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RESEARCH ESTABLISHMENT

LUCAS HEIGHTS

AN EXAMPLE OF SPHERE BRIDGING IN A CIRCULAR CHANNEL

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ABSTRACT

A bridged system of spheres in a circular channel with a channel-to-ball diameter ratio of 4.7 has been examined. The basic bridge structure consisted of two diametric arches at about 60° relative displacement. Associated with these arches was a stable hexagon ring of spheres and a central sphere held at five contact points.

CONTENTS

1. INTRODUCTION

It has been known for some time and adequately reported that spheres under gravity flow may bridge and jam flow in a channel (Sanderson and Porter 1958; Fraas et al. 1961). The parameters associated with this blockage include:

(a) the geometry of the channel and the particular value of the ratio of channel diameter to sphere diameter,

(b) the surface finish and hardness of both the spheres and channel,

(c) uniformity of size and shape of the spheres,

(d) the density of the spheres, and

(e) the presence or otherwise of mechanical agitation.

Many experiments have been conducted on the flow characteristics of uniform spheres through circular channels (Sanderson and Porter 1958). It has been concluded that bridging is:

(a) impossible for channel-to-sphere diameter ratios between 1.1 and 1.7,

(b) probable for ratios between 1.7 and 5.0,

(c) unlikely for ratios between 5.0 and 6.0, and

(d) highly improbable for ratios greater than 6.0.

Hence, the actual ratio selected for design will most likely depend on:

(a) the requirement of "single-file" flow or large cross-section flow,

(b) the incidence of chipped and broken spheres, and

(c) the inventory limit and possible cooling problems associated with a large number of spheres in a channel.

While some information exists on the bridging probability with varying channel-to-sphere diameter ratios, no information can be found on the actual mechanism of bridging. Thus when a blockage actually occurred during an experiment on vibration flow, the system was examined for any useful information which might be extracted. The channel-to-sphere diameter ratio was

4.7 which is very close to the reportedly critical ratio of 5. This report describes the bridge formation in detail.

2. CONDITIONS AT THE TIME OF BRIDGE FORMATION

A clean Perspex cylinder, nominally 4.75 inches inside diameter, had been mounted on a rigid bracket vertically above a horizontal vibratory feeder tray. The lower end of the cylinder was 1.5 inches above the tray surface. Smooth wooden spheres, 1.010 ± 0.005 inches mean diameter, 5.59 grams average mass, had been dropped into the cylinder to a depth of 2.5 feet. The channel-to-sphere diameter ratio was therefore 4.70. The spheres were allowed to flow under gravity by mechanical agitation of the tray surface.

The top free surface of the spheres moved 12 inches down the cylinder before a plug of 88 spheres formed. The rest of the spheres (about 500) discharged normally under the influence of the vibrations. The system was photographed prior to further study (Figure 4).

3. EXAMINATION OF THE BRIDGE

The system was first "fixed" with a washing of clear varnish. This process held the spheres at their points of contact with each other and the cylinder wall.

3.1 Measurement of Sphere Centres

The relative positions of spheres of the lower surface and those for two rows around the cylinder wall were measured using a cathetometer, accurate to 0.01 mm. The centres were then compared in terms of sphere diameter and are tabulated in Table 1. For convenience the spheres were designated by number (Figure 1) and sphere 10 was assumed as reference sphere.

3.2 Mapping of Lower Surface

Mapping of the lower surface was necessary to obtain a cross-section through this surface. This would reveal any bridging structure in two dimensions at least. The lower surface was photographed (Figure 5) and the sphere centres accurately located. The resulting plan is shown in Figure 2. The angular displacement of spheres referred to sphere 26 and cross-section BB is tabulated in Table 2.

3.3 Replication of Lower Surface

A calcium sulphate (plaster of Paris) impression was taken of the lower surface. Another Perspex cylinder of channel-to-sphere diameter ratio 4.70 was placed over the impression. Wooden spheres were then placed into the depressions and, guided by the original model, a replication of the bridged system was formed. The bridged system could now be examined completely or in part.

