The inhomogeneities factor considered by Merkblatt covers the aspect of void content, manufacturing defects and curing inconsistencies. In BS 4994 this is accounted for by the curing factor. The particular analyses of safety factors by the procedures results in a safety factor between 6 and 10 for the Merkblatt and 8 and 20 for BS 4994. The American design procedures tend to predominantly use a factor of 10, Pearson (1966) and ASTM D3299 (1974). It must be remembered that the lower limit of the BS 4994 safety factor has increased from 6, BS 4994 (1973), to 8 in the latest revised version (1985).

Strain:

The most prominent cause of GRP failure is as a result of debonding along the fibre/matrix interface Jones (1975). An attempt to link isotropic thin shell theory to GRP design applications has resulted in the recommendation of a design strain limitation. This limitation would consider the difference in strain between the fibre and the matrix structure.

BS 4994 recognises a GRP vessel design to be either strain or load limited. In this respect it supplies a design strain limitation of 0.2% or 0.1 x resin strain, whichever is smaller, to be sufficient. This applies particularly to handlaminated or spray-up manufacturing techniques. The 0.2% strain limit has been chosen according to the findings of work performed on loaded laminates. The generalised elastic load extension behaviour of GRP shows irregularities at strains of 0.2% - 0.3% Owen (1981). Research undertaken by Owen (1982), confirms this by indicating that resin microcracking and debonding occurs in this strain range.

Filament Winding:

For filament winding a strain limitation of 0.1% is required. This is in agreement with ASTM D3299 and the Owens Corning (1966) design criteria. Isham (1967) describes a unique temperature dependent vessel design approach for filament wound vessels and considers this strain limitation suitable.

Design Data (1981), using laminate theory for GRP laminates explained in Lubin (1969) and in work performed by Krenchel (1964), are able to provide optimum winding angles for cylindrical filament wound shells under specified internal loads. The techniques mentioned are of a rigorous mathematical nature and relatively unsuitable for design applications. In studies undertaken by Eckold (1985), a design method for filament wound shells is developed. This method has been incorporated into BS 4994 (1985). It provides results which when compared to those of laminate theory produce laminates up to twice the latter method's thickness. The applicability of this theory to the vessel design should thus be carefully analysed.

Netting analysis, utilising a geometrical approach, is another optimisation method suggested by Blythe G. (1983). Although successfully used, it requires that the hoop stress be twice that of the longitudinal stress. Further shortcomings found by Shibley (1969) are that the analysis considers the fibres to be the load carriers and the resin matrix to be the fibre supports. Also the Poisson's ratio and the resin modulus of elasticity which contribute largely to the modelling of the unidirectional laminate are not included. Jones H.L. (1968) reinforces this view by indicating that netting analysis has its limitation in describing the stress levels. The netting approach will demonstrate different laminate moduli at below one third ultimate stress levels when compared to loads approaching rupture. Furthermore he states that long term fatigue, cyclic loading and shear engender unique phenomena beyond the scope of netting analysis. The filament wound laminate response to torsion or flexure cannot be effectively analysed with netting theory but rather by macromechanical theory.

Design research performed by Isham (1967) indicates a temperature dependent vessel design procedure. A linear relationship between the specific gravity of the vessel contents, strain and wall thickness is equated to the operating temperature. A shortfall of the theory is that besides using short term material data for chemical environments, the option of finding a wind angle has to be considered using alternative theory ie. netting analysis or macromechanical laminate theory.

Nozzle Attachments:

BS 4994 using specified material lap shear strengths , determines the Unit Strength of the wall laminate and the loss in laminate strength due to a cut out (pipe diameter). A compensation overlay diameter is found with a suitable laminate layup. The approach offered by Dow (1980) however, bases the laminate overlay dimensions directly to shell thickness. By using specified factors the overlay diameter, pipe overlay length and thickness are found. Merkblatt utilises the hoop stress formulae with pre-determined weakening factors to find a minimum shell thickness in the region of the pipe. This approach must be performed in both the longitudinal and transverse directions with the relevant weakening factors. Both the ASME X and the ASTM D3299 utilise the equal areas replacement method. The diameter of the overlay is set to two times the diameter of the pipe. The ASTM D3299 further stipulates the pipe compensation overlay lengths. These are proportional to the thickness of the pipe wall.

