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DEPARTMENT OF CIVIL ENGINEERING

Stress Evaluation of a Monolithic Refractory Concrete Rotary Calciner Lining for Tioxide Southern Africa

Presented to the Board of Studies in the School of Engineering in partial fulfillment of the requirements for the Masters Diploma in Technology (Civil Eng.) (Structural)

by
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DEDICATION

This work is dedicated to my loving wife Brenda, for all her encouragement and support.

CONTENTS

APPENDICES

LIST OF FIGURES

LIST OF TABLES

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CHAPTER ONE

THE PROBLEM AND ITS SETTING

1.1 INTRODUCTION

Tioxide Southern Africa is a producer of Titanium Dioxide pigments, and is situated at Umbogintwini on the Natal South coast. Part of the process of making the pigment is "calcination". This involves allowing the pigment to move under gravity through a 40m long rotating vessel called a calciner (sometimes referred to as rotary kiln), which allows the pigment slurry to dry out and crystallise. There are two calciners at Tioxide Southern Africa, and their plant reference numbers are 02/322 numbers 1 and 2.

The calciner is fired from the discharge end with gas, which leads to temperatures of around 1000°C at the discharge end, and around 400°C at the feed end. A drawing showing the layout of a calciner appears in figure 1.1.

The calciner consists of a steel outer shell, lined internally with a refractory material that protects the steel shell from heat, abrasion and chemical attack. At Tioxide Southern Africa (TSA), the calciners were originally internally lined using refractory bricks, but in 1982, sections of the lining were replaced using a monolithic concrete, as repairs using bricks were becoming expensive and time consuming. Since 1982, monolithic refractory concretes have steadily replaced brickwork in the calciners, and the materials and casting techniques used in placing the monolithic concretes have also developed.

In August 1989, refractory lining repairs were carried out to number 1 calciner. A new monolithic refractory material was used, a low cement high strength castable called "Hikast Super", and it was cast using the rotorcast technique, whereby the concrete is continually cast circumferentially whilst rotating the calciner. In August 1990, the calciner was inspected, and the lining was severely damaged in the first 14m from where the pigment enters the calciner (feed end). A photograph of the damaged lining appears in figure 1.2.

Failure of the lining in 12 months was unacceptable, as the rotary calciner is the largest and one of the most important items of equipment in the company and is vital in the manufacturing process, and cannot be by-passed. It is therefore required to be on-line for as long a time as possible. The contract cost to do a complete concrete re-line is in the order of three-quarters of a million rand, which would double if any shell damage were discovered. The loss in sales due to 1 calciner being off-line is approximately R300 000 per day.

If this matter were left unattended, the costs to the company would spiral as the cost of material and labour, as well as the effects of lost production continuously worsen.

This study therefore sought to investigate the structural stability of the lining in an attempt to isolate possible factors causing failure and thus resulting in the need to replace the lining at such short intervals.

Should it be found that the failures were as a result of thermo- structural loading, this study would be able to provide TSA with a facility to input different material properties and hence to evaluate the changes prior to physically carrying out the changes and waiting for the results.

The benefits of a solution are vast, increased kiln up-time will have a positive financial effect that is obvious. It will also enable the company to carry out planned shutdowns when the company requires them, and not when lining failures dictate. This will ensure that shutdowns are executed under planned conditions, and not rushed into, and that other plant maintenance can then be incorporated into the plan.

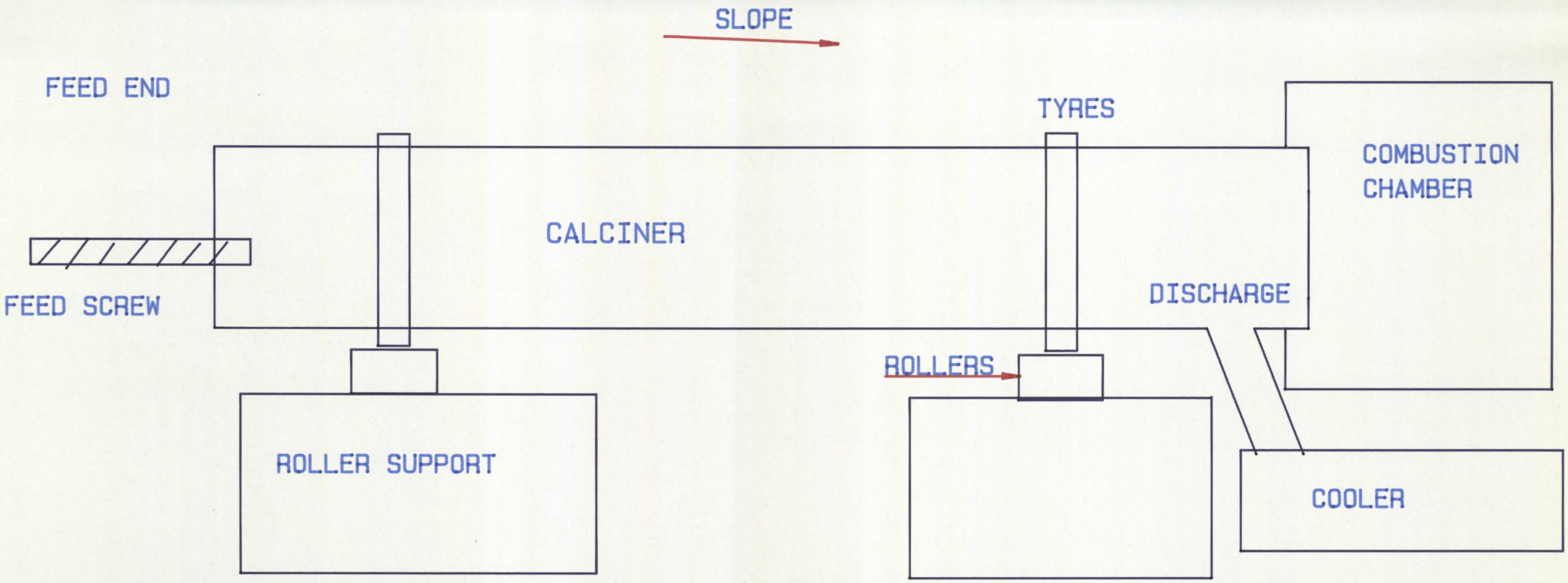

FIGURE 1.1: CALCINER ARRANGEMENT

Figure 1.2: Damaged Feed End Concrete - No. 1 Calciner

1.2 THE STATEMENT OF THE PROBLEM

The purpose of this study is to investigate the stress levels present in the monolithic refractory concrete linings of the rotary calciners at S.A.Tioxide in terms of thermo-structural properties, for the purpose of developing a PC based design program suitable for evaluating the structural integrity of the linings.

1.3 THE SUBPROBLEMS

1.3.1 Subproblem 1

The first sub-problem is to evaluate the stress levels in the refractory concrete lining using Finite Element Analysis based on material engineering properties evaluated to BS 1902 (1987), in order to establish whether the currently used lining material can withstand stresses imposed on it due to the most severe operating conditions.

1.3.2 Subproblem 2

The second sub-problem is to evaluate the trends in the stress and strain levels of the refractory concrete linings, in terms of variable thermo-structural parameters, in order to observe the influence of the variables on the structural integrity of the calciner linings.

1.3.3 Subproblem 3

The third subproblem is to establish a PC based program for the evaluation of the refractory concrete lining stresses, in terms of variable thermo-structural parameters, in order to establish a practical site-useable design tool.

1.4 HYPOTHESES

1.4.1 Hypothesis 1

It is hypothesised that under the most severe operating conditions, the lining stress levels will be low enough to not adversely influence the structural integrity of the lining.

1.4.2 Hypothesis 2

It is hypothesised that a combination of changes in the variables will increase the lining stress levels to a point that will adversely affect the structural integrity of the lining.

1.4.3 Hypothesis 3

It is hypothesised that linear assumptions made for writing the PC based program will provide a more conservative stress evaluation than the Finite Element Analysis.

1.5 DELIMITATIONS

1.5.1 This study will be limited to 1 of the two rotary Calciners (plant flow sheet number 322/1) at Tioxide S.A., Umbogintwini, Natal, and will not include investigations into Calciners in other Tioxide or similar plants.

1.5.2 In 1982 Tioxide S.A. embarked on a program to replace the brick Calciner linings with concrete. This study will be limited to examining the behavior of monolithic concrete calciner linings and will exclude calciners with masonry linings.

1.5.3 This study will be limited to investigating the stress and strain values in the linings in terms of thermo-structural properties, and will negate the possible effects of plant maloperation.

1.5.4 Fowler (1982) states that the internally generated thermal loads on refractories are the main factors for consideration, this study will be limited to investigating the internally generated thermal stresses, and will not investigate the effects of calciner rotation.

1.5.5 This study shall ignore the effects of stress relaxation and creep.

1.6 ASSUMPTIONS

1.6.1 The engineering properties of the lining obtained in the C.S.I.R laboratory analyses as displayed in C.S.I.R. Report number 450/57403, shall be assumed as being a true representation of the engineering properties of the lining *in service*.

1.6.2 For the finite element analysis, the relationship between known material data points shall be assumed to be linear.

1.6.3 Due to the complex nature of monolithic castable refractory concretes, the following assumptions are made with respect to the engineering data for non Finite Element analysis:

a) Steady state thermal conditions exist, and transient heating and cooling can be neglected.
b) Shrinkage varies linearly with temperature, and the shrinkage gradient therefore is linear.
c) The reversible thermal expansion coefficient is linear over the temperature range considered.
d) The elastic modulus is uniform through the lining. cross section.

e) Stress-strain relationships are purely elastic.

1.6.4 For the purpose of this study, the calciner operating temperatures shall be accepted as being the values recorded on the calciner control instrumentation panel. The hot end temperature shall be taken as the reading "combustion chamber temperature", and the cooler end temperature shall be taken as the reading " feed end temperature".

1.6.5 As no thermo couples are present in the calciners at Tioxide S.A., it is assumed that the heat profile through the calciner follows the curve displayed in figure 3.2, as provided by Tioxide Italy for a similar calciner in their plant.

1.7 THE DEFINITIONS OF TERMS

1.7.1 "Calciner" shall mean the rotary vessel used for calcining pigment at Tioxide S.A., these vessels are also referred to as Rotary Kilns in other industries, however, for the purpose of this study, the term "calciner" shall mean exclusively number 1 calciner, flow sheet number 1/322/1 at Tioxide S.A., Umbogintwini.

1.7.2 "Thermo-Structural" shall mean the structural effect on the linings caused by temperature, and shall exclude any effects of calciner rotation.

1.7.3 "Engineering properties" shall mean the material properties required to carry out an engineering stress analysis, these properties will be evaluated in a laboratory, and may not necessarily be the values provided in the material suppliers data sheets.

1.7.4 "Worst Case operating conditions" as stated in subproblem 1 shall be operational parameters chosen from historical or research data, and taken as the operating parameters most likely to cause the highest stress level in the lining.

CHAPTER 2

REVIEW OF THE RELATED LITERATURE

2.1 OVERVIEW

The calciners at Tioxide Southern Africa perform the role of rotary kilns in other industries such as paper, steel and cement manufacturing. The rotary kiln has historically been the subject of extensive investigative research. Not least of the problems associated with rotary kilns is the question of what factors affect satisfactory refractory linings.

The recent advances in monolithic refractory linings as opposed to brick linings has given kiln owners access to linings that are easier to install, quicker to repair, and sometimes less expensive. Unfortunately, the linings are usually seen to be only a sacrificial lining to protect the vessel from the adverse effects of high temperature (Fowler, 1978).

Very little effort has been made to design the linings in terms of structural properties, and the failure of the linings is more often than not something that can be greatly reduced with a sound design approach (Bakker, 1982 ;Bortz, Firestone & Greaves, 1982 ; Fowler, 1978). At Tioxide S.A. the approach has also been to view the relatively short lining life in terms of purely operational wear-and-tear, and this study will provide Tioxide with the basis for a sound engineering approach, and a better understanding of the nature of the elements that interact when kilns operate.

An all-too-common approach to refractory failure is the trial-and-error method, the need exists to establish the stability of the lining via careful, detailed design. The trial-and-error approach is based on relative material properties, whereby a correction of a suspected failure mode is attempted using modified material properties, Fowler (1982) states that this approach can be very costly and time consuming, and may be completely incorrect.

It follows, thus, that refractory linings are poorly understood in terms of structural properties. Failures have therefore resulted as a result of inadequate engineering approach (Wygant & Crowley, 1964). This could well be the case at Tioxide S.A., where insufficient themo-structural data has lead to a lack of understanding of the forces that influence the stability of the calciner linings.

2.2 STRESS EVALUATION IN LININGS

The evaluation of stresses in monolithic refractory linings is a complex issue due to the fact that the material is cast and then fired from one side only, unlike brick which is uniformly cast and fired. This has the effect of placing the monolithic material under a thermal gradient, whereby the engineering properties of the material vary through the thickness of the lining . Bortz et.al. (1982) indicate that the non-uniform firing of a castable causes variations in the thermal conductivity, elastic modulus, strength, density, and other properties. Tseng (1982), has carried out a detailed study of the stresses in refractory monolithic linings, and the evaluation of the engineering properties through the lining cross section is a highly complex procedure.

The evaluation of the stresses in monolithic refractories has been researched and documented by various authors. (Farris, 1978 ; Fowler, 1978 ; Palin, 1981 ; Pierce & Bressi, 1972 ; Schacht, 1982 ; Tseng, 1982 ; Wygant & Crowley, 1964); and the types of analyses vary from complex Finite element analyses, to linear basic principle stress evaluations.

The method of analysis should be determined by careful evaluation of the resources available, and the expected benefit of the results. Fowler (1982), states that levels of detail implied in rational analysis is not justified for all applications, and that the method of analysis may be simplified by making certain assumptions, provided the nature and effect of the assumptions is understood.

The method of analysis used in this study comprises a Finite Element Analysis, based on certain assumptions, as well a linear elastic analysis, and a comparison between the two methods. The use of certain simplifying assumptions used in this study has been discussed by Farris (1978), Palin (1981), and Schacht (1986).

The nature of the critical stresses to be examined in an analysis on refractory monolithics has been discussed by Fowler (1982), Palin (1981), and Wygant & Crowley (1964), where the maximum stress orientation is the hoop stresses induced by thermal parameters, these are the stresses that are examined in this study.

2.3 P.C. BASED DESIGN

Wygant & Crowley,(1964) have carried out design checks on monolithic linings, using a number of fundamental assumptions and then checked the design using laboratory simulation. They concluded that the non-linear properties of the material that were assumed as linear for the calculations had the effect of cancelling each other out, and that the design was therefore valid. The validity of applying elastic linear equations to monolithic refractory linings has been thus been demonstrated and validated experimentally.

Use has been made of this method as the basis for the simplified P.C. design program, the variables used in the Finite Element Analysis have been inputted into this program, and the correlation between the two methods has been examined.

This approach to monolithic refractory lining design is in no way a perfect design tool, due to the complex nature of the engineering properties, however, it should prove a useful guide to the suitability of the lining system, and will allow engineering personnel a more confident approach to the problem.

CHAPTER THREE

THE RESEARCH DATA AND THEIR APPLICATION

3.1 INTRODUCTION

The data required for this study was divided into three main groups. Firstly, all the relevant material properties of the refractory concrete had to be obtained. Secondly, the steel shell configuration had to be ascertained, and thirdly, the operating conditions of the calciner had to be evaluated.

The refractory concrete properties that are available from the suppliers data sheets are usually not sufficient in detail to be used for an engineering analysis. This was apparent from the onset of this study, and has been highlighted as being a problem by Fowler (1982). As a result of this, the material properties had to be obtained by experimental methods, and the C.S.I.R's Material Science division was utilised for this purpose.

The engineering properties of the refractory concrete in the calciner are extremely complex in nature, due to the fact that the material is fired from one side only, hence the properties vary through the lining section. Where possible, the material properties have been obtained at temperatures sufficient to simulate the conditions in the calciner during operation. However, these values are by no means exact values as present in the calciner, due to the fact that laboratory firing of test samples is somewhat different from the actual conditions in the calciner.

It should again be emphasised here, that this study does not attempt to obtain exact values for the stress levels in the lining, but rather to observe the order of magnitude of stress, and the effects of variables on the stress levels.

3.2 SUBPROBLEM 1

The first sub-problem is to evaluate the stress levels in the refractory concrete lining using Finite Element Analysis based on material engineering properties evaluated to BS 1902 (1987), in order to establish whether the currently used lining material can withstand stresses imposed on it under assumed worst case operating conditions.

The data required to perform the Finite Element Analysis in subproblem 1, made up a large portion of data required for this study.

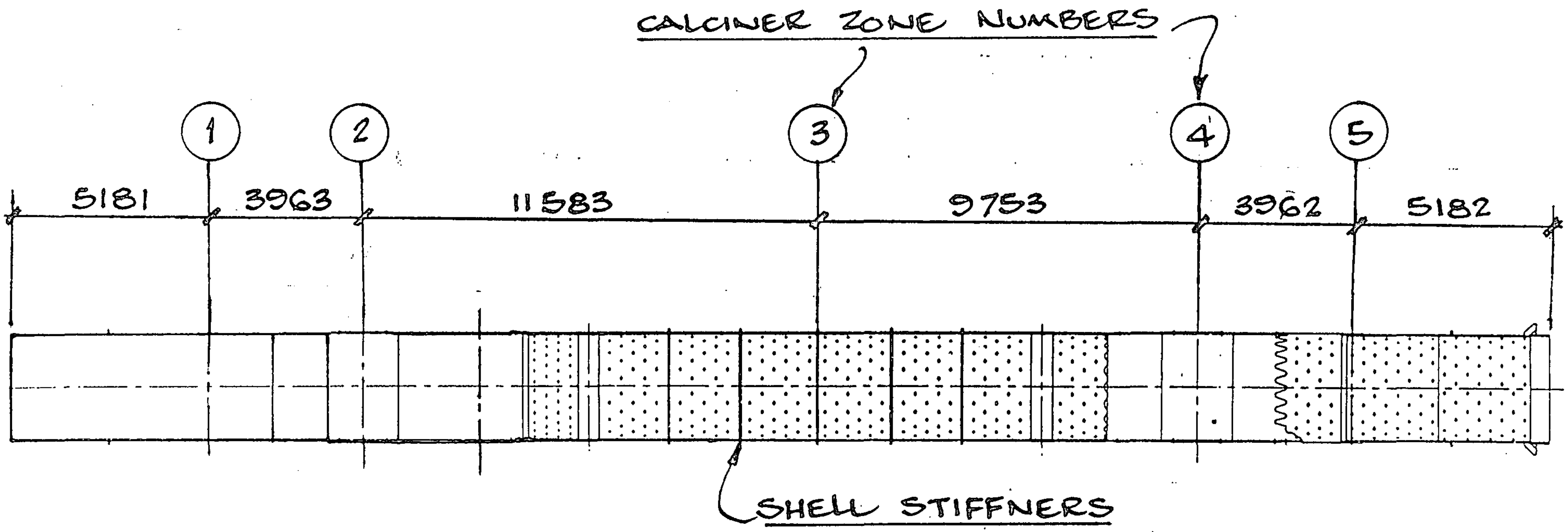

Figure 3.1: Diagrammatic Layout of Calciner No. 1

3.2.1. Scope

A diagrammatic layout of Tioxide's calciner number 1, (plant flow sheet number 01/322/1) appears in Figure 3.1. Two locations on the calciner were used for the stress analysis for subproblem 1. These positions are indicated on Figure 3.1, namely zone 2 & zone 4. These positions were chosen due to the fact that they are equidistant from the respective ends of the calciner, and their shell geometries are identical. Both positions are over the calciner tyres where the calciner makes contact with the rollers.