3.4 Analysis of the Bridged System

Two major bridge structures were apparent. These have been designated Bridge 1 and Bridge 2 and are shown in Figures 2 and 3. Each bridge was characterised by a "spring-ball" at the cylinder wall. The "spring-ball" positions were primarily dependent on friction and, although other spheres at the wall contributed frictional force, the "spring-balls" were judged to be basic components of the structure. Common to both bridges was a hexagon ring with sphere 26 held at five points in the centre of the ring.

Replication tests proved the existence of the two bridges; no other combination of spheres on the lower surface acted as an arch. Further tests indicated the stability of the hexagon ring. It could not collapse toward the centre and, provided sufficient friction existed between the "spring-balls" and the cylinder wall, it behaved as a stable structure.

The importance of sphere 26 was questionable. The bridged system could be replicated and isolated from the mould with or without sphere 26. However, owing perhaps to the slight variation in sphere size and the fineness by which sphere 26 was originally held, it did not lift with the rest of the system. In fact, a sphere directly above it fell to occupy part of the volume originally occupied by sphere 26. This other sphere then acted as a "key-ball" for the two bridges and locked them with more convincing arches than sphere 26 had done. The tests suggested that sphere 26 was not a basic component of the structure, but, owing to the fine tolerances necessary to reproduce the original conditions exactly, a definite conclusion on its importance was not possible.

4. DISCUSSION

Basically, the bridged system consisted of two diametric arches at about 60° relative displacement. Associated with these arches was a stable hexagon ring of spheres and within the ring was another sphere held at 5 points.

The examination indicated that:

(1) The bridge "spring-balls" were primarily dependent on friction between the wooden spheres and Perspex cylinder wall.

(2) The hexagon ring was a stable geometric arrangement and only indirectly dependent on friction.

(3) The central sphere (26) did not appear to be a basic component of the bridged system as a whole, but it was a basic component of each separate bridge.

When jamming of flow occurs in a circular channel with a channel-to-sphere diameter ratio of less than 5, an arch (either concave or convex downwards) will result. For channels of greater size the probability of a bridge occurring lessens owing to the increasing instability of spheres that are one sphere diameter or more away from the channel wall.

It was concluded that the bridged system depended on both friction and geometric arrangement of spheres for its stability.

5. REFERENCES

Fraas, A.P., et al. (1961). - Preliminary design of a 10 MW pebble bed reactor experiment. Oak Ridge National Laboratory CF 60-10-63.

Sanderson and Porter (1958). - Design and feasibility study of a pebble bed reactor steam power plant. NYO-8753.

TABLE 1

VERTICAL LOCATION OF SPHERE CENTRES REFERRED TO SPHERE 10 AS DATUM, WITH DISPLACEMENT IN TERMS OF SPHERE DIAMETER

Sphere Number	Relative Displacement (diameters)	Sphere Number	Relative Displacement (diameters)
1	0.313	17	0.260
2	1.314	18	1.221
3	0.699	19	2.146
4	1.735	20	0.590
5	0.238	21	1.477
6	1.265	22	0.729
7	0.651	23	2.008
8	1.911	24	1.929
9	1.351	25	0.908
10	Datum 0.000	26	0.337
11	0.906	27	0.656
12	0.160	28	0.434
13	1.026	29	0.600
14	0.812	30	0.517
15	1.783	31	0.588
16	2.106	32	0.641

TABLE 2

RELATIVE ANGULAR DISPLACEMENT OF SPHERES COMPRISING THE LOWER SURFACE WITH SPHERE 26 AS ORIGIN AND CROSS-SECTION BB AS REFERENCE AXIS

Sphere Number	Angular Displacement	Sphere Number	Angular Displacement
26	Origin	28	188° 30'
31	4° 42'	10	202° 12'
25	19° 48'	11	217° 0'
22	50° 42'	27	241° 30'
30	67° 30'	9	243° 30'
20	86° 48'	7	268° 30'
17	116° 30'	32	298° 36'
29	130° 0'	5	298° 36'
14	147° 42'	3	324° 42'
12	169° 18'	1	354° 42'

