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INFLATED MOBILE LIFTING STRUCTURES: PRACTICAL DESIGN AND TRIALS OF A CIRCULAR PLANFORM MODEL USING MEMBRANE CONSTRUCTION

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SUMMARY

Early lifting structures had planforms with two straight sides and circular ends and with many lifting points in order to encompass road vehicles economically. Problems of load slinging and structural inflexibility, however, precluded the use of the system for most practical applications.

This paper describes tests carried out on a circular planform model to ascertain the effect on performance of only four load attachment points. After several modifications, a practical design was evolved, for use as a basis for a full scale prototype. Appendix B includes a possible application for such a device.

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* Replaces R.A.E. Technical Report 68154 - A.R.C. 30866

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1 INTRODUCTION

1.1 Background

The general concept and theoretical design of inflated mobile lifting structures has been described and analysed by W.G.S. Lester and I.S.H. Brown[1]. A full scale working model, of 1 ton lifting capacity and oval planform, was followed by an 8 ton version which is the subject of a report by I.S.H. Brown and F.T. Kiernan[3]. The design of the 8 ton model was based on the principle of optimum use of fabric, and the resulting shape in elevation is similar to that chosen for the circular model described in this Report.

All three of these lifting vessels are based on air-cushion principles and were conceived with problems of vehicle recovery in mind, particularly where vehicles may be stranded in areas of soft or marshy ground or perhaps have to be removed over a stretch of water.

1.2 8 ton lifting vessel

An exposition of the reasons behind the design and the steps taken in testing the circular model can be made by pointing out some of the drawbacks of the 8 ton lifting vessel, and endeavouring to show how these have been overcome.

For most practical applications the requirements of an inflated mobile lifting system are basically lightness, packability, simplicity and rapid preparation for use. Depending on site conditions and facilities, the 8 ton version may take a minimum of six men up to two hours to deploy. The configuration requires approximately sixty lifting and restraining cables, and more than half of these have to be attached to the vehicle to be lifted, which means vehicle modifications would be necessary. Other points are dealt with later in this Report as they arise.

The 8 ton vessel achieved success in its first objectives, and in spite of drawbacks, the effort was considered a worthwhile step towards the development of a practical lifting system. It was apparent, however, that planforms with straight sides introduce problems which are likely to make solution difficult.

1.3 Circular lifting vessel, initial considerations

The aim was to improve on the 8 ton lifting vessel, especially with respect to the basic requirements of simplicity and rapid preparation for use, and also to investigate the principles of inflated lifting structures of circular planform. The idea of using only four attachment points on a vehicle's suspension stemmed directly from the difficulties of multi-suspension systems demonstrated by the 8 ton vessel. A four point lifting system conveniently fits a circular planform, which has the additional advantage of not requiring vessel cross bracing. It was therefore decided to construct and test a vessel of this form.

To confine the tests to practical limits either a specific load, or a particular vehicle, had to be chosen around which to design the model, as it was considered that lifting vessels should be tailor-made for a particular task.

The $5\frac{1}{2}$ ton Army Scout Car was chosen as the basis for design of a new circular lifting vessel, because the plan view of it's projecting wheel hubs almost forms a square, so providing simple attachment points. The main lifting patches can be arranged symmetrically in a circular pattern, and the slight misalignment will be taken up by the elasticity of the fabric structure.

2 CIRCULAR MODEL. PRACTICAL DESIGN AND ADVANTAGES

2.1 Choice of model size

To obtain the best value from a research model some thought must be given to intended practical uses and working conditions so that the task of future development is simplified.

It is difficult to scale the stiffness of a fabric structure, particularly at the seams. The model therefore has to be large enough to prevent this increased stiffness from having serious effects, and must allow sufficient room for personnel to work inside, yet not be so large as to make it difficult to operate and tedious to modify. If it can be made small enough for one man to handle, the time and work involved to test and transport for possible modifications is greatly reduced.

The small circular model made over a dozen trips from the R.101 shed to the Cardington fabric shop for alteration, and with a large model this would have required a considerable number of man hours.

For these reasons a half scale model of the $5\frac{1}{2}$ ton Scout Car lifting vessel was chosen. This was designed to use full scale pressure in order to retain some semblance of full scale flotation, skirt behaviour and dust and spray generation. At full pressure the scale lift is $1\frac{3}{8}$ tons, but for simplicity the model was assumed to have a $1\frac{1}{4}$ ton capacity. Had the pressure also been reduced to half full scale the lift would have been only 1400 lb.

The resulting model had a diameter of $10\frac{1}{2}$ ft in plan and an upper canopy height of $5\frac{1}{2}$ ft with the $1\frac{1}{4}$ ton load lifted 6 in off the ground. The latter's base measured approximately 5 ft x $4\frac{1}{2}$ ft.

2.2 Suspension arrangement

A 2 ton "V" suspension patch had already been designed and tested for the large lifting vessel, and by using 8 such patches at half scale on the model (Fig.1) a safety factor of approximately six was achieved for the design load of $1\frac{1}{4}$ tons. The lifting cables were shackled in pairs and called for only four attachment points on the vehicle. Later, additional load restraining cables were shackled with the suspension cables to the same four attachment points on the vehicle. (Mod.1 see Figs.5 and 6.) The number of cables ultimately required for lifting and restraining the load totalled 16, (Mod.V1) but 4 additional horizontal strops were fitted between pairs of lifting patches to relieve the angular pull of the main lifting cables (Fig.3). There was no need for horizontal cross-bracing under the load to maintain the shape, since the planform was circular.

Apart from the number of lifting cables in the 8 ton design, the closeness of lifting patches produced a very stiff fabric structure of "V" section. Inaccurate cable lengths generated unequal loads in the lifting cables which in turn produced high stresses in adjacent lifting patches and resulted in overloading. It was also difficult to provide sufficient lifting points at equal distances around the vehicle without it being specially modified.

The circular model showed an improvement in this respect since any offloading of one lifting point increased the tension in the other three points. This caused the load, which was symmetrically distributed between the four attachment points, to tip and swing to a new balanced position. Since the canopy was sufficiently flexible to adjust to any small discrepancy in cable length, it was considered that it would be adequate to measure tensions in single cables of the lifting and restraining systems respectively to assess the tensions in the system brought about by lifting the load and moving the vessel. The problem is greatly simplified when compared with that for the 8 ton vessel with 26 lifting cables, the tensions of which could all be affected by unequal lengths.

2.3 Shape and deformation

Another advantage of the circular planform is that it forms a flat base which tends to hover free of the ground. The straight-sided shape arches it's back and presses firmly on the ground at both ends, causing relatively high ground friction when an attempt is made to tow the device.

Hoop stress is constant all round the lower edge of the circular model and this is complemented by uniform vertical canopy tensions and affected in a regular manner by the restraint cables. Oval or basically straight sided shapes suffer from a combination of hoop stresses at the ends, and longitudinal stresses modified by cross-bracing stresses along the sides.

Although local stresses near load carrying patches are relatively high in the circular design the overall loading in the fabric near the base is not sufficiently unbalanced for unequal strains to account for arching or deformation along the sides. This phenomenon has been noticed in lightly stressed structures of the straight sided shape, even without load carrying patches.

In instances where the load is not roughly circular or square, the circular vessel shape would be less economical in space, and probably in fabric. However, it was possible to take advantage of the continuous hoop stresses and employ an almost vertical wall with subsequent saving in fabric and side area. In turn this could provide an accessible location for a doorway and further, the chances of scooping water in rough weather or at high towing speeds would be reduced.

2.4 Stability

The canopy was designed to fit over the guided weapon version of the Scout Car but, for simplicity, no attempt was made to reproduce a model vehicle or correctly distributed load apart from arranging that the planform of the lifting points was similar to that of the vehicle's wheel hubs. It was appreciated that the centre of gravity of a full scale system would be higher, proportionally, than the present model.

