# Some Thoughts on ACV Structural Impact Design Requirements

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## INTRODUCTION

When developing safety standards which involve mathematical calculation, regulatory authorities are occasionally forced to adopt arbitrary or empirical calculation methods in the absence of precedents or fundamental formulae. The arrival of the Aeromobile series of craft in 1958-59, and of SRN-1 in 1959, and subsequent recognition that a new transportation vehicle with unprecedented design features would require some safety regulation, was one such occasion. Since initial major development took place in U.K., it fell to the U.K. regulatory authority of the day, the Air Registration Board (A.R.B., and now Civil Aviation Authority, or C.A.A.) to grapple with the problem. Amongst the design criteria to be established were the structural loadings imposed by wave impacts, and collisions, and these were included in the initial safety requirements published by ARB in 1962 (Ref.1). The U.K. successor publication (Ref. 2) and its Canadian counterpart (Ref. 3) repeat them. Other authorities have, perhaps wisely, refrained from stating quantified criteria.

In the intervening quarter of a century or so, great strides have been made in skirt technology which was in its infancy in 1962, raising the craft structure from a few centimetres to heights measured in metres above the surface and introducing a large shock absorber of no mean capacity. It is quite possible that this now results in current ACV structures being penalized by unnecessarily stringent requirements.

The intent of this paper is to briefly review the background to the calculation methods, examine them in some detail, and provoke some thought as to whether it is not now opportune to investigate more meaningful methods. In so doing, it is recognized that other calculation methods have been, and are being, used for experimental or military vehicles in other countries; their application to date appears to have been limited and available information about them is insufficient to enable comments to be made. So far as this author is aware, the U.K. and Canadian requirements, which are essentially identical, contain the only quantified criteria in current use applied by national regulatory authorities, and which are the subject of this paper.

## 2. Wave Impact Inertial Loading.

As with any other form of transport, an ACV must be designed to withstand the loads imposed upon it by the influences of the medium in or over which it operates. In the case of an amphibious ACV operating over water, the most stringent loads arise from the inertia forces generated by wave impacts at speed.

In the truly bow or stern symmetrical impact cases, these inertial forces determine the strength requirements for the hull bending longitudinally; assymmetric impacts determine the strength requirements in torsion. Thus, the wave impact loadings can be said to dictate at least the primary structure of the hull. One might therefore be forgiven for assuming that the method of calculating these loadings involved some precision. But making such an assumption ignores the practical difficulties involved in dealing with a vehicle having freedom in heave, pitch and roll travelling over irregular waves at arbitrary angles of attack.

In the early rush to formulate some design criteria in anticipation of rapid hovercraft development, and faced with these practical difficulties, some empirical solution had to be found, at least to meet immediate needs. Full scale testing is very time-consuming, and in any case at that time there were very few craft available and these were fully engaged in development work. Model testing is not fully valid since not all parameters are amenable to scaling. SRN-1 structural strength was calculated by considering nose-diving into a wave following engine failure, and also a collision with a floating object. The first resulted in a calculated vertical bow acceleration of 8g, while the collision case involved a deceleration of 4g. But there were 2 practical criteria that dictated SRN-1 structure. "The first was whether it could be stood on without buckling and the second was whether the material was available in the shop" (Stanton Jones, ref 4). Such was the state of structural design knowledge in 1959-60. On a more serious note, Stanton Jones revealed more data, in Ref. 5, relating to SRN-1 and early considerations of wave impact loading. With a design safety factor of 1.5, the ultimate loading for a bow wave impact was 12g. In actual trials, he quotes a peak recorded bow acceleration of 4g at 40 knots, noting that the general level was in the order of 1.5g when operating over 30 to 45 cm. waves with a hoverheight of only 10 cms.

Since Saunders-Roe and Vickers-Armstrong, the most active hovercraft developers of the day, both had experience with flying-boats, it was perhaps natural that they and A.R.B. would research flying boat hull structural design criteria for an analogous method of calculating water impact loads. Such a method already existed in the ARB's British Civil Airworthiness Requirements, and using the limited data from SRN-1 and some U.S. research on planing surfaces, this was modified and included in ref. 1, published in 1962. It is this calculation method, with no changes, which is currently in use today. It is reproduced here as a direct extract from the Canadian safety requirements (Ref. 3).

