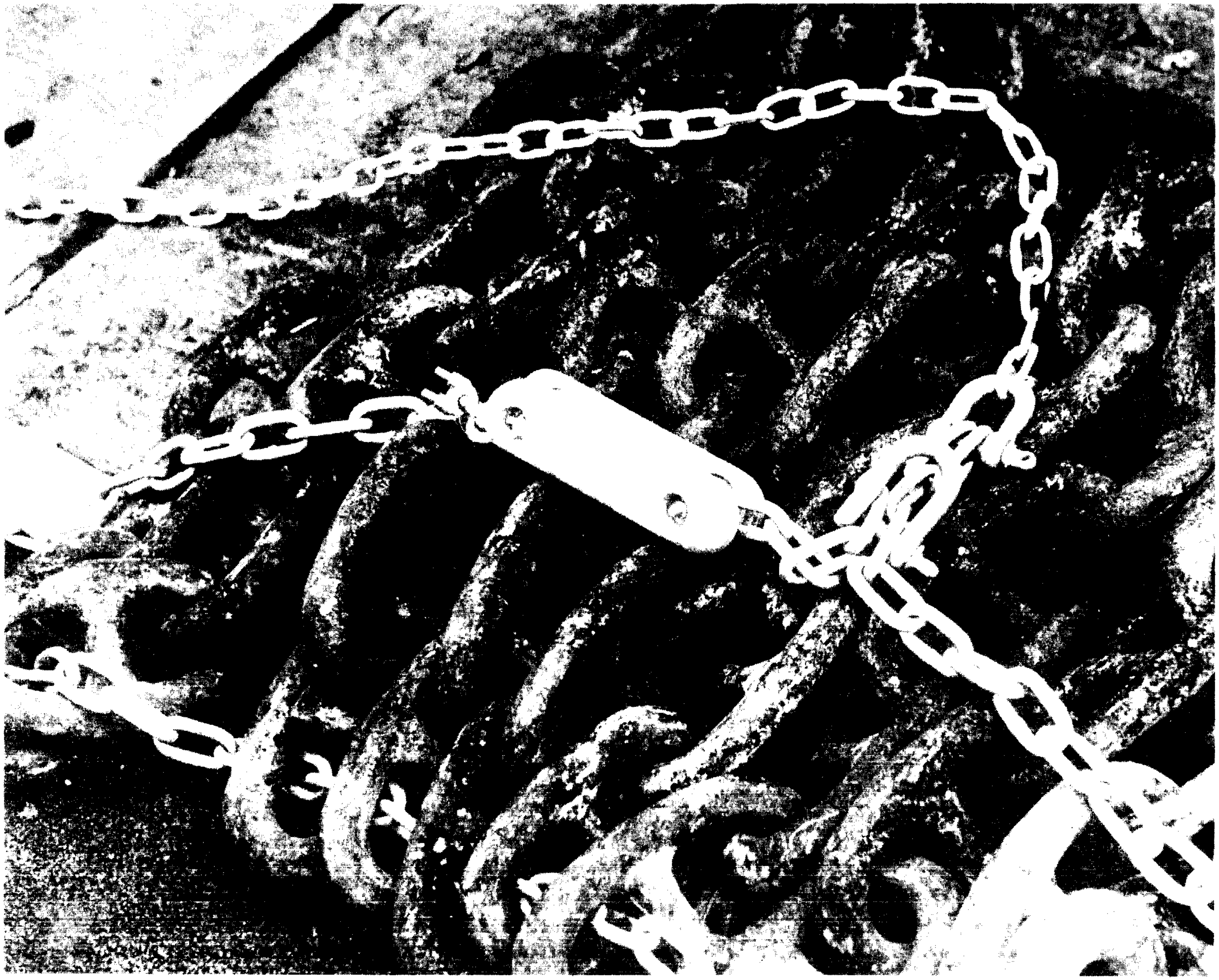

Fig 6 1 tonne anchor clump with 12.5 mm chain strop and sacrificial anode, riser chain and shackles.