Fowler (1982) has stated that internally generated thermal loads are the greatest cause of stress in monolithic refractory linings. The stresses induced by thermal loading occur as a result of the expansion and contraction of the lining caused by a temperature difference between the hotter inside face of the lining, and the cooler outer face.

In order to examine the "worst case" of lining stresses, the temperature values used in this subproblem were selected as those values likely to cause the highest lining stresses. The selection of temperature values for the purpose of this subproblem appears in section 3.2.5.

3.2.2 Calciner Shell Dimensions

In order to evaluate the concrete lining stresses, it was necessary to calculate how the steel shell that contains the lining would behave under the applied thermal loads. It was therefore required to ascertain the steel shell dimensions.

Tioxide drawing number UC3-264-46214 provided a detailed drawing of the calciner shell layout. This drawing was used to ascertain the calciner diameter and shell thickness. The data obtained from the drawing to be used in this study was as follows:

- Shell thickness = 50mm. (both zones)
- Calciner internal diameter = 2743mm. (both zones)

3.2.3 Calciner Lining Dimensions

These dimensions were obtained from Tioxide drawing number UE3-264-4656. Zone 2 is close to the feed end of the calciner, and zone 4 is close to the discharge end of the calciner. As the calciner is heated from the discharge end, the internal temperatures are considerably higher at that end. The refractory lining is therefore required to perform more insulation of the steel shell towards the discharge end of the calciner than is required towards the feed end. As a result, the refractory concrete lining is thicker in zone 4 than in zone 2.

- The respective lining thicknesses are as follows:

  - Zone 2 lining thickness = 127mm (5")
  - Zone 4 lining thickness = 254mm (10")

3.2.4. Engineering Properties of the Steel Shell

For the Finite Element Analysis, it was necessary to have specific properties pertaining to the steel shell. The stress/strain properties were required in order to analyse the elastic behaviour of the steel shell under the operating temperatures, it was therefore necessary to obtain values for the elastic modulus, as well as Poissons ratio. It was also necessary to ascertain the rate at which the shell would expand, therefore the coefficient of thermal expansion was also required. The standard values for carbon steel obtained from the South African Steel Construction Handbook (1990) were used:

- Modulus of Elasticity = 206 GPa.
- Thermal expansion coefficient = 11.7 x 10^{-6}/ °C.
- Poissons ratio = 0.3.

3.2.5 Calciner Operating Data

3.2.5.1 Internal operating temperatures

In order to examine the stress/ strain behaviour of the lining due to the effects of temperature, it was necessary to use operating internal temperatures that were as accurate as possible, as well as the corresponding outer shell temperatures. These temperatures were required at both zone 2 and zone 4.

Accurate information of the calciner internal temperature profile was not readily available, as no thermocouples are present in the calciner. The calciner operating instrumentation only provides temperature readings at the two extremities of the calciner, i.e. the feed end and discharge end, the values for these temperatures, recorded randomly over a six month period, appear in Table 3.1.

Table 3.1 Randomly Recorded Feed and Discharge end Temperatures for Calciner Number 1.

Date	Discharge End Temp °C	Feed End Temp °C
08/04/91	1006	397
05/06/91	1000	395
18/07/91	978	380
31/07/91	992	388
19/08/91	1010	400
13/09/91	1016	402
21/11/91	986	385
13/01/92	1009	397

However, at Tioxides' plant in Italy, the calciners do have thermocouples, and an internal temperature profile for their calciners has been drawn. A reproduction of the temperature profile appears in Figure 3.2. As can be seen in Figure 3.2, the temperature profile is not linear through the calciner length.

Using the known maximum feed and discharge end temperatures obtained from the calciner instrumentation panel (Table 3.1), the 50m Italian profile was used to generate a "trended maximum temperature profile" for the 40m long South African Calciner, this profile appears in Figure 3.3.

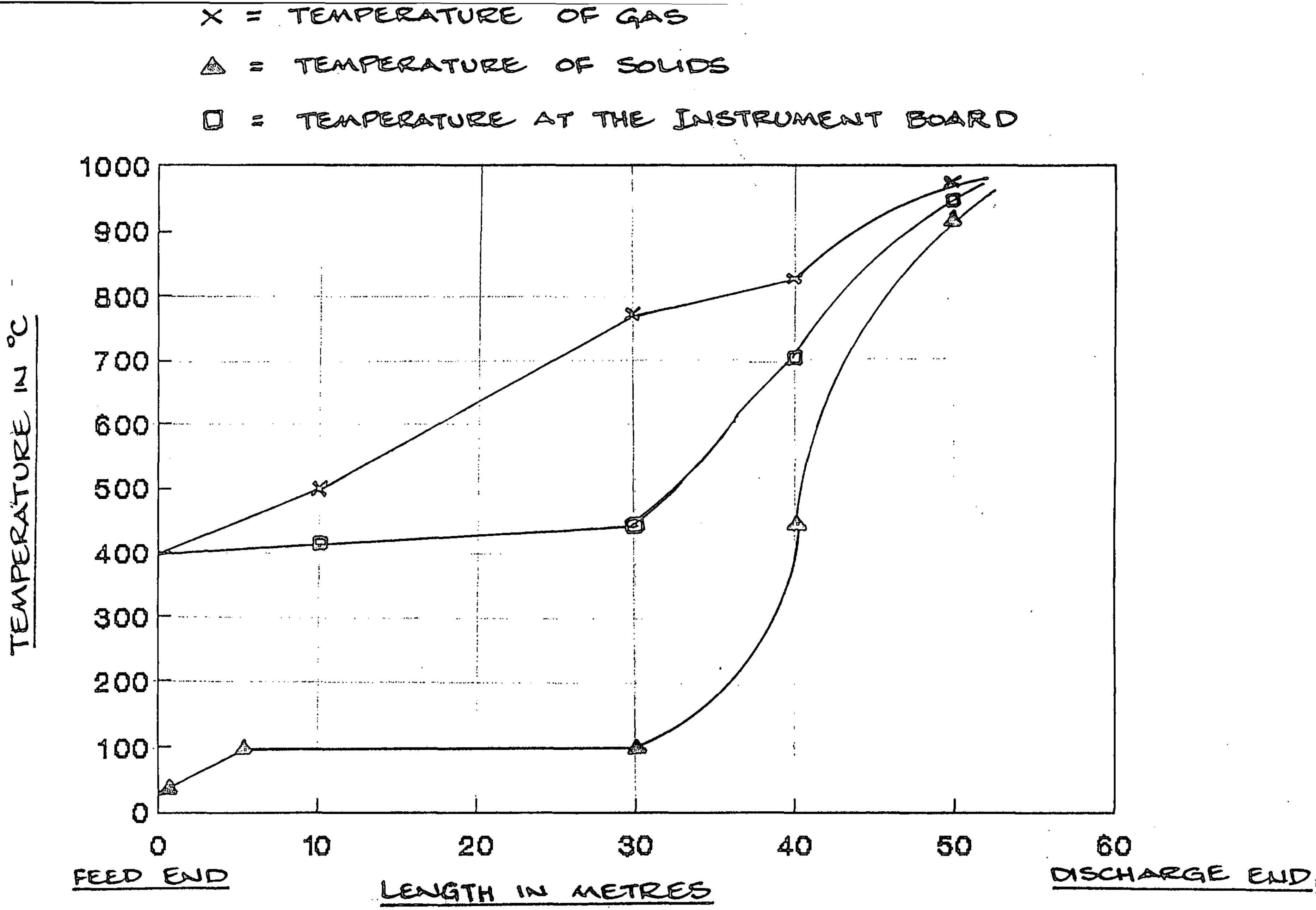

Figure 3.2: Tioxide Italy's Calciner Thermocouple Profile
(Source Facsimile No. DS66/54155 Tioxide Scarlino Factory)

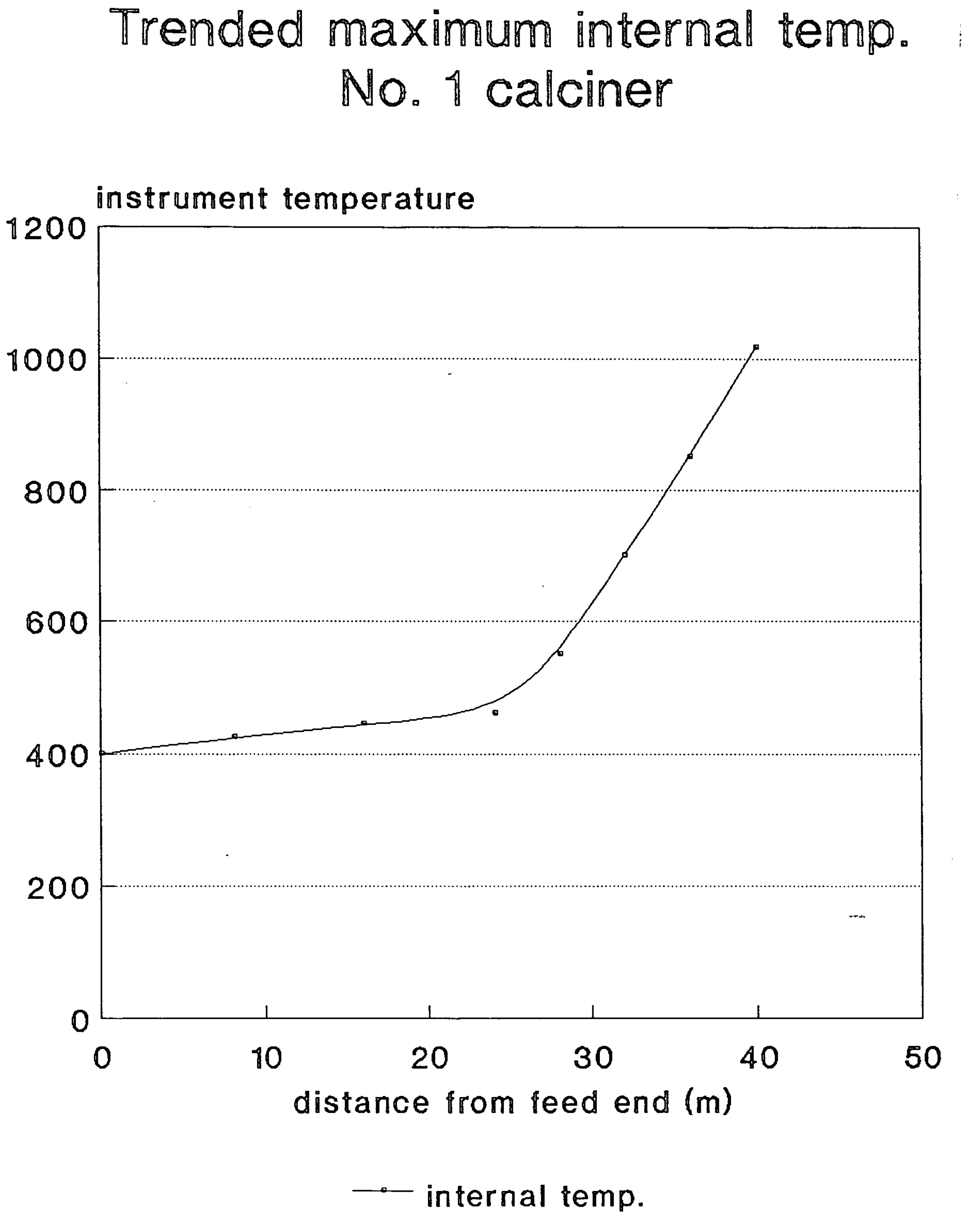

Figure 3.3: Trended Temperature Profile For Tioxide S.A.

The trend of the profile from Figure 3.3 was used to estimate the operating internal temperatures at zone 2 and zone 4 the evaluation of the temperatures at zones 2 and 4 were carried out as follows:

The data points for the temperature profile in Figure 3.3 appear in Table 3.2.

Table 3.2 Data Points For 40m Long Calciner Internal Temperature Profile

position along length meters	temperature °C
0	402
8	423
16	445
24	460
28	550
32	680
36	850
40	1016

As can be seen from the temperature profile in Figure 3.3 the curve between data points around zones 2 and 4 (9.14m from the feed and discharge ends respectively) is very close to a straight line. The values for the temperatures at zones 2 and 4 were thus obtained by linear interpolation between known points as follows:

X= Distance from feed end mm

T= Internal temperature °C

Zone 2 = 9.14m from feed end.

from Table 3.2: @ X = 8   T = 423

@ X = 16   T = 445

Therefore @ X = 9.14 T = 426

Zone 4 = 40 - 9.14 = 30.86m from feed end.

from Table 3.2: @ X = 28   T = 550

@ X = 32   T = 680

Therefore @ X = 30.86 T = 643

The maximum internal operating temperatures thus obtained for the two zones under consideration were as follows:

- Zone 2 : 426° C.
- Zone 4 : 643° C.

3.2.5.2 External shell temperatures

At Tioxide, heat scans of the calciners are done on a random basis. This is done by means of an optical pyrometer, and the calciner is divided into zones for the purpose of the scan. The entire zone is scanned for a full revolution of the calciner, and the maximum and minimum temperatures for the zone are recorded on Tioxide drawing number UC3-264-46222. It is known that this procedure does not provide 100% accurate temperature readings, but as this study is more concerned with the order of magnitude of the stress levels than a 100% accurate value, the figures have been accepted for use

in this study. A copy of the measured shell temperatures recorded during six scans appears in Table 3.3.
The temperature induced stresses in the lining are caused by the difference in temperature across the lining. This difference in temperature may be referred to as a temperature gradient, as it has a slope and an x and y axis. The maximum stress, or "worst case" as required in this subproblem is going to occur when the temperature gradient, or slope, is at a maximum. This would occur when the internal temperature is at a maximum, and the external temperature is at a minimum. For the purpose of this sub problem, the maximum recorded internal temperatures at zones 2 and 4 (from 3.2.5.1) were used in conjunction with the minimum recorded shell temperatures for zones 2 and 4 for the lining stress evaluation. Although the internal and external temperatures thus used did not actually occur simultaneously, the use of a maximum temperature differential within the normal operating limits of the system would be representative of the maximum possible stress case allowing for any errors in temperature readings.

As can be seen from the measured shell temperatures on 07/09/91, the calciner was considerably cooler than any other time, this may due to the fact that the ambient temperature was very cool at the time of the scan.

Table 3.3 Randomly recorded calciner shell temperatures for zones 2 and 4.

date	zone 2		zone 4	
	max	min	max	min
04/04/91	121	120	120	109
20/06/91	125	114	125	111
23/07/91	161	154	156	141
07/09/91	111	97	109	83
03/12/91	155	140	150	144
04/02/92	140	133	136	131

3.2.6 Evaluation of the Engineering Properties of the Refractory Concrete Lining Material.

The refractory concrete lining material used in the calciners at Tioxide S.A. is Vereeniging Refractories' "Hikast Super", a low cement high strength castable. In order to obtain the engineering properties of the lining material, the C.S.I.R's division of materials science was used. The results of the tests carried out by the C.S.I.R. appear in report number 450/57403. The properties to be evaluated for use in the Finite Element and subsequent analyses were as follows:

- Thermal expansion coefficient (/°C)
- Permanent linear change (% at temperature)
- Modulus of Elasticity (GPa)
- Poissons ratio (no units)
- Ultimate compressive strength (MPa)
- Ultimate tensile strength (MPa)

3.2.6.1 Thermal expansion coefficient

The evaluation of the thermal expansion coefficient was carried out to standard BS 1902 section 5.3: 1990, the standard was modified to include a value at 1500°C, as all other tests gave a value at this temperature, and the different material properties could therefore be tabulated at the same temperatures for stress analysis.

The results of the analysis have been depicted graphically, and the graph appears in Figure 3.4. As can be seen from Figure 3.4, the relationship between temperature and expansion is very close to being linear, the value obtained for the coefficient of thermal expansion is therefore a constant temperature dependant ratio. The value thus obtained was 5.27 x 10e-6 / °C.

The graph shown in Figure 3.4 shows the expansion of the material as the temperature increases, at the maximum temperature, the material undergoes shrinkage after being held at the maximum temperature. Upon being cooled to ambient temperature, the material has undergone shrinkage from the original sample size, this shrinkage is the permanent linear shrinkage of the material.

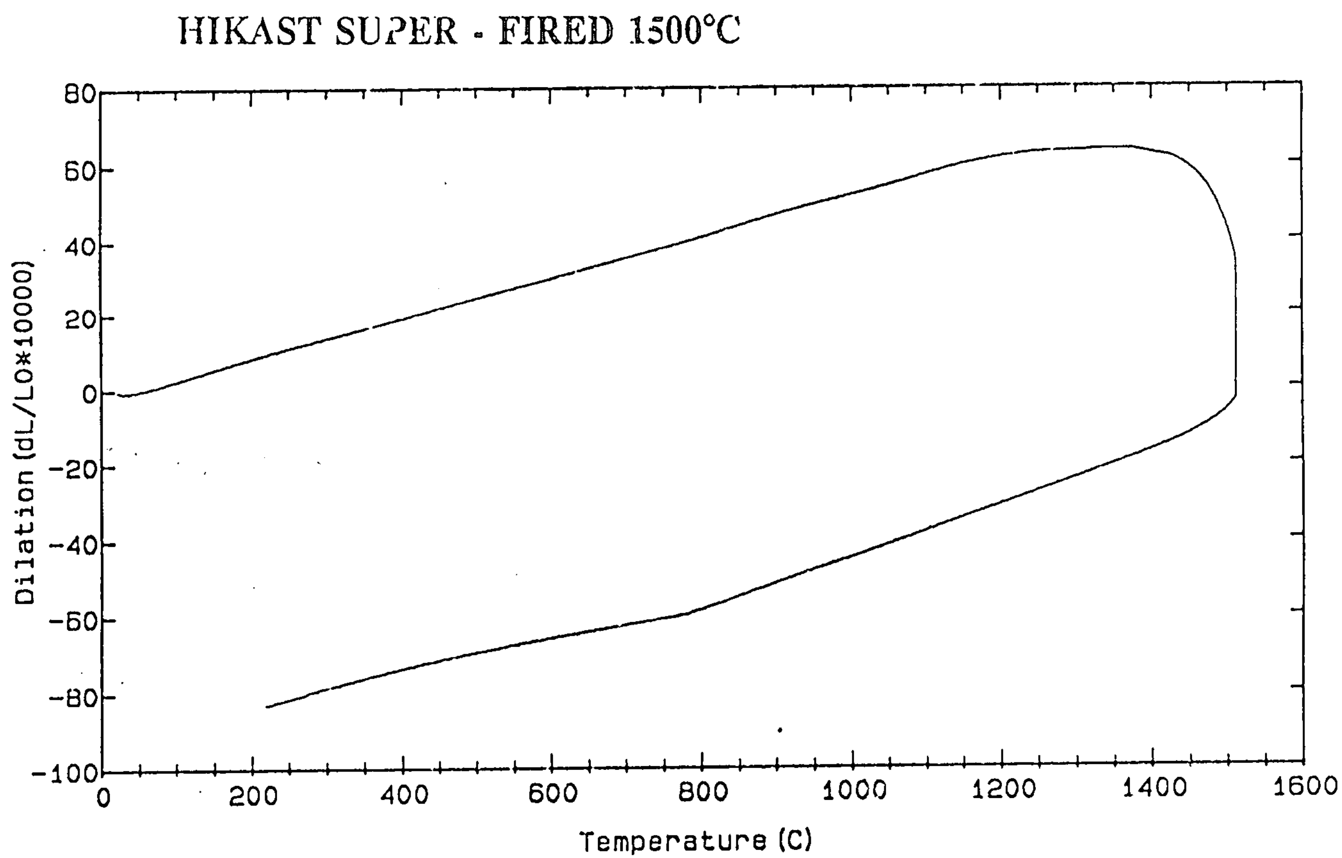

Figure 3.4: Temperature vs. Expansion/Shrinkage - Hikast

3.2.6.2 Permanent linear change (PLC)

The permanent linear change is a measure of the difference in dimensions of a sample before and after firing to certain temperatures. In effect, it is the amount of permanent shrinkage that a sample has undergone after being heated and cooled to room temperature.

