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EXTREME RESIDUAL CURRENT SPEEDS UPON THE UK CONTINENTAL SHELF

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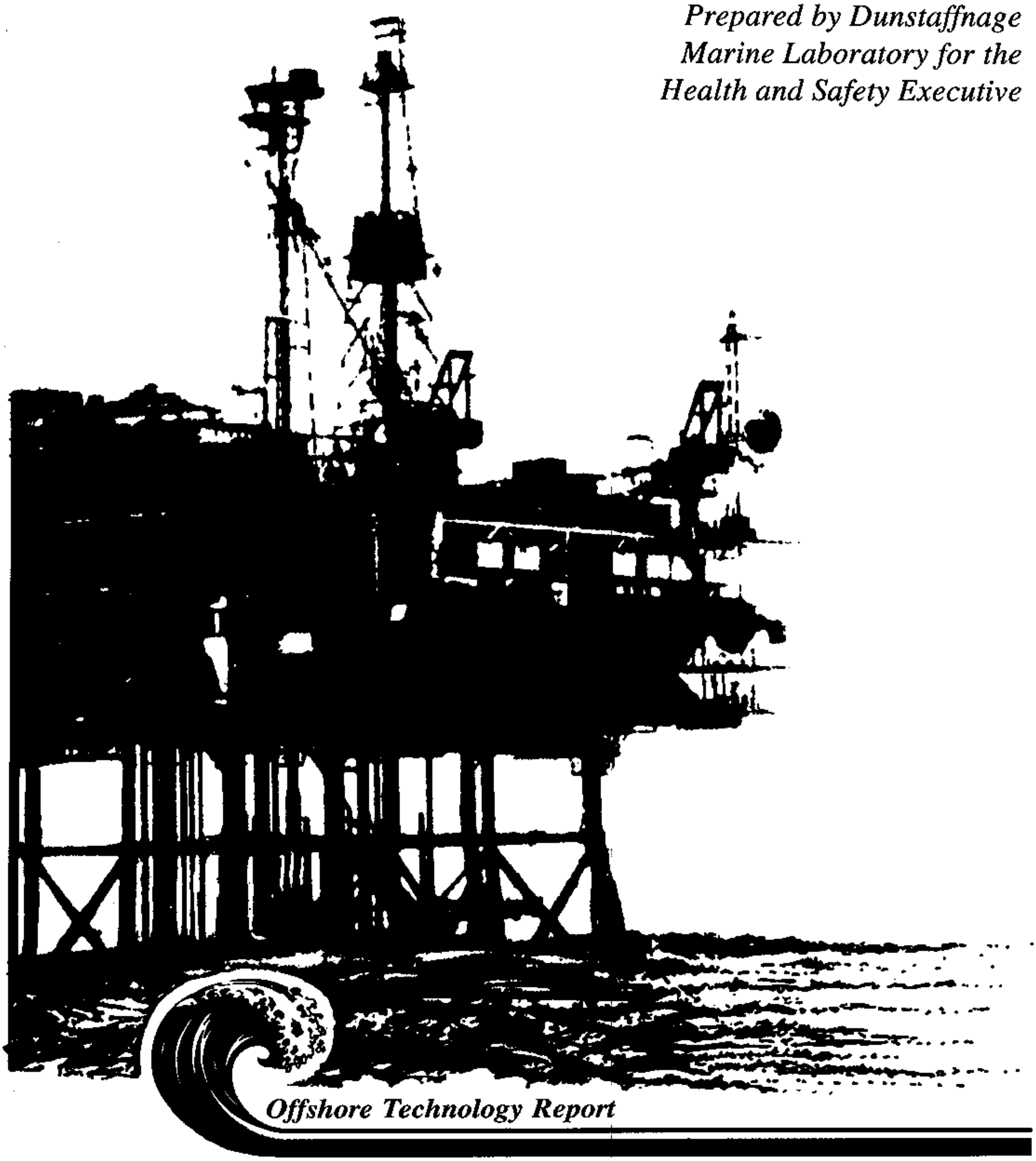

Health and Safety Executive

EXTREME RESIDUAL CURRENT SPEEDS UPON THE UK CONTINENTAL SHELF

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SUMMARY

Residual current speeds have been calculated for 19 sites upon the UK continental shelf. The selection criterion was the availability of good quality recording current meter data extending over a total period of at least 9 months.

By fitting a three-parameter Weibull distribution to the residual speeds, estimates of the 50-year extreme residual current have been obtained and tabulated. These are compared to the indicative values of depth-averaged 50-year return storm surge current speeds given in "Offshore Installations: Guidance on Design, Construction and Certification", Fourth Edition, 1990, HMSO.

CONTENTS

Page

1. INTRODUCTION

Knowledge of the extremes of residual currents (i.e., the underlying current which remains when tidal currents have been removed) is extremely sparse, and mostly fortuitous. During the North Sea storm surge of 1953, for instance, residual currents at the Varne Lightvessel in the Straits of Dover averaged an unusually high value of 60 cm s^{-1} over a full lunar day (Lawford, 1954), but due to the method of recording there is no means of obtaining the peak current speed, which is likely to have been notably greater.

Although long-term measurements of residual currents were initiated at light vessels around the European coasts during the early part of the present century, interest was in the daily drifts of fish larvae and plankton for the purposes of fishery research, and the mechanical current meters of the day were designed for this purpose. Practical technology for long-term recording at short time intervals was not available until the arrival of magnetic tape as a medium during the early 1960's, when prototypes of the present Aanderaa current meter appeared. Most of the available data come from instruments which are basically of this type, although equipment with solid state memory has been entering service during the last decade. Collecting accurate data with the electro-mechanical current meters of the 1960-1985 period has required high standards of maintenance and processing, and when the hazards of a hostile environment, fouling problems and a well-fished continental shelf area are also taken into account, the rather small number of long-term residual current measurement series available for examination is unsurprising.

A desire of the regulatory body, at the time the Department of Energy and now the Health and Safety Executive, to provide parameters for guidance in the design of offshore structures has led to the commissioning of a tidal atlas for UK waters (Howarth, 1989), a study of deep-water current extremes (Carter et al, 1987) and the present examination of residual currents upon the UK continental shelf. Apart from the two current meter moorings maintained west of Scotland by the Dunstaffnage Marine Laboratory (DML), available within house, data were obtained through the British Oceanographic Data Centre (BODC), Bidston, the initial request being for data series of greater than 9 months' duration. Considerations of suitability and accuracy, discussed below, have reduced the total number of series available for analysis to seventeen, of which four were collected on behalf of the UK Offshore Operators Association (UKOOA), four by individual oil companies, four by the Ministry of Agriculture, Fisheries and Food (MAFF), Lowestoft, three by the Proudman Oceanographic Laboratory, (POL), Bidston, and two by DML, Oban, and these have been examined in detail. In the next section a brief discussion is given of the situation from which each of these records was obtained, with a note of any relevant publications pertaining to currents at these sites.

Close examination of the records highlighted the timing problems and other difficulties which could occur with these electro-mechanical current meters, and for comparison purposes two shorter series of observations collected from moorings in which near-surface data were obtained from rapid-sampling solid state instruments are discussed. These data were collected in the North Sea by DML for the Department of Energy.

2. CURRENT METER MOORING SITES

Details of the current meter mooring sites are given in Table 1, and their positions plotted in Figure 1. A broad grouping by the degree of exposure of the sites to the open ocean and prevailing winds, as follows, allows the general current regime at each to be appreciated:

- Sites 1 - 5 (DB-1, Boyle, R, Fitzroy and Stevenson) are situated on the continental shelf open to the Atlantic or Norwegian Sea and with no close shelter from any direction.
- Sites 6 - 8 (Total 1, Total 2 and Frigg) are on the northern North Sea continental shelf in soundings of 110 to 130 m, close to the median line between Scotland and Norway, and also with no close shelter.
- Sites 9 - 12 (JONSIS 2, Leman, NS 2 and NS 3) are in offshore regions of the North Sea, in relatively shallow water where sandbanks constrain the directions of tidal flows.
- Sites 13 - 16 (JONSIS 1, Humber, Inner Dowsing and Sizewell) each lie close to the east coast of England with a degree of shelter from the prevailing southwesterly winds.
- Sites 17 - 19 (Swansea Bay, Sellafield and Tiree Passage), though close to land, are exposed to southwesterly winds.

The origin of the data from each position and references to any previously published work are listed below:

1. **DB-1** These data were collected from the UK data buoy, DB-1, moored upon Little Sole Bank, some 30km from the shelf-edge west of Ushant, and about 220km from the Scilly Isles. Depth of water at the mooring was 170m. The buoy was operated by consultants on behalf of UKOOA. Data were collected for almost four years, from 8 June 1978 to 13 March 1982.

   Important effects arise at the Celtic Sea shelf-edge due both to the abrupt depth change and to the canyons which indent this margin of the shelf. Currents are affected by internal tides, internal waves and by the propagation of eddies from the deep ocean on to the shelf, and these phenomena have been intensively investigated by Pingree (1979), Pingree et al (1984), Pingree and Mardell (1985) and Pingree and LeCann (1990).

2. **Boyle** These data were also collected on behalf of UKOOA at a mooring maintained in conjunction with shipboard weather observations from the same position. The site is in soundings of 107m with a rather level sea-bed extending from it for a radius of 25km. Beyond this to the southwest and south two narrow banks lying upon southwest-northeast axes rise to 60-80m (Labadie Bank) and 70-80m (North West Bank) respectively, although the latter rises in a small outcrop to 38m at Haig Fras. The position is roughly equidistant at 110-120km from the Scilly Isles and the Cork coast. Data collection was from May 1974 until May 1977, using NBA recording current meters.

   The general physical oceanography of the Celtic Sea has been discussed by Pingree (1980), who shows that the Boyle position can be occupied by stratified water for up to nine months of the year.

3. **R** Mooring R was situated 5km east of the Hebridean shelf-edge in soundings of 125-135m. The nearest land, Barra Head at the southern end of the Outer Hebrides, was 80km distant. In this vicinity the shelf-edge trends north-northwestward from an easterly bulge in the slope zone some 30km to the south. Immediately to the east of the site soundings are level and a little deeper for 50-60km. The moorings were maintained by the Scottish Marine Biological Association (now DML) between May 1975 and April 1982, using Plessey and Aanderaa current meters.

Table 1
Long-term current meter records upon the UK continental shelf

Ref. No.	Site	Lat. N. o '	Long. o '	Sdg. (m)	Meter ht above bott.	Days of good data
1	DB-1	48 42.9	8 53.3 W	170	167	1029
2	Boyle	50 40.0	7 30.0 W	107	92	441
					31	649
					3	823
3	R	57 00.0	9 00.0 W	125-135	98	645
					28	968
4	Fitzroy	60 00.0	4 00.0 W	122-137	107	280
					46	213
					3	357
5	Stevenson	61 20.0	0 00.0 E	159	144	391
					129	368
					83	414
					3	435
6	Total 1	60 28.6	1 41.5 E	130	2	371
7	Total 2	60 20.9	1 54.2 E	120	2	274
8	Frigg	59 51.9	2 00.4 E	110	2	288
9	JONSIS 2	54 23.0	1 06.0 E	41-43	29	517
					8	649
10	Leman	53 03.0	2 14.0 E	36	23	375
11	NS 2	54 03.6	1 02.5 E	48	46	222
					20	164
					5	219
12	NS 3	53 51.9	2 22.3 E	38	36	166
					15	221
					5	221
13	JONSIS 1	54 13.8	0 01.8 E	53-57	40	1076
					5-8	1317
14	Humber	53 33.0	0 32.0 E	21	4	324
15	Inner Dowsing	53 19.8	0 33.9 E	17	14	456
16	Sizewell	52 14.0	1 40.0 E	12	6	359
17	Swansea Bay	51 31.5	3 52.5 W	21	10	289
					2	484
18	Sellafield	54 24.0	3 33.0 W	15	9	327
19	Tiree Passage	56 37.5	6 24.0 W	47	23	625
					11	1719

Tidal currents on the western Scottish shelf have a strong diurnal component (Cartwright, 1969), and the residual currents at R have shown a clear seasonal signal (Dickson et al, 1986). The latter appears to arise from a broadening of the north-going slope current during the winter season, so that it spreads across the western margin of the shelf (Booth and Ellett, 1983). In summer, residual currents are weak and southeast-going. In general, the water column stratifies in May and is mixed again by December (Ellett, 1979).

4. **Fitzroy** A mooring at this site was maintained by UKOOA in conjunction with shipboard weather observations, from December 1973 to April 1976. NBA current meters were used. The position is on the West Shetland Shelf, about 90km from Orkney, 130km from Shetland and 25km southeast of the Norwegian Sea shelf-edge. The mooring was in 122m of water and within a radius of 25km the rather uneven bottom ranges from 100-150m depth.

   Diurnal currents are detectable here, but are much weaker than upon the shelf west of the Hebrides (Huthnance et al, 1988). Gordon and Huthnance (1987) found storm-generated shelf waves to be of more importance at Fitzroy, where they observed oscillatory responses with the inertial period of about 23hr, and quasi-steady responses flowing along the isobaths. The upper waters over the slope may occasionally meander shorewards in the manner observed further to the northeast by Dooley et al (1976).

5. **Stevenson** This mooring near the continental shelf-edge of the Norwegian Sea in soundings of 159m 70km north of Shetland was also operated for UKOOA during 1973 to 1976 using four current meters. To the north of this position the upper part of the slope-zone descends more gently than in the region south of 61°N.

   Short-term moorings deployed 20km further north in depths of 190m during the winter of 1982-83 showed an easterly residual current along the isobaths (Conslex Group, 1984), and satellite-tracked drogues over the upper slope-zone also passed eastwards in this vicinity to subsequently enter the northern North Sea along the western edge of the Norwegian Rinne (Booth and Meldrum, 1987).

6. **Total 1** Data were collected at this site for the Total/Compagnie Française Total/TOMEC Oil Companies using a single current meter during 1982 to 1983. The area, known as the Bressay East Ground, has low relief and soundings of 110-140m extending southwards from the Alwyn Oil Field. 40km to the east, the crest of Viking Bank rises to 85m depth.

   Hydrographically, the region lies between the shelf-edge input to the northern North Sea, which roughly follows the 200m isobath southwards along the western margin of the Norwegian Rinne, and the shelf input flowing south to the east of Shetland (Svendsen et al, 1991), and local circulation might be expected to be largely wind dependent.

7. **Total 2** This position was 20km southeast of "Total 1", and data were obtained here between 1982 and 1983 with one meter for the Total/Compagnie Française Total/TOMEC Oil Companies. It is sited close to the eastern limit of the Bressay East Ground, where this rises to a narrow north-south ridge with soundings slightly less than 100m.

   As with "Total 1", it seems probable that this is an area where wind driven currents predominate, between the main south-going Atlantic inflows at the shelf-edge of the Rinne and east of Shetland.

8. **Frigg** These data were collected jointly for the Total/Compagnie Française Total/TOMEC Oil Companies during 1982 and 1983 using one current meter. The Frigg Gas Field lies mid-way between Shetland and the Norwegian coast some 50km south of the preceding station in relatively level soundings of 98-110m. The broad plateau of the northern North Sea shelf extends a further 70km eastward before meeting the western slope of the Norwegian Rinne.

Again, the few existing descriptions of the hydrography of this part of the northern plateau of the North Sea (e.g. Dooley, 1974) suggest a mostly wind-driven regime for the currents, but reliable evidence has been lacking to confirm this.

9. **JONSIS 2** This mooring formed part of the international Joint North Sea Information System observation network and was maintained by the MAFF Fisheries Laboratory, Lowestoft, between December 1975 and November 1978. The site lay in 43m depth, 45km west-southwest of the shallowest part of the Dogger Bank, the South West Patch where the water shoals to 16m, and 85km from the Yorkshire coast at Flamborough Head. In this locality, known as `The Hills', narrow banks aligned upon west-northwest/east-southeast axes and rising to about 30m alternate with similarly aligned channels descending to 50-60m. Plessey and Aanderaa current meters were used.