The vertical acceleration of the c.g. may be obtained from:-

$$N_w = \frac{0.12 . k_1 . V . V_v}{w^{1/3} (1+x^2)^{2/3}}$$

Where $N_w$ is the vertical acceleration of the c.g., in g

$k_1$ is a hull station weighting factor, reducing linearly from a value of 1.5 at the bow to a value of 1.0 at the station of the longitudinal c.g., thereafter remaining constant.

V is the vehicle velocity relative to the water

$V_v$ is the vehicle vertical relative velocity, given by:-

$$V_v = \frac{2.26 . \pi . h}{\sqrt{\lambda}} + 0.61 \text{ m/sec (2 ft/sec)}$$

where h is wave height; $\lambda$ is wave length, and $\frac{h}{\lambda}$ is 10

W is vehicle weight

x is the ratio of the length between the impact point considered and the c.g. to the radius of gyration in pitch.

It will be noted that the maximum value of $N_w$ will not necessarily result from consideration of maximum values of W or of V.

In examining the formula critically, it is immediately obvious that there is no recognizable term in the equation which addresses the alleviation which may be expected from the cushion and skirt. Given the date when the equation was developed, and its origin, this is perhaps not surprising. What is surprising, at first glance, is that the general calculation method has not been questioned or revised previously. Upon reflection, however, this passive acceptance can perhaps be justified, and can even be construed as being wise. Once the merits and potential of skirts were recognized, development and proliferation of designs of widely different concepts was rapid, and up until about 1969, the black art of evolution was producing constant changes. Any attempt to modify the calculation method to account for any load attenuation from the cushion would have been overtaken by a new design. The attenuation provided by the different concepts of bags, segments, juppes, peri-cells, etc., would probably not be covered by one unique equation.

A large factor in the lengthy and varied evolution of skirts was the high incidence of damage and maintenance, which is indicative that skirts and skirt support structure bore the brunt of wave impacts. One early result of this damage was a change of bow shape. All early skirted craft in the U.K. had pointed bows, and stress concentrations at the bow discontinuity caused continual tears. All subsequent craft have had generally semi-circular bows. It's somewhat ironic that the original, non-skirted SRN-1 had a semi-circular bow, and at that time, Stanton Jones (Ref. 5) somewhat prophetically, but in a different context, opined that "It is fairly clear that detailed consideration of the bow design can do a great deal to reduce the responses when impact is likely to occur".

Limited craft availability, instrumentation requirements (including wave measurement), and the vagaries of weather all combined to severely limit the opportunities to collect full scale data. In 1965-66, sophisticated preparations were made to conduct trials which would have yielded data on SRN-3. For month after month, the English Channel remained obstinately calm; when the weather was right, the craft was not available. Evidence of the effect of wave impact attenuation by the skirt is therefore mainly anecdotal, with minimal data.

In 1966, an SRN-5 engaged in Arctic trials at Tuktoyaktuk, N.W.T., repeatedly made crossings of an ice pressure ridge with a profile analogous to a steep isolated sinusoidal wave 1.7 m. high. On the down-stream side the profile dropped almost vertically for 1.2 m. and craft entry speed was 30 knots. The resultant craft pitch attitude was in the order of 10 degrees nose down, but not once was hard structure impact experienced, and neither was there any skirt damage. Unfortunately, no accelerometers were installed. Later that year, SRN-3 suffered severe skirt damage from a broadside wave impact, and in 1968 the first SRN-4 suffered similar damage, rupturing the plenum chamber plating, during development trials. During the first year in commercial service, SRN-4 was continually plagued with finger and skirt failures. These examples are within the author's experience, and are not quoted as being specifically related to products of BHC. They are offered as a sample of the examples that indicate the absorption by the skirt of wave impact loads which would otherwise have been imparted directly to the hull structure.

