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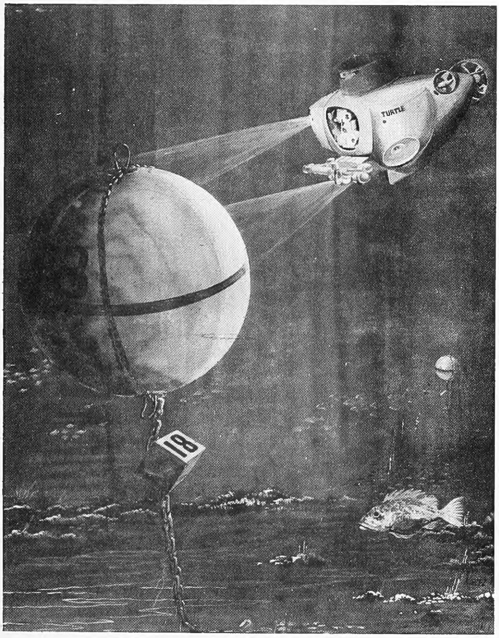

Navy submersible TURTLE performing inspection of concrete spheres.

LONG-TERM DEEP-OCEAN TEST OF CONCRETE SPHERICAL STRUCTURES—Part I: Fabrication, Emplacement, and Initial Inspections

by Harvey H. Haynes

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20. ABSTRACT (*Continue on reverse side if necessary and identify by block number*)

This report summarizes the fabrication, emplacement and inspections during the first 1.2 years of submergence of eighteen 66-inch-OD concrete spheres. The spheres are located 4 miles south of Santa Cruz Island, California, in depths of water from 1,840 to 5,075 feet. The purpose of the test is to collect data on time-dependent failure, permeability and durability of concrete pressure-resistant structures. Findings from the inspections showed that two spheres located at the depths of 3,725 and 4,330 feet had imploded and that the

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quantity of seawater which permeated through the concrete for phenolic-coated spheres was about 0.8 cu ft and for uncoated spheres it was about 1.6 cu ft. This test program is planned to continue through 1981 (total of 10 years).

CONTENTS

INTRODUCTION

Numerous experimental studies have been performed at the Civil Engineering Laboratory (CEL)[a] on the behavior of concrete structures under hydrostatic loading [1-11].[b] These studies have shown that concrete is well suited as a construction material for pressure-resistant structures to depths of 3,000 feet. The empirical data were obtained from test specimens subjected to relatively short-term loading conditions where the longest loading-period for any specimen was 42 days. This series of ocean tests was conducted to supplement the earlier research by providing data on concrete structures subjected to in-situ deep-ocean conditions for periods of up to 10 years.

The objectives of the test program were to obtain design information on time-dependent failure, permeability, and durability of the concrete spheres. Data on time-dependent failure will permit a rational factor of safety to be applied to pressure-resistant structures; data on seawater permeability of concrete will allow predictions of the quantity of water to be expected to penetrate to the structure's interior; and data on the durability of plain and steel reinforced concrete will determine such factors as strength changes with time, chemical composition changes of the concrete, and steel corrosion problems.

TEST DESCRIPTION

Eighteen, 66-inch-OD concrete spheres were placed in the ocean at depths ranging from 1,840 to 5,075 feet (Table 1). This depth range corresponds to a sustained pressure-to-short-term implosion pressure ratio, P_s/P_{im},[c] of 0.36 to 0.83. It was anticipated that the spheres subjected to a P_s/P_{im} ratio of 0.70 or greater would implode with time [8]; therefore, the six spheres at greatest depths were equipped with clocks that would count days in periods up to three years. If a sphere imploded, the clock would record the day of failure.

Permeability data will be gathered using the following method: the spheres are buoyant by approximately 1,000 pounds and are tethered 32 feet off the seafloor by a 2-1/4-inch-diameter chain. As seawater permeates the concrete, the weight of the sphere will increase. The reduced buoyancy of the sphere means less chain can be suspended off the seafloor, so the sphere moves closer to the seafloor. A change in height of one chain link (2-1/4-inch chain) corresponds to 0.5 cu ft of seawater which has permeated to the hull interior.

The permeability rate of seawater through waterproofed and nonwaterproofed concrete will be determined. Eight spheres were coated on the exterior with a two-part phenolic coating; another eight spheres remained uncoated. All sixteen of these permeability specimens were of unreinforced concrete. The remaining two spheres were reinforced with conventional steel bars of 0.5-inch diameter. The reinforcement was covered with 1 or 2.5 inches of concrete. Also, one-half of the exterior of each sphere was coated with the phenolic compound while the other half remained uncoated.

The durability of the concrete will be studied by determining the changes in strength and chemical composition with time. The concrete compressive strengths will be obtained from core specimens drilled from 14 x 18 x 18-inch blocks. Blocks are located with the spheres in the deep ocean and on land,

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[a] Formerly the Naval Civil Engineering Laboratory; now a detachment of the Naval Construction Battalion Center, Port Hueneme, California.

[b] Numbers in brackets indicate references.

[c] The short-term implosion pressure, P_{im}, is calculated by the following empirical equation [8]:

$$P_{im} = [5.02(t/D_o) - 0.038]\, f_c'$$

Table 1. Test Description

Sphere No.	Depth (ft)	P_s/P_{im} [a]	Concrete Water-proofed	Comments
1	5,075	0.83	Yes	clock inside sphere
2	4,875	0.80	Yes	clock inside sphere
3	4,330	0.72	Yes	clock inside sphere
4	4,185	0.81	No	clock inside sphere
5	4,100	0.78	No	clock inside sphere
6	3,875	0.70	No	clock inside sphere
7	3,725	0.58	Yes	
8	3,665	0.60	Yes	
9	3,295	0.62	No	
10	3,190	0.56	No	
11	3,140	0.50	Yes	
12	2,790	0.55	No	
13	2,635	0.41	Yes	
14	2,440	0.44	Yes	
15	2,300	0.43	No	
16	2,120	0.40	No	
17	1,980	0.38	*b*	steel reinforcement in walls
18	1,840	0.36	*b*	steel reinforcement in walls

[a] Sustained pressure-to-short-term implosion pressure ratio.

[b] One hemisphere is waterproofed while the other hemisphere is not waterproofed.

exposed to ambient conditions. Chemical composition changes of the concrete will be determined by comparing x-ray diffraction patterns with those of the concrete at age 20 months.

FABRICATION

Concrete hemisphere sections were cast in a steel mold and the following day were removed from the mold. Twelve 6 x 12-inch-long control cylinders and one 14 x 18 x 18-inch control block of concrete were also cast with each hemisphere.

Moist-curing of the hemisphere, six control cylinders, and the control block was accomplished by wrapping the specimens in wet burlap and then in polyethylene film: the remaining six control cylinders were placed in the fog room. Moist-curing continued for 28 days at ambient temperature inside an open building followed by 28 days of room-curing conditions, and then on-land field-curing conditions.

After several weeks of field curing, the hemispheres were prepared for assembly into spheres. The equatorial edges were ground flat by using a large steel plate, and silica carbide grit and water as the cutting agent. A titanium hull penetration at the apex

Figure 1. Fabrication of spheres.

of each hemisphere was epoxy-bonded into place. The exterior surfaces of the hemispheres were lightly sand blasted and a two-part phenolic compound (Phenoline No. 300) was applied.[d] Finally, to fabricate a sphere two hemispheres were bonded together with an epoxy adhesive (Furane Epocast 8288). Figure 1 shows several of these operations.

All of the spheres had the same dimensions and variations in out-of-roundness. Extensive measurements [8] were taken on one hemisphere, and Table 2 summarizes the dimensions. In summary, the mean outside diameter was 65.886 inches and the mean wall thickness was 4.124 inches.

Conventional 1/2-inch-diameter steel reinforcing bars were embedded in the concrete of two spheres. Arrangement of the steel bars is shown in Figure 2. Alternate longitudinal bars had a nominal concrete cover of 1 or 2.5 inches; however, in certain locations near the apex the minimum cover was as low as 0.5 inch.

Clocks were placed in Spheres 1 through 6 to record the day of implosion, if the sphere should fail. The clock records days on a counter and has a projected life of 3 years.[e] Figure 3 shows the clock and its pressure housing which was a 4-inch-OD pipe section. The pipe was attached to the top penetrator of the sphere.[f]

[d] Pinholes existed in the final waterproof coating at a rate of approximately 1 per 2 sq in.

[e] For zero time in the ocean, the clocks read 41 days for Spheres 1-3, and 38 days for Spheres 4-6.

[f] Upon retrieval, safety precautions should be followed in handling the pressure housing because water at high pressure could be inside. Prior to opening, drill a 1/8-inch-diameter hole through the steel wall to relieve any internal pressure.

Figure 2. Arrangement of steel bar reinforcement for Spheres 17 and 18.

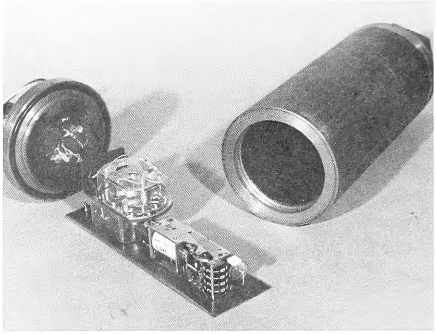


Figure 3. Clock mechanism and its 4-in.-OD pressure housing.

