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Investigation into the Plowing-in and Overturning of Ground Effect Machines

Report No. 27

by

Norman K. Walker and Edwin P. Rood Jr.

Edited ____________

Approved ____________

Prepared by

Norman K. Walker Associates Inc.
7240 Wisconsin Avenue
Bethesda 14, Maryland 20014

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INTRODUCTION

I. HISTORICAL

For many years it has been suspected that disastrous instabilities could occur with Ground Effect Machines in forward flight. In 1961, the analysis by the writer of existing Wind Tunnel Tests suggested that at the second critical speed, when air began to pass below the machine, a GEM became dangerously unstable and also acquired a strong change of trim causing a violent pitch up or pitch down.[1]

The second critical velocity occured at values of air dynamic pressure equal to the total head in the jet or with thin jets at values much less than the total head in the jet.

Later this analysis was extended to the case of the simple 'skirt' or the parallel 'trunk' which depended on base pressure for its stability, and it was shown that the critical dynamic pressure was now reduced to roughly 60% of the jet total head.[2]

In July 1961, the SRN-1, with short skirts, encountered what was then called the 'plowing-in' phenomenon with a violent pitchdown at 60 knots causing the hard structure to strike the water surface, giving a 12g deceleration . Fortunately, to cope with intermittent wave contact, the SRN-1 was fitted with a hydrodynamic bow and hence recovered normal attitude, and did not overturn.*

Similar phenomena were reported of the Princeton P-GEM,* the Bell Carabao,* and the SRN-2,* fitted with balloon trunks. In July 1964, the writer attended a conference on GEM's at Swansea and also visited the NPL at Feltham, where Mr. Everest showed him pictures (also shown at Swansea but still unpublished) which showed that, with a simple jet issuing from a wedge, a wave built up ahead of the jet. As the speed increased, the wave increased

* From unreported conversation between N. K. Walker and the appropriate design and test engineers.

in height and could attach to the wedge structure ahead of the jet. Normally, with a further increase in the speed, the wave detached and passed below the machine; but under some circumstances this did not occur and the wave rose higher and higher causing an enormous drag, and, possibly, a negative lift. (This was the matter of most concern to Everest.) If this occurred on the 'balloon' trunks of a Hovercraft then the water load would tend to collapse the trunk and the craft would pitch or roll striking the water. At high speed in the straight flight I feared that this could cause a Dutch roll oscillation.

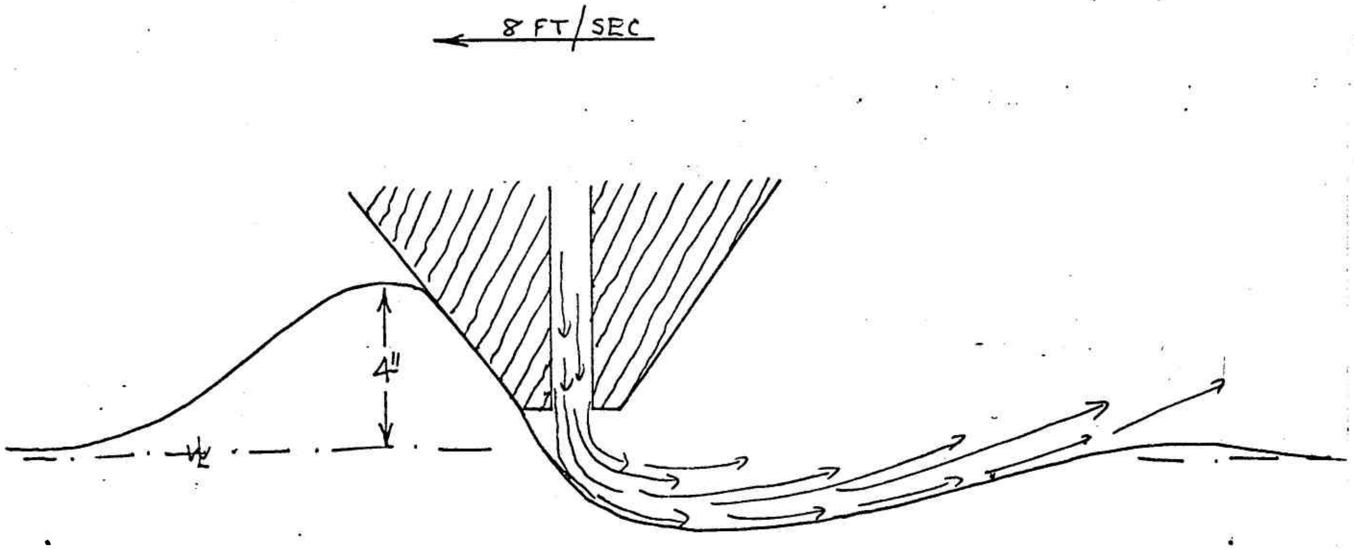


Figure 1. Build up and Attachment of Bow Wave to Jet Nozzle.
Everest-NPL - Feltham

Discussing this matter with Commander Antrobus of the British Ministry of Defense, the writer learned that no tendency to Dutch roll had yet been noticed. On one occasion with SRN-3 a very violent nose-down pitch had occured which Antrobus was sure was due to the adherence of water to the trunk and subsequent collapse as postulated by Everest, and on another occasion an extra high wave rose below the machine and then drew the whole machine down as it collapsed.

These results were discussed with Code 420, BuShips, and we agreed that there was no immediate cause for alarm since the suction could no doubt be broken with the use of 'steps' as on the seaplane hull and, if necessary, with forced ventilation.

About a year ago a model of the SRN-2 overturned in roll and a hurried investigation by Saunders-Roe convinced them that should a skirt collapse on the SRN-2 itself, this machine would also capsize. This information was relayed to Bell and led to an investigation into the stability of SKMR-1 at Norfolk in February and March of 1965 to assure the Bureau of its safety for rough water trials.[3]

In April 1965, an SRN-5 overturned in roll in Norway, a circumstance at first ascribed to the failure of the central stabilizing keel.[4] But in May a second SRN-5 overturned in San Francisco Bay and the keel was shown to be intact. The present note summarizes my ideas and gives some experimental evidence on the cause of the accidents of the SRN-5, which are believed to be easily cured.

2. PLOWING-IN

Plowing-in is now a generic term used to describe any downward divergence in pitch or heave. It may be conveniently divided into:

(a) Aerodynamic instability

(b) Trunk collapse due to adhesion

2.1 Aerodynamic Instability

The writer believes that plowing-in due to aerodynamic instability will occur whenever the aerodynamic pressure due to forward motion is sufficient to force air under the cushion. It will occur over water but can also occur over land.

The critical velocity at a given base loading is reduced by the use of a thinner jet or by the use of a single large skirt as on the Carabao, or thin gently convergent flexible trunk extensions as on the SKMR-1 Bell trunks.

The critical velocity is increased, that is to say, safety is increased, by the use of a thick jet or by the use of the trunks pressurized substantially to jet total head such as the Saunders-Roe balloon trunks.

Note that aerodynamic instability can also cause a violent upward divergence (flight tests with Princeton P-GEM) as well as the more usual nose-in.

2.2 Trunk Adhesion

Under certain conditions, as yet undefined, it is possible water can attach to the trunks and cause a hydrodynamic drag, a suction on the lowest part of the trunk, and a high pressure rather higher up.

These lead to a downward pitching moment and the subsequent collapse of the trunk, when the GEM will pitch violently nose down until the hard structure contacts the water. Since the bow is normally designed for wave impact no further divergences occur, and the GEM recovers operating altitude once the reduction in speed is sufficient for the trunk to re-deploy.

It could by prevented by a suitable array of 'steps' and the forced ventilation of the trunk's surface.

2.3 Base-Adhesion

Suppose a wave crest of more than average height rises below the GEM and wets the surface of the base. As the wave collapses a suction is created and the GEM will be drawn downwards.

This may cause additional wave impacts on the base resulting in vertical 'g' loads but is more likely to be followed by additional wave impacts at the bow caused by the reduced hover height.

Base adhesion could be prevented very simply by the use of 'steps' or other protuberences in the base coupled with forced ventilation.

3. OVERTURNING IN ROLL

The initial explanation as given by Bell of the overturning of SRN-2 was that the trunks tended to collapse and the machine would then roll over due to the excessive aerodynamic forces and moments.[3] It was therefore definitely linked to a very strong side wind condition giving a large rolling moment. It was also claimed that the worst conditions for trunk collapse occured at the sideways critical Froude number of 0.5 and attempts were made at Norfolk to reproduce the phenomenon with SKMR-1. These attempts were happily unsuccessful but the use of a proroll rolling moment by adding weights coupled with the action of the following wave which caught up with the craft following turn did produce a roll of 9° and it was shown calculations were in substantial agreement with measurements in this case. No tendency to trunk collapse was noted.

3.1 Preliminary Investigations by Saunders-Roe[3]

These consisted of towing the machine sideways, with a line attached at the center of gravity, in a towing tank. The results given by this procedure show that at a critical lateral speed which is roughly that of the hump speed going sideways, the normal towing tank model would overturn. However, in practice it was later shown that this need not in fact occur. The towing forces necessary to overturn the machine can usually only be derived from a loss of momentum. If the initial kinetic energy is insufficient the craft can never overturn, but will simply decelerate. Hence, towing experiments with a cable to the CG are unprofitable. They give no information of any importance on basic stability characteristics except perhaps some information on the forces on the trunk, if the line tension is recorded.

3.2 Investigation in the Static Roll Stability of SKMR-1

There still seems to be some doubt about the stability of SKMR-1, so we have prepared Figure 2, which shows the estimated stability of SKMR-1 in roll, allowing for the flexibility of the trunk, starving of the jets, and the water forces on the trunk. We have assumed that the trunks will collapse under the influence of water overloads and the form of the collapse will be determined by the condition that the static pressure of the water surface under the trunk is equal to the total head delivered by the fan.

Initially, in Figure 3, the machine starts off with the moment due to the air cushion. We assume that the air flow remains constant with an average of 12 inches clear airwall clearance below the machine. This initial moment up to the first 2° is taken from the curves produced by Bell.[3] The trunk remains completely inflated until it has reached an angle of roll of approximately 5° when we assume that no air whatever is coming out of the lower trunk but that air is still issuing from the raised side of the machine and the airwall clearance on the raised side of the machine is still 12 inches. In other words we are assuming that the total head of the air supply is not affected by the closure of the other trunk.