However, it was estimated that if the model could be made to behave stably over water then the normal increase in stability found in large air inflated structures would more than compensate for the change in height of the cg (see section 9.2).

2.5 Buoyancy tube

At the outset, a 9 in diameter buoyancy tube was fitted to increase the stiffness of the lower edge of the canopy and at the same time to provide a firm base for air retaining devices, such as a skirt.

As a means of simplifying deployment, it was intended that the tube should provide some rigidity so that, when positioned on it's edge beside the vehicle, it could be dropped over, carrying most of the canopy with it. The buoyancy tube was later removed (see Mod.V, para.8 and conclusions (5)).

2.6 Construction

Normal manufacturing techniques and materials were used in the construction; the canopy was made with 16 gores of two ply 100 lb/in aluminised balloon fabric; with a circular panel of a yellow 60 lb/in two ply dinghy fabric to provide natural lighting at the top.

These materials allowed a safety factor of five on the fabric tensions due to plenum pressure (see Appendix A).

Three small circular windows were positioned on the sides so that the interior could be viewed while lifting tests were in progress (see Fig.1).

The eight double 1 ton "V" patches were attached to the outside of the canopy and the double webbing was taken through to the inside to carry removable light alloy toggles, in turn carrying the main lifting cables.

The buoyancy tube of 9 in diameter section was made from 16 panels of 100 lb/in balloon fabric, joints taped externally, and fitted with a standard $1\frac{1}{2}$ psi combination inflation, relief valve and deflator. It was considered that an 8 ft diameter 9 in section tube, inflated to this pressure, would give reasonable stiffness for deployment, see section 2.5 above.

Four patches were equally spaced around the inside of the tube, so that four horizontal restraint cables could be attached to the load. These were not used initially.

3 INITIAL PERFORMANCE

3.1 Test equipment

The general arrangement for the test is shown in Fig.2. A 12 hp two stroke J.L.O. engine driving a 15 in centrifugal fan with blades facing backwards was set up on a trolley, and air was fed through a 27 ft long and 2 ft diameter sleeve to the model.

The quantity of air supplied was controlled by the engine throttle and a calibrated orifice and water manometer were included in the air line for flow measurement. Plenum pressure depended upon the load in the lifting vessel, provided the fan was running sufficiently fast (see Fig.8).

3.2 Initial test

At the first test the full load of $1\frac{1}{4}$ tons was lifted to the designed height of 6 in from the ground, with a plenum pressure of 8.8 in water gauge.

The load remained balanced without any form of restraint, i.e. the load was suspended from the canopy roof only and there were no horizontal or vertical restraint cables.

Fig.3 shows the load in position, with just sufficient pressure to lift the canopy. Felt was required initially to prevent fabric damage from the sharp corners of the load; positive restraint strops were fitted later and damage was then only likely to occur through careless or sudden inflation.

3.3 Balance areas

In the balanced position described above, and referring to Fig.4, the area of ground inside the buoyancy tube, πR_h^2 or "hovering area" equalled the plan area of the canopy inside the horizontal tangent to the outer radius of the canopy, πR_ℓ^2 or "lifting area". Any increase in air supply beyond this point only resulted in extra ground clearance along one side of the buoyancy tube.

3.4 Oscillations

If the loaded vessel was moved slightly, the small acceleration applied to the load caused an imbalance of areas as defined above, due to change in shape of the canopy[2]. The imbalance resulted in a fall in lift height, h until the system rebalanced itself.

The motion was slow and self damping unless the vessel was moved rapidly, when the vertical motion became more severe, often resulting in dropping the load suddenly on the ground.

3.5 Vibrations

Apart from these relatively slow vertical oscillations of the load and top canopy, a high frequency vibration occurred between the lower side of the buoyancy tube and the ground, particularly if the vessel was operating over linoleum but less over rougher surfaces. This produced a very loud drumming noise and the vibrations rapidly wore through a light balloon fabric rubbing strip[4].

3.6 Improvements

The initial tests were sufficiently encouraging to warrant a programme of modification to the model, with the object of reducing the ground vibration and improving the stability in dynamic tests. The aim was to reach a point where movement over rough ground and water was obtainable.

4 MODIFICATION I

4.1 Modification

A $\frac{5}{8}$ in × $\frac{3}{8}$ in foam rubber strip covered with light fabric was fitted to the buoyancy tube at the line of contact with the ground.

Four horizontal restraint cables were secured to the patches located at equal intervals round the buoyancy tube, and shackled to the lifting points on the load (see Figs.5 and 6).

4.2 Result

The loud drumming was reduced by about 75%, but when the vessel was moved the vertical oscillations increased considerably, to a point where any further movement could only be effected in a series of hops; occasionally with complete loss of pressure.

4.3 Discussion

It is difficult to make a perfectly flat based buoyancy tube owing to slight distortions at the panel joints. The effect of the foam rubber strip was to prevent completely the escape of air under the buoyancy tube until the vessel hovered. The resultant sudden increase in air leakage at lift off was aggravated still further by moving the vessel.

It was not easy to apply a purely horizontal force at the same height as the cg and the vessel tipped slightly, causing the forward edge of the buoyancy tube to rub on the ground; and swing the load forward.

A sudden loss of pressure relaxed the tensions in the fabric, the load dropped, and there was an immediate increase in lifting area together with a rise in pressure due to the ground seal reforming. On reaching the point of balance during re-lifting, the load continued upwards under the effects of inertia until the lifting area grew too small and allowed the load to drop once more.

This change in lifting area can be explained as follows. It is seen (Fig.4) that when the height of the load, h increases, point A moves vertically to A', since the upper canopy A to O is part of a sphere and therefore its radius, R_a cannot increase. This movement induces B, the contact point between the outer canopy and its horizontal tangent, to move inwards from R_ℓ to R'_ℓ. At the same time the base radius, R_h tends to decrease, due to the restraint cables FG acting on E, the ground contact point, but this decrease in area caused by the movement of the latter is not sufficient, or fast enough, to counteract the initial upward movement of the load. An increase in areas, or the reverse, occurs when the load overshoots or falls. The load, fabric and air supply form an oscillatory system comprising in effect a mass, a spring and an exciting force which is affected by the motion of the mass on the spring.

This motion has marked similarities with the low-frequency oscillations of Hovercraft Skirts, although with the latter it is the interaction of bag pressure and cushion pressure change which causes the unstable conditions. Crago states[4] that "the phenomenon of skirt oscillation is a highly non-linear one and no acceptable theory has yet been formulated for predicting either its occurrence or magnitude".

5 MODIFICATION II

5.1 Modification

The foam rubber strip was removed and replaced 2 in. inboard from the point of ground contact in the form of a discontinuous strip, and a neoprene nylon rubbing strip was added to the original position. This produced a form of double seal between the corner of the foam strip and the rubbing strip (Fig.5 Mod.II).

5.2 Result

The drumming of the buoyancy tube remained the same as at the first modification, but the vertical oscillations of the load were reduced to a point where it was possible to move the full load without setting up violent bouncing.

5.3 Water test

The fully laden vessel was tested for water-borne characteristics by sliding it, while hovering, down an earth ramp into a test pond. Large vertical oscillations of the entire fabric structure were set up with the accompaniment of a considerable amount of spray. After two or three seconds the load sank into the water, leaving the buoyancy tube on the surface.

All attempts to re-lift the load by gradually increasing the pressure (opening the throttle) failed. It had been noted that the vertical oscillations could be controlled to some extent on dry land by setting the throttle only just wide enough to raise the load.