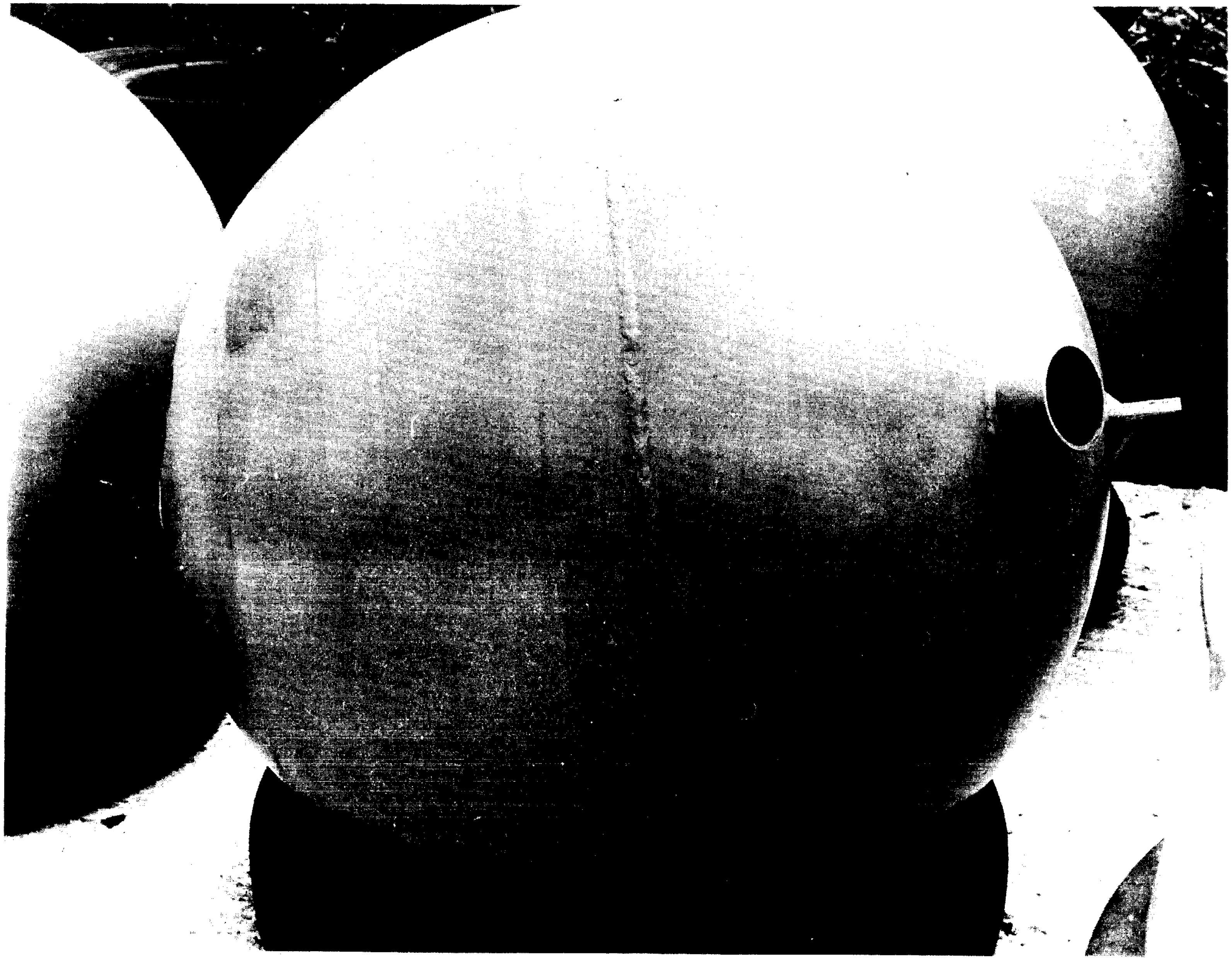

Fig 7 Sub-surface float. (Note: Top eye has not yet been welded flush with upper surface, and oval sacrificial anode has not yet been welded to the lower hemisphere.)