   The water column in the neighbourhood of the Dogger Bank is well-mixed throughout the year (Lee, 1980). Surface currents are very variable with wind direction, but near-bottom currents are believed to vary seasonally. Ramster (1965) gives evidence from bottom drifters for an early summer clockwise circulation south of the Dogger, and a winter anti-clockwise flow as part of the Atlantic-derived inflow down the east coast of Scotland and Northern England.

10. **Leman** Although in an offshore situation 50km from the Norfolk coast, this site is in the vicinity of sandbanks which rise to within 5m of the sea-surface and break in rough weather. The southeast - northwest lying shoals are roughly 10km apart and are separated by channels of about 30m depth. The Leman Gas Field lies towards the southern end of these parallel banks. Data were collected by the Amoco Oil Company between December 1972 and September 1974 at a position where the sounding was 36m.

    In this vicinity the southward Atlantic inflow down the east coast of Britain meets the northward flow out of the Southern Bight of water from the English Channel and the Thames, resulting in a generally eastward movement towards the Helgoland Bight (Lee, 1980). Strong tides ensure a well-mixed water column throughout the year.

11. **NS 2** This mooring and the following one were deployed by DML in the period November 1986 to July 1987, primarily to investigate near-surface currents and to transmit half-hourly observations via the Argos satellite data system in near real- time. Full details of the special mooring system have been given by Ellett, Griffiths and Meldrum (1990), and of the data by Griffiths and MacDougall (1990). The upper current meter, at 2m below mean wave trough level, was an Interocean S4 electromagnetic instrument. North and east current components over a two-minute period every five minutes were obtained by averaging the components sampled at 2hz. The two lower meters were conventional Aanderaa meters fitted with the newer "paddle wheel" rotor.

    The mooring was sited in water of 48m soundings at the southwestern end of the Outer Silver Pit, the east-west channel to the south of the Dogger Bank which may provide the topographic steering for the current setting eastward from Flamborough Head, from the vicinity of the JONSIS 1 mooring, noted below.

12. **NS 3** This mooring was similar in design to NS 2, and carried a near-surface Interocean S4 electromagnetic current meter and two Aanderaa instruments.

    The site was on the southern side of the eastern Outer Silver Pit in 38m of water, and about 90km north of the Leman mooring. There are thus east-west topographic influences to the north of the location and southeast trending sandbanks to the south, and the currents in the lower water column may reflect the seasonal pattern discussed for the JONSIS 2 mooring.

13. **JONSIS 1** This MAFF mooring was 13km from the coast at Flamborough Head in soundings of 53-57m. Data were collected here between January 1971 and November 1978, using Plessey and

Aanderaa current meters. To the north of this position the North Sea is largely an open continental shelf, deepening gradually northwards; to the south it shoals rapidly and is broken up by sandbanks and estuarine mudflats.

The southward flow close to the east coast of Atlantic water from the northern North Sea appears to separate from the coast at Flamborough Head, setting to the southeast in the general direction of NS 2 and NS 3 in reaction to the southward shoaling bottom and perhaps to the Humber outflow. Offshore bottom salinity is in some seasons higher than at the surface, although the water column is normally homothermal (Lee,1980).

14. **Humber** This site is 27km due east of the River Humber estuary in soundings of 21m upon a broad shelf of 10-20m depth lying between the Lincolnshire coast and the narrow 90m deep of the Silver Pit. Plessey and Aanderaa current meters were deployed here by MAFF between June 1977 and September 1978.

    Although the offshore east coast current starts to turn easterly off the south Yorkshire coast, inshore waters carrying the River Humber outflow continue southward (Lee,1980). Stratification on the outgoing tides will be destroyed, except possibly at neaps, by vigorous mixing over the shallow flats.

15. **Inner Dowsing** Aanderaa current meters were suspended by IOS, Bidston, from February 1972 to June 1973 from the Inner Dowsing Light-tower, a former gas production platform sited in 17m of water 2km from the northern end of the Inner Dowsing shoal, which rises to within 1-2m of chart datum. The tower is 16km from the Lincolnshire coast and 24km south of the Humber current meter position discussed above. A somewhat deeper channel of 20-30m depth runs from the Wash to the southern end of the Silver Pit 6-8km to the east of the tower.

    Pugh and Vassie (1976) discuss the observations in detail, especially in relation to the propagation of tide and surges in the North Sea. Residual currents were to the northwest, which Pugh and Vassie consider to be a local reversal, but they point out that the tidal flow was not rectilinear, the ebb being north-going and the flood becoming southwest-going at higher velocities, and this could have distorted the small residuals.

16. **Sizewell** This mooring was deployed by IOS Taunton, between August 1976 and April 1979 in 12m of water. The site was 0.5km to the east of Sizewell Bank, which runs north-south parallel to the Suffolk coast and 2km from it. The bank rises to within about 3m of chart datum. Eastwards the sea floor slopes gently over 3-4km to a level area of 20-25m depth and there are no sheltering off-lying banks in this section of the Southern Bight.

    IOS research has been reported in a series of reports summarised by Lees (1983). With the evidence of additional short-term moorings from the vicinity, a complex residual circulation is suggested, partly due to an eddy formed by a headland to the south of Sizewell Bank which causes a southerly current to flow for 7 hours during each tidal cycle. Lee (1980) suggests a southerly inshore surface current along this coast. From the returns of bottom drifters released in this vicinity Riley and Ramster (1969) deduce southward near-bottom current throughout the year inshore even though bottom currents a few km offshore appear to reverse in winter.

17. **Swansea Bay** This mooring was operated between October 1975 and September 1977 by IOS Taunton. The site was in 21m depth, almost equidistant at 8km from Mumbles Head and Port Talbot. Although open to the west to southwest, the position was sheltered by the coast from northwest through north to southeast, and to the south by the Scarweather Sands, which dry to 1-3m above chart datum.

    The IOS surveys included short-term moorings and much other research aimed at the study of the sedimentation regime in the bay, and are summarised by Heathershaw et al (1981). The long-term mooring was deduced to be on the northern side of a clockwise eddy situated over the Scarweather Sands, but wind-driven currents were judged to have the major effect upon residual currents in the bay.

18. **Sellafield** As part of its radiological protection function, the MAFF Lowestoft laboratory has maintained a current meter mooring close to the seaward end of the pipeline through which low-level wastes are discharged from Sellafield Works, BNFL. The site is in 15m of water about 3km to seaward of the rather straight north-northwest to south-southeast trending coast. The sea bed deepens only gradually, the 20m isobath being a further 3-4km west of the mooring. Data reports have been published by Norris (1985) and Jones and Norris (1988).

    From Irish Sea current meter and drifter results Ramster and Hill (1969) deduced a north-going residual along this coast at the surface, with south- to onshore-going residuals at the bottom. This may arise as the deeper waters move shorewards to compensate for offshore movement of the lighter estuarine surface waters of Liverpool Bay and Morecambe Bay. In such shallow water, however, meteorological effects may be expected to predominate during much of the year.

19. **Tiree Passage** Between the islands of Coll and Mull a current meter mooring has been maintained during the past decade, with some interruptions, by DML. The site is in a depth of about 40m upon a bank in the centre of the Tiree Passage, protected to the east and west by the islands, but open to the southwest and to the north. Strong tidal streams run through the passage, and the general northerly residual of the coastal current west of Scotland is assisted by the prevailing southwesterly winds.

    The annual cycle of wind strength appears to be reflected in the annual variation of the strength of the northerly residuals in the Tiree Passage (Economides et al, 1985), and may be enhanced by the additional buoyancy added to the coastal current by fresh water run-off added to the estuaries (Simpson and Hill, 1986). Studies of Windscale effluent show that the larger part of the coastal current that flows northward west of Scotland passes between Mull and Coll (McKay et al, 1986), and hence can be readily monitored by current meters at this site.

3. DATA SELECTION AND METHODS OF ANALYSIS

As noted earlier, current meter data were obtained from the database of the British Oceanographic Data Centre (BODC). The selection was limited to the shelf seas surrounding the British Isles in water depths of less than 200m. Sites were selected where the total duration of current meter data exceeded 270 days at a given nominal height above the sea floor. Some allowance was made for variability in mooring positions and vertical height variations. Seventeen of the sites in Figure 1 and Table 1 fulfilled these criteria, providing nearly 46 years of data in 460 data series collected between 1972 and 1989. The longest series from any site is from the mooring maintained in the Tiree Passage (site 19, Figure 1) off the west coast of Scotland, which represents nearly five years of current data collected since 1983.

The two additional sites, NS2 and NS3 (sites 11 and 12) in the southern North Sea, just fail to meet the original selection criteria as to length, but have been included because they provide data from near-surface instruments moored at a depth of 2m.

Most of the series had already been validated by BODC, and any suspect values appropriately flagged. A similar methodology was applied to the remaining data sets using a wild point searching routine (Griffiths and MacDougall, 1989). All suspect values were inspected and manually edited from the series as required. No automatic editing routines were used. The sampling time interval of the series ranged from five minutes to one hour. All data sets were reduced to hourly values in order to unify the analyses.

Subsequently the individual short-term deployments were grouped by site and depth level. This produced a total of 35 time-series of hourly current speed and direction. These were then reduced to series of north-south and east-west velocity components, and a separate harmonic analysis was performed on each component. A standard list of 70 constituents was used in the analysis. No constituents of period longer than 28 hours were used. The predictions from the harmonic analysis were then subtracted from the original records to form the residuals for each component, which were then recombined to form time-series of residual speed and direction.

The predictions were also used to generate 19 years of hourly current values. These were scanned to find the maximum tidal current speed, i.e., the Highest Astronomical Tidal current (HAT). These values are shown in Table 2 together with the average spring tidal current formed by the addition of the M2 and S2 major axes. The predictions do not include any long-period constituents; their contribution to the maximum predicted current is very small compared to the diurnal and semi-diurnal constituents.

Any dubious results were identified, and after removal the harmonic analysis was repeated. Reference was made to the information sheets held for each current meter series by BODC. The residual time series were inspected for obvious errors using techniques similar to those employed by Pugh and Vassie (1978). The commonest problem encountered, especially with the earlier current meters, was the prevalence of timing errors within the records.

Only recently have the instruments acquired the ability to record time with each scan. In the earlier data timing errors can have arisen due to a number of reasons; incorrect logging of start and end times, dropped information during the translation process, or the net loss or gain of data scans during deployment.

There is no simple method to correct for these timing errors. Such errors can lead to spuriously large residual values, and consequently to an overestimate of extremes. It was therefore decided to recalculate the harmonic analysis for each of the separate deployments of a site using relationships derived from the harmonic analysis of the complete records of that site. This approach also reduced errors caused by small variations in the mooring positions between deployments as well as variations due to the use of different models of instrument.

Table 2
Average spring tidal current (M2 + S2, major axes),
the Highest stronomical Tidal current (HAT) and their ratio.

Ref. No.	Site	Sdg. (m)	Meter ht above bott.	Av Spring (M2+S2) (cm/s)	HAT (cm/s)	Ratio HAT Av S
1	DB-1	170	167	44.8	70.8	1.58
2	Boyle	107	92	39.7	70.2	1.77
			31	31.2	59.0	1.89
			3	26.4	46.9	1.77
3	R	125-	98	32.9	49.8	1.51
		135	28	27.8	45.0	1.62
4	Fitzroy	122-	107	30.6	53.1	1.74
		137	46	23.9	44.2	1.85
			3	18.3	30.9	1.69
5	Stevenson	159	144	17.3	31.6	1.83
			129	17.0	26.2	1.54
			83	16.3	26.9	1.65
			3	10.2	20.2	1.98
6	Total 1	130	2	12.1	21.7	1.79
7	Total 2	120	2	14.3	26.1	1.83
8	Frigg	110	2	13.2	23.8	1.80
9	JONSIS 2	41-	29	56.6	84.3	1.49
		43	8	47.9	70.2	1.47
10	Leman	36	23	76.6	102.9	1.34
11	NS 2	48	46	53.3	80.7	1.51
			20	55.9	86.7	1.55
			5	44.7	68.3	1.53
12	NS 3	38	36	50.6	76.8	1.52
			15	53.1	80.7	1.52
			5	43.6	61.5	1.41
13	JONSIS 1	53-	40	86.0	115.9	1.35
		57	5-8	65.5	88.4	1.35
14	Humber	21	4	97.0	121.0	1.25
15	Inner Dowsing	17	14	94.5	132.3	1.40
16	Sizewell	12	6	101.2	150.3	1.49
17	Swansea Bay	21	10	57.8	87.2	1.51
			2	53.7	68.6	1.28
18	Sellafield	15	9	47.3	64.2	1.36
19	Tiree Passage	47	23	64.7	90.5	1.40
			11	54.9	74.8	1.36

Because of the sensitivity of the residuals to timing errors, a second technique has also been used to remove the tidal signal from the current meter records. This is the "HILOW" 72-hour low-pass filter (Cartwright et al., 1980). The amplitude response of this filter is given by Pugh (1987). It should be noted that the filter, in removing the tidal signal, also removes non-tidal signals below the cut-off, which is likely to lead to underestimations of extreme residual currents. Removing the tidal energy by filtering is less sensitive to timing errors than the harmonic technique. The residuals computed from tidal predictions contain energy in the tidal bands because energy which is not tidally coherent is not included in the tidal predictions. A low-pass filter suppresses both coherent and non-coherent tidal energy (Pugh and Vassie, 1976) and this method provides a minimal estimate of extremes from data for which it is not possible to confirm the suitability of harmonic analysis.

A drawback of the filtering technique is the loss of 6 days' data from every continuous block, whereas the harmonic analysis technique is performed with a least-squares fit and hence retains all observations. In the extreme case of the DB1 data set (Site 1), there are 620 separate data blocks, and these have not therefore been filtered. Timing errors within this set have also reduced the amount of data analysed harmonically.

4. RESULTS AND COMPARISONS WITH MODEL DATA

Histograms were constructed in 1cm/s bin sizes for both the residual and low-pass speed time series. From these the cumulative probability distribution has been calculated. In Weibull's scheme the three parameter distribution of speed, v (cm/s), is represented by the probability, F, that the speed v is exceeded:

$$F(v) = 1 - \exp\{- [(v - \text{lower limit}) / \text{scale}]^{\text{shape}}\}$$

with values of the three parameters, lower limit (cm/s), scale (cm/s) and shape as given in the figures. The speed cumulative distribution has been fitted to the Weibull distribution using an iterative correlation technique in which scale and shape are fitted using least-squares for the upper 50% of the distribution. The lower limit was found using iteration to maximise the correlation coefficient.

There is no theoretical justification for choosing a three-parameter Weibull distribution, though as can be seen from Figures 2 to 36, the distribution appears to be a reasonable fit to the residual data. The data were also fitted to Fisher-Tippett II and Fisher-Tippett III distributions, but these gave an inferior fit by comparison with the three-parameter Weibull. Only in the case of Figures 19 (Jonsis 2) and 29 (Humber) is there concern over the fit, regardless of chosen distribution. The return periods from these two sites must therefore be treated with caution.

The 50-year return value of hourly residual speed, v_{50}, is that which is exceeded on average once in 50 years. In practice, it is convenient to work with cumulative probability,

$$\begin{aligned}\text{Cumulative probability } (v > v_{50}) &= 1 - \text{probability of exceedance of } v_{50} \\ &= 1 - 1/(365.25 \times 24 \times 50) \\ &= 0.99999772\end{aligned}$$

Also shown in the figures are return residual speed values for 1, 5 and 50 years.

The 50-year return values are shown in Table 3.

Carter and Challenor (1981) state that there can be no statistical justification for extrapolating from a single year's data to the 50-year return value. In the case of wind data, (Dept. of Energy, 1989), a three-parameter Weibull function has been used to obtain a 5-year value of wind speed. These values have then been divided by 0.83, after Jenkinson (1977). The ratios of the 5-year residual current speed to the 50-year residual speed derived from the Weibull extrapolation are shown in Table 4. The mean value of this ratio is 0.82.