By 1970, skirt design had become relatively stable, and possibly a review of the wave impact calculation method could have been attempted, but the attention of certification authorities, and much of their time, was focussed upon developing the international safety standard under the auspices of IMCO. This occupied much of the 1970 decade by the end of which the vast majority of amphibious ACV's in commercial service had skirts of one of two fairly stable generic types - either the tapered "compliant" BHC bag and finger, or the loop and segment type based upon H.D.L. work. Compared with skirts of 10 years previous, the bag and finger type now had a much lower bag/cushion pressure ratio, this providing a smoother response to wave impacts. Significant developmental changes can be said to have effectively ceased, with current emphasis being upon 'fine tuning'. A major result of this lengthy development has been greatly improved ride quality, implying lower wave impact accelerations. But are they lower? The sea and waves have not changed, and therefore the impact forces have not changed - they are simply being absorbed and attenuated more effectively. Perhaps it is now appropriate to recognize this, and review the empirical wave impact formula to include a cushion attenuation factor. Skirts and cushions now appear to be sufficiently stabilized to permit this review without fear of rapid obsolescence.

At this point, it is pertinent to mention that at least one other calculation method for estimating vertical accelerations due to wave impacts has been published.

This is contained in ref. 6, published by the Norwegian classification society Det Norske Veritas. It is, however, intended for application to a broad spectrum of high speed marine craft including both amphibious and sidewall ACV's, catamarans and hydrofoils. The calculation method is prefaced by a statement that it may be used "Unless other values are justified by calculations according to accepted theories, model tests or full scale measurements". For two examples of amphibious ACV's for which this author has sufficient design data, comparative results using the DNV and the CAA calculation methods gives the following bow vertical accelerations (g) -

| | DNV | CAA/CCG |
|---|---|---|
| Craft A | 2.66 | 1.78 |
| Craft B. | 2.8 | 3.25 |

Clearly, there are major discrepancies; without being critical, the DNV method is based entirely on geometry, with no terms relating to vehicle weight or inherent inertia. Neither method includes terms relating to cushion attenuation. It is impossible to make useful comment upon the validity, either individual or relative when only two pieces of data are available; the point to be made is that probably each method is invalid for general use with current amphibious ACV's, for different reasons, and the method used by regulatory authorities requires review to determine its invalidities and make appropriate adjustments.

Having discussed cushion alleviation at length, there is another factor in the calculation method which bears comment. This is the term "Vv", relative vertical velocity.

This is clearly a direct descendant of the original seaplane empiricism, the degree of which is emphasised by the second term of its equation. In the U.K. version, this second term is "Vs", defined as "rate of sink (in the absence of more precise information, this is assumed to be 2 ft/sec)". Recognising the already high state of empiricism, the Canadian version merely uses 0.61 m/sec for this term. In practical operation in waves, a craft is simultaneously heaving and pitching (rolling), and it is very difficult to arrive at a meaningful value for either rate of sink or relative vertical velocity. Again, for unskirted craft of the SRN-1 era, they had direct significance; with large-volume cushions acting as shock-absorbers, the very high damping renders them insignificant. One meaningful example of the effect of "Vv" known to the author was when a British Army SRN-6, operating in surf, reputedly fell some 3 metres vertically into a wave trough, resulting in rupture of the thin plenum chamber plating. This may have been fortuitous, since in the negotiation of the Maipures Rapids of the Amazon in a later operation, another SRN-6 suffered a much rougher passage without similar damage. Such operations, however, are generally outside the normal loading envelopes considered for commercial craft certification. It would appear that the "Vv" term is worthy of further study in any general review of the calculation method.

Using the present calculation method results in a maximum vertical acceleration at the bow of about 4 or 5g being calculated as the response to a symmetrical bow impact for a typical modern high speed commercial amphibian. Applying a safety factor of 1.5, the hull longitudinal bending must therefore be designed to accept up to about 7g at the bow.

In the light of accumulated experience, and with the lack of substantial recorded data, this would appear to be ultra-conservative; recognizing this, tacit agreement between manufacturers and certification authorities permits the calculated loadings to be reduced by an arbitrary 30% to allow for cushion attenuation for craft designed with bag and finger skirts. While such reduction has not resulted in any reported structural problems, this cannot be regarded as a positive result, particularly when it must be accepted that craft are occasionally exposed to operational conditions beyond their design conditions. A case in point was the Bell Voyageur, which was originally certified for operation up to 35,500 Kg; with no structural change and no change to the operating envelope, the maximum certified weight was increased eventually to 40,200 Kg; in reduced sea states, operation at 47,600 Kg was permitted. It must be emphasized, of course, that increasing weight generally results in a reduction of "V" in practical terms, both of which lead to a reduction of "Nw"; but the design value of "V" cannot be changed since in a down-wind, down-sea condition, it can readily be maintained, and the possibility of bow wave impacts is generally increased.