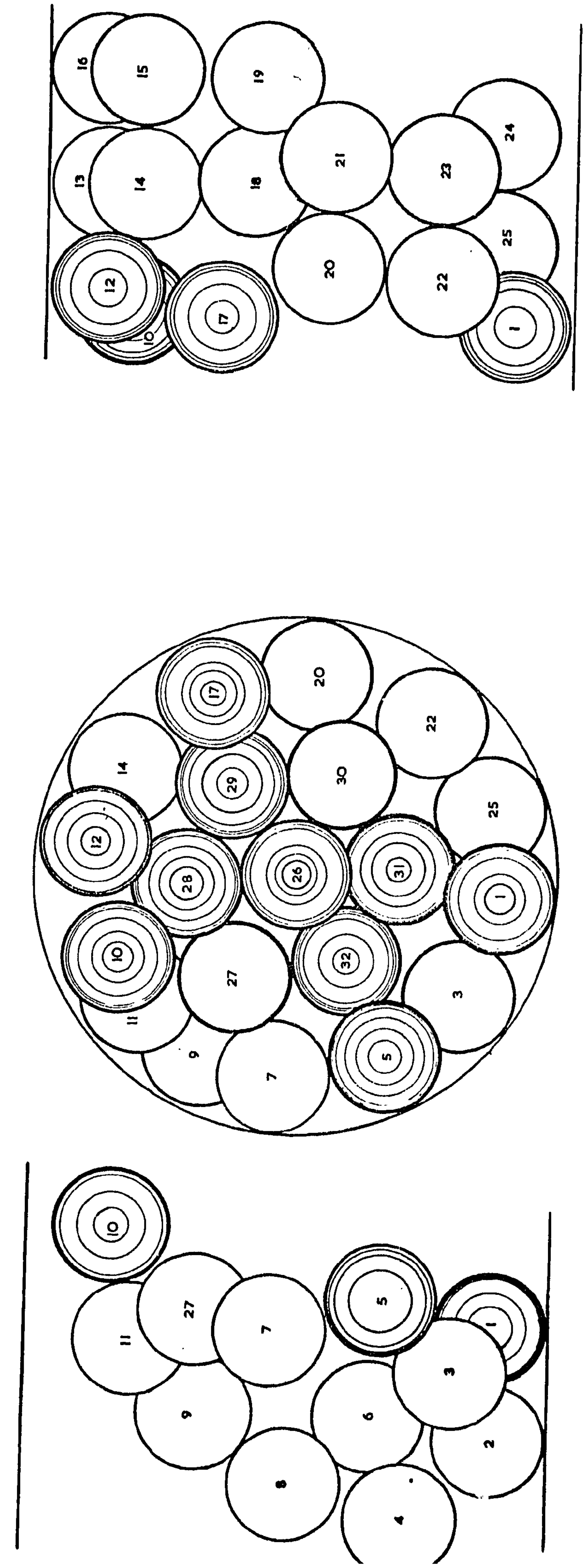


FIGURE 1 BALL DESIGNATION — LOWER SURFACE AND SIDES