The test to establish the PLC of the Tioxide Southern Africa's Calciner lining material was carried out by the CSIR, to British Standard BS 1902 Section 5.10: 1986 and Section 7.6: 1987.

For this study, the tests were carried out after firing to 500, 1000 & 1500 degrees C. The results appear in Table 3.4.

Table 3.4. Permanent linear change of Hikast Super.

3 hr prefiring temp.	PLC dry to fired
500°C	- 0.13%
1000°C	- 0.40%
1500°C	- 0.26%

The results in Table 3.4 indicate that Hikast Super undergoes permanent shrinkage as a result of elevated temperatures. The amount of shrinkage increases between 500°C and 1000°C, and decreases again towards 1500°C.

The implications of permanent shrinkage are that once a material has been heated to the temperature under consideration, and allowed to cool, the material undergoes shrinkage that will affect the lining stresses upon reheating. The application of the PLC value is discussed in 3.3.3.4.

3.2.6.3. Modulus of Elasticity & Poissons Ratio

Alder & Masaryk (1986) and Tseng (1982) have both shown the methods and procedures for obtaining the modulus of elasticity (MOE) and Poissons ratio (PR) at elevated temperatures. The procedures include the construction of special test equipment, and the complexity of the tests is beyond the scope of this study.

As refractory concrete has historically been accepted in industry as being a sacrificial non-structural element in equipment (Fowler 1978), the stress/strain relationship data of modulus of elasticity and Poissons ratio are not readily available from the lining material suppliers. This was evident when the material supplier was contacted to request information on these properties, and it became apparent that requests for values of MOE and PR were very uncommon.

On further discussions with the C.S.I.R. (Messrs Johan Esterhuizen and Nigel Stone, August 1991), it became evident that the evaluation of MOE and PR could be obtained at room temperature with relative ease, but that the evaluation of these properties at temperature was a very complex exercise.

Alder and Masaryks study (1986) included evaluation of the Modulus of Elasticity, and Poissons Ratio for a low cement 45% Al_2O_3 castable refractory concrete. Hikast Super, the material used in the calciner is a low cement 48% Al_2O_3 castable. Without going through the complex analysis procedures required to evaluate MOE and PR at temperature, the values obtained by Alder & Masaryk (1986) were the most accurate figures available, and were therefore used in this study. It is accepted that this is not a 100% accurate approach, but the nature of this study is such that it was considered to be sufficiently accurate. Subproblem 2 deals with variances in the Modulus of Elasticity, and the effects of a change in this property are shown in 4.3.3.

The values obtained from the paper by Alder & Masaryk (1986) for use in this study appear in Table 3.5

Table 3.5 Temperature dependent stress/strain data for a low cement 45% Al_2O_3 castable. (Source-Alder & Masaryk (1986))

Reference Temp. (°C)	Elastic Modulus (GPa)	Poissons Ratio
22	59	0.15
538	48	0.17
816	31	0.17
1093	38	0.23

3.2.6.4 Ultimate strengths

As the refractory concrete lining expands upon heating, the rate of expansion and degree of interference induced by the steel shell determine the magnitude and nature of the stresses induced in the lining. In a circular vessel such as a calciner, the stresses induced by expansion lead to compressive stresses on the inside face of the lining. Depending on the lining/shell interface, the outer face of the lining, closest to the shell, should be tensile in nature.

Due to the fact that the lining can be subjected to both tensile and compressive stresses, it was necessary to establish the ultimate strength of the refractory concrete in tension and compression.

The ultimate strength values have no effect on the evaluation of the stresses, but are used to establish whether the lining can withstand the imposed thermal stresses, or whether failure will occur. The values used for the ultimate strengths of Hikast Super were obtained by the C.S.I.R. using standard methods BS 1902, sections 4.3: 1985, 4.4: 1984, & 7.6: 1987.

For the purpose of this study, the ultimate compressive strength is deemed to be equivalent to the "Cold Crushing Strength" (CCS), and the ultimate tensile strength as the "Modulus of Rupture" (MOR). The values obtained in the study by the C.S.I.R. appear in Table 3.6.

Table 3.6: Laboratory Values for the Ultimate strengths of Hikast Super (Source C.S.I.R.)

3 hr prefiring temp (°C)	CCS (MPa)	MOR (MPa)
cured	100.4	9.9
500	86.7	9.3
1000	82.6	11.8
1500	92.3	10.0

As can be seen from Table 3.6, the lining material is approximately 10 times as strong in compression as in tension, this is typical of ordinary Portland Concrete as well. As a result of the relative weakness in tension, it would be expected that a tensile stress would be the limiting stress in a lining, being the first failure area. This has been reported by Wygant & Crowley (1964), who state that it is preferable to have a lining under nett compression, but that the compressive stress value on the hot face should not approach the cold crushing strength of the lining.

Also noticeable in Table 3.6 is that the CCS of the lining material drops after heating, and then rises again towards the hotter 1500°C. This is typical of a refractory castable, and has been explained by Bakker in the American Concrete Institute report R-79 (1987) as follows:

The material at the lower room temperature is still in the hydraulic bond stage, similar to the strength gaining system of ordinary Portland concrete. The effect of very high temperature places the material under a ceramic or "glassy" bond, hence the increase in strength at 1500°C. The phase in between the hydraulic bond and the ceramic bond is called the "intermediate" phase. The relative weakness of the intermediate phase results from the material losing some of the benefits of the hydraulic bond as the water is driven off from the lining, but not yet reaching a high enough temperature to turn "glassy".

3.2.7. Manipulation of Lining Material properties data for Finite Element Analysis.

The material properties of the lining are temperature dependant. Therefore the values of the engineering properties of the lining material vary with a change in temperature.

The application of the finite element analysis is discussed in 3.2.9. in detail. In order for the finite element analysis to be performed accurately, it was necessary for the engineering properties to be entered into the computer program as values tabulated against temperatures. This would allow the analysis to automatically obtain the value of the material property at the relevant temperature of the element under consideration.

For the elastic modulus and Poissons ratio, the data in Table 3.6 was entered into the analysis as a data Table.

For the thermal expansion coefficients, the analysis was provided with a linear relationship of 5.27x $10e^{-6}$ /°C, according to the value obtained in 3.2.6.1.

The values for permanent linear change listed in Table 3.4 are strain values, calculated as a percentage of the original specimin length. The effect of PLC is in fact a shrinkage effect that opposes (or reduces) the effects of expansion, as indicated in Figure 3.4. This means that the gradient of the thermal expansion of the lining plotted as dilation vs temperature remains constant, but that the curve shifts away from positive expansion. This effect would not be present during the linings' initial heat-up at lower temperatures, but once the lining has been allowed to cool, it has effectively shrunk, and the thermal expansion effect is thus reduced.

For the finite element analysis, the effect of the PLC was simulated as follows:

i) The values listed in Table 3.4 were taken as the strain value corresponding to the relevant temperature.

ii) The relationship between successive known points was assumed as being linear, therefore unknown values were interpolated between two known points.

iii) The PLC value was divided by the coefficient of thermal expansion (5.27×10^{-6} /°C). This yielded a answers as temperatures eg:

At 500°C PLC = -0.13% (Table 3.4)

$-0.0013/(5.27 \times 10^{-6})$ °C

= -247°C

iv) This "temperature" was subtracted from the relevant operating temperature to reduce the thermal expansion proportionate to the effect of the PLC eg:

500°C - 247°C = 253°C

Wygant & Crowley (1964) have included in their calculations, a "construction temperature". This value is the assumed temperature value at which the lining

was after casting, prior to firing. The effect of this temperature is a reduction in overall thermal expansion due to the fact that the increase in temperature of the lining is lower. For example:
Assuming a construction temperature of 25°C, and the lining is fired to 500°C. The increase in temperature is not 500-0 =500°C, but rather 500-25 =475°C.
For the purpose of this study, a construction temperature of 25°C was used throughout.

3.2.8 Utilisation of the Lining Material Engineering Properties in the Finite Element Analysis.

A detailed description of the finite element analysis modelling techniques appears in 3.2.9.

The following steps were adopted to evaluate the liner stresses using the lining material properties obtained in 3.2.6, and manipulated in 3.2.7:

i) The maximum internal temperatures obtained in 3.2.5.1 of 426°C in zone 2 and 643°C in zone 4 were used in conjunction with the minimum recorded shell temperatures from Table 3.3, of 97°C for zone 2 and 83°C for zone 4, to obtain a linear temperature profile through the lining.

ii) This profile was entered into the computer, which calculated the shell inner temperature, based on a thermal conductivity for the steel shell of 57 W/m.K.

iii) A sketch of the different temperature boundaries for the analysis appears in Figure 3.5. The estimation of the lining outer temperature was based on a nominal 1 degree increase in temperature between the lining outer face, and the shell inner face. This value is extremely difficult to quantify, as it depends on the gap between the shell and the lining (if any), and the gap size would not be known until the analysis had been completed. The lining outer temperature could have been calculated from the known internal temperature and the coefficient of thermal conductivity of the lining, but a calculation of such a nature is dependent on the amount of build-up on the internal face of the lining, as well as the density of the lining, and was thus considered to be innaccurate

iv) The boundary temperatures obtained above were then reduced to allow for permanent linear shrinkage and construction temperature as described in 3.2.7.

v) The resultant operating boundary temperatures thus obtained for zone 2 are listed in Table 3.7, and in Table 3.8 for zone 4. There is a linear temperature profile between successive boundary temperatures.

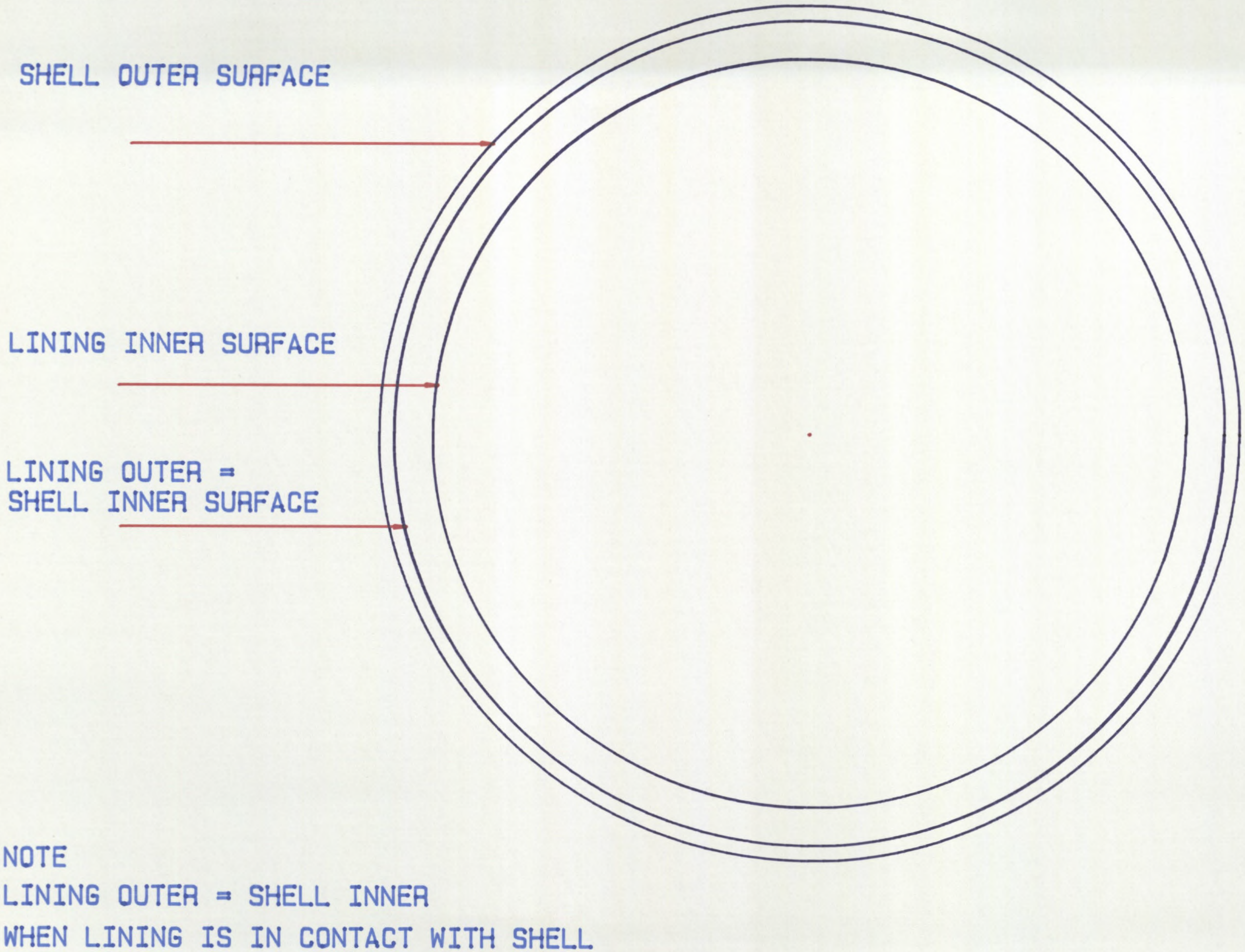

FIGURE 3.5.

DIAGRAMMATIC LAYOUT OF LINING AND SHELL BOUNDARIES

Table 3.7 Boundary temperatures for zone 2

Surface	Operating Temp	PLC Temp	Construction Temp	Resultant Temp
lining inner	426	-210	25	191
lining outer	100	- 49	25	26
shell inner	99	0	25	74
shell outer	97	0	25	72

Table 3.8 Boundary temperatures for zone 4

Surface	Operating Temp	PLC Temp	Construction Temp	Resultant Temp
lining inner	644	-394	25	225
lining outer	85	- 42	25	18
shell inner	84	0	25	59
shell outer	82	0	25	57

vi) The resultant temperature profiles were stored in the computers' thermal finite element program, for automatic access during the stress analysis.

vii) The stress finite element analysis was then carried out, and the relevant temperature for each node of the model was then obtained from the thermal profile, and transferred to the structural analysis.

viii) The temperature dependent liner material properties were then selected for each element of the model, the value depending on the calculated element temperature

ix) The resultant temperatures and material properties were then applied to the model to estimate the thermal strains and resulting hoop (circumferential) stresses. The results of the stress analyses appear in figures 4.1 and 4.2.

3.2.9 Finite Element Modelling

Tseng (1982), Schacht (1982), and Fowler (1982), have all shown a use of finite element methods for the stress analysis of refractory vessel linings. In all cases, the calculated values are performed in two stages, firstly the temperature analysis is carried out to establish a temperature profile through the lining and shell, and secondly a stress analysis is carried out in order to evaluate the lining stresses and strains caused by the high temperatures. This study was performed using the same two stages on LUSAS Finite Element Analysis System Version 10 (1990).

3.2.9.1 Temperature Profile Modelling

The method of obtaining the temperature profile has been described in 3.2.8, and the modelling of the temperature profile for the finite element analysis was carried out using four noded plain field elements in two dimensions for the liner and shell. Thermal links were used between the liner and the shell.

3.2.9.2 Stress analysis.

The lining and shell were modelled with two dimensional plain strain continuum elements. A fifteen degree segment of a circumferential section through the lining and shell was been modelled for both zones 2 and 4. The model for zone 2 is shown in Figure 3.6, and the model for zone 4 is shown in Figure 3.7.