It is strongly suggested that, with skirt design now fairly stabilized, the time is opportune to reassess the method by which the major structural loadings are derived. Such re-assessment, it is suggested, should review all the relevant factors and influences contributing to the loadings, which would identify the requirements for a series of full scale instrumented trials. By careful choice of parameters to be recorded, it should be possible to determine not only the structural loadings of the main hull, but also the individual components which combine to develop those loadings. Such an undertaking is no small task, but it is one which would assist the further development of the true potential of amphibious ACV's.

## 3. Pressure Resulting From Wave Impacts.

The calculation method discussed above related to overall design for structural bending and torsion; more detail design for stiffness of bottom panels requires an estimation of local pressures resulting from wave impact. This also is directly derived from the original seaplane work; but in this case, experience has been instrumental in modifying the formula. At present, the requirements estimate the local pressure is 0.0162 $K_2V.V_v$, where $K_2$ is a station weighting factor. Initially, the co-efficient was 0.0324, so the cushion attenuation is assumed to permit a 50% reduction. In early attempts to include a cushion alleviation factor, the cushion effect was over estimated, resulting in some damage during heavy weather to the bow plating of SRN-4. More recent experience with current cushion designs suggest that the present formula may err on the conservative side; skirt design now permits speed to be maintained heading into wave-heights which, in theory, should cause the design bottom pressures to be exceeded. It is perhaps worthy of note that the term "Vv" is common to both the wave impact load and the pressure calculation methods.

It is not intended to dwell at length on this topic, since the discussion in the previous section applies equally, leading to a repetition of the suggestion that the calculation method be reviewed in the light of dedicated trials, using current technology.

## 4. Crash Deceleration Loadings.

While the intent of designing for wave impact and wave pressure loads was to ensure integrity of the craft structure within its normal operating envelope, there is also a need to protect craft occupants from injury caused by large heavy components, such as engines, breaking loose under crash decelerations.

The values originally chosen, still in use today were again arbitrarily based upon those used for light aircraft, and are quoted for the three axes:-

Vertical - 4g down to 3g up.
Sideways - 0 to 3g.
Longitudinal - 6g forward to 3g backward.
Combined - 6g resultant.

The design requirement is that primary structure shall not fail in such a way as to cause injury, and that machinery and equipment shall not break loose so as to cause injury, when subjected to these loadings. The crash that is of most interest in the forward deceleration, since craft are generally travelling forward when at speed; it also happens to be the highest value.

The selection of this arbitrary value deserves considerable thought, since it determines the longitudinal energy absorption requirements of the bow structure. With a uniform deceleration of 6g, neglecting energy absorption, a head-on-collision will result in the following lengths of bow structure collapse before the wreckage comes to rest:-

| | | | | |
|---|---|---|---|---|
| Entry Speed (knots) | 20 | 30 | 40 | 50 |
| Collapse Length (metres) | 0.9 | 2.03 | 3.6 | 5.66 |

These collapse lengths are inversely and linearly proportional to the chosen value of deceleration.

The value of 6g for longitudinal deceleration has apparently been widely adopted without regard to size of craft - it appears in the U.K. and Canadian standard requirements (Refs. 2 & 3), and it also appears in Safety Requirements for small and racing hovercraft under the auspices of the Hover Club of Great Britain, and Hoverclub of America, and also in Canadian requirements for "light" hovercraft. Always the emphasis is upon security of machinery and equipment - ensuring that it will not break adrift and fly forward to injure passengers or crew. Treatment of the bow structure, so far as safety requirements in this context are concerned, is not specifically spelled out. Being totally dispassionate, one could say that the bow of a craft and anything that it contains is sacrificial in the interests of preserving contents further aft. There is little, if any, need to site examples of craft design where, considering craft speed capabilities, there are occupants within the quoted collapse length. Fortunately, occurrences are few and far between; however, since collisions are not anticipated occurrences, there are no recorded acceleration levels.

