

AD-A209108

UNLIMITED

Copy No. 11



MINISTRY OF DEFENCE

ROYAL

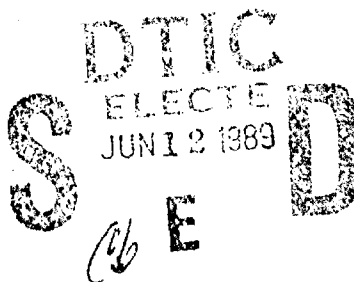
ARMAMENT RESEARCH AND DEVELOPMENT ESTABLISHMENT

REPORT 12/88

A Design Assessment for Metallic Pressure Vessels
Circumferentially Reinforced with a Pre-Tensioned
High-Specific-Strength Anisotropic Composite Overwind

A Groves

J Margetson



Westcott

Gucks

89 6 09 046

UNLIMITED

March 1989

0036961

CONDITIONS OF RELEASE

BR-109774

MR PAUL A ROBEY
DTIC
Attn:DTIC-FDAC
Cameron Station-Bldg 5
Alexandria
VA 22304 6145

U

COPYRIGHT (c)
1988
CONTROLLER
HMSO LONDON

Y

Reports quoted are not necessarily available to members of the public or to commercial organisations.

UNLIMITED

CONTENTS

1	Introduction	3
2	10GPa Transverse Moduli Overwind	4
	2.1 Stress Distribution Calculations	5
3	1GPa Transverse Moduli Overwind	6
	3.1 Stress Calculations	8
4	Conclusions	9
	4.1 10GPa Transverse Moduli Composite Overwind	9
	4.2 1GPa Transverse Moduli Composite Overwind	10
5	Acknowledgements	10
6	References	11
	Tables 1-3	
	Figures 1-13	

Accession For	
NTIS GRA&I	☒
DTIC TAB	☐
Unannounced	☐
Justification	
By _____	
Distribution/	
Availability Codes	
Avail and/or	
Dist	
A-1	

1 INTRODUCTION

Circumferentially reinforcing thick-walled metallic cylindrical pressure vessels with a pre-tensioned filament overwind for the induction of compressive stresses is not new. Indeed the technique can be traced back many years to when wire was used as the reinforcing material (Ref 1). However, with the advent of the new high-specific-strength (strength to weight ratio) fibre-reinforced composites, eg GFRP, CFRP, etc, the technique has seen a revival of interest, particularly in the construction of lightweight high performance pressure vessels. These composites have resulted in substantial weight savings in many aerospace applications (Refs 2,3) and it is likely that they will yield similar benefits in the design of high pressure containment vessels. Unfortunately, the simplified design techniques and documented behavioural characteristics (Ref 1) associated with the early wire wrapped vessels cannot be applied to vessels circumferentially reinforced with these new composite materials because of their underlying isotropic theory. The behaviour of the vessels and, moreover, the suitability of reinforcing them with highly anisotropic composites are therefore unknowns and before they can be adopted as viable reinforcing materials detailed assessment studies must be undertaken. Such assessments must be comprehensive and every attempt should be made to identify the interaction between all of the design variables. These variables include the initial pre-stressing parameters, ie winding tension and number of layers, material properties, geometry and possibly machining tolerances.

It should be noted that such assessments are further complicated by virtue of the reinforcement material having an almost infinite range of property values through the choice of fibre lay-up and matrix selection. However, in this study, where the composite is used only as a circumferential reinforcement, it is convenient to assume that the reinforcing fibres will lie solely in the circumferential direction. Consequently, circumferential property variations in the reinforcement will be governed essentially by the fibre type selected, though it should be appreciated that different matrix resins will have a significant effect on the very low transverse properties (radial and axial). It is expected that these very low properties will have a large influence on the vessels' behavioural characteristics and indeed quantifying this influence forms an important feature of the assessment studies.

In this paper such an assessment is presented. To conserve space the underlying stress analyses are omitted but they are nevertheless well documented in Reference 4. It should be noted, though, that of the two techniques detailed in Reference 4 for analysing the initial winding process, ie an exact discrete approach and an approximate continuous approach, only the latter will be used owing, principally, to its greater computational efficiency. Nevertheless, computations have shown that for the vessels under consideration the errors associated with this approximation are very small, typically $\ll 1$ per cent.

Because of the many independent design variables it is not possible to carry out a complete comprehensive assessment. It has therefore been decided to consider the most important study in which metal is removed from the external surfaces of an original all-metal reference vessel

UNLIMITED

(details of which are presented in Table 1) and calculations are performed to evaluate the thickness of reinforcement necessary to return the vessel to its original load bearing configuration. Such an assessment also has the benefit of being easily repeated for a wide range of composite types with economical presentation of results. The assessment is therefore repeated for five potential fibre reinforced composites, two glasses (GFRP) and three carbons (CFRP), with two different, but typical, transverse moduli, 10GPa and 1GPa. Material properties pertaining to these composite overwinds with the 10GPa and 1GPa transverse moduli are presented in Tables 2 and 3.

Although this study is confined to a reinforcement thickness assessment it is nevertheless possible to use the resulting information in a series of ancillary analyses, for example, weight comparisons, maximum composite strain to failure strain calculations as well as detailed stress computations. Such analyses are particularly useful for establishing optimum configurations and, moreover, identifying the most suitable reinforcing material.

2 10GPa TRANSVERSE MODULI OVERWIND

Using the material property data given in Tables 2-3 and the reference vessel data presented in Table 1, the dependence of the reinforcement thickness on material properties and liner thickness has been assessed for an arbitrarily chosen 500MPa winding tension. The resulting computations are presented in Figure 1. Composite circumferential moduli are used to differentiate between the five composite types considered. In addition, for comparative purposes the thickness of original metal required to return the vessel to its original strength condition is also shown. It should be noted that, unless otherwise stated, all curves terminate when the liner yields in compression during winding.

From the figure it is immediately apparent that for reinforcement thickness purposes the CFRPs yield the most favourable design solutions owing to their higher moduli. Indeed, the 40GPa GFRP requires approximately twice the reinforcement of that for the 240GPa CFRP. Nevertheless, it is of interest to note that when these reinforcement thicknesses are added to the liner thicknesses all of the vessels exhibit external dimensions smaller than that of the original monolithic structure. A further and unexpected feature of the assessment was the existence of maxima in the reinforcement thickness vs liner thickness curves for the 180 and 240GPa CFRPs. Detailed computations revealed that these maxima correspond to the point where the winding induced stresses increase more rapidly than the pressure induced stresses with decreasing liner thickness.

Preliminary calculations have indicated that the CFRPs are likely to yield the most favourable design solutions. However, other information such as weight and maximum composite strain to failure strain also need to be considered. In Figure 2 the weight calculations follow anticipated similar trends to those of the reinforcement thickness studies since the density of GFRP is greater than that of CFRP (see Tabs 2 and 3) with all the CFRPs offering similar weight savings. However, when Figure 3 is considered, where the ratios of maximum composite strain to failure

UNLIMITED

strain are plotted against liner thickness, these trends are modified. In terms of safety it can be seen that the 60GPa GFRP offers the most satisfactory design, with a typical strain ratio of 0.3, while the 240GPa CFRP offers the least satisfactory design, with a strain ratio in the region of 0.7 (although in excess of unity for 6mm liners or less). In the design of high-specific-strength pressure vessels it is recognised though that in order to minimise component weight the constituent materials should be used well into their operating ranges. On this basis Figures 2 and 3 would therefore suggest that the 240GPa CFRP should be used as the reinforcing material. A more rigorous inspection of Figures 2 and 3 reveals, however, that the 180GPa CFRP is likely to yield an even more satisfactory design solution since not only are the weight savings comparable with those of the higher modulus CFRP, but the margin of safety to composite failure is some 75% greater. The 60GPa GFRP offers even greater margins of safety, but the weight penalties associated with this reinforcement (see Fig 3) clearly outweigh this potential advantage.

2.1 Stress Distribution Calculations

A detailed knowledge of the stress distributions through the vessel is important for two reasons: firstly, to identify those regions most highly stressed, and secondly, to establish whether the stresses are sufficient to cause failure of the composite reinforcement. The former is important from a design point of view in that it may permit the engineer to identify more efficient, and hence cost-effective routes of manufacture. For example, for the very highly stressed regions of the vessel it may be desirable to wind with an expensive, though high modulus, composite, whereas for the remainder of the vessel a lower quality and less expensive composite may suffice.

A notable example is the use of high-specific-strength sleeves to line conventional medium quality steel pressure vessels. However, such fabrication routes are beyond the scope of these initial assessment studies and will not be discussed further. The second reason, which is of equal importance, arises from the fact that the stresses may themselves cause transverse failure of the composite overwind. Although uniaxial composites exhibit very high tensile strengths in the direction of fibre alignment (in excess of 1GPa) (Ref 2) their strengths in the transverse directions are very much lower, typically 125MPa. Since the Table 1 internal pressure is very much greater than this value, problems may arise at the liner/composite interface where, for particularly thin liners, the interface pressure may exceed 125MPa. Furthermore, it is known that for vessels overwound with highly anisotropic reinforcements the axial stress is non-zero (Ref 5). Although these values are likely to be small, they must nevertheless be considered.

In order to undertake a detailed stress analysis it is necessary to identify a suitable geometry. From the previous calculations it is evident that the final geometry is heavily dependent on the selected liner thickness since, when established, the reinforcement thickness readily follows from Figure 1. Previous analyses have shown that for the 180GPa CFRP liner, thicknesses as thin as 5mm are attainable (see Fig 1). It must be appreciated, however, that the liner may also be required

UNLIMITED

to support additional loads (possibly due to inertia and thermal effects) which were not considered in that figure. Furthermore, sufficient thickness must exist to take into account any inhomogeneity prevailing in the liner material. Unfortunately for overwound pressure vessels such information is either very scant or unavailable and as a result it is not possible to choose with precision an exact liner thickness. Detailed computations, based on the very limited information available, have however shown that liner thicknesses of 20mm or less leave little margin for error and furthermore would be unlikely to support all of the applied loads without yielding. For the vessel under consideration a more acceptable liner thickness would therefore lie in the 20 to 30mm range. For engineering purposes the weight benefits offered by a 20mm liner over a 30mm liner are small, approximately 8 per cent relative to the monolithic vessel, and in view of this fact coupled with the uncertainties associated with the axial loads, a 30mm liner was selected as the basis for the stress analysis calculations. Once the liner thickness had been determined the reinforcement thickness for the 180GPa CFRP readily followed from Figure 1 as 35.5mm.