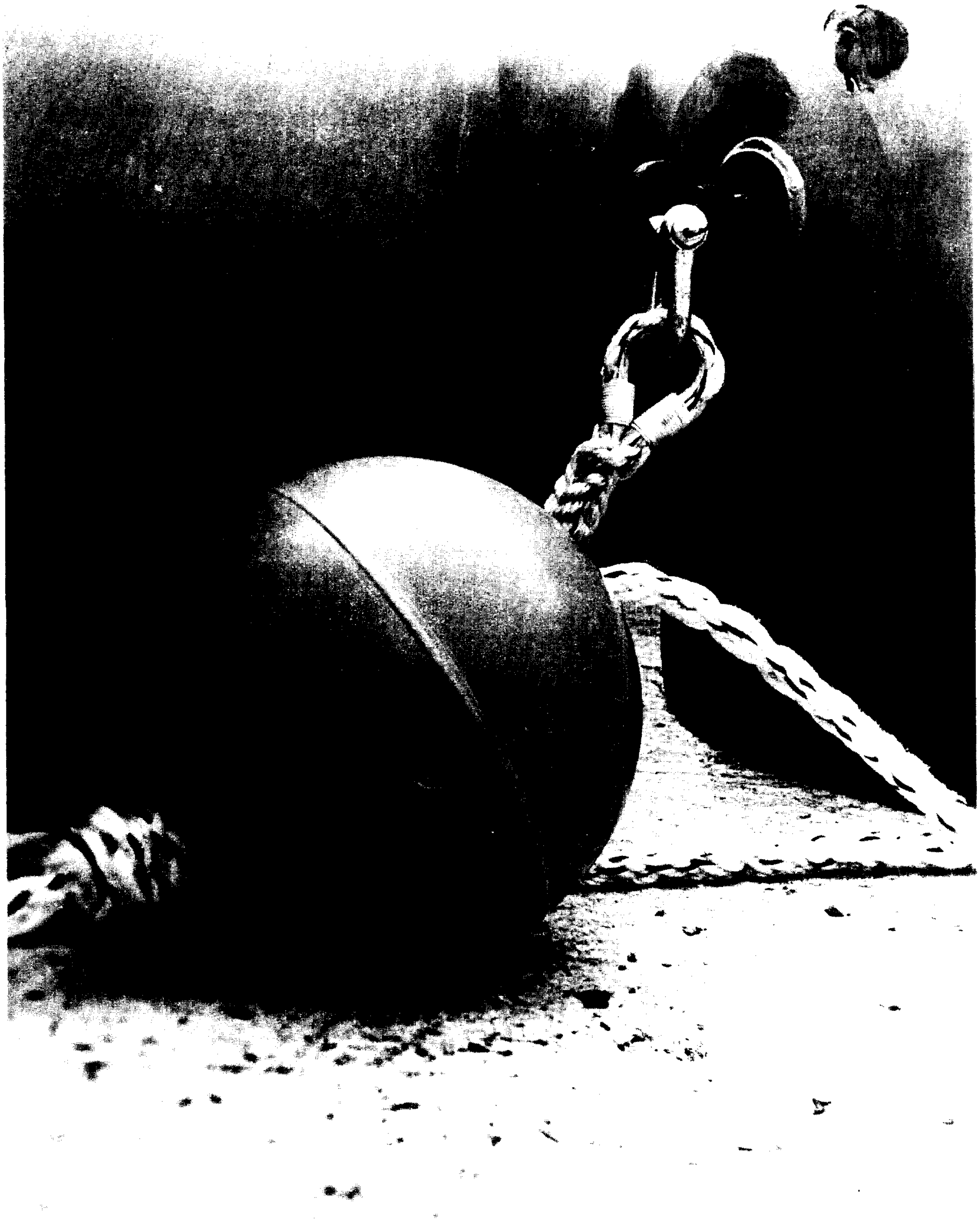

Fig 8 16 mm polypropylene rope strop with 275 mm central-hole trawlfloat attached to sub-surface float.