To meet the requirements of vessel design, the procedures analysed do not all offer complete analytical design steps. BS 4994 provides an attempt to fully design GRP vessels while considering all aspects of the requirements of hydrostatic, internal and external pressurised vessels. It covers seams, pipe branches and vessel wall structures for a range of vessel ends, ie. hemispherical, semiellipsoidal, torispherical and cone. The manufacturing procedures used are also those most widely used in South Africa, mainly as a result of the type of glass and resin product available, ie. glass mats, continuous roving and liquid resin. Together with this it is continually revised and the recent update offers less conservative material design Unit Strengths and Extensibilities when compared to the 1973 version. As a result of these aforementioned reasons BS 4994 has been used as the basis of the theory for the GRP vessel research project.

1.1.2 STRESS CONCENTRATIONS AROUND NOZZLE ATTACHMENTS.

Recent years have seen a considerable improvement in pressure vessel design particularly those made of steel. A large number of design computer programs are available which can be utilised for obtaining optimum dimensions and material requirements of a vessel. Together with this investigations can be performed on high stress regions such as seams and nozzle attachments using elastic and finite element analysis techniques.

Regions with discontinuities in slope, radius and thickness are cause for increased material stress. The aspect of nozzle attachments thus is of prime concern in vessels used in high pressure applications. Steel materials because of their isotropic nature, have permitted satisfactory correlations between theoretical and experimental stress analysis results, Kitching (1965). The results obtained from an elastic stress model are further reported to be reliable for use as a design method.

Limited literature is available covering stress analyses around nozzle attachments on GRP pressure vessels. For this reason it was necessary to cover literature which pertained specifically to vessels of steel construction, with references to GRP literature where applicable in the various instances.

The concept of stress compensation entails the strengthening of the region around the nozzle area by means of increasing the local wall thickness. This is achieved either by welding a pad over the specified local area, increasing the overall vessel wall thickness or by increasing the nozzle wall thickness. Megyesy (1981), indicated that an inherently reinforced opening is one which is attached to a shell of twice the required wall thickness. This results in the halving of the expected stresses in the region of the opening. An increase in wall thickness near an opening also results in a decrease in the local strain due to bending, with a resultant drop in stress as by indicated Fukunaga (1983) and Kitching (1965). Further to this, the compensation material may be placed outside the shell, inside the shell or on both sides of the shell near the location of the opening. From studies by Bickell (1967), it was shown that the compensation material should preferably be on both sides of the shell. This structure would reduce the bending stress in the vessel wall as the nozzle/shell junction is without eccentricity. His findings also indicate that the stress concentration factor may be reduced by 27% when material is placed on the inside of the shell. It may thus be concluded that the pressure stress on the inside of the shell is higher than on the outside of the shell in the nozzle region.

Various techniques have been developed for determining suitable stress compensation material requirements for nozzle attachments. These have been extended for use in design procedures and are discussed further in the following section.

Equal Areas Replacement Method.

The principle of this method is to provide material equal in cross sectional area to that removed from the nozzle cut-out hole in the shell wall. The equivalent amount of compensation material removed is placed in an effective area located around the opening in the vessel shell. The excess material provides restoration of the general yield strength of the vessel material which is affected by the bending stresses induced in the region due to the nozzle attachment when the system is under load, BS PD 6437 (1969). A shortcoming of the method is that it does not provide information on the distribution of the material around the opening ie. its effective length on the shell as measured from the nozzle axis. Further to this there is no means for determining the length of material required on the nozzle attachment for inhibiting pullout loads. The method also does not provide optimal solutions for all nozzle/shell configurations, BS PD 6437. This fact led Harvey (1963), to the belief that a hard spot could be created in the vessel due to the compensation. This would inhibit the natural growth of the vessel under pressure which would result in a change of the general strain pattern. When comparing ratios of the hole cross sectional area to that of the total overlay area, for ratios of 65% to 115% it is found that there is negligible improvement of the maximum stress around the opening.