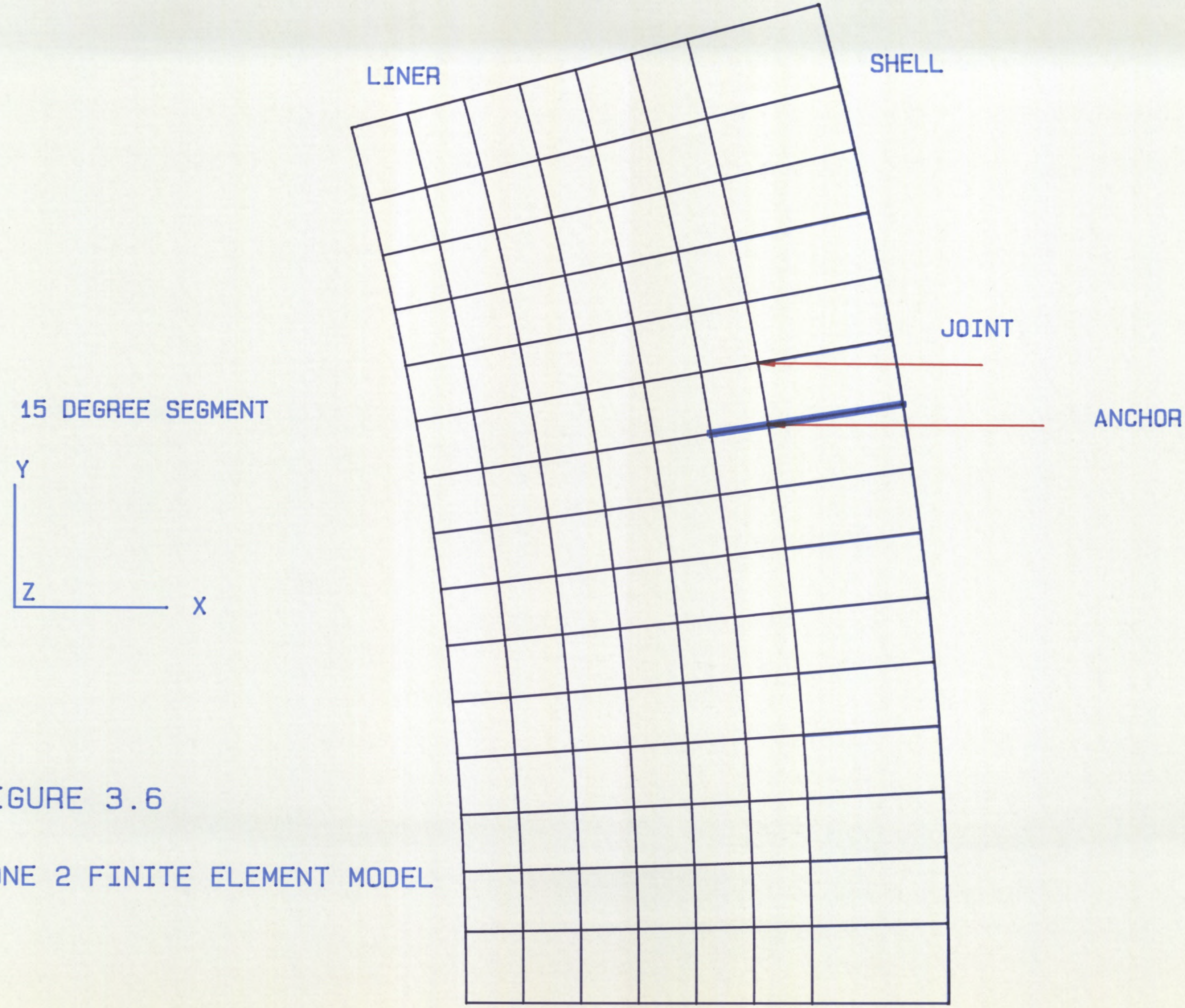

FIGURE 3.6

ZONE 2 FINITE ELEMENT MODEL

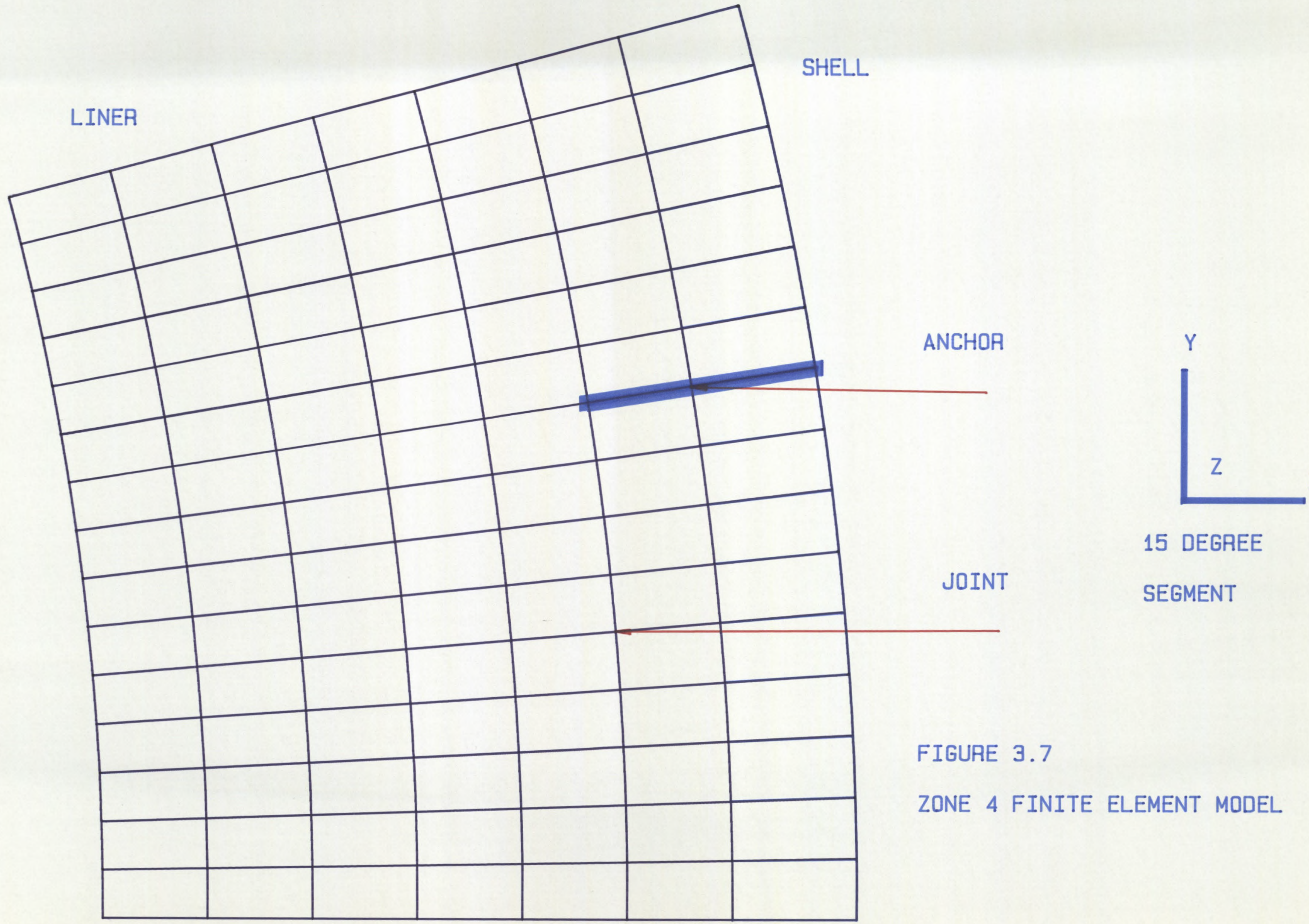

FIGURE 3.7

ZONE 4 FINITE ELEMENT MODEL

3.2.9.3 Structural behaviour

The liner has been modelled on the assumption that the liner has not cracked, as modelling the cracked case would be extremely complex, and was considered to be outside the scope of this study.

The liner has been modelled with the anchor points as the only attachment to the shell (see Figure 3.8). Initially, the effects of the anchors were ignored, and two dimensional joints were used at the contact surface, to simulate the non-linear geometric behaviour of the lining/shell interface. The smooth contact (frictionless) non-linear joint model is shown in Figure 3.9. The compression stiffness was set to very high values ($1*10^{15}$) to simulate the impenetrable shell surface. The tensile stiffness was set to zero, i.e. unrestrained shrinkage of the lining. The gap between the lining and the shell at construction temperature was set to zero.

When the liner shrinkage is greater than that of the shell, a gap will form between the lining and the shell. Therefore under these conditions, and away from the anchor points, the shell has no influence on the stress distribution in the lining. When linear expansion in the lining is greater than that of the shell, there will be surface contact between the lining and the shell, that is the shell will be restraining the expansion of the lining. Under these conditions, the shell will impact on the stresses in the lining.

The effects of the anchors on the lining stresses were calculated in order to ascertain the increase in liner stresses local to the anchor, for this purpose, the joint was given a tensile stiffness value equivalent to the tensile stiffness of the anchor viz. 215x10e6 N/m.

The results of the analysis for subproblem 1 appear in section 4.2.

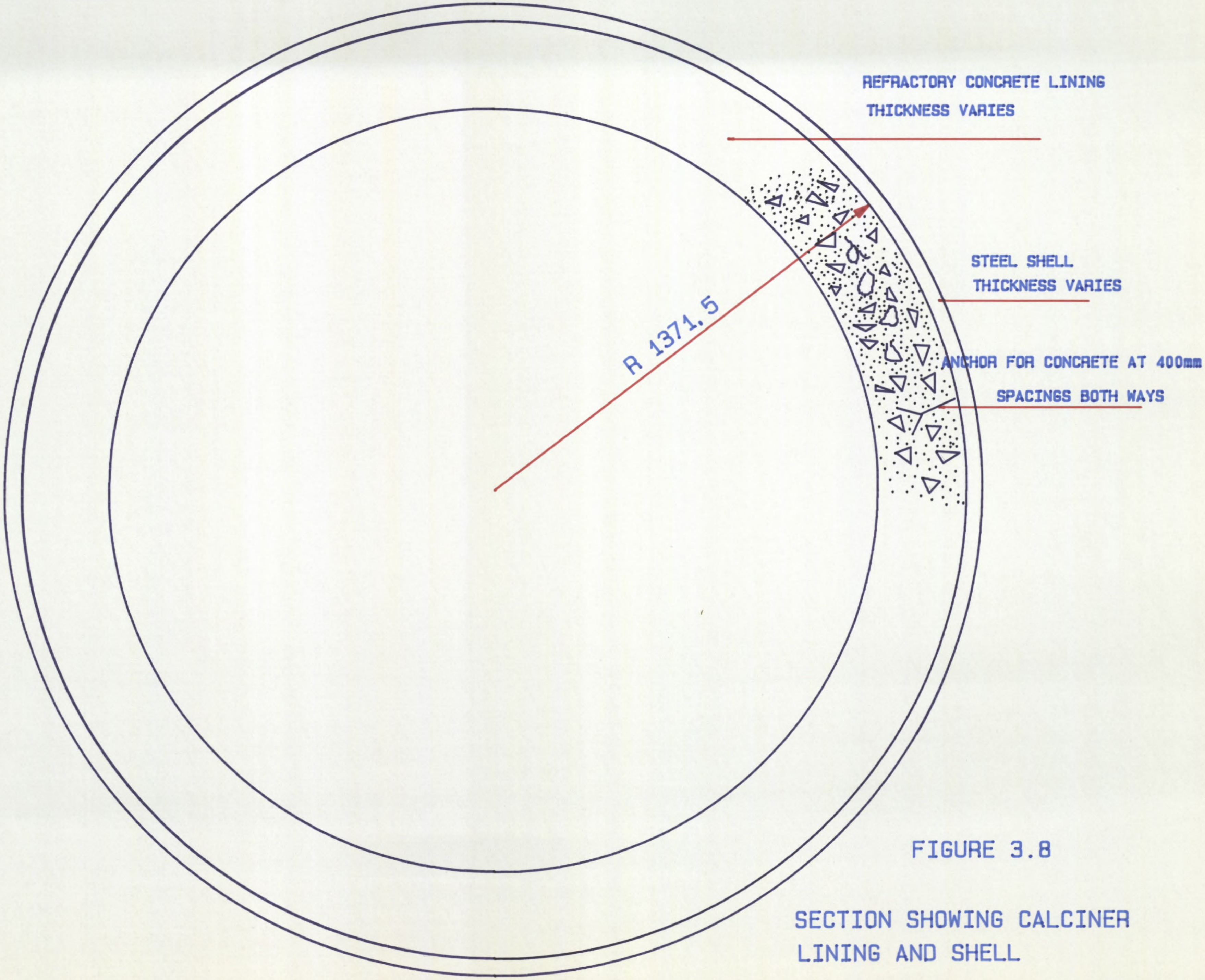

FIGURE 3.8

SECTION SHOWING CALCINER LINING AND SHELL

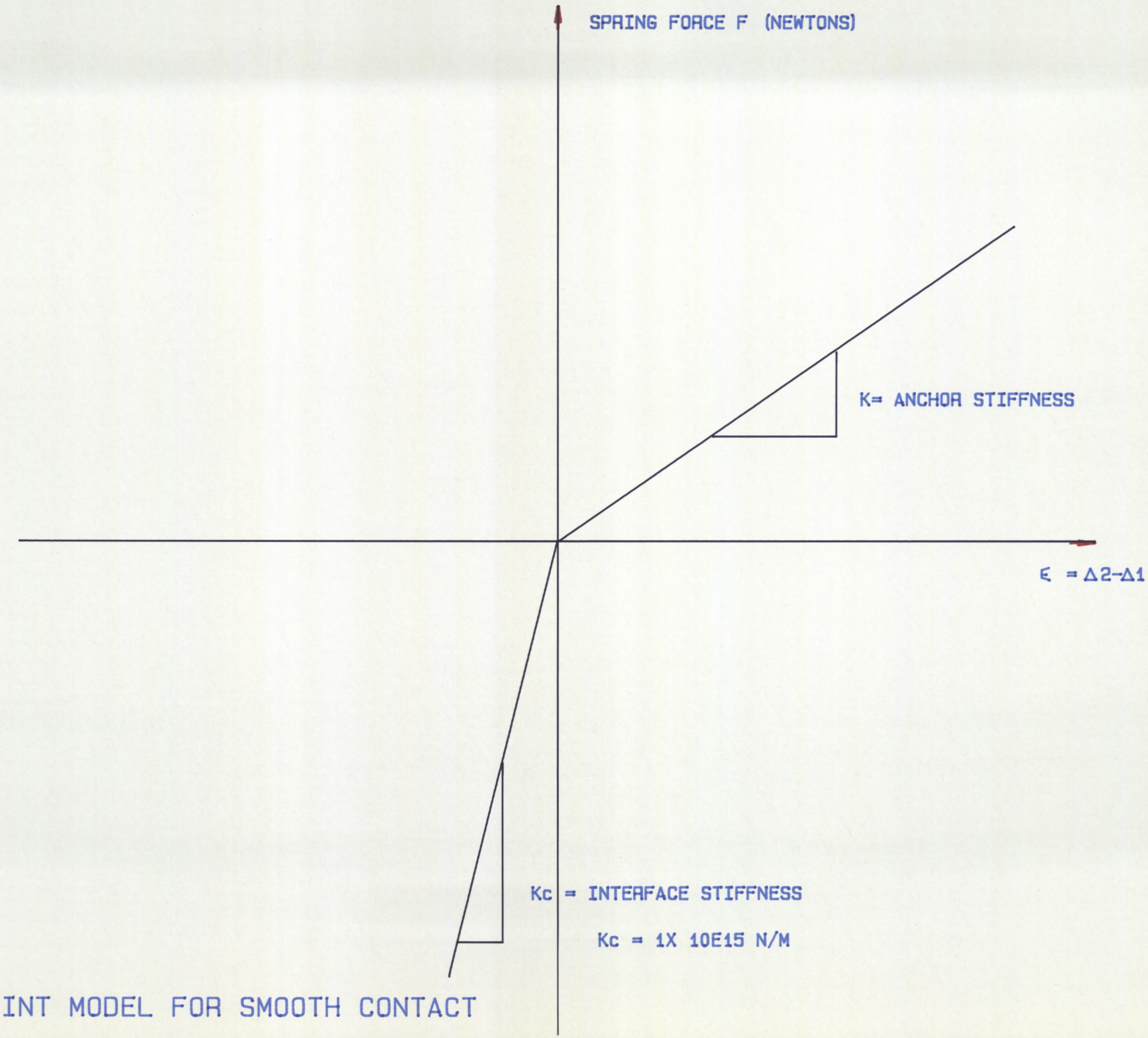

FIGURE 3.9
NONLINEAR JOINT MODEL FOR SMOOTH CONTACT

3.3 SUBPROBLEM 2

The statement of subproblem 2 was as follows:

The second subproblem is to evaluate the trends in the stress and strain levels of the refractory concrete linings, in terms of variable thermo-structural parameters, in order to observe the influence of variables on the structural integrity of the calciner linings.

3.3.1 Overview of the Variables

This subproblem sought to indicate the influence of changes in variables on the lining stress levels. It was necessary, therefore, to examine all the variables that influence the stress in the lining, and highlight those variables that could conceivably change. Palin (1981), and Fowler (1982), have discussed the effects of changes in operating parameters and engineering properties on lining stress levels, and the following is a list of variables that could conceivably alter in reality, and were therefore chosen as variables for this analysis.

Lining thickness
Internal temperature
Modulus of Elasticity
Permanent linear change

From Table 3.5 it can be seen that the value for Poissons ratio only increases by 0.02 for an increase in temperature of 794°C, because of this nominal change, the effects of changes in Poissons ratio were not chosen for this study.

3.3.2 Scope of the analyses

The reason for carrying out this study came about as a result of calciner lining failures at Tioxide. This developed a need to understand the stress behaviour of the linings, and the influence of engineering and operational variables on the stresses. The failure at Tioxide occurred in zone 2, therefore the changes in stress according to changes in variables were only evaluated at zone 2, and not at zone 4.

With 4 variables, assuming that one wishes to observe the effects of an increase, as well as a decrease in the value of the variable, combining the effects of changes in all the variables would lead to $3^4 = 81$ permutations. This would mean 81 different computer runs, and as this subproblem sought to evaluate the effects of individual variables on the lining stress levels, this information would be extraneous.

3.3.3 Method of Solution

Once the lining configuration had been initially modelled for subproblem 1, making changes to the input variables was a straightforward task. The method of analysis was similar to the methods described in 3.2.8. with only an alteration in the variable under consideration.

3.3.3.1 Lining thickness

During the calciner shutdowns at Tioxide, the calciner lining is inspected for cracking and general wear. When a problem has arisen that leads to lining failure, it has been found that the failed lining has reduced in thickness considerably. Using this phenomenon as a basis, it was therefore decided to examine only a reduction in lining thickness, and not an increase in lining thickness.

The selection of a Figure to use as a reduced thickness was chosen as an arbitrary Figure, based on the approximate average material loss observed in zone 2 of the last calciner no.1 shutdown. The Figure thus obtained was a 25% reduction. As the original lining thickness for zone 2 was 127mm the lining thickness was therefore reduced from 127mm to 95mm.

For the purpose of this evaluation, the following steps were taken:

- The maximum internal operating temperature was retained as the value used in subproblem 1, as the internal operating temperature is independent of lining thickness.

- The resultant cold face temperature was calculated from the known temperature gradient calculated in 3.2.7. as follows:

  let $t1$= internal temperature

  let $t2$= external temperature.

  from Table 3.7 with lining thickness = 127mm

  $t1= 426°C$ $t2= 100°C$

  therefore gradient= (426-100)/127= 2.567° per mm

  Revised t2 (95mm thick lining) =

  426°C - 2.567*95= 182°C

  - An increase in t2 meant that all the temperature dependent material properties would change on the lining outer face. This meant that the effect of the PLC as described in 3.2.6 and Table 3.7 would change according to the revised lining outer temperature. The simulation of this revised PLC effect was calculated manually before the computer analysis was carried out, and resulted in revised boundary temperatures. A sample of the manual calculation follows:

From Table 3.4:

at 0°C PLC= 0

at 500°C PLC= -0.13%

(assuming a linear relationship between successive known points), between 0 °C and 500°C the PLC reduces by: (0.13 - 0)/500 per degree.

= 0.00026% per °C

therefore at 182°C PLC = 182*.00026% = -0.0473%

To convert to a negative temperature divide by the thermal expansion coefficient of 5.27 x $10e^{-6}$ (see 3.2.6)

-0.000473/(5.27 x $10e^{-6}$) = -90°C

The resultant temperatures thus obtained appear in Table 3.9

Table 3.9 Boundary temperatures for zone 2 with lining thickness reduced by 25%

Surface	Operating Temp	PLC Temp	Construction Temp	Resultant Temp
lining inner	426	-210	25	191
lining outer	184	- 90	25	67
shell inner	183	0	25	158
shell outer	181	0	25	156

The lining stresses obtained from this analysis appear in 4.3.1.

3.3.3.2 Modulus of elasticity

As discussed in 3.2.5.3, the method of obtaining the values for the elastic modulus of the lining material were not 100% accurate, but based on the elastic modulus of a similar material. This meant that the selection of elastic modulus for the solution of subproblem 1 was at best an approximation, and it was therefore necessary to examine the effect of this approximation.

The value used in 3.2.5.3 could have been either higher or lower than the actual value for Hikast Super, so it was therefore necessary to trend the effect of both a higher and lower elastic modulus. As the purpose of this particular investigation was to observe the trends in the lining stress due to an alteration in elastic modulus, an arbitrary Figure was chosen to change the elastic modulus to. A Figure of 20% was chosen.

The values listed in Table 3.5 for elastic modulus were increased by 20 %, and the increased figures were entered into the finite element analysis properties Table, and the finite element analysis performed. Thereafter, the values in Table 3.5 were reduced by 20% and the analysis was performed.

Whilst the elastic modulus was changed, the lining thickness was retained at its original thickness, in order to observe the effect of a change in 1 variable (elastic modulus) only.

The results and explanation thereof for these analyses appear in 4.3.3.

3.3.3.3 Internal temperature

The impact of an increase in internal temperature was tested in order to evaluate the effects of increased liner expansion. As the values of Permanent Linear Change and Youngs Modulus are temperature dependent, the values for elastic modulus and PLC at the lining inner face had to be changed in order to account for the increase in lining internal temperature.

As stated in 3.3.3.2, this study sought to observe trends in lining stress levels due to changes in variables, therefore a selection of what value to increase the lining temperature to was arbitrary in nature, again, a value of 20% was chosen.

The elastic modulus values listed in Table 3.5 were tabulated in the finite element analysis, therefore an increase in lining inner temperature would cause the computer to automatically select the corresponding value for elastic modulus.