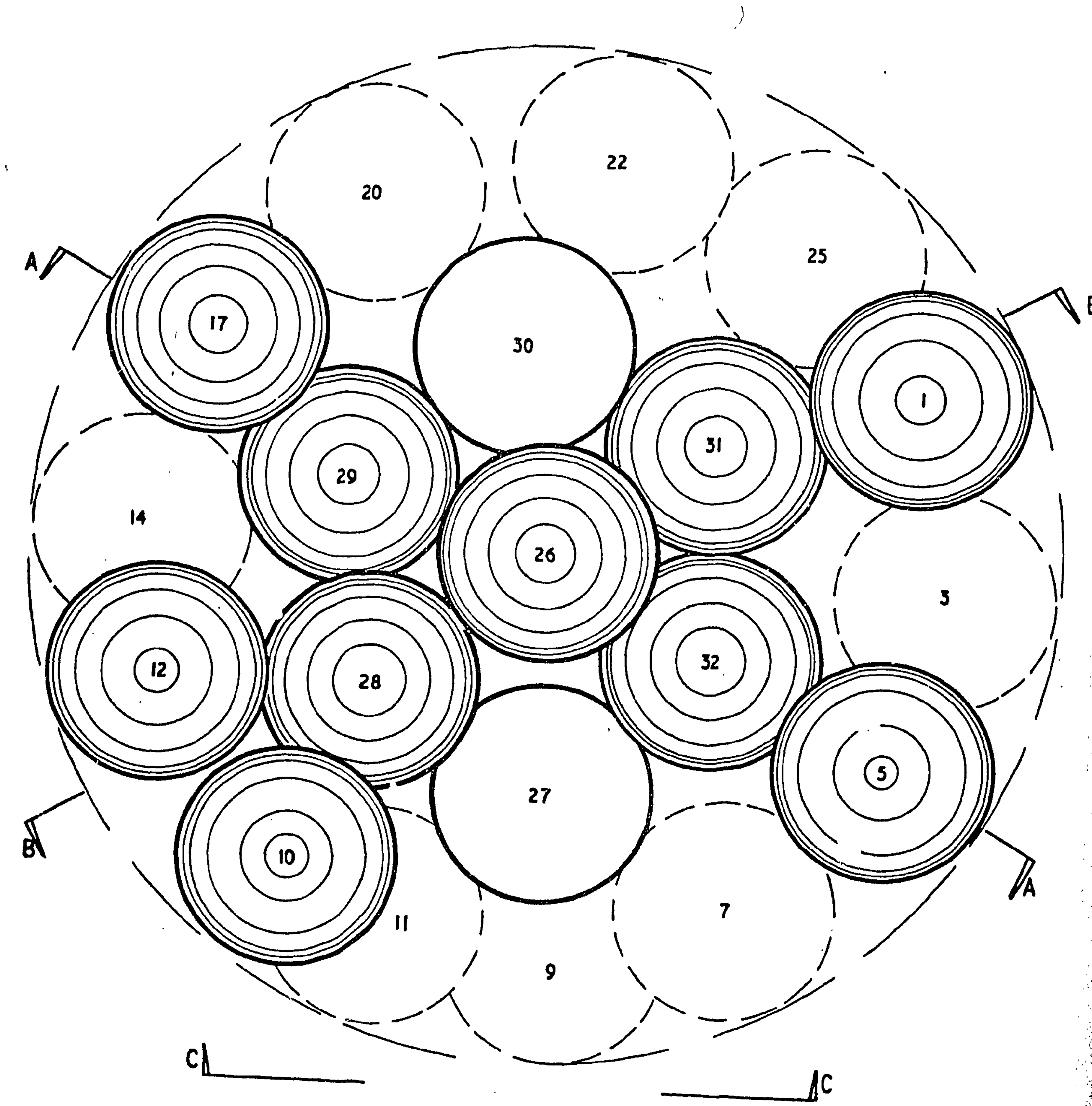


FIGURE 2 PLAN OF LOWER SURFACE