6g does not appear to be an unreasonable value, neither does it appear to have been contentious for high-speed amphibians. However, it is this author's opinion that, in conjunction with it, there is a strong case for a requirement addressing the collapse of the bow in more specific terms than at present. Whilst admittedly the craft should be operated with appropriate caution when in proximity to obstructions, it must be recognized that the thrust requirements for maintaining service speed in average sea states permit potentially high speed impacts over level surfaces or calm conditions. In practice, a craft commander faced with an impending head-on-collision will probably attempt avoiding action, at the same time "dumping" his cushion. A resultant collision may therefore be at any angle within the "bow semi-circle". This is tantamount to saying that, for a craft capable of 50 knots, the forward 5.7 metres is liable to destruction in a head-on collision. But no requirements relate specifically to occupant safety or craft equipment within that area.

It should appear to be reasonable to require bow structural design to include energy-absorbing structure which would collapse in such a way as to afford protection to passengers, crew and equipment such as fuel tanks.

At this point, it should be recalled that the crash deceleration requirement of 6g longitudinally applies to all craft, regardless of size and speed capability. There are numerous applications of ACV's where speed is not a dominant requirement, and, if collapse length is a criteria, then the crash deceleration requirement could be adjusted to recognize the lower potential collision speed. Reference to Fig. 1, illustrates the effect of speed upon deceleration given a constant collapse length - a 40 knot collision maintaining 6g deceleration results in the same collapse length as a 25 knot collision at about 2.5g. While it is not suggested here that collapse length should be the criteria, it is indicative of the need to consider a review of the crash deceleration loadings, the benefits of which to the designer and operator are immediately obvious.

Having examined the head-on collision deceleration at some length as being the most severe (and likely) case, brief mention should be made of the other cases. The author finds it extremely difficult to reconcile the required vertical acceleration design requirements with reality. An ACV can only fall freely, and then only for short distances compared to the aircraft from which this requirement was derived, and it is impossible, in practical terms, to achieve an impact velocity, even neglecting cushion attenuation, which would approach the 4g requirement; it is equally difficult to appreciate the requirement for 3g upward. For sideways and backward collisions, 3g is quoted; bearing in mind the (likely) bow impact velocities in these directions, and given the evolution of a general design where peripheral structure is essentially light secondary or tertiary structure, this value appears to be appropriate. It would, however, be worthy of inclusion in any review of crash requirements.

## 5. Plans for a Review.

Recognition of the need for a review dawned in Canada in the Spring of 1988, and the first step was to research the rationale behind the origins of the requirements. In an exchange of correspondence with CAA, it transpired that similar concerns were being expressed in U.K., where an amendment to the collision acceleration requirements is under active consideration. CAA is also considering active research into wave impact and pressure design calculations. Within this exchange, there is a mutual expression of desire to attempt a joint full scale data gathering programme.

Before the CAA's actions were known, we had already made informal approaches for a research programme, so that when the CAA response was received, it was a most encouraging sign that we might be doing something right. Our approaches had already fallen on sympathetic ears, so the possibility of a joint U.K.-Canada programme should add greatly to the possibility of proceeding.

It is very much too early to be specific, but the scenario which will probably be explored is installing limited but meaningful instrumentation into "Waban-Aki", the CCG AP.1-88 and carrying out a short period of dedicated trials in recorded sea states in the St. Laurence River. The data gathered would be in support of reviewing wave impact and pressure design requirements. So far as collision acceleration requirements are concerned, there are two interdependent aspects to be investigated - the numerical values themselves, and the possibility of designing structures to be more "crashworthy". As a first step, we could as in the past simply follow the latest CAA thinking, but this only addresses the vehicles of relatively low speed. A more general approach, embracing the concept of more "crashworthy" structure may be explored, initially reviewing work carried out for a similar objective on aircraft at the University of Toronto and possibly other centres.

It must be emphasized that these plans are still very fluid gleams in the author's eye; before they can be regarded as a commitment on the part of Canadian Coast Guard to proceed, a lot of spade work has to be done.

## 6. Closing Remarks.

It is hoped that this paper has illustrated the need to review some of the major structural design requirements for ACV's. In so doing, it is also an attempt to illustrate that regulatory authorities can perceive needs to overhaul and review their own requirements, and take action. Certainly in this respect, Canadian Coast Guard encourages dialogue concerning safety standards and is always prepared to make justifiable adjustments where possible, provided that overall safety levels are not compromised.