The technique is predominantly used in American procedures for pressure vessel design. The ASTM D3299 (1974), and the ASME X (1973), have incorporated this technique for GRP nozzle compensation design. The ASME X extends the process by stipulating that the effective length of the compensation on the shell is equal to the diameter of the nozzle as measured from the nozzle axis. This agrees with that specified in ASTM D3299 which also states that the bond area length on the pipe attachment is dependent on the pipe attachment wall thickness and is chosen from Table 5 of the Standard.

Experimental Yield or Bursting Method.

This technique involves the burst and yield pressure for various nozzle/shell configurations. The German AD Merkblatt B9 (1979) pressure vessel specification provides factors found after a series of tests performed on cylindrical pressure vessels having openings and shells of various dimensions. These weakening factors are determined by dividing the maximum stress of an unpierced shell by that required to produce a 0.2% strain at the nozzle/shell junction. The factor is then incorporated in the basic shell formula.

The German method whilst being sound for applications under fatigue loading, Ruiz (1967), ignores the fact that bursting may arise at the nozzle interface when under static load. This consideration is recognised by the equal area replacement method.

The German design procedure for GRP vessels AD Merkblatt (1969), has also adopted this method for determining the stress compensation overlay requirements. It is listed in tabulated form in the standard.

A fundamental problem in using yield criteria for composite materials is that this mode of failure is relatively non existent. It is commonly found that whereas isotropic materials obey the Tresca and Von Mises failure criteria, composites closely obey the Tsai Hill failure mode as stated by Jones (1975). In other words, the longitudinal and transverse stresses together with the inplane shear stress of the material are related and failure criteria obtained for the specific materials used in the laminate. This technique is used in the design of filament wound rocket motor casings, Fukunaga (1983). He found that material strains were linear up until the discontinuity (nozzle compensation), where bending moments were induced. It is added that two techniques may be used for designing axisymetrical shells of revolution with a single opening , these being the failure criteria and the performance factor methods. The latter is combined with Davidson-Fletcher-Powell's optimisation techniques for determining the reinforcing material requirements in the region.

Elastic Stress Analysis Method:

The method is based on the mathematical modelling of the nozzle reinforcement area of the vessel. Using isotropic theory and matrix techniques it is possible to determine approximate stresses in the nozzle region.

Ruiz (1967), using elastic methods determined the stress concentration factors, (SCF) for nozzles on a sphere. He found that the factors ranged from 2.25 to 2.5. Studies performed by Harvey (1963), on flat plates with holes in a biaxial state of stress produced a SCF of 2.0. This drop in the SCF indicates that the curvature of the shell together with the induced bending moments increased the nominal stress in the nozzle region. Photoelastic stress analysis work performed by Stone (1967), on multiple nozzle configurations on a cylinder provide SCF ranging from 1.5 to 2.5 depending on the distance between the nozzles.

The elastic method for determining stress concentration factors is predominantly used in British design procedures. The BS5500 (1985), provides graphical results of a factor C which relates the branch and overlay compensated thickness to that of the relationship between the shell and pipe diameter. This enables the effective determination of the compensation thickness required.

A simplification of the elastic method is adopted in BS 4994 (1973,1985). The overlay strength requirements are based on the unit strength of the material removed by the hole from the shell. Although the method provides equations for determining the diameter of the overlay, it stipulates that the reinforced region is to have a thickness not less than 1.5 times the shell thickness. This as described previously will ensure a reduction of the stress in the attachment region. The method however, does consider the pull-out load on the nozzle by stipulating a minimum branch compensation overlay of 75mm. The findings of Bickell suggest it better to compensate inside the shell as higher pressure stresses are found here. This is also recommended in BS4994(1985), by the minimum requirement of 600g/m^2 chopped strand mat placed inside the nozzle wall for all high pressure cases.