The changed PLC value due to increased internal lining temperature was obtained by linear interpolation as follows:

From 3.2.5.1 maximum internal operating temp. (t1) = 426°

20% increase in temperature = 426°* 1.2 = 511°C

from Table 3.4: PLC at 500°C = -0.13%

PLC at 1000°C = -0.40%

therefore PLC varies (0.4-0.13)/500 = 0.00054 per °C

PLC at 511°C = 0.00054*11 + 0.13 = 0.136%

from 3.2.6 PLC "temperature effect" = 0.00136/ 5.27 $*10^6$

= -258°C

The affects of increasing the lining internal temperature are a higher expansion value, and higher likelyhood of the shell interfering with the lining. In order to maximise the simulation of this effect, the lining outer temperature as well as shell temperature were kept the same as for subproblem 1 (Table 3.5). Applying a change in which the internal temperature is increased, and the external temperature is kept the same, has the effect of placing the lining under a much steeper temperature gradient, and is in effect equivalent to applying a change in the thermal conductivity of the material. The thermal conductivity is dependent on the cast density of the material, which in turn is reliant on the quality of the concrete placement techniques, and is therefore subject to variation. The boundary temperatures thus obtained for a 20% increase in internal temperature are presented in Table 3.10

Table 3.10 Revised boundary temperatures for zone 2 (applying a 20% increase in internal temperature.)

Surface	Operating Temp	PLC Temp	Construction Temp	Resultant Temp
lining inner	511	-258	25	228
lining outer	100	- 49	25	26
shell inner	99	0	25	74
shell outer	97	0	25	72

The results showing the stress values in the lining after applying a 20% increase to the lining internal temperature appear in 4.3.5.

3.3.3.4 Permanent Linear Change

The effects of permanent linear change have been discussed in detail in 3.2.5.2. This subproblem sought to change the PLC value, and evaluate the effect such a change would have in. A reduction in PLC would result in higher compression on the inner face of the lining due to higher expansion. Due to the fact that an increase in lining compression on the inner face would be more detrimental to the stability of the lining, it was decided only to reduce the PLC value, and not to examine the effects of an increase in PLC value for the finite element analysis.

Alder & Masaryk (1986), Tseng (1982), and Palin & Padgett (1988), have all discussed the effects of thermal "history" on the engineering properties of refractory concrete linings. They have shown that the idealised material properties chosen for the stress evaluation carried out in the first subproblem of this study, actually change depending on a number of factors concerning the heating up and cooling down of the lining in service. These factors are:

- The rate at which the lining is initially heated up after installation.

- The number of times the lining is allowed to cool down and be reheated in service.
- The rate at which the lining is allowed to cool down and heat up in the above mentioned fluctuations.

- Transient heating and cooling caused by the process involved.

The above are a number of the complex criteria that influence the lining's engineering properties, every time the lining is subjected to a cool down and subsequent reheat, the properties change. The effects of thermal history are extremely difficult to quantify. The permanent linear change of the lining is one of the properties that may vary depending on the lining history, in order to capture the full range of possible values for the PLC, it was decided to reduce the PLC values in Table 3.4 by 50%, and then to carry out the comparative lining stress evaluation. In order to ascertain whether the effect of lining PLC is beneficial to the lining in terms of stress, the effect of zero PLC were also examined.

The reduced temperature dependent PLC's were again converted into negative temperatures as done in 3.2.6,, and the resultant temperatures were entered into the Finite Element Analysis, and the lining stresses were evaluated. The resultant boundary temperatures appear in Table 3.11. & 3.12. All the other variables were kept as per subproblem 1. The results showing the lining stress values due to a 50% reduction and zero value for PLC appear in figures 4.11 & 4.12 respectively.

Table 3.11 Boundary temperatures for finite element analysis zone 2 (PLC reduced by 50%)

Surface	Operating Temp °C	PLC Temp °C	Construction Temp °C	Resultant Temp °C
lining inner	426	-105	25	296
lining outer	100	- 24.5	25	50.5
shell inner	99	0	25	74
shell outer	97	0	25	72

Table 3.12 Boundary temperatures for finite element analysis zone 2 (PLC reduced to 0)

Surface	Operating Temp °C	PLC Temp °C	Construction Temp °C	Resultant Temp °C
lining inner	426	0	25	401
lining outer	100	0	25	75
shell inner	99	0	25	74
shell outer	97	0	25	72

3.4 SUBPROBLEM 3

The statement of subproblem 3 was as follows:

The third subproblem is to establish a PC based program for the evaluation of the refractory concrete lining stresses, in order to establish a practical site-usable design tool.

3.4.1 Overview

The use of finite element analysis techniques has been used in subproblems 1 and 2 to evaluate the lining stresses in the calciner linings. Irrespective of how advanced the computerised system one uses, the validity of the results obtained depends on good quality accurate input data. In the case of this study, the input data required was the lining material properties, the steel shell properties, and the operating conditions of the calciner. The use of the input data for the finite element analysis in this study was based on the following assumptions:

- The temperature effects inside the calciner were assumed to be steady state, and transient heating and cooling was ignored.

- The effects of thermal "history" were ignored.

- The engineering properties required were linearly interpolated between known values.

- The operating temperatures were taken as the values recorded at the calciner instrumentation panel, and fitted to a temperature profile curve.

The assistance obtained by the finite element analysis was the ability of the computer program to obtain values for the engineering properties at different positions through the lining cross section, and to use the values to carry out the lining stress evaluation in incremental steps, thereby obtaining an accurate value for the lining hot and cold face stresses.

The use of finite element systems is a costly exercise, and the value of it is entirely dependent on the quality of information available as input data. Based on the assumptions made for the solutions of subproblems 1 and 2, it is apparent that a simpler, more readily available analysis tool may have been as effective in analysing the stresses as the finite element analysis.

A paper presented by Wygant & Crowley to the American ceramic society in May 1963, has been used as reference by researchers in more recent papers. (Tseng 1982; Farris 1978)

The method used in the study by Wygant and Crowley was based on the assumptions that all reactions are purely elastic, and that the lining properties are uniform throughout the lining cross section. These assumptions are the fundamental difference between the approach by Wygant and Crowley, and the finite element approach.

In their paper, Wygant and Crowley carried out theoretical stress analyses on a refractory concrete lining in a vessel, based on the following assumptions:

- That all stress/strain relationships are purely elastic.
- That shrinkage varies linearly with temperature.
- That the thermal conductivity is constant through the lining.
- That the Elastic modulus is constant through the lining.
- These assumptions lead to linear shrinkage, temperature, and strain gradients through the lining.

The results obtained from the abovementioned theoretical method were verified by constructing a model of the vessel and measuring the lining stresses using strain gauges. The results of the model test showed that the theoretical values calculated were conservative.
The purpose of this subproblem was to compare results obtained using the finite element analysis with results

obtained using the method proposed by Wygant and Crowley.

3.4.2 Methodology

The method used in the paper by Wygant and Crowley was based on the assumptions mentioned above, and was formed on the basic principle of elastic stress/ strain behaviour. The assumptions made were dealt with in detail in the Wygant and Crowley paper, and are discussed in this paper in section 5.4. The result of the assumptions made in the Wygant and Crowley paper is a simplification of the very complex thermo-structural behaviour of a refractory concrete lining in service, and followed the following steps:

- The first step was to calculate the unknown shell temperature, using the thermal conductivity coefficients of the lining and shell, and the known internal temperature. (units - °C)

- Next the thermal expansion and resultant elongation of the shell were calculated.(units - mm/mm)

- The lining expansion and shrinkage based on the mean (at centre depth) temperature were calculated next, and the difference between shrinkage and expansion yielded the net strain value.(units - mm/mm)

- The mean circumferential lining stress was calculated next by multiplying the net lining strain with the elastic moduli.(units - MPa)

- The following step was to calculate the hot and cold face stresses, by finding the stress differentials from the mean due to shrinkage and expansion, and applying them numerically to the mean stress value.(units - MPa)

Wygant and Crowley used a fully worked example to elucidate their method. The example that was used provided a lining that was in contact with the shell, and the stress values were thus affected by this. Under the assumption that the lining is free to move until it makes contact with the shell, the lining hot and cold faces would be in equilibrium (Popov 1978), with the neutral axis in the centre of the lining cross section, until contact with the shell is made. In the Wygant and Crowley paper, the effect of the lining making contact with the shell was that the lining hot and cold faces were numerically different, therefore the lining neutral axis had moved from the centre of the lining.

3.4.3 Application of the Wygant and Crowley method

In the application of the method of Wygant & Crowley to this study, the shell temperatures were known, along with the internal temperatures, thus the determination of these values was not necessary. Other than this deviation, the method used in this study was taken directly from the Wygant and Crowley paper.

The Wygant and Crowley method was written into a personal computer based program using the "C" programming language, the steps followed in the program are thus as follows:

- The external shell temperature is assumed to be equal to both the internal shell temperature and the lining outer temperature.

- nomenclature for the analysis is as follows:

  D = internal shell diameter (mm)
  Ls= thickness of steel shell (mm)
  Es= elastic modulus of shell (MPa)
  αs= thermal expansion coefficient of shell (per °C)
  μs= Poissons ratio for the shell
  Ll= thickness of the lining (mm)
  El= elastic modulus of the lining (mm)
  αl= thermal expansion coefficient of the lining (per °C)
  μl= Poissons ratio of the lining

Stl= PLC of lining at internal lining temp. (mm/mm)

Sts= PLC of lining at shell temp. (mm/mm)

Tc= temperature of lining at construction (°C)

Ti= operating internal temperature (°C)

Ts= measured shell temperature (°C)

Tl= mean lining temp. = $(Ti+Ts)/2$ (°C)

P= internal operating pressure (MPa)

- Step 1 is to calculate the stress caused by vessel internal pressure:

  $\sigma p = P.D \;/\; (2.Ls)$ .... eqn 1

- Step 2 is to calculate the hoop strain effect caused by the applied stress.

  $\epsilon p = (\sigma p/Es) \;.\; (1-\mu s/2)$ .... eqn 2

- Step 3 calculates the thermal expansion of the shell

  $\beta s = \alpha s(Ts-Tc)$ .... eqn 3

- Step 4 sums the total shell expansion ignoring the lining stress.

  $\Sigma s = \epsilon p+\beta s$ .... eqn 4

- Steps 1 to 4 calculated the shell strains, the next steps calculate the lining strains. Step 5 calculates the mean thermal expansion of the lining.

  $\beta l = \alpha l(Tl-Tc)$ .... eqn 5

- Next, step 6 calculates the mean shrinkage of the lining.

  $\theta l = 0.5(Sts=Stl)$.................. eqn 6

- Step 7 calculates the net unrestrained expansion of the lining.

  $\Sigma l = \beta l - \theta l$......................... eqn 7

- Step 8 calculates the differential in expansion between the lining and the shell.

  $\Sigma = \Sigma s - \Sigma l$......................... eqn 8

- A negative value for Σ indicates interference of the lining expansion by the shell, a positive value indicates that the lining has not made contact with the shell, and based on the assumption that the lining is free to expand until contact with the shell is made, the value would therefore be hypothetical, and is hence equated to 0.

- Step 9 is to calculate the mean lining <u>stress</u>.

  $\sigma lm = El.\Sigma\ (Es.Ls/(El.Ll+Es.Ls))$... eqn 9

  in the case of the lining expansion being less than the shell expansion, Σ would be 0, and hence σlm would be 0, this is valid, as the lining stresses would be in equilibrium.

- Step 10 calculates the difference in lining outer face stresses from the mean, caused by thermal expansion.
  $\sigma lt= El.\alpha l(Ti-Ts) / (2(1-\mu l))$..... eqn 10

- Step 11 calculates the difference in lining outer face stresses caused by the shrinkage gradient.
  $\sigma ls= El(Stl-Sts) / (2(1-\mu l))$...... eqn 11

- Step 12 calculates the circumferential lining stress at the exposed (hot) face.
  $\sigma h= \sigma lm-\sigma lt+\sigma ls$.................. eqn 12

- Step 13 calculates the circumferential lining stress at the cold face (adjacent to shell).
  $\sigma C= \sigma lm+\sigma lt-\sigma ls$.................. eqn 13

- Negative stresses indicate compression, and positive stresses indicate tension.

The example used in the paper by Wygant & Crowley was used to check the accuracy of the program, and the results were as follows:

	lining stress (MPa)	
	PC program	Wygant & Crowley
hot face	-7.11	-6.79
cold face	+5.84	+6.04

comparitive results show that the pc based program was accurate to around 4.5%, but the absolute mean of the values were the same. For a order of magnitude study, the program was thus considered to be sufficiently accurate.

3.4.4 Analysis procedure.

As this subproblem sought to compare the finite element results with results from the method proposed by Wygant and Crowley, the analysis procedure that was adopted was only of value providing that the same data was used in this sub problem as was used in sub problem 2.

Initially, in order to obtain a full comparison between the two methods, the same input data as that used for the finite element analysis in subproblem 1 was used, in order to obtain a comparison with the results obtained in subproblem 1. The results of the analysis using the Wygant and Crowley method appear in Table 4.2.

The next steps in the analysis were to run the program using the same input data as used for the finite element analysis of sub problem 2.
The resultant stress values obtained appear in Table 4.2.

CHAPTER FOUR

THE RESEARCH RESULTS

4.1 INTRODUCTION

In section 3.2.6.4, the effects of the lining expansion under high temperatures, and the effects of the steel shell on the lining expansion have been discussed. The results of the finite element analyses in this study are highly dependent on the interface between the lining and the shell. When the lining has expanded, and is not in contact with the shell, stress equilibrium must exist. In other words, the inner and outer face stresses of the lining would be equal in magnitude, but opposite in nature. Under these equilibrium conditions, the lining stresses would vary linearly with a linear change in any stress related variable.

Should the lining make contact with the shell, the shell would have a restraining effect on the lining expansion, and the stresses would differ in magnitude on the hot and cold faces.

Two samples of the printouts of the finite element analyses appear in appendix A, one of which represents an equilibrium condition, the other a non -equilibrium condition. The hoop stresses are located under the column heading " direct stress Y direction". The equilibrium condition can be seen from the fact that the lining inner and outer face stresses are of the same magnitude, (23.5 and 23.9 MPa at nodes 8 and 105), and that the shell stresses are relatively low (3.6 MPa at nodes 120, 121, 136, and 137). The non -equilibrium condition can be seen from the difference in the hot and cold face stresses, and the relatively high shell stresses (same node numbers). It was considered extraneous to include printouts of every analysis in the presentation of the results.

In both the linear and non-linear cases, the maximum lining stress would occur on one or both of the outer faces. The hot and cold face stresses are thus the critical values in this study.

Wygant and Crowley (1964) have stated that circumferential stresses are larger, and hence more critical, than axial stresses in cylindrical vessels such as the calciner. The results hereunder are thus cylindrical or "hoop" stresses.

4.2 THE RESULTS OF SUBPROBLEM 1

4.2.1 "Worst case" scenario Zones 2 and 4 (anchor effects ignored)

The method used to establish the results for subproblem 1 has been discussed in detail in section 3.2. The purpose of the subproblem was to use what was found to be the most severe temperature conditions prevalent in Tioxide S.A's number 1 calciner, in order to obtain a maximum applied stress value due to the effects of temperature.

The first part of subproblem 1 was to calculate the lining stresses in zones 2 and 4 without the effects of anchors interfering with the thermal movement of the lining and shell. The second part was to carry out the same analyses with the effects of anchors as discussed in 3.2.9.3. Presentations of the results of the finite element analyses (without anchors) appear in Figure 4.1 for zone 2 , and in Figure 4.2 for zone 4.

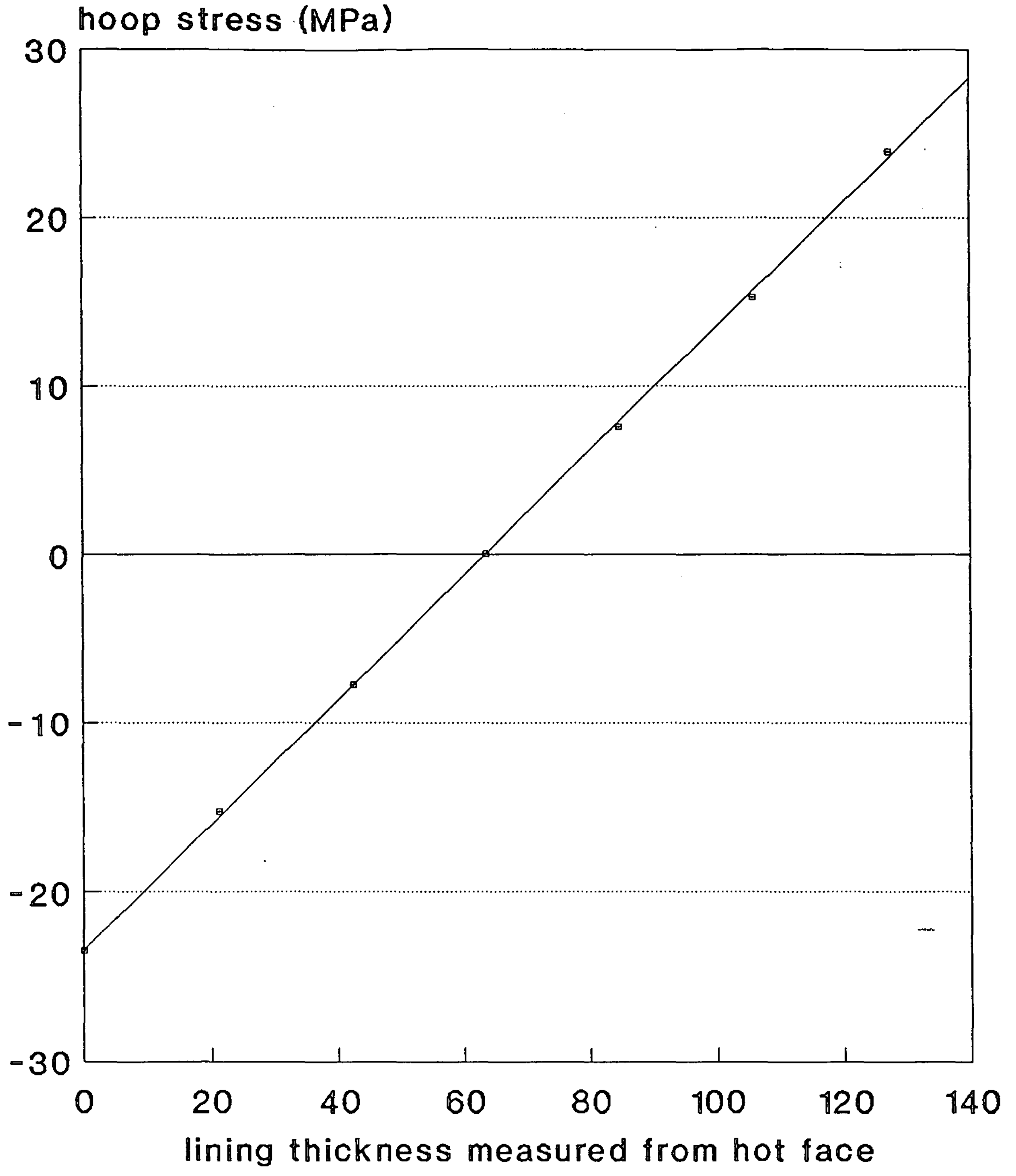

Figure 4.1: Lining stresses for zone 2 using maximum temperature gradient (ignoring anchor effects).