Table 3
Comparison of model-derived 50-year surge currents with 50-year extreme currents derived from the residual and low-pass currents.

Ref. No.	Site	Sdg. (m)	Meter ht above bott.	Model speed	Weibull 50-year speed (cm/s)	
				(cm/s)	Residual	Low-pass
1	DB-1	170	167	23.9	88.1	-
2	Boyle	107	92	42.7	58.0 (49.2)	26.6 (18.9)
		31			67.7	20.8
		3			21.9	9.2
3	R	125-	98	37.2	66.4 (65.4)	40.2 (42.4)
		135	28		64.5	44.6
4	Fitzroy	122-	107	41.1	73.0 (54.4)	32.8 (31.0)
		137	46		50.8	31.0
			3		39.5	29.2
5	Stevenson	159	144	21.6	49.8 (55.3)	20.2 (27.5)
		129			50.2	21.8
		83			64.8	21.1
		3			56.4	47.0
6	Total 1	130	2	41.6	40.4	28.7
7	Total 2	120	2	41.6	54.2	33.3
8	Frigg	110	2	37.1	43.6	28.4
9	JONSIS 2	41-	29	101.6	135.0 (107.4)	43.7 (71.5)
		43	8		79.7	99.3
10	Leman	36	23	92.2	81.4	23.6
11	NS 2	48	46	88.0	110.8 (101.1)	82.6 (66.8)
		20			65.6	28.8
		5			126.9	88.9
12	NS 3	38	36	96.2	101.1 (88.1)	49.8 (51.1)
		15			78.7	42.8
		5			84.5	60.8
13	JONSIS 1	53-	40	76.3	97.2 (75.4)	45.6 (31.8)
		57	5-8		53.5	18.0
14	Humber	21	4	78.4	143.8	14.7
15	Inner Dowsing	17	14	46.4	62.1	14.3
16	Sizewell	12	6	61.5	135.6	68.1
17	Swansea Bay	21	10	22.8	68.9 (63.3)	13.2 (23.4)
		2			57.7	33.5
18	Sellafield	15	9	29.0	79.3	43.2
19	Tiree Passage	47	23	46.1	196.1(153.2)	87.7 (68.2)
			11		110.3	48.7

Values in brackets ( ) are the average of the extreme speed extrapolations at different depths, *presented for comparison with the model output speeds.*

Table 4

5-year and 50-year extreme residual current speeds (cm/s) derived from the Weibull extrapolations.

Ref. No.	Site	Sdg. (m)	Meter height above bott.	5-year extreme residual	50-year extreme residual	5/50 year ratio
1	DB-1	170	167	76.8	88.1	0.87
2	Boyle	107	92	45.7	58.0	0.79
			31	43.4	67.7	0.64
			3	19.2	21.9	0.88
3	R	125-135	98	55.8	66.4	0.84
			28	53.4	64.5	0.83
4	Fitzroy	122-137	107	61.6	73.0	0.84
			46	44.1	50.8	0.87
			3	34.7	39.5	0.88
5	Stevenson	159	144	43.5	49.8	0.87
			129	44.6	50.2	0.89
			83	52.7	64.8	0.81
			3	46.3	56.4	0.82
6	Total 1	130	2	35.4	40.4	0.88
7	Total 2	120	2	46.3	54.2	0.85
8	Frigg	110	2	37.8	43.6	0.87
9	JONSIS 2	41-43	29	102.7	135.0	0.76
			8	75.3	79.7	0.94
10	Leman	36	23	65.5	81.4	0.80
11	NS 2	48	46	87.1	110.8	0.79
			20	54.0	65.6	0.82
			5	91.1	126.9	0.72
12	NS 3	38	36	82.4	101.1	0.82
			15	65.1	78.7	0.83
			5	67.3	84.5	0.80
13	JONSIS 1	53-57	40	76.0	97.2	0.78
			5-8	41.5	53.5	0.78
14	Humber	21	4	136.2	143.8	0.95
15	Inner Dowsing	17	14	51.4	62.1	0.83
16	Sizewell	12	6	105.1	135.6	0.78
17	Swansea Bay	21	10	52.1	68.9	0.76
			2	44.9	57.7	0.78
18	Sellafield	15	9	64.0	79.3	0.81
19	Tiree Passage	47	23	161.6	196.1	0.82
			11	94.7	110.3	0.86

Mean value of 5-year to 50-year ratio 0.82

5. DISCUSSION

There are no published extreme residuals from the UK continental shelf. The only other work of relevance has been the calculation of extreme total current at the Inner Dowsing platform (Site 15) by Pugh (1982) and over the continental slope west and north of Scotland by Carter et al (1987). Both these analyses extend the joint probability method developed by Pugh and Vassie (1980).

Estimates of 50-year return depth-averaged hourly-mean storm-surge currents have been calculated for the UK shelf by means of numerical model simulations (Flather, 1987). These are the source of the values given in section 11 of "Offshore Installations: Guidance on Design, Construction and Certification", fourth edition, 1990, HMSO. Table 3 summarises the values derived from the model for the 19 sites where 50-year values have been obtained from current meter data.

Very little is known about the vertical structure of storm surge currents and no clear picture emerges from the 50-year Weibull extrapolations. Only five of the sites analysed have current meters at three or more depths, and only one of these (Site 4, Fitzroy) shows a steadily decreasing extreme speed with depth. For the purposes of the numerical model comparison, average values are given in brackets in Table 3 for sites with current meters at two or more depths.

The sites for which current meter data are available are not those which would ideally be chosen for comparison with the model, and the relatively coarse grid resolution (approximately 30 x 30km) of the model results in some nearshore regions being poorly represented. This is particularly the case for inshore Sites 13 to 19. Similarly, the mathematical condition employed at the open (Atlantic and Norwegian Sea) boundaries of the model is not able to represent accurately the true surges there, and this must be borne in mind when making comparisons with Sites 1 and 3 to 8. The model simulations did not include any large surge in the Celtic Sea and western English Channel, a factor to be remembered in comparisons with Site 2.

In general, Table 3 shows that the values derived from the model are bounded by the residual and the low-pass extremes. The model values were obtained from the examination of sixteen separate storm events. The low-pass extremes will underestimate the storm-surge currents due to the characteristics of the filter used, which has a cut-off at 28.8hr, and due to the characteristics of the filter will result in the loss of some energy up to a period of three days. The low-pass values have been included as an alternative method of deriving extremes in records where numerous timing errors were present. The residual extremes will represent all contributing factors, including timing errors, and not solely those from the storm-surge population.

Earlier reservations suggest that the best agreement should be found in the central North Sea area at Sites 9 to 12, which are far from the open boundaries and relatively offshore and this proves to be the case. Useful additional assurance of the validity of the results also comes from the close agreement between the "mean" residual extremes from two sites, 9 (JONSIS 2) and 11 (NS 2), lying within 40km of one another, but where the data were collected over different periods separated by about eight years.

Subsequent to the selection of data for this study, six moorings have been maintained for 15 months in the southern North Sea as part of the NERC North Sea Project. In addition to conventional current meters of the Aanderaa and Interocean S4 type, data have also been obtained using Acoustic Doppler Current Profilers (ADCPs). There have also been long-term deployments in the Straits of Dover of the Ocean Surface Current Radar (OSCR). Analysis of data sets such as these can increase our understanding of the vertical structure of extreme events.

6. CONCLUSIONS

"Offshore Installations: Guidance on Design, Construction and Certification", Fourth Edition, 1990, HMSO (Guidance) states that a high-quality data set extending over at least 1 year, and preferably longer is necessary for the prediction of 50-year return residual currents from site-specific data alone. In fact, only 22 records which satisfy this condition exist within the BODC current meter data bank, 90% of the bank consisting of data from deployments of 2 months or less. It should be noted that of the 22 longer records the majority were collected during the 1970s, the decade when experience was being gained in the routine use of recording current meters, and consequently some of these sets are not of modern quality.

For the present study, the selection criteria were therefore relaxed first to include records of duration between 9 months and 1 year, and then slightly further for the inclusion the two sites (NS 2 and NS 3) where currents were measured through the water column from the surface (Ellett et al, 1990). It must therefore be accepted that at present there are insufficient long-term data to offer confident estimates of 50-year residual currents over most of the UK continental shelf. This report provides estimates in Table 4 of extremes by two methods at 19 positions which show some consistency between neighbouring sites. The estimates fall within the limits (0.2 to 1.4 m/s) indicated in Table 11.12 of Guidance for the range of storm surge depth-averaged current speeds in the UK continental shelf seas.

The report also gives (Table 2) ratios at each mooring between the average spring tidal current and the Highest Astronomical Tidal current.

The available data were insufficient to examine the vertical structure of the extreme current profile, and our knowledge of currents in the near-surface remains poor. The largest residual currents observed 3m below the surface at Site 1 (DB 1) were during the summer months, but this will have been influenced by the degree of stratification, and hence surface wind effects may not necessarily lead to greater extremes in winter at this level. The only other data sets for the near-surface were from Sites 11 and 12 (NS 2 and NS 3), where records did not span the summer months, so that it is not known whether summer 50-year extremes might have been even greater than the 100cm/s levels calculated from the available data.

At present, extension of spatial coverage to areas without long-term records must rely upon model results. At the site where Table 4 gives the highest estimates, in the Tiree Passage (Site 19), measurements started in 1981 are continuing as part of a DML programme monitoring flow in the coastal current. The data being accumulated will be valuable to test the convergence of 50-year residual estimates with the lengthening series, but the small-scale and complex bathymetry of the west of Scotland make this an atypical site.

7. REFERENCES

Booth,D.A., and D.J.Ellett, 1983. The Scottish continental slope current. Continental Shelf Research, 2, 127-146.

Booth,D.A., and D.T.Meldrum, 1987. Northeast Atlantic satellite-tracked buoy drifts. Dept. of Energy Offshore Techn. Rept, OTH 87 270, 95pp.

Carter,D.J.T., and P.G.Challenor, 1981. Estimating return values of wave height. Inst. Oceanogr. Sciences Rept, 116, 111pp.

Carter,D.J.T., J.Loynes and P.G.Challenor, 1987. Estimates of extreme current speeds over the continental slope off Scotland. Inst. Oceanogr. Sciences Rept, 239, 143pp.

Cartwright,D.E., 1969. Extraordinary tidal currents near St. Kilda. Nature, 223, 928-932.

Cartwright,D.E., A.Edden, R.Spencer and J.M.Vassie, 1980. The tides of the northeast Atlantic Ocean. Phil.Trans. Roy. Soc. Lond., 298, (1436), 87-139.

Conslex Group, 1984. The UK Continental Slope Experiment; IOS and SMBA current meter data. IOS Internal Doc., 239pp.

Dept. of Energy, 1989. Metocean parameters - parameters other than waves. Dept. of Energy Offshore Technol. Rept, OTH 89 299, 151pp.

Dickson,R.R., W.J.Gould, C.R.Griffiths, K.J.Medler and E.M.Gmitrowicz, 1986. Seasonality in currents of the Rockall Channel. Proc. R. Soc. Edinb., 88B, 103-125.

Dooley,H.D., 1974. Hypotheses concerning the circulation of the northern North Sea. J. Conseil int. Explor. Mer, 36, 54-61.

Dooley,H.D., J.H.A.Martin and R.Payne, 1976. Flow across the continental slope off northern Scotland. Deep-Sea Res., 23, 875-880.

Economides,B.E., M.S.Baxter and D.J.Ellett, 1985. Observations of radiocaesium and the coastal current west of Scotland during 1983-85. Int. Council for the Exploration of the Sea, CM 1985:C24, 10pp.

Ellett,D.J., 1979. Some oceanographic features of Hebridean waters. Proc. R. Soc. Edinb., 77B, 61-74.

Ellett,D.J., C.R.Griffiths and D.T.Meldrum, 1990. Near-surface current measurements in the North Sea. Dept of Energy Offshore Technol. Rept, OTH 90 331, 13pp, HMSO.

Flather,R.A., 1987. Estimates of extreme conditions of tide and surge using a numerical model of the North-west European continental shelf. Est. Coast and Shelf Sci., 24, 69-93.

Gordon,R.L., and J.M.Huthnance, 1987. Storm-driven continental shelf waves over the Scottish continental shelf. Continental Shelf Res., 7, 1015-1048.

Griffiths,C.R., and N. MacDougall, 1989. Current meter use and analysis at SMBA, Oban. Int. Counc. Explor. Sea Coop. Res. Rept, 165, 26-36.

Griffiths,C.R., and N.MacDougall, 1990. North Sea: Near-surface current measurements June 1985 to July 1987. Dept of Energy Rept , OTO-90-013, 193pp.

Heathershaw,A.D., A.P.Carr and M.W.L.Blackley, 1981. Swansea Bay (SKER) Project topic report : 8. Inst. Oceanogr. Sci. Rept, 118, 67pp.

Howarth,M.J., 1989. Atlas of tidal elevations and currents around the British Isles. Dept of Energy Rept, OTH-89-293, 17pp, 27 charts, HMSO.

Huthnance,J.M., J.Loynes and A.C.Edden, 1988. An investigation of meteorological effects on currents; 1, Analyses. Proudman Oceanogr. Lab. Rept, 2, 211pp.

Jenkinson,A.F., 1977. Analysis of maximum significant wave height data for selected North Sea storms, Meteorological Off., Met. O. 13 Branch Memo., 55.

Jones,S.R. and S.W.Norris, 1988. Current meter observations near the Sellafield pipeline, 1984-1986. Data Rept, MAFF Direct. Fish. Res., Lowestoft, 14, 12pp.

Lawford,A.L., 1954. Currents in the North Sea during the 1953 gale. Weather, 9, 67-72.

Lee,A.J.,1980. North Sea: Physical Oceanography. In: The North-west European shelf seas, ii, Eds Banner,F.T., M.B.Collins and K.S.Massie, Elsevier, Amsterdam, pp 467-493.

Lees,B.J., 1983. Sizewell - Dunwich Banks field study topic report : 7. Inst. Oceanogr. Sci. Rept 146, 43pp.

McKay,W.A., M.S.Baxter, D.J.Ellett and D.T.Meldrum, 1986. Radiocaesium and circulation patterns west of Scotland. J. Environ. Radioact. 4, 205-232.

Norris,S.W., 1985. Current meter observations near the Sellafield pipeline, May 1981 - December 1983. Data Rept, MAFF Direct. Fish. Res., Lowestoft, 4, 14pp.

Pingree,R.D., 1979. Baroclinic eddies bordering the Celtic Sea. J. Mar. Biol. Assn 59, 689-698.

Pingree,R.D., 1980. Physical oceanography of the Celtic Sea and the English Channel. In: The North-west European shelf seas, ii, Eds Banner,F.T., M.B.Collins and K.S.Massie, Elsevier, Amsterdam, pp 415-493.

Pingree,R.D., D.K.Griffiths and G.T.Mardell, 1984. Structure of the internal tide at the Celtic Sea shelf break. J. Mar. Biol. Assn, 64, 99-113.

Pingree,R.D. and B.LeCann, 1990. Structure, strength and seasonality of the slope currents in the Bay of Biscay region. J. Mar. Biol. Assn, 70, 857-885.

Pingree,R.D. and G.T.Mardell, 1985. Solitary internal waves in the Celtic Sea. Progress in Oceanogr., 14, 431-441.

Pugh,D.T., 1982. Estimating extreme currents by combining tidal and surge probabilities. Ocean Engineering, 9, 361-372.

Pugh,D.T., 1987. Tides, surges and mean sea level. Wiley, New York, 472pp.

Pugh,D.T. and J.M.Vassie, 1976. Tide and surge propagation off-shore in the Dowsing region of the North Sea. Deutsch. Hydrogr. Zeitschr., 29, 163-213.