For overwound pressure vessels the stress state will be essentially the summation of two components, one due to overwinding and one due to pressurisation. A further component resulting from the additional loads described above may also exist, but for the purposes of this study these additional load components will be neglected. Since both of these loads may not be acting on the vessel at any one time, it is necessary to look in detail at both of the stress states arising from these two components. For the 30mm liner overwound with 35.5mm of 180GPa CFRP subject to the 300MPa internal pressure detailed in Table 1, the resulting stress distributions in the circumferential, radial and axial directions are presented in Figures 4-6 respectively. The combined stress state is also given. From Figure 4 it can be seen that the circumferential stress distributions are well behaved in that no steep stress gradients are observed. A further and most encouraging feature is the almost uniform stress distribution in the reinforcement, indicating excellent load transfer under the most severe loading conditions. When the radial stress distribution is considered (see Fig 5) it can be seen that the radial stress at the liner/composite interface is, unfortunately, in excess of the transverse strength of the reinforcement. However, the strength figures quoted are based on tensile loading and the mechanism governing compressive failure may be significantly different. Furthermore, the most highly stressed material is constrained from free movement by external layers of composite operating at lower radial stress levels. This may also have an effect on the radial stress to failure at the liner/composite interface. Such failure mechanisms are subjects for future research. Finally, although the axial stress distributions (see Fig 6) are of interest, they are nevertheless very small and for engineering purposes may be neglected.

3 1GPa TRANSVERSE MODULI OVERWIND

The analyses presented in Section 2 have been concerned solely with the 10GPa transverse moduli composite overwinds. It was indicated in Section 1, however, that the overwinds may, through the resin selected, have an even lower transverse modulus, eg 1GPa. In order to assess

UNLIMITED

quantitatively the influence of such low transverse moduli on the behavioural characteristics of the overwound vessel, the reinforcement thickness, weight and maximum composite strain to failure strain calculations described previously were repeated using, in this case, the 1GPa transverse moduli material properties given in Tables 1 and 2. The results of these three studies are presented in Figures 7-9. When the resulting computations were compared with those obtained from the 10GPa transverse moduli overwinds (see Figs 1-3) several markedly different trends were observed. Firstly, the relationship between the reinforcement thickness and the liner thickness ceases to be generally linear and becomes very non-linear, particularly for thin liner thicknesses. Furthermore, with the exception of the 40GPa GFRP, all of the curves were observed to tend to infinity before yielding the liner in compression. Secondly, there exists, for a particular composite, a minimum liner thickness below which a vessel cannot be fabricated to meet its in-service loads, and thirdly, the vessel weights pass through minima. For engineering purposes the values of these minima can be assumed to be independent of the liner thickness and reinforcement material properties and are approximately equal to 700 grams per mm length. The relationship between the liner thickness and material properties corresponding to these minima is, however, complex, but computations show that the liner's thickness decreases with decreasing circumferential modulus and vice versa. A further interesting feature is the fact that the most suitable composite overwind for minimum reinforcement thickness purposes varies as a function of the liner thickness. For example, for an 80mm liner the 240GPa CFRP yields the minimum reinforcement thickness, while for a 40mm liner the 40GPa GFRP is required.

While the reinforcement thickness calculations and weight studies for the 1GPa transverse moduli overwinds have been found to be markedly different from those for 10GPa transverse moduli overwinds, the maximum observed composite strain to failure strain analyses were found to be similar (see Figs 3 and 9) with the most suitable overwind again being the 60GPa GFRP and the least suitable the 240GPa CFRP. The only notable feature arising from the figure is that the maximum composite strain is now almost independent of the liner thickness.

For the vessels reinforced with the 10GPa transverse moduli overwinds the 180GPa CFRP was chosen as the reinforcing material by carefully trading off weight benefits against factors of safety. For the 1GPa transverse moduli overwinds the reinforcement selection process is more straightforward since the maximum attainable weight savings are independent of the reinforcing material. Thus in the absence of other over-riding requirements the 60GPa GFRP should be selected as the reinforcing material because of its high strain to failure properties.

The features observed in vessels reinforced with 1GPa transverse moduli overwinds are notable and in many respects in direct contrast to those of vessels reinforced with the 10GPa transverse moduli overwinds. In order to gain an insight into the mechanics governing these two contrasting behaviours it is necessary to consider in detail the manner in which the dominant circumferential stresses are built up during the overwinding process for both the 10GPa and 1GPa transverse moduli composite overwinds. For a 30mm liner overwound with a 180GPa CFRP with 10GPa and

UNLIMITED

1GPa transverse moduli such studies are presented in Figures 10 and 11 respectively. In both figures the stress distributions presented are those resulting from 10,20,30,40 and 50mm of applied reinforcement. For the 10GPa transverse moduli CFRP overwind the results are as expected, that is the compressive stress in the liner is seen to increase with increasing reinforcement, from -160MPa for 10mm of reinforcement to -520MPa for 50mm of reinforcement. Furthermore, the loss in tensile stress in the applied layers is seen to decrease almost uniformly as additional layers are introduced. When the 1GPa transverse moduli CFRP is considered these trends are modified owing principally to the "squashing" effects associated with the reinforcement's very low radial modulus. For the first 10mm of reinforcement both the 10GPa and 1GPa transverse moduli CFRP overwound pressure vessels are seen to exhibit similar trends. When additional layers of reinforcement are introduced two markedly different features are observed. Firstly, the intermediate layers of the 1GPa transverse moduli overwind are seen to lose more of their tensile stresses than those at the interface, and secondly, the compressive stress in the liner asymptotes to a maximum more rapidly than that of the vessel overwound with the 10GPa transverse moduli CFRP. The low radial modulus of the 1GPa transverse moduli overwind therefore acts as a "load absorber", and prevents the winding induced loads being transferred into the liner material. When the internal pressure situation is considered, the reverse situation occurs, as shown in Figures 12 and 13, where the pressure induced circumferential stresses for the 10GPa and 1GPa transverse moduli CFRP overwound vessels are plotted respectively for the same reinforcement thicknesses considered above. For the 1GPa transverse moduli CFRP, the composite material adjacent to the interface is seen to compress readily thus preventing efficient load transfer from the liner through to the external layers of composite reinforcement. Consequently the benefits of applying more and more layers of reinforcement become increasingly small and indeed it can be seen that the pressure induced stress in the liner asymptotes to a minimum after 50mm of reinforcement has been applied. For the 10GPa transverse moduli CFRP a similar situation occurs, though the trends are not so pronounced. For example, although the pressure induced stress in the liner is observed to asymptote gradually to a minimum, this situation has still not occurred after the 50mm of reinforcement illustrated in the figure has been applied.

The radial modulus is therefore an important feature in the design of overwound vessels and due regard must be given to its effects on the behaviour of the vessel. For example, if the combined asymptotic stress state in the liner is greater than that for the resulting strain to meet the Table 1 design requirements the application of further layers will have no beneficial effects. This feature governs the highly non-linear reinforcement thickness vs liner thickness curves observed in Figure 7.

3.1 Stress Calculations

Although the preceding analyses indicate that a 10GPa transverse moduli overwind is preferable to a 1GPa transverse moduli overwind, situations do exist where low transverse moduli overwinds may have to be employed. A typical example is in high temperature applications.

UNLIMITED

Since situations therefore exist where very low transverse moduli overwinds may have to be employed, this paper would be incomplete if no attempt were made to assess the stress response of such vessels. For a truly rigorous study this would require the stress analysis of a considerable range of vessel geometries, but for the purposes of this study it is considered reasonable to restrict the stress analysis to that of a typical overwound vessel, namely the minimum weight configuration for the 60GPa GFRP overwound vessel, ie a 46.0mm liner overwound with 63.8mm of GFRP (see Figs 7 and 8).

Contrary to the authors' expectations, based on the preceding discussions, the resulting stress distributions were again well behaved and indeed the trends were generally similar to those already observed in Figures 4 to 6. The only notable differences were:

- a. The combined circumferential stress through the composite, though reasonably uniform, is approximately one half of that for the 10GPa transverse moduli reinforcement.
- b. The radial stress at the composite/liner interface is approximately 30% less than that shown in Figure 5.

Both of these features are largely attributable to the increased liner and composite thicknesses. As previously, the axial stress was very small and can be neglected as a second order quantity.

4 CONCLUSIONS

A design assessment for thick-walled metallic cylindrical pressure vessels circumferentially reinforced with a tensioned high-specific-strength anisotropic composite overwind has been presented. This assessment has been confined to a study of the relationship between the thickness of composite reinforcement and the liner thickness necessary to produce an overwound vessel comparable in strength to an initial monolithic reference vessel. This assessment was repeated for five different reinforcement composites with firstly 10GPa transverse moduli and secondly 1GPa transverse moduli. Although confined to a reinforcement thickness study the resulting information was nevertheless used in a series of ancillary analyses, namely weight calculations, maximum composite strain to failure strain studies and three dimensional stress evaluations, to identify optimums and eliminate unsuitable reinforcement overwinds. These studies clearly indicated that the vessels' behavioural characteristics are heavily dependent on the magnitude of the transverse moduli of the composite overwind. This is clearly illustrated in the following observations derived from the pressure vessel design data under consideration.