Table 2. Hemisphere Dimensions and Out-of-Roundness Variations

Item	Mean Dimension (in.)	Standard Deviation		Maximum Local Variation	
		Measured (in.)	Percent of Wall Thickness	Measured (in.)	Percent of Wall Thickness
Interior radius	28.820	±0.093	±2.26	+0.145 -0.213	+3.51 -5.16
Exterior radius	32.943	±0.083	±2.01	+0.150 -0.247	+3.64 -5.94
Wall thickness	4.124	±0.060	±1.45	+0.181 -0.165	+4.26 -3.90

Power was supplied to the clock from dry-cell batteries placed in a watertight, but not pressure-resistant container located at the bottom of the sphere. When implosion occurs, the batteries are destroyed or shorted, and the lead wires running to the clock are broken.

Final assembly of the spheres is shown in Figures 4 and 5. The descriptive information on Figure 5 gives important details on the assembly.

Documentation of the concrete material is given in Appendix A. The mix proportions, compressive strengths, cement compositions, and x-ray diffraction patterns of the concrete are presented. In general, the concrete was made from a high-quality mix design where the cement factor was 7.8 sacks per cu yd and water-cement ratio was 0.40; the compressive strength at 28 days was an average 7,660 psi.

Disposition of the control cylinders and blocks is as follows: of the six control cylinders placed in the fog room, three were tested at 28 days; their compressive strengths are given in Appendix A, Table A-2. The remaining three control cylinders will stay in the fog room and will be tested when the spheres are retrieved from the ocean. Three of the six control cylinders cured with the hemisphere were tested at age 28 days and the remaining three were tested approximately one month prior to emplacing the spheres in the ocean (Table A-2); these later tests gave the compressive strength used in calculating the short-term implosion pressure, P_{im}. There were two control blocks per sphere; one block went with the sphere into the ocean and the other block stayed on land, located within 50 yards of the ocean. Both blocks will be cored and tested when the sphere is retrieved.

EMPLACEMENT

The spheres were emplaced in the ocean 4 miles south of Santa Cruz Island, California (Figure 6), on 23 September 1971. The method of emplacing the spheres was as follows: a barge loaded with the spheres (Figure 7) was towed by a surface vessel (*USNS Gear*) which maintained a constant course over a location where the seafloor increased in depth at a fairly uniform rate. At predetermined depths, the appropriate sphere was pushed overboard to free-fall to the seafloor. The method worked well with most of the spheres landing within a few hundred yards of the target location. Final location of the spheres is given in Table 3. Figure 8 shows a plan view and Figure 9 a profile view of the sphere locations.

Water samples were obtained from the depth of 2,530 feet and gave the following data: temperature of 5.33°C, salinity of 34.41 ppt, pH of 7.2, oxygen content of 0.06 ml/l, and velocity of sound of 1,483.9 m/sec. A water sample from 4,740 feet gave a temperature of 5.16°C and a pH of 7.0.

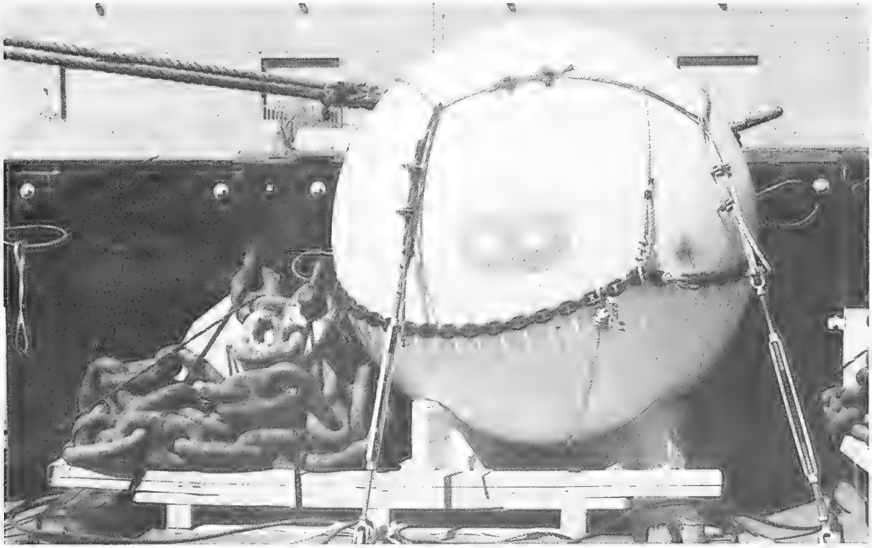
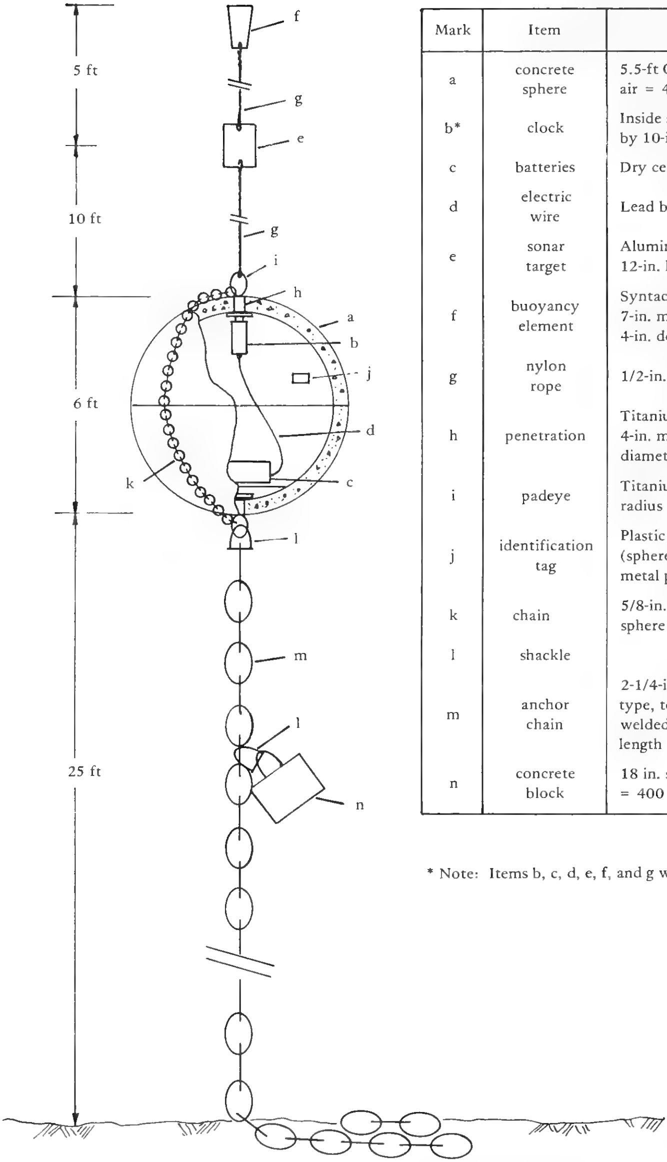


Figure 4. Final assembly of sphere.



Mark	Item	Remark
a	concrete sphere	5.5-ft OD by 4-in. wall; weight in air = 4,400 lb
b*	clock	Inside steel pipe capsule, 4-in. OD by 10-in. long, weight in air = 15 lb
c	batteries	Dry cell batteries inside PVC pipe
d	electric wire	Lead between batteries and clock
e	sonar target	Aluminum pipe, 10-in. OD by 12-in. long, by 1/8-in. wall
f	buoyancy element	Syntactic foam, 4-in. min width by 7-in. max width by 14-in. long by 4-in. deep
g	nylon rope	1/2-in. diameter
h	penetration	Titanium Ti-6Al-4V; conical plug, 4-in. major diameter and 3-in. minor diameter
i	padeye	Titanium, 1/2-in.-diameter rod, 3.5-in. radius
j	identification tag	Plastic tag with sphere number engraved (sphere number also stamped on most metal parts)
k	chain	5/8-in. steel chain wrapped around sphere and through padeyes
l	shackle	
m	anchor chain	2-1/4-in.-diameter steel chain, die-lock type, total length 53 ft, bottom links welded in triangle shape so hanging length = 42 ft, weight in air = 2,630 lb
n	concrete block	18 in. sq by 14 in. high; weight in air = 400 lb

* Note: Items b, c, d, e, f, and g were used with only Spheres 1-6.

Figure 5. Details of sphere assembly.

Table 3. Location of Spheres

Sphere No.	Surface Location at Launch: Lorac Coordinates G	Surface Location at Launch: Lorac Coordinates R	Surface Location at Launch: Distance Between Spheres (yd)	Surface Location at Launch: Azimuth Between Spheres (°T)	Seafloor Location Found by *Turtle*: Lorac Coordinates G	Seafloor Location Found by *Turtle*: Lorac Coordinates R	Seafloor Location Found by *Turtle*: Distance Between Spheres (yd)	Seafloor Location Found by *Turtle*: Azimuth Between Spheres (°T)	Depth (ft)	Sphere No.
1	479.6[a]	324.4							5,075	1
			680	346						
2	481.5	320.0							4,875	2
			2,400	340						
3	489.9	305.2			490.0	302.0			4,330	3
			600	341			400	349		
4	491.4	302.6			491.0	299.2			4,185	4
			200	340						
5	492.6	300.8							4,100	5
			2,650	344						
6	501.9	284.3							3,875	6
			400	344						
7	503.2	282.2			500.0	280.9			3,725	7
			900	343			800	326		
8	506.6	277.1			504.7	277.2			3,665	8
			1,580	350			1,920	352		
9	511.2	268.0			509.0	265.5			3,295	9
			280	350			380	309		
10	511.7	266.6			511.7	264.4			3,190	10
			1,250	345			1,180	346		
11	516.0	259.3			516.0	258.0			3,140	11
			1,720	337			1,650	339		
12	524.4	250.8			523.5	249.5			2,790	12
			540	337			970	280		
13	527.0	248.0			532.5[b]	249.7			2,635	13
			650	347			630	332		
14	528.8	244.4			536.1[b]	246.8			2,440	14
			400	355			700	23		
15	530.2	242.4			534.6	242.6			2,300	15
			300	345			550	5		
16	531.7	240.8			535.0	239.5			2,120	16
			300	324			200	10		
17	533.0	239.4			535.0	238.3			1,980	17
			200	352			200	347		
18	534.0[c]	238.3			535.3	237.5			1,840	18

[a] Geographic coordinates 33°49'15"N by 119°33'30"W.
[b] These locations may be in error.
[c] Geographic coordinates 33°56'15"N by 119°36'15"W.