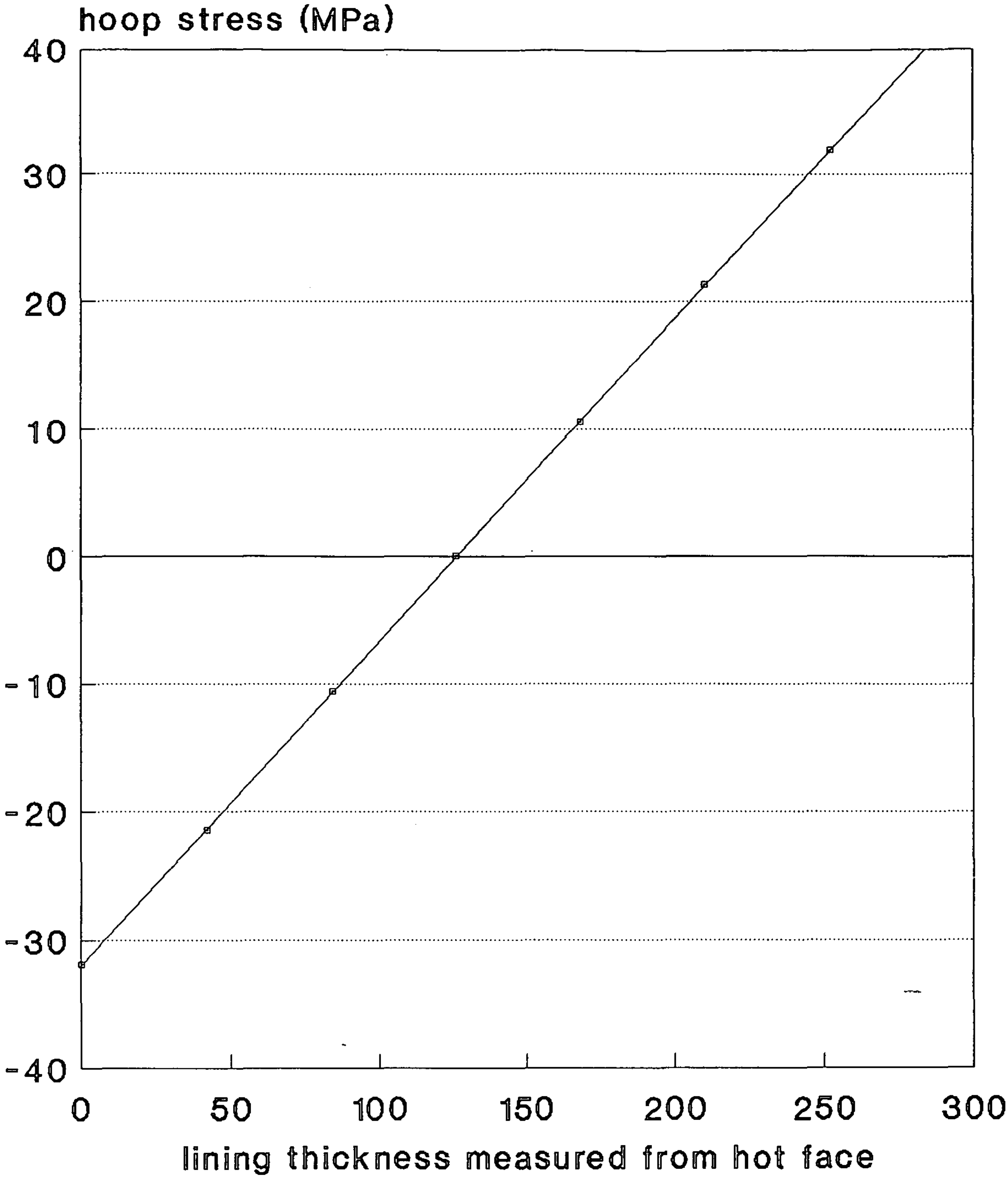

Figure 4.2: Lining stresses for zone 4 using maximum temperature gradient (ignoring anchor effects).

Figure 4.1 shows that the lining stresses are in equilibrium, due to the fact that the hot and cold face stresses are the same. The actual values obtained from the finite element analysis are 23.5 MPa at the hot face (compression), and 23.9 MPa at the cold face (tensile). This implies that the lining is not in contact with the shell under the conditions of this particular analysis. Figure 4.3, shows the computer graphical representation of the analysis, and the gap between the shell and lining can be clearly seen.

The maximum value of around 24 MPa is not sufficient to cause failure of the lining on the compressive (hot face) side, as the cold crushing strength of the material as indicated in Table 3.6 is of the order of 80 - 100 MPa. The cold face of the lining would definately have cracked under the 23.9 MPa tensile stress, as the modulus of rupture as indicated in Table 3.6 is only of the order of 9 - 10 MPa. The stress profile shown in Figure 4.3 indicates that cracking would occur from around 80mm in depth, through to the outer surface of the lining.

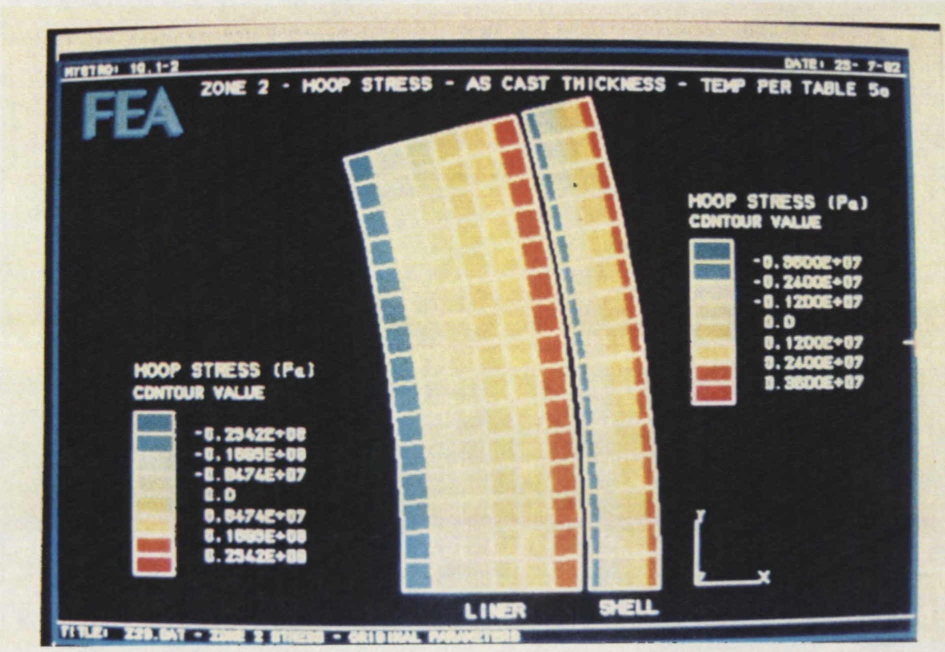

Figure 4.3. Computer Graphic of Zone 2 Hoop stress distribution

In Figure 4.3, as well as all the following finite element photographs, the lining stresses are shown on the left hand scale, and the right hand scale indicates the steel shell stresses. The gap between the lining and shell is representative of the actual gap calculated, and is not diagrammatic or theoretical. These are photographs taken of the screen after the finite element analysis had been completed.

The stress analysis result shown in Figure 4.2 shows that the lining in zone 4 is subject to equilibrium stresses of 31.9 MPa. The equilibrium of the stresses shows that the lining is not in contact with the shell under the maximum applicable temperature gradient (ignoring anchor effects). The stress evaluation computer graphics for this analysis are shown in Figure 4.4. The gap between the lining and shell is relatively small, which indicates that the lining expansion is close to being restrained by the shell.

The increase in lining stresses above those obtained for zone 2 is as a result of the increased expansion of the lining caused by the higher temperature in zone 4.

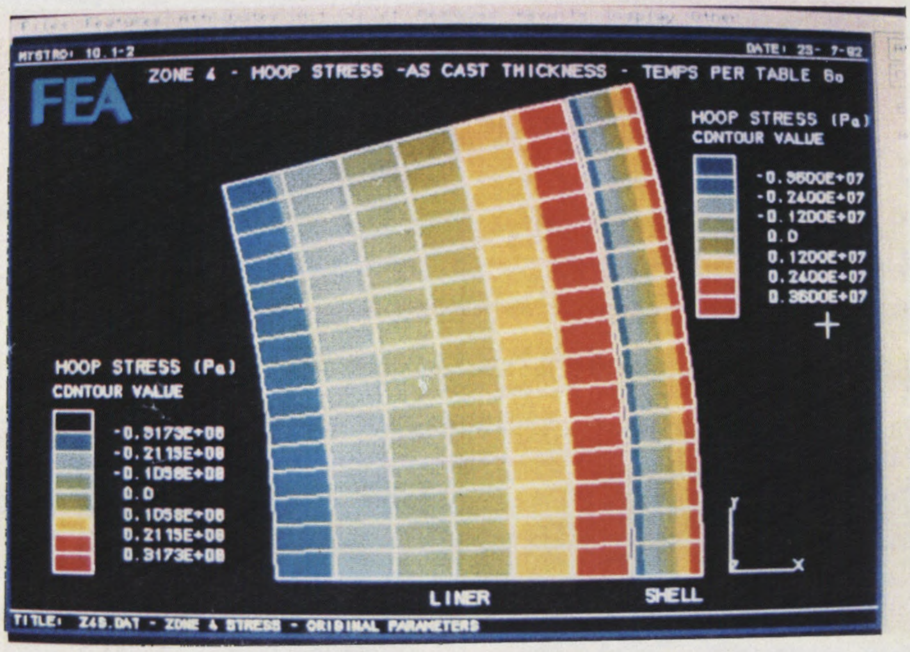

Figure 4.4. Computer Graphic of Zone 4 Hoop Stress Distribution

4.2.2 "Worst case" scenario Zones 2 and 4 (anchor effects included)

The finite element computer graphics showing the lining stress distribution including the effects of the steel anchors as discussed in 3.2.9.3 appear in Figure 4.5 for zone 2, and Figure 4.6 for zone 4.

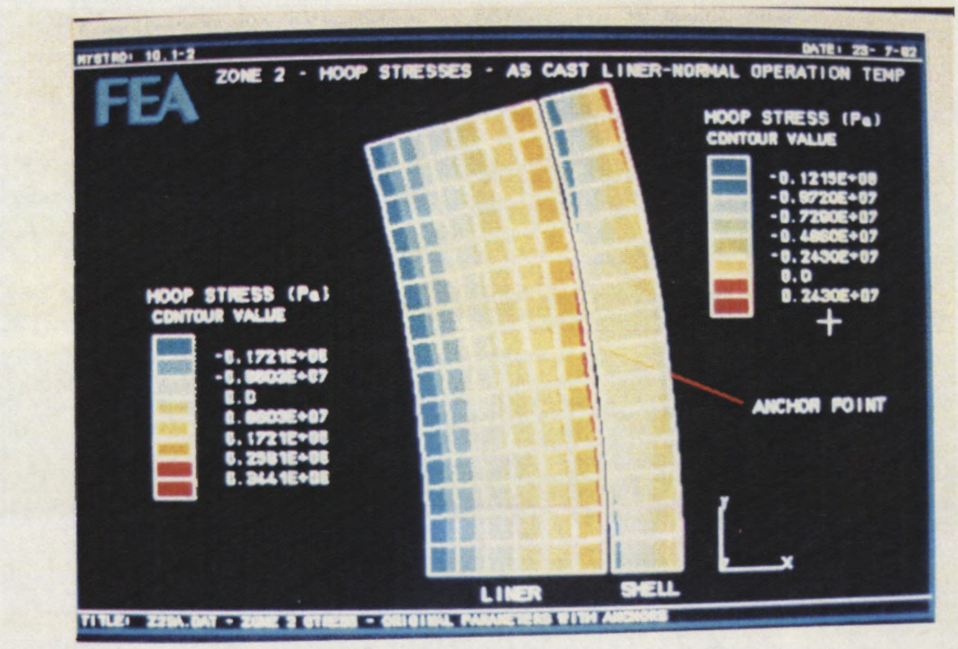

Figure 4.5: Finite Element Analysis Graphic Showing Lining stresses for zone 2 using maximum temperature gradient (including anchor effects).

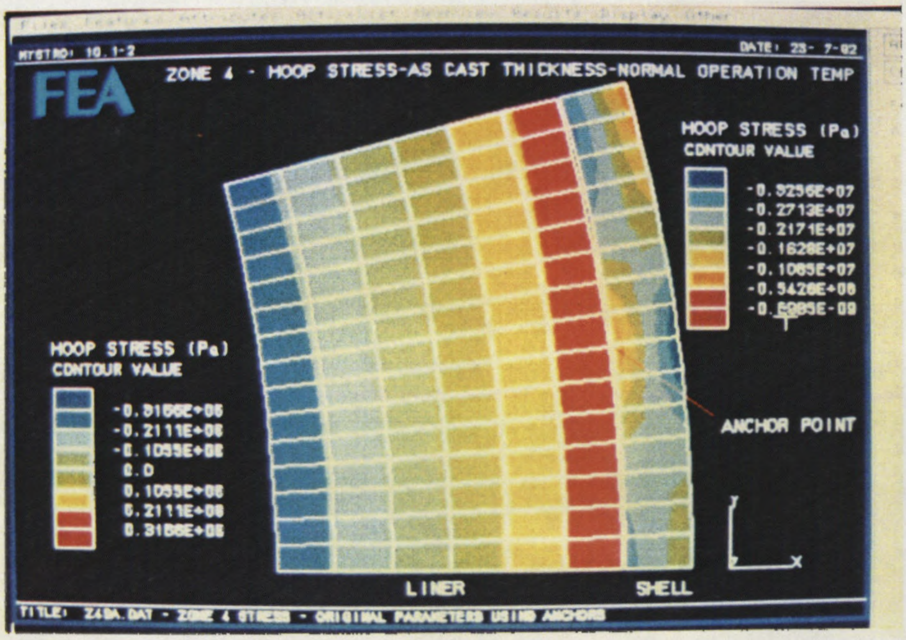

Figure 4.6: Finite Element Analysis Graphic Showing Lining stresses for zone 4 using maximum temperature gradient (including anchor effects).

The graphical representation of the lining stresses shown in Figure 4.5 shows a slightly higher stress at the anchor than away from it. This increase in lining stress comes about as a result of the shell expansion causing a stress concentration where the lining is "pulled" by the anchor. The increase in stress at the anchor point results in a maximum stress value of a little more than 25.8 MPa, this is only just higher than the stresses observed in 4.2.1, and is local to the anchor only. Away from the anchor, the cold face stresses stresses are around 25.8 MPa, which is a negligable difference to those in 4.2.1. The hot face stresses are approximately 24 MPa, which in terms of concrete stresses is a negligable difference to the lining stresses shown in Figure 4.1.

With the results shown thusfar, the high tensile stress of the cold face of the lining would be the most likely cause of failure. Although the anchor effects are small, any increase in cold face stress would be detremental to the lining stability.

Figure 4.6 shows the hot and cold face stresses in zone 4 with anchor effects as being in equilibrium, at values of around 31.7 MPa. These values are the same as those in Figure 4.2, showing the lining stresses in zone 4 without the effects of the anchors. This similarity in results shows that the anchors have no effect on the lining stresses in zone 4. The lack of influence of the anchors on the lining stresses is as a result of the stiffness of the thick lining in zone 4, which is large when compared with the stiffness of the anchors. Another factor that would account for the lack of anchor influence, is the relatively small gap between the lining and the shell.

The lining used in the no.1 calciner at Tioxide S.A. failed in tension under assumed worst case conditions, this meant that the first hypothesis stated in 1.4.1, was rejected.

4.3 THE RESULTS OF SUBPROBLEM 2

4.3.1 Decreased lining thickness

The application of a decreased lining thickness in order to observe the lining stress trends has been discussed in detail in 3.3.3.1. The lining thickness was reduced by 25% and the finite element stress analysis was carried out. The graphical depiction of the result of the finite element analysis carried out for zone 2 with a 25% reduction in lining thickness appears in Figure 4.7.

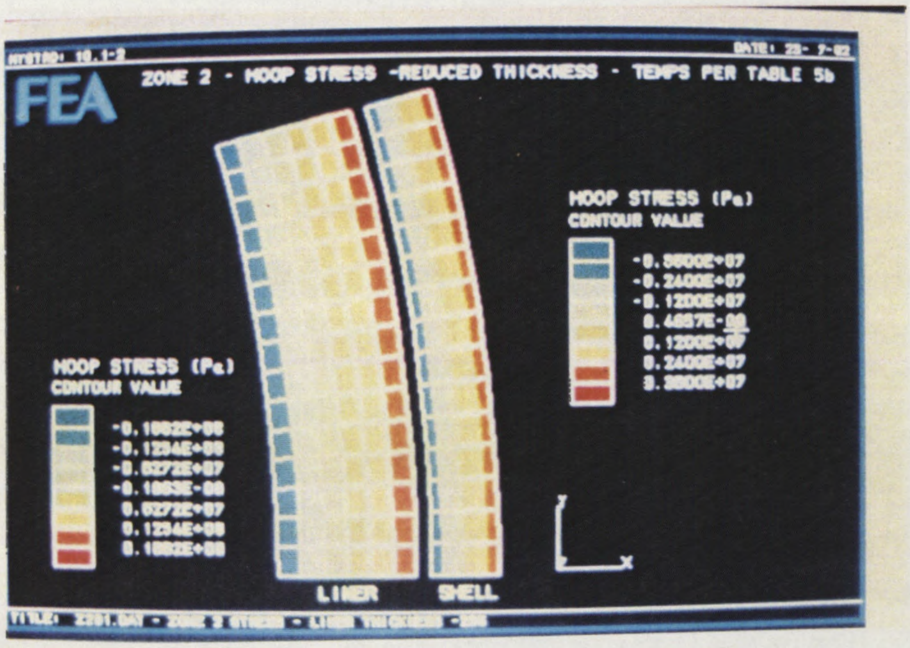

Figure 4.7: Zone 2 Hoop Stress With Lining Thickness Reduced by 25%

Figure 4.7 shows that the lining stresses are of equal magnitude on the hot and cold faces at 18 MPa, thus equilibrium had been maintained, and the lining and shell would not have been in contact. The value of 18 MPa represents a reduction of 24% from the value of 23.7 MPa average shown in Figure 4.1.

The reduction in stress is as a result of the increased lining cold face temperature which reduces the temperature gradient, thereby reducing the thermal strain, and hence the stress.

Due to the fact that the lining is under equilibrium and free expansion, and that the temperature dependent variables were assumed to have a linear variation with temperature, the ratio of 24% (approx. 25%) for a lining thickness reduction of 25% would be expected.

4.3.2 Changes in modulus of elasticity

The changing of modulus of elasticity (MOE) in the finite element analysis has been discussed in 3.3.3.2. The values for MOE used in subproblem 1 were increased, and then decreased by 20%, and entered into the finite element analysis, in order to ascertain the effects of MOE on the lining stresses in Tioxides number 1 calciner. The results of the changes appear in Figure 4.8 (20% increase), and 4.9 (20% decrease).

