
Explanatory supplement to BS 5500 : 1988 'Specification for unfired fusion welded pressure vessels', section three 'Design'

Part 2. Openings and branch connections

Supplément explicatif à la norme BS 5500 — Récipients sous pression
non soumis à la flamme soudés par fusion : Section 3 : Conception
Partie 2. Ouvertures et renforcements

Erläuterungen zu BS 5500 : Schmelzgeschweißte Druckbehälter
Abschnitt 3 : Auslegung
Teil 2. Öffnungen und Ausschnittsverstärkung

Foreword

This Part of PD 6550 has been prepared under the direction of the Pressure Vessel Standards Policy Committee.

This explanatory supplement to section three 'Design' of BS 5500 'Specification for unfired fusion welded pressure vessels', has been written to assist both the newcomer to pressure vessel design and the experienced vessel designer. It describes the background to BS5500 and its theoretical basis in design. Answers are given to many of the questions that are asked about the detailed and complex rules/requirements concerning the design of pressure vessels to BS 5500.

PD 6550 is published in separate Parts.

Each Part of the supplement is current with the 1988 edition of BS 5500, the nomenclature of which has been followed throughout. It is assumed that the reader is reasonably familiar with the terms used in BS 5500.

The committee wishes to acknowledge the fundamental contribution of Mr R A McFarlane of British Petroleum International Limited, as the primary author of the text of this Part of the supplement.

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1 Introduction

The method in BS 5500 sub-clause 3.5.4 for the design of branch compensation is the result of a search for a design method based on analysis rather than on empirical rules. It has shown itself to be both economic in its use of material and safe.

Branch compensation is one of the more complex stress problems in pressure vessel design. When the branch is in a spherical shell, the configuration is axisymmetric and mathematical solutions for the stresses based on centre line shell analysis exist. When the branch is in a cylindrical shell, such solutions are not readily available and in BS 5500 the design rules are formulated using either carefully selected approximations or the results of experimental work.

The design method, in addition to determining the maximum stresses, should also include an assessment of the service performance of the most highly stressed region at the nozzle penetration. In BS 5500, this is achieved in one operation. The key information is provided in figures 3.5.4. (1) to (4). These figures, although containing a large amount of data, are easy to use. Terms such as stress concentration factor, design stress or shakedown factor do not appear. They are included but in a non-explicit form.

This Part of PD 6550 describes the method, its limitations and in particular the origins of the four figures.

NOTE. The titles of BSI publications referred to in this Part of PD 6550 are listed on the inside back cover.