5.4 Water behaviour, discussion

To lift the full load of $1\frac{1}{4}$ tons over water, a pressure of almost 9 in water gauge (46 lb/ft^2) was required inside the vessel. If the vessel was to displace an equal amount of water, the surface of the water outside should have been approximately level with the top of the buoyancy tube, since this was also 9 in deep (Fig.5, Mod.II).

Under normal operating conditions, over land or water, the plenum pressure acts on the buoyancy tube, and provides a downward force which is transmitted to the walls of the vessel. However, any movement of the load, resulting from the vessel being pushed down a slope onto water, would cause a rolling moment, which depresses one side of the buoyancy tube below its balanced position. This eventually produces a net upward unbalanced force due to buoyancy which provides a small righting moment. At the same time the far side of the tube is now above its floating position in the water and a large air escape results, causing loss of lifting pressure. There is no possible means of recovery once the load falls into the water, due to an adverse balance of lifting and hovering areas.

One method of overcoming this difficulty would be to fit a conical skirt sufficiently long to allow for the total depth of water displacement. The buoyancy tube would then only occasionally come into contact with the external water surface, and the download would not be overcome by buoyancy forces. The conical skirt in itself could provide sufficient change of Centre of Buoyancy to covercome rolling moments.

However, a skirt with a vertical depth of 9 in could have led to further difficulties of stability and obstacle catching on land, therefore a 3 in conical skirt was fitted as an interim measure. (Fig.5, Mod.III)

It should be noted that, whereas the 8 ton vessel never suffered from this type of instability, it tended instead always to roll and blow off on one side while on water. This was probably due to the large resultant download on the buoyancy tube and the relatively confined area of air leakage due to the vessel arching its back (see section 2.3). The same fan/motor unit was used for both vessels.

6 MODIFICATION III

6.1 Modification

A simple 3 in conical skirt was attached to the buoyancy tube in place of the foam strips. (Fig.5, Mod.III.)

6.2 Result

Very bad vertical instability occurred on land at all but the lowest throttle settings, and the vessel was almost impossible to move.

6.3 Reason

The addition of the skirt had provided an almost perfect seal and the operating characteristics were similar to those produced by Mod.I.

7 MODIFICATION IV

7.1 Modification

Small circular bleed holes were progressively cut in the skirt until the vessel operated with the edge of the former resting steadily on the ground. (Fig.5, Mod.IV.) This was achieved by 64 $\frac{7}{8}$ in diameter and 160 $\frac{3}{8}$ in diameter holes evenly spaced around the skirt.

7.2 Result

The vessel now operated well at full load, and the vertical oscillations of the load were acceptable even at full blower pressure. The maximum load on water with stability was found to be 4 cwt.

7.3 Water behaviour

If the airflow is assumed to pass right under the skirt with negligible jet thickness and not escape through the bleed holes, and the vessel is in perfect balance, then the maximum theoretical load with this skirt is $6\frac{1}{2}$ cwt. Any further loading would depress the buoyancy tube into the water and tend to set up instability (see section 4.3/5.4).

8 MODIFICATION V

8.1 Modification

The buoyancy tube and load restraining cables were removed and replaced by a conical skirt in neoprene nylon with a half-cone angle of 45° and a depth of 18 in. The bleed holes used in Mod.IV were repeated. (See Fig.5, Mod.V.)

8.2 Result

Without horizontal restraint ropes it was quite impossible to achieve any degree of stability. However, with 8 ropes spaced radially around the canopy and attached to the corners of the load, an almost perfect static balance could be obtained, although rough handling while manoeuvring the vessel could induce the load to fall. The ropes were attached to the canopy by circular patches which dimpled inwards some three inches allowing a similar movement of the load. The resultant shift of the centre of gravity relative to the centre of pressure caused instability while handling the vessel.

9 MODIFICATION VI

9.1 Modification

An annular ring of fabric reinforced with a steel cable grommet was attached to the lower edge of the skirt and radially to the load by eight cables (Figs.1 and 5).

9.2 Result

The effect was to pull the edge of the skirt right under and form a partial "bag" type skirt. The load was held rigidly and the skirt formed a good anti-fouling configuration.

This modification produced for the first time a really stable lifting system. It was almost impossible to cause the load to drop even with a hard upward push on the canopy, and any such movements were rapidly damped out. Linoleum surfaces produced the familiar loud drumming noise, but in spite of this only 15 lb side thrust was required to move the $1\frac{1}{4}$ ton load. By comparison, around 80/90 lb are required to move a normal 1 ton vehicle on its road wheels along a smooth surface.

9.3 Load towing

Towing the vessel at 5 mile/h was possible on flat surfaces but directional instability occurred on cambered roadways, and it was difficult to maintain position on the crown of the road. This could be overcome by hand, but at times the test model was completely enveloped in dust, making such assistance unpleasant, even at the end of a 25 ft rope.

9.4 Water behaviour

The vessel behaved well on water and remained stable with an extra 100 lb offset 2 ft from the centre of the load tray. The vessel blew off around three quarters of it's periphery under these conditions. Considerable spray was developed at all times over water. Three men were able to haul the fully laden vessel out of the water up a rough surfaced incline of approximately 1 in 12.

10 SUMMARY OF INFORMATION FROM TRIALS

The modifications above completed the initial trials with the small circular lifting vessel, and a summary of the main points of interest is as follows:-

(1) Loads of over a ton can be moved with a relatively simple and stable system requiring only four attachment points.

(2) Nearly vertical walls for circular lifting vessels are possible, and effective for saving space, fabric and weight.

(3) Wrap-under skirts provide adequate stability and clearance for movement over rough concrete and water.

(4) Circular lifting structures are susceptible to vertical oscillations of the load, and are generally accompanied by vibrations of the skirt, particularly on smooth surfaces.

(5) Buoyancy tubes incorporated in circular lifting vessels appear to cause major stability problems over water. If used as stiffening rings (to aid erection of canopy over the load) they should be placed above the external water level.

(6) Pressures of the order of 50 lb/ft^2 will be required for lifting road vehicles or loads of similar densities, although in selecting working pressures the particular application will have to be taken into account and generally the vessel will be made as small as possible to accommodate the load, tending towards higher pressures.

(7) Dust clouds and water spray may be considerable in certain environment and efforts to reduce vessel size, with subsequent increase in pressure, may be limited by the need to protect the blower unit and personnel from such irritants.

(8) With the double canopy construction the height of the main lifting patches at "Hover" can be predicted (Appendix A), since the lifting area can be determined and vertical restraint is unnecessary. However, horizontal load restraint is essential for reasons of stability.

Some theoretical work was done on the distribution of fabric stresses, but lack of suitable instrumentation to measure fabric strains, and particularly to carry out any measurements under dynamic conditions, prevented this being pursued on a practical basis. A note on some aspects of fabric stresses and a hypothetical treatment of some of the canopy mechanics is included in Appendix A.

11 CONCLUSIONS

(1) Trials with the double canopy circular lifting vessel have shown that this design, using only four attachment points, can successfully lift and transport a $1\frac{1}{4}$ ton load over land or water in a stable manner.

(2) Confident design of new full scale lifting structures requires further study of the problems of vertical oscillation and dynamically induced stresses in the fabric. Models of approximately 8 to 10 ft diameter appear to be of adequate size for future research work.

(3) A full scale model able to lift $5\frac{1}{2}$ tons using the same pressure as the half scale model, but requiring twice the flow to cover the double escape area, would (from interpolation of manufacturer's charts and the area-flow curve plotted for the model) call for approximately 20 hp. A petrol engine-fan unit of this output would weigh in the region of 500 lb and would require a fairly substantial trailer. It could be more practicable to mount the unit permanently on a cross country vehicle making use of a power take-off unit to drive the fan.