SHOWING BRIDGES 1 AND 2 AND HEXAGON RING

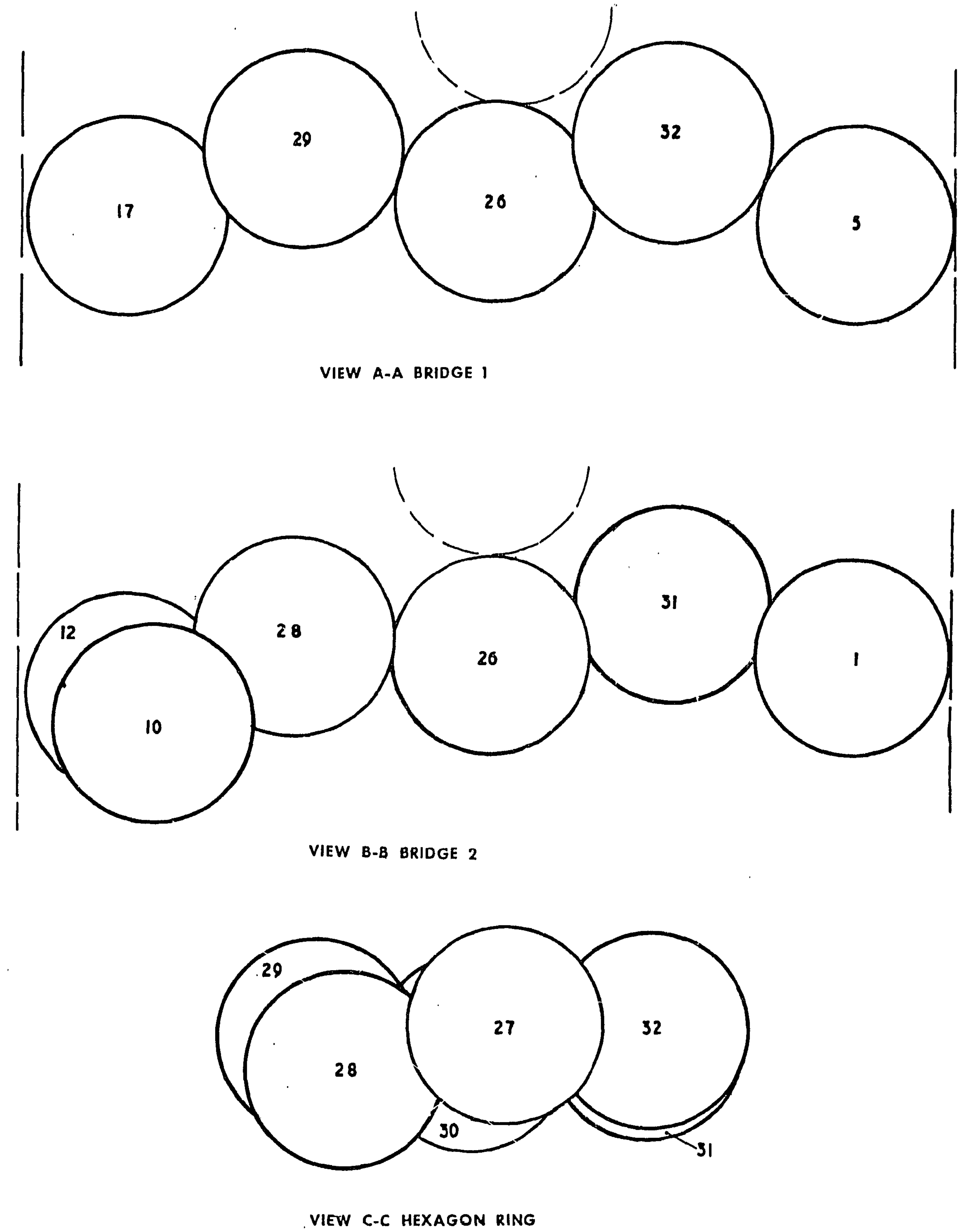