Now we assume that the trunk collapses due to the water pressure exceeding the fan pressure. It may collapse in various ways. We can assume that the trunk maintains its original shape with some form of internal diaphragm but that under excessive pressure it is simply flattened at the bottom. We may also assume as an alternative - which gives greater stability - that the total periphery of the trunk remains the same and it spreads sideways to accomodate the extra material made available. Finally, and we believe this to be by far the most correct assumption, we may assume that the machine is in any case being forced sideways now even from a standing start by the air pressure

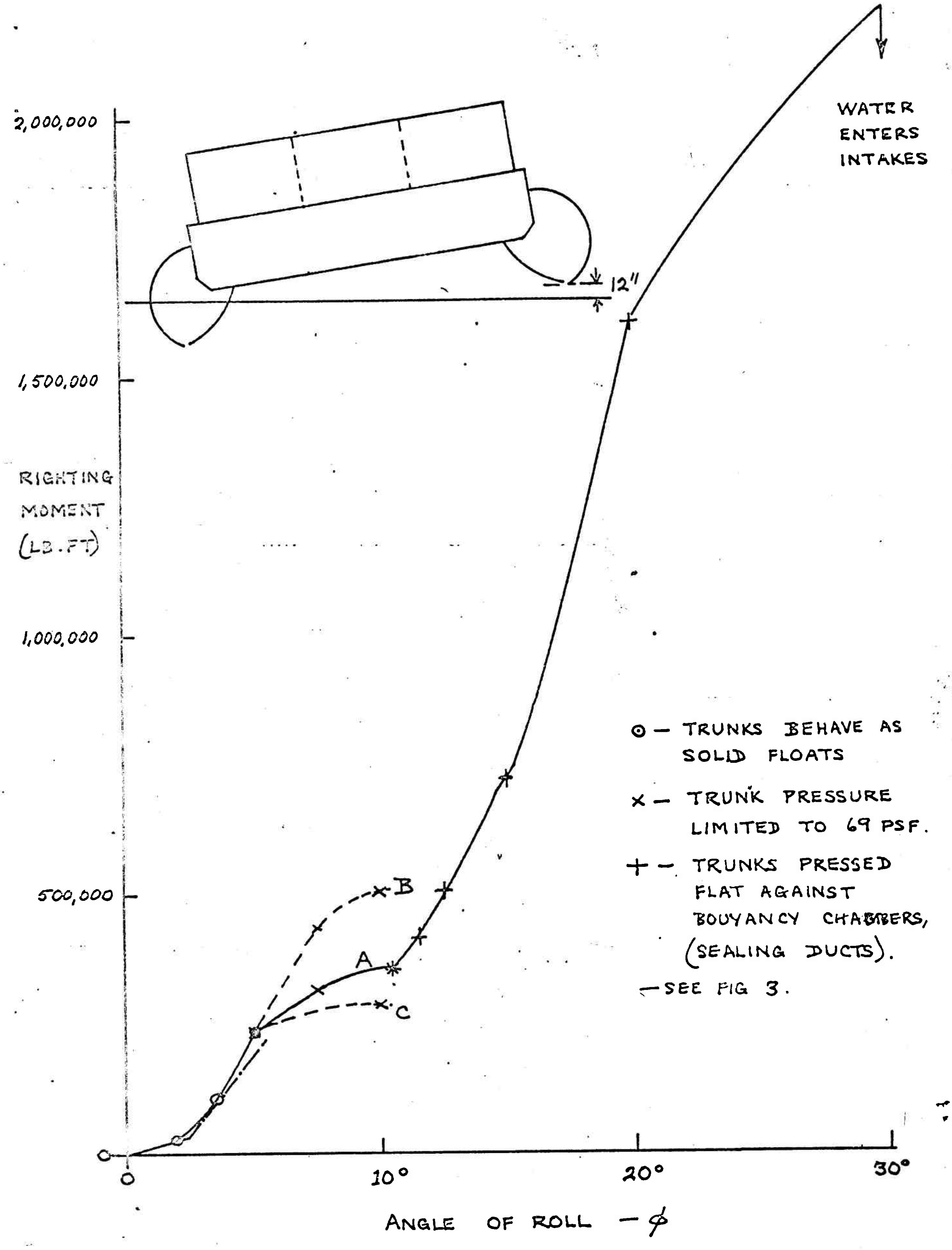
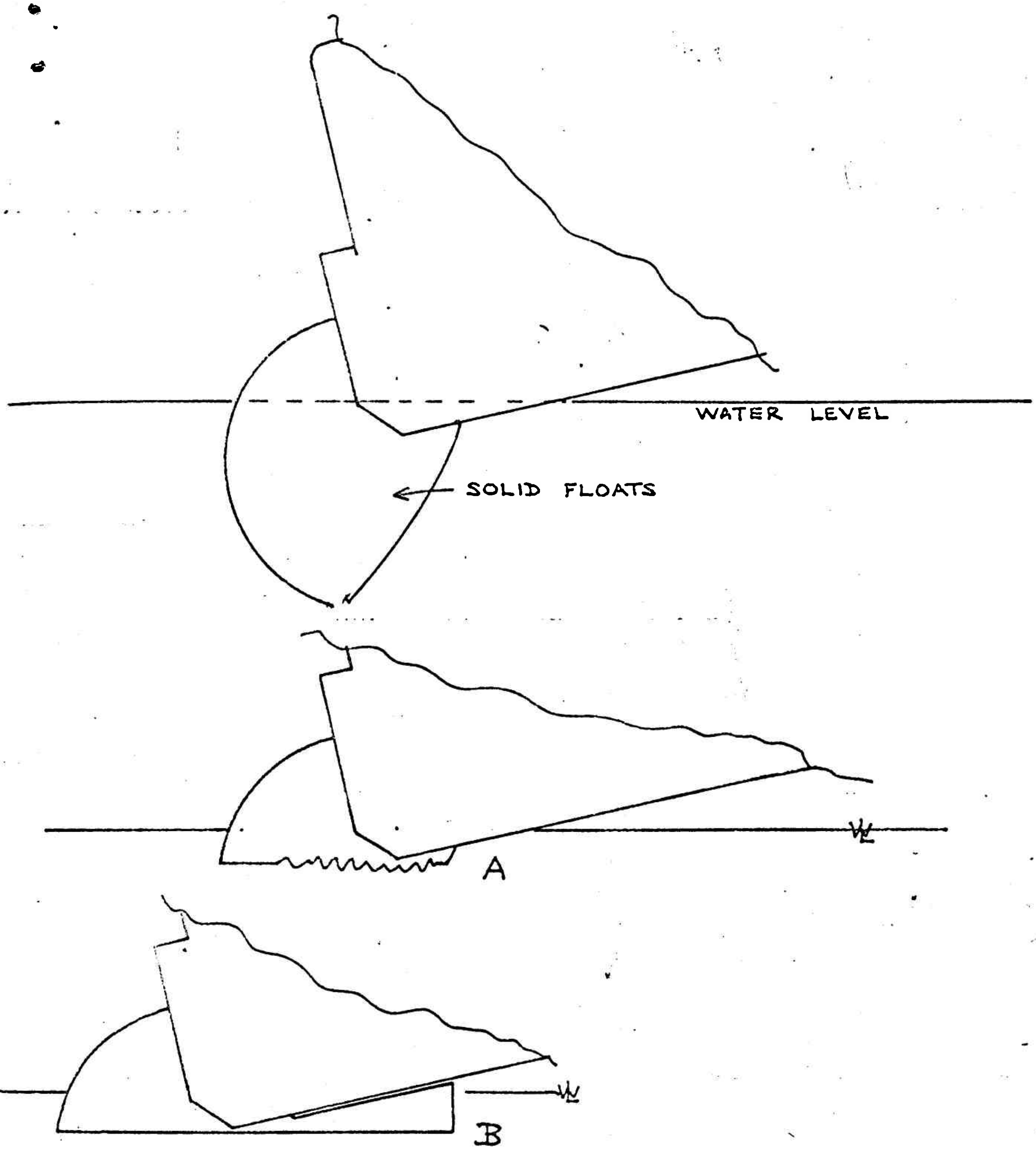


FIG. 2 ESTIMATED STATIC ROLL STABILITY — SKMR 1



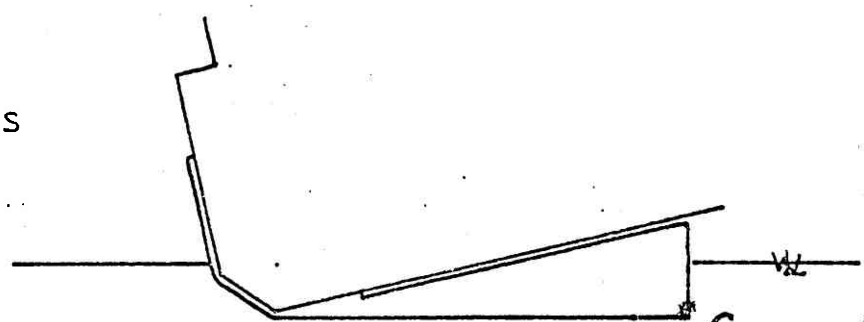


FIG. 3. ASSUMED FORMS OF DEFLECTED TRUNKS

exerted by the raised side of the machine. Hence the trunk which is now underwater will have a force exerted on it. It will be dragged against the hard structure as much as is possible leaving an inflated bubble of the maximum amount of material below the machine. Under this condition the moment is substantially invarient with the angle from 5^o until $10\text{-}1/2^o$ when the hard structure of the machine itself contacts the water. The jets are, of course, assumed to be sealed by the presence of the trunk folded over them, and this is almost certainly true unless for some reason the trunk itself is torn away due to water forces alone (which it seems most unlikely).