4.1 10GPa Transverse Moduli Composite Overwind

- a. The reinforcement thickness is inversely related to the composite's circumferential modulus, and vice versa.
- b. A 180GPa CFRP was found to yield the most favourable design solution based on reinforcement thickness, weight and

UNLIMITED

maximum composite strain to failure strain calculations. This is attributable to the composite's comparatively high modulus and good strain to failure properties.

c. For a 180GPa CFRP, liner thicknesses as thin as 5mm can be achieved. It is unlikely though that such a liner could support any significantly additional axial loads. In practice the liner thickness will lie somewhere between 20-30mm, offering weight savings of approximately 70 per cent of the original monolithic vessel.

d. Stress calculations for a 30mm liner overwound with a 180GPa CFRP indicate that the stress distributions are well behaved with no steep stress gradients being observed. Furthermore, for the combined loading condition, ie overwinding and pressurisation, the circumferential stress was observed to be fairly uniform through the composite, indicating efficient load transfer. Axial stresses were sufficiently small to be neglected.

4.2 1GPa Transverse Moduli Composite Overwind

a. The relationship between the reinforcement thickness and liner dimensions is very non-linear. Furthermore, but with the exception of the 40GPa GFRP, there exists, for a particular composite overwind, a minimum liner thickness below which a vessel cannot be fabricated to meet its in-service loads.

b. Vessel weight vs liner thickness curves are observed to pass through minima before increasing rapidly as the liner dimensions are further reduced. The values of these minima are, for engineering purposes, equal, indicating that the maximum attainable vessel weight savings are independent of reinforcement properties and liner dimensions. The liner dimensions corresponding to these minima are, however, complex functions of the reinforcement properties and decrease with decreasing composite circumferential modulus, and vice versa.

c. The most suitable reinforcement material was a 60GPa GFRP because of its high failure strain properties.

d. A low radial modulus acts as a serious "load absorber" preventing efficient load transfer from the tensioned composite to the liner during winding and from the liner through the composite during pressurisation.

e. Weight savings are not as great as those attainable from the 10GPa transverse moduli overwinds.

5. ACKNOWLEDGEMENTS

The authors would like to thank Messrs Parratt, Cook and Hinton and Miss Howard for their invaluable discussions and comments and for providing the material property data used throughout this report.

UNLIMITED

6 REFERENCES

- 1 Nicholas R W Pressure Vessel Engineering Technology. The Design of Vessels for High Pressure, 1971, Chapter 8, pp 402-473, Applied Science Publishers Limited, London.
- 2 Jones R M Mechanics of Composite Materials, 1975, McGraw-Hill Book Company.
- 3 Hinton M Unpublished MOD Report
- 4 Margetson J Analytical Stress Equations for Thick-Walled
Groves A Pressure Vessels Circumferentially Reinforced
 with an Anisotropic Composite Overwind.
 Unpublished MOD Report.
- 5 Stanley P Failure Probability Analysis of an Elastic
Margetson J Orthotropic Brittle Cylinder. Int. Journ. of
 Fracture, 1977, 13, pp 787-806.

Reports quoted are not necessarily available to members of the public or to commercial organisations.

UNLIMITED

TABLE 1 Reference Vessel Design Data and Material Properties

Dimensions

External Radius 300mm
Bore radius 200mm

Internal Pressure

Internal pressure 300MPa

Fatigue Limiting Strain

Maximum permitted bore strain $4.35 \times 10^{-1}\%$

Material Properties

Young's Modulus 200GPa
Yield stress 1150MPa
Poisson's ratio 0.3
Density 7.8×10^{-3} grams/mm³

TABLE 2 GFRP Material Properties

Property	Material	
	40GPa GFRP	60GPa GFRP
<u>MODULI</u>		
Circumferential (GPa)	40	60
Radial and Axial		
1GPa transverse moduli (GPa)	1	1
10GPa transverse moduli (GPa)	10	10
<u>POISSON RATIOS</u>		
Circumferential/Radial		
1GPa transverse moduli	0.0075	0.005
10GPa transverse moduli	0.075	0.05
Axial/Radial	0.3	0.3
Axial/Circumferential	0.3	0.3
<u>DENSITY</u>		
(grams/mm ³)	0.002	0.002
<u>STRAIN TO FAILURE</u>		
(%)	3	4

UNLIMITED

TABLE 3 CFRP Material Properties

Property	Material		
	120GPa CFRP	180GPa CFRP	240GPa CFRP
<u>MODULI</u>			
Circumferential (GPa)	120	180	240
Radial and Axial			
1GPa transverse moduli (GPa)	1	1	1
10GPa transverse moduli (GPa)	10	10	10
<u>POISSON RATIOS</u>			
Circumferential/Radial			
1GPa transverse moduli	0.0025	0.001666	0.00125
10GPa transverse moduli	0.025	0.01666	0.0125
Axial/Radial	0.3	0.3	0.3
Axial/Circumferential	0.3	0.3	0.3
<u>DENSITY</u>			
(grams/mm ³)	0.00156	0.00156	0.00156
<u>STRAIN TO FAILURE</u>			
(%)	1.5	1.5	0.75