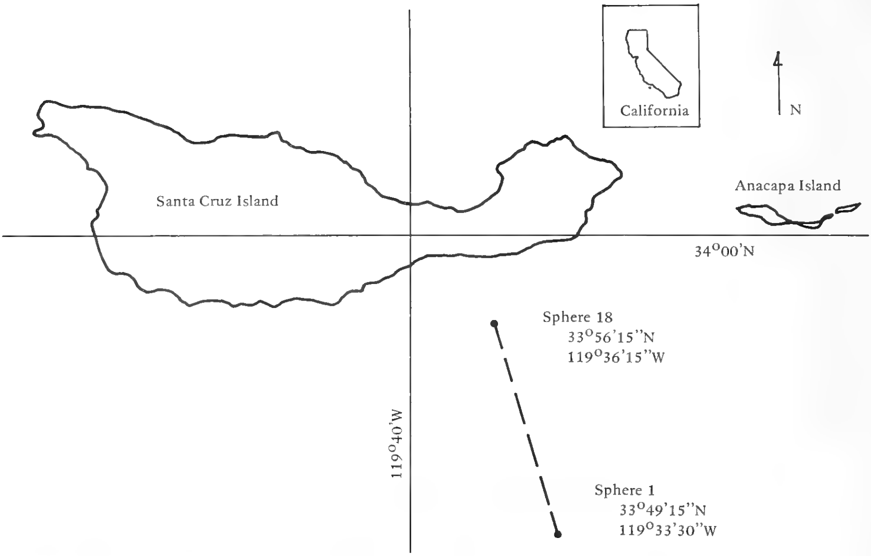


Figure 6. Location of spheres off California coast.

Figure 7. Spheres rigged on barge in preparation for free-fall launch.

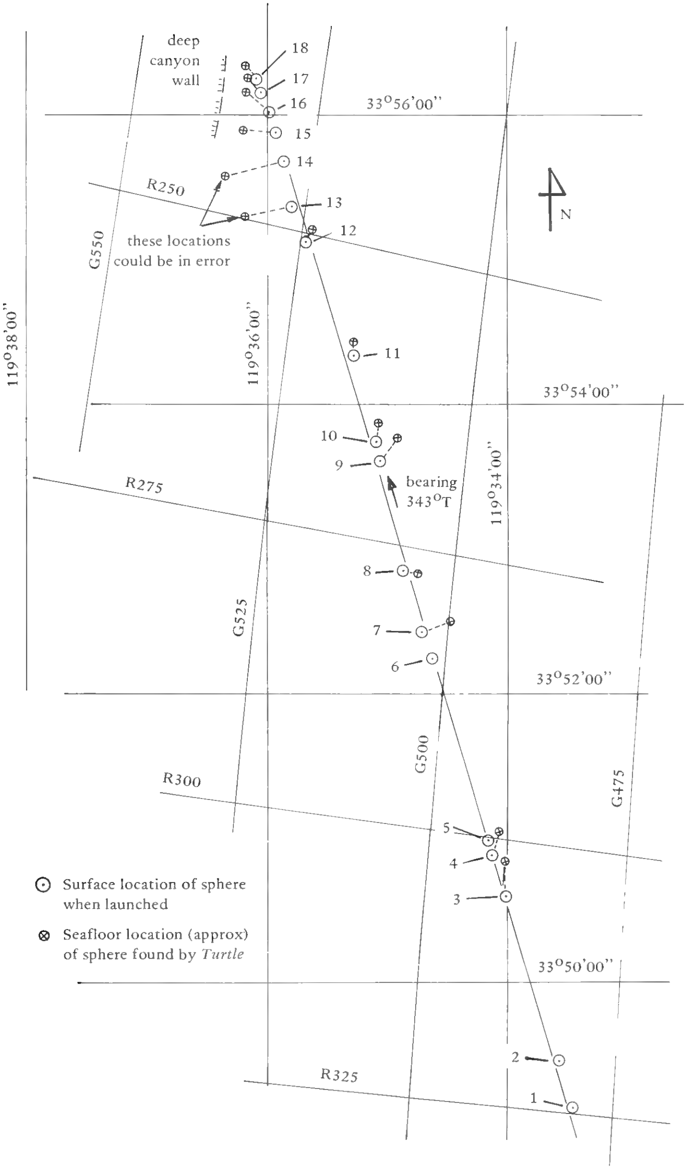


Figure 8. Plan view of sphere location.

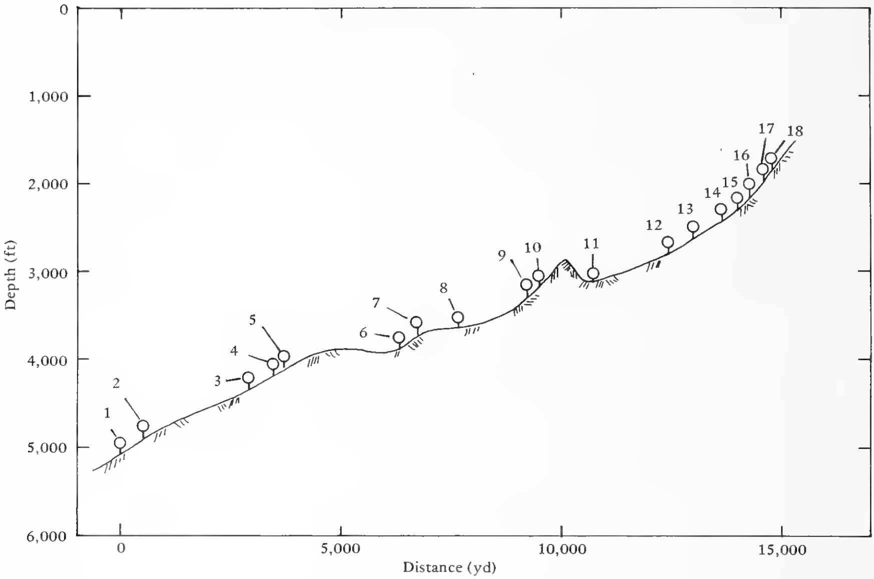


Figure 9. Bottom profile at sphere location directly below surface launch.

A soil sample was obtained at the depth of 4,100 feet near Sphere 5. Data from the core are presented in Appendix B, Table B-1.

INSPECTIONS

Three inspection visits have been made to view as many spheres as possible. Of the 18 spheres, 15 have been viewed once, and of those 15, five have been viewed twice.

The first and third inspections were made by the Naval Submarine Development Group One using the submersible *Turtle*. The second inspection was made by Scripps Institution of Oceanography using the Remote Underwater Manipulator (RUM).

Turtle is a manned submersible capable of operating to depths of 6,500 feet. During the inspections with the submersible, however, those spheres at depths greater than 3,800 feet were not inspected because of the possibility of implosion of a test sphere. Investigators with the *Turtle* were successful in inspecting Spheres 7-18. The spheres at greater depths (1-6) were to be inspected with the unmanned RUM vehicle. Within the time available for the inspection cruise with RUM, Spheres 3-5 were inspected successfully; the remaining spheres (1, 2, and 6) have not been inspected.

Data collected during the inspections are given in Table 4. The chain link count is the number of links of chain suspended off the seafloor by the buoyant spheres. If a sphere was found imploded or if anything unusual was observed, this information was recorded. Figures 10 and 11 show an uncoated sphere and a coated sphere tethered off the seafloor.

RESULTS

Implosion

Two spheres, 3 and 7, have imploded. Fragments of Sphere 3 were observed during the RUM inspection to be scattered over an area of what appeared to

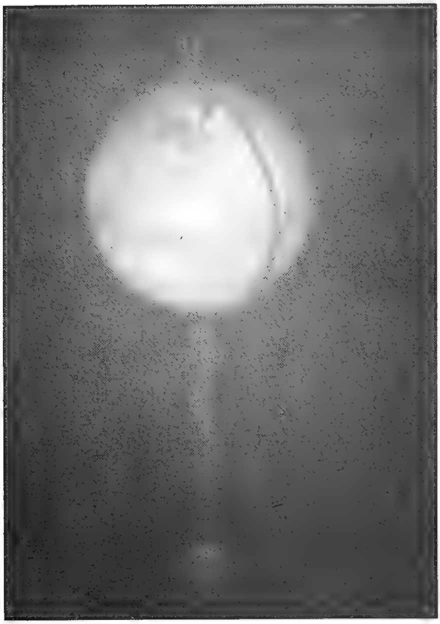


Figure 10. View of uncoated sphere (No. 12) at a depth of 2,790 feet after 431 days.