From now on the moment is purely due to the buoyancy tanks. At an angle of 20^o the deck edge itself is immersed and at an angle of roughly 30^o water begins to enter the intakes of the fan. SKMR-1 can be made to stand a 30^o angle of heel relative to the horizontal before anything is likely to happen. The angle of heel of 9^o recorded in earlier[3] SKMR-1 trials was almost certainly due mainly to a change in the angle of the water surface itself due to the following wave.

It is most important to realize that the most pessimistic estimate yet produced of rolling moment has been of the order of 90,000 foot pounds. The trunk will not collapse-unless the water forces are enormous-until an angle of 10^o is reached with at least 250,000 foot pounds, or water adheres to the trunk with a lateral velocity of 8 ft/sec or more for a fairly long time. The moment due to the buoyancy tanks continues to increase up to more than 2,000,000 foot pounds. It is our contention therefore, that no conceivable shift of cargo or aerodynamic force that any speed or crosswind conditions SKMR-1 can attain, with or without presence of ducts or a fan or any other unfavorable circumstances, can possibly cause overturning due to aerodynamic forces alone. This is, of course, only true of the SKMR-1 shape itself which is singularly fortunate in having a high sealed freeboard. It is also true that the estimates were prepared for a constant cross section machine of length of 50 feet. It is possible that water may enter a little earlier around the stern and thus our estimate of over 2,000,000 foot pounds may be in excess by about 1/2 million. Nevertheless, we believe it will still take 1,000,000 foot pounds under the most unfavorable circumstances to overturn the SKMR-1.

3.3 Overturning Due to Momentum and Hydrodynamic Forces

It is our contention that the overturning of SRN-5 can be very, simply explained in terms of the basic structural cross section of the machine. Consider the SRN-5 hovering (Figure 4a). Now it skids sideways and a wave builds up and attaches to the trunk, Figure 4b. Suppose Everest's forebodings are correct. A pressure develops on one side of the trunk,

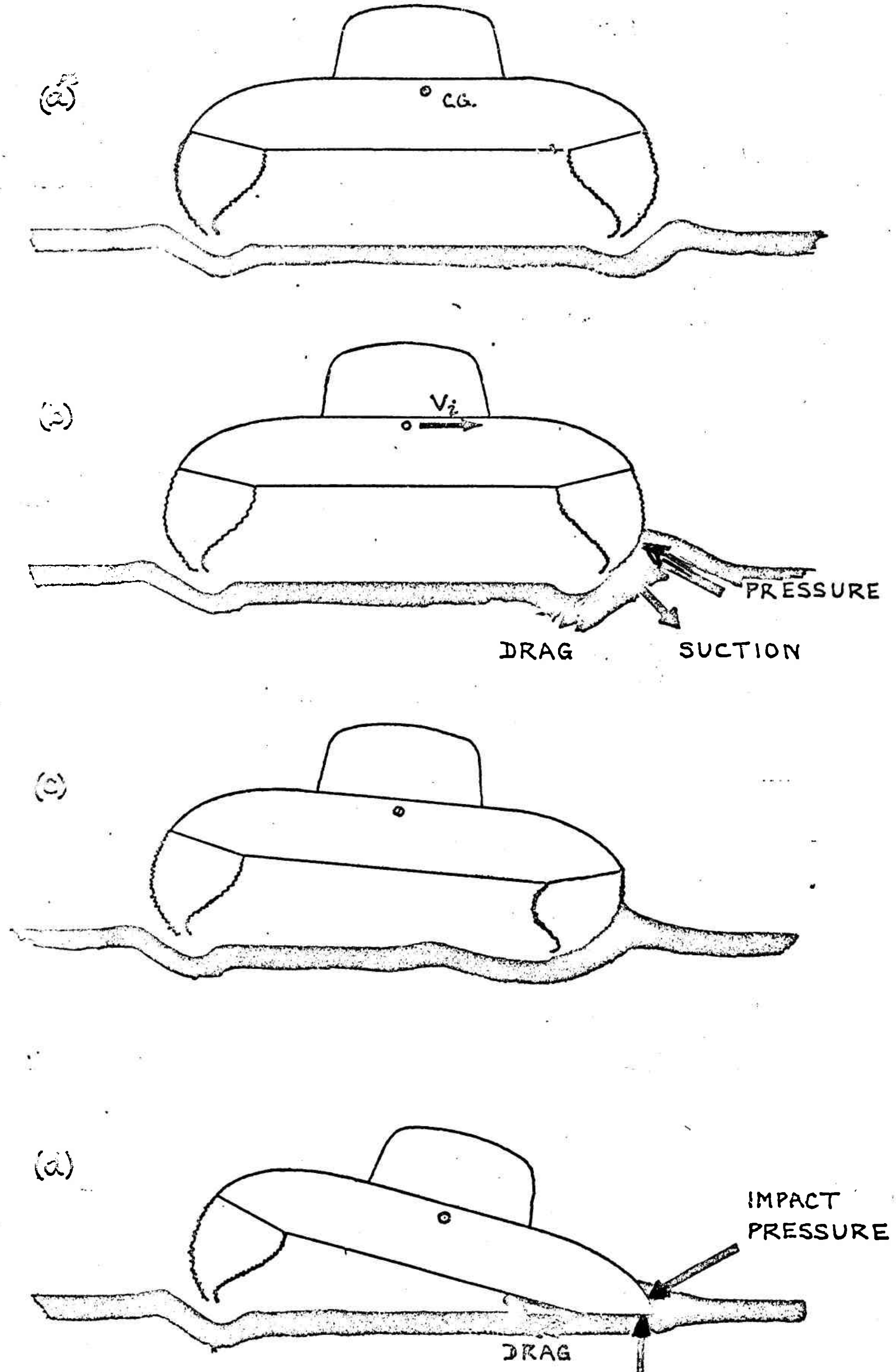


FIG. 4 OVERTURNING OF S.R.N-5
– INITIAL STAGES

which is greater than the total head of the fan, and at the same time there exists a suction force or even a frictional drag on the trunk causing it to remain extended. It must now collapse slowly and progressively like a bellows, forcing the air out of the trunk itself through the nozzle, if this is not at too great a depth, and also forcing it back through the feeding holes into the plenum chamber and out through the trunk on the other side, Figure 4c. This will take some time, perhaps several seconds. If this condition arises, therefore, we are likely to see the machine slowly sink on one side as that trunk deflates. This process can only be halted by the machine coming to a stop so that the hydrodynamic pressure due to the water is no longer greater than the total head of the fan. This would imply in the case of the SRN-5 a water speed of less than about 5 feet per second. Alternatively the driver must increase the lifting power suddenly and, in effect, shake the trunk loose. This may not work. The extra lift may simply create an additional rolling tendency. It will work if the driver is very alert and takes this correcting action at the first sign of trouble. Failing this, the trunk will continue to deflate and the machine will roll over, with the other trunk remaining clear of the water with an airwall clearance at least as great as it had in the steady state condition.

Now the trunk is folded flat against the machine; the machine is still going sideways. It is possible, if the speed is still very low, that the impact of the flat surface, formed by the rubber trunk sealing the air duct, on the water may create sufficient force to stop the overturning moment, and possibly the drag will have been high enough to bring the machine to a halt. However, the most likely thing to occur is that the machine will continue to sink and move sideways. (The lower edge must, in any case, continue to go below the surface until the static pressure now exerted on the bottom is roughly equal to the base pressure elsewhere on this machine.) This means that it will sink, under with steady state water surface, to the extent, in the case of this machine, of perhaps 6 inches. We now have the situation shown in Figure 4d.

Suppose that the machine is still traveling sideways at some appreciable velocity. Water will now pile up on the upper surface of the machine to an extent given by the total head due to the lateral motion of the craft. There will therefore be a spillage of water over the deck adding to the weight on the machine and giving a strong download and overturning tendency, Figures 4d and 5a. The greater the speed the greater the depth of water. The greater the depth of water the greater the angle, and eventually suction forces will begin to develop along lower surfaces. As the machine tilts more and more it will rely more and more heavily upon this part of the machine for buoyancy and will dive deeper into the water. There is a very large drag force being exerted below the center of gravity, and the center of gravity is still moving sideways. If the remaining kinetic energy of the machine is greater than the potential energy acquired by a 90° roll then the machine will overturn, Figure 5b.