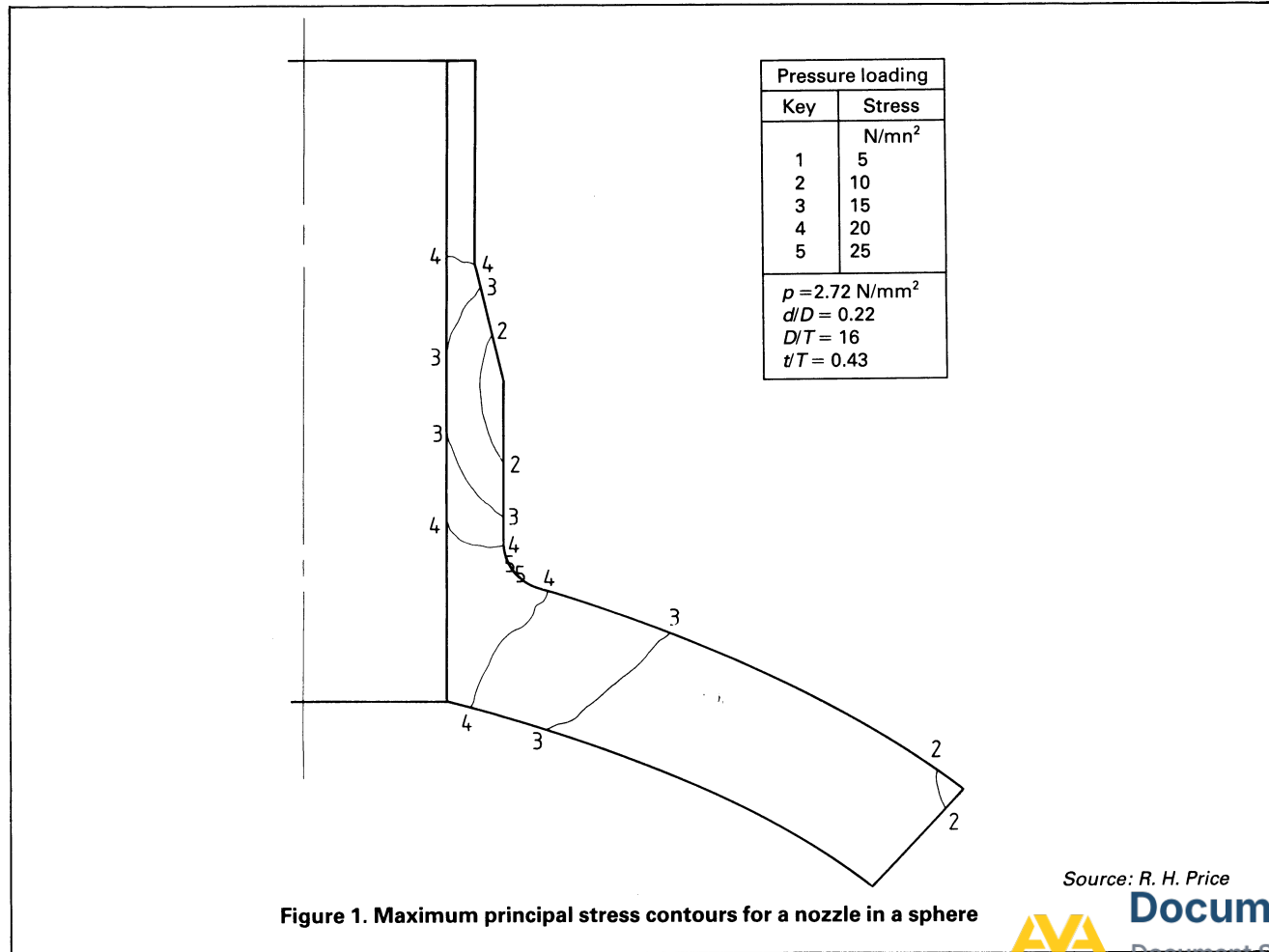
References to publications (other than BSI publications) are identified in the text by numbers in square brackets and are listed in clause 12.

2 Branch compensation design

2.1 Stress distribution at nozzles

A branch in a pressure shell disturbs the stress pattern in the shell and creates a local increase in stress, a stress concentration.