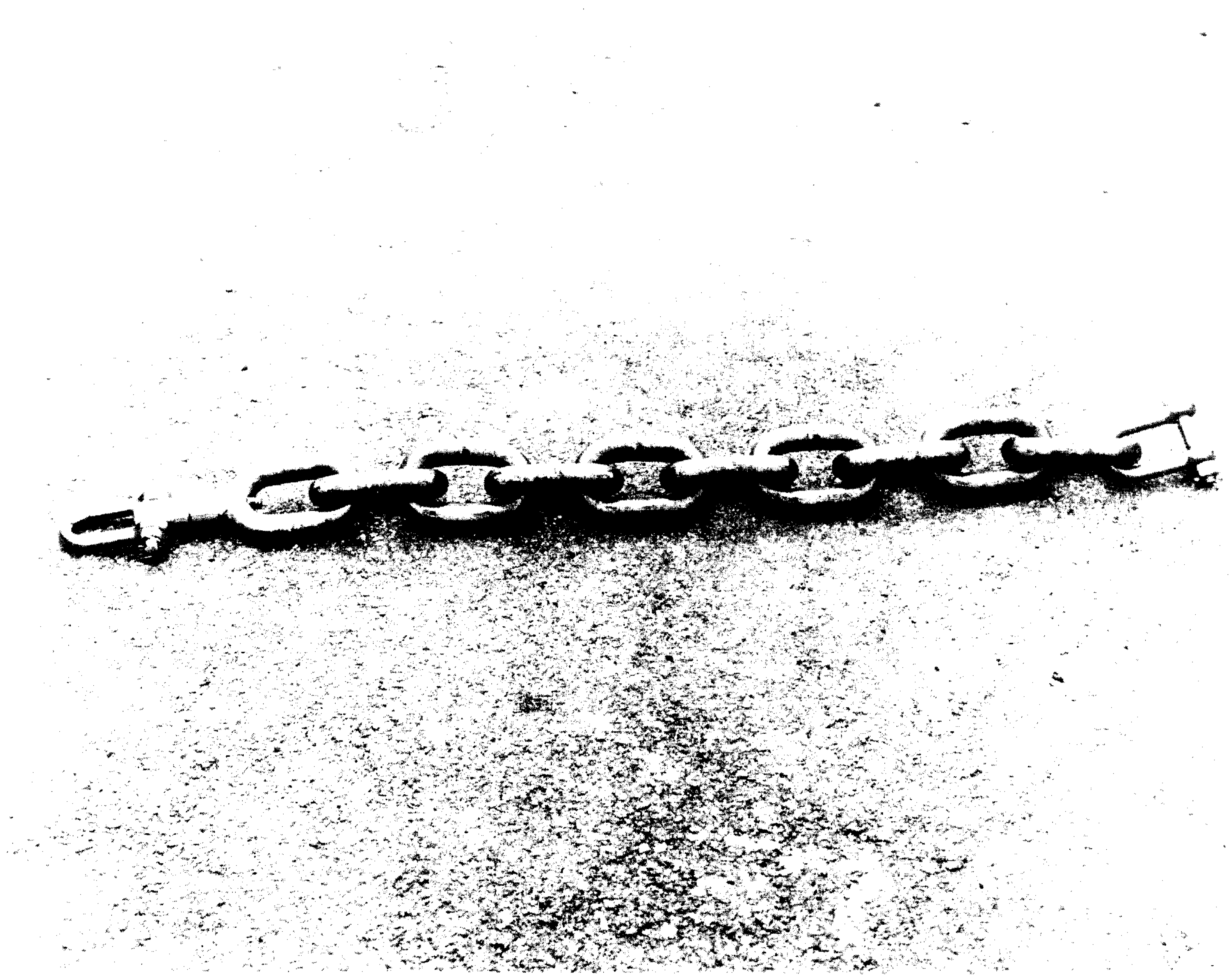

Fig 9 Datawell stainless steel stabilizing chain with swivel and shackles.