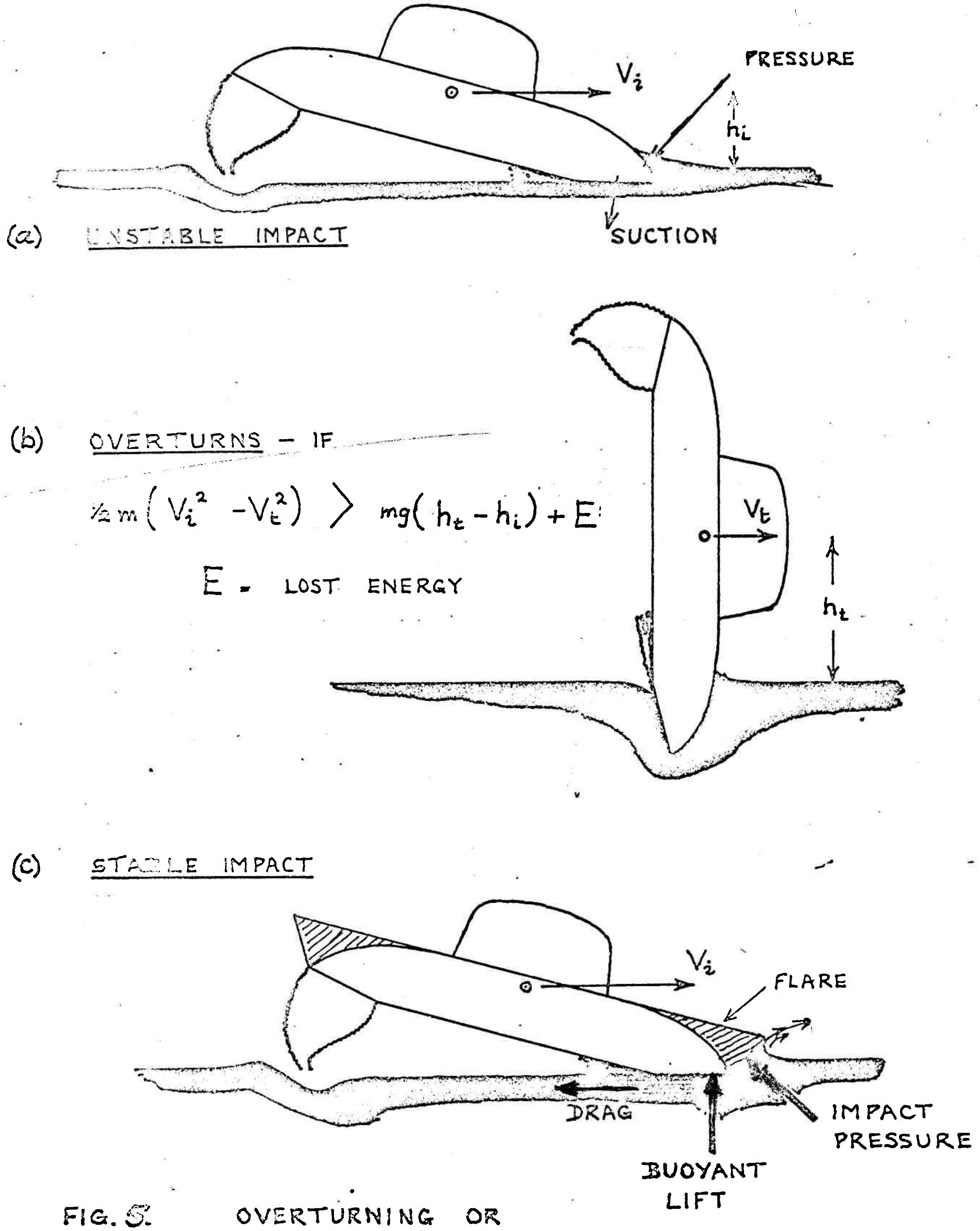


FIG. 5. OVERTURNING OR RECOVERY OF S.R.N.-5

Note, however, that if a 'flare' is fitted along the edge of the machine then the resultant forces due to water contact will pass above the center of gravity and the GEM will experience a righting moment. It will then cease to roll over and will decelerate in the rolled position. With a real machine it will then recover either by deflating the other trunk or by permitting the deflated trunk to reinflate. Figure 5c.

This hypothesis focusses attention at the problem of achieving safe water contact behavior rather than at solving the problem of trunk 'adhesion'.

4. THEORY OF HYDRODYNAMIC OVERTURNING IN ROLL

4.1 Simple Impact Theory

From Figure 5b, the machine will overturn if the initial kinetic energy at contact is greater than the potential energy when the CG is vertically above P. Or - writing the energy balance equation:

$$1/2\, m(V_i^2 - V_t^2) = mg\,(h_t - h_i)$$

where:

V_i	=	Velocity of CG at impact
V_t	=	Velocity of CG when machine is vertical
m	=	mass
g	=	acceleration of gravity
h_i	=	height of CG above surface at impact
h_t	=	height of CG above surface in vertical position

This equation is necessarily crude, but it does suggest that if one were to measure V_t for various values of V_i one could plot the initial kinetic energy at impact versus the minimum kinetic energy in roll-over, and obtain a line of slope of 45° with the critical conditions defined by the intersection with the axis for zero residual kinetic energy.

This is equivalent to plotting V_i^2 on the y axis against V_t^2 on the x axis; $V_t^2 = 0$ being the critical condition.

If the GEM does not turn over then there will not be sufficient kinetic energy at impact to reach the critical condition, and it will instead rise only to the height h^1 and fall back. To complete the graph we may express the altitude deficit as a potential energy deficit $mg\ (h^1 - h_t)$ and the kinetic energy deficit at turnover as $(1/2m\ V^2_t) = mg(h^1 - h_t)$, which will be negative.

This will yield a negative value for $(V_t)^2$, which may then be plotted on the x axis.

4.2 Improved Theory

(a) The simple theory assumes that all the kinetic energy which is lost at impact is transformed into potential energy. However, the buried edge will not remain stationary but will move through the water and energy will be lost. Let us assume this energy is 'E'.

(b) There will be appreciable rotational energy due to the turnover. $E_k = 1/2mk^2 \quad \phi^2_t$ where k=radius of gyration, ϕ^2_t = angular velocity about CG at turnover. This term will be appreciable in high speed turnovers, but will be zero in the critical condition.*

(c) The GEM is not an inert mass. The weight is supported by the air cushion, and until this lift is lost by the opening gap on the rising side it will aid the GEM to turn over.

It can easily be shown that this is roughly equivalent to reducing the value of h_t by about 1.5h where 'h' is the hoverheight of the GEM over a hard surface. This term is small since 'h' is usually small.

* Note however, that a large inertia in roll will slow down the actual turnover, and more energy will be lost doing work against water drag before the turnover occurs.

Hence the revised equation now reads:

$$1/2\, m\, (V_i^2 - V_t^2) = mg\, (h_t - h_i - 1.5h) + E + 1/2\, mk^2\, \phi_t^2$$

the last term being zero in the critical condition.

We may also write this as:

$$V_i^2 = V_t^2 + 2g\, (h_t - h_i - 1/5h) + \frac{2E}{m}$$

Hence, as before, a plot of V_i^2 versus V_t^2 will be a line of slope 45° (Apart from the rotational inertia correction) and the intercept on the V_i^2 axis will be:

$$V_i^2 = 2g\, (h_t - h_i - 1/5h) + \frac{2E}{m}$$

which may be easily be calculated for the case E=0.

4.3 Conclusion From Theory

If the simple theory is even approximately correct we may conclude:

(a) The higher the trunk is in relation to the beam, the greater the danger of roll over. In particular if the trunk height is equal to the beam, the roll angle at impact will be so great that it will be extremely difficult to control the roll.

(b) The higher the CG the worse the danger of roll over.

(c) The heavier the machine the greater the danger since less energy will be lost, in proportion, in moving through the water, and the machine at 90° roll will sink deeper. A machine which has little buoyancy in the 90° roll position (such as the SRN-5) is more likely to roll over.

(d) If a flare is fitted to the edges of the machine to ensure that the forces due to water contact at impact produce a righting moment about the CG (paragraph 3.3, Figure 5c), roll over will be prevented.

5. EXPERIMENTAL VERIFICATION OF SIMPLE THEORY

Evidently all that is necessary to verify the simple theory is to project a model GEM over the water with one trunk sealed up flat against the bottom, and at a roll angle such that the hard edge is just striking the water when the trunk on the other side is clearing the water by a distance equal to the hover height. It would then be possible to plot V_i^2 against V_t^2 and verify that the predicted turnover conditions were correct.

This procedure is extremely difficult since it would require a dynamically scaled model with lift fans, and scaled flexible trunks.

However, this complexity is unnecessary if the impact hydrodynamic terms are dominant, since the effect of the lift fans, etc., is included in the term "1.5h", which is small. The deployed trunk is also unnecessary since its only function is to preserve the 'cushion', which is in any case lost shortly after contact occurs, and it does not contact the water.

Hence, it should be sufficient for our purpose to catapult onto the water, at the correct roll angle, a model of the hard structure of the GEM only, and if we assume that the collapsed trunk will tend to seal the jets, this could be a simple solid model of styrofoam with roughly the correct total weight. Experiments with a simple model of this type (only 6" beam and 10" long) were made and are described in the Appendix.

5.1 Results with the SRN-5 Model

Early attempts to produce overturn of the SRN-5 model were unsuccessful, probably because without the drag of the deflated trunk the forces on the lower edge passed above the CG and were stabilizing. However, by increasing the roll angle from $\alpha_i = 0°$ successively to $-7.5°$, impacts closely resembling the full scale accident were obtained.* In this condition the critical impact speed was 125 cms/sec or 16 knots full scale. Figure 6.

It is evident that during roll over the machine rotates about a point about midway between the edge and the water surface, suggesting that the theory of paragraph 4 may be approximately correct. The results were analyzed by plotting V_i^2 against V_t^2 for various angles of impact, and are compared with the theory in Figure 7.

*The model tests of Figure 6 show that from impact to roll over would occupy about 3 seconds full scale, agreeing with observers reports.