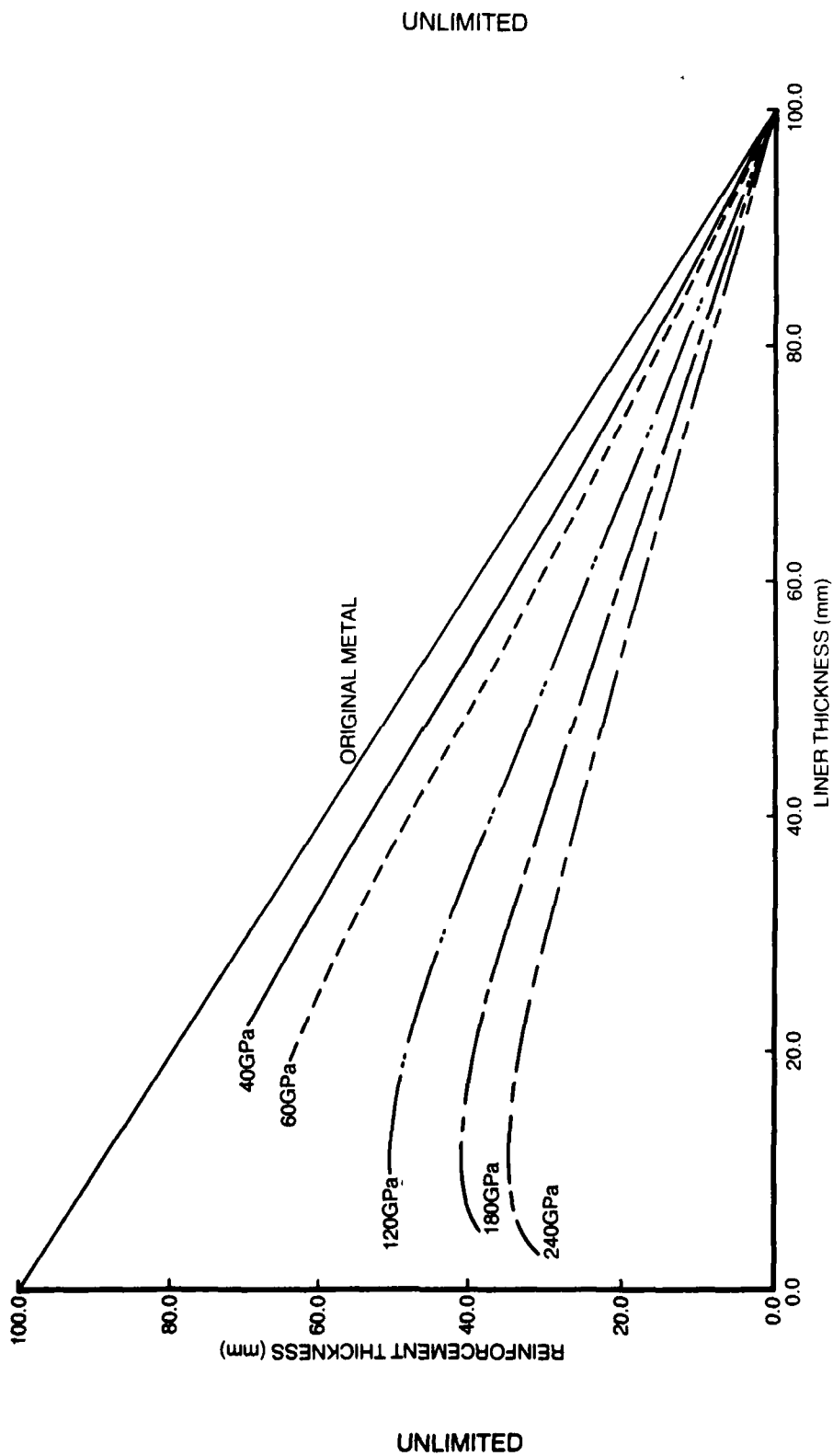


FIG. 1

FIG. 1 REINFORCEMENT THICKNESS vs LINER THICKNESS: 10GPa TRANSVERSE MODULI COMPOSITE OVERWINDS

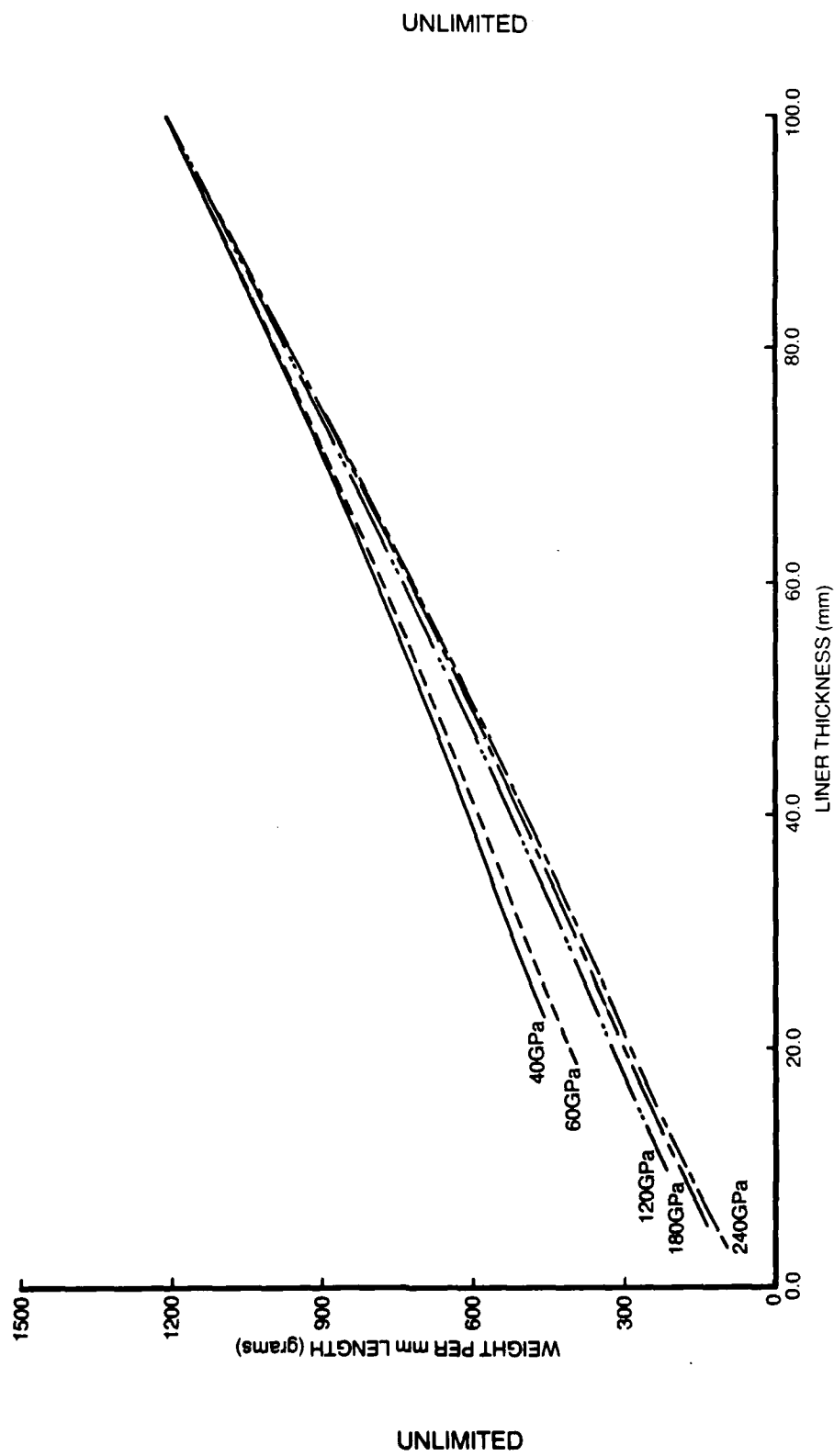


FIG. 2

FIG. 2 VESSEL WEIGHT PER mm LENGTH vs LINER THICKNESS: 10GPa
TRANSVERSE MODULI COMPOSITE OVERWINDS

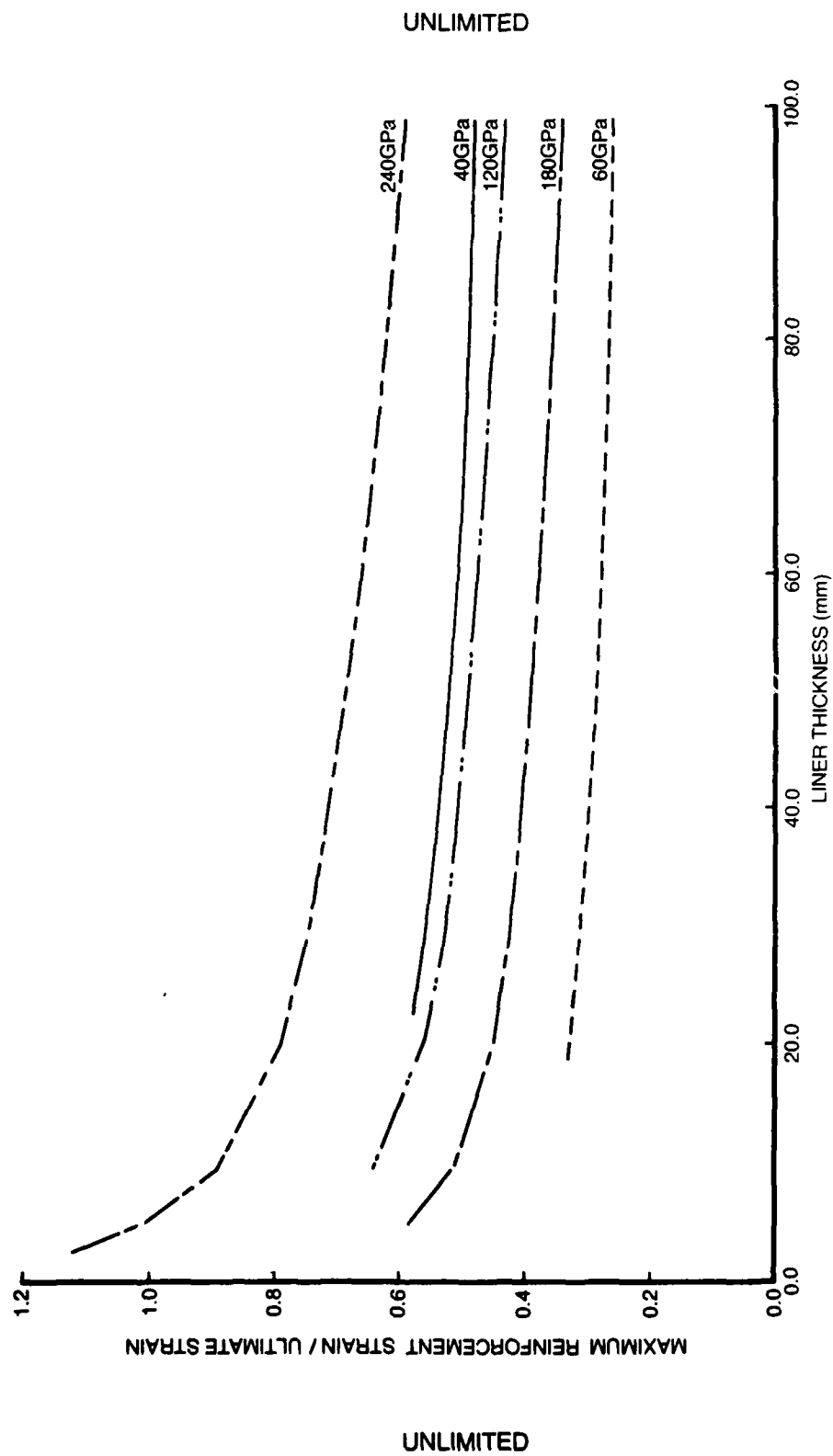


FIG. 3

FIG. 3 MAXIMUM REINFORCEMENT STRAIN / ULTIMATE STRAIN vs LINER THICKNESS: 10 GPa TRANSVERSE MODULI COMPOSITE OVERWINDS