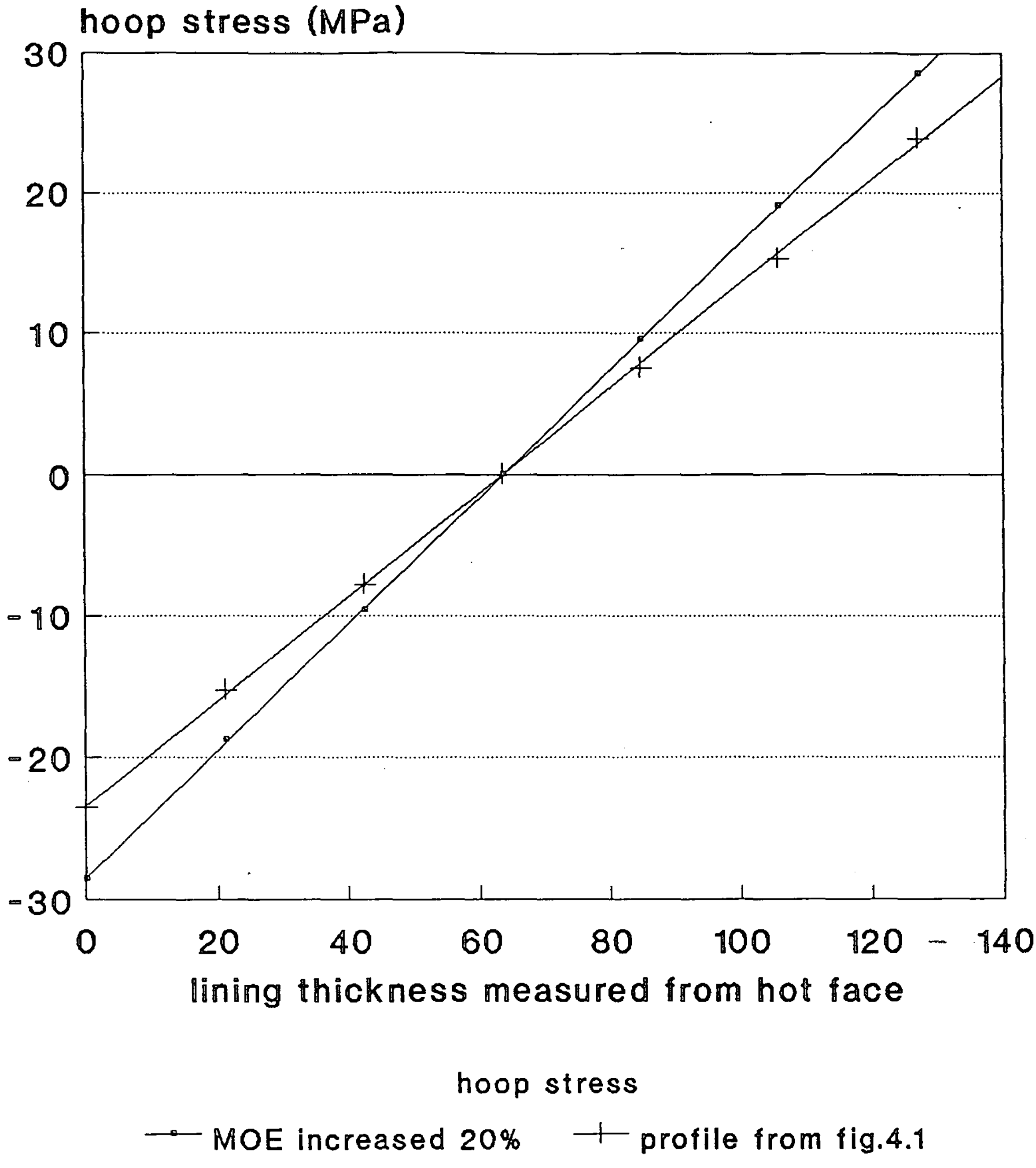

Figure 4.8: Zone 2 Hoop Stress with Modulus of Elasticity Increased by 20%.

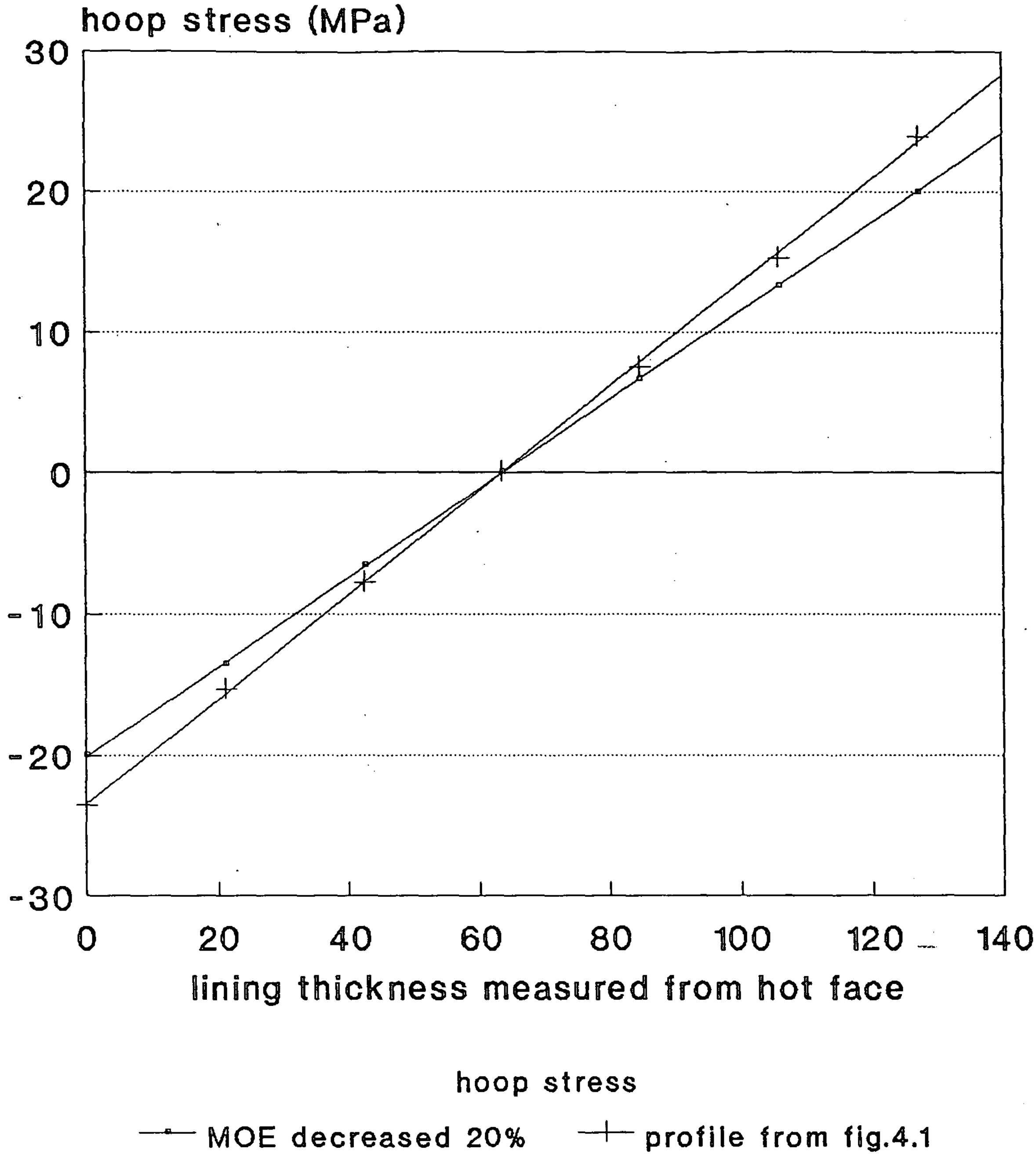

Figure 4.9: Zone 2 Hoop Stress with Modulus of Elasticity Decreased by 20%.

In both cases (incresed MOE and decreased MOE), the lining hot and cold face stresses were in equilibrium, showing that the lining and shell had not made contact. The assumed linear temperature dependent nature of the modulus of elasticity meant that under equilibrium conditions, the lining stresses would vary linearly with a change in the MOE. Therefore the lining stresses have increased and decreased respectively by 20%, to 28.5 MPa and 19.5 MPa. The basic elastic equation of (MOE = Stress/strain) implies that the higher the value of MOE, the higher the stress would be for the same strain, and vice versa. This therefore confirms the values obtained.

4.3.3 Internal temperature increased by 20% The internal temperature was increased by 20% in accordance with 3.3.3.3. Whereafter the finite element analysis was carried out. The lining cold face temperature was maintained the same as in 4.2.1, this coupled with the increased internal temperature lead to a steeper temperature gradient, as well as different temperature dependent variables through the lining cross section. The results obtained from this analysis appear in Figure 4.10.

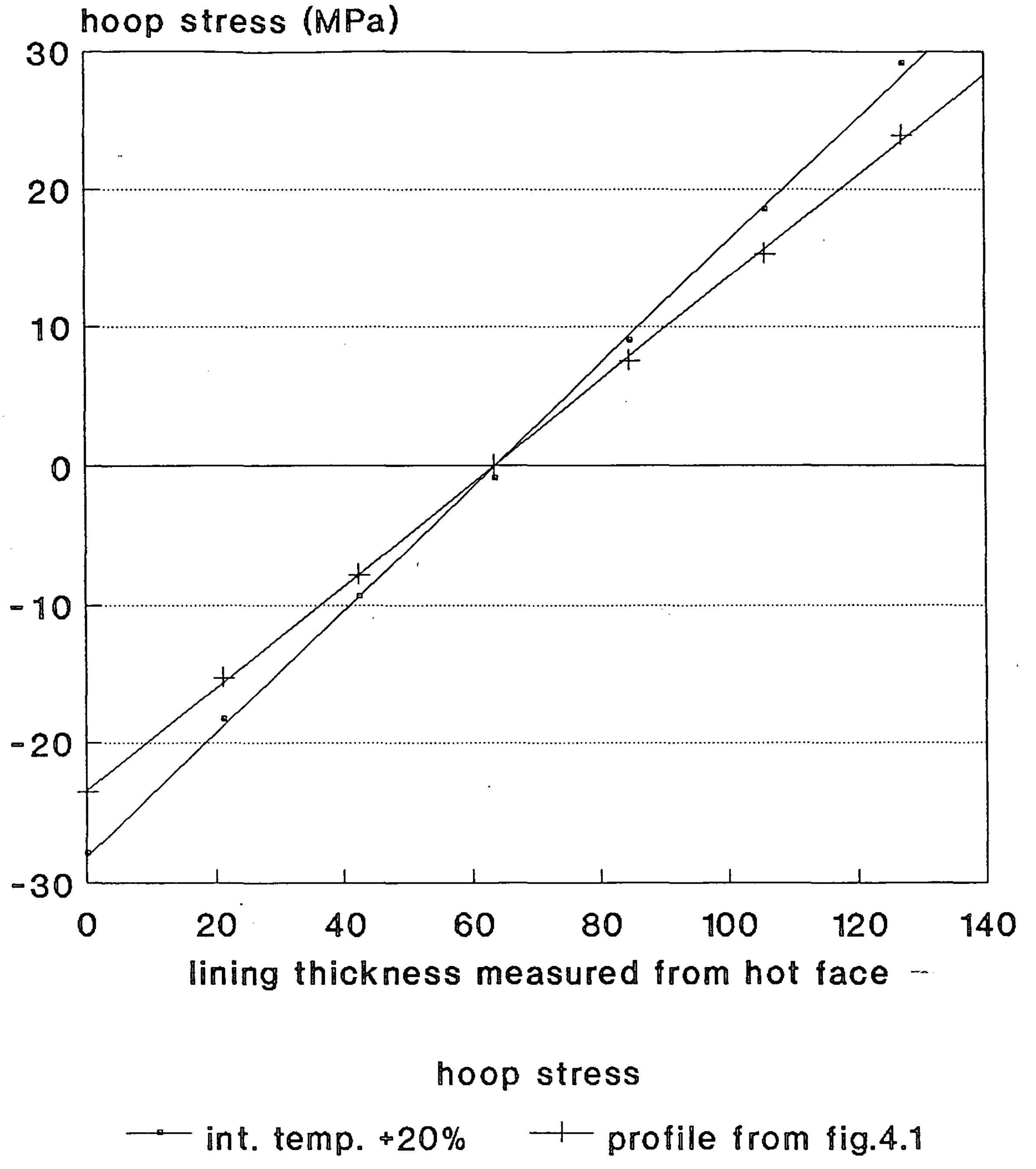

Figure 4.10: Zone 2 Hoop Stresses (Internal Temperature Increased by 20%)

The presentation of results in Table 4.10 shows a small difference of 1.2 MPa between the hot face stress at 27.95 MPa, and the cold face stress at 29.1 MPa. This difference is not significant enough to suggest that the lining and shell are in contact. The finite element analysis for this particular analysis showed the shell stress as being identical to the value given for the analysis of subproblem 1 (4.2.1), at a low value of 3.5 MPa. This fact would substantiate the statement that the lining and shell would still not be in contact under this increased internal temperature.

4.3.4 Permanent Linear Change reduced by 50%

The reduction of permanent linear change (PLC) as input data for the finite element analysis has been discussed in 3.3.3.4. The Table of reduced PLC values was stored in the finite element analysis program, and the analysis was performed. The result of the analysis appears in Figure 4.11.

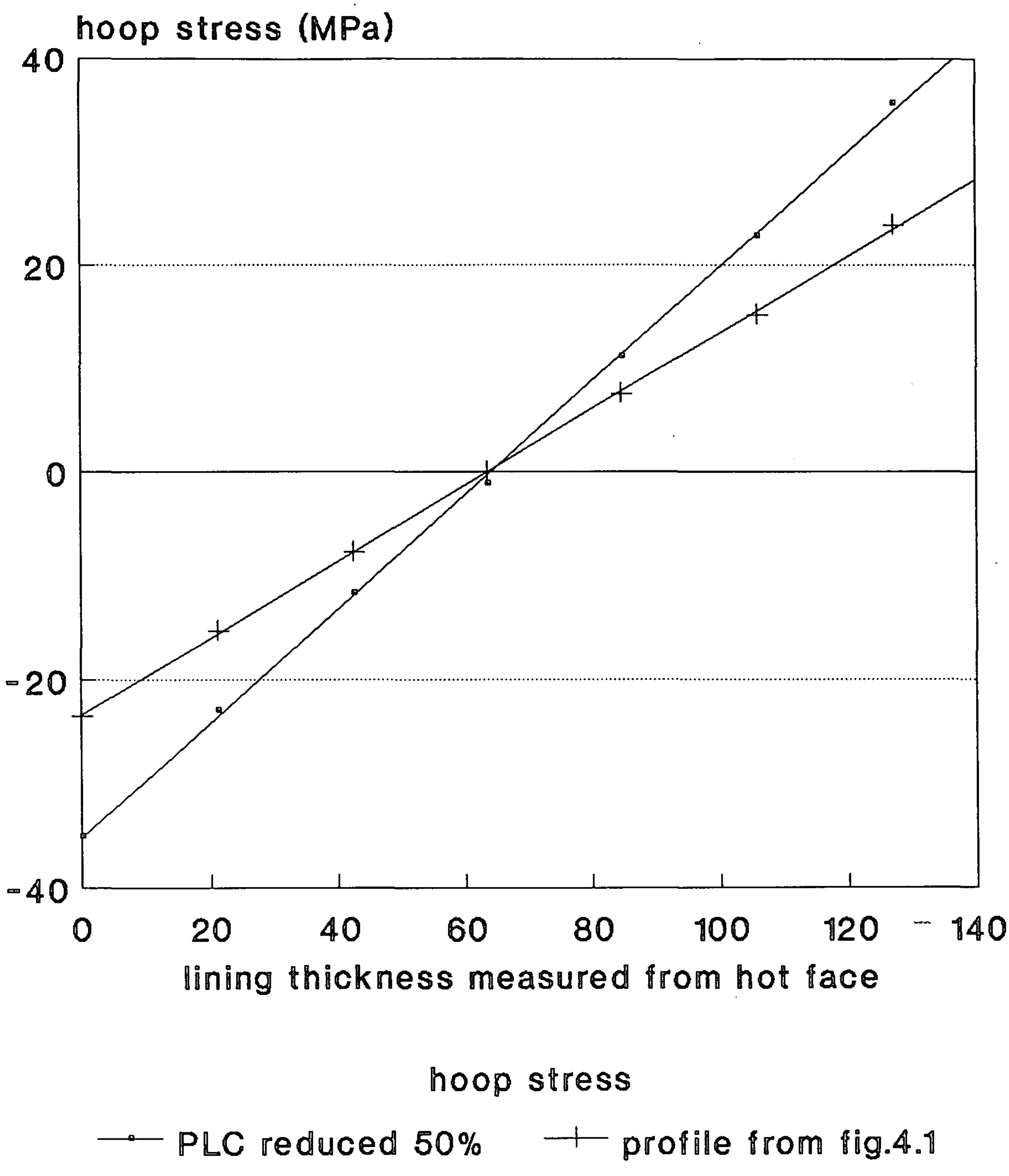

Figure 4.11: Zone 2 Hoop Stress (Permanent Linear Change Reduced by 50%)

The hot and cold face stresses of 35.1 MPa and 35.6 MPa respectively shown in Figure 4.11 represent increases of 49% in lining stress over the figures shown in Figure 4.1. Again as in all cases where the hot and cold face stresses are equal in magnitude, the lining would not have come into contact with the shell, and equilibrium conditions would apply. Under the equilibrium conditions, it is anticipated that a 50% change in the PLC, would result in a 50% difference in the applied stress.

The increase in stress is as a result of the increased net expansion due to the reduction in permanent linear shrinkage.

4.3.5. Permanent Linear Change reduced to zero

Reducing the value of the PLC to zero was done in this study in an effort to maximise the lining expansion, and to observe the effects of maximum expansion on the lining stress levels. The Table of values in the finite element analysis for PLC was set to zero, and the finite element analysis was carried out. The results of this analysis appear in Figure 4.12.

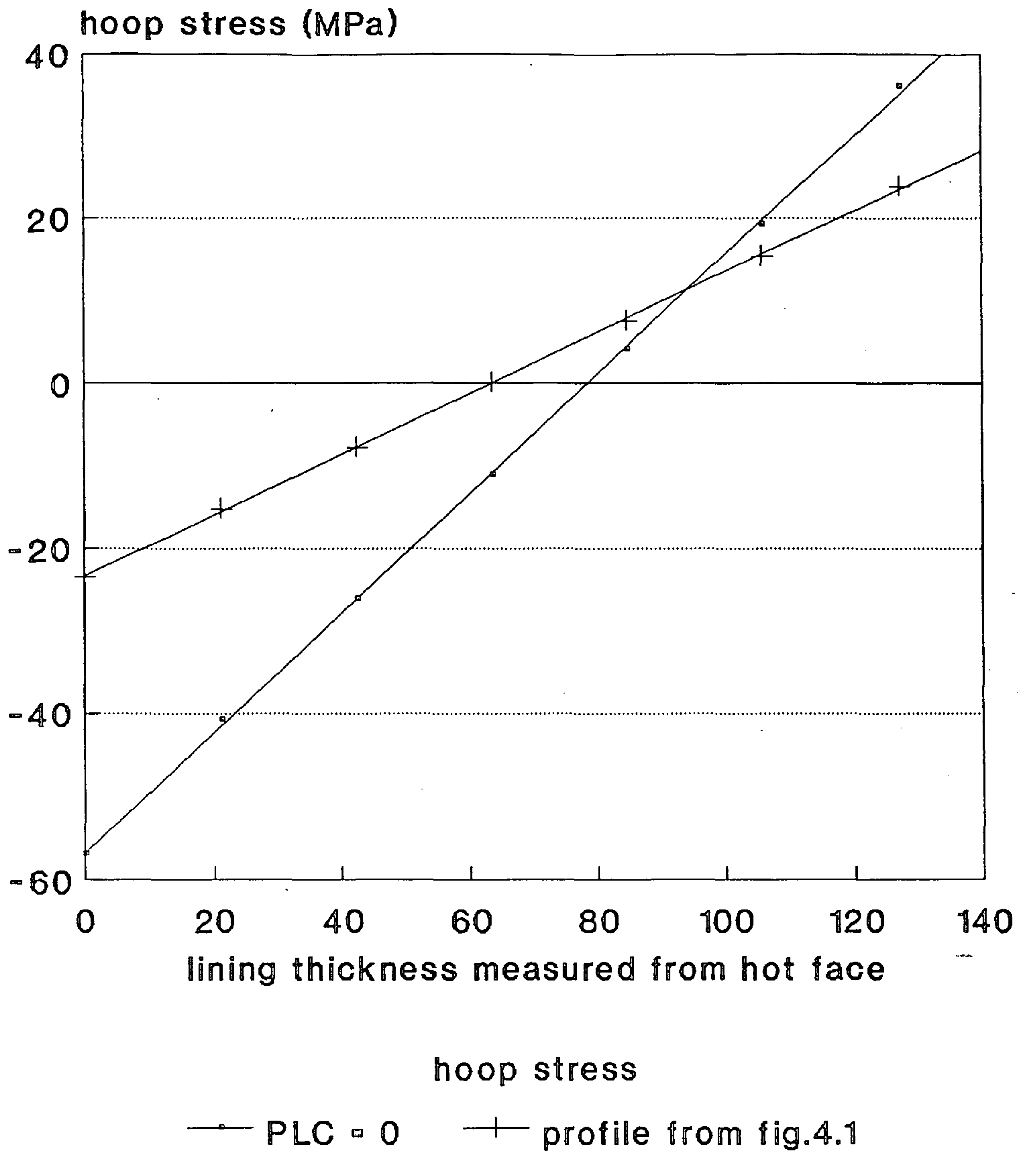

Figure 4.12: Zone 2 Hoop Stress (Permanent Linear Change reduced to zero)

The results presented in Figure 4.12 clearly show a higher at the hot face than at the cold face. This difference in stress is a clear indication that the shell has interfered with the lining expansion, and is tending to cause high compression on the hot face. The hot face compression value of 57 MPa is an increase of 142% over the 23.5 Mpa shown in Figure 4.1, and the cold face value of 36.2 MPa is an increase of 51.5% over the corresponding Figure 4.1 value of 23.9 MPa. This difference in relative values is as a result of the neutral axis shifting outwards with the increase in lining hot face compressive stress.

