I.O.S.

REPORT ON THE FEASIBILITY OF USING AN EXISTING 28" DIAMETER ALUMINIUM ALLOY FORGED SPHERE (IOS DESIGN 4994) TO A DEPTH OF 6000 METRES

V. A. LAWFORD and D. I. GAUNT

IOS REPORT NO. 75

1979

NATURAL ENVIRONMENT RESEARCH COUNCIL
INSTITUTE OF
OCEANOGRAPHIC
SCIENCES

INSTITUTE OF OCEANOGRAPHIC SCIENCES

Wormley, Godalming,
Surrey, GU8 5UB.
(0428 - 79 - 4141)

(Director: Dr. A.S. Laughton)

Bidston Observatory,
Birkenhead,
Merseyside, L43 7RA.
(051 - 653 - 8633)

(Assistant Director: Dr. D.E. Cartwright)

Crossway,
Taunton,
Somerset, TA1 2DW.
(0823 - 86211)

(Assistant Director: M.J. Tucker)

On citing this report in a bibliography the reference should be followed by the words UNPUBLISHED MANUSCRIPT.

REPORT ON THE FEASIBILITY OF USING AN EXISTING 28" DIAMETER ALUMINIUM ALLOY FORGED SPHERE (IOS DESIGN 4994) TO A DEPTH OF 6000 METRES

V. A. LAWFORD and D. I. GAUNT

IOS REPORT NO. 75

1979

Institute of Oceanographic Sciences,
Wormley, Godalming,
Surrey GU8 5UB

6) For tests at pressures greater than that at 4000m., the pressure vessel is to be lined with timber - to reduce damage in the event of failure. Also, the sphere is to be filled with water, with a pipe leading to atmosphere - to reduce the amount of energy available in the event of sphere failure.

7) Finally, monitoring those strain gauges showing the highest levels, the sphere is to be subjected to a pressure equal to a depth of 6000m. During this test the output of the gauges and the volumetric contraction of the sphere are to be continually examined for any deviation from linearity.

Calculations

Sphere O/D	28in.	(0.711m.)	R_1 = 14in.	(0.355m.)
Sphere I/D	25.5in.	(0.684m.)	R_2 = 12.75in.	(0.342m.)

Material specification for R.R.77 aluminium alloy:

0.1% proof stress (f_c)	463MN/m^2
Modulus of elasticity (E)	73.3GN/m^2
Poisson's ratio (m)	0.3

Values for f_c, E and m have been extracted from the manufacturers' specifications; from our previous experience with this material they may be considered very reasonable.

From thick wall theory: $P = \frac{2}{3} \frac{f_c}{R_1^3} (R_1^3 - R_2^3)$ where P is the external pressure.

Thus with a factor of safety of 1.5, the maximum allowable depth is 4900m.
" " 1.3 " " " 5660m.
" " 1.2 " " " 6130m.

And collapse would be expected at 7330m. This theory predicts a stress of 376MN/m^2 at a depth of 6000m.

From thin wall theory: $P = \dfrac{2f_c(R_1-R_2)}{R_1}$

contd. /

Report on the feasibility of using an existing 28 inch diamter aluminium alloy forged sphere (IOS design 4994) to a depth of 6000 metres

These spheres were originally designed to contain instrumentation for seismic and similar work, on the sea floor, to a depth not exceeding 5000m.

The two hemispheres and the equatorial ring that make up the sphere are forged from R. R. 77 aluminium alloy and anodised after machining.

As the original specification called for the sphere to be designed with the maximum possible amount of buoyancy at 5000m., a low factor of safety on the collapse strength was used. In view of this, it was decided to proceed with considerable caution before actually subjecting a sphere to the full 6000m. pressure in one of our pressure vessels.

The following programme of tests and checks was drawn up and adhered to throughout the investigation:

1) Calculate stress and volumetric strain using manufacturers' specified values for the 0.1% proof stress, compressive proof stress, modulus of elasticity and Poisson's ratio, the calculations being based upon a true homogeneous sphere.

2) Decide, in the light of the calculations, on a factor of safety to be worked to and thus the maximum allowable stress.

3) Investigate the pattern of strain on the internal face of the sphere using straing sensitive lacquer.

4) Fix a number of strain gauges to the internal face of the sphere at positions to be determined from the previous test and investigate their outputs at low stress levels.

5) At no time during the investigation up to this point was the sphere to be subjected to a pressure greater than that at 4000m.

Thus with a factor of safety of 1.5, the maximum allowable depth is 5400m.
" " 1.3 " " " 6220m.
" " 1.2 " " " 6720m.

And collapse would be expected at 8050m. This theory predicts a stress of $343 MN/m^2$ at a depth of 6000m.

At this point it was decided that a factor of safety of less than 1.3 could not be tolerated. And if the assembled sphere could be shown to behave between or better than these two theories, then they would be considered suitable for operation at 6000m. A factor of safety of 1.3 on the 0.1% proof stress allows a maximum working stress in the material of $356 MN/m^2$.

Again using thick wall theory:

$$\text{Decrease in } R_2 = \frac{PR_2}{E}\left[\frac{3R_1^3(1-m)}{2(R_1^3-R_2^3)}\right] = \Delta R_2$$

$$\text{Therefore volumetric change} = 4/3\,\pi\left(R_2^3 - (R_2 - \Delta R_2)^3\right)$$

At 6000m. this theory predicts a volumetric contraction of the sphere of 1560ml.

For subsequent strain gauge tests, using a factor of safety of 1.3, a limit of 4900.ε was imposed.

Preliminary Tests

A number of preliminary tests were made in order to check that the strain gauging techniques in use were suitable (Appendix A); also to determine whereabouts on the hemisphere strain gauges should be attached.

A strain sensitive lacquer was applied to the inside surface of one of the hemispheres. The sphere was then assembled and subjected to a pressure of $20 MN/m^2$ for a few hours to allow the lacquer to set hard. When the sphere was opened the cracks in the lacquer were stained and photographed. These photographs are shown in Plates 1 - 6.

Plate 1: This shows a general view of the hemisphere. The lacquer shows as the dark

shiny area. The location of the remaining photographs may be determined by the numbered tags.

Plate 2: This is the area at the centre of the hemisphere.

Plates 3 and 4: These show the middle area either side of Plate 2.

Plates 5 and 6: These show the edges of the hemisphere.

In the central areas - Plates 3 and 4 - the strains are moderate and show little directionality. This area approximates most nearly that of a true sphere. Moving down to the centre of the hemisphere - Plate 2 - the effect of the boss is clearly shown. An increase in radial stress is indicated by the increased density of the cracks as the boss is approached. On the boss itself, the cracks radiate from the two holes in the classical fashion. Towards the rim of the hemisphere - Plates 5 and 6 - the cracks become strongly unidirectional, indicating more hoop stress and less axial stress. However, at about 5cm from the rim the pattern changes sharply. In line with the bolting bosses the cracks change direction through 90° and the closeness of the cracks indicates a generally high stress area. Between the bolting bosses directionality is lost. In the area nearest the rim stress again becomes predominantly hoop.