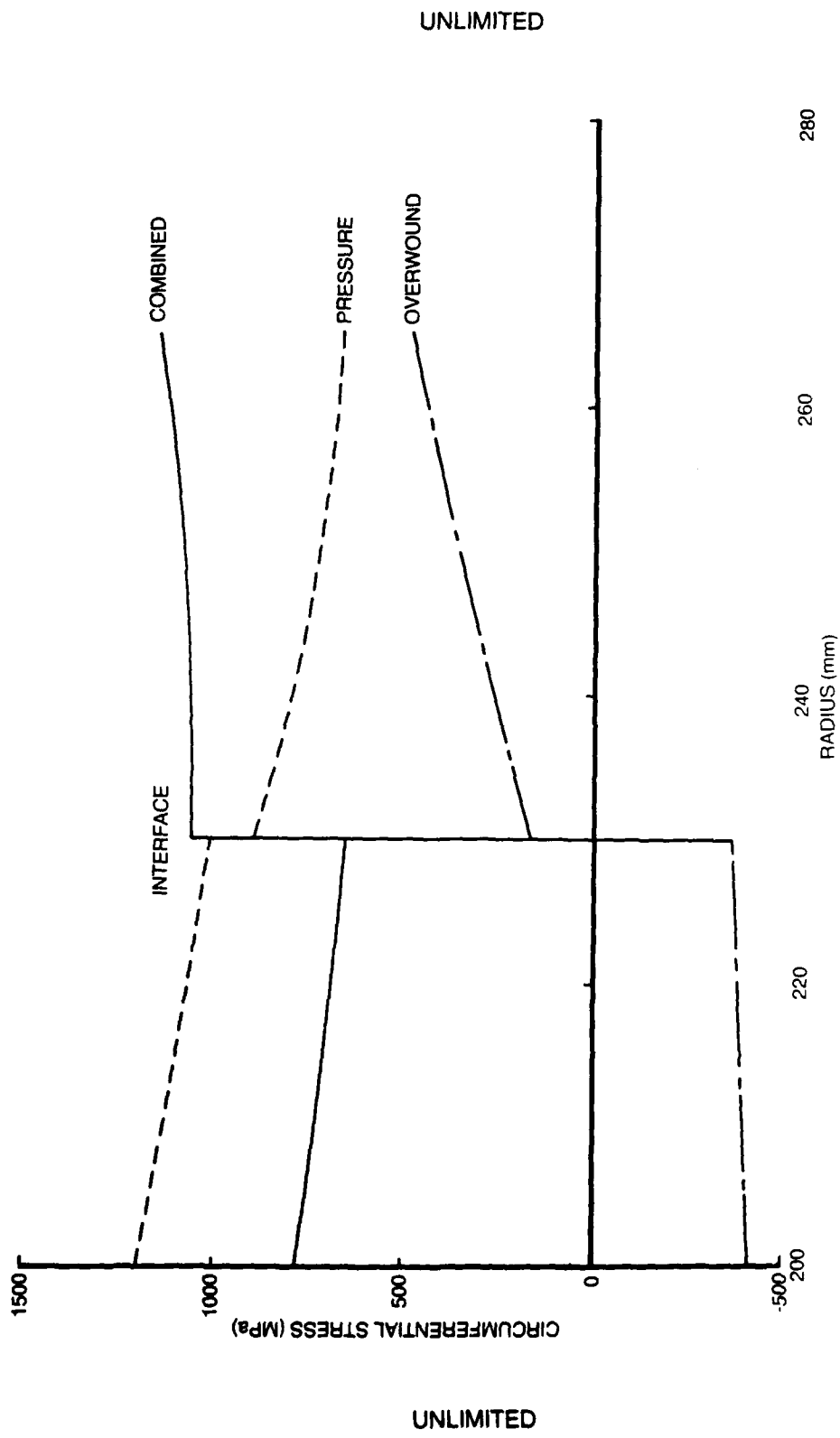


FIG. 4

FIG. 4 CIRCUMFERENTIAL STRESS vs RADIUS FOR 10GPa TRANSVERSE MODULI
180GPa CFRP OVERWIND

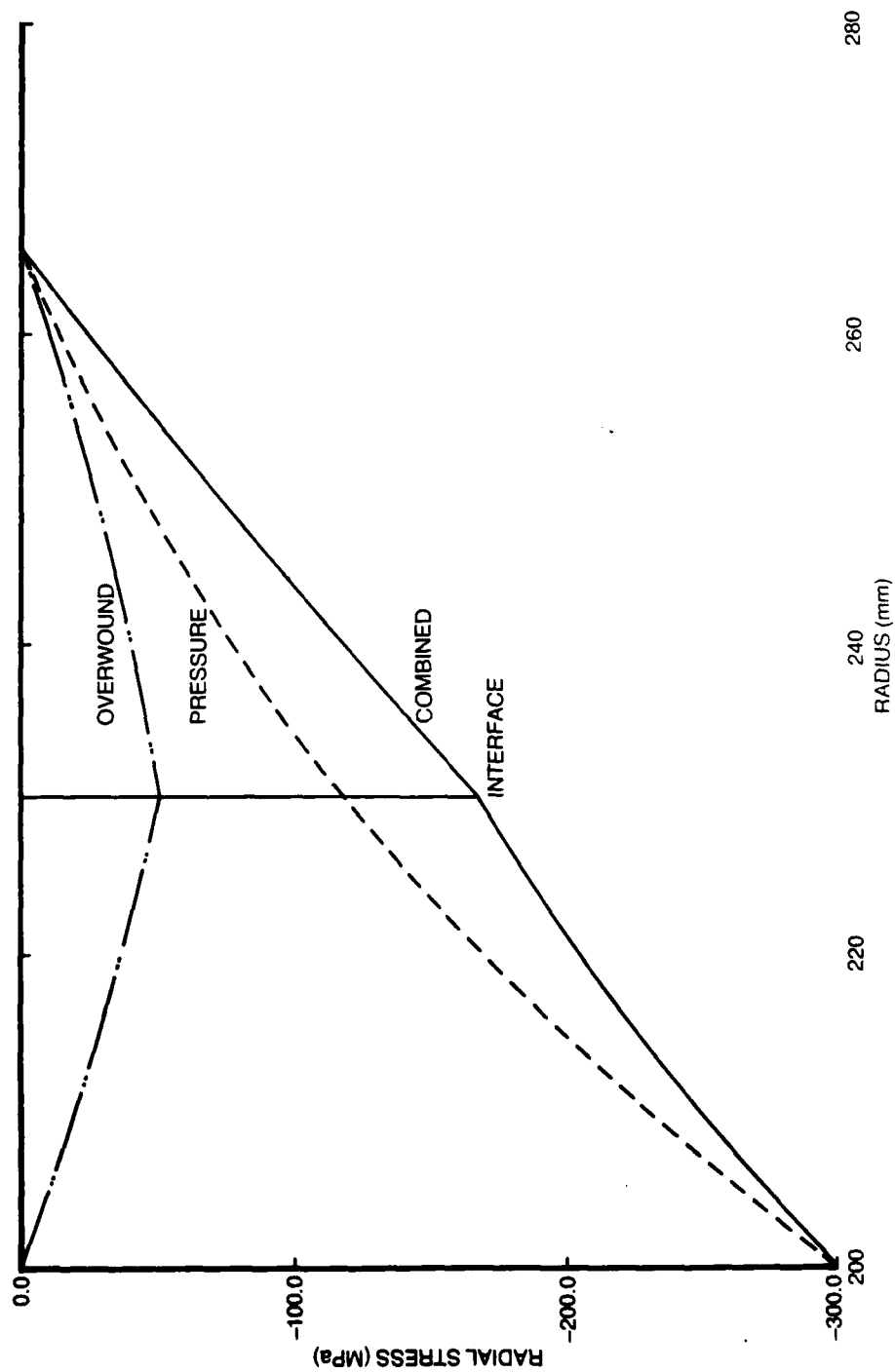


FIG. 5

FIG. 5 RADIAL STRESS vs RADIUS FOR 10GPa TRANSVERSE MODULI 180GPa CFRP OVERWIND

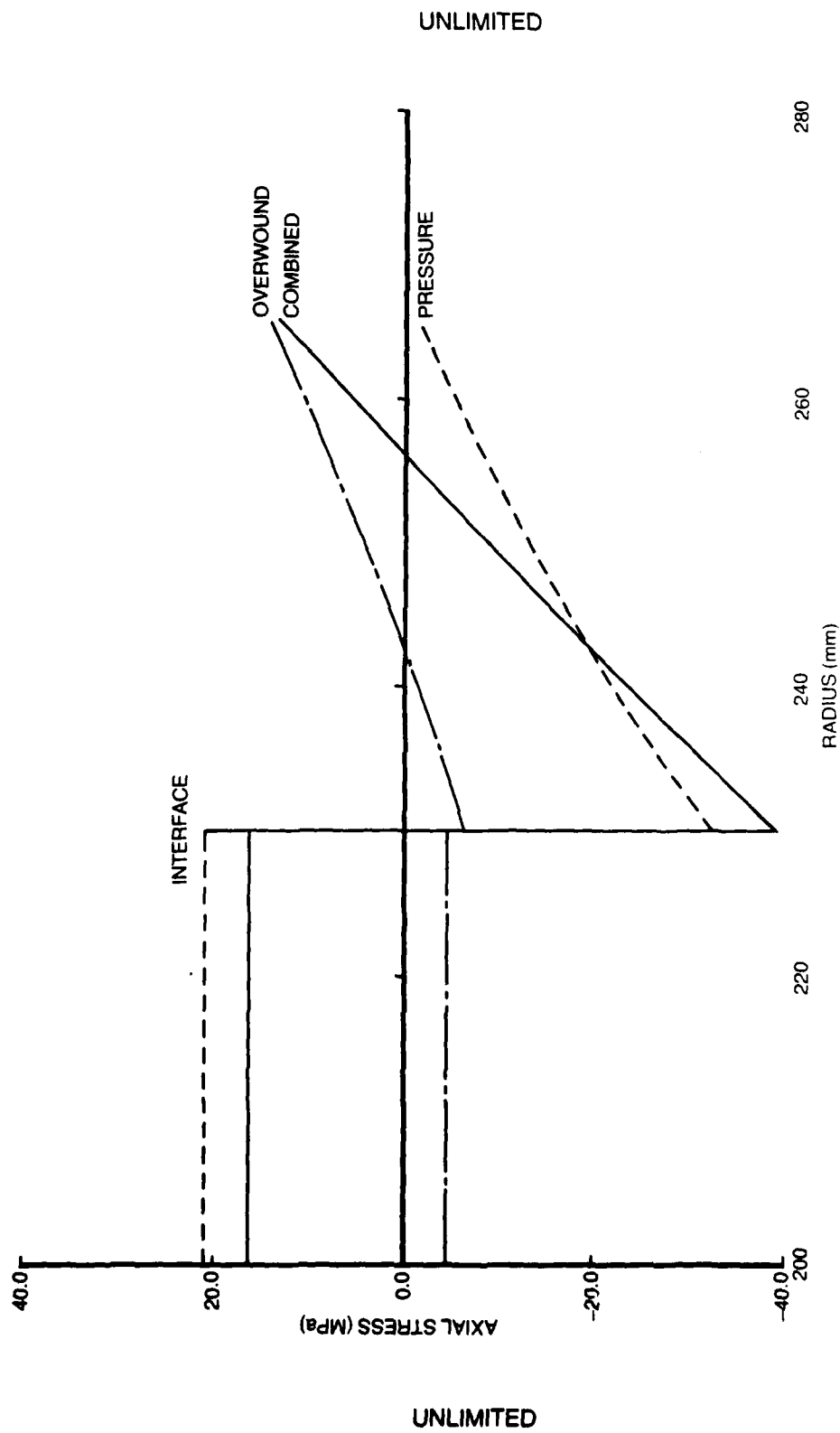


FIG. 6 AXIAL STRESS vs RADIUS FOR 10GPa TRANSVERSE MODULI 180GPa CFRP OVERWIND