(4) In competition with "Hoverpallets", pressure vessel systems would not compare favourably in size when operating in confined spaces, or probably in speed and simplicity in operation, but they would gain on portability, weight, and the advantage of being able to pick up the load from above without the use of pallets or jacks.

(5) The development of a really practical system for heavy vehicle recovery, or the movement of bulk loads over rough ground and water, would require considerable work on methods of deploying the lifting vessel to the site, and

of fitting it prior to inflation. A possible method for deployment of a small 16 ft diameter lifting vessel is described in Appendix B.

(6) In specialised cases of the sort shown in Appendix B and elsewhere in unusual conditions where it is also obligatory to lift the load from above, there may be a practical use for these devices. It is difficult to see how they could otherwise be utilised with advantage.

Appendix A

FABRIC STRESSES

A.1 Upper canopy

The upper canopy AO (Fig.6 and section 2.6) inflates to form part of a sphere of radius R_a.

From the theory of a membrane under pressure,

$$\begin{aligned} T_a &= PR_a/2 \\ &= 5.35 \text{ lb/in} \end{aligned}$$

where $P = 0.32$ lb/in^2.

Fabric strength at it's weakest point is 60 lb/in which gives a factor of safety of approximately 11. In practice the circumferential tension in the fabric at the junction of both canopies A is to a large extent alleviated in the model by the horizontal inward components of the lifting points attached at this position, however, local stresses near the lifting patches along the length of the gore will be increased.

A.2 Lower canopy

Considering circumferential hoop stresses in a horizontal plane, point C has the largest radius R_p, and therefore the greatest tension. All other points work at less radius and need not be calculated for hoop stresses, in a simple stress analysis.

$$\begin{aligned} T'_c &= PR_p \\ &= 20.2 \text{ lb/in} \quad . \end{aligned}$$

Fabric strength at this point is 100 lb/in, which gives a factor of safety of 5. This is reasonable as it is normal to work with a safety factor of at least 3 with inflated fabric structures.

Theory indicates that there is no longitudinal tension at point E, as a free edge is formed while the vessel is hovering just clear of the ground. In practice there is a small inward tension T_f due to cables at FG which are fitted with a small initial tension of a few pounds. These cables also transmit the inertia loads caused by moving the lifting vessel. Theoretically these are small unless friction occurs along the base of the vessel, when it is possible for large loads to occur.

The longitudinal tension T_d at C, can be calculated from the plan area of the lower canopy CDE.

Total longitudinal or vertical load, downwards from C $= P\,\pi(R_p^2 - R_h^2)$

$= 1710$ lb

Length of fabric at C $= 2\pi\,R_p$

$= 395$ in.

Therefore longitudinal tension at C,

$$T_d = 4.34 \text{ lb/in} \quad .$$

With a fabric strength of 100 lb/in factor of safety is approximately 20.

If the pressure vessel is inflated without a load the fabric will take up a shape of maximum volume (see Fig.7). The pressure builds up inside sufficiently to lift the weight of the vessel, and therefore the tensions in the fabric will be very small. However, if a load is fitted and the vessel reinflated the tensions in the fabric can be considered to be caused by the load, and they must conform to the theory for membranes under pressure. This enables the shape of the vessel and in particular the height of load lift to be estimated.

The radius of the upper canopy, and in particular point A, is fixed, since it forms part of a sphere. Similarly the conical portion of the lower canopy and in particular point C, is fixed since it forms part of a cone. However, A is free to move vertically relative to C, insofar as the area balance and load restraints allow.

At A the balance of forces presents a complex problem. The net down load, at the junction of the canopies A, is 8 equally spaced 350 lb loads, which are transferred into the fabric via the two arms of the "V" patches. One arm is attached to the upper canopy with a fabric tension of approximately 5 lb/in (part of a sphere) and the other to the lower canopy with a fabric tension of approximately 8 lb/in (hoop). If the total load carrying capability for the two parts of canopy which meet at A is calculated on a pressure/tension basis, it approaches the design load 2800 lb. Radii of curvature were distorted in the region of the "V" patches due to local stress concentrations, which make an accurate assessment of stresses difficult.

The toggles and lifting cables which transferred the load to the "V" patches were calculated to have a safety factor of over 4. During early tests the lifting patches and the canopy suffered severe shock loads due to "inflation" instability; no signs of over-stressing were detected.

Appendix B

A POSSIBLE RECOVERY SYSTEM FOR VEHICLES UP TO 5½ TONS

(see section 10)

The system comprises a special duty landrover fitted with 6 ft diameter balloon tyres[5], front mounted hydraulic winch and an engine driven fan unit mounted at the rear, leaving space for the deflated pressure vessel, inflation sleeve, and collapsable 300 lb derrick (Fig.9).

The normal recovery procedure supposes that trees or hard ground suitable for screw pickets are to be found within reasonable distance in line with the recovery path. Having firmly attached the winch cable, the recovery vehicle reverses towards the stranded vehicle paying out cable as it goes. At the recovery site the derrick is deployed and the specially packed canopy is lowered to a position just over the stranded vehicle. A helicopter type release is operated allowing the sides of the canopy to roll down around the vehicle and personnel who attach the four main lifting strops to the vehicle's hubs.

The towing cables are fitted between canopy and towing vehicle, so it only remains for the canopy to be inflated, and provided lift-off is effected the winch can be engaged and the vehicles hauled to hard standing.

In theory two men could easily operate the system in good weather conditions, provided there was no hurry. Pot holes and ditches would have to be filled in in order to maintain a steady lift and forward progress.

Where the stranded vehicle had travelled some distance from any trees or firm ground, it might be feasible to use the relatively small traction power of the recovery vehicle itself, since it could be argued that the stranded vehicle would only have got so far if the going had not been difficult in the first place.

SYMBOLS

R_a	radius of curvature of upper canopy
R_b	inner radius of curvature of lower canopy
R_c	outer radius of curvature of lower canopy
R_h	radius of curvature of ground contact
R_p	maximum radius of curvature of lower canopy
R'_ℓ	radius of curvature of horizontal tangent to lower canopy
R_ℓ	radius of curvature of secondary horizontal tangent to lower canopy
h	height of load from ground
h'	secondary height of load from ground
M_g	the load mass
T_a	tension in upper canopy (spherical from A to A')
T'_a	tension in canopies (horizontal hoop, at A and A')
T_b	tension in lower canopy (vertical hoop, from A to B)
T_c	tension in lower canopy (vertical hoop, from B to C)
T_d	tension in lower canopy (vertical hoop, from C to D)
T'_c	tension in lower canopy (horizontal hoop, at C and C')
T_f	tension in restraint cables
T_g	tension in lifting cables
P	internal pressure to lift the design load
d	depth of skirt

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No.	Author	Title, etc.
1	W.G.S. Lester	Inflated mobile lifting structures. Analysis of generator-cord construction for circular planforms. A.R.C. R & M 3377 (1962)
2	I.S.H. Brown	Inflated mobile lifting structures. Analysis of membrane construction and design optimisation for oval planforms. A.R.C. R & M 3378 (1962)
3	I.S.H. Brown F.T. Kiernan	An inflated mobile lifting system for an 8 ton load. R.A.E. Technical Report 67190 (A.R.C. 29789)(1967)
4	W.A. Crago	Problems associated with the use of skirts on Hovercraft ADL 2/68 I. Mech. E. Automobile Division (1967)
5	A.Y. Simpson	The Cardington balloon wheel fitted to a landrover. R.A.E. Technical Report 68196 (1968)