The preliminary strain gauge tests were carried out on a piece of aluminium alloy tube made from R. R. 77 and anodised. These tests indicated that making no allowance for the expected errors an agreement with theory of better than 5% may be expected in what is a quite simple stress system. They also showed that our gauging techniques and electronics were adequate. The results of these tests are shown in Appendix A.

Strain gauges were now fixed to one of the hemispheres at the eight positions shown on Plates 2, 4, and 6. Each position had gauges aligned to measure both hoop and axial strains. The hemisphere to which the gauges were attached was slightly different to the one used for the lacquer tests and shown in the photographs. Plate 2 shows the centre of the hemisphere protruding down slightly and being flat; whereas the hemisphere that was gauged had had this area machined to be continuous with the spherical curve.

As it was not possible to bring all the leads from the gauges out of the pressure vessel at one time, three tests were carried out to prove the system and to decide which gauges should be monitored during the final tests. For these initial tests the assembled sphere was left air filled and the pressure applied was limited to 25 MN/m^2. The measurements made are shown in Appendix B, Tests 1, 2 and 3, and are summarised in the Table of Results.

Final Proof Tests

From the above tests it was decided which positions should be monitored for the final proof tests. For these tests also, a small bore copper pipe was led from the sphere, via a 0.012in diameter orifice, to the pressure vessel lid, through a gland and then to a calibrated container. The sphere was filled with fresh water for these final tests and the contraction was measured in the calibrated container.

The measurements made during tests 4 and 5 are shown in Appendix B and are summarised in the Table of Results. At the start of test 4 a cable connector inside the pressure vessel failed and so measurements were made at only three positions and of the volumetric contraction.

The Table of Results sums up the results of all five tests conducted on the assembled sphere. Measurements were started at a pressure of 3.45 MN/m^2 for two reasons: firstly, the assembly seemed to suffer some initial settling and secondly, due to the quantity of timber inside the pressure vessel it took 1½ hours to obtain this pressure, longer than the remainder of the test. The final reading at 3.45MN/m^2 was taken at least 2½ hours after that pressure had been reached. It took that long for all the water to be sucked back into the sphere from the measuring container.

Conclusions

From the stress/depth graph it can be seen that the maximum measured stress is slightly below that predicted by either thick wall or thin wall theory. Also it shows that the maximum allowable stress in the material, 356 MN/m^2, will not be reached until a depth of about 6500m. is attained. Therefore we would recommend that only selected and specially tested spheres, to I.O.S. design number 4994, be used to a depth not exceeding 6000m.

A number of further points arise from this investigation:

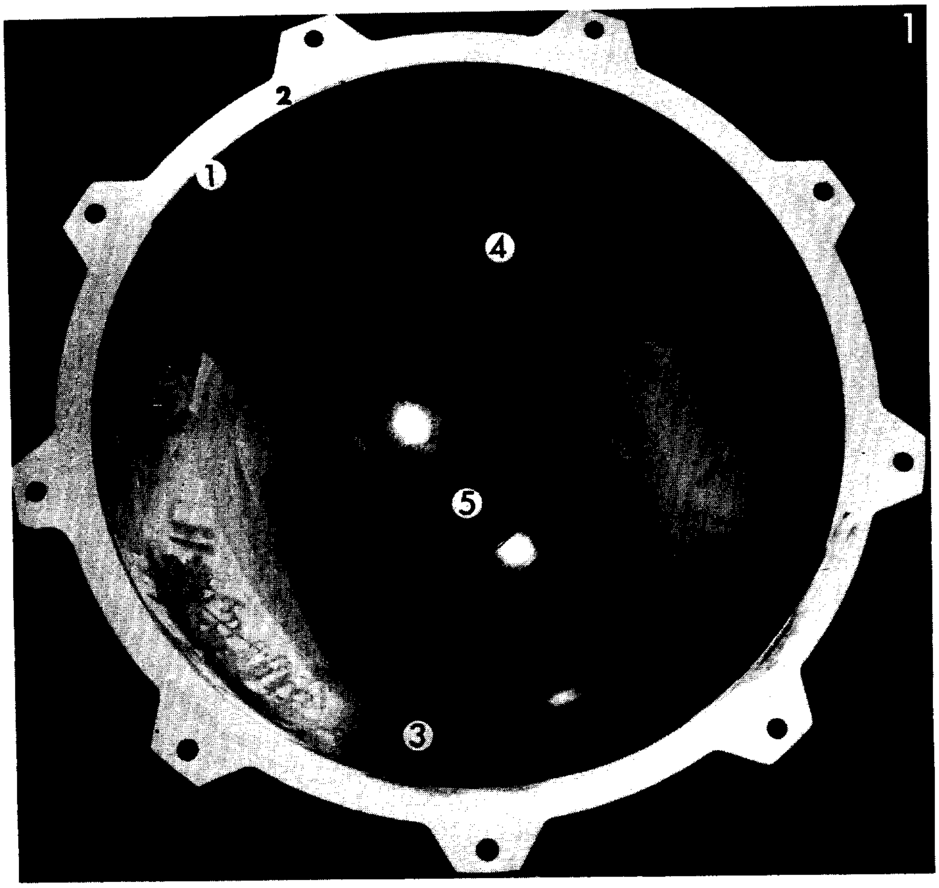
1) From the stress/depth graph it is obvious that in this particular case both Thick Wall and Thin Wall theories are conservative. It was originally expected that position 'B' on the hemisphere would behave in a similar manner to a true sphere. There are a number of possible reasons for the discrepancy. In all the assumptions made in the application of the theories, figures used tended to err on the side of safety e. g., the value for the Modulus of Elasticity used is a manufacturers' guaranteed minimum. Also, the thickness of the hemisphere used is the minimum allowable. Lastly, no allowance was made for the effect of the very strong equatorial ring which must be responsible for considerable stiffening of the assembled sphere in that area.