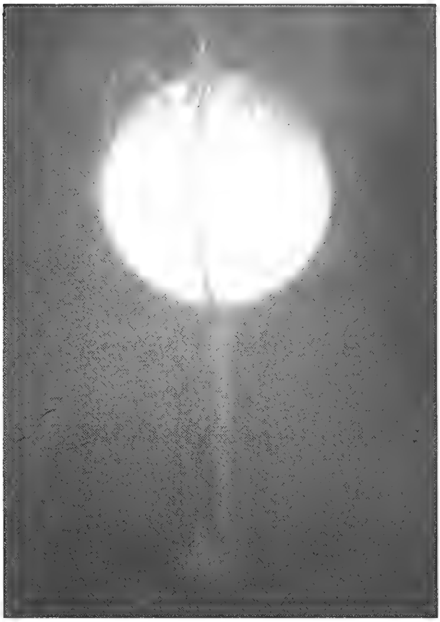


Figure 11. View of coated sphere (No. 13) at a depth of 2,635 feet after 431 days. Material on top of sphere is sediment. Nylon rope on left side of sphere was used to secure 5/8-in. chain around sphere (see Figure 4).

be a 25-yard radius. To retrieve the clock, the manipulator on RUM picked up the 5/8-inch chain to which the clock was attached. Once on the surface, it was learned that the clock was not retrieved. Implosion forces must have "blown" the clock off the chain. Hence, the time to implosion for Sphere 3 was not obtained; however, from information obtained during the third inspection it has been deduced that the sphere imploded during descent. The *Turtle* operators thoroughly searched the Sphere 3 site for the clock, which was not located, but observations showed that fragments of concrete were spread over a radius of 50 yards. Also, the anchor chain was not at the center of debris or at the location of highest fragment density. This information meant that the sphere probably imploded during descent which allowed the fragments to disperse.

In the case of Sphere 7, the fragments were all located within a 10-yard radius. Sphere 7 did not contain a clock, so the time to implosion is between 1 and 431 days.

For Spheres 3 and 7, the P_s/P_{im} ratio was 0.72 and 0.58, respectively. This level of long-term loading was considered relatively low for implosion to occur. However, seven other spheres are subjected to P_s/P_{im} ratios greater than 0.58, four of which have been inspected and are performing well.

The concrete control block for Sphere 3 was retrieved. The compressive strengths of this block and other control specimens stored at on-land field

Table 4. Inspection Data

Sphere No.	Chain Link Count[a] at–				Time to Implosion (days)	Comments
	Emplacement (By: CEL Date: 23 Sep 71 Time: 0 days)	Inspection No. 1 (By: *Turtle* Date: 4 Mar 72 Time: 163 days)	Inspection No. 2 (By: RUM Date: 26 Aug 72 Time: 340 days)	Inspection No. 3 (By: *Turtle* Date: 1 Dec 72 Time: 431 days)		
1	29.7[b]	–	–	–	–	
2	29.7	–	–	–	–	
3	29.4	–	imploded	–	0	
4	29.4	–	23	–	–	Insp. No. 3, observed sphere intact and floating high.
5	29.6	–	21	–	–	
6	29.6	–	–	–	–	
7	31.5	–	–	imploded	1-431	
8	31.5	–	–	0	–	Insp. No. 3, sphere intact but on seafloor.
9	31.6	–	–	–	–	Insp. No. 3, chain tangled on block.
10	31.6	–	–	24	–	
11	38.0	–	–	31	–	
12	32.1	–	–	24	–	
13	32.1	28	–	28	–	
14	48.4	39	–	39	–	
15	32.2	26	–	25	–	
16	31.8	26	–	25	–	
17	32.6	29	–	28	–	
18	32.6	–	–	25	–	

[a] Number of links suspended off seafloor by buoyant sphere.

[b] Calculated number of links suspended off seafloor by sphere with concrete at room dry condition.

conditions and fog-room conditions are given in Appendix C. The control block from Sphere 7 was not retrieved as the *Turtle* was not rigged for a retrieval operation.

Permeability

The method used to determine the permeability of seawater through the concrete walls produced a fairly accurate indication of in-situ permeability behavior of the spheres. This method used the change in number (reduced number) of chain links to calculate the gain in weight of the sphere due to seawater intake. The accuracy of the quantitative results depend on several approximations; these are discussed in Appendix D. The accumulative effect of these approximations is estimated to be a maximum of ± 0.8 cu ft of seawater. This error can be reduced to ± 0.3 cu ft by comparing the change in link counts from actual inspections instead of using the calculated link count from zero days.

Table 5 gives the total quantity of seawater intake, **Q**, for the different time intervals between emplacement and inspections. Seawater intake includes the seawater absorbed by the concrete and the seawater that permeated through the concrete. Figure 12 shows the **Q** versus time behavior. Three items of interest are observed. One item is that the uncoated concrete spheres have a greater **Q** than the coated spheres; after 431 days, the coated spheres showed an average **Q** of about 2.6 cu ft and the uncoated spheres about 3.6 cu ft. Another item is that the spheres which have been inspected twice showed a considerable decrease in the rate of seawater intake. The last item is that **Q** increased for specimens at greater depth, but the increase was not pronounced.

The actual quantity of seawater permeating the wall, Q_p, was estimated by subtracting the quantity of absorbed seawater from the total seawater intake. Earlier work on 66-inch-OD spheres [8] showed that the concrete (same concrete as used in this study) absorbed approximately 3 percent by weight (or 7 percent by volume) of seawater. This corresponds to 2.0 cu ft of seawater absorbed by the concrete. Table 5 shows the Q_p values for the different time intervals. At 431 days, the average Q_p for the coated spheres was 0.8 cu ft and for the uncoated spheres was 1.6 cu ft.

Reference 8 reports permeability results from two 66-inch-OD concrete spheres subjected to seawater hydrostatic pressure tests. The permeability data are shown in Table 6. D'Arcy's permeability coefficient, K_c, was determined from the data as an average of 0.13×10^{-12} ft/sec. D'Arcy's permeability coefficient can be expressed as follows for the spheres:

$$K_c = \frac{Q_p\, t}{T\, A h} \qquad (1)$$

where K_c = permeability coefficient, ft/sec

Q_p = quantity of permeability seawater, cu ft

T = time, sec

t = wall thickness, ft

A = exterior surface area, cu ft

h = depth (or pressure head), ft

Using the K_c value of 0.13×10^{-12} ft/sec as a baseline, the data from the spheres in the ocean can be compared to that from the pressure vessel tests. Table 5 lists the K_c values for the ocean spheres. In all cases, the permeability coefficient was lower for the spheres in the ocean than for the spheres in the pressure vessels. The average K_c values for the coated spheres were 0.06×10^{-12} ft/sec at 163 days and 0.02×10^{-12} ft/sec at 431 days, and for the uncoated spheres were 0.11×10^{-12} ft/sec at 163 days and 0.06×10^{-12} ft/sec at 431 days. Other K_c values were those attained between the time interval of 163 to 431 days; for the coated spheres, no increase in Q_p was observed, so K_c was zero, and for the uncoated spheres the average K_c was 0.04×10^{-12} ft/sec.

The permeability data from the pressure vessel tests showed that a straight line curve of Q_p versus log T fit the data with fair accuracy. The empirical semi-log relations[g] for one sphere (specimen CWL-9A) at a simulated depth of 2,520 ft was:

$$Q_p = 0.34 \log_{10} T - 0.11 \qquad (2)$$

[g] Equations 2 and 3 are presented in this report with time, T, in days. These equations are different from those in Reference 8 which give time, T, in hours.

Table 5. Permeability Data

Sphere No.	Concrete Water-proofed	Depth (ft)	Change in Link Count, ΔL, and Total Seawater Intake, Q, for—								Seawater Permeating Interior, Q_p,[a] and D'Arcy's Permeability Coefficient, K_c, for—							
			0-163 Days		0-340 Days		0-431 Days		163-431 Days		0-163 Days		0-340 Days		0-431 Days		163-431 Days	
			ΔL (links)	Q (cu ft)	ΔL (links)	Q (cu ft)	ΔL (links)	Q (cu ft)	ΔL (links)	Q (cu ft)	Q_p (cu ft)	K_c ft/sec $\times 10^{-12}$	Q_p (cu ft)	K_c ft/sec $\times 10^{-12}$	Q_p (cu ft)	K_c ft/sec $\times 10^{-12}$	Q_p (cu ft)	K_c ft/sec $\times 10^{-12}$
4	no	4,185	–	–	6.4	3.1	–	–	–	–	–	–	1.1	0.03	–	–	–	–
5	no	4,100	–	–	8.6	4.2	–	–	–	–	–	–	2.2	0.07	–	–	–	–
10	no	3,190	–	–	–	–	7.6	3.7	–	–	–	–	–	–	1.7	0.05	–	–
11	yes	3,140	–	–	–	–	7.0	2.8	–	–	–	–	–	–	0.8	0.02	–	–
12	no	2,790	–	–	–	–	8.1	3.9	–	–	–	–	–	–	1.9	0.07	–	–
13	yes	2,635	4.1	2.0	–	–	4.1	2.0	0	0	0	0	–	–	0	0	0	0
14	yes	2,440	9.4	3.1	–	–	9.4	3.1	0	0	1.1	0.12	–	–	1.1	0.04	0	0
15	no	2,300	6.2	3.0	–	-	7.2	3.5	1.0	0.5	1.0	0.11	–	–	1.5	0.06	0.5	0.04
16	no	2,120	5.8	2.8	–	–	6.8	3.3	1.0	0.5	0.8	0.10	–	–	1.3	0.06	0.5	0.04
17	half/ half	1,980	3.6	1.5	–	–	4.6	1.9	1.0	0.4	0	–	–	–	0	–	0	0
18	half/ half	1,840	–	–	–	–	7.6	3.1	–	–	–	–	–	–	1.1	0.07	–	–

[a] To obtain seawater permeability, Q_p, the seawater absorbed by the concrete was estimated as 2.0 cu ft and was subtracted from the total seawater intake, Q.