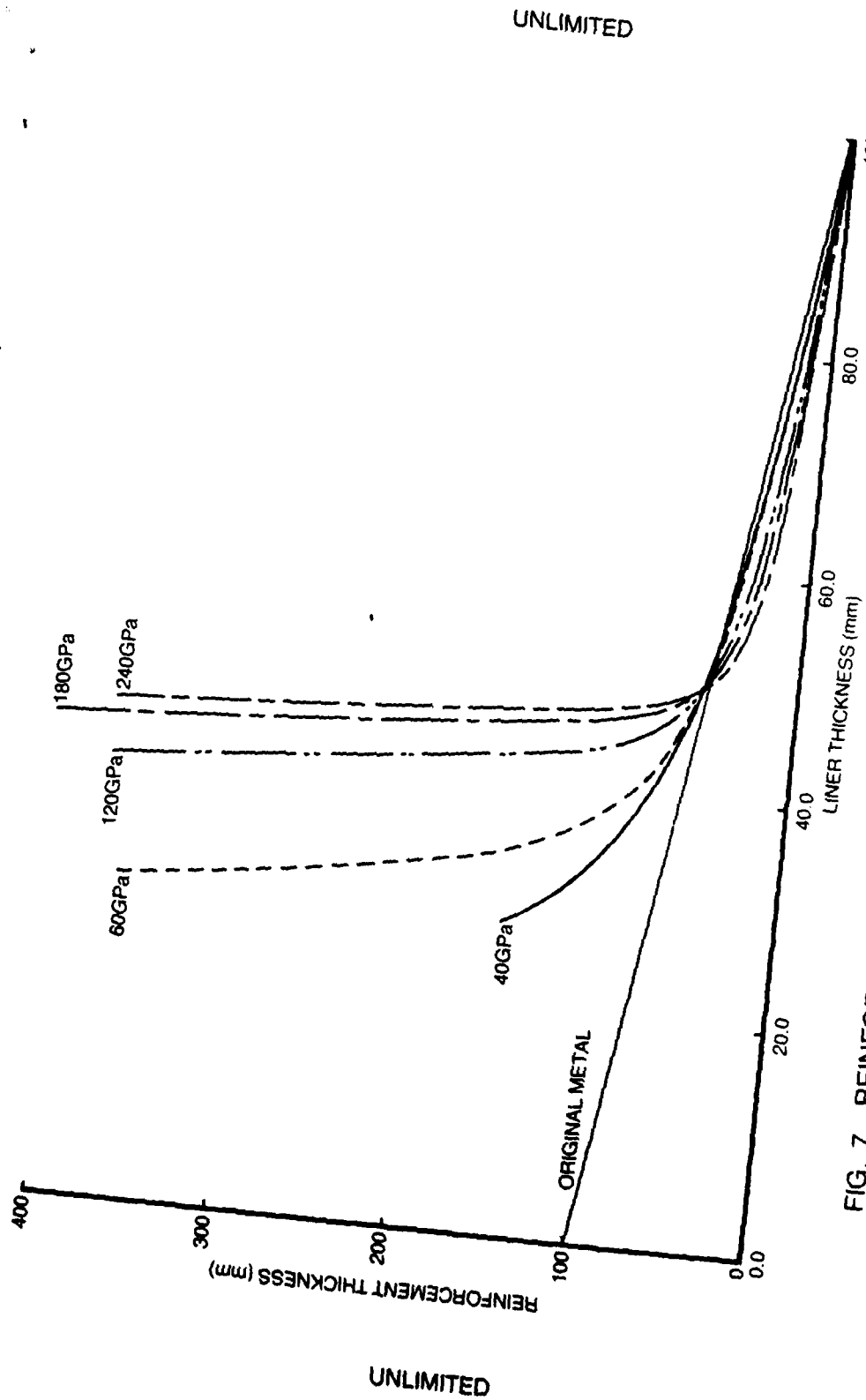


FIG. 7 REINFORCEMENT THICKNESS vs LINER THICKNESS: 1GPa TRANSVERSE MODULI COMPOSITE OVERWINDS

FIG. 7

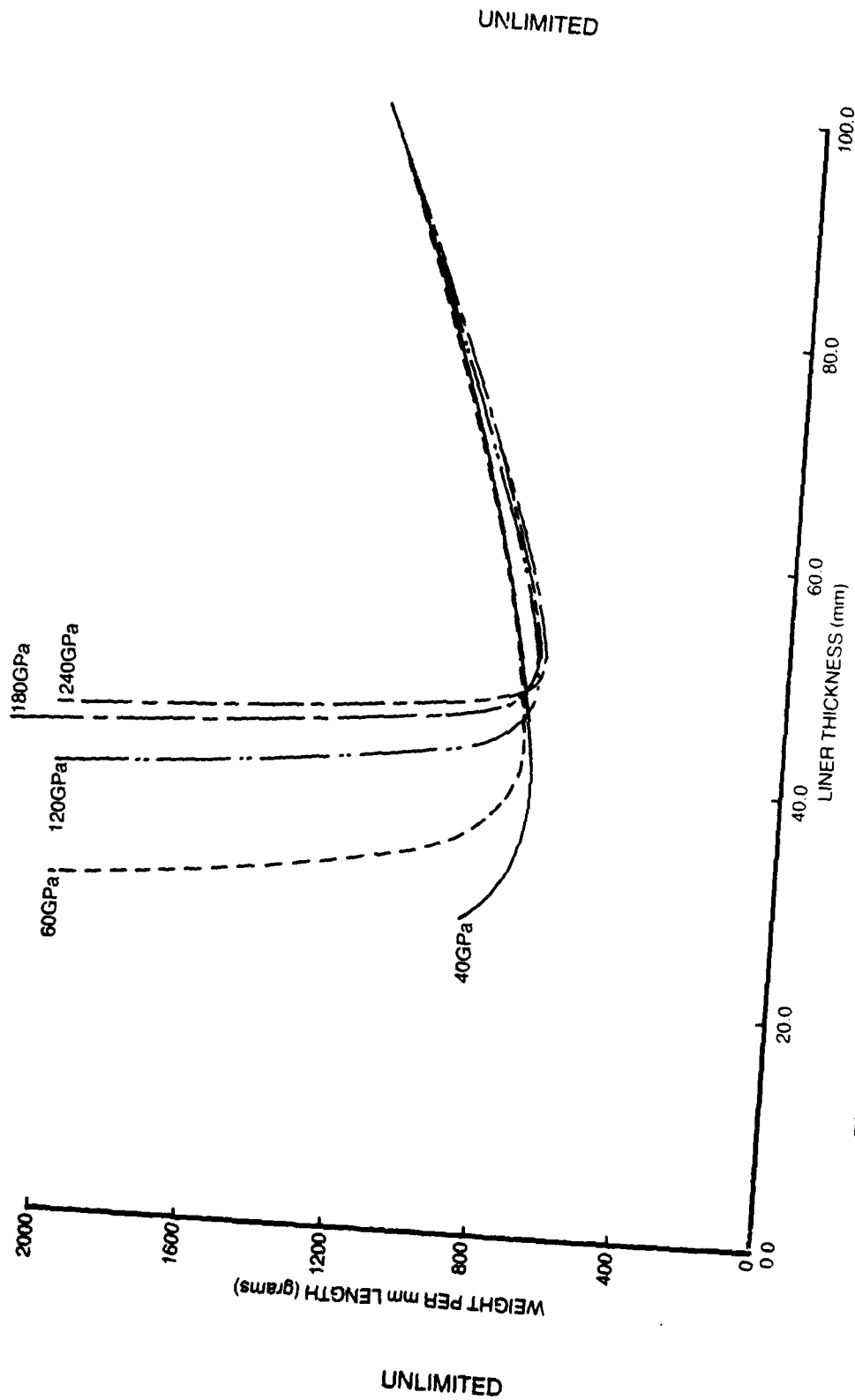


FIG. 8 VESSEL WEIGHT PER mm LENGTH vs LINER THICKNESS: 1GPa
TRANSVERSE MODULI COMPOSITE OVERWINDS

FIG. 8

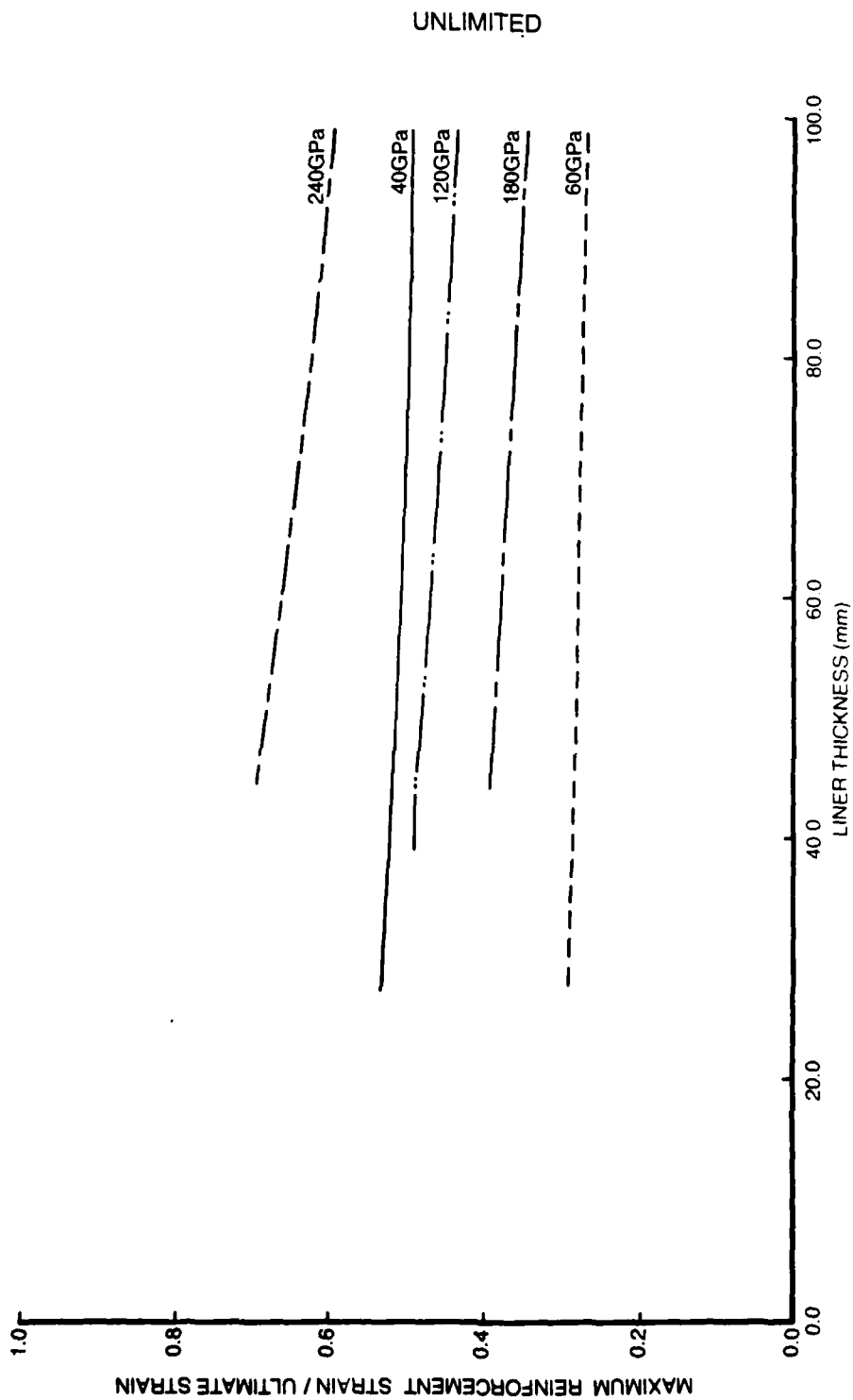


FIG. 9