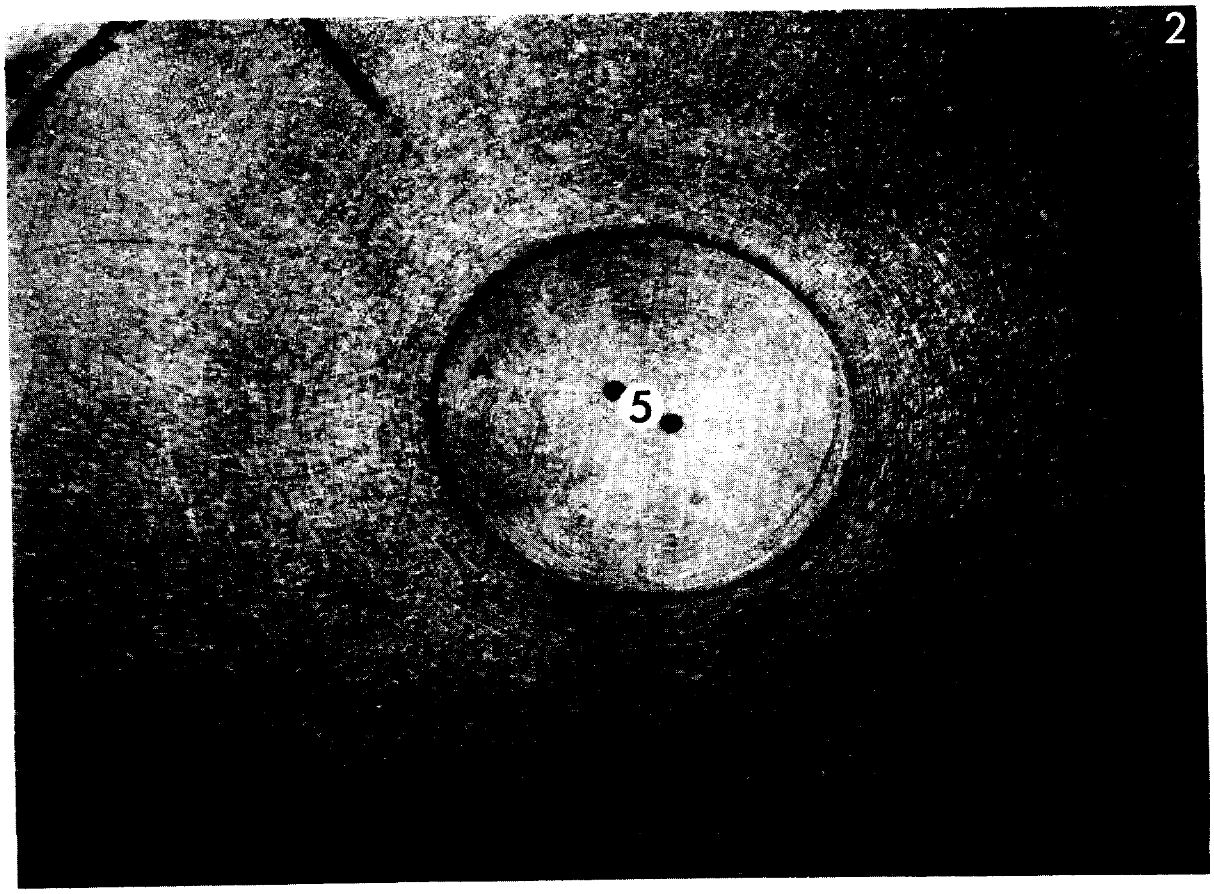
2) Stain lacquer techniques are useful in this context for determining the general strain pattern and indicating areas of particular interest. However, due to the difficulty in controlling both temperature and humidity during the application and curing of the lacquer, both of which seriously effect its strain calibration, it was not considered worthwhile attempting to obtain quantitative information.

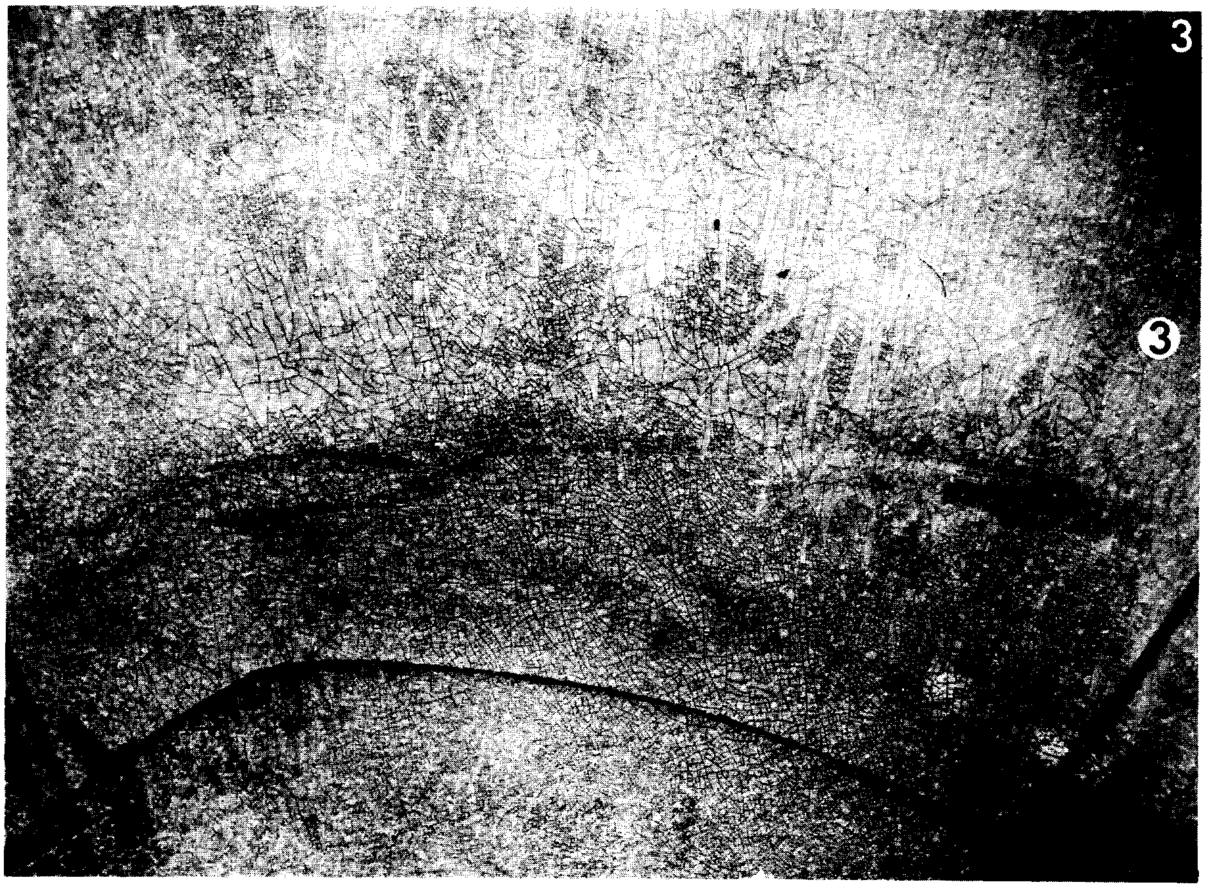
3) The stresses measured generally matched the strain pattern obtained with the lacquer.