## 7. Acknowledgment.

After pondering over the need to review the CCG structural design requirements for some time, the author was finally prodded into action by a discussion with Derek Jones, of Jones Kirwan and Associates; his encouragement, and subsequently that of Jacques Laframboise, of T.D.C. is gratefully acknowledged. Thanks is also due to Jacques, wearing his CACTS hat, for his invitation to present a paper at this Conference. Finally, the unwitting encouragement and assistance provided in responses received from Tony Seal, of CAA in U.K. is also acknowledged.

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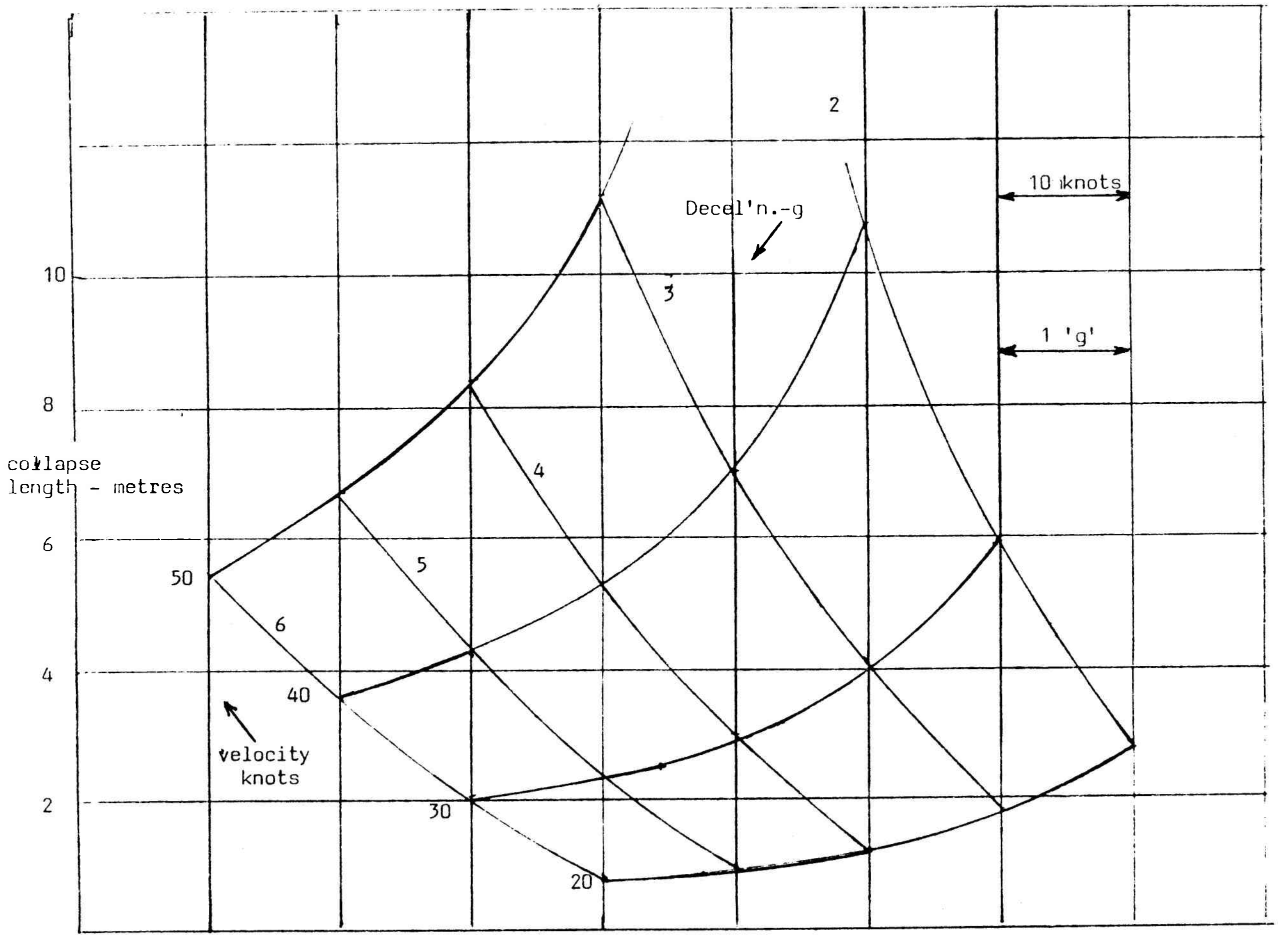

Fig. 1 collapse length v deceleration v velocity