FIG. 9 MAXIMUM REINFORCEMENT STRAIN/ULTIMATE STRAIN vs LINER THICKNESS: 1GPa TRANSVERSE MODULI COMPOSITE OVERWINDS

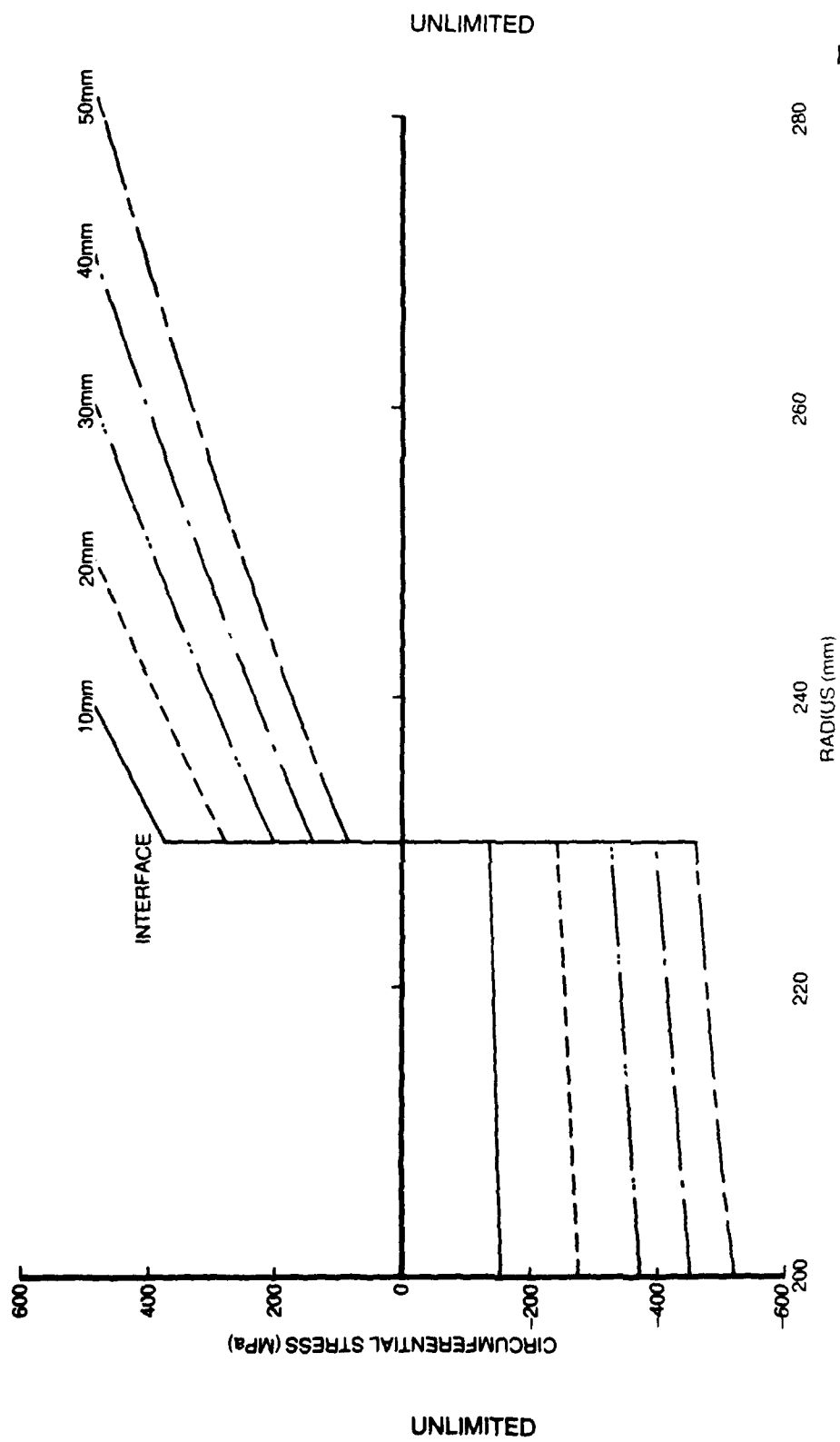


FIG. 10

FIG. 10 CIRCUMFERENTIAL PRE-STRESS vs RADIUS FOR VARIOUS REINFORCEMENT THICKNESSES: 10GPa TRANSVERSE MODULI 180GPa CFRP OVERWIND

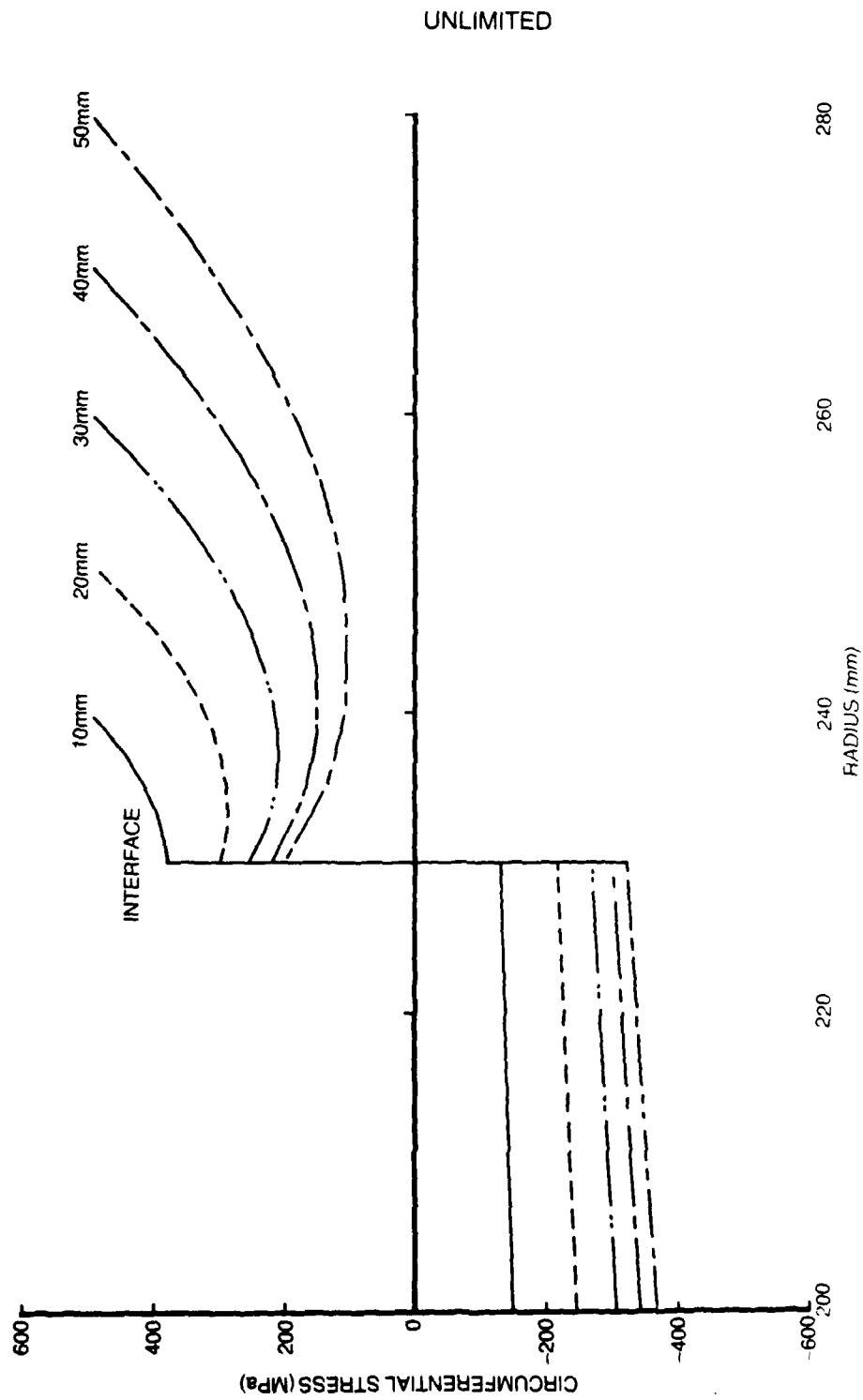


FIG. 11

FIG. 11 CIRCUMFERENTIAL PRE-STRESS vs RADIUS FOR VARIOUS REINFORCEMENT THICKNESSES: 1GPa TRANSVERSE MODULI 180GPa CFRP OVERWIND