4) This type of investigation is very necessary when attempting to design complex structures with low factors of safety.

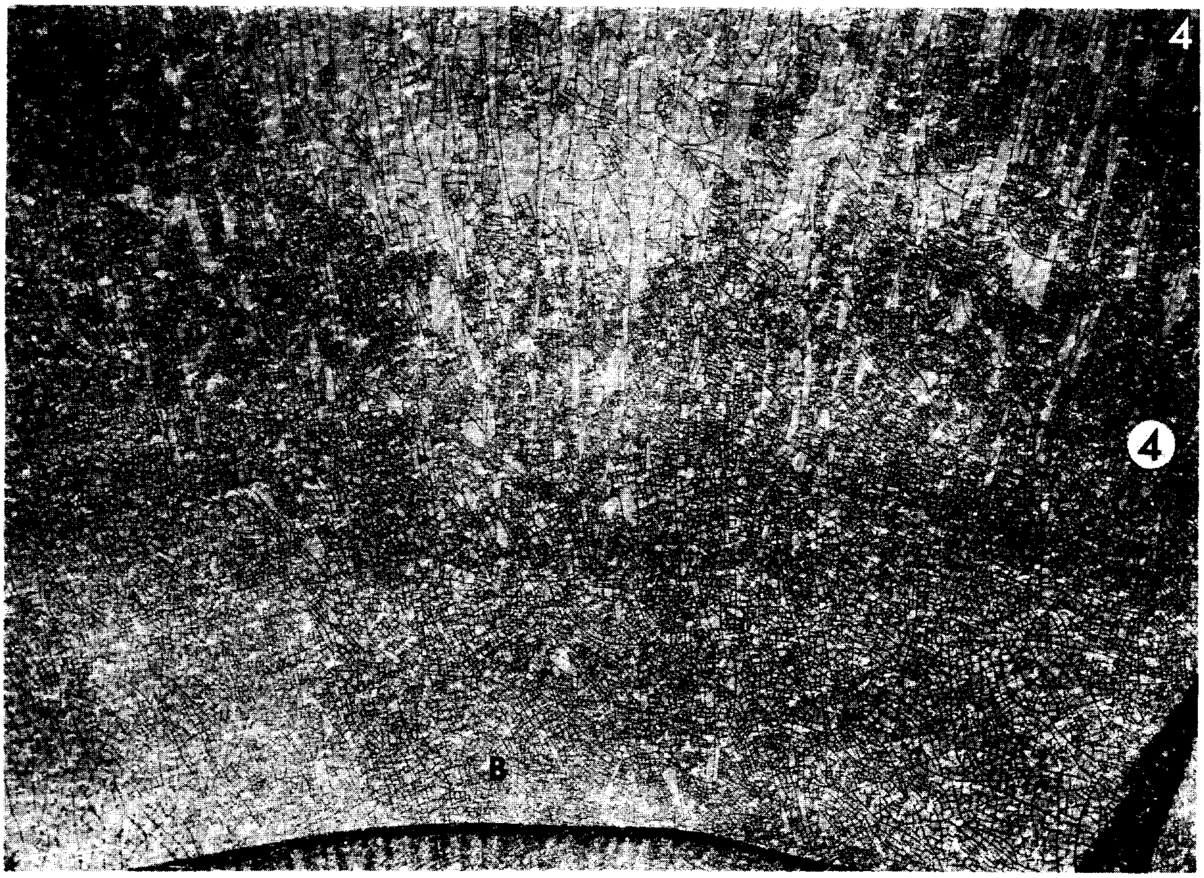
5) The measurement of the change in volume of the sphere gives a good overall check on the suitability of the sphere at maximum depths and it is recommended that this parameter be used for the proof testing of all spheres required to operate in 5000-6000m. depths. The volumetric change obtained, 1. 5 litres, agrees extremely well with the predicted figure of 1. 56 litres at 6000m. depth. The gain of buoyancy calculated from this change of volume and taking into account the change in the density of sea water - see Appendix C - is 0. 64Kg/ 1000m. change in depth. This is a significant change in buoyancy at 6000m. on a complete system that may have little more than 10Kg positive buoyancy at the surface.