Pugh,D.T., and J.M.Vassie, 1978. Extreme sea levels from tide and surge probability. Proc. ASCE 16th Coast. Engin. Conf., Hamburg, 911-930.

Pugh,D.T., and J.M.Vassie, 1980. Applications of the joint probability method for extreme sea level computations. Proc. Inst. Civil Engineers, 69, (2), 959-975.

Ramster,J.W., 1965. Studies with the Woodhead sea-bed drifter in the southern North Sea. Lab. Leafl. Fish. Lab., Lowestoft, 6, 4pp.

Ramster,J.W. and H.W.Hill, 1969. Current system in the northern Irish Sea. Nature, 224, 59-61.

Riley,J.D. and J.W.Ramster, 1969. The pattern of bottom currents along the coast of East Anglia in 1968. Int. Council for the Exploration of the Sea, CM1969, C 15, 30pp.

Simpson,J.H. and A.E.Hill, 1986. The Scottish coastal current. In: The role of freshwater outflow in coastal marine ecosystems, Ed Skreslet,S., Springer-Verlag, Berlin, pp 295-308.

Svendsen,E., R.Saetre and M.Mork, 1991. Features of the northern North Sea circulation. Continental Shelf Research, 11, 493-508.

8. FIGURES

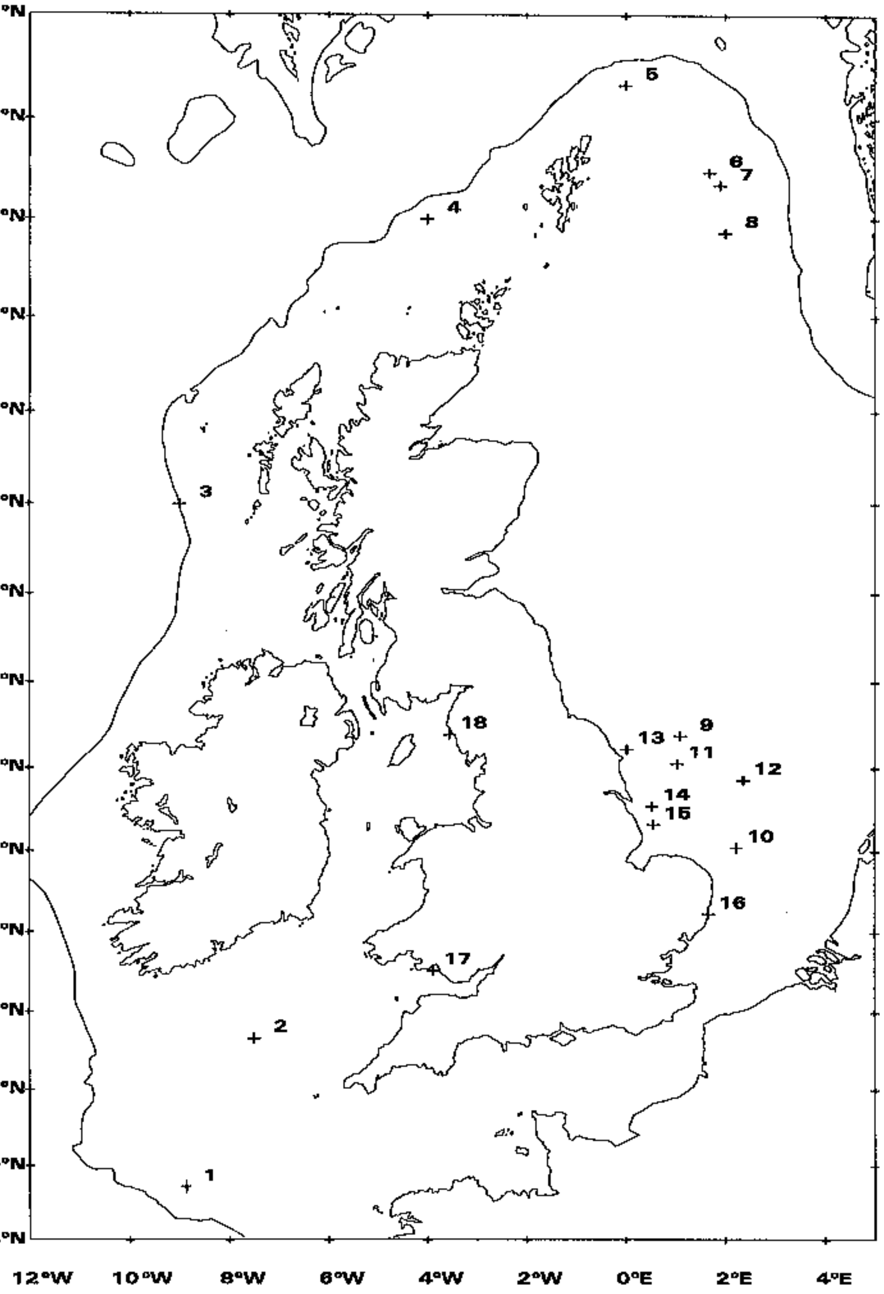

Figure 1
Sites upon the UK continental shelf where current meter records of duration longer than nine months were available for this study. Reference numbers are those used in the text. At sites 11 and 12 shorter records from modern instruments have been used for comparison.

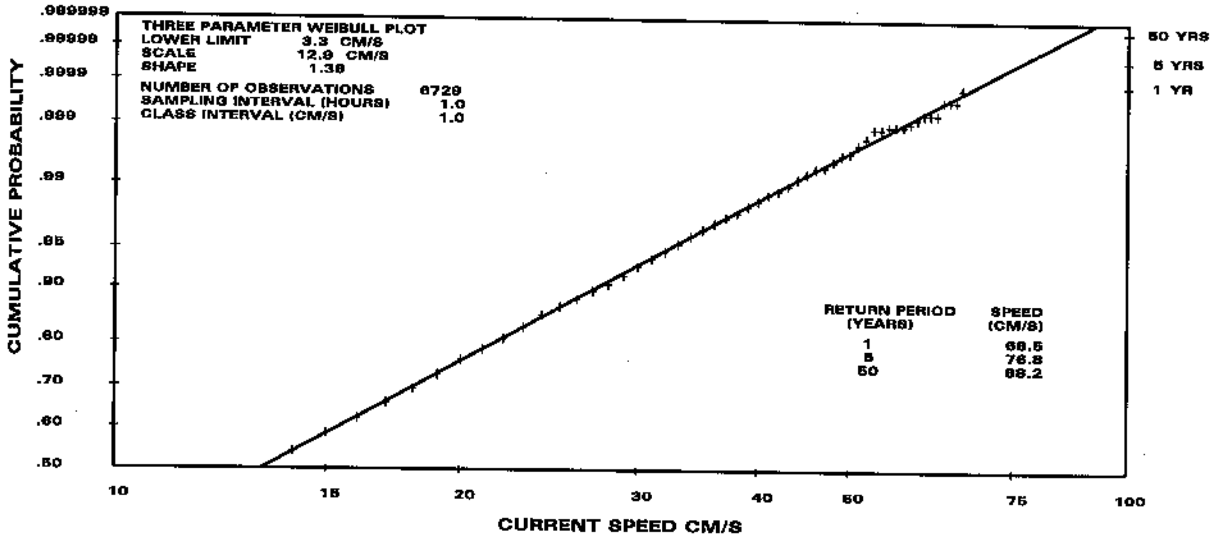

Figure 2

Three parameter Weibull Distribution: Site 1,DB1,(1981),48°42.9'N,8°53.3'E; 3m below the surface in 170m of water.

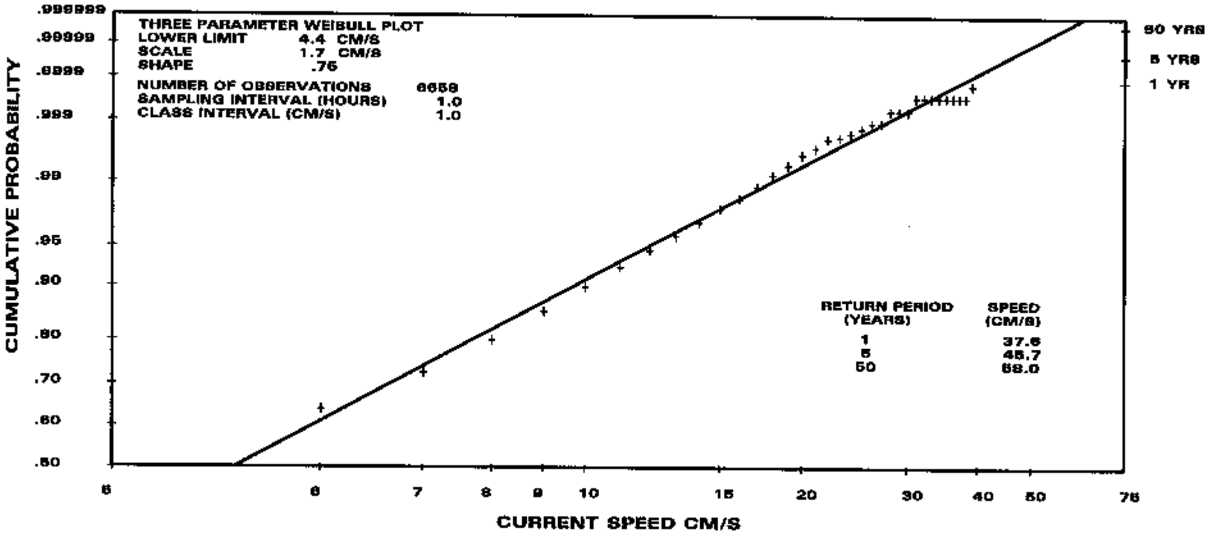

Figure 3

Three parameter Weibull Distribution: Site 2,Boyle,50°40.0'N,7°30.0'W; 92m above the botom in 107m of water.

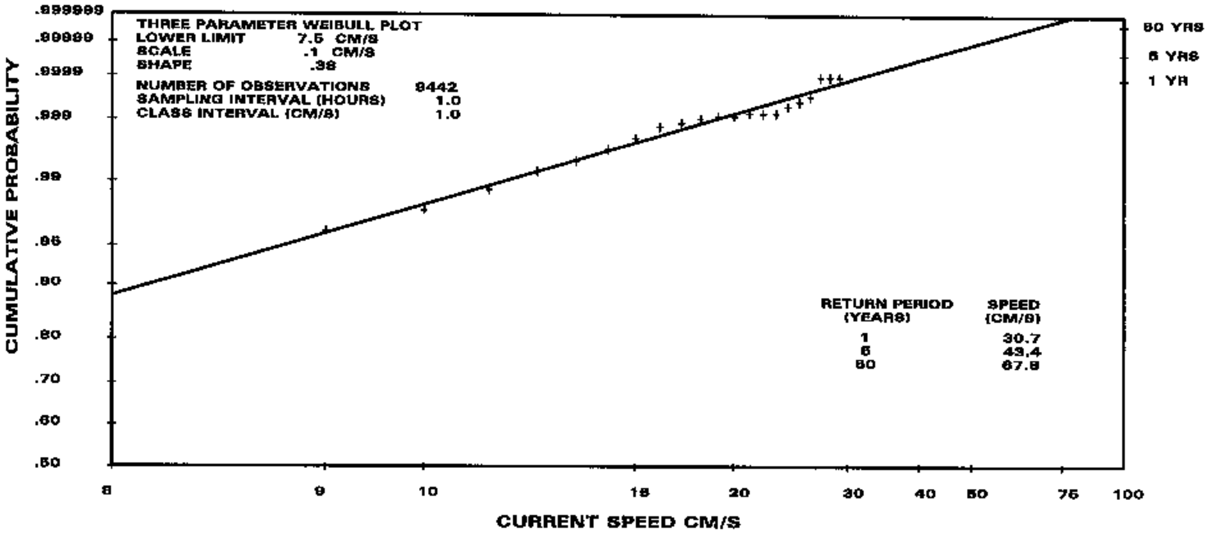

Figure 4

Three parameter Weibull Distribution: Site 2,Boyle,50°40.0'N,7°30.0'W; 31m above the bottom in 107m of water.

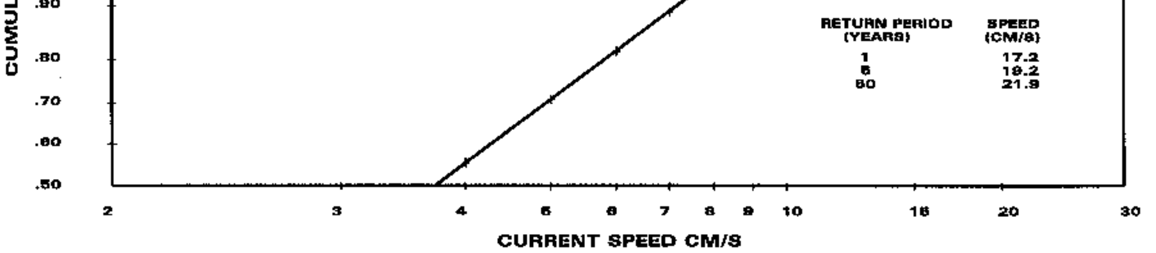

Figure 5

Three parameter Weibull Distribution: Site 2,Boyle,50°40.0'N,7°30.0'W; 3m above the botom in 107m of water.

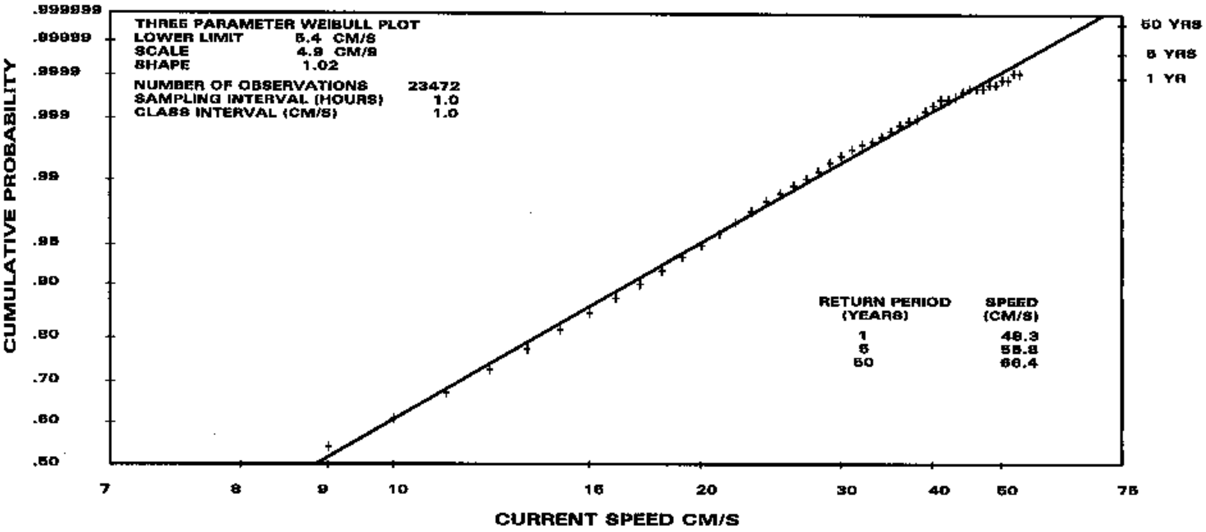

Figure 6

Three parameter Weibull Distribution: Site 3,R,57°00.0'N,9°00.0'W; 98m above the bottom in 130m of water.