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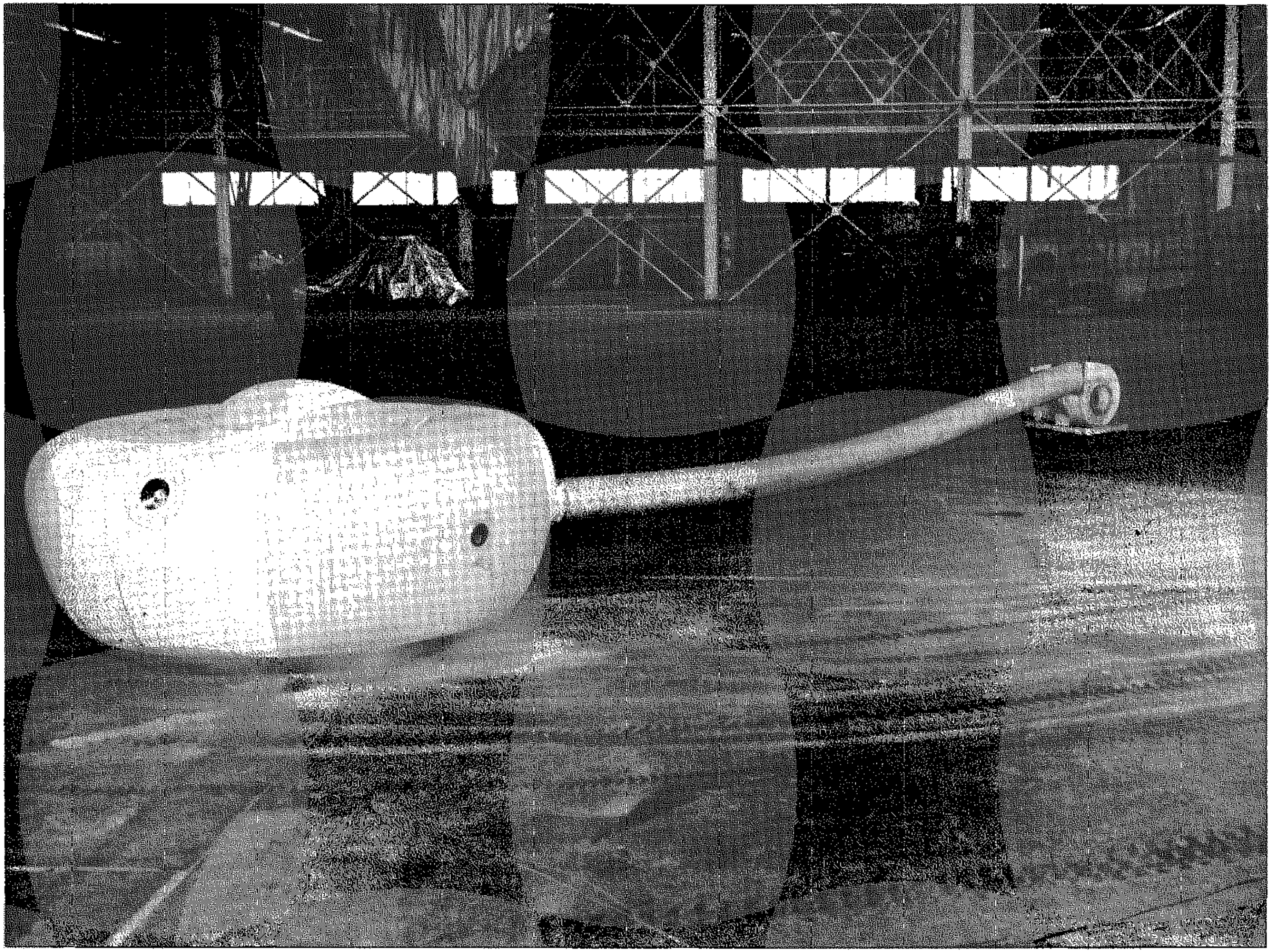