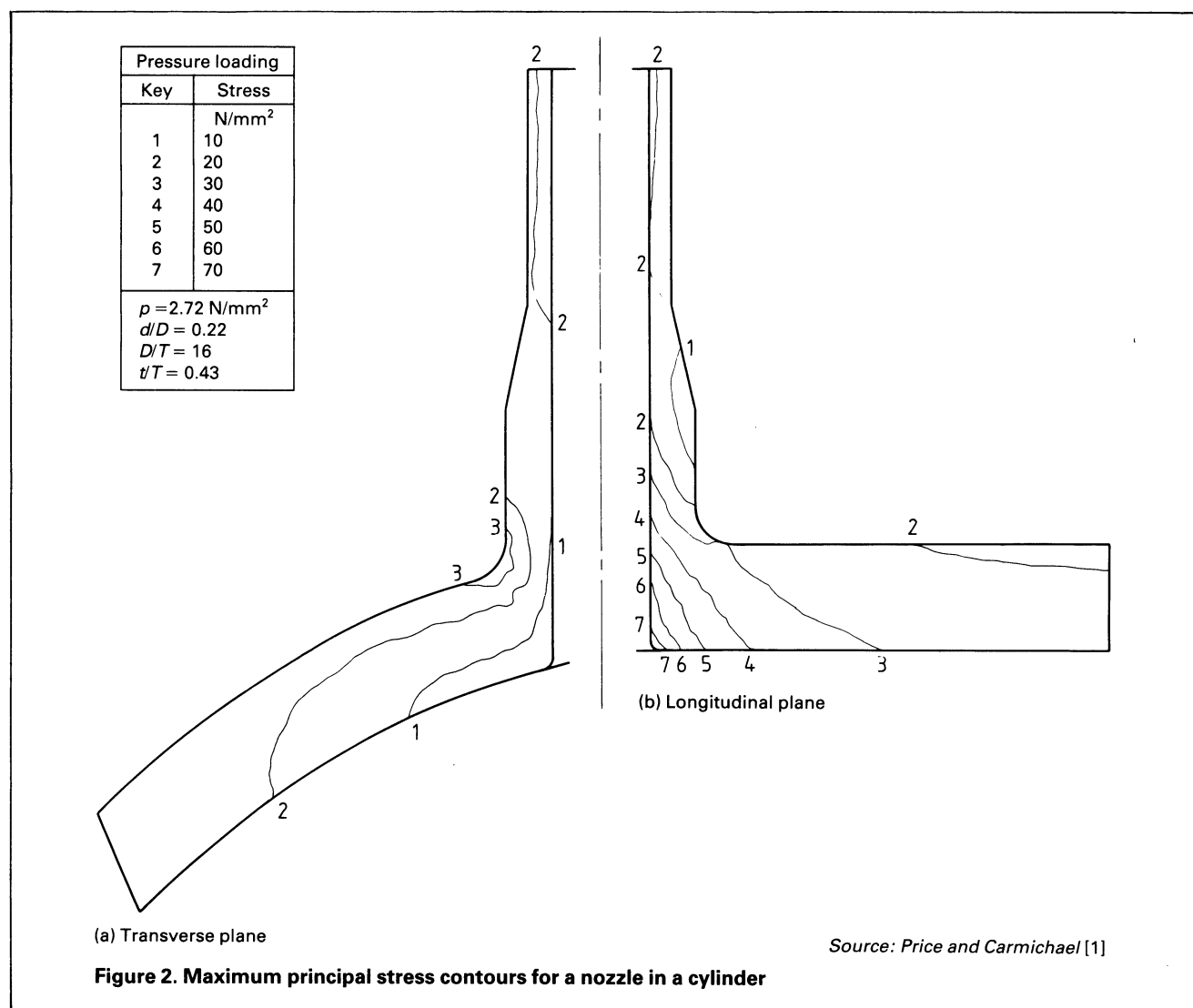
A typical stress distribution at a nozzle in a sphere is shown in figure 1. The stresses are calculated from elastic finite element analysis and are due to internal pressure only. If the surface stresses were checked with strain gauges, very similar results would be obtained. The maximum stress lies on the outside surface of the nozzle. With nozzles in spheres, the maximum stress is usually found either on the outside surface at the radius between the nozzle and the shell, or on the inside surface near the nozzle crotch corner.