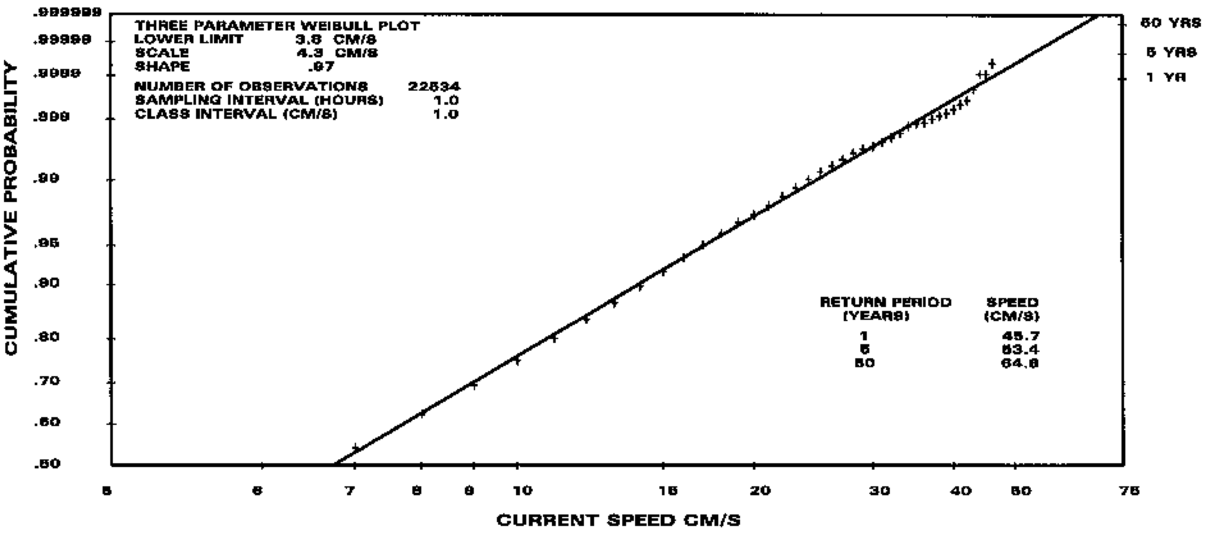

Figure 7

Three parameter Weibull Distribution: Site 3,R,57°00.0'N,9°00.0'W; 28m above the bottom in 130m of water.

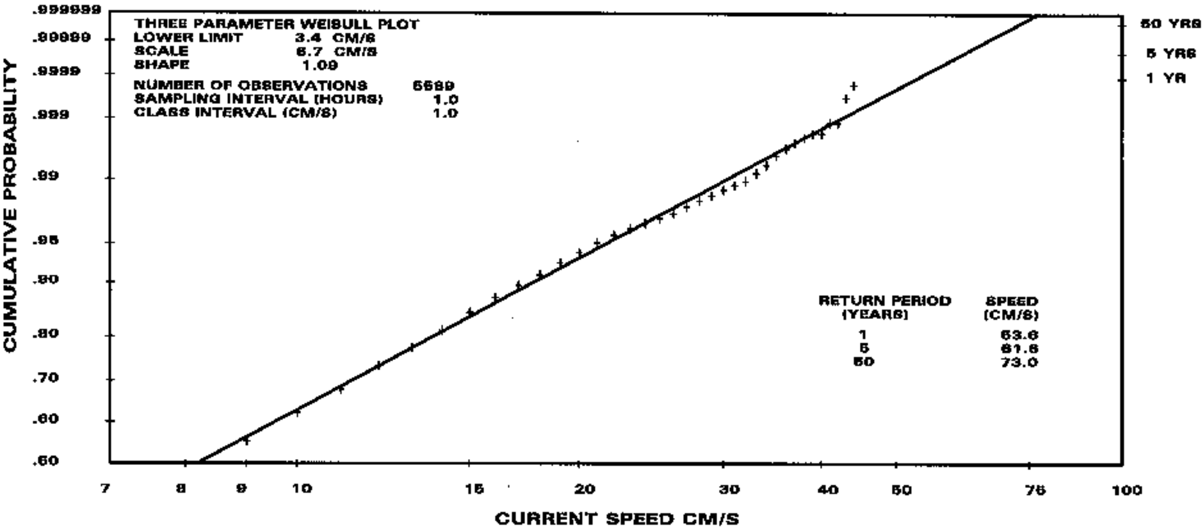

Figure 8

Three parameter Weibull Distribution: Site 4,Fitzroy,60°00.0'N,4°00.0'W; 107m above the bottom in 130m of water.

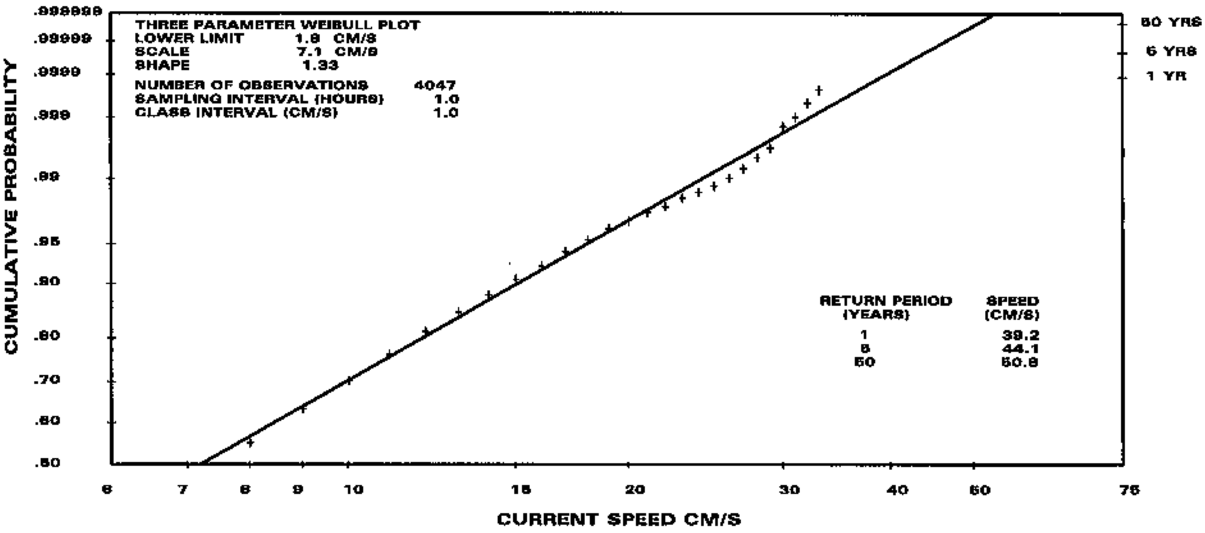

Figure 9

Three parameter Weibull Distribution: Site 4,Fitzroy,60°00.0'N,4°00.0'W; 46m above the bottom in 130m of water.

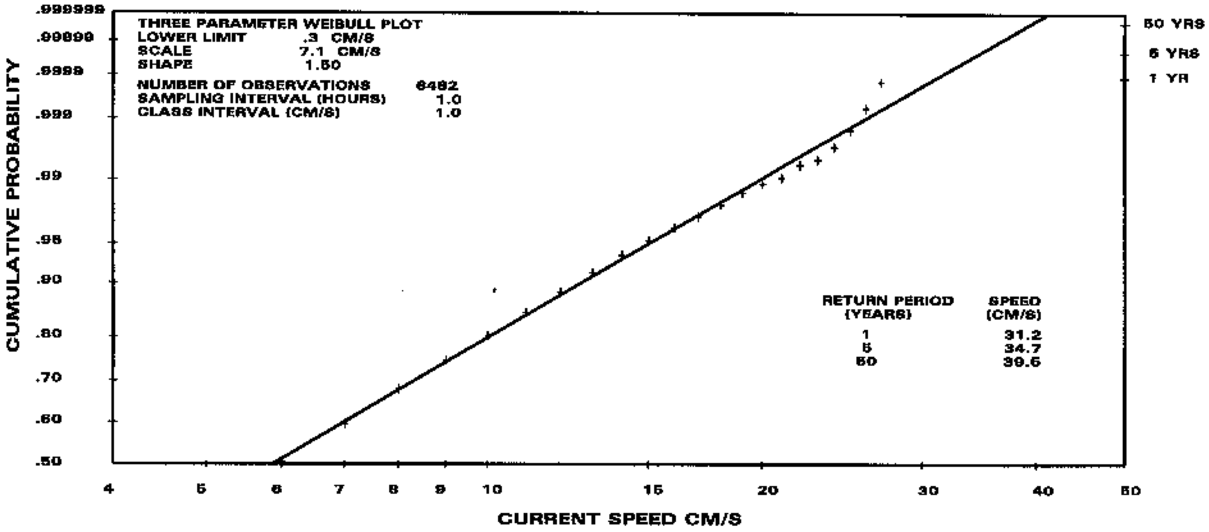

Figure 10

Three parameter Weibull Distribution: Site 4,Fitzroy,60°00.0'N,4°00.0'W; 3m above the bottom in 130m of water.

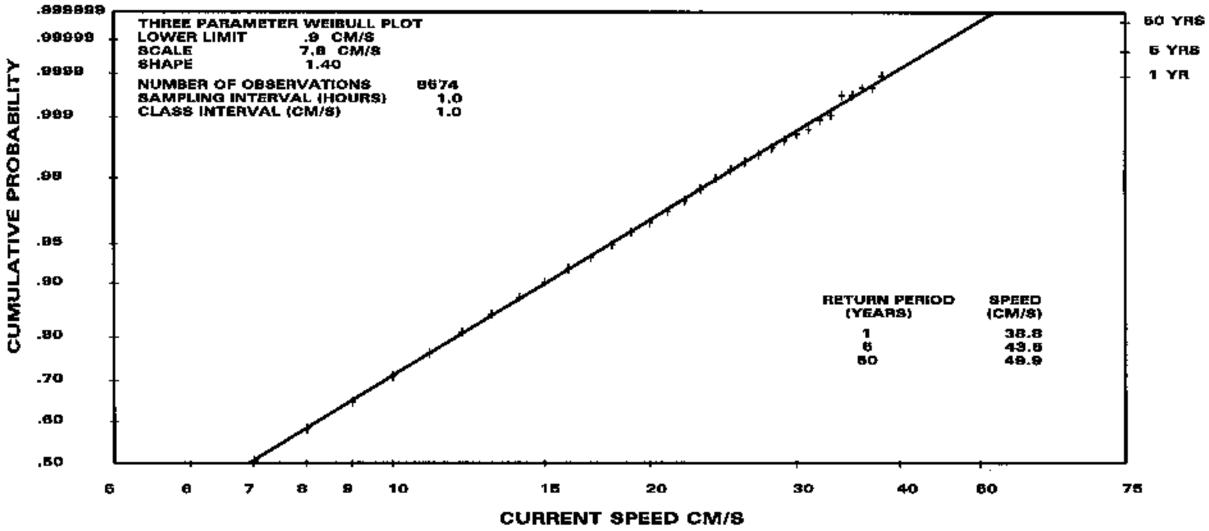

Figure 11

Three parameter Weibull Distribution: Site 5,Stevenson,61°20.0'N,0°0.0'E; 144m above the bottom in 159m of water.

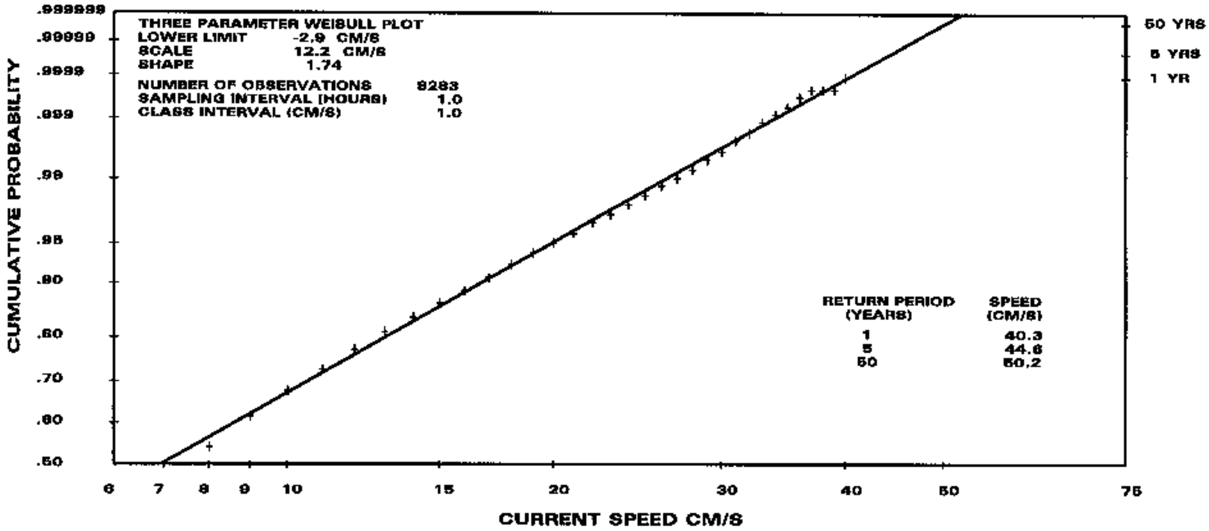

Figure 12

Three parameter Weibull Distribution: Site 5,Stevenson,61°20.0'N,0°0.0'E; 129m above the bottom in 159 of water.

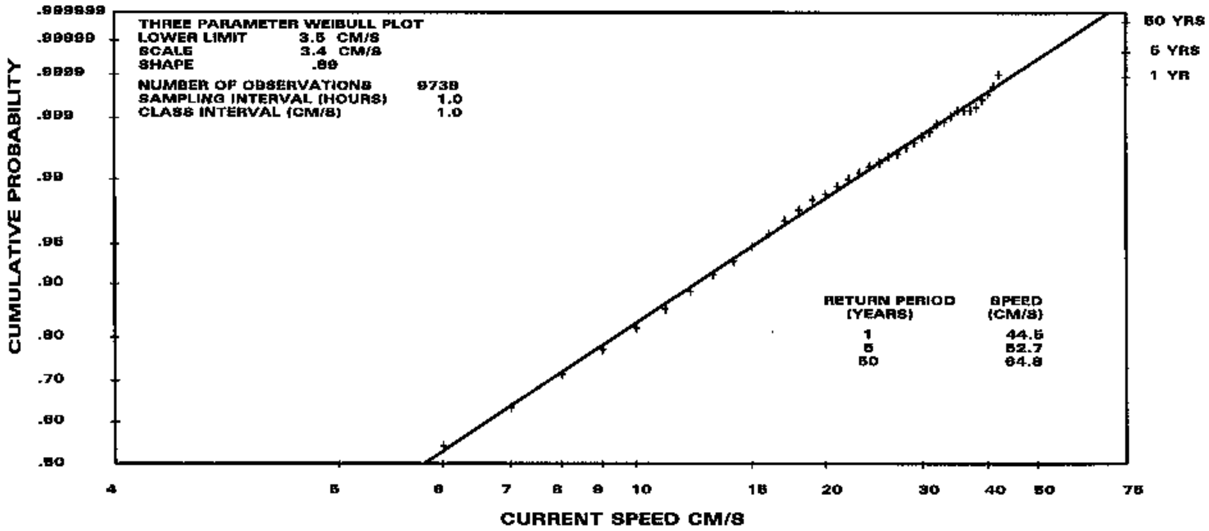

Figure 13

Three parameter Weibull Distribution: Site 5,Stevenson,61°20.0'N,0°0.0'E; 83m above the bottom in 159m of water

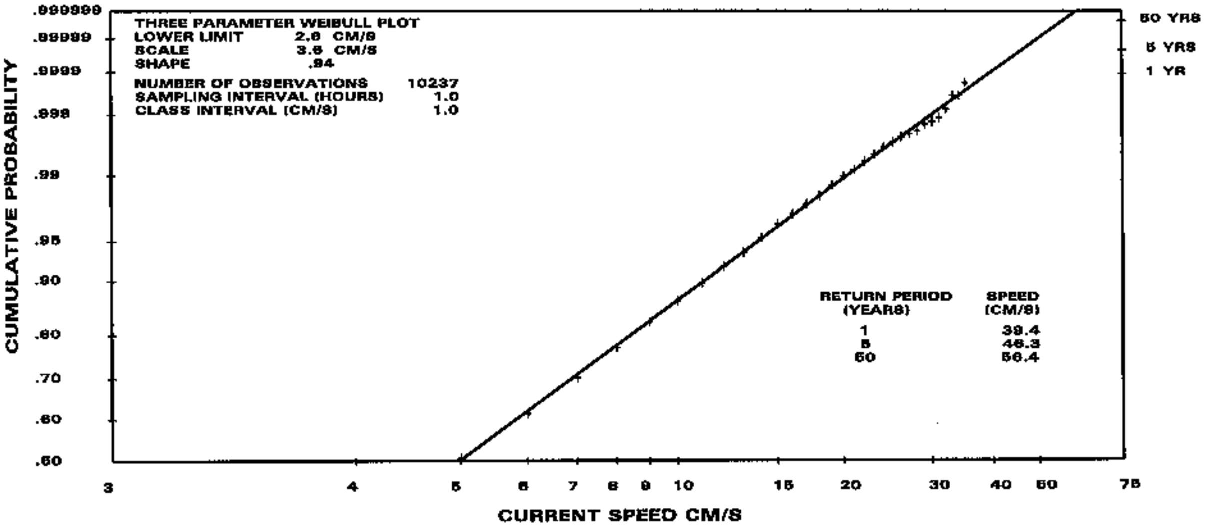

Figure 14

Three parameter Weibull Distribution: Site 5,Stevenson,61°20.0'N,0°00.0'E; 3m above the bottom in 159m of water.