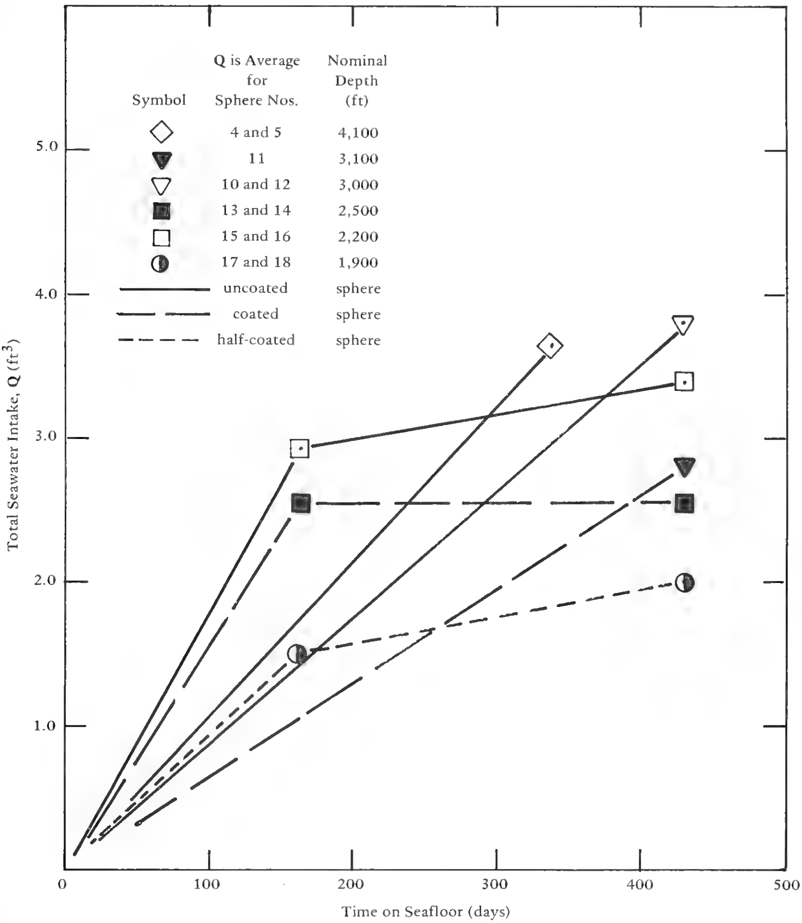


Figure 12. Total seawater intake of concrete spheres.

and for another sphere (specimen CWL-6) at a simulated depth of 3,760 feet it was:

$$Q_p = 0.32 \log_{10} T - 0.01 \qquad (3)$$

where T is time (days).

Figure 13 shows a comparison between D'Arcy's equation, Equation 1, using $K_c = 0.13 \times 10^{-12}$ ft/sec and the empirical equations, Equations 2 and 3. Data from the ocean spheres are shown to be bracketed by the D'Arcy and empirical semi-log relations. D'Arcy's relation assumes a constant rate of permeability, whereas the extrapolation of the empirical semi-log relation assumes a decreasing rate with time. It is not apparent at this time which approach defines the permeability behavior of the concrete spheres. Additional data from inspections are required.

Sphere 8 was found intact but sitting on the seafloor after 431 days. A total seawater intake of 15.3 cu ft or more was required to overcome the positive buoyancy of the sphere. This quantity of seawater was three to four times that of the other

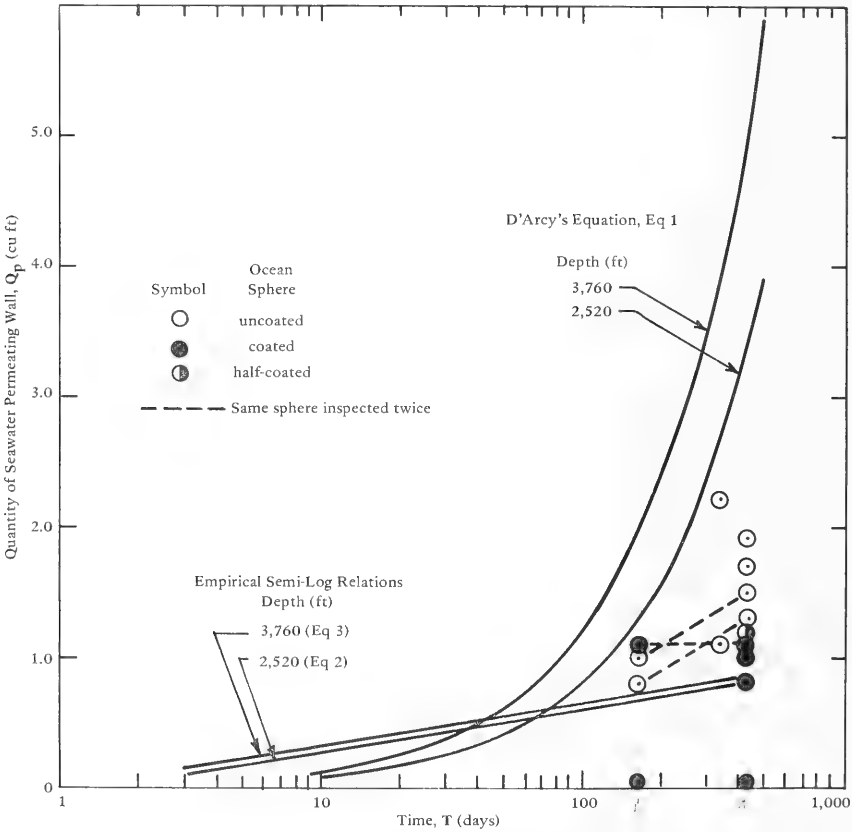


Figure 13. Comparison of ocean sphere permeability data with the D'Arcy equation and the empirical semi-log relations as given in Reference 8.

Table 6. Permeability Data (After Haynes and Kahn [8])

Specimen No.	Simulated Depth (ft)	Time (days)	Permeability, Q_p (cu ft)	D'Arcy's Permeability Coefficient, K_c (ft/sec x 10^{-12})
CWL-9A	2,520	21	0.34	0.16
CWL-6	3,760	42	0.52	0.10

NOTE: Spheres started the test having the concrete in a wet condition. The procedure for obtaining wet-concrete walls was to place an uncoated sphere on the bottom of the pressure vessel and allow the seawater to fill the inside of the sphere, and then apply hydrostatic pressure. The pressure was maintained usually for 7 days at 500 psi or until the pressure became constant and showed no decrease, thus indicating that the voids of more significant size were filled with water.

spheres, so it was evident that Sphere 8 leaked. Experience in fabricating concrete spheres has shown that periodically a specimen leaked at a concrete-epoxy joint.

SUMMARY

Of the original eighteen spheres emplaced at depths between 1,840 and 5,075 ft, fifteen spheres have been inspected at least once. Of the spheres that were inspected, the one at greatest depth was at 4,185 feet, and was performing well after 431 days. Two spheres have imploded; one sphere imploded during emplacement to the depth of 4,330 feet and the other sphere imploded during the time interval of 1 to 431 days at a depth of 3,725 feet.

The quantity of seawater that had permeated through the concrete walls was about 0.8 cu ft for the coated spheres (waterproofed concrete) and 1.6 cu ft for the uncoated spheres (non-waterproofed concrete).

D'Arcy's permeability coefficient, K_c, was on the average 0.02×10^{-12} ft/sec for the coated spheres and 0.06×10^{-12} ft/sec for the uncoated spheres between the time interval of 0 to 431 days on the seafloor. These K_c values were less than the K_c value of 0.13×10^{-12} ft/sec obtained from pressure vessel tests on similar uncoated spheres for time intervals up to 42 days [8].

The concrete spheres are to remain in the ocean through 1981 with periodic inspections to determine implosion and permeability data.

ACKNOWLEDGMENTS

The author wishes to acknowledge the assistance of Mr. L. F. Kahn during the planning and fabrication stages, of Mr. N. D. Albertsen in emplacing the spheres in the ocean, of Mr. P. C. Zubiate as senior project technician, and of Mr. D. W. Widmayer in fabricating the spheres.

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Appendix A

CONCRETE MATERIALS

The mix design for the concrete is given in Table A-1. Transit-mix trucks delivered the concrete, and final determination of water content was based on workability. Table A-2 gives the properties of the fresh concrete; average values were (1) water-to-cement ratio of 0.40, (2) slump of 1-1/2 inches, (3) air content of 2.4 percent by volume, and (4) unit weight of 145.2 lb/cu ft.

Compressive strength of the concrete at age 28 days (Table A-2) averaged 7,660 psi for the fog-room-cured specimens and 7,690 psi for the on-land field-cured specimens (moist-cured in wet burlap and wrapped in plastic for first 28 days). The compressive strength of the concrete at ages varying from 45 to 174 days was obtained prior to emplacing the spheres in the ocean (Table A-2). These strengths were used to calculate the short-term implosion pressure of the spheres (the compressive strength of the weaker hemisphere was used) so that projected emplacement depths could be calculated. For the uncoated spheres, the control cylinders were saturated with seawater prior to testing. The method of saturation was to place the specimens in a pressure vessel and apply 500 psi pressure for 7 days. The strength of saturated concrete has been found to be 10% lower than room-dry concrete [8]. The coating was assumed to maintain the concrete in a dry condition, so the control cylinders were tested in a dry condition.

Table A-3 is a copy of a typical mill test report on the portland cement used by the transit-mix supplier, Southern Pacific Milling, during the fabrication of the hemispheres. All of the cement meets ASTM specification C-150-70, Type II, Low Alkali, Portland Cement.

X-ray diffraction patterns for three concrete blocks, W-15, W-39, and W-41, were obtained (Figures A-1 through A-3) for documentation of the chemical composition of the concrete at the early stages of the test program. At the end of the test program, which could be many years away, samples of concrete can be analyzed to determine whether or not the concrete has been attacked by the sulphates in seawater. Table A-4 gives the diffraction angle (2θ) of the expected intensity peaks for concrete attacked and unattacked by sulphates in seawater [12].