Fig.2. Pressure lifting vessel and blower

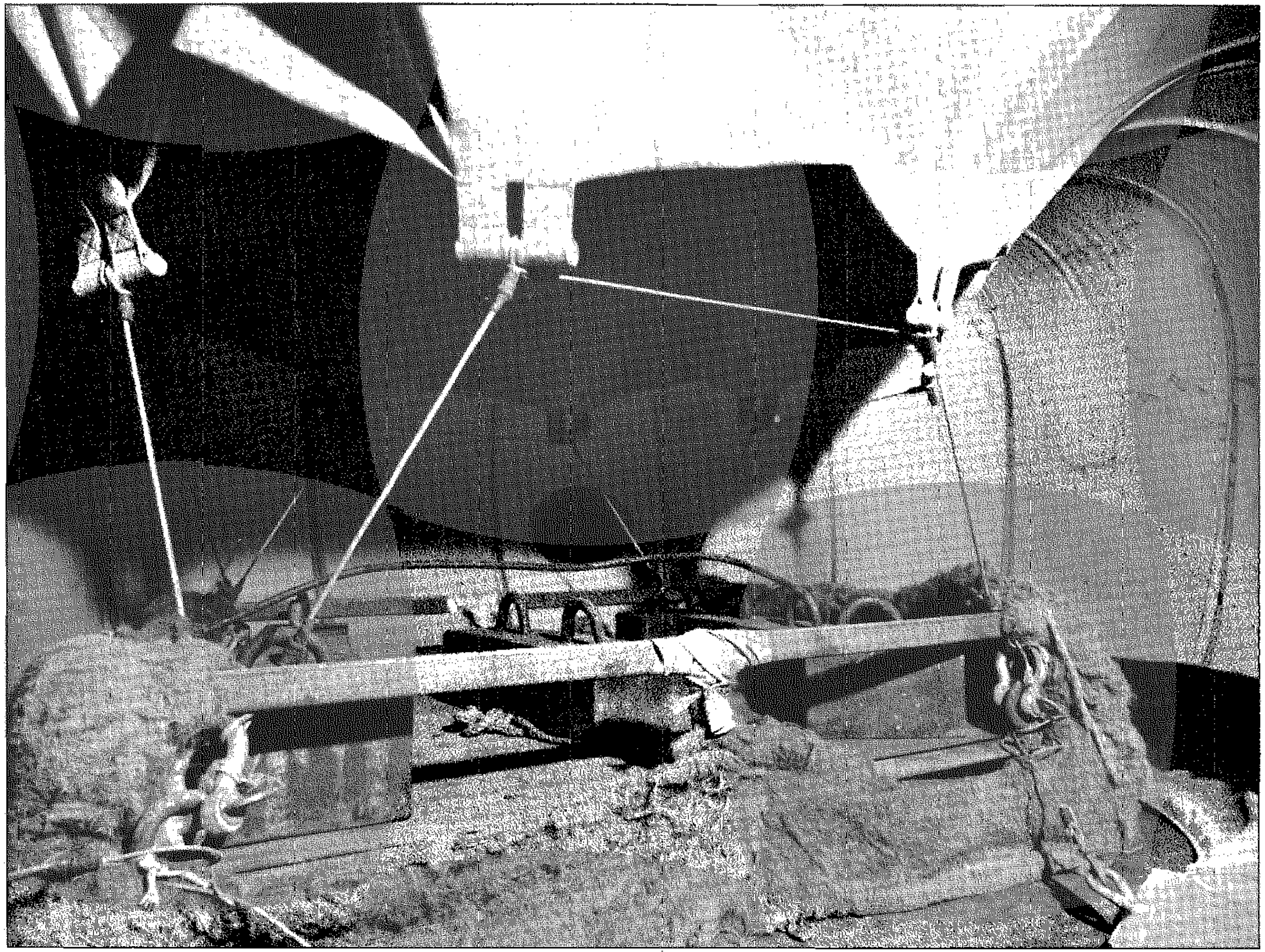


Fig.3. Padded 1¼ ton load and method of attachment

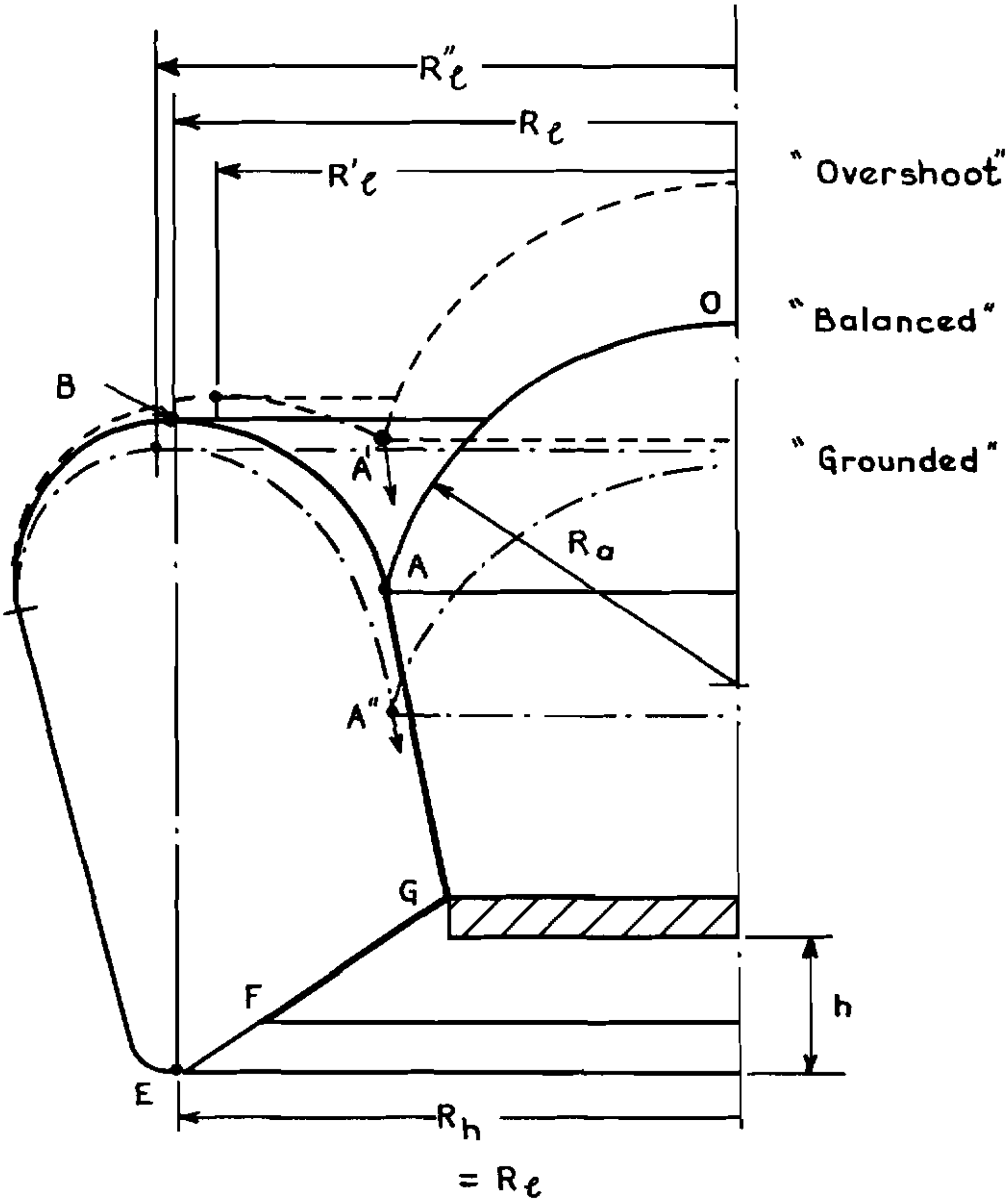


Fig. 4 Change in lifting area (mod 6)