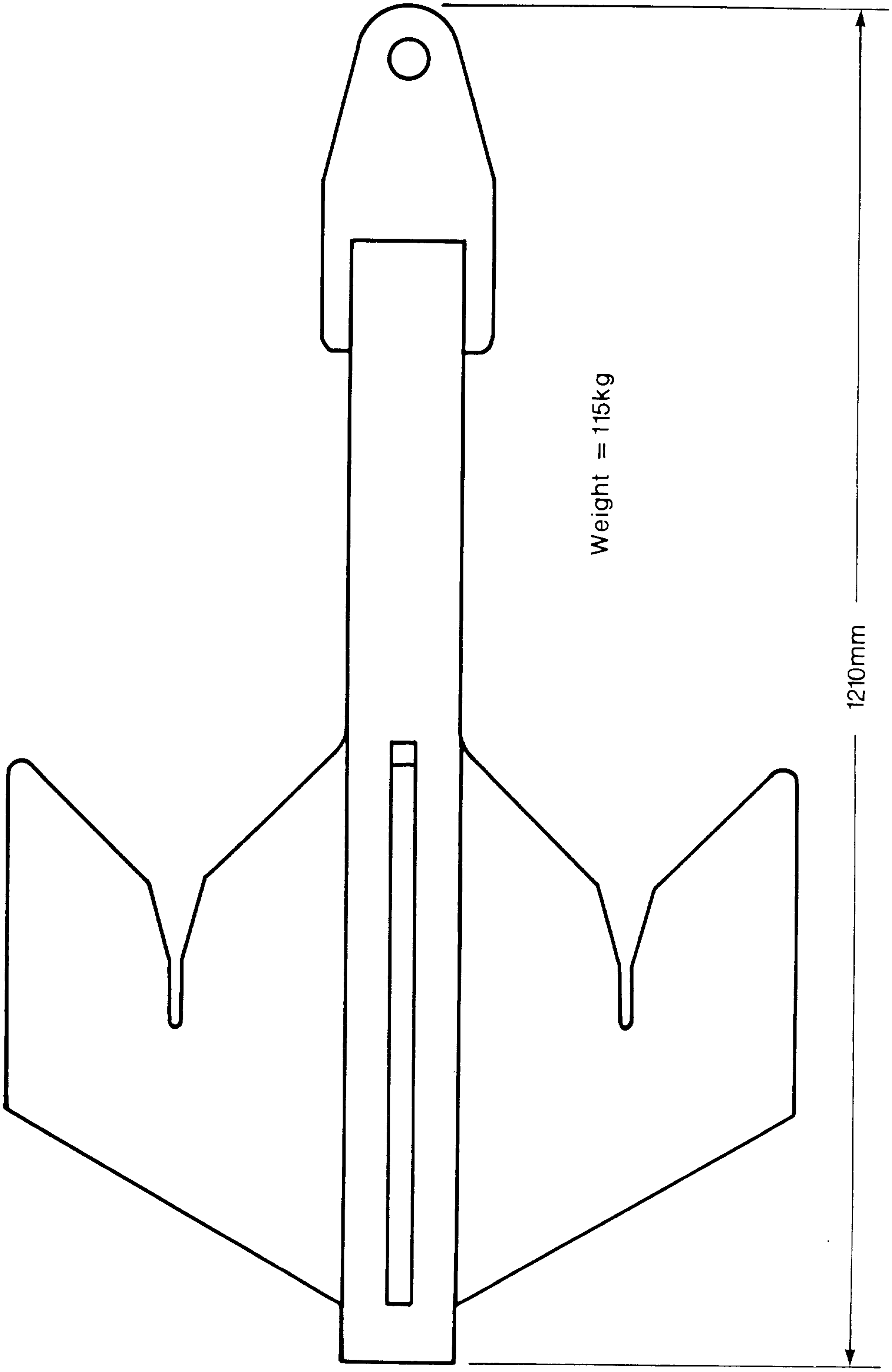

Fig 10 Heavy recovery grapnel.