Table A-1. Concrete Mix Design

Portland cement, Type II, low-alkali
Santa Clara River aggregate
Water-to-cement ratio = 0.41
Sand-to-cement ratio = 1.85
Coarse aggregate-to-cement ratio = 2.28
Water-reducing admixture = 2 oz/slack of Plastiment

Material	Aggregate Gradation		
	Sieve Size Designation	Percentage Retained	
		Individual	Cumulative
Sand	3/8 inch	0	0
	no. 4	2	2
	no. 8	11	13
	no. 16	17	30
	no. 30	28	58
	no. 50	28	86
	no. 100	11	97
	pan	3	100
Coarse aggregate	3/4 inch	0	0
	3/8 inch	70	70
	no. 4	30	100

Table A-2. Concrete Control Cylinder Data

Sphere No.	Hemisphere No.[a]	Characteristics of Fresh Concrete Cylinders				Compressive Strength, f'_c, at 28 Days (psi)		Age, Condition, and Compressive Strength, f'_c, Prior to Ocean Emplacement		
		Water-to-Cement Ratio	Slump (in.)	Air Content by Volume (%)	Density (lb/cu ft)	Wrapped Wet Burlap and Plastic[b]	Fog Room[b]	Age (days)	Condition of Concrete[c]	f'_c (psi)
1	W-4	0.42	3/4	2.3	146.0	7,300	8,520	174	dry	8,940
	W-35	0.41	1-1/4	2.2	145.2	8,070	8,070	65	dry	9,360
2	W-8		1-1/4	2.2	146.4	8,050	8,250	164	dry	9,950
	W-7	0.38	1-1/2	2.2	145.2	7,590	7,940	162	dry	8,970
3	W-16[d]	0.38	1-3/4	2.1	145.1	7,940	8,400	132	dry	9,650
	W-15	0.38	1-1/4	2.3	147.8	7,260	8,520	134	dry	8,840
4	W-6	0.41	1/4	5.8	138.3	8,470	8,760	170	wet	8,320
	W-5	0.43	1-1/4	2.7	146.4	7,310	8,050	172	wet	7,600
5	W-10	0.44	1-1/4	2.5	144.9	7,210	7,730	156	wet	8,090
	W-9	0.40	1-1/4	2.1	146.1	7,620	8,240	158	wet	7,690
6	W-14	0.42	1-1/4	2.2	147.0	8,100	8,580	143	wet	8,510
	W-13	0.41	1-1/2	2.6	148.0	7,960	8,060	144	wet	8,370
7	W-20	0.39	1-1/2	2.7	143.9	7,720	7,660	117	dry	9,530
	W-17	0.36	2	2.1	147.2	7,370	7,750	126	dry	9,480
8	W-22	0.41	1-1/4	2.5	144.1	7,690	7,520	111	dry	9,030
	W-19	0.38	1-3/4	2.2	145.2	7,940	8,410	119	dry	9,380
9	W-28	0.42	1-3/4	1.6	147.0	6,970	6,920	94	wet	7,820
	W-25	0.38	1-3/4	2.1	145.2	7,890	8,070	104	wet	8,740
10	W-30	0.39	1-1/2	2.1	145.6	7,950	8,190	88	wet	8,560
	W-27	0.42	1-1/4	2.3	146.2	7,620	7,900	97	wet	8,330
11	W-24	0.38	1-1/2	2.1	145.2	7,670	7,540	103	dry	9,820
	W-21	0.36	1-3/4	2.4	146.0	7,670	7,720	113	dry	9,190
12	W-32	0.40	1-1/2	2.4	145.8	7,510	7,570	80	wet	8,390
	W-29	0.40	1-3/4	1.7	146.0	7,030	7,240	89	wet	7,430
13	W-26	0.39	1-1/4	2.3	145.0	7,990	8,070	98	dry	10,210
	W-23	0.39	1-1/4	2.7	143.9	7,860	7,640	105	dry	9,370

continued

Table A-2. Continued

Sphere No.	Hemisphere No.[a]	Characteristics of Fresh Concrete Cylinders				Compressive Strength, f'_c, at 28 Days (psi)		Age, Condition, and Compressive Strength, f'_c, Prior to Ocean Emplacement		
		Water-to-Cement Ratio	Slump (in.)	Air Content by Volume (%)	Density (lb/cu ft)	Wrapped Wet Burlap and Plastic[b]	Fog Room[b]	Age (days)	Condition of Concrete[c]	f'_c[b] (psi)
14	W-12[d]	0.42	1-1/4	3.2	136.6	6,730	6,990	144	dry	8,170
	W-11	0.43	3/4		–	7,440	7,550	148	dry	9,200
15	W-34	0.37	1-1/2	2.1	145.6	7,800	8,170	74	wet	7,830
	W-31	0.38	1-1/4	2.0	146.4	7,880	7,810	82	wet	8,740
16	W-36	0.38	1-1/2	2.3	145.4	7,520	7,220	67	wet	7,780
	W-33	0.41	1-1/2	2.4	145.8	8,050	7,930	75	wet	8,340
17	W-39	–	1-1/4	2.1	145.4	7,690	8,050	51	dry	9,050
	W-40		1-1/2	2.0	145.8	7,740	7,730	52	wet	7,730
18	W-41	–	1-1/2	2.6	144.3	7,600	8,620	48	dry	8,770
	W-42	–	1-1/2	2.5	144.5	7,810	7,970	45	wet	7,590

[a] Hemisphere number listed first refers to the top hemisphere of the sphere.
[b] Average of three 6 x 12-in.-long control cylinders.
[c] Dry refers to cylinders from on-land field conditions.
Wet refers to cylinders placed in seawater under 500 psi for 7 days.
[d] Some expanded shale aggregate found in cylinder.

Table A-3. Copy of Mill Test Report on Cement

PACIFIC WESTERN INDUSTRIES, INC.

LOS ROBLES CEMENT DIVISION

POST OFFICE BOX 1247 • (805)248-6733

LEBEC, CALIFORNIA 93243

MILL TEST REPORT

We certify that 17,982 bbls. of LOS ROBLES Portland Cement in Silo or Lot No. 1-802 has the following chemical and physical characteristics as tested in our plant laboratory:

CHEMICAL ANALYSIS:

Silicon Dioxide, SiO_2	22.28	%
Aluminum Oxide, Al_2O_3	4.62	%
Ferric Oxide, Fe_2O_3	3.04	%
Calcium Oxide, CaO	64.24	%
Magnesium Oxide, MgO	1.46	%
Sulphur Trioxide, SO_3	2.73	%
Loss on Ignition	1.38	%
Insoluble	0.05	%
Alkalies, Comb. as Na_2O	0.42	%

POTENTIAL COMPOUNDS:

3 $CaO.SiO_2$	49.0	%
2 $CaO.SiO_2$	26.9	%
3 $CaO.Al_2O_3$	7.1	%
4 $CaO.Al_2O_3.Fe_2O_3$	9.2	%

FINENESS:

Blaine, Sq. Cm. per Gram	3476
Wagner, Sq. Cm. per Gram	

SOUNDNESS:

Autoclave, Percent Expansion .000

TIME OF SETTING:

Vicat	1 hrs.	45	min.
Gilmore, Initial Set	2 hrs.	50	min.
Final Set	4 hrs.	30	min.

COMPRESSIVE STRENGTH:

1 day	1552	psi
3 days	2838	psi
7 days	4411	psi
28 days	6802	psi

THIS CEMENT MEETS OR EXCEEDS THE FOLLOWING DESCRIBED SPECIFICATIONS:

ASTM: C-150-70 Type II Low Alkali

FEDERAL: SS-C-192g Type II Low Alkali

CALIFORNIA: State Div. of Hwys. Std. Spec. 90-2.01 Mod. Type II Low Alkali

OTHER:

MAIN OFFICE:

3810 Wilshire Boulevard

Los Angeles, California 90005

(213) 381-3181

Pacific Western Industries, Inc.

BY: ______ CHIEF CHEMIST 4-2-71 DATE

Table A-4. Expected Intensity Peaks [12] From X-Ray Diffraction Analysis of Concrete Attacked and Unattacked by Seawater

Diffraction Angle (2θ) at Intensity Peak (deg)	Material	Remarks
Concrete Attacked by Sulfates in Seawater		
9.1 15.8	Ettringite, $3CaOAl_2O_33CaSO_432H_2O$	
11.2	Hydrocalumite, $Ca_{16}Al_{18}(OH)_{54}CO_321H_2O$	May not be present.
11.7	Gypsum, $CaSO_42H_2O$	Very soluble, may not be present.
29.4	Calcite, $CaCO_3$	Due to carbonation.
26.2 27.2	Aragonite, $CaCO_3$	Formed at cold temperatures, may not be present.
Concrete Unattacked		
18.1 34.1	Lime, $Ca(OH)_2$	Created from hydrated cement.
broad peak ~28-33	Tobermorite gel	Created from hydrated cement.
32.3 32.7 33.1	C_3S C_3S and C_2S C_3A	Traces of unhydrated cement, usually hard to see in older concrete.
29.4	Calcite, $CaCO_3$	Due to carbonation.
10.5 20.9 26.6[a] 27.8	Aggregates	Some of the larger peaks from the aggregate.

[a] Quartz aggregate.