$\alpha_i = -7.5^\circ$

IMPACT OCCURS AT FRAME 4

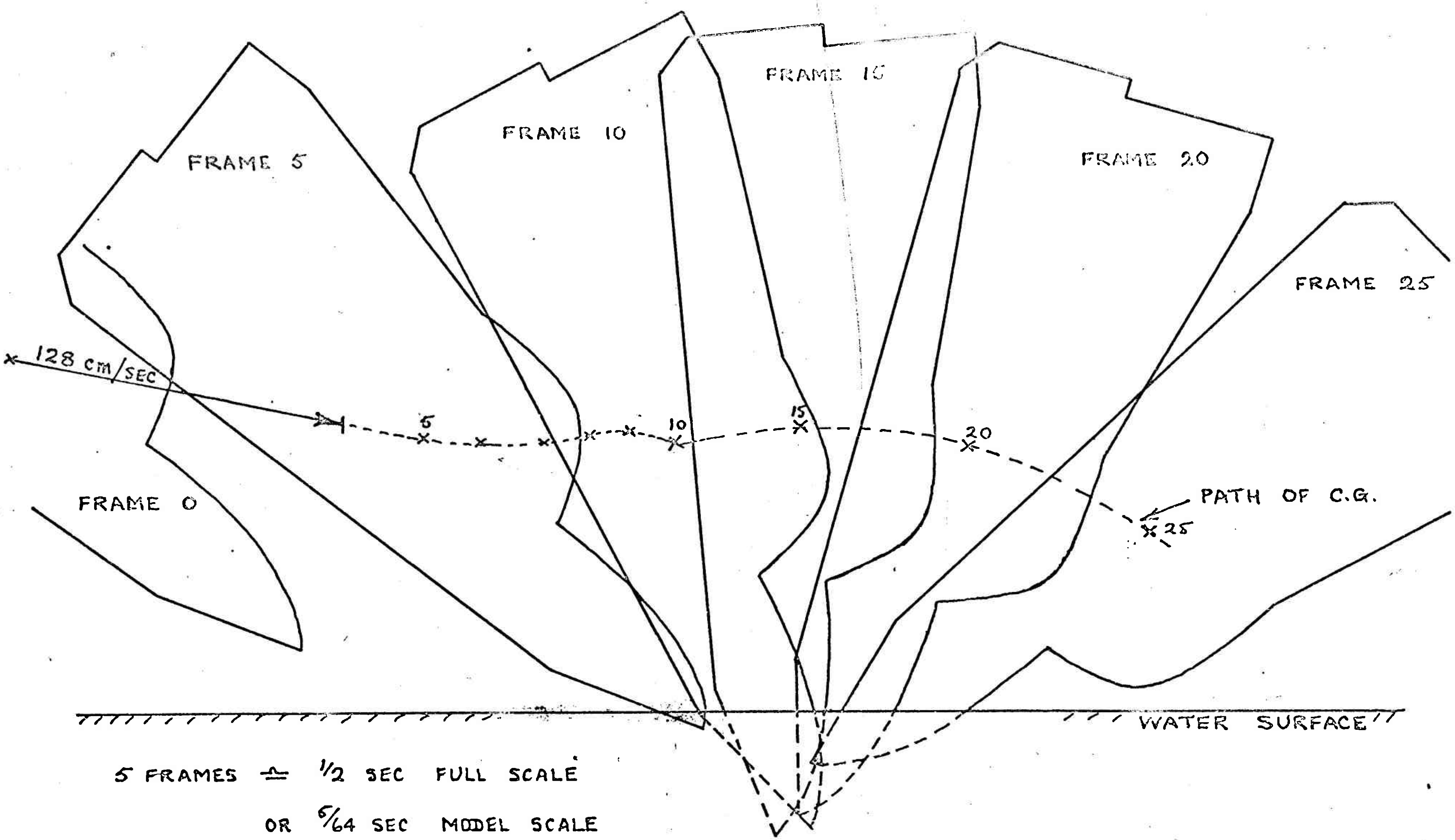


FIG. 6. OVERTURNING OF MODEL S.R.N.5.

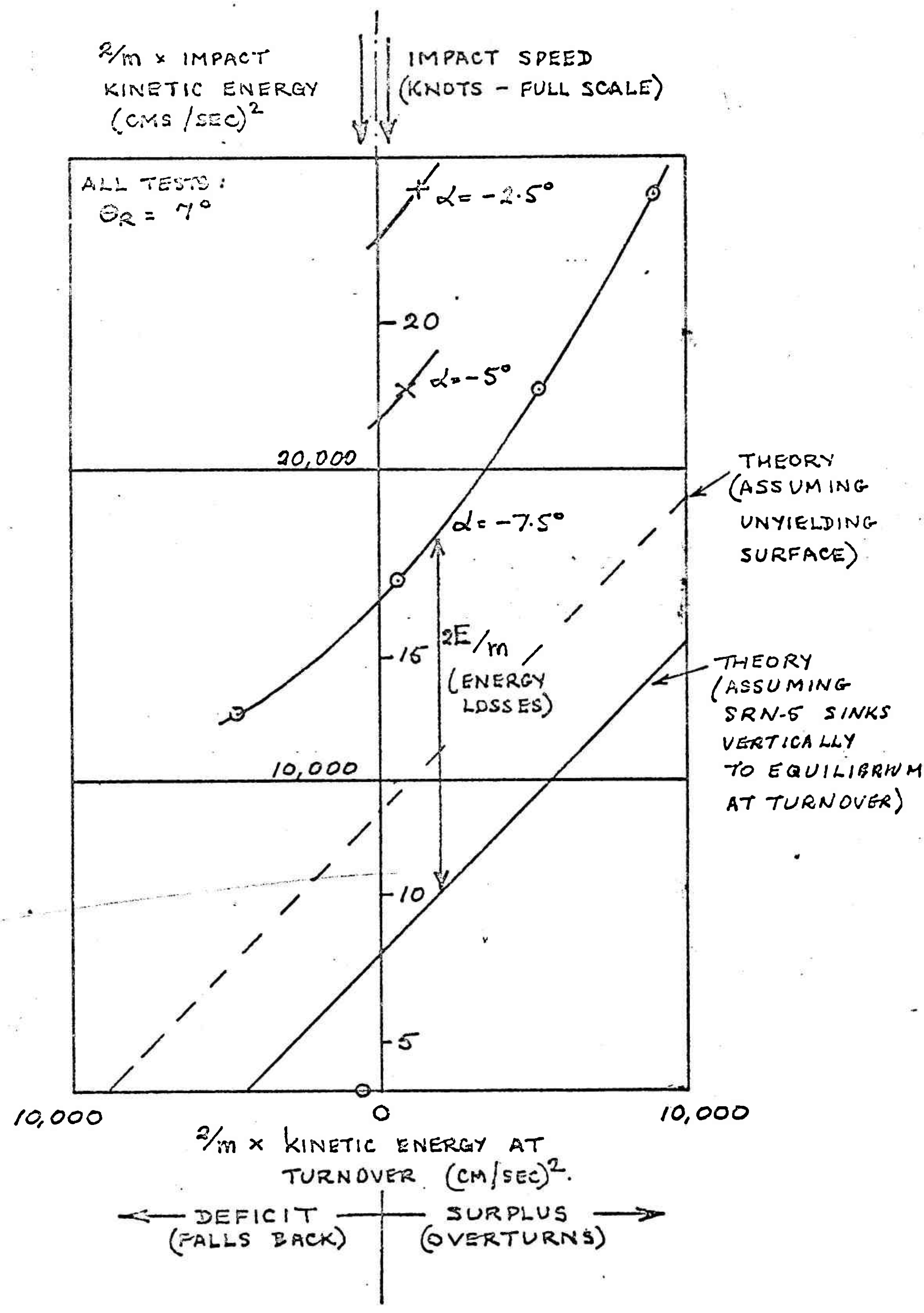
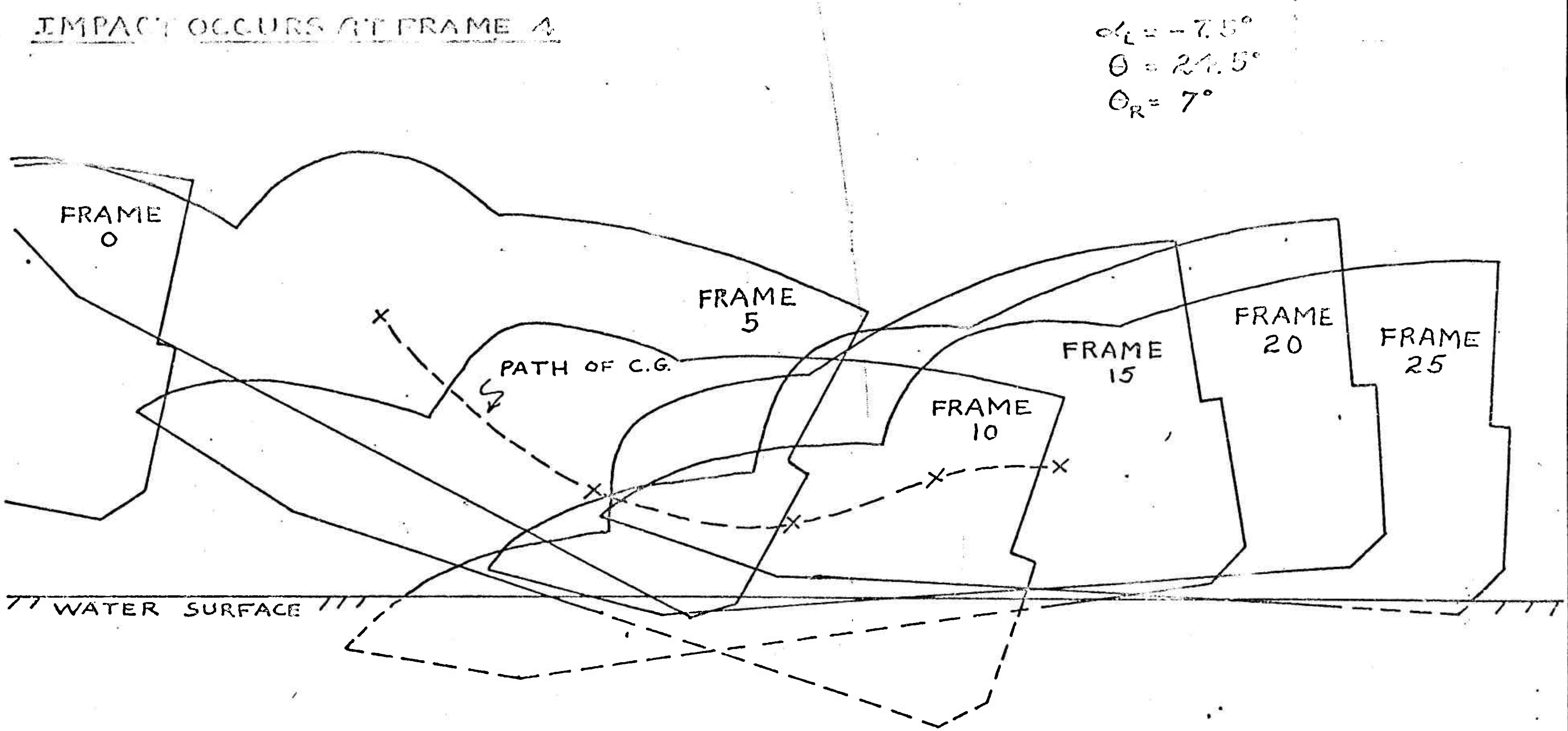


FIG. 7. S.R.N.-5. COMPARISON OF MODEL TESTS OF OVERTURNS AND THEORY.



5 FRAMES ≏ 1/2 SEC. FULL SCALE
OR 5/64 SEC. MODEL SCALE

A VERY HEAVY SHEET OF WATER (NOT SHOWN) IS THROWN UP AHEAD OF THE MACHINE

FIG. 8. ROLLING OF MODEL SKMR-1

These results show that the theory is approximately correct, and that the loss of energy during turnover, E, is roughly independent of impact speed but increases as the impact angle becomes less negative.

The calculated turnover speed for the SRN-5, assuming E=0, is 8.6 knots. The actual speed is believed to have fallen between the experimental value and calculated value.