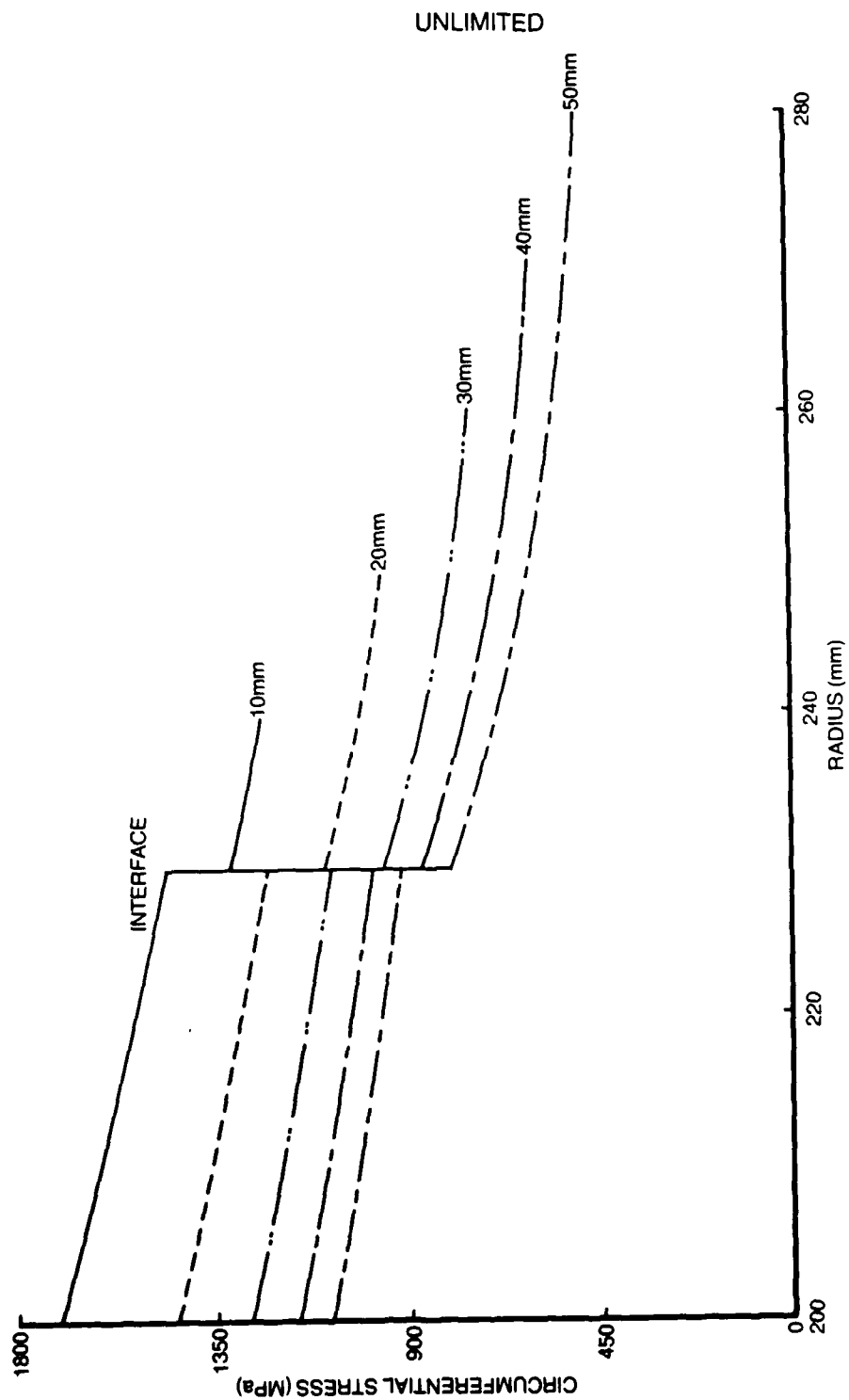


FIG. 12

FIG. 12 PRESSURE INDUCED CIRCUMFERENTIAL STRESS vs RADIUS FOR
VARIOUS REINFORCEMENT THICKNESSES: 10GPa TRANSVERSE MODULI
180GPa CFRP OVERWIND

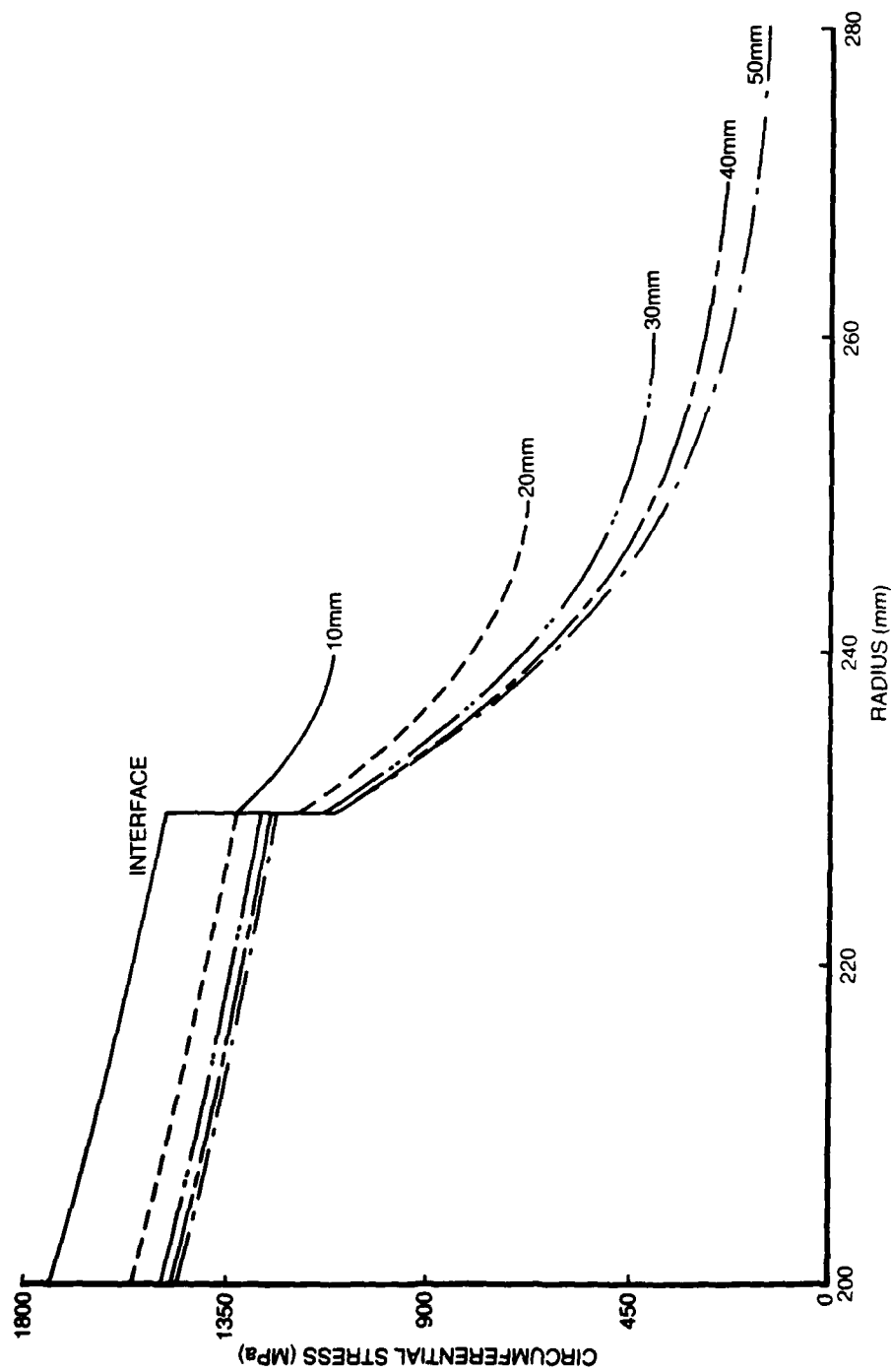


FIG. 13

FIG. 13 PRESSURE INDUCED CIRCUMFERENTIAL STRESS vs RADIUS FOR
VARIOUS REINFORCEMENT THICKNESSES: 1GPa TRANSVERSE MODULI
180GPa CFRP OVERWIND

REPORT DOCUMENTATION PAGE

(Notes on completion overleaf)

Overall security classification of sheet Unlimited

(As far as possible this sheet should contain only unclassified information. If it is necessary to enter classified information, the box concerned must be marked to indicate the classification eg (R), (C), or (S)).

1. DRIC Reference (if known)	2. Originator's Reference Report 12/88	3. Agency Reference	4. Report Security Classification Unlimited
5. Originator's Code (if known) 7699775V	6. Originator (Corporate Author) Name and Location Royal Armament Res.+Dev.Est.,Westcott,UK		
5A. Sponsoring Agency's (Code (if known))	6A. Sponsoring Agency (Contract Authority) Name and Location		
7. Title A Design Assessment for Metallic Pressure Vessels Circumferentially Reinforced with a Pre-Tensioned High-Specific-Strength Anisotropic Composite Overwind			
7A. Title in Foreign Language (in the case of translation)			
7B. Presented at (for conference papers). Title, place and date of conference			
8. Author 1, Surname, initials Groves, A	9A Author 2 Margetson, J	9B Authors 3, 4...	10. Date pp ref March 80 26 5
11. Contract number and Period		12. Project	13& 14 Other References.
15. Distribution statement Unlimited			
Descriptors (or keywords) Reinforcement - structures Pressure vessels Anisotropy Design Metals Composite materials Stress analysis			
Abstract A design assessment is presented for thick-walled metallic pressure vessels circumferentially reinforced with a pre-tensioned high-specific-strength anisotropic fibre reinforced composite overwind. The assessment is restricted to the most important study of evaluating, for five potential composite overwinds, the relationship between the reinforcement thickness and metallic liner thickness to yield a vessel of comparable strength to an all-metal reference vessel. The resulting data are nevertheless used in a series of ancillary analyses, namely weight comparisons, strain to failure studies and detailed stress computations, to establish optimum configurations and, moreover, to identify the most suitable overwinding material. The influence of variations in the considerably lower transverse moduli (radial and axial) of the circumferentially reinforcing material is also considered by repeating the assessment studies for both 10GPa and 10Pa transverse moduli composite overwinds.			