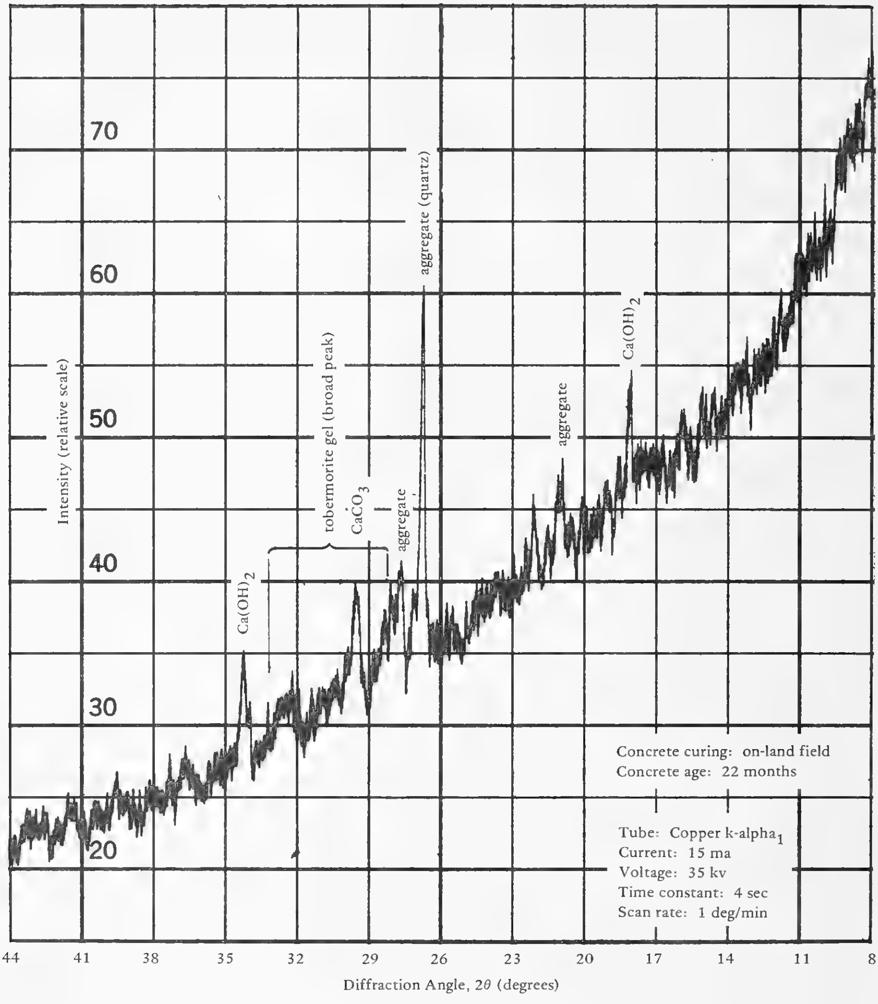

Figure A-1. X-ray diffraction pattern for concrete from W-15 control block.

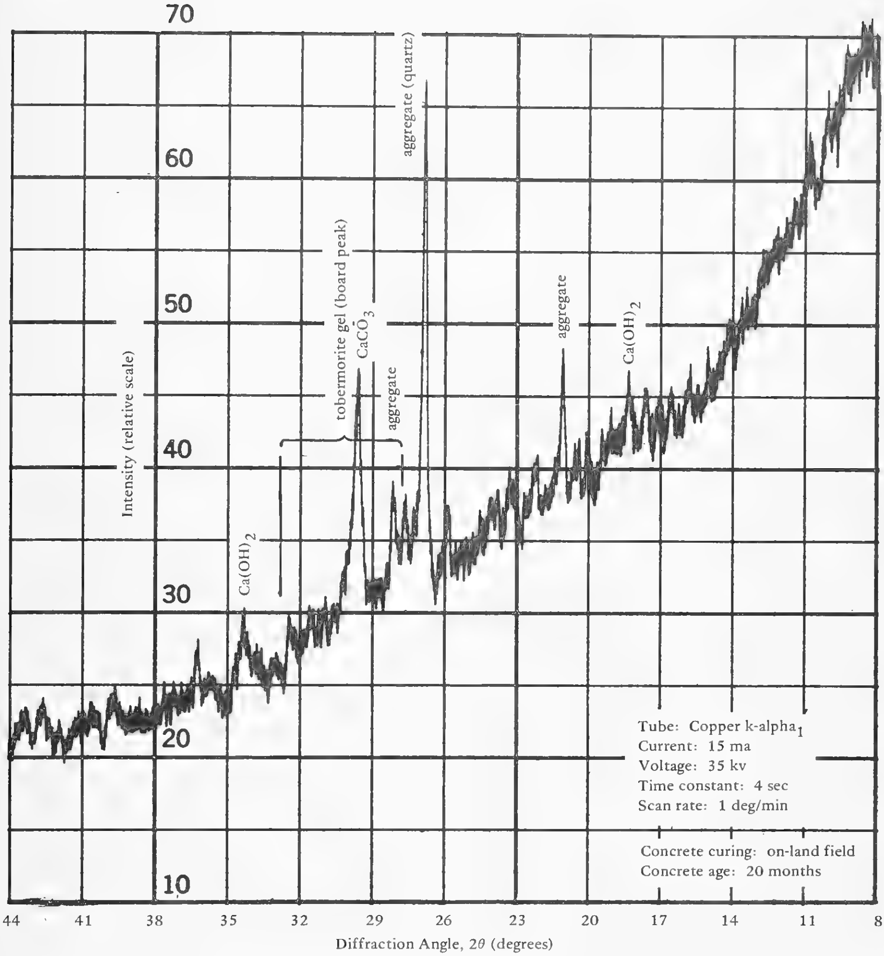

Figure A-2. X-ray diffraction pattern for concrete from W-39 control block.

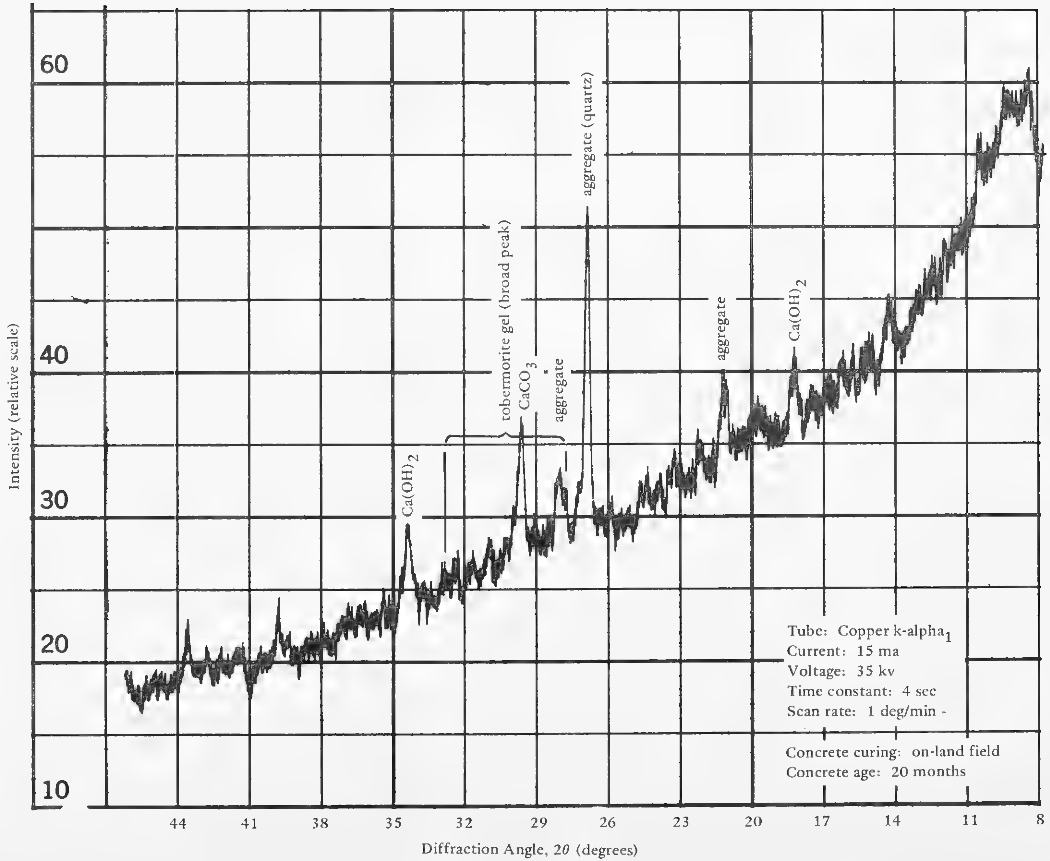

Figure A-3. X-ray diffraction pattern for concrete from W-41 control block.

Appendix B

SOIL PROPERTIES

Table B-1. Soil Data

(Core specimen obtained at 4,100 feet near Sphere 5; core diameter was 2.75 inches.)

Item	Properties of Soil Sample From Core by Intervals		
	0-3 In.	6-9 In.	13-16 In.
Bulk wet density (pcf)	90.64	94.53	94.20
Water content (%)	82.69	83.39	85.54
Vane shear strength (psi)	0.296	1.074	1.431
Remolded shear strength (psi)	0.037	0.394	0.566
Sensitivity	8.0	2.7	2.5
Liquid limit	81.7	91.0	112.3
Plastic limit	42.3	39.9	42.5
Plasticity index	39.4	51.1	69.8
Specific gravity	2.63	2.57	2.61
Unified soil classification	MH	MH	CH
Type of soil	silt	silt	clay-silt

Appendix C

COMPRESSIVE STRENGTH OF CONCRETE FOR SPHERE 3

Even though Sphere 3 imploded on descent to the seafloor, the control block of concrete was not retrieved until 340 days later. This control block was fabricated of the same concrete as one of the sphere's hemispheres, W-16. This concrete experienced a history of 172 days of on-land field curing and 340 days of in-ocean field curing.

The other hemisphere, W-15, had a corresponding control block that was continuously stored out-of-doors; hence, this concrete underwent a continuous 514 days of on-land field curing. Simultaneously, three 6 x 12-inch-long cylinders for both hemispheres underwent continuous fog room curing.