In the majority of GRP vessel design procedures, methods of opening compensation are stipulated which are predominantly used in steel vessel design. It is the object of this research to analyse the stress concentrations found around a single nozzle on a GRP hemispherical dome. The results obtained will then be compared to theoretical predictions found using isotropic thin shell theory. An attempt will be made to validate the suitability of isotropic theory for determining stress compensation requirements of nozzle attachments in GRP vessel design.

1.2 PURPOSE AND AIMS

The research proposes to analyse the stress distribution found around an axisymetrically placed nozzle on an internally pressurised GRP hemispherical dome.

Data obtained from experimentation is to be compared with the theoretical results obtained from a first principles isotropic model and a personal computer driven finite element method model.

It is hoped that the following aims can also be achieved within the scope of the project:

- A hemisphere with an axisymmetrically placed nozzle is to be designed according to the requirements of BS 4994 (1985).

- The hemisphere is to be constructed by a local GRP manufacturer in order to assess the effectiveness of the design code in the commercial environment.

- A post experimental testing laminate analysis is ~~to~~ be undertaken to determine whether the hemisphere was constructed as specified.

- The aspect of laminate asymmetry will be considered in the structure of the vessel wall and overlays, and possible recommendations given.

- The strains on the inside and outside of the wall laminate are to be found at various pressure readings.

- The strains are to be utilised with lamination theory for determining the force, moment, strain, curvature and stress distribution on the nozzle overlay.

- The shortcomings of present design theories are to be examined and their validity questioned.

In terms of the objectives of the project it was necessary to develop a suitable testing rig and test procedure. The steps involved in the preparation of the experiment are described in the next section.

2.0 PREPARATION AND TEST PROCEDURE

Scope: This section covers the preparation of the experiment and encompasses the following aspects:

- Design of the hemisphere/nozzle testing rig
- Determination of the mechanical properties of the materials used
- Preparation of the test rig and equipment
- The test procedure used
- Processing of data
- Brief description of the computer models

2.1 DESIGN OF THE HEMISPHERE/NOZZLE TESTING RIG

The hemisphere was designed according to the requirements of BS4994 (1985).

The resin system used was Derakane 470-36 vinyl ester resin and 450 g/m^2 Chopped Strand Mat (CSM) and Woven Roving (WR) glass reinforcement. It was designed to withstand a hydraulic pressure of 2 bars up to an operating temperature of 60 deg. Celsius. A design factor of safety of 12 was used and the chemical barrier was included in the strength calculations.

Appendix A provides the mathematical background of the design of the hemisphere wall and nozzle overlay region. It must be remembered that BS4994 does not use laminate properties, as determined from test laminates of the resin/fibre system, in the design calculations of the vessel. Instead a tabulation of material design Unit Strength values are specified for furane and non-furane based resins. In this particular design the Unit Strength used for CSM was 200 N/mm and for WR 250 N/mm per kg/m² of glass. In Fig. 1 a diagrammatic representation of the hemisphere is given with salient dimensions shown.