1
2
①
④
⑤
③

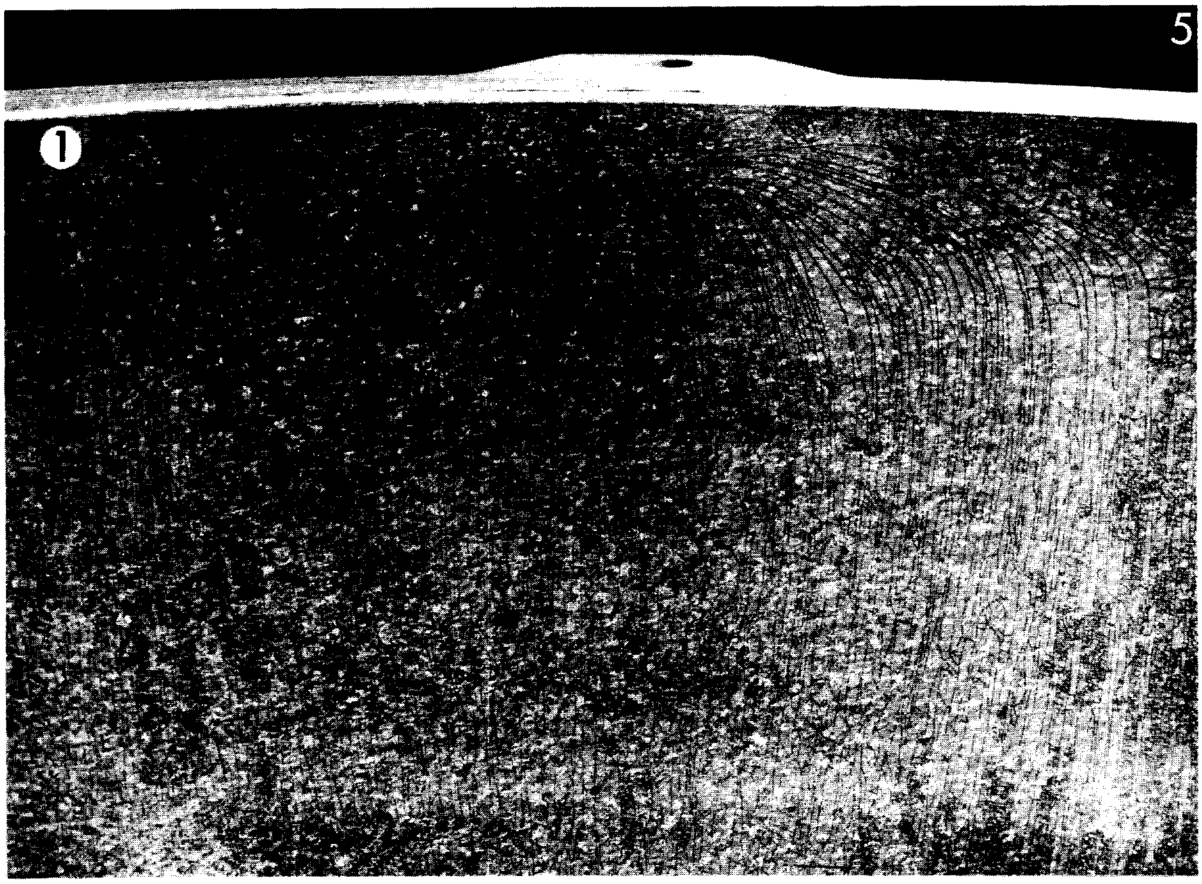

2
5


3

③


4

④


5
①

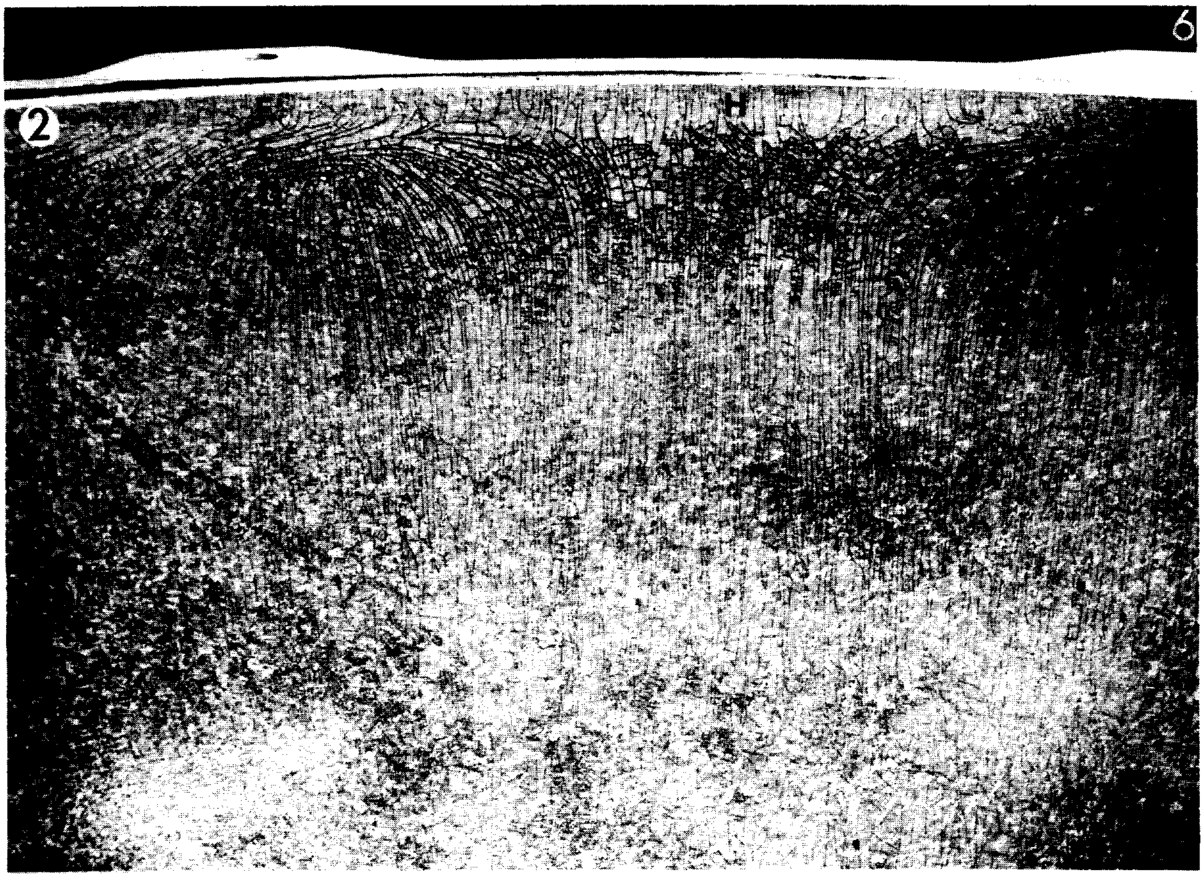
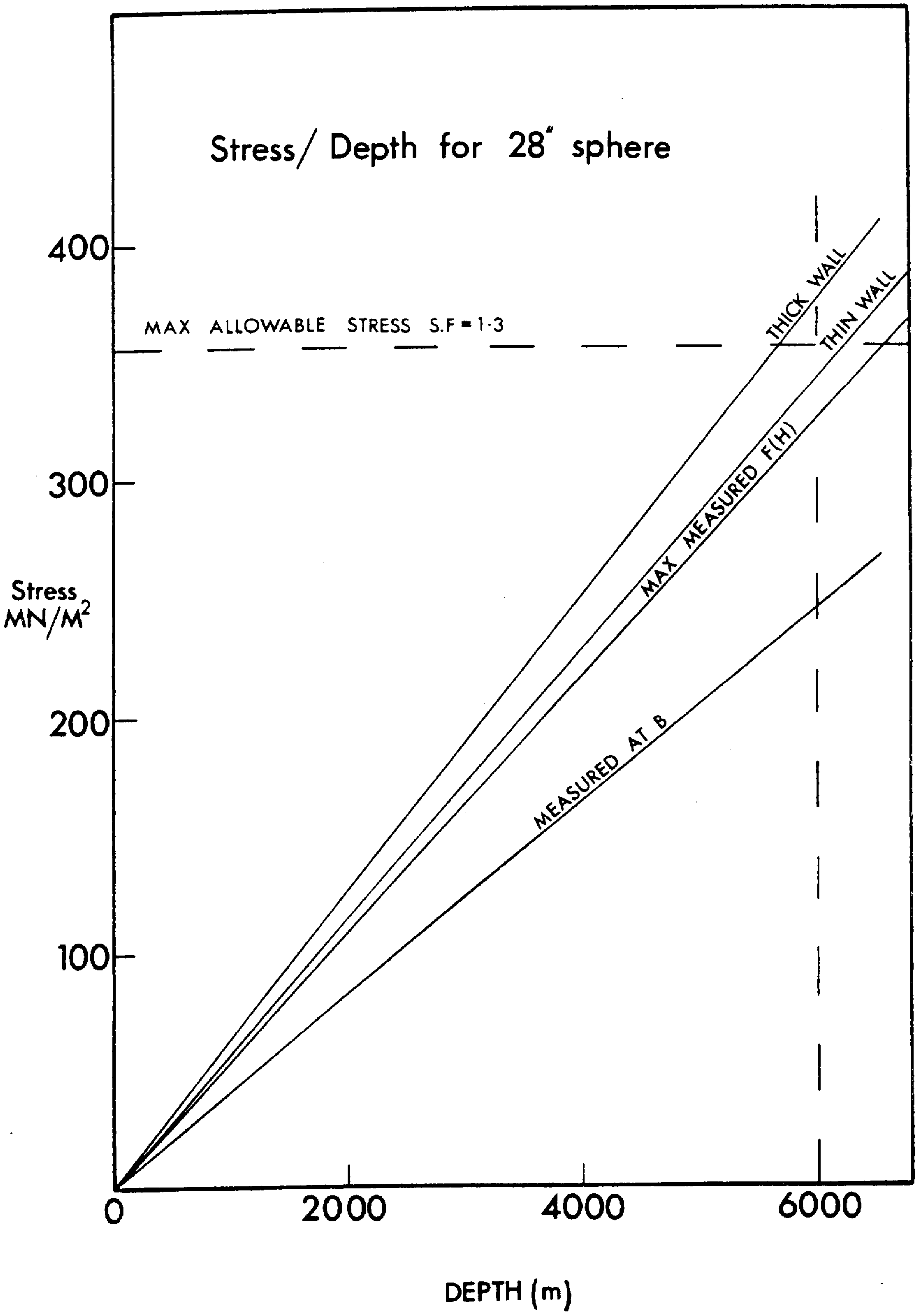