The compressive strengths for the concrete are shown in Table C-1 and Figure C-1. The fog-cured concrete increased 23 percent in average strength, from 8,460 to 10,420 psi. The on-land field-cured concrete leveled off in strength at an average of 8,650 psi after 134 days. The in-ocean field-cured concrete decreased in strength from an average of 9,650 psi after 132 days of on-land curing to an average of 7,600 psi after 340 days in the ocean; this was a 21 percent decrease in strength. Wetting of the dry concrete would account for 10 percent of the decrease [8]; perhaps under the long-term hydrostatic pressure the total decrease in strength was due to saturation of the concrete. Previous work by Russians [13] showed a decrease in compressive strength of 28 percent due to saturating dry concrete under high hydrostatic pressure; however, the test procedure used to obtain the saturated concrete was not discussed.

Concrete from block W-16 was analyzed by x-ray diffraction techniques. It was found that the concrete was not attacked by the seawater.

Table C-1. Control Cylinder Data for Sphere 3

Hemisphere	Curing Condition	Total Age (days)	Saturated With Seawater Prior to Test	Number of Control Specimens	Compressive Strength, f'_c (psi)	Coefficient of Variation (%)
W-15	Fog Room	28	no	3	8,520	–
	Field[a]	28	no	3	7,260	–
	With Hemisphere[a]	134	no	3	8,840	–
	Fog Room	514	no	3	10,470	3.9
	Field at CEL[a, b]	514	no	4	8,650	3.7
W-16	Fog Room	28	no	3	8,400	–
	Field[a]	28	no	3	7,940	–
	With Hemisphere[a]	132	no	3	9,650	–
	Fog Room	512	no	3	10,360	1.5
	In ocean[a, b] (at 4,400 ft for 341 days)	512	yes	4	7,600	4.0

[a] First 28 days: moist-cured in wet burlap wrapped in plastic sheeting.
[b] 6 x 12-in.-long cylinders cored from block 18 x 18 x 14 inches.

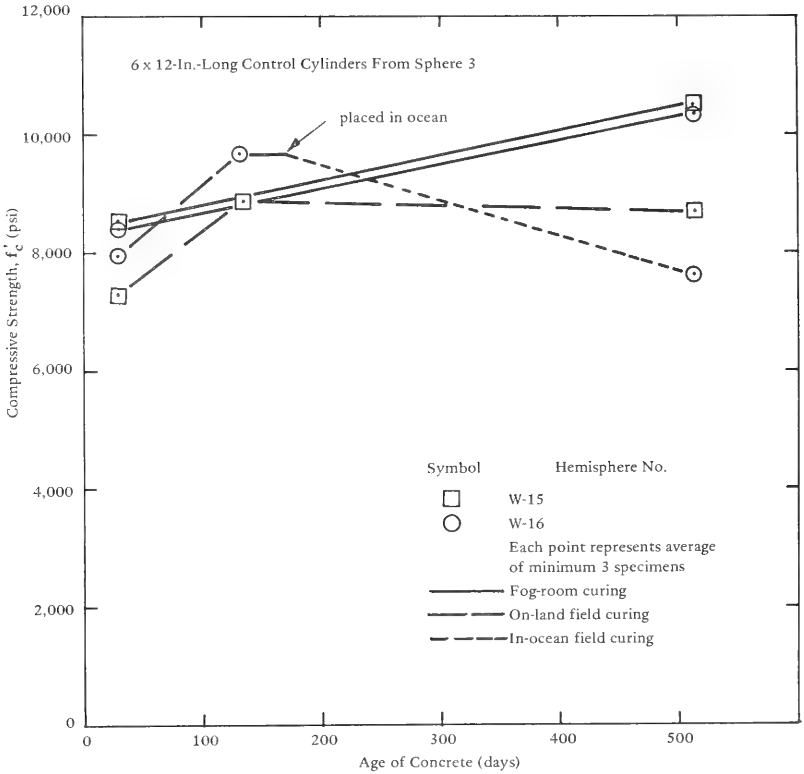

Figure C-1. Compressive strength of concrete for Sphere 3.

Appendix D

CALCULATION OF SEAWATER INTAKE

The method used to calculate the total quantity of seawater intake by the spheres depends on obtaining the change in number of chain links suspended off the seafloor by a sphere. The reduction in number of links is converted into quantity of seawater intake, **Q**. The accuracy of determining **Q** is dependent on several approximations.

One approximation is the criterion by which the submersible operators counted the chain links. They counted only whole links; or, in other words, the bottom-most link counted was the one in a vertical position.

Another approximation is estimating the original number of links suspended off the seafloor when the spheres had dry-concrete walls. The associated calculations are shown below, in part, and are completed in Table D-1.

Buoyancy of Hull

Dimensions D_o = 65.886 inches and D_i = 57.640 inches

Weight of Displaced Seawater, W_D

W_D = 64 pcf (86.64 cu ft) = 5,545 lb

Weight of Concrete Sphere, W_C

W_C = 145.2 pcf (28.625 cu ft) = 4,156 lb

Positive Buoyancy = 1,389 lb for bare concrete hull

In-Water Weight of Components on Spheres

5/8-inch chain	67 lb
Wet-concrete control block	220 lb
Steel components	40 lb
Titanium components	8 lb
Load on Spheres 7-16 (also common load to other spheres)	335 lb
Clock (estimated in air weight)	20 lb
Batteries (estimated in air weight)	40 lb
Common load	+335 lb
Load on Spheres 1-6	395 lb
Steel bar reinforcement (in-water weight)	150 lb
Common load	+335 lb
Load on Spheres 17 and 18	485 lb

Column D in Table D-1 was another approximation. This was the apparent weight gain of the system due to the change in volume of the sphere under load. Using data from Reference 8, it was assumed that the maximum long-term strain for the spheres at greatest depths was 2,500 μin./in. This strain resulted in a change in volume sufficient to reduce the buoyancy by 40 pounds. For the spheres in shallower water, a proportional buoyancy adjustment was made.

It was estimated that the maximum error in the net positive buoyancy values was ±50 pounds. In terms of chain links (2-1/4-inch chain), the error was ±1.5 links; or in terms of seawater intake, the error was ±0.8 cu ft.

The error associated with permeability reading between inspections is ±20 pounds, or ±0.3 cu ft.

Table D-1. Calculation of Number of Links Off Seafloor at Zero Days

Sphere No.	A Positive Buoyancy of Concrete Hull (lb)	B Weight[a] of Components on Hull (lb)	C Weight[a] of Shackles (lb)	D Apparent Weight Gain (lb)[b]	E = A - [B + C + D] Net Positive Buoyancy (lb)	F Chain Size (in.)	G Weight[a] of Each Chain Link (lb/link)	H = E/G Number of Links Off Seafloor
1	1,389	395	28	40	926	2-1/4	31.2	29.7
2	1,389	395	28	40	926	2-1/4	31.2	29.7
3	1,389	395	42	35	917	2-1/4	31.2	29.4
4	1,389	395	42	35	917	2-1/4	31.2	29.4
5	1,389	395	42	30	922	2-1/4	31.2	29.6
6	1,389	395	42	30	922	2-1/4	31.2	29.6
7	1,389	335	42	30	982	2-1/4	31.2	31.5
8	1,389	335	42	30	982	2-1/4	31.2	31.5
9	1,389	335	42	25	987	2-1/4	31.2	31.6
10	1,389	335	42	25	987	2-1/4	31.2	31.6
11	1,389	335	42	25	987	2-1/4	26.0	38.0
12	1,389	335	28	25	1,001	2-1/4	31.2	32.1
13	1,389	335	28	25	1,001	2-1/4	31.2	32.1
14	1,389	335	28	20	1,006	2	20.8	48.4
15	1,389	335	28	20	1,006	2-1/4	31.2	32.2
16	1,389	335	42	20	992	2-1/4	31.2	31.8
17	1,389	485	42	15	847	2-1/8	26.0	32.6
18	1,389	485	42	15	847	2-1/8	26.0	32.6

[a] In-water weight.

[b] Due to change in volume of sphere under load.

LIST OF SYMBOLS

A	Exterior surface area, cu ft
D_i	Inner diameter of concrete sphere, in.
D_o	Outer diameter of concrete sphere, in.
f'_c	Uniaxial compressive strength of concrete, psi
h	Depth (or pressure head), ft
K_c	Permeability coefficient, ft/sec
P_{im}	Short-term implosion pressure, psi
P_s	Sustained pressure, psi
Q	Total quantity of seawater intake, cu ft
Q_p	Quantity of seawater permeating wall of sphere, cu ft
T	Time, sec, hr, days
t	Wall thickness, ft, in.
W_C	Weight of concrete sphere, lb
W_D	Weight of displaced seawater, lb

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LONG-TERM DEEP-OCEAN TEST OF CONCRETE SPHERICAL STRUCTURES. Part I. Fabrication, Emplacement, and Initial Inspections, by Harvey H. Haynes
TR-805 43 p. illus March 1974 Unclassified

1. Submerged concrete structures 2. Seawater permeability of concrete I. DOT 3.1610

This report summarizes the fabrication, emplacement and inspections during the first 1.2 years of submergence of eighteen 66-inch-OD concrete spheres. The spheres are located 4 miles south of Santa Cruz Island, California, in depths of water from 1,840 to 5,075 feet. The purpose of the test is to collect data on time-dependent failure, permeability and durability of concrete pressure-resistant structures. Findings from the inspections showed that two spheres located at the depths of 3,725 and 4,330 feet had imploded and that the quantity of seawater which permeated through the concrete for phenolic-coated spheres was about 0.8 cu ft and for uncoated spheres it was about 1.6 cu ft. This test program is planned to continue through 1981 (total of 10 years).

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