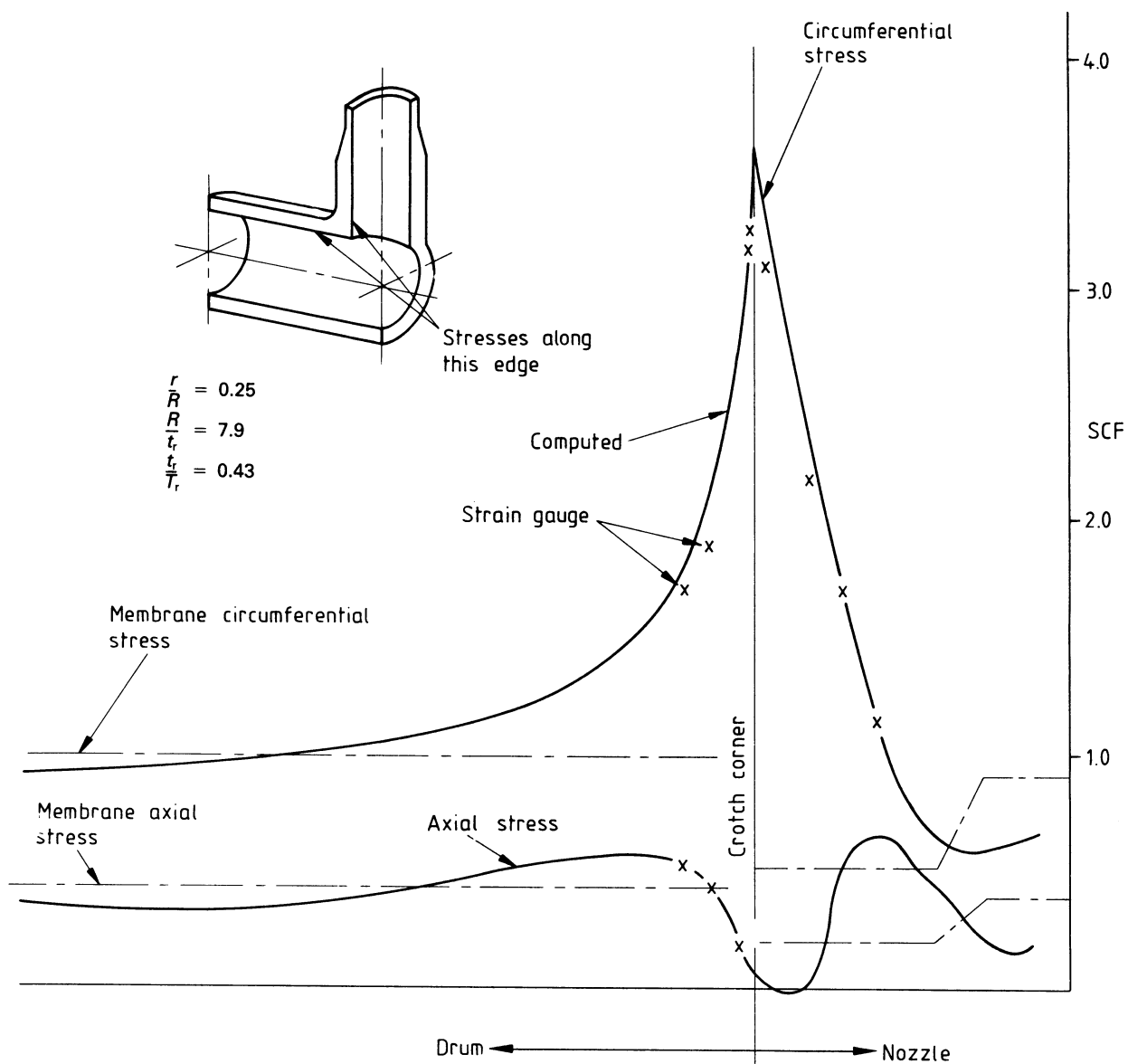


Source: R. H. Price

The stress patterns at a branch in a cylinder are shown in figure 2. They are shown in both the transverse plane and in the longitudinal plane. The stresses in the longitudinal plane are clearly much greater than those in the transverse plane. The peak stress is at the inside corner of the branch in the longitudinal plane, which is usual for nozzles in cylinders.

The stress distribution in the longitudinal plane along the inside surface of a nozzle and cylinder is plotted in figure 3. The peak of the circumferential stress at the crotch corner is clearly evident.





Source: Price and Carmichael [1]

Figure 3. Stress distribution in the longitudinal plane along the inside surface of a cylinder and nozzle

2.2 The main components of the method in 3.5.4 of BS 5500

To develop a method for branch design based on analysis rather than empirical rules, two objectives have to be met.

The first is that a method has to be found for calculating the maximum stress at the nozzle. The results from this are often expressed in terms of a stress concentration factor (SCF) where the peak stress is divided by the membrane stress local to the nozzle.

In 1963, this objective was achieved by Leckie and Penny [2]. They published a method for calculating the stresses in flush and protruding nozzles in spheres and gave SCFs for a wide range of geometries. Subsequent experiments suggested that their solutions gave important information also applicable to the more complex cases of:

- (a) protruding nozzles in cylinders and cones;
- (b) flush nozzles in cones;
- (c) flush nozzles in cylinders (where $d/D < 0.3$).