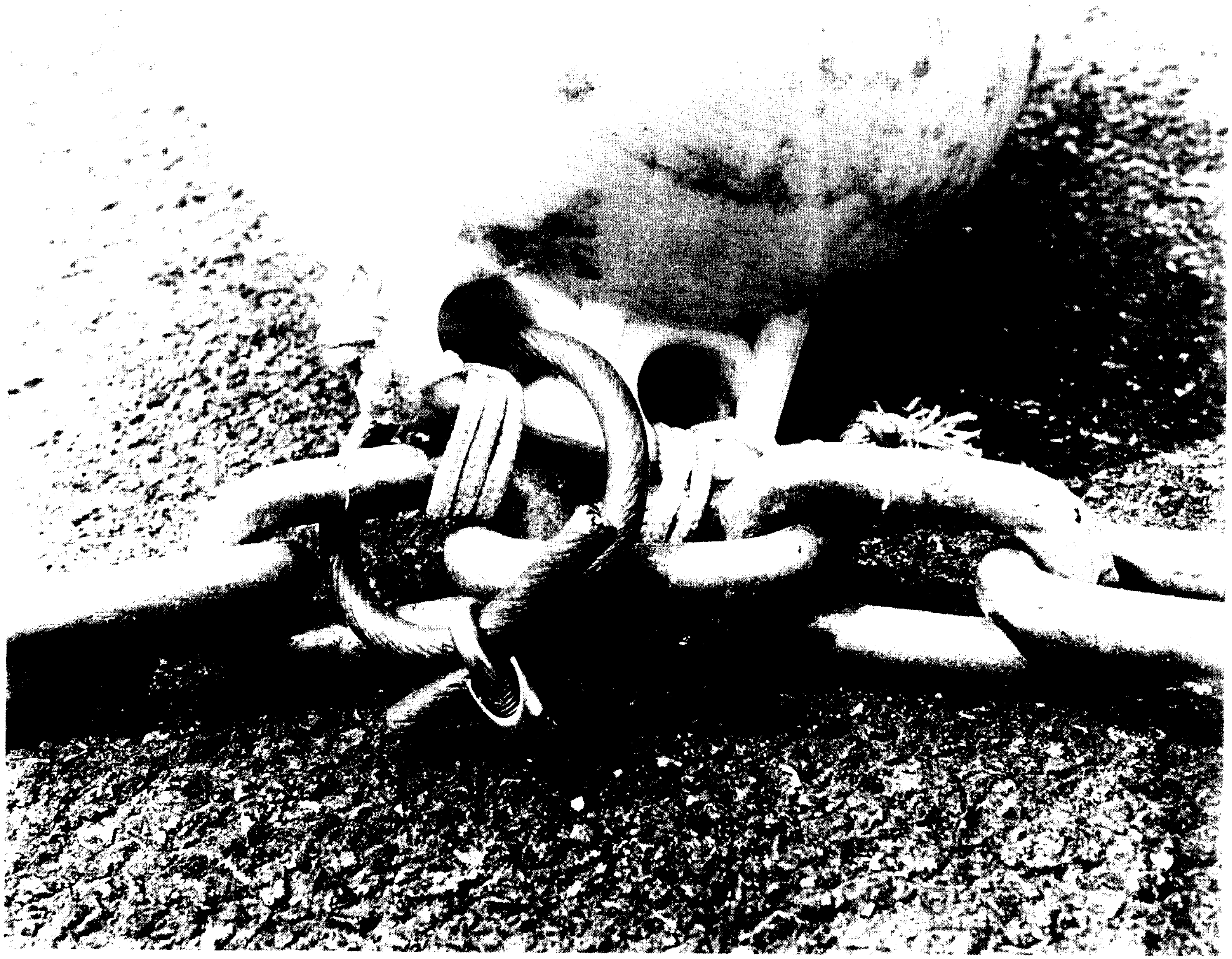

Fig 11 200 mm side-handle trawlfloat attached to 12.5 mm galvanised long link chain.