5.2 Results with the SRN-5 Model Flared to Resist Overturn

Further experiments were made with a flare attached to the side, and this modified SRN-5 could not be overturned at any impact velocity, since the roll angle always decreased after impact, due to favorable rolling moments.

5.3 Results with SKMR-1

Finally tests were made on a model representing the SKMR-1 overloaded to 84,000 lbs. gross weight, total, with the CG centered, and also with the CG displaced 18% beam in the pro-roll direction. Neither model could be made to roll over but the initial water moments tended to cause roll. The calculated lateral overturn speed for SKMR-1 is 14.1 knots. See Figure 8.

Conclusions

From the evidence and model tests we may conclude:

(1) Plowing-in and roll-over are similar phenomena due to water adhesion on the trunks.

(2) The cause of the actual overturning is hydrodynamic forces arising at impact.

(3) All GEM's must be designed so that impact with the water at any reasonable speed and attitude, either with or without trunks,* will produce favorable moments about the CG.

(4) The model technique described in the Appendix gives good results, and can easily be improved to give a reliable indication of a fundamental tendency to overturn. All future Gems should be tested in this way.

*A VA-3 under test at Norfolk lost the whole trunk on one side through contact with an obstruction, and the flotation chambers were punctured. However, the craft managed to maneuver back to the ramp. Had this occurred with the SRN-5 it is possible that an overturn might have resulted. (The VA-3 has a flare).

(5) Investigations must be made into the causes of trunk adhesion and possible cures. Nevertheless, even if successful, this will be no substitute for correct hydrodynamic shape owing to the possibility of the loss of a trunk due to obstructions or enemy action.

(6) The simple theory gives a good, but low, estimate of the speed at which a GEM will overturn if the forces due to water contact are destabilizing.

Calculated lateral overturn speeds are:

SRN-5 ; 8.6 knots or F*=0.54
(just at the hump)

SKMR-1 ; 14.1 knots or F=0.67
(just above the hump)

(7) A flare produces stabilizing moments at impact which will prevent overturn at any impact speed, as long as the flare is not swamped.

Note, however, that the shape of SRN-5 at impact is such that the destabilizing moments are large, and little additional energy is needed to cause turnover.

The shape of the SKMR-1 produces very small destabilizing moments. As a result, although in theory it will turn over, the losses of energy are so great that this never occurred in model tests up to 22 knots full scale.

*F = Froude Number = $\frac{V}{\sqrt{gb}}$ (b= beam)

Appendix I
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Model Tests on the Overturning of Ground Effect Machines

by

Norman K. Walker

Peter W. Ford

William Elder

and

Edwin P. Rood Jr.

Prepared by

Norman K. Walker Associates Inc.
7240 Wisconsin Avenue
Bethesda 14, Maryland 20014

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1. INTRODUCTION

As described in the main body of the report, it appeared possible that the overturning of the SRN-5 was due to the side of the machine being decelerated at impact by very large forces passing below the CG.

Any excessive kinetic energy could then cause the machine to rotate around the point of impact, causing an overturn.

On the otherhand if the hydrodynamic shape were favorable, i.e., if the resultant force at impact passed above the CG then the machine could not roll over, no matter what the impact speed.

It appeared that a very simple test of launching a model of the hard structure of the GEM onto a still water surface would settle the point and possibly yield quantitative data.

2. EXPERIMENTAL MODEL AND EQUIPMENT

Since, according to the theory developed in the main body of the report, the rotational inertia was unimportant, a simple two dimensional model 25.4 cms long was carved from styrofoam plank, and, to economize, one side was made approximately 1/43 scale of the cross section of the SRN-5 while the other was approximately a 1/52 scale model of the U.S. Navy SKMR-1. Figure 1.

The model was trimmed with clay to balance on the center line, and, in this condition, weighed approximately 96 grams, corresponding to an AUW for the SRN-5 of 17,200 lb, or for the SKMR-1 of 40,000 lbs.

With an additional ballast weight B1 of 110 grams, the model represented SKMR-1 at a considerable overload condition (86,000 lbs), and this ballast could be shifted laterally to position B1 to give a CG shift of 18% of the beam, or an applied rolling moment of over 270,000 lb. ft.

The model was supported in a pendulum rig so that the pendulum could be deflected a known initial angle θ and then released to gather speed. At a predetermined release angle θ_R the pendulum support was halted, release pins were withdrawn, and the model flew free to contact the water at a calculable speed and impact angle.

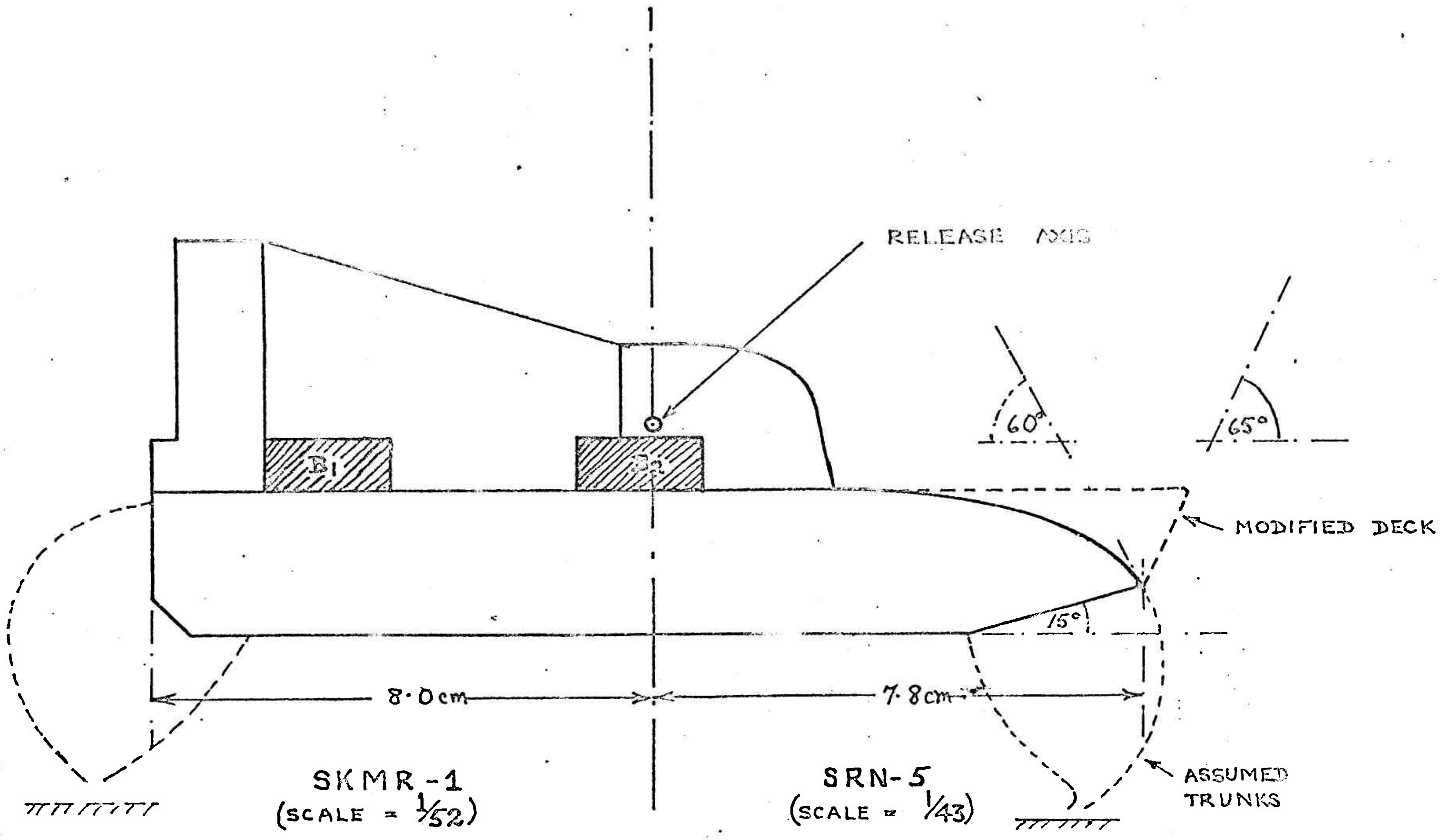

FIG. 1. TEST MODEL ~ FULL SCALE

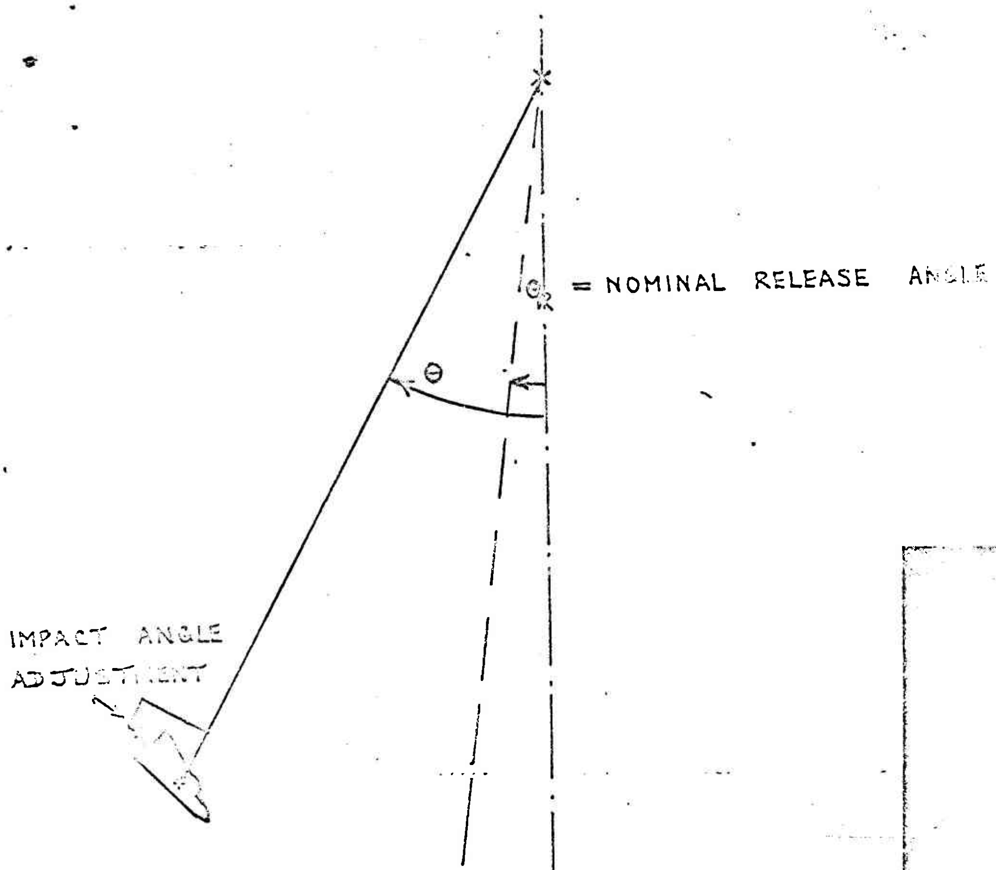

Figure 2. Diagram of Pendulum Launcher

Figure 3. SRN-5 Model Ready for Launch ($\Theta = 21.5^{\circ}$ $\alpha = 0^{\circ}$)