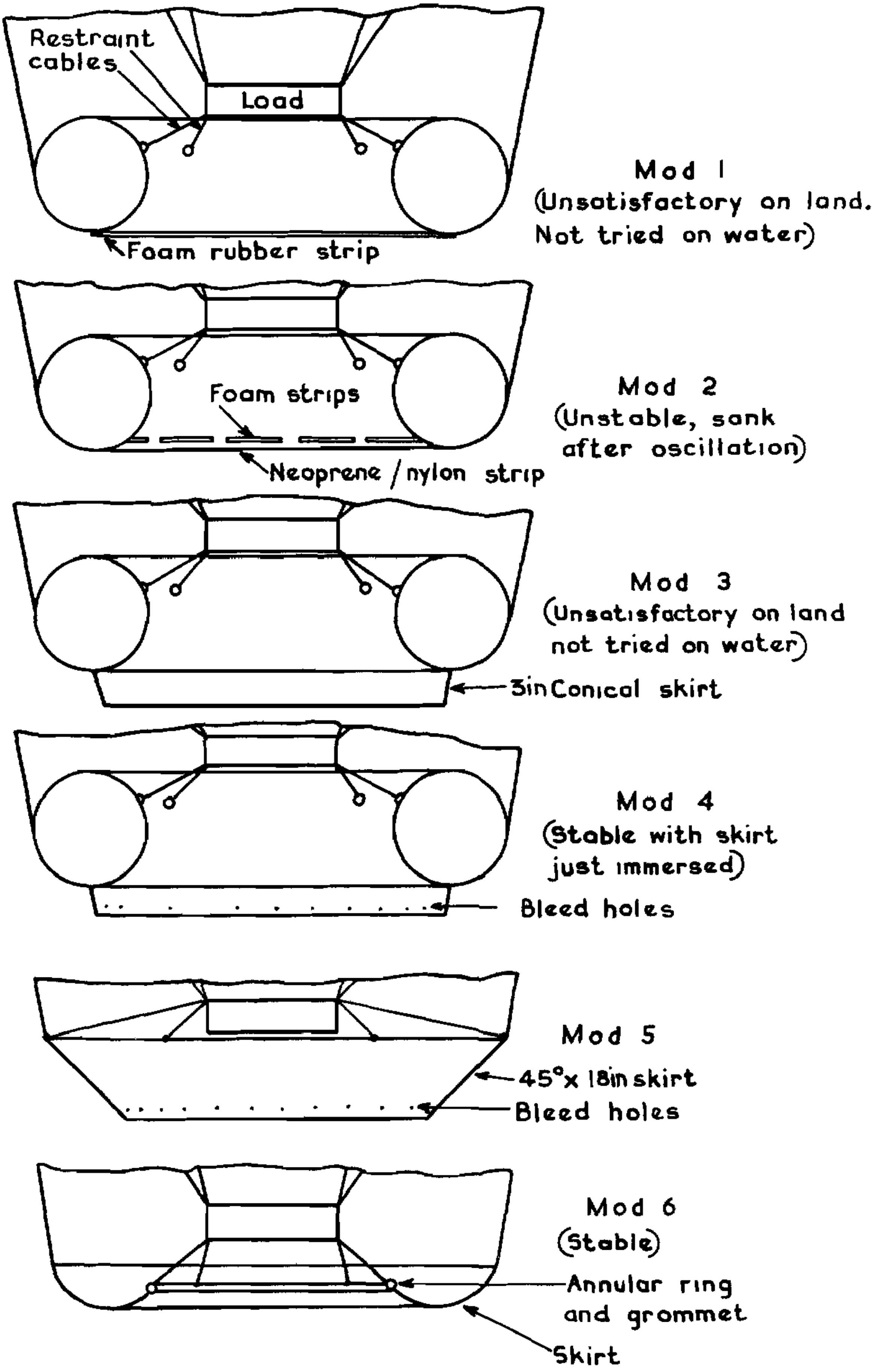
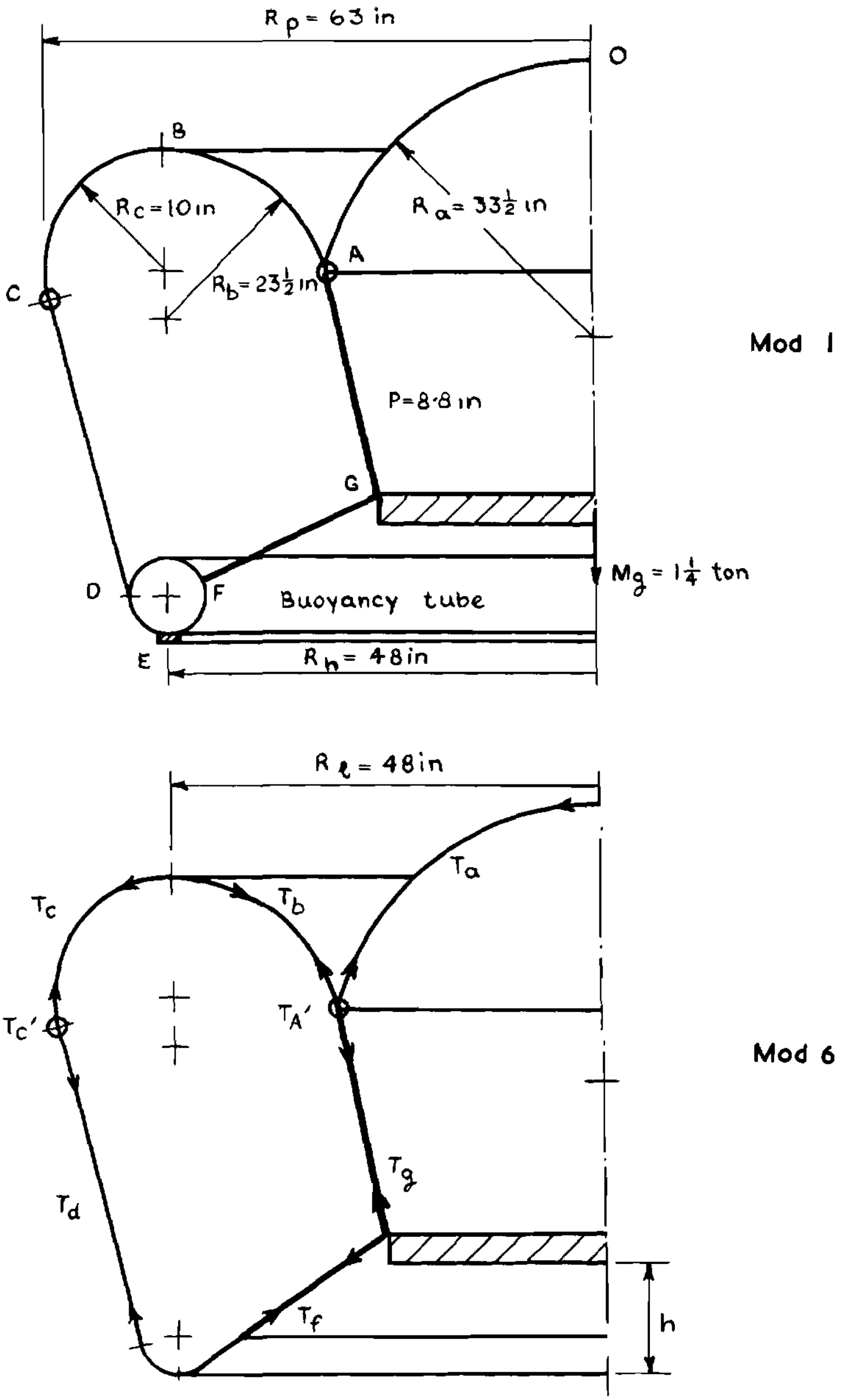