6
②
H

TABLE OF RESULTS

GAUGE POSITION		TEST 1 V_1=1.011			TEST 2 V_1=1.013			TEST 3 V_1=2.007			TEST 4 V_1=2.011			TEST 5 V_1=2.075			MEAN STRESS AT 6000m (MN/m^2)
		K	Mean Vo (mv) per 10MN/m^2	Mean Stress per 10MN/m^2	K	Mean Vo (mv) per 10MN/m^2	Mean Stress per 10MN/m^2	K	Mean Vo (mv) per 10MN/m^2	Mean Stress per 10MN/m^2	K	Mean Vo (mv) per 10MN/m^2	Mean Stress per 10MN/m^2	K	Mean Vo (mv) per 10MN/m^2	Mean Stress per 10MN/m^2	
A	(A)	2.125	0.357	48.7				2.125	0.734	50.5				2.125	0.726	48.3	300
	(H)				2.125	0.302	41.1	2.125	0.624	42.9				2.125	0.652	43.4	262
B	(A)				2.135	0.266	36.1	2.135	0.633	43.3				2.135	0.640	42.4	252
	(H)	2.125	0.505*	34.5	2.10	0.241	33.2	2.10	0.604	42.1				2.10	0.620	41.7	240
C	(A)				2.125	0.305	41.5	2.125	0.595	40.9							253
	(H)				2.10	0.261	36.0	2.10	0.563	39.2							231
D	(A)	2.10	0.309	42.7													262
	(H)	2.125	0.324	44.2													271
E	(A)	2.10	0.290	40.1							2.10	0.594	41.2	2.125	0.584	38.8	246
	(H)	2.10	0.370	51.1	2.10	0.360	49.6	2.10	0.732	51.0				2.10	0.733	49.3	306
F	(A)	2.125	0.271	37.0				2.125	0.575	39.5	2.125	0.560	38.4	2.125	0.581	38.6	236
	(H)	2.125	0.389	53.1	2.125	0.393	53.5	2.125	0.795	54.7				2.125	0.785	52.2	326
G	(A)				2.10	0.289	39.8				2.10	0.559	38.8	2.10	0.562	37.8	237
	(H)							2.10	0.639	44.5				2.10	0.643	43.3	268
H	(A)				2.10	0.287	39.6										243
	(H)							2.10	0.679	47.2				2.10	0.647	43.5	274
MEAN VOLUME CHANGE											248ml/10MN/m^2			244ml/10MN/m^2			1510 ml

*This bridge had two active gauges.


Stress/ Depth for 28" sphere
Stress MN/M^2
400
300
200
100
0
2000
4000
6000
DEPTH (m)
MAX ALLOWABLE STRESS S.F = 1·3
THICK WALL
THIN WALL
MAX MEASURED F(H)
MEASURED AT B

APPENDIX A

For these tests an R. R. 77 tube of 6in. (0. 15m.) O/D by 4. 5in. (0. 11m.) I/D long was used. The tube was soft anodised and had internal threads machined on each end.

Two foil strain gauges (Micro Measurements EA-13-125AD-120) were fixed to the outside of the tube, sealed with water, and subjected to pressure in a water filled pressure vessel.

Gauge factors (K) 2. 09 Supply Voltage (V_1) 2. 500V Output Voltage (V_o)

Modulus of elasticity (E) 73. 3 GN/m^2

$$\text{Then strain} = \frac{Vo \times 2}{KV_1} \times 10^{-6}$$

$\therefore$ 0. 383Vo = micro strain.

$\therefore$ Linear strain at 10MN/m^2 $= \frac{10}{3E} = 4.55 \times 10^{-5}$

$\therefore$ Output (Vo) for a 10MN/m^2 change in pressure

$$= \frac{4.55 \times 10^{-5}}{0.383} = 0.119\text{mv}$$

Pressure (MN/m^2)	V_o (mv)
0	0. 02
6. 89	0. 10
13. 79	0. 17
20. 69	0. 25
27. 58	0. 34
34. 47	0. 42
27. 58	0. 34
20. 69	0. 26
13. 79	0. 18
6. 89	0. 10
0	0. 02

This test gives an average of 0. 116mvper 10MN/m^2 change in pressure, 3% less than the predicted figure.

This test was then repeated at higher pressures:

Pressure (MN/m^2)	V_o(mv)	Pressure (MN/m^2)	V_o (mv)
0	0.06	48.26	0.61
6.89	0.13	41.37	0.53
13.79	0.21	34.47	0.46
20.69	0.29	27.58	0.38
27.58	0.38	20.69	0.30
34.47	0.45	13.79	0.22
41.37	0.53	6.89	0.14
48.26	0.61	0	0.06
55.15	0.69		

This test gives an average of 0.114 mv for a change of pressure of 10MN/m^2, about 4% less than predicted.

There are however a number of errors as follows:

1) K is quoted as ± 0.5%
2) Transverse gauge sensitivity ± 0.5%
3) Pressure effect on gauge surface ± 0.7%
4) Non-linearities in the Wheatstone Bridge ± 0.7%

Lastly, in this series of tests, end caps were fitted to the tube and the gauges then measured simple hoop strain in the thick walled tube.

$$\text{Hoop stress} = P \left[\frac{R_2^{\ 2} \ (2R_1^{\ 2})}{R_1^{\ 2} \ (R_1^{\ 2} - R_2^{\ 2})} \right]$$

Where R_1 is 0.076m., and R_2 is 0.057m.