The second objective is the provision of an analytical approach which ensures adequate service life from the most highly stressed region in the nozzle to shell junction. This was achieved in two ways:

- (1) In the case of flush nozzles in spheres, figure 3.5.4 (2), a limit on the maximum elastically calculated stress of $2.25f$ was specified. This had been used in an earlier standard (for nuclear reactor design) BS 3915.

- (2) For protruding nozzles and nozzles in cylinders, figures 3.5.4 (1), (2) and (4), the shakedown concept was applied. This ensures that after a few initial pressure cycles shakedown is achieved and that only elastic action then takes place. The lower bound estimate of the shakedown factor, derived by Macfarlane and Findlay [3], was used. To ensure that the design pressure did not exceed the shakedown pressure, an additional design margin of 1.1 was included.

By these means, BS 5500 ensures that alternating plasticity (which could lead to high strain-low cycle fatigue) and incremental collapse are avoided. If creep is significant, additional precautions (described in 8.2 of this Part of PD 6550) are taken. Where high cycle fatigue or buckling could be relevant failure criteria, the method in 3.5.4 of BS 5500 specifies that checks, that are provided elsewhere in BS 5500, are applied.

A novel feature of BS 5500 was that a factor was included to provide extra compensation where there are piping forces and moments in addition to pressure to be considered. This is factor C . It is put equal to 1.1 when design is for pressure loading only. When the loadings from the pipework are to be taken into account, C is put equal to a value less than 1.1, usually 1.0. Extra compensation is then provided to strengthen the shell and nozzle.

For convenience and reference, the main components of the method in 3.5.4 are listed in table 1.

Table 1. The main components in BS 5500, figures 3.5.4 (1) to (4)

Figure no.	3.5.4(1)	3.5.4(2)	3.5.4(3)	3.5.4(4)
Branch type	Protruding	Flush	Flush	Flush
Shell type and limit on d/D	Sphere $d/D < 0.5$ Cylinder and cone $d/D < 1/3$	Sphere $d/D < 0.5$ Cone $d/D < 1/3$	Cylinder $0 < d/D < 0.3$	Cylinder $0.2 < d/D \leq 1.0$
Stress concentration factors	BS 3915	BS 3915	Lewis and Price	Money
Shakedown factor	Macfarlane and Findlay	Not applied	Macfarlane and Findlay	Macfarlane and Findlay
Limit on elastic stress range	Not applied	$2.25f$	Not applied	Not applied
Additional design margin	1.1	None	1.1	1.1
Factor C	Included	Included	Included	Included

The alternative to the analytical method of 3.5.4 is an empirical method based on providing reinforcement with a cross-sectional area equal to or greater than the cross-sectional area of the metal removed by the hole. The method is known as area replacement and has been in use for many years. It has been retained in BS 5500 as appendix F.

The area replacement method is not based on a quantitative assessment of maximum stress and the maximum stress found in one design can vary significantly from that found in another. The method provides no consistent margin with respect to shakedown, distortion or fatigue.

It was dissatisfaction with the area replacement method which led in the early 1960s to the start of the method now in 3.5.4 of BS 5500. A programme of research on nozzles was carried out by the British Welding Research Association (now the Welding Institute). Results from this together with analysis were presented in 1961 at the I. Mech. E. Symposium on Pressure Vessel Research towards Better Design [4].

Following the symposium, a design method for flush and protruding nozzles in spheres and cylinders based on the analysis of Rose and Thompson [5] was presented by Rose to the responsible BSI Committee. It was also published [6]. It proposed an allowable SCF of 2.5 and used a nomogram in the method. Consideration of the need to permit closer pitching of unreinforced openings led to the decision to reduce the allowable SCF to 2.25. In 1963, Leckie and Penny's analysis [2] was published. This was applicable to larger values of d/D than Rose and Thompson's and also had the advantage that the results were presented solely in terms of

$$\frac{d \sqrt{D}}{D \cdot 2T_r} (= \rho)$$

which permitted graphical presentation rather than a nomogram.

Thus, the method entered BS 3915. It was subsequently used in BS 1515 which was the predecessor to BS 5500, and then in BS 5500 itself. Its development for BS 5500 is described in detail elsewhere in this Part of PD 6550.