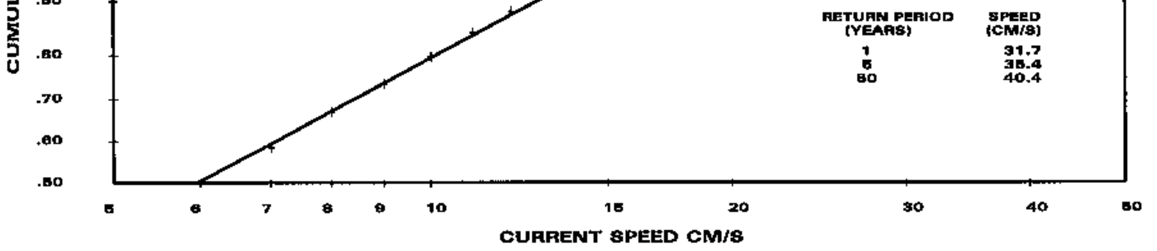

Figure 15

Three parameter Weibull Distribution: Site 6,Total 1,60°28.6'N,1°41.5'E; 2m above the bottom in 130m of water.

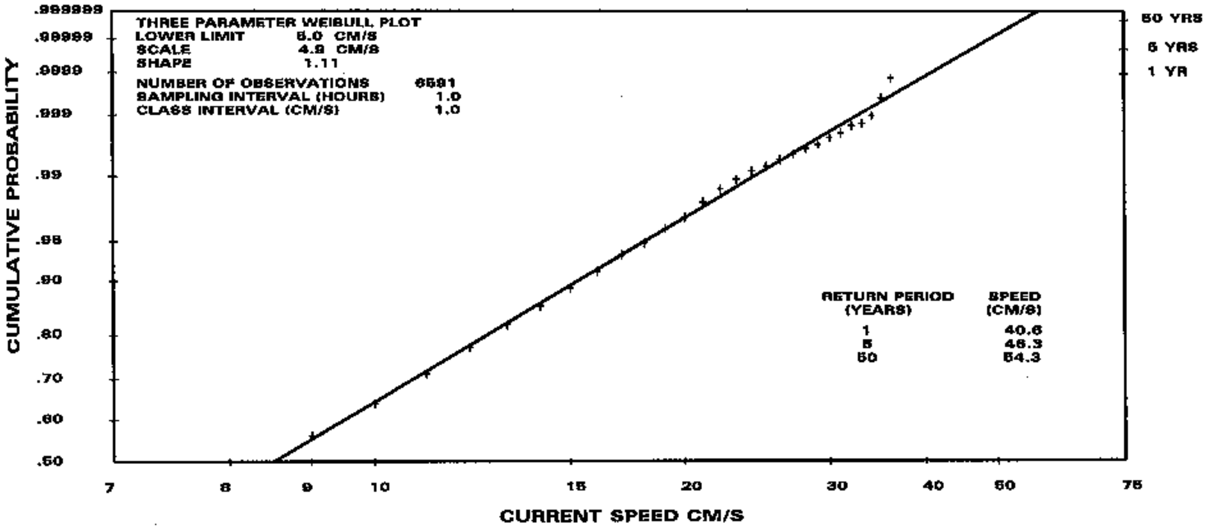

Figure 16

Three parameter Weibull Distribution: Site 7,Total 2,60°20.9'N,1°54.2'E; 2m above the bottom in 120m of water.

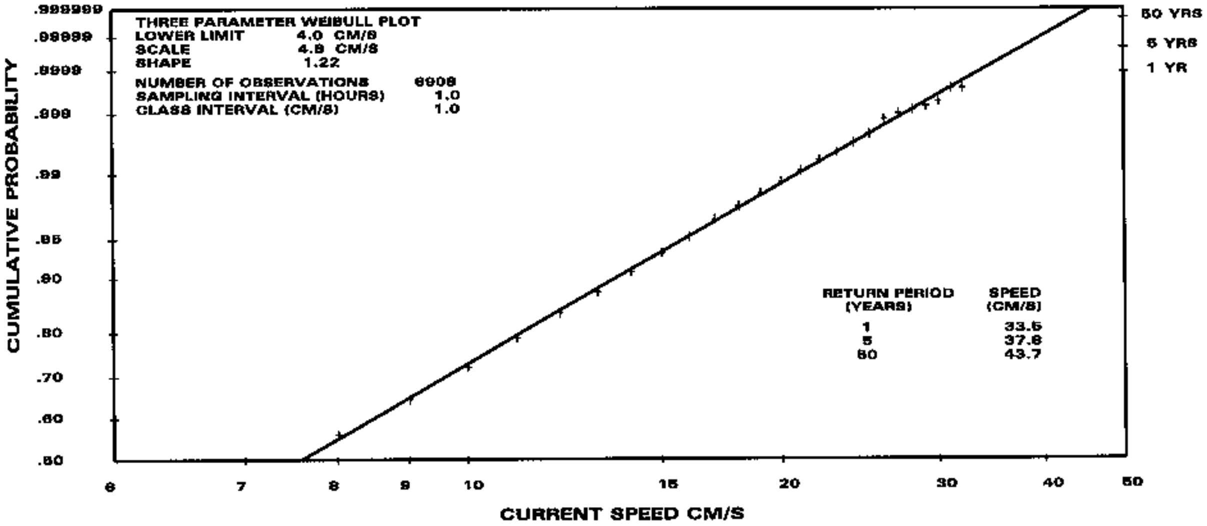

Figure 17

Three parameter Weibull Distribution: Site 8,Frigg,59°51.9'N,2°00.4'E; 2m above the bottom in 110m of water.

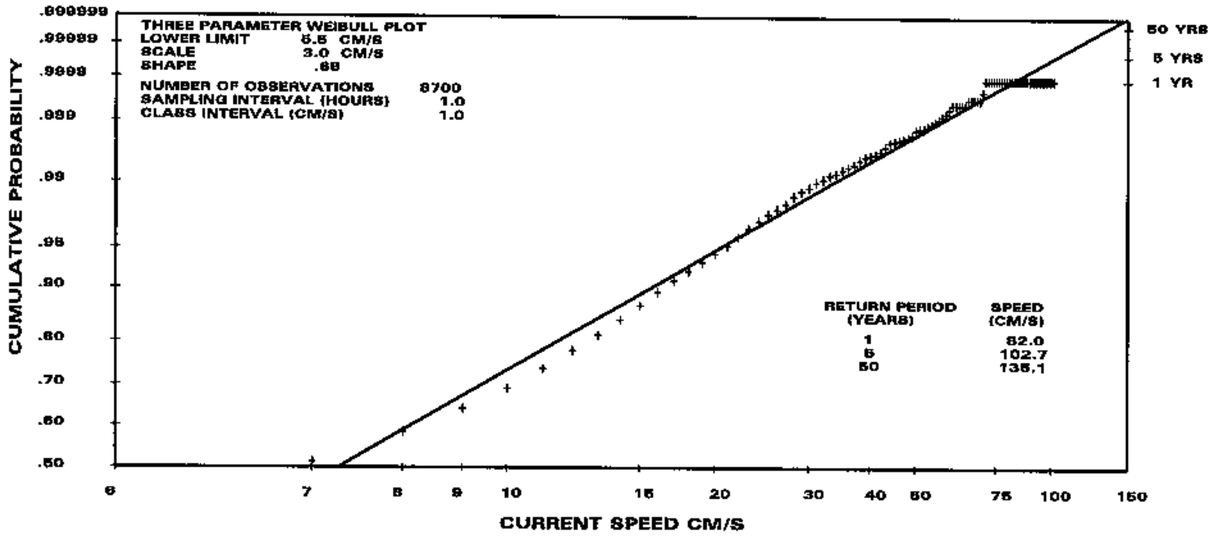

Figure 18

Three parameter Weibull Distribution: Site 9,JONSIS 2,54°23.0'N,1°06.0'E; 29m above the bottom in 42m of water.

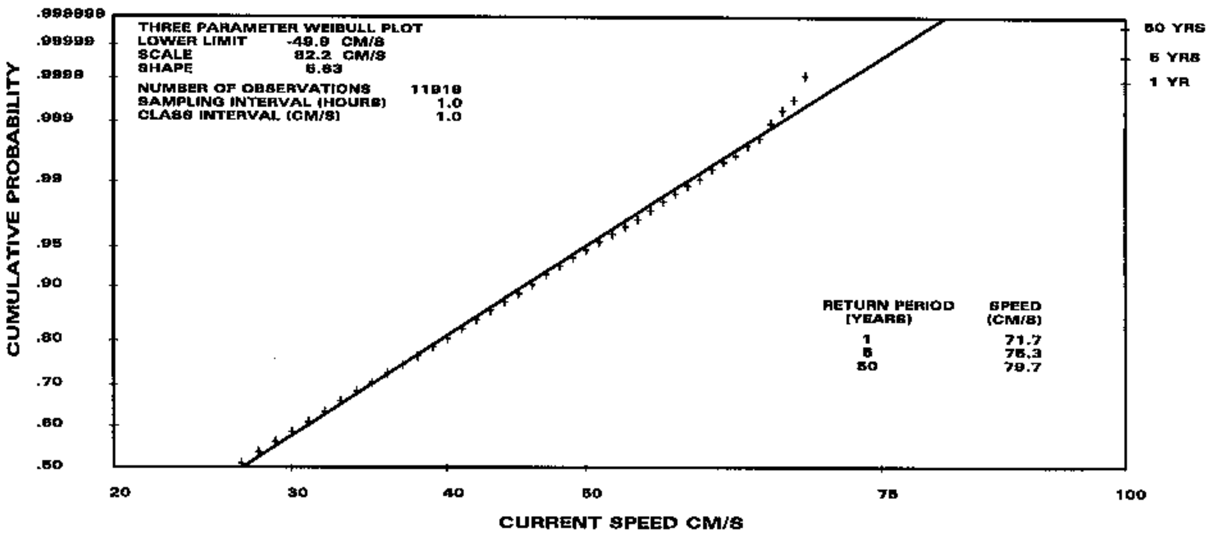

Figure 19

Three parameter Weibull Distribution: Site 9,JONSIS 2,54°23.0'N,1°06.0'E; 8m above the bottom in 42m of water.

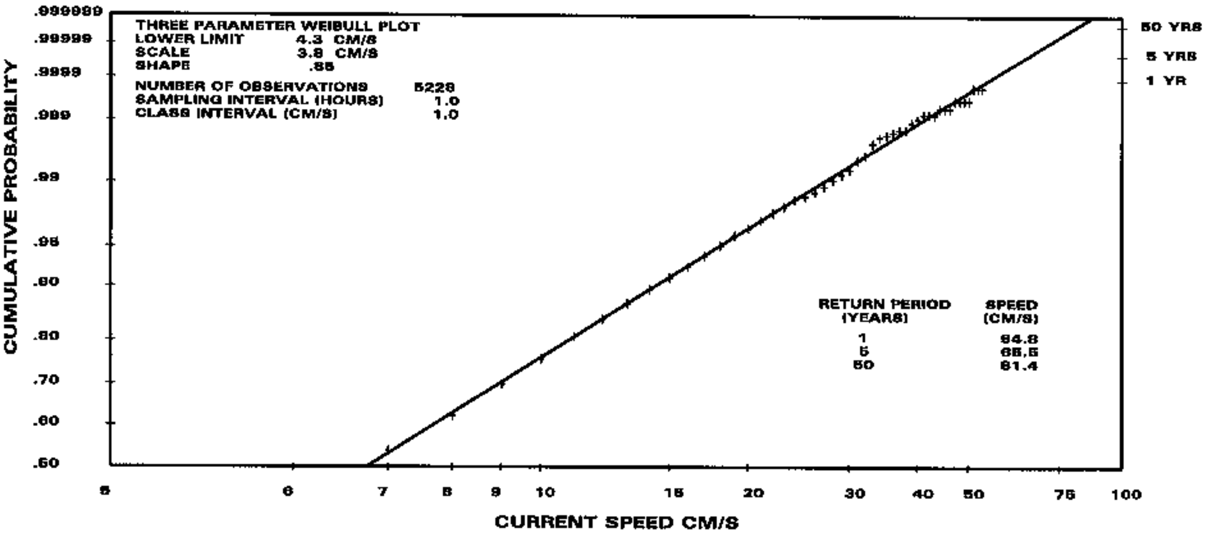

Figure 20

Three parameter Weibull Distribution: Site 10,Leman,53°03.0'N,2°14.0'E; 23m above the bottom in 36m of water.

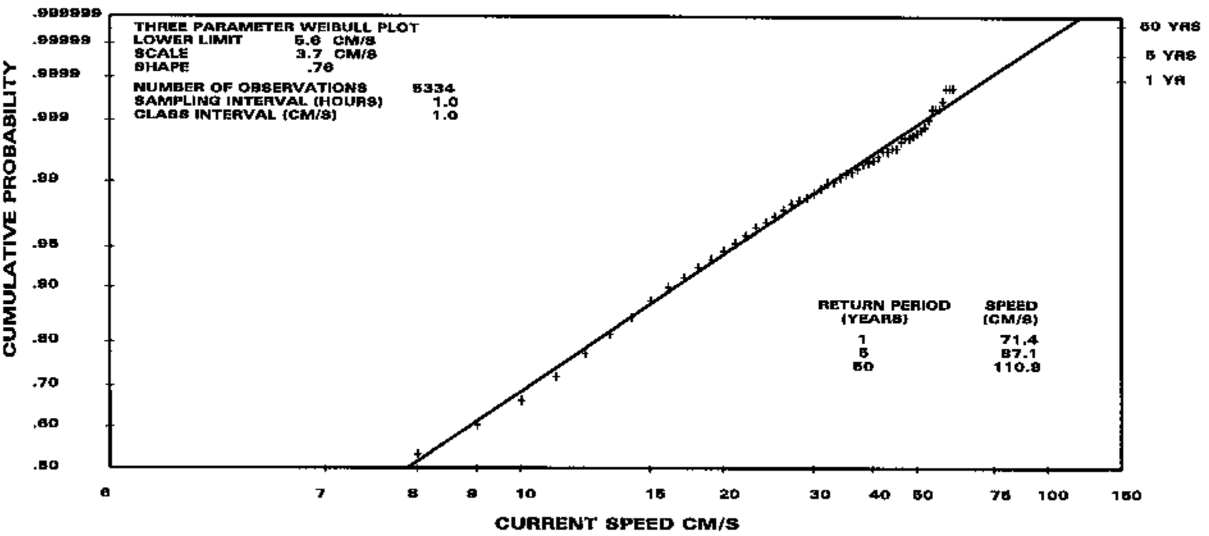

Figure 21

Three parameter Weibull Distribution: Site 11,NS 2,54°03.6'N,1°02.5'E; 46m above the bottom in 48m of water.