Fig. 5 Modifications to achieve stability on water



Mod 1

Mod 6

Fig. 6 Model diagrams showing tension notation & dimensions

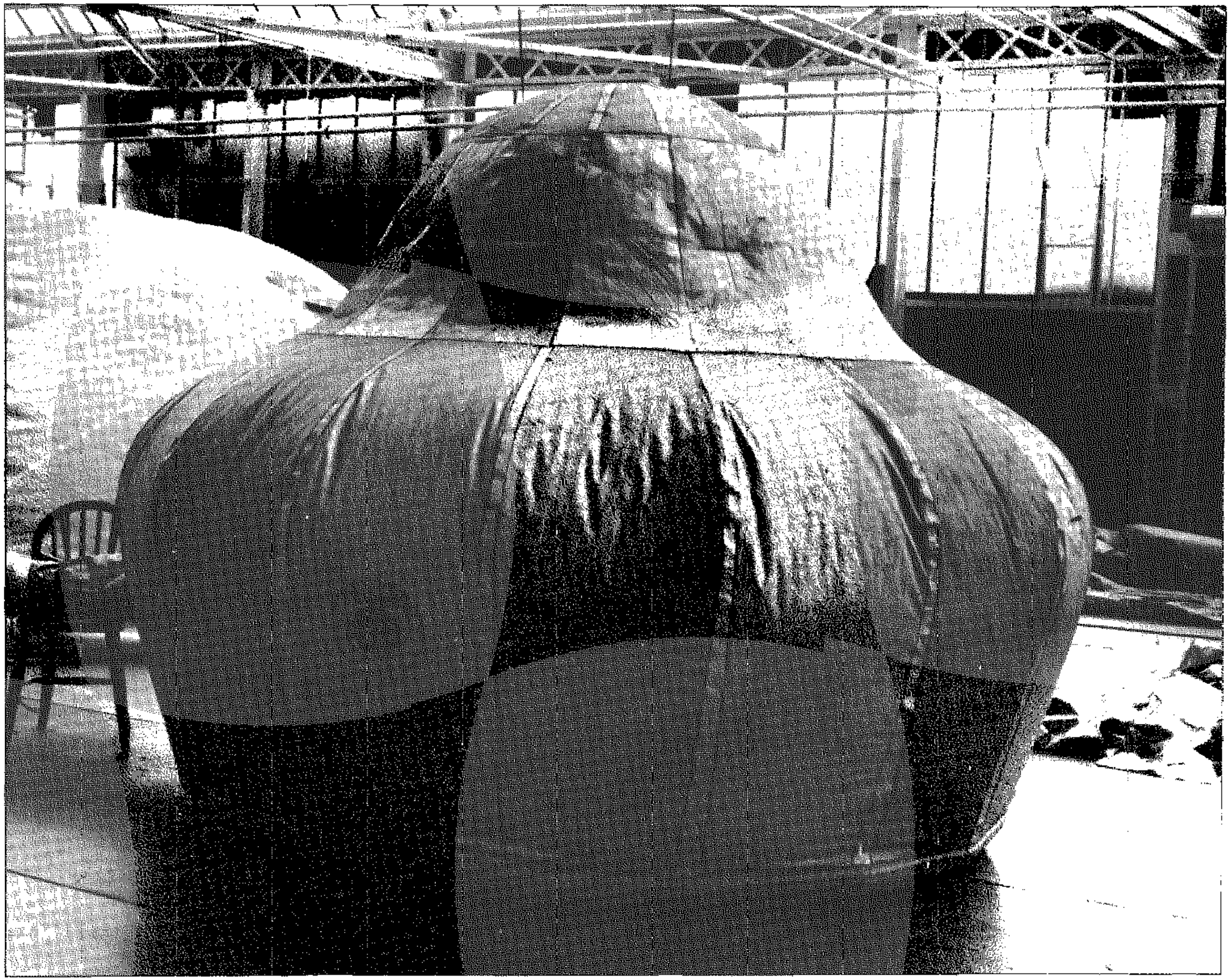


Fig.7. No load, fully inflated

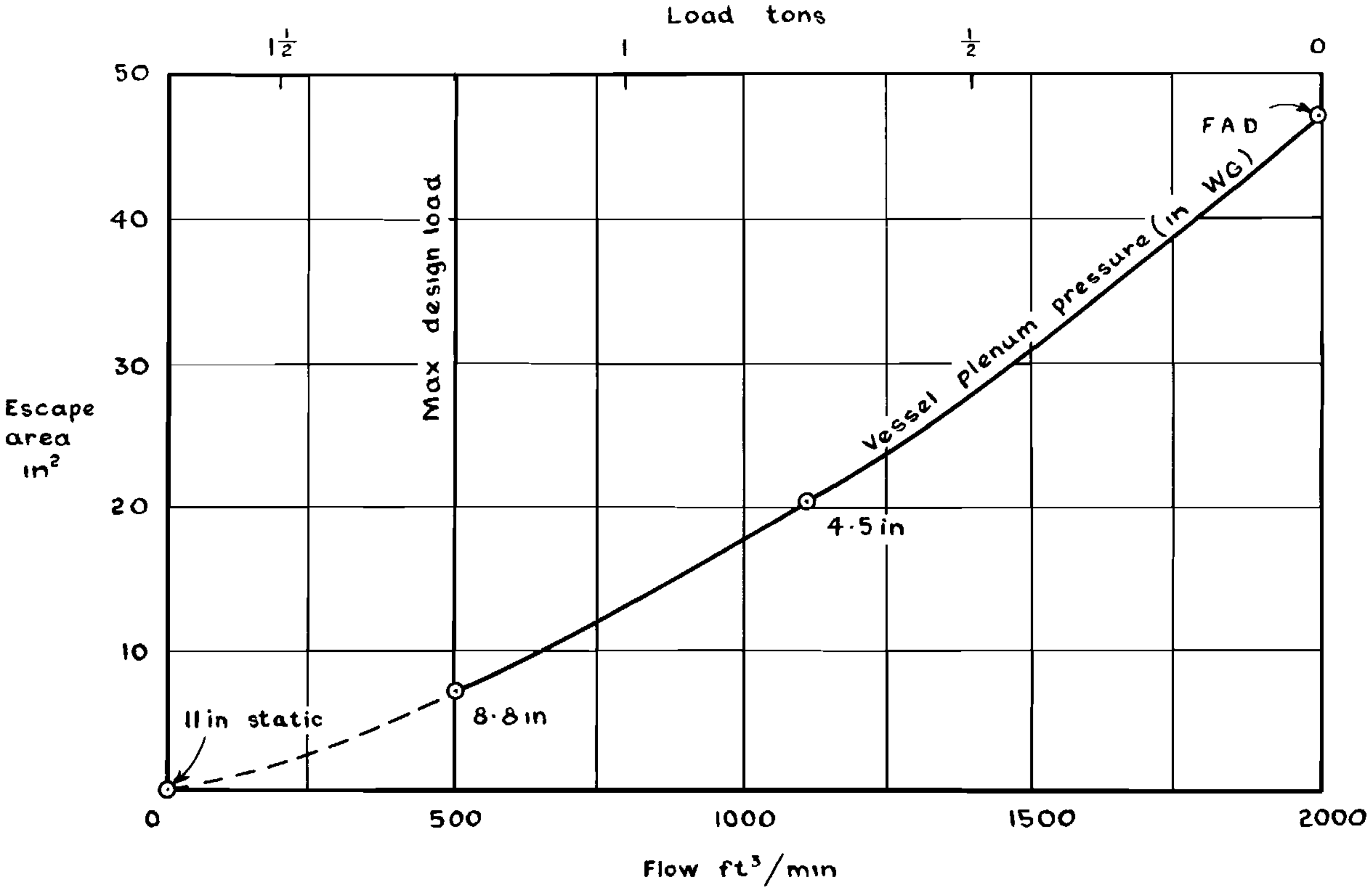


Fig. 8 Typical escape area / flow curve (constant throttle setting)

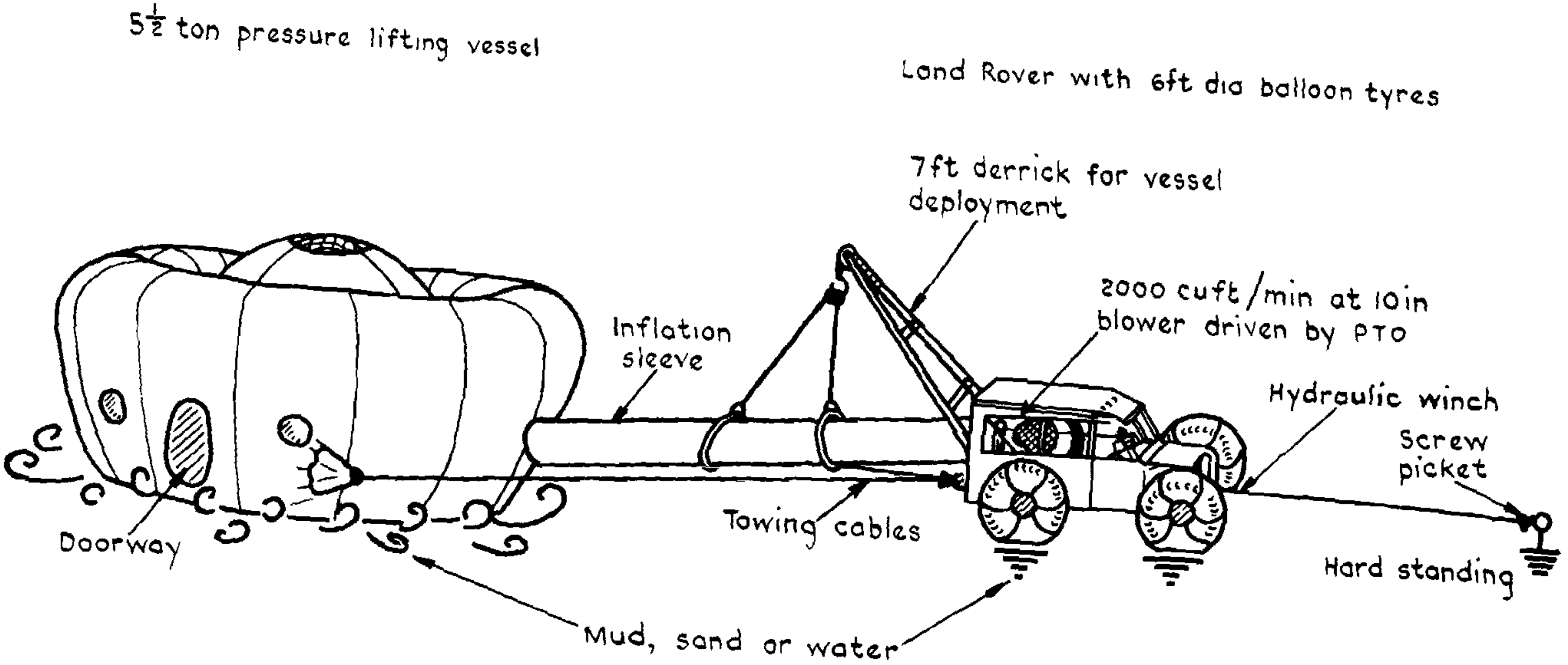


Fig. 9 Land Rover recovery system

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