$\therefore$ Hoop stress at $P = 10$MN/m^2 is 25.71MN/m^2

$\therefore$ Strain $= \dfrac{25.71}{E}$

$\therefore$ V_o for a 10MN/m^2 change in pressure = 0.916 mv.

Pressure (MN/m^2)	Vo (mv)
0	0.065
6.89	0.70
13.79	1.34
20.69	1.95
27.58	2.60
34.47	3.22
27.58	2.59
20.69	1.96
13.79	1.33
6.89	0.68
0	0.065

This test gives an average of 0.916mv for a change of pressure of $10MN/m^2$, coinciding with the theoretical figure.

This completed the tests that were made in order to show that the strain gauging techniques in use were suitable.

APPENDIX B

The following five tables list the readings taken from the various strain gauges. Tests 1, 2 and 3 were designed to show:

1) that the gauges were operating
2) that all outputs were linear
3) which of the various positions chosen measured the highest strain.

Tests 4 and 5 are the final proof tests up to the full working pressure of the sphere.

The gauge positions on the hemisphere are shown on plates 2, 4 and 6, the postscripts indicate measurement of hoop or axial strain.

TEST NO. 1

GAUGE POSITION	A(A)	B(A)	B(H)	D(A)	D(H)	E(A)	E(H)	F(A)	F(H)	SUPPLY VOLTS
K	2.125	2.125	2.125	2.10	2.125	2.10	2.10	2.125	2.125	(V_1)
NO. OF ACTIVE GAUGES	1	2	2	1	1	1	1	1	1	
PRESSURE MN/m^2	V_o (mv)									
3.45	0.050	Failed	0.158	0.035	-0.063	0.023	0.024	0.200	0.035	1.0136
6.89	0.185	"	0.408	0.160	0.065	0.128	0.155	0.280	0.160	1.0100
10.34	0.295	"	0.560	0.234	0.166	0.218	0.289	0.380	0.297	1.0106
13.79	0.415	"	0.720	0.347	0.260	0.330	0.412	0.470	0.433	1.0103
17.24	0.544	"	0.897	0.460	0.389	0.425	0.543	0.565	0.571	1.0100
10.34	0.297	"	0.589	0.250	0.173	0.235	0.302	0.380	0.307	1.0105
3.45	0.056	"	0.230	0.045	-0.049	0.027	0.046	0.174	0.032	1.0102
AVERAGE Vo per 10MN/m^2	0.357		0.505	0.309	0.324	0.290	0.370	0.271	0.389	1.0110

Note: B(A) failed due to poor adhesion of the foil gauge.
B(A) and B(H) had two active gauges thus their outputs were twice that of the other bridges.

APPENDIX B

TEST NO. 2

GAUGE POSITION K	A(H) 2.125	B(A) 2.135	B(H) 2.10	C(A) 2.125	C(H) 2.10	E(H) 2.10	F(H) 2.125	G(A) 2.10	H(A) 2.10	SUPPLY VOLTS
PRESSURE MN/m^2					V_o (mv)					
3.45	0.027	0.194	0.125	0.030	-0.112	-0.037	0.061	-0.100	0.040	1.0076
6.89	0.132	0.295 0.015	0.320 0.015	0.144	-0.026	0.099	0.220	0.006	0.136	1.0070
10.34	0.225	0.171	0.161	0.235	0.054	0.206	0.348 0.000	0.098	0.246	1.0048
13.74	0.320 0.015	0.360 -0.293	0.325 -0.311	0.350 0.046	0.141	0.324 -0.316	0.125	0.190	0.360 -0.270	1.0033
17.24	0.116	-0.125	-0.165	0.145	0.235	-0.204	0.266	0.295 -0.310	-0.195	1.0000
20.69	0.229	0.021	-0.010	0.263 -0.283	0.343 -0.305	-0.072	0.420 -0.292	-0.204	-0.065	1.0010
24.13	0.346 -0.306	0.170	0.144	-0.173	-0.205	0.045	-0.151	-0.100	0.030	0.9997
27.58	-0.208	0.475	0.320	-0.075	-0.118	0.180	-0.020	0.0	0.135	1.0270
20.69	-0.420	0.050	0.0	-0.275	-0.310	-0.055	-0.285	-0.190	-0.040	1.0270
13.74	-0.625 0.450	-0.080	-0.340	-0.480 0.450	-0.480 0.480	-0.315	-0.560 0.590	-0.395	-0.265	1.0270
6.89	0.250	-0.685	-0.680	0.250	0.310	-0.570	Not read	-0.595	-0.465	1.0270
AVERAGE Vo per 10MN/m^2	0.302	0.266	0.241	0.305	0.261	0.360	0.393	0.289	0.287	1.013

Note: All bridges had only one active arm.
The bridge was kept reasonably in balance during the test by occasionally resetting the offset.

TEST NO. 3

APPENDIX B

GAUGE POSITION	$A_{(A)}$	$A_{(H)}$	$B_{(A)}$	$B_{(H)}$	$C_{(A)}$	$C_{(H)}$	$E_{(H)}$	$F_{(A)}$	$F_{(H)}$	$G_{(H)}$	$H_{(H)}$	SUPPLY VOLTS
K	2.125	2.125	2.135	2.10	2.125	2.10	2.10	2.125	2.125	2.10	2.10	
PRESSURE MN/m^2	V_o (mv)											
3.45	-1.99	-1.95	-2.09	-1.87	-1.90	-2.05	-1.89	-2.01	-1.97	-1.95	-1.81	2.008
6.89	-1.72	-1.74	-1.87	-1.66	-1.70	-1.86	-1.63	-1.82	-1.70	-1.73	-1.53	2.007
10.34	-1.44	-1.50	-1.60	-1.40	-1.45	-1.61	-1.34	-1.57	-1.41	-1.47	-1.40	2.008
13.74	-1.20	-1.30	-1.40	-1.21	-1.25	-1.45	-1.11	-1.41	-1.16	-1.28	-1.11	2.008
17.24	-0.95	-1.10	-1.19	-1.01	-1.07	-1.26	-0.86	-1.22	-0.89	-1.06	-0.90	2.007
20.69	-0.70	-0.89	-0.97	-0.80	-0.87	-1.08	-0.62	-1.02	-0.62	-0.84	-0.66	2.007
24.13	-0.45	-0.67	-0.76	-0.60	-0.66	-0.89	-0.36	-0.82	-0.33	-0.63	-0.43	2.006
27.58	-0.18	-0.45	-0.53	-0.39	-0.46	-0.69	-0.11	-0.62	-0.04	-0.40	-0.21	2.006
20.69	-0.70	-0.89	-0.97	-0.81	-0.87	-1.08	-0.62	-1.02	-0.61	-0,84	-0.66	2.005
13.74	-1.19	-1.30	-1.40	-1.22	-1.27	-1.46	-1.12	-1.41	-1.14	-1.28	-1.11	2.005
6.89	-1.68	-1.72	-1.81	-1.62	-1.69	-1.86	-1.61	-1.80	-1.67	-1.71	-1.55	2.006
AVERAGE V_o per 10MN/m^2	0.734	0.624	0.633	0.604	0.595	0.563	0.732	0.575	0.795	0.639	0.679	2.007