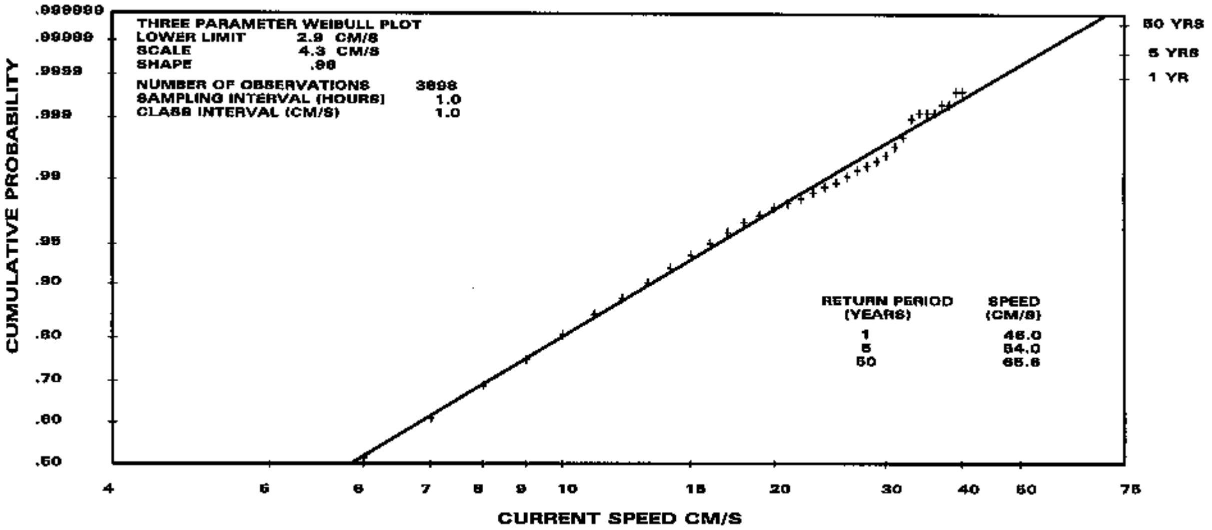

Figure 22

Three parameter Weibull Distribution: Site 11,NS 2,54°03.6'N,1°02.5'E; 20m above the bottom in 48m of water.

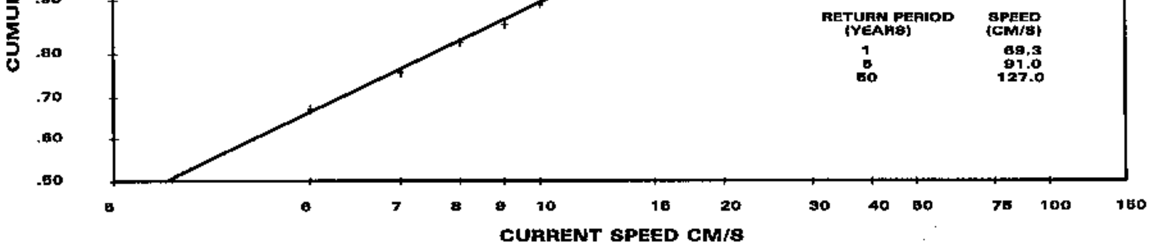

Figure 23

Three parameter Weibull Distribution: Site 11,NS 2,54°03.6'N,1°02.5'E; 5m above the bottom in 48m of water.

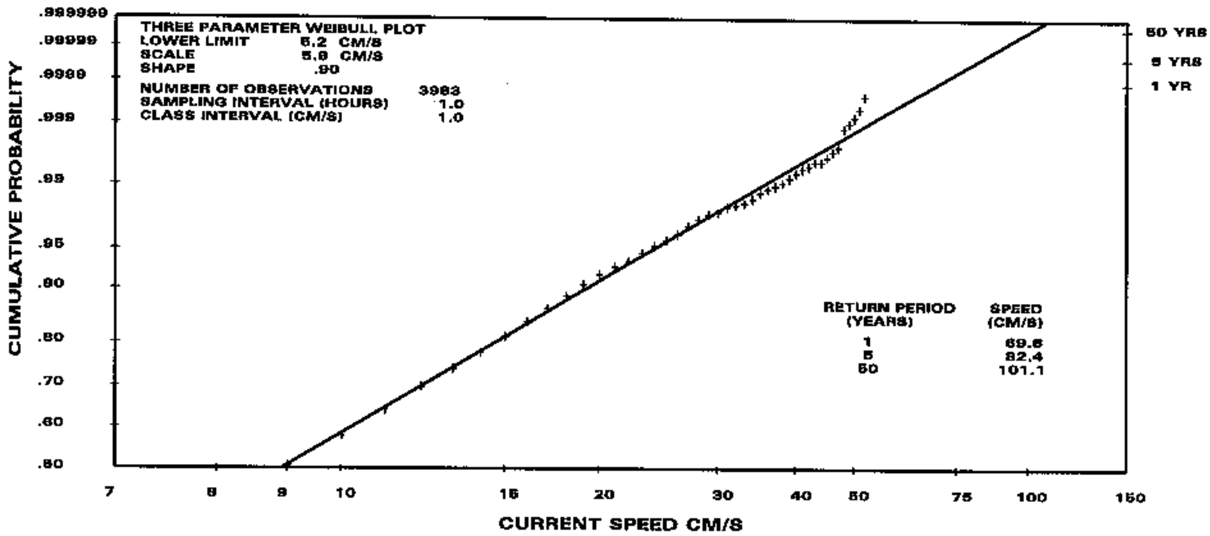

Figure 24

Three parameter Weibull Distribution: Site 12,NS 3,53°51.9'N,2°22.3'E; 36m above the bottom in 38m of water.

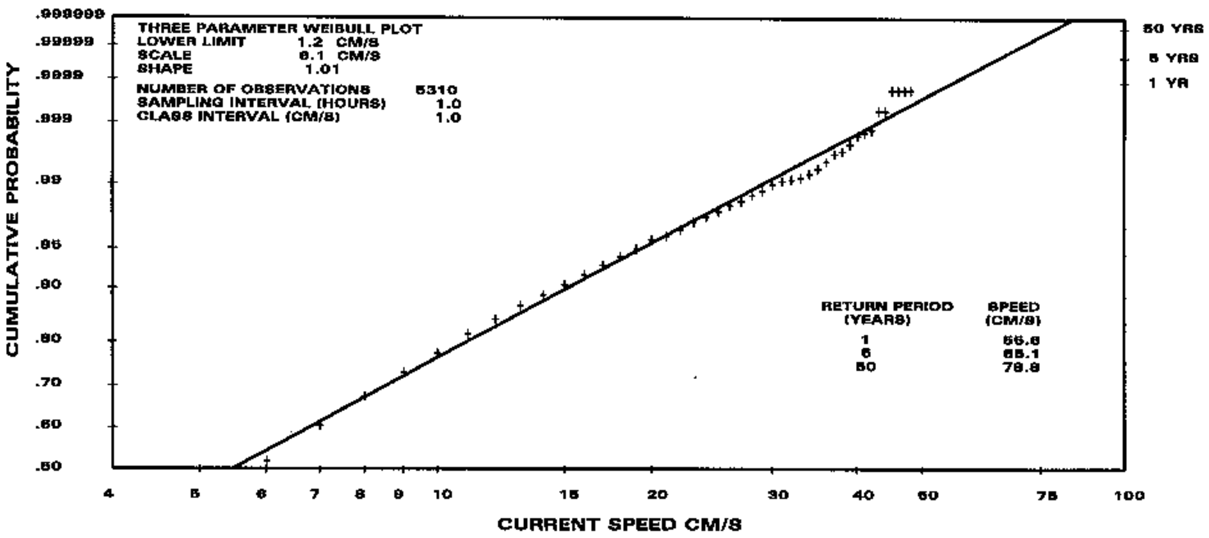

Figure 25

Three parameter Weibull Distribution: Site 12,NS 3,53°51.9'N,2°22.3'E; 15m above the bottom in 38m of water.

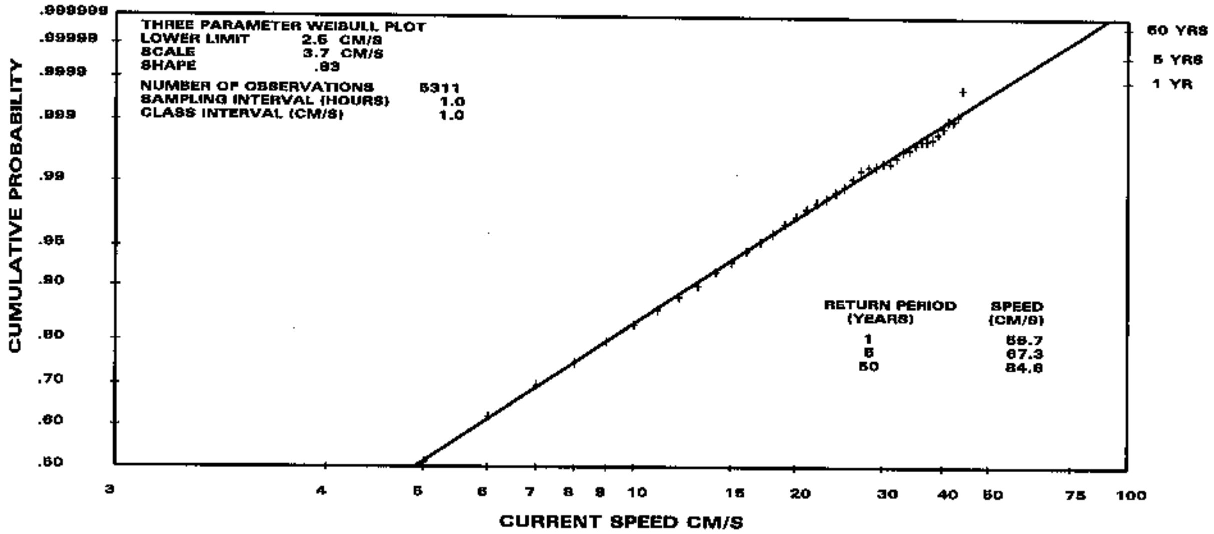

Figure 26

Three parameter Weibull Distribution: Site 12,NS 3,53°51.9'N,2°22.3'E; 5m above the bottom in 38m of water.

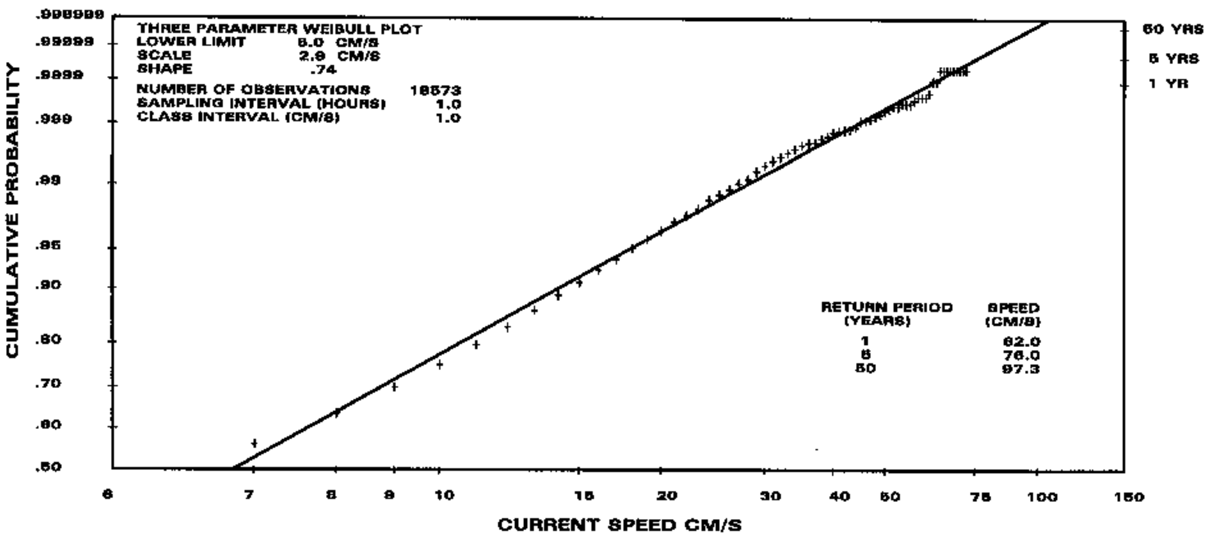

Figure 27

Three parameter Weibull Distribution: Site 13,JONSIS 1,54°13.8'N,0°01.8'E; 40m above the bottom in 55m of water.

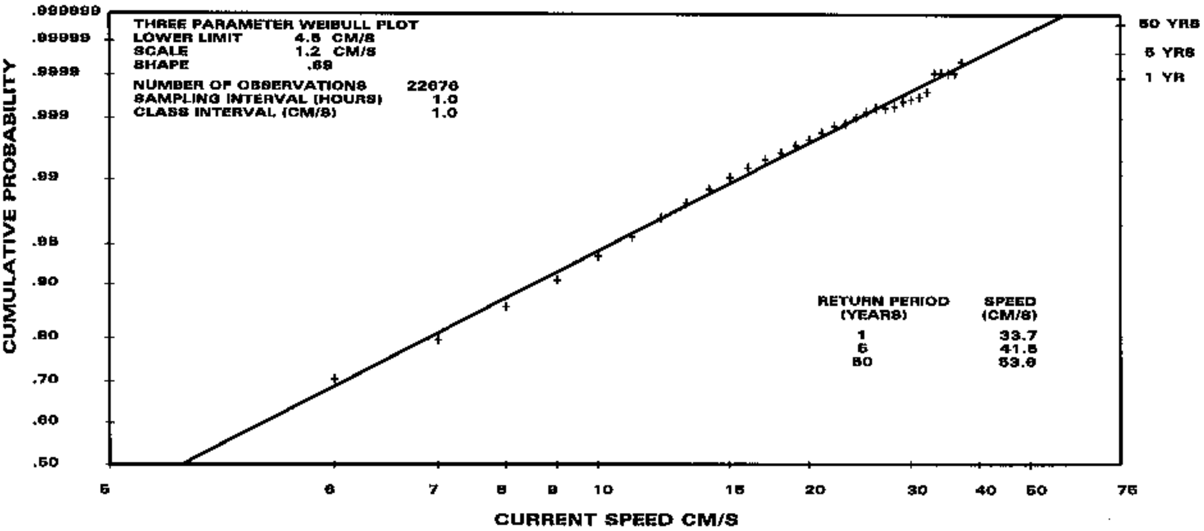

Figure 28

Three parameter Weibull Distribution: Site 13,JONSIS 1,54°13.8'N,0°01.8'E; 5m above the bottom in 53m of water.

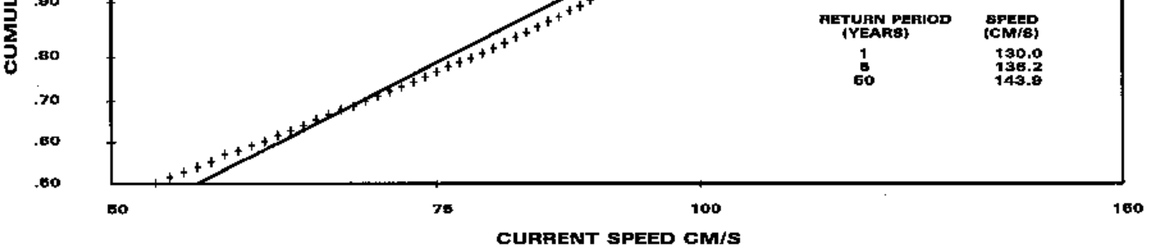

Figure 29

Three parameter Weibull Distribution: Site 14,Humber,53°33.0'N,0°32.0'E; 4m above the bottom in 21m of water.