The model was initially set up with the pendulum at rest. ($\Theta=0^{\circ}$). The model roll angle, as shown in Figure 10, was adjusted so that for the basic impact position, $\alpha = 0^{\circ}$, undeflected trunk - if present - would clear the water by the hover height, and the lower edge would just clear the water. This setting was used to set the zero of the impact angle scale.

At other impact angles, e.g., $\alpha = -7.5^{\circ}$, the water level was adjusted to suit.

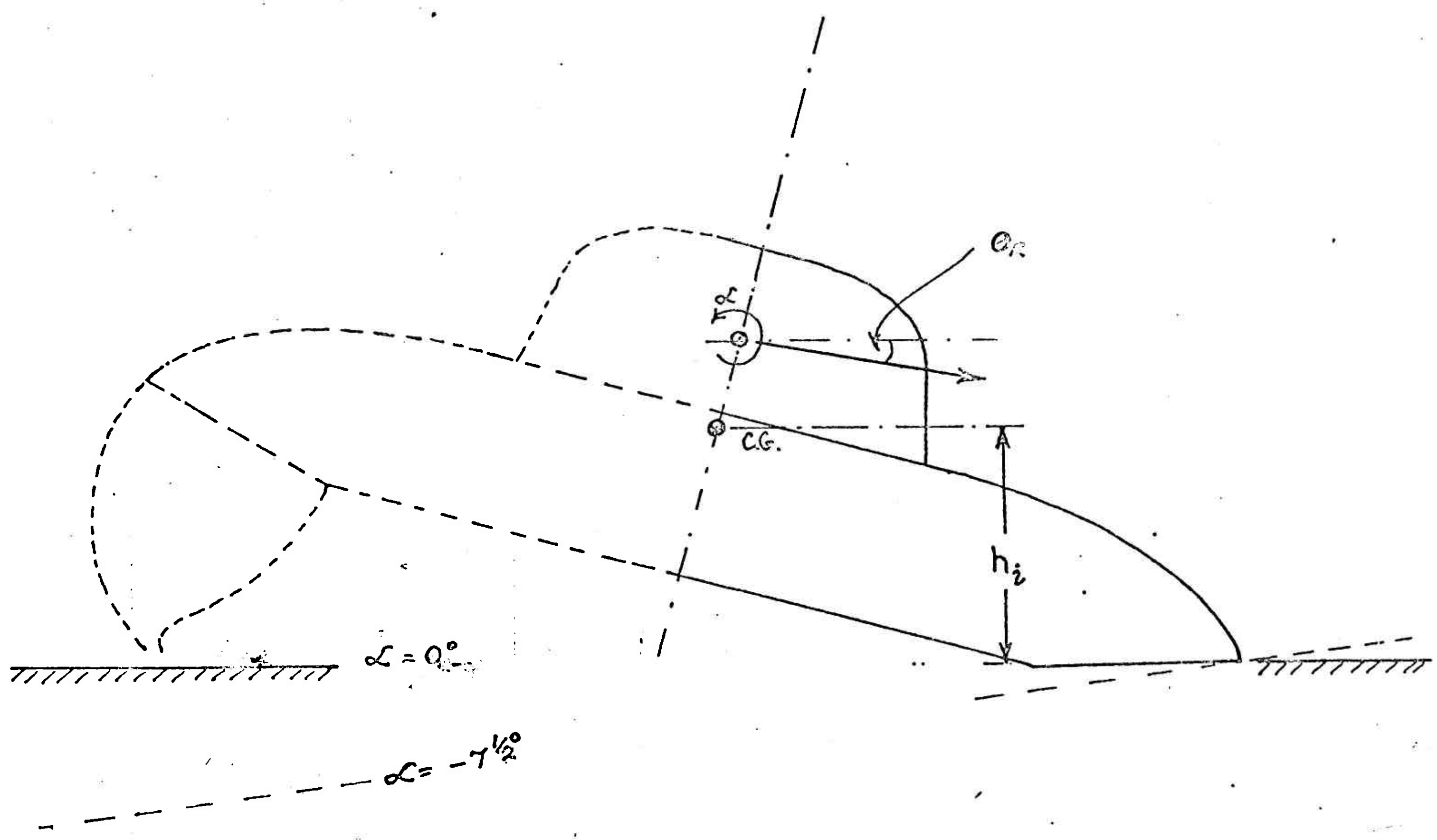

FIG. 4 S.R.N.-5 MODEL ~ IMPACT CONDITIONS ($\alpha = 0°$)

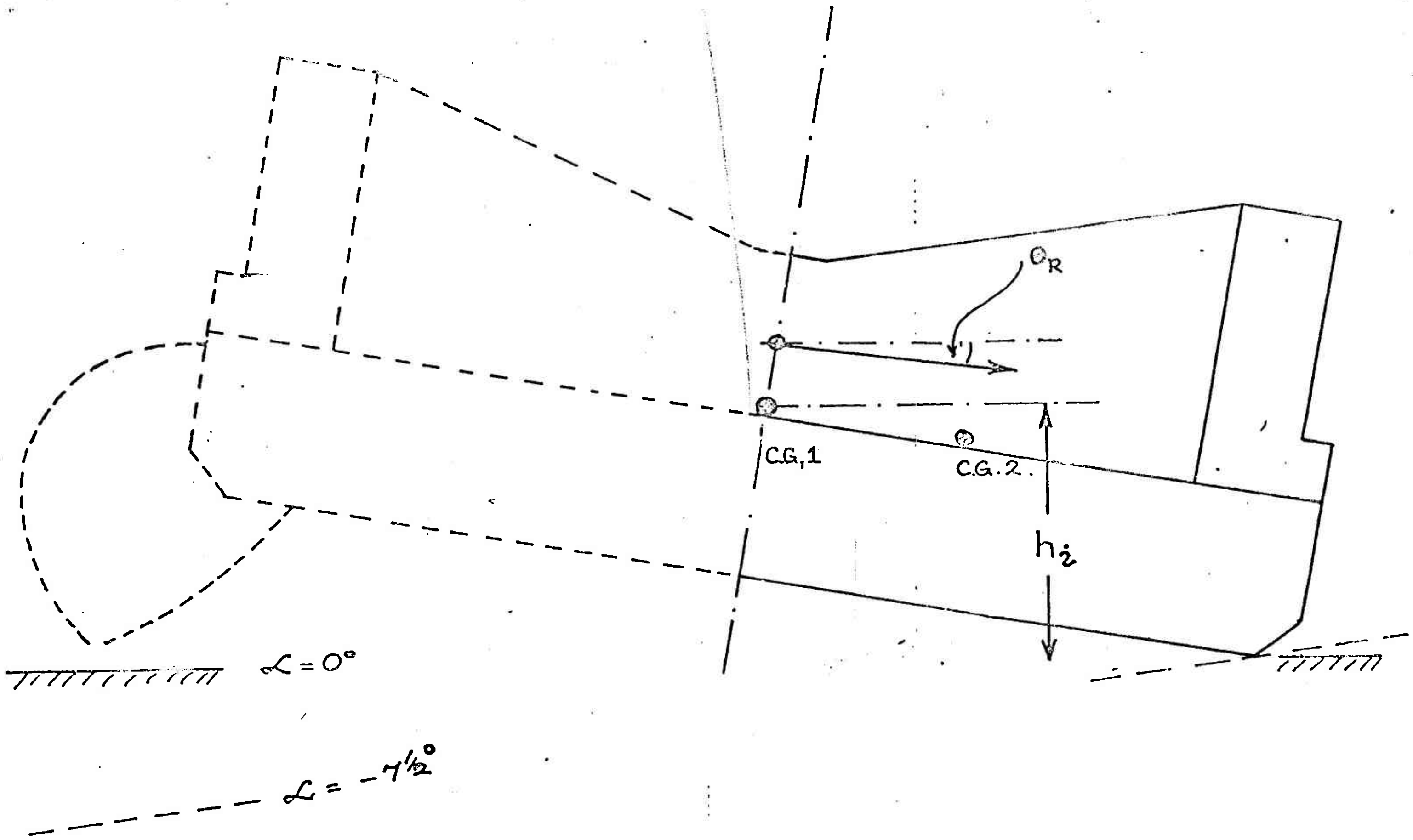

FIG. 5. SKMR-1 MODEL ~ IMPACT CONDITIONS ($\alpha = 0°$)

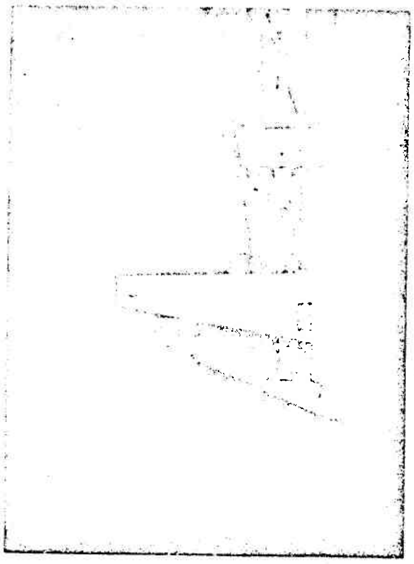

Figure 6. SRN-5 Model in Pendulum Launcher, ($\theta = 0^{\circ}$, $\alpha = -7.5^{\circ}$)

Results were obtained by testing the model at a fixed roll angle, and observing the results of decreasing the speed in stages. Each impact was photographed with an 8mm Bolex movie camera using Kodacolor II film at 64 frames/sec., and the lateral velocity of the CG at turnover, V_t, was determined by analyzing the film.