2.3 The calculation stages

There are essentially three stages in the design calculation in 3.5.4 of BS 5500. A sketch showing the notation as it applies to spheres is given in figure 4.

The designer will have established from earlier calculations the required thickness T for the shell plate. A value for T_r , the total thickness of the shell as defined in 3.5.4 of BS 5500, is now selected. An estimated value for t_r , the total thickness of the branch is chosen. Using these, mean diameters D and d can be calculated. A value must be assigned to factor C dependent on whether there are pipe loadings to be taken into account. This is the first stage in the calculation.

The second stage is to calculate CT_r/T and, where appropriate, ρ . The relevant figure, of figures 3.5.4 (1) to (4), is entered and from the abscissa is read either t_r/T_r or Y . The required value of t_r is calculated from this. If the required value is greater than the estimated value, re-calculation has to be made with a higher initial estimate. If the required t_r is less than the estimate, the latter is acceptable. For maximum economy, the iteration should be continued until the required value is equal to, or just less than, the estimated value.

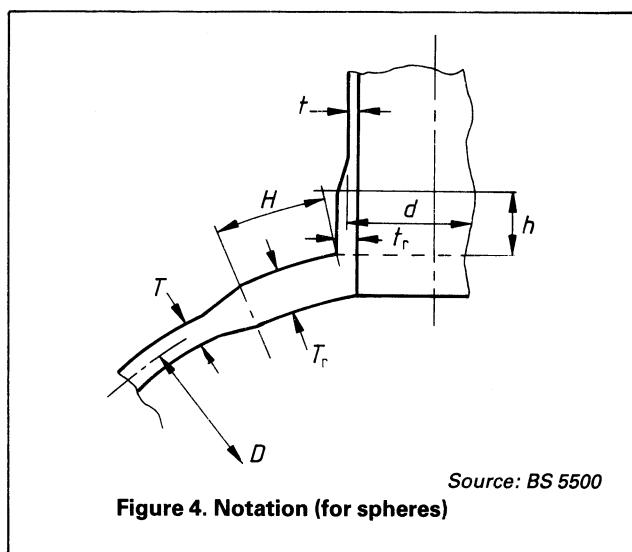


Figure 4. Notation (for spheres)

The third stage is to ensure that sufficient lengths and thicknesses of reinforcement are available in both the nozzle or shell. Limits of reinforcement are specified in 3.5.4.3.4 of BS 5500. If the compensation has to be re-distributed to accommodate the branch geometry this must be done in accordance with figures 3.5.4(21) and (22).

It is desirable for the purposes of minimising stress concentration to have what is known as balanced reinforcement, although this may not be the cheapest design of compensation. BS 5500 does not direct that balanced reinforcement should be provided and it is a matter for the designer. Balanced reinforcement is where there is extra material in both the branch and the shell. In cylindrical vessels it is disposed according to the following approximate relation:

$$\frac{t_r}{d} \approx \frac{T_r}{D}$$

3. Flush branches in spheres and cones

3.1 Derivation of BS 5500, figure 3.5.4(2)

The stress concentration factors for flush branches in spheres were obtained from the work of Leckie and Penny [2]. For the solution of the elastic stress analysis of the branch to sphere junction, Leckie and Penny developed small displacement, thin shell equations for the nozzle and sphere. Complete solutions to the differential equations were then obtained by adding to the membrane solution the effects of the edge forces and moments. The latter are necessary to give compatibility of the displacements of the cylinder and sphere at the intersection. It was assumed in the analysis that the two shells are joined where their centre lines meet and that plane sections remain plane when loaded.

The general analytical solutions of the differential equations are complex involving n th order Bessel and Kelvin functions. The particular cases of uniform pressure loading, axial load, lateral shear and bending moment were considered. Leckie and Penny presented their results in a simple graphical form in which SCF is plotted against ρ and t_r/T_r . Their graphs are given in figures G.2(29) to G.2(36) of BS 5500. The one for uniform pressure loading, figure G.2(29), is reproduced here as figure 5(a).