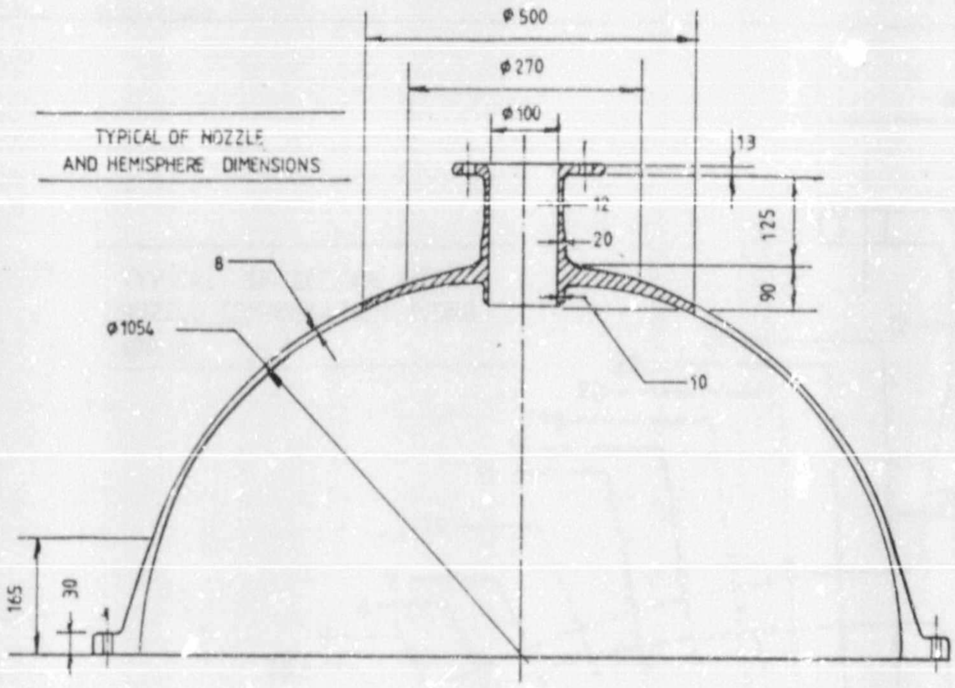

Figure 1. Nominal dimensions of the test rig.

The dim·nsions of the overlay can be better seen in Fig. 2 in which dimensions are given of the laminate along its length. In Table 3 a comprehensive description is provided of the material content , the thickness and the woving roving lay angle for each station laminate element on the hemisphere.

Note

It should be noted that although the wall dimensions closely resemble those calculated using BS 4994, the vessel was not manufactured as specified per drawing in terms of the laminate structure. This was discovered after testing was complete and burnoffs were taken of sections of the vessel wall to determine glass contents and laminate structure. It was found that a 1 x 450 Woven Roving layer was used instead of the 2 layers specified. This material shortfall was also found in the overlay region.