TEST NO. 4

GAUGE POSITION	E(A)	F(A)	G(A)	SUPPLY VOLTS	VOLUME ml.	E(A)	F(A)	G(A)	SUPPLY VOLTS	VOLUME ml.
K	2.10	2.125	2.10			2.10	2.125	2.10		
PRESSURE MN/m^2	V_o (mv)					V_o (mv)				
3.45	-2.04	-2.78	-1.99	2.018	440	-2.31	-2.88	-2.03	2.007	485
6.89	-1.85	-2.58	-1.82	2.017	505	-2.13	-2.71	-1.86	2.008	565
10.34	-1.67	-2.41	-1.63	2.017	585					
13.74	-1.46	-2.21	-1.43	2.016	685	-1.74	-2.33	-1.51	2.013	750
17.24	-1.25	-2.00	-1.23	2.016	780					
20.69	-1.05	-1.81	-1.06	2.015	855	-1.34	-1.94	-1.13	2.009	940
24.13	-0.84	-1.61	-0.86	2.015	965					
27.58	-0.63	-1.39	-0.65	2.015	1060	-0.94	-1.55	-0.75	2.007	1125
31.02	-0.43	-1.21	-0.48	2.015	1150					
34.47	-0.24	-1.01	-0.28	2.013	1240	-0.56	-1.18	-0.39	2.010	1305
37.92	-0.04	-0.82	-0.09	2.013	1330					
41.37	0.16	-0.62	0.11	2.012	1430	-0.17	-0.80	-0.02	2.011	1480
48.26	0.54	-0.24	0.50	2.011	1615					
51.71	0.75	-0.05	0.65	2.012	1705	0.20	-0.42	0.35	2.010	1670
55.15	0.95	0.15	0.84	2.011	1800					
58.60	1.15	0.34	1.06	2.011	1910	0.58	-0.04	0.70	2.007	1845
62.05	1.36	0.56	1.28	2.009	2020					
34.47	0.60	-0.18	0.54	2.010	1620	0.97	0.36	1.11	2.008	2040
48.26						0.18	-0.43	0.33	2.009	1680
34.47						-0.56	-1.17	-0.39	2.004	1340
20.69						-1.38	-1.97	-1.18	2.010	960
6.89						-2.20	-2.77	-1.95	2.011	600
3.45	-1.95	-2.64	-1.81	2.008	500	-2.29	-2.92	-2.20	1.994	485
AVERAGE Vo per $10MN/m^2$	0.594	0.560	0.559			AVERAGE VOLUME CHANGE per $10MN/m^2$				248

Note: This test included two cycles to $62MN/m^2$.
The averages are taken over both cycles.

TEST NO. 5

GAUGE POSITION	A(A)	A(H)	B(A)	B(H)	E(A)	E(H)	F(A)	F(H)	G(A)	G(H)	H(H)	SUPPLY VOLTS	VOLUME CHANGE ml.
K	2.125	2.125	2.135	2.10	2.125	2.10	2.125	2.125	2.10	2.10	2.10		
PRESSURE MN/m^2	V_o (mv)												
3.45	2.04	-2.04	-1.98	-1.97	-1.94	-1.97	-1.96	-2.09	-1.94	-1.98	-2.02	2.075	420
6.89	1.80	-1.81	-1.75	-1.74	-1.74	-1.73	-1.75	-1.90	-1.75	-1.75	-1.81	2.075	485
10.34	1.54	-1.58	-1.52	-1.52	-1.53	-1.50	-1.55	-1.66	-1.56	-1.52	-1.59	2.076	560
13.74	1.29	-1.36	-1.30	-1.30	-1.32	-1.23	-1.34	-1.42	-1.36	-1.28	-1.36	2.075	640
20.69	0.77	-0.91	-0.85	-0.87	-0.92	-0.73	-0.94	-0.86	-0.96	-0.92	-0.91	2.075	820
27.58	-0.25	-0.42	-0.38	-0.44	-0.51	-0.24	-0.53	-0.29	-0.56	-0.47	-0.46	2.075	1000
34.47	0.23	-0.04	0.05	-0.02	-0.10	0.29	-0.13	0.27	-0.18	-0.02	-0.01	2.075	1200
41.37	0.72	0.54	0.50	0.39	0.29	0.80	0.25	0.81	0.21	0.42	0.45	2.074	1385
48.26	1.23	1.01	0.94	0.81	0.71	1.31	0.65	1.45	0.60	0.87	0.89	2.074	1560
55.15	1.71	1.43	1.36	1.23	1.10	1.83	1.04	2.05	0.98	1.34	1.35	2.077	1750
62.05	2.20	1.92	1.77	1.63	1.47	2.33	1.42	2.65	1.35	1.80	1.87	2.075	1930
41.37	0.74	0.64	0.49	0.39	0.27	0.82	0.27	0.98	0.22	0.51	0.49	2.075	
20.69	0.75	-0.56	-0.82	-0.84	-0.92	-0.71	-0.90	-0.65	-0.92	-0.79	-0.81	2.075	
3.45	2.03	-1.66	-1.93	-1.93	-1.96	-1.97	-1.93	-1.97	-1.92	-1.91	-1.79	2.074	440
AVERAGE V_o per MN/m^2	0.726	0.652	0.640	0.620	0.584	0.733	0.581	0.785	0.562	0.643		2.075	244

APPENDIX C

The change of buoyancy of the sphere due to the decrease in volume and the increase in the density of sea water with respect to depth may be calculated:

If V_o is the original volume of the sphere

and V_m is the volume at depth m,

If P_s is the density of sea water at the surface,

and P_m is the density at depth m,

Then increase in buoyancy at depth m $=$ $V_oP_s - V_mP_m$

If it is assumed that the change in volume of the sphere and the change in density of sea water are both linear with respect to depth,

$$\text{the increase in buoyancy} = \left[\tfrac{4}{3}\pi (0.355)^3 \times 1028.10\right] - \left[(V_o - 0.0015) \times 1056.94\right]$$

$$= 3.82\text{Kg.}$$

or 637g/1000 metres depth.