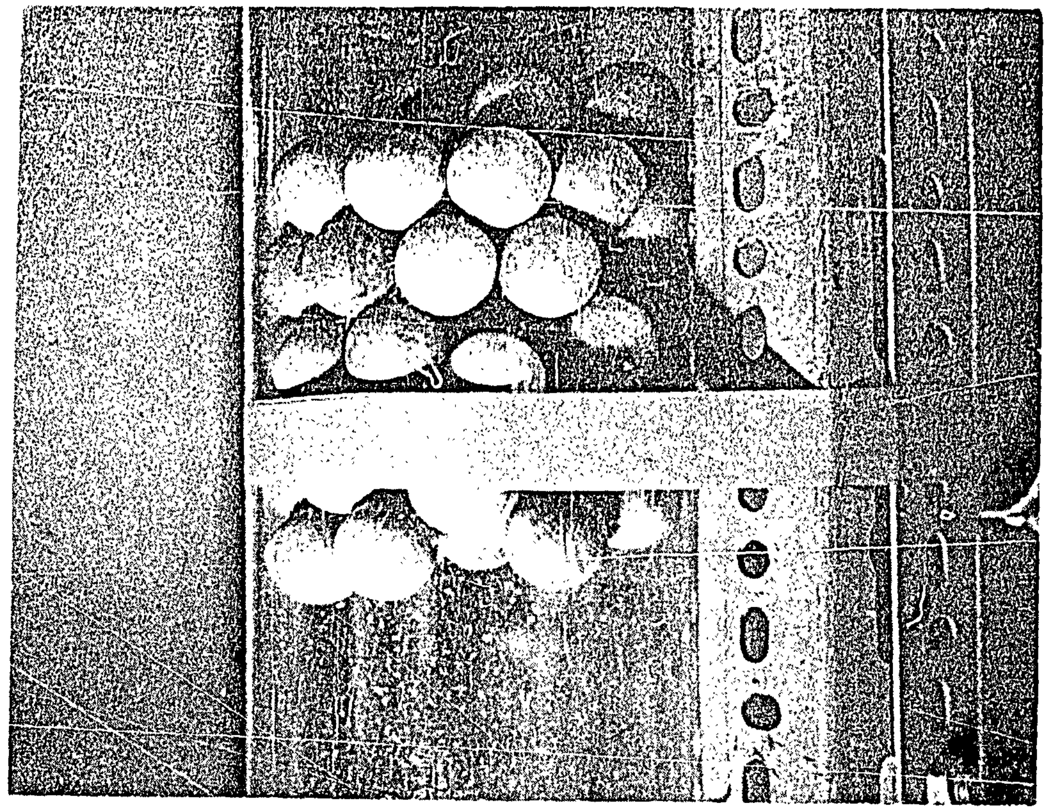
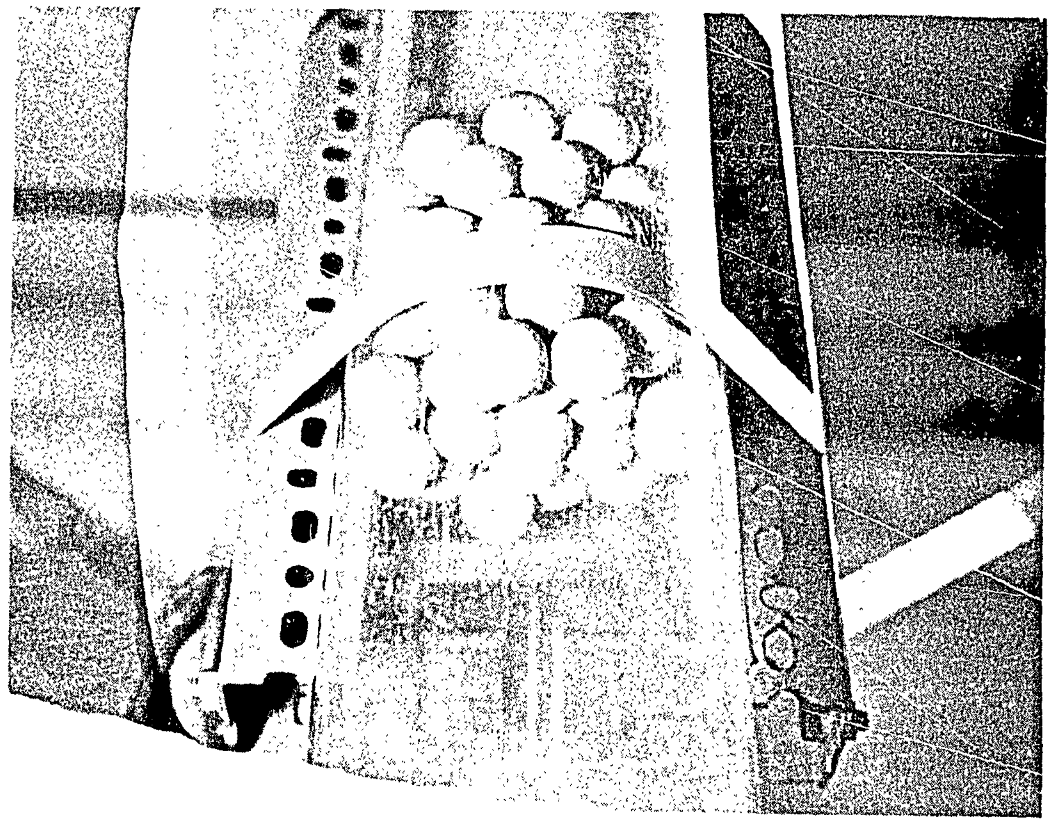