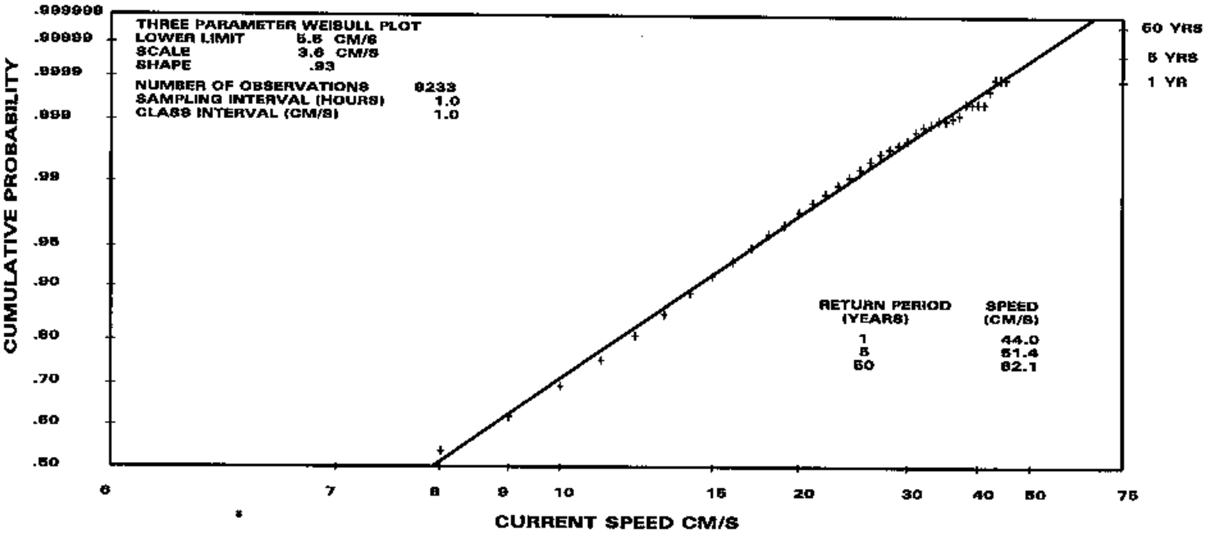

Figure 30

Three parameter Weibull Distribution: Site 15,Inner Dowsing,53°19.8'N,0°33.9'E 14m above the bottom in 17m of water.

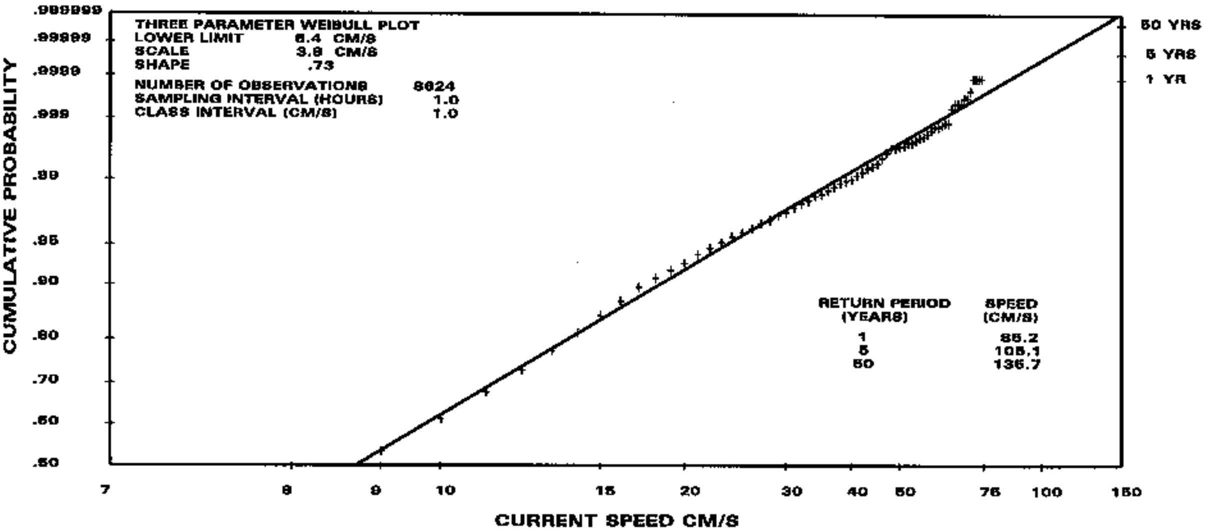

Figure 31

Three parameter Weibull Distribution: Site 16,Sizewell,52°14.0'N,1°40.0'E; 6m above the bottom in 12m of water.

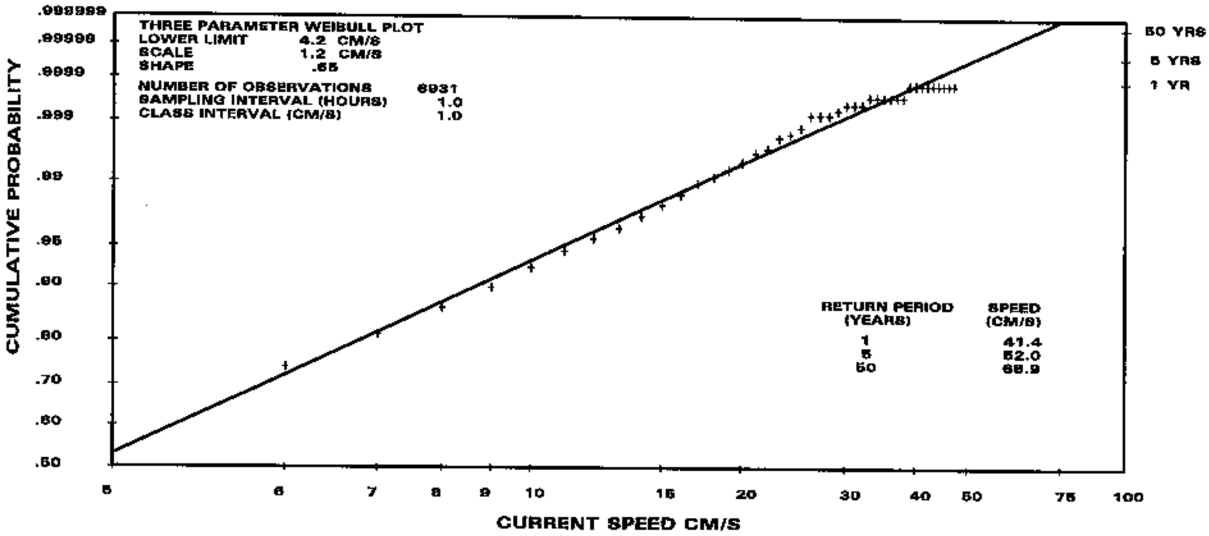

Figure 32

Three parameter Weibull Distribution: Site 17,Swansea Bay,51°31.5'N,3°52.5'W
10m above the bottom in 21m of water.

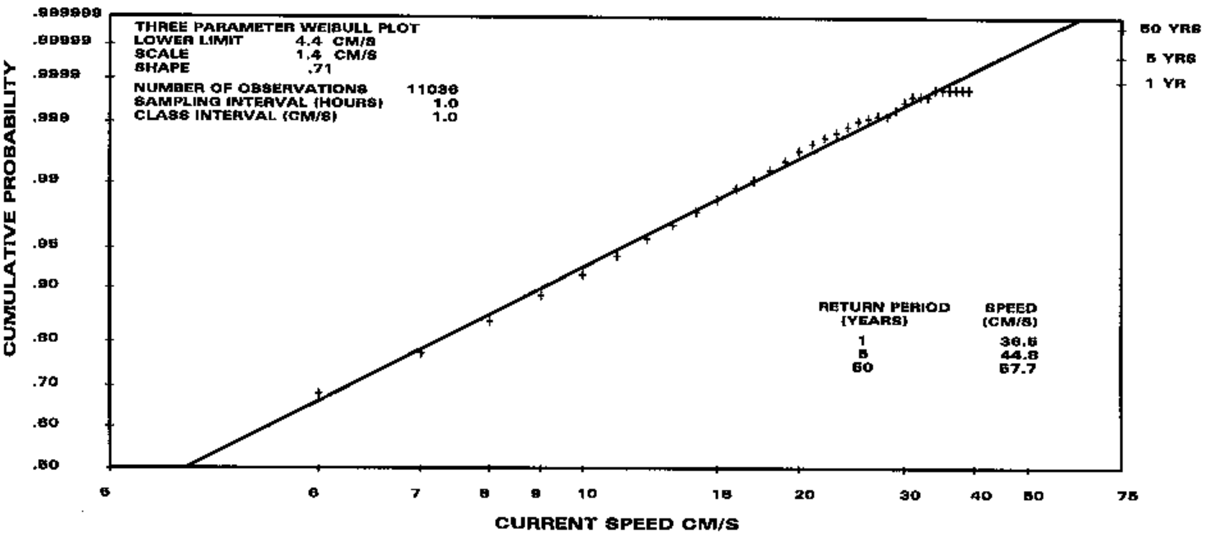

Figure 33

Three parameter Weibull Distribution: Site 17,Swansea Bay,51°31.5'N,3°52.5'W
2m above the bottom in 21m of water.

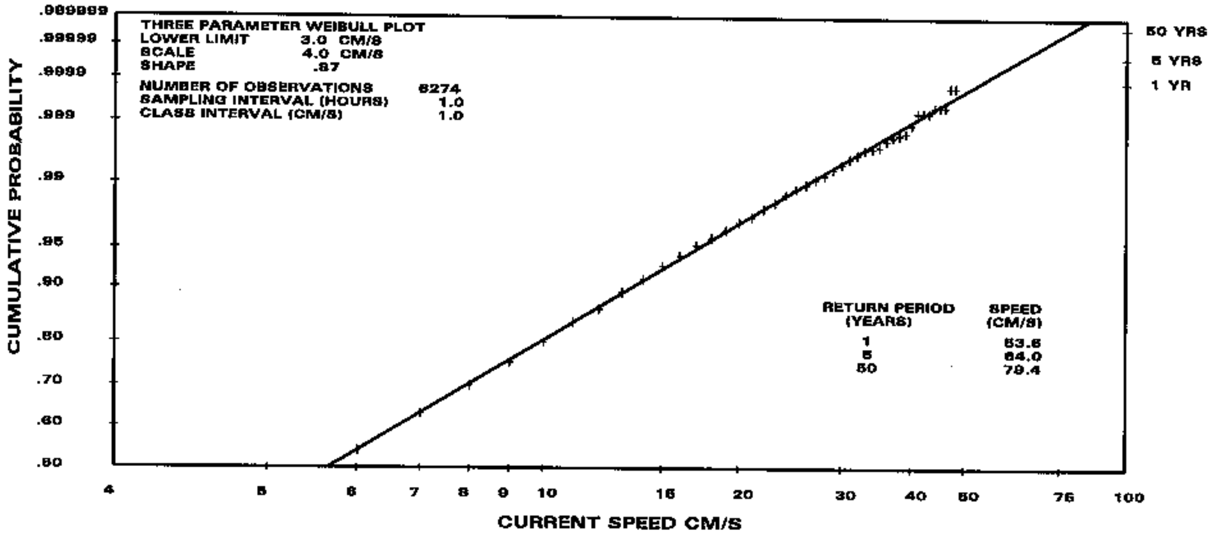

Figure 34

Three parameter Weibull Distribution: Site 18,Sellafield,54°24.0'N,3°33.0'W; 9m above the bottom in 15m of water.

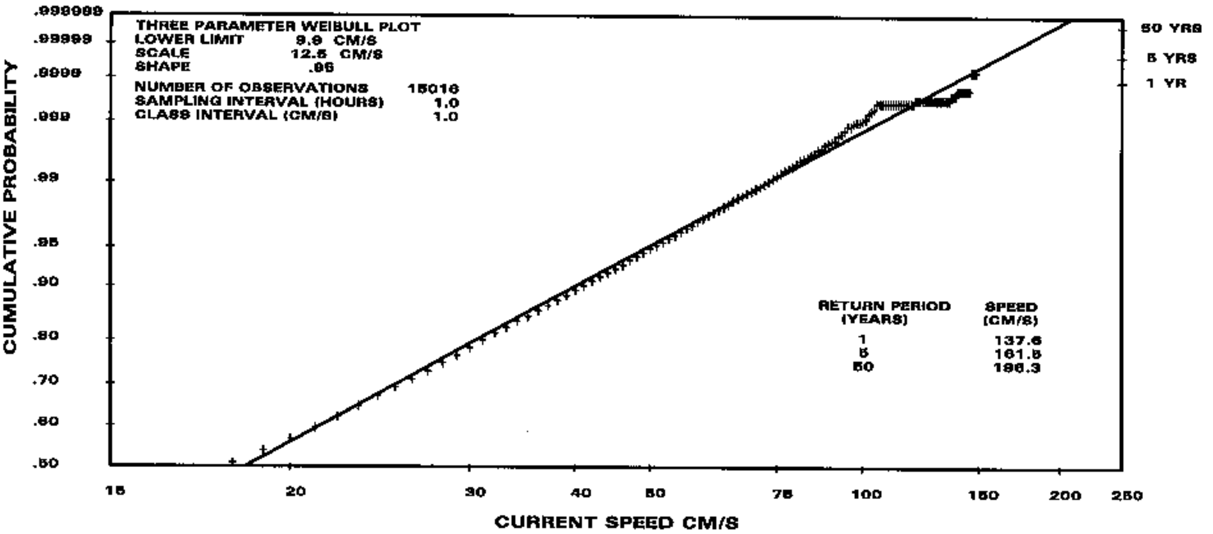

Figure 35

Three parameter Weibull Distribution: Site 19,Tiree,56°37.5'N,6°24.0'W; 23m above the bottom in 45m of water.

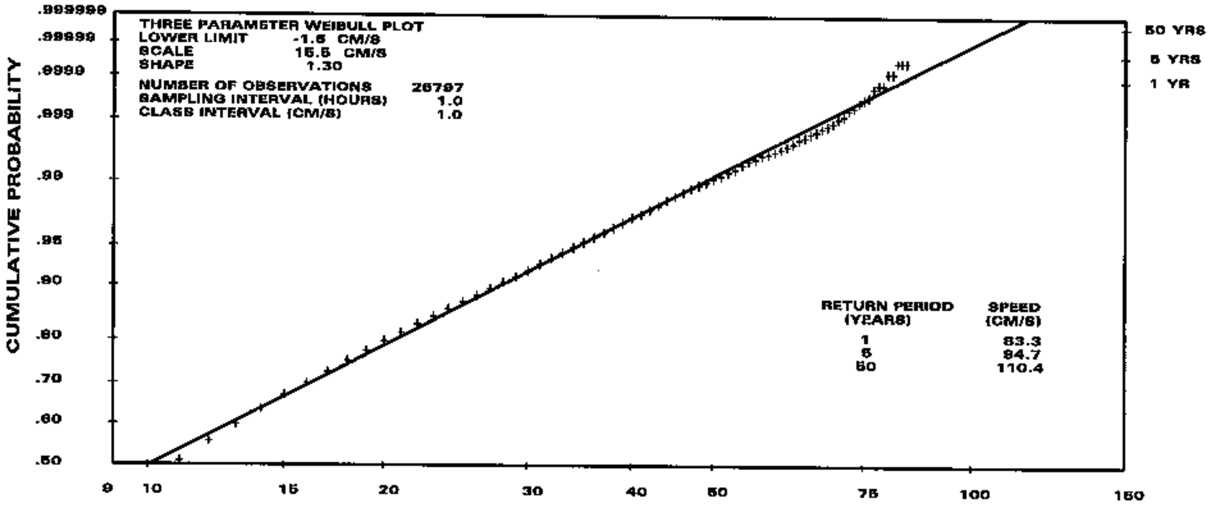

Figure 36

Three parameter Weibull Distribution: Site 19,Tiree,56°37.5'N,6°24.0'W; 11m above the bottom in 45m of water.

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C2 5/96