This procedure was satisfactory for the models with the CG on the center-line. Difficulty was experienced with the SKMR-1 model with off-set CG since the incidence locking pin pulled out just before the model flew free, and appreciable increases of roll angle occurred during release.

This was offset to some extent in later tests by raising the water level so that water contact was made during release. The effect of the raised water level did not seem to be large and, in any case, would cause pessimistic results.

Finally, selected film shots were collected together into a film which was then reprocessed to 16mm. A scenario of the film is given as Appendix II of the re[illegible] Note that as the SRN-5 model is 1/43 scale each frame repre[illegible] [illegible]3 seconds or 0.102 seconds. For the SKMR-1 model (1/52 sca[illegible] [illegible] ame represents 0.112 seconds.

3. RESULTS

3.1 SRN-5

3.1a At Standard Weight

It was found that overturning did not always occur for the SRN-5 model at the nominal angle of impact ($\alpha = 0^{o}$). Sometimes the model would tend to dig in but sometimes it would experience a nose up pitching moment and plane over the surface.

However, the model was considered likely to give optimistic results owing to the absence of the drag from the deflating trunk before solid impact, and the absence of the lifting cushion.

Hence, the impact angle was successively made more negative, and reliable, repeatable, overturns occurred at $\alpha = -2.5^{o}$, -5.0^{o}, and -7.5^{o}, the latter apparently closely corresponding to full scale in regards to the critical impact speed. (The water level was adjusted each time to ensure that the model made contact just after release). A typical overturn is shown in Figure 6 of the main report, and the position of every 5th frame is plotted. (Approximately 0.5 seconds full scale).

These show a very rapid initial rotation, with the model digging into the water to the equilibrium position, and rotating about a point somewhat between the edge of the GEM and the surface.

The results were plotted in terms of V_L^2 against V_t^2 in Figure 7, of the main report, and the results show consistent behavior, and general agreement with theory, remembering that considerable energy must be lost due to the drag force acting on the model as it plows through the water. (The impact which failed to produce turnover could still be plotted by determining the deficit in potential energy from the film). The energy lost due to turnover, however, seems to be almost independent of the impact speed, but increases as the roll angle is made less negative.

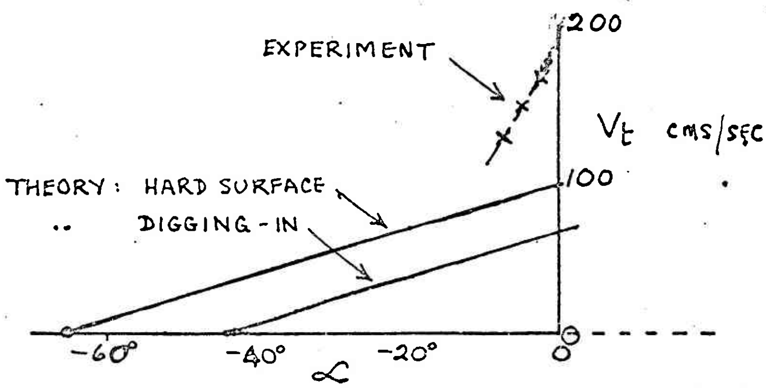

FIG. 7. EFFECT OF IMPACT ANGLE ON VELOCITY REQUIRED TO OVERTURN SRN-5

The effect of changing the impact angle α is shown in Figure 7. The theoretical energy to overturn is a maximum, of course, for a grazing impact, and falls to zero as α approaches -90°, but in fact the drag energy 'E' varies very rapidly with α, as would be expected.

3.1b Effect of Overload Weight

Tests were also made on the SRN-5 model with the overload weight installed (AUW-37,000 lbs). These showed that overturn occurred somewhat more easily, but the general features were the same. This case was recorded on the film but was not analyzed in detail as the changes observed seemed to agree with the theory.

3.2 SRN-5 With Flared Side

A modification was made to the SRN-5 model to ensure that the impact forces passed above the CG. Figure 1. This entailed an additional styrofoam block giving a flat deck from the cabin level, with the freeboard inclined outward 25° from the vertical, increasing the weight to 103 grams. Such a modification seemed to be feasible full scale and would have operational advantages. (A slightly less extreme 'flare' had been fitted to the VA3 in England before it was shipped to the U.S. for rough water trials).

Experiments were made on all available launch speeds with $\alpha = -5^{\circ}$ and $\alpha = -7.5^{\circ}$, but in no case was any tendency to overturn noted though there remains a remote possibility that overturning could still occur if the flare were swamped. (However, unrecorded tests with overload weight showed that the flare did swamp on occasion, but the model still recovered).

3.2 SKMR-1

3.2a With Maximum CG Shift

Early experiments showed that the SKMR-1 was particularly resistant to overturn, so the CG was shifted 18% in the pro-roll direction.

No overturning occurred, though it does remain a possibility at very high speed since the initial roll angle increases to almost 50°. However, a very interesting phenomenon occurs which may produce additional roll damping, and hence a powerful stabilizing effect. A very heavy sheet of water is thrown up ahead of the machine, and is in contact with the very high vertical sides of the machine. Any rotational velocity will be resisted by the inertia of the flowing water mass. (A similar phenomena once occured in tests of the NRA Aquagem, according to Beardsley, Reference 4).

Tests with maximum CG shift introduced experimental problems, since the CG was now no longer directly below the support in the pendulum rig. The incidence control pin released first, and as a result the model could acquire a more negative impact angle and a definitely unfavorable rolling velocity.

Hence tests were repeated with different release angles Θ_R, and with the water level adjusted each time to give minimum possible fall. No noticeable change in behavior occurred so the phenomenon is not considered serious.

3.2b With No CG Shift

With no CG shift no release problems occurred; the model was still initially unstable in that the roll angles increased after contact and increased with impact speed, but the angles reached were not serious over the whole range tested.

4. CONCLUSIONS

1. The model tests indicate that the SRN-5 has an inherent overturning tendency due to the hydrodynamic shape of the edge after a trunk is folded under or torn away.

2. The kinetic energy required to overturn is much larger than the simplest theory would indicate, owing to the losses due to drag at impact.

3. The model test results are in a good quantitative agreement with observers' reports of the two SRN-5 overturns.

4. The model tests indicate that the addition of a flare would completely eliminate the overturn.

5. Tests on the SKMR-1 show that although there is an initial tendency to overturn this is controlled by the high freeboard, and SKMR-1 is safe even with an applied rolling moment of 270,000 ft/lbs.

Film Scenario - 'Overturn'

Scene

1. Title 'Overturn' - Nobs 90127

2. Still: Overturn clipping from San Francisco "Chronicle"

3. Still: Diagram of Model (Figure 8 of Report)

4. Caption: Overturning of SRN-5 model 96 grams all-up-weight

5. Mounting of model in pendulum launcher

6. Impact of SRN-5 model on water $\alpha = -7.5^\circ$, $\theta = 28^\circ$, 24.5° 21°, 16.5°. Weight 96 grams.

7. Impact of SRN-5 model on water $\alpha = -5^\circ$ $\theta = 28^\circ$, 24.5°

8. Impact of SRN-5 model on water. Weight increased to 212 grams $\alpha = -7.5^\circ$, $\theta = 28^\circ$, 24.5°, 21°

9. Impact of SRN-5 model on water. Weight increased to 212 grams $\alpha = -5^\circ$, $\theta = 28^\circ$, 24.5°, 21°

10. Caption. 'Overturning Process'

11. Still: SRN-5 Collapse of trunk (Figure 4 of Report).

12. Still: Overturning of SRN-5 - initial stages of overturn (Figure 5 in Report)

13. Caption: SRN-5 modified weight = 103 grams

14. SRN-5 modified $\alpha = -7\text{-}1/2^\circ$, $\theta = 28^\circ$, 24.5°, 21°

15. SRN-5 modified $\alpha = -5^\circ$ $\theta = 28^\circ$, 24.5°, 21°

16. Caption: SKMR-1 206 grams Scale = 1/52 1/b = 1.6 (2.15)

17. Mounting of model in Plenum launcher

18. Maximum CG shift $\alpha = -7.5^\circ$ $\theta = 28^\circ$, 24.5°, 21°, 16.5°

19. No CG shift $\alpha = -7.5^\circ$ $\theta = 28^\circ$, 24.5°, 21°, 16.5°, $\theta_R = 7^\circ$

20. Max. CG shift; WL raised to contact at $\Theta_R = 7^\circ$ $\alpha = -7.5^\circ$ $\Theta = 28^\circ$

21. No CG shift; WL raised to contact at $\Theta_R = 7^\circ$ $\alpha = -7.5^\circ$ $\Theta = 28^\circ$

22. Max. CG shift & no CG shift $\alpha = -5^\circ$ $\Theta = 28^\circ$ WL raised

23. Max. CG shift & no CG shift $\alpha = -2\ 1/2^\circ$ $\Theta = 28^\circ$ WL raised again

24. Max. CG shift and no CG shift $\alpha = 0^\circ$ $\Theta = 28^\circ$ WL raised

REFERENCES

1. Walker, Norman K., "Some Notes on the Lift and Drag of Ground Effect Machines", National Meeting on Hydrofoil and Air Cushion Vehicles. A.I.A.A., Washington, D. C. September 1962.

2. Walker, Norman K., "Final Report on Contract No. Nobs 90127" - to be issued.

3. "U. S. Navy Hydroskimmer SKMR-1" Report on Preliminary Analysis and Tests on Low Speed Roll Instability. Bell Aerosystems Co. Report No. 2073-950006. April 1965.

4. Sundry articles and letters, Air Cushion Vehicles, supplement to Flight International. May through December 1965.