FIGURE 3 ELEVATIONS OF BRIDGES 1 AND 2 AND HEXAGON RING



(a) View on plane of lower surface



(b) Oblique view of lower surface

FIGURE 4 PHOTOGRAPH OF BRIDGED SYSTEM IN PERSPEX CYLINDER BEFORE EXAMINATION

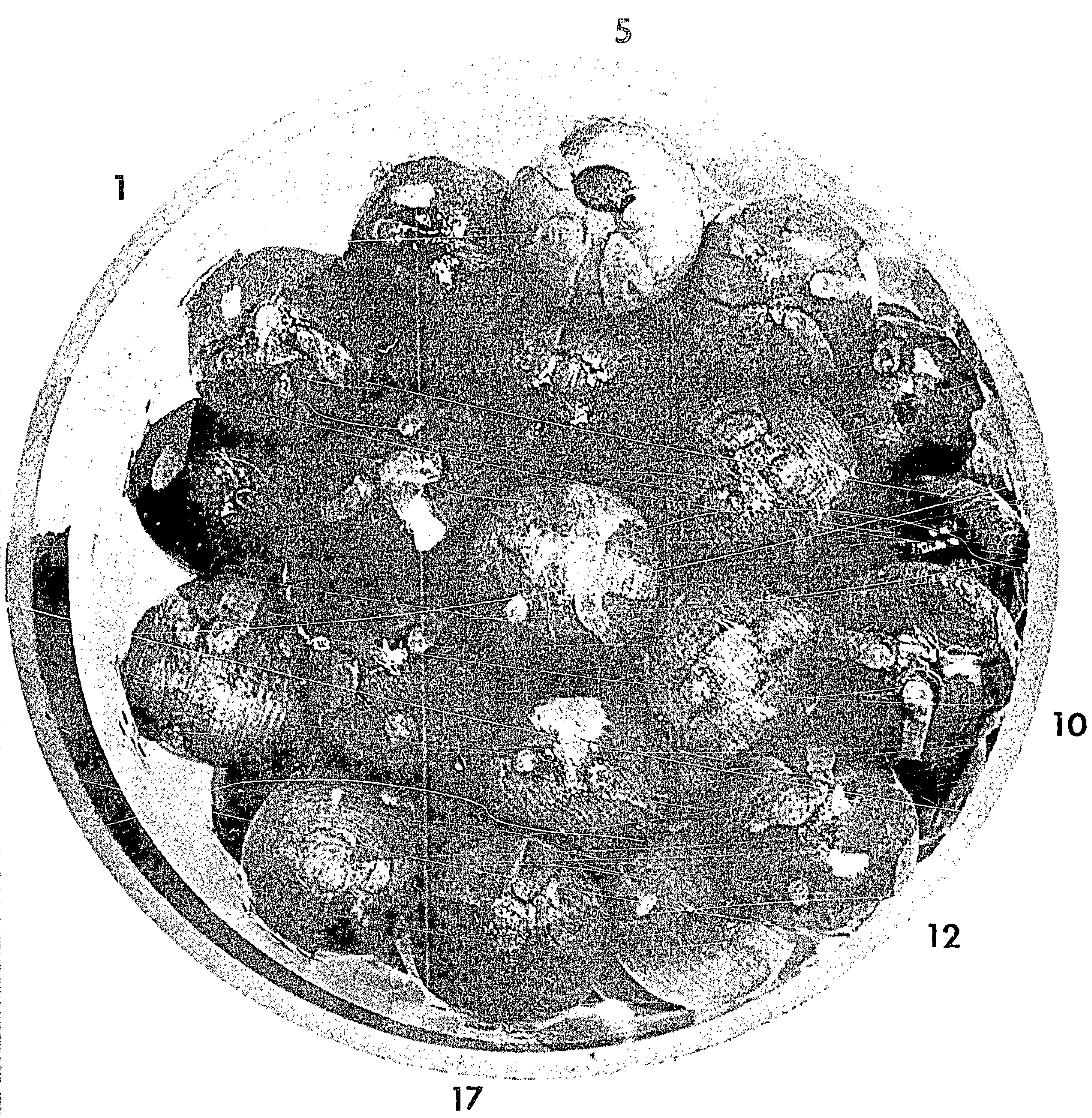


FIGURE 5 PHOTOGRAPH OF LOWER SURFACE AFTER FIXING WITH VARNISH