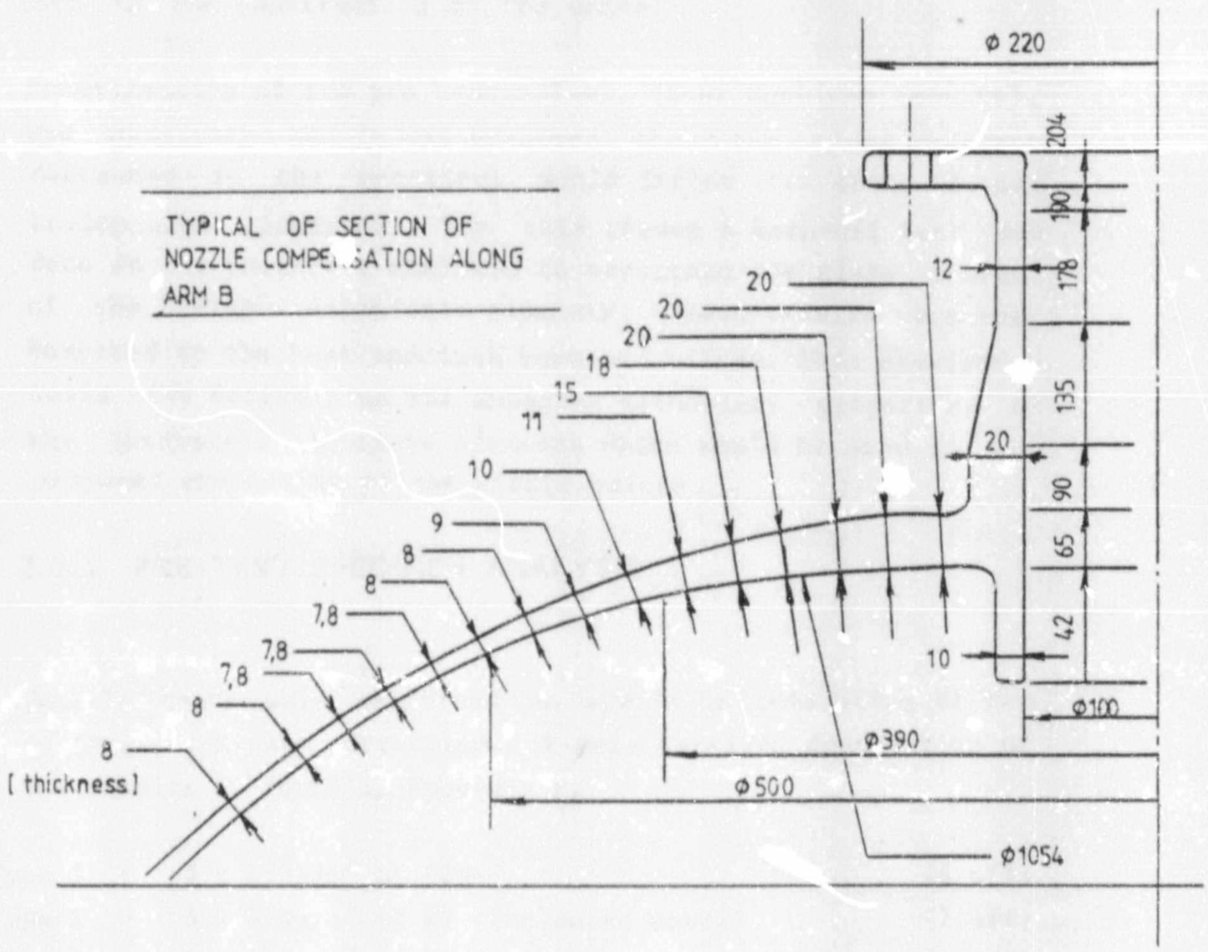

Figure 2. Dimensions of elements of the nozzle region.

Although the manufactured product differed to that specified, it has in no way influenced the data processing as a result of the post laminate analysis described in the following section.

2.2 DETERMINATION OF THE MECHANICAL PROPERTIES OF THE MATERIALS USED

The pre and post test analyses serve for the determination of the mechanical properties of the resin/glass laminate system used in the construction of the vessel

Normalisation of the pre test values, (test specimen results), was necessary as it was expected that the glass content contained in the specimens would differ to that of the hemispheres' laminate. For this reason a burn-off test was done in the post-test analysis to ascertain the glass content of the hemisphere laminate elements. These results were then compared to the test specimen burn-off values. This provided a basis for determining the expected mechanical properties of the hemisphere laminate elements which would be used in the computer processing of the strain values.

2.2.1 PRE-TEST SPECIMEN ANALYSIS

Tensile tests were performed on specimens consisting of the following laminate structures. A more detailed description of the results is found in Appendix B.

Type 1	-	5 x 450g/m² of CSM	(6 off)
Type 2	-	5 x 450g/m² of WR (balanced weave)	(7 off)
Type 3	-	5 x 450g/m² of WR at 45° (balanced weave)	(4 off)

Ei(MPa) - Initial Modulus of Elasticity.
σf(MPa) - Ultimate Failure Stress.

The resin system used was Derakane 470-36 vinyl ester resin.

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Table 1. Material properties of the Resin/Glass Reinforcement System

Type	Mechanical Properties		Poisson's Ratio	% Glass content (by weight)
	Ei(MPa)	σf(MPa)	v	
Type 1	11776	127,9	0,339	38,95
Type 2	21507	246,3	0,0947	57,41
Type 3	10383	221,6	-	58,94

2.2.2 POST-TEST HEMISPHERE WALL ANALYSIS

It was expected that the hemisphere wall laminate would probably not have the same glass content as that of the test specimens. To validate this and to determine a meaningful glass to resin ratio for the hemisphere the following test was performed.

Burnoffs were taken, described in Appendix B, of 14 sites on the nozzle overlay and wall laminate. This indicated the average % glass fraction by weight to be 32% which meant that the results of Table 1 had to be normalised. Due to the wall structure consisting predominantly of CSM the following percentage glass to resin ratios were used in the normalisation process.