From the results in Figure 4.12, it would be unacceptable to have such a situation in the calciner at Tioxide, as the lining would have developed tension cracks on the cold face, and the hot face compression would be around 70% of the cold crushing strength of the lining material, which is not a high factor of safety.

4.3.6 Comparison of results

As the goal of subproblem 2 was to observe the influence of changes in variables on the lining stress levels, it is necessary to compare all the results from subproblem 2 with the stress values obtained in subproblem 1 for zone 2 without the anchor effects. The comparison of all the results obtained thusfar appears in Table 4.1, and has been depicted in Figure 4.13. The figures in Table 4.1 have been rounded off to the nearest MPa for clarity.

Table 4.1: Comparison of All Changed Variable Stress Analyses with the Results from Subproblem 1.

	Zone 2		
Variable Changed	Hot Face Stress (MPa)	% Change	Cold Face Stress (MPa)
no changes (subproblem 1)	24		24
lining thickness reduced by 25%	18	-25	18
Elastic modulus increased by 20%	29	+21	29
Elastic modulus decreased by 20%	20	-17	20
Internal temperature increased by 20%	29	+21	28
PLC reduced by 50%	35	+50	36
PLC reduced to 0	57	+138 +50	36

The comparison of the results shown in Table 4.1 and Figure 4.13 shows linear relationships between changes in the value of the thermo-structural variables, and the change in lining stresses, when the lining is not in contact with the shell. This is applicable to all the cases in Table 4.1 except the case where PLC = zero.

The linear relationship mentioned in the above paragraph is reasonable to accept due to the linear assumptions made with respect to the temperature dependent variables. However, the linear relationship is only valid providing the lining is under stress equilibrium.

The result of equating the PLC to zero was that the lining expansion was greater than the shell expansion would accommodate, the result was a very high compressive stress on the inside face, but a less increase in tension on the cold face. The lower cold face stress is as a result of the shell taking part of the total stress.

Based on the assumptions made with respect to the temperature dependent variables, the observations thus made during the evaluation of the effects of changes in the variables on the lining stresses in Tioxide S.A's number 1 calciner are as follows:

i) A reduction in lining thickness yields a directly proportionate reduction in both the lining hot and cold face stresses. In considering lining stress only, this would be beneficial, however, the effect on the shell would need to be examined.

ii) A change in the value of the modulus of elasticity of the lining material provides a directly proportionate change in the lining stresses. An increase in modulus of elasticity would deepen the tension cracks on the cold face, but would have to be significantly large to cause excessive compression on the hot face.

iii) An increase in the lining internal temperature while maintaining the lining outer temperature constant causes the lining stresses on both the hot and cold faces to increase in direct proportion. The increased cold face stress would increase the severity of tension cracks, but in this case is not sufficient to do any serious damage to the lining inner face.

iv) A reduction in the permanent linear shrinkage value of the lining material yields an increase in lining hot and cold face stresses in direct proportion to the reduction in PLC, providing the lining is not in contact with the shell.

v) A significant reduction in the lining permanent linear change value is required in order to cause a dramatic increase in the lining hot face compressive stress.

Even with a zero PLC value, the lining hot face would not be stressed sufficiently to cause lining compression failure.

vi) As soon as the lining makes contact with the shell, the lining cold face stress remains constant as the shell shares the total stress, and the lining compression on the hot face continues to increase.

Changes in variables such as temperature, PLC, elastic modulus, made in order to observe their influences on lining stability resulted in both increased as well as decreased stresses. Combined effects of multiple changes to variables were not simulated, therefore the hypothesis stated in 1.4.2 remains untested.

4.4 THE RESULTS OF SUBPROBLEM 3

The goal of subproblem 3 was to establish a practical design tool for monolithic refractory lining stress evaluation in the form of a PC based program. The PC program was written, and the analyses performed in subproblems 1 and 2 using finite element analysis were repeated using the PC program.

4.4.1 The presentation of the results

The results of the PC program analyses and their comparisons with the values obtained in subproblem 2 appear in Table 4.2. Samples of the computer printouts for the PC program appear in appendix B.

Table 4.2: Comparison of Results Between the Finite Element Analysis and the PC Based "Wygant and Crowley (1964)" method.

description of variable status and zone	Hoop Stress (MPa) finite element analysis results		Wygant and Crowley method results	
	hot face	cold face	hot face	cold face
all variables standard as per 4.2 (zone 2)	-23.5	+23.9	-25.3	+25.3
all variables standard as per 4.2 (zone 4)	-31.9	+31.9	-30.2	+30.2
25% reduction in lining thickness (zone 2)	-18.0	+18.0	-18.4	+18.4
20% increase in MOE (zone 2)	-28.5	+28.5	-30.3	+30.3
20% decrease in MOE (zone 2)	-20.0	+20.0	-20.2	+20.2
20% increase in internal temperature (zone 2)	-28.0	+29.1	-29.2	+29.2
50% reduction in PLC (zone 2)	-35.1	+35.6	-38.4	+37.0
PLC reduced to 0 (zone 2)	-57	+36.2	-61.6	+39.0

4.4.2 Discussion

The comparative results shown in Table 4.2 indicate that in all cases excluding the second case, the PC based method gives a higher value than the finite element analysis. This implies that the Wygant and Crowley method is more conservative than the finite element analysis, indicating that it would be useful to Tioxide Southern Africa as a design basis. However, both types of analyses are open to fluctuations in results depending on the accuracy of the input data, and the rounding off of numbers.

On average, the PC based method yields results 7.4% higher than the finite element analysis. This difference would be more significant at the cold crushing strength of around 100 MPa than it is in the region of 30 MPa.

The fact that the simplified approach formulated by Wygant and Crowley (1964) yields results so close to the results obtained in the finite element analysis, is an indication of the fact that the results obtained in both analyses represent true order - of - magnitude values for the data used.

The finite element analysis has been verified numerically, and vice versa. This should always be true for valid discrete analyses.

For the purpose of lining stress evaluation, using the approach set forth in this study, the PC based adaptation of the Wygant and Crowley method is as useful as two dimensional finite element analysis.

The evaluations used in this study (Tioxide S.A's number 1 calciner) indicated in all cases except 1, that the lining and shell have a gap between them, and that stress equilibrium conditions exist. Only 1 case of shell "interference" was apparent, although the comparison of results was similar, it cannot be categorically stated that this would be true for further expansion beyond the values listed in Table 4.2 for PLC = 0.

The positions in the calciner evaluated in this study indicated a lining that was not in contact with the shell. Stress equilibrium conditions existed, and linear elastic assumptions made for this study resulted in the finite element analysis and pc based analyses to be within 10% of each other. The hypothesis stated in 1.4.3 is therefore rejected.

CHAPTER FIVE

THE GENERAL DISCUSSION

5.1 DISCUSSION ON THE RESULTS

5.1.1 Introduction

The monolithic refractory concrete lining in Tioxide S.A's No.1 Calciner has been analysed in terms of lining stresses during operation.

The lining stresses were firstly evaluated under an assumed "worst case" operating condition, in order to establish the maximum applied lining stress likely to occur during operation.

Secondly, in order to establish the influence of engineering variables on the lining stresses, stress analyses using applied changes in variables were carried out.

Thirdly, a PC based program was developed, in order to provide Tioxide S.A. with a practical site useable design tool, for use in evaluating monolithic refractory lining systems.
The stress analyses were carried out using finite element

analysis techniques, and the PC based program results were compared with the finite element analysis results.

5.1.2 Calciner Lining Stresses and the Effects of The Engineering Variables

The results are shown in chapter 4, and were obtained using the data from chapter 3.

For all cases, barring one, the lining in both the feed end, and discharge ends of the calciner is not in contact with the steel shell. This has the effect of placing the lining under stress equilibrium, giving rise to compressive stresses on the inner hot face, and tensile stresses of equal magnitude on the cooler outer surface.

In all cases, the tensile outer face stresses are higher than the allowable limit for the lining material, hence the lining would be cracked on the outer surface during operation. The depth and width of the cracks would vary depending on the location under consideration. Upon cooling the calciner for shutdown, the tensile cracks will propagate through to the inner surface, and become visible. These cracks would have a tendency to become contaminated during a shutdown, with the result that they would be unable to close fully during warm up. This would result in the edges of the cracks breaking away, and causing wide grooves along the lines of the cracks. This phenomenon has already been seen in the calciner at Tioxide S.A, and is shown in figures 1.2 and 1.3.

The tensile stresses are "high" in comparison with the lining capabilities, but the compressive stresses are only around a quarter of the allowable limit of the lining, hence compressive crushing of the lining on the hot face will not occur under any of the cases examined, including the assumed worst case.

The effect of lining permanent linear change is only apparent after a period of sustained heating. Therefore initially, after the first warm up after lining installation, the lining would be under net expansion only. This effect was modelled, and it was found that the lining would be in contact with the shell in the feed end zone, prior to the effects of shrinkage becoming apparent. The lining stresses under this condition were the highest observed on both the inner and outer faces, although the change in neutral axis position lead to a greater increase in inner face compression than outer face tension.

The individual effects of changes in the lining properties on the lining stresses has been discussed in chapter 4. Due to the linear relationship assumed between successive known data points for the lining material engineering properties, and the fact that the lining expansion was not interfered with by the shell, changes in the temperature dependent properties of a given percentage resulted in changes to the lining stresses of approximately the same order of magnitude. It should be noted here, that this is only valid due to the lack of shell influence, and would not have been the case had the shell been in contact with the lining.

The abovementioned relationship between the change in engineering variables, and the corresponding change in lining stress is an indication that the assumed linear relationship between known data points was very much a simplified approach. It is an indication that it would have been preferable to have had a larger number of valid experimental data points.

5.3 THE IMPLICATIONS OF THE DELIMITATIONS

The delimitations made for this study were noted in section 1.5. The delimitations made in 1.5.1 and 1.5.2 relate to the practical size of the study, and would not have had an effect on the order of magnitude of the results of this study.

The delimitations stated in 1.5.3 and 1.5.4 delimit this study to observing the internal thermally applied stresses only, and ignore the effects of both plant operation, and calciner rotation. It is a well documented fact (Tseng 1982; Bakker 1982; Fowler 1982), that the warm up and cool down rate, as well as the steadiness of operation of a process vessel directly influence the lining stability. However, due to the relative lack of historical data available at Tioxide S.A. pertaining to the warm up and cool down histories, it was impractical to include this facet in the study. Tioxide have corrected this, and now have a system for recording all calciner operating history, future studies will thus be able to include this as part of the study.

The rotational effect of the calciner is unlikely to impose high additional stresses on the lining, except in the cases of poor alignment of the calciner rollers, shell ovality, or a similar mechanical problem, due to the relative stiffness of the deep circular section of the calciner. Tioxide's no.1 calciner rollers were overhauled in 1991, and there was no evidence to support the theory of roller misalignment. At the same time, the calciner was checked for ovality at the feed end are

(zone 2), and was found to be circular.
The delimitation of this study to exclude the effects of creep and stress relaxation was noted in 1.5.5. However, creep and stress relaxation can have a marked effect on the lining stress, although the value of the effect is difficult to quantify.

Tseng (1982) shows in his study that creep of monolithic refractory concretes has the effect of releasing the compressive stresses during heat up, and that this would lead to earlier cracking on the hot face, and worsen the tensile cracking during cool down. This implies that creep strain should be minimised in material selection. This effect is confirmed by Shacht (1986), who also states that creep tends to relax the hot face stresses, while causing the thermal expansion stresses to "shift out" towards the outer surface of the lining.

It therefore follows, that a systematic inclusion of creep effects in this study would have lead to increased cold face stresses, but decreased hot face stresses. This effect would therefore be detremental to the lining stability as it has been analysed in this study. The implication of this to Tioxide, is that the effect of the stresses calculated in this study would be more severe in reality, however, Wygant & Crowley have stated that the effects of creep are normally cancelled out, this has been discussed in section 5.4.

5.4 THE IMPLICATIONS OF THE ASSUMPTIONS

The assumptions made for this study appear in section 1.6.

The assumption stated in 1.6.1 indicates that, for the purpose of this study, experimental data obtained under laboratory conditions would be used to represent the data pertaining to the lining in service, and that the thermal history of the lining would be ignored.

Whilst the laboratory values for the temperature dependent lining properties were useful for obtaining the order of magnitude of the lining stresses, the C.S.I.R laboratory values would have been different had the effects of thermal history of the calciner been included.

Bakker (1982), Tseng (1982), and Fowler (1982) have all discussed the fact that heating and cooling of refractories, and the rate at which the temperature change is carried out, have an effect on the temperature dependent material properties. However, the exact magnitude of the effects appear open to some debate. Whilst it is accepted that extrapolation of the laboratory analyses to the real life operating system is an over simplification, for an order- of - magnitude study such as this one, it is considered to be

sufficient.
Assuming a linear relationship between known successive data points from the laboratory analysis as indicated in 1.6.2, although being a simplified approach, is not likely to affect the order of magnitude of the lining stresses significantly. To have had a larger number of recorded data points would have required additional laboratory analysis work, with a resulting increase in cost. As the cost of the laboratory analyses were significant in terms of the overall cost of this project, the additional costs were not incurred.

The implications of the assumptions made for the non-finite element analysis as indicated in 1.6.3, have been discussed in detail by Wygant and Crowley (1964). The authors state that in reality, the actual stresses in a vessel are lower than those calculated using the assumed linear method. They also state that " In the steady state, most effects of the listed departures from ideal assumptions tend to cancel out. Hot face compression is increased by nonuniform thermal conductivity and nonlinear thermal expansion gradients, but is diminished by nonlinear shrinkage gradients and nonuniform elastic moduli. These individual errors, and their collective effects, are relatively small." This implies that the assumptions made in this study for the steady state linear elastic analysis are valid for an order of

magnitude study such as this one.
The assumptions made in 1.6.4 and 1.6.5, relate to the thermal operating profile of the calciner. In reality, the only 100% accurate way to determine the calciner internal temperature profile, is to have a measuring system such as thermocouples. The calciner in Italy is the only one in the Tioxide group that has thermocouples, and is hence the only source of this information. The calciner operating specification and work requirement is identical for both the Italian and South African calciners, and Tioxide S.A. staff use the Italian profile for operational reference.

In 3.2.8.3, it was stated that the lining was assumed as being uncracked for analysis purposes. This is a simplified approach, as the presence of cracks affects the thermal conductivity of the lining material. Tseng (1982) carried out studies into the effects of cracks, and found that hoop or axial cracks had very little effect on the lining temperature distribution, but radial cracks had a significant effect. As this study examined the effects of hoop stress, the effects of radial cracks have been ignored.

5.5 THE IMPLICATIONS OF THE DATA MANIPULATION

The use of calciner shell temperature scans to calculate the thermal profile through the lining cross section has been discussed in 3.2.5.2. This approach to evaluating the magnitude and profile of the temperature gradient in this study was a simplification of a very complex thermal analysis. Bortz, et al, (1982) stated that the thermal conductivity of a monolithic refractory concrete in service, is a function of both temperature, and bonding condition, and is time-temperature dependent. Tseng (1982), has stated that the temperature distributions are sensitive to stress-induced cracks and the prescence of process gas, as they change the thermal conductivity of the lining. All of the abovementioned relationships make the accurate thermal evaluation of a refractory monolithic a very complex issue. The use of an optical pyrometer in the evaluation of the shell temperature is by no means a 100% accurate method. In addition, the presence of a gap between the lining and shell would also have an effect on the accuracy of the reading. The question of accurate temperature profiling of monolithic linings in rotary calciners is an area that would benefit from further study.

The manipulation of the data with respect to the permanent linear change (PLC), was discussed in detail in 3.2.6.2. and 3.2.7. The PLC is, like all temperature dependent properties, subject to changes depending on the thermal "history" of the lining. The manipulation of the PLC values to equate them to a "negative" temperature, was an simplified method of modelling the effects of permanent linear shrinkage, however, in reality, the thermal expansion effect is reduced proportionately to the value of the PLC at that temperature. This effect was simulated in the approach used in this study.

The selection of modulus of elasticity (MOE) and Poissons ratio (PR) from a previous study, and using it in this study, as discussed in 3.2.6.3, was a decision that had a direct effect on the results obtained in this study. It was an unscientific method of obtaining data that was as near as possible to the required values. Whilst this method may be unscientific, it was selected due to the financial and scope constraints of this study. It should be borne in mind, that the overall purpose of this study was to develop a PC based program for the evaluation of stresses, that can be used by Tioxide in future lining selection, therefore, the comparison of results as well as their order of magnitude, were the required output data, rather than a 100% accurate answer.

5.6 IMPLICATION OF THE RESULTS TO TIOXIDE S.A.

Observations from the results obtained in Chapter 4, are that the lining in calciner no.1 at Tioxide S.A. is not "compressive" enough. The overall stress condition through the lining cross section should be placed under a condition that the lining makes contact with the shell. This would put the hot face under higher compression, and cause the neutral axis to shift towards the lining outer surface. The result would be less cracking on the hot face after cooling down, and hence reduced spalling of the hot face after subsequent re-heats.

The magnitude of the stresses calculated in this study indicate that the lining failure could be attributed at least in part, to incompatible material specification for the application. However, this study was not broad enough to state that lining overstressing is the only cause of failure.

Increased overall compression could be acheived by using a material with a lower PLC. This has been reported by Tseng (1982), as being of paramount importance in lining material selection. However, in this study, in Tioxide S.A's No.1 Calciner, a decrease in PLC resulted in an

increase in cold face tension, although at a lower rate than the increased hot face compression, a compromise should be sought. Higher compressive conditions could also be achieved by using a material with a higher coefficient of thermal expansion. The fluctuation between compression and tension on the hot and cold faces of the lining needs to be kept to a minimum.
Care must be taken where the lining is thicker (discharge end), that the hot face compression does not reach the crushing strength of the lining.

As the currently used lining material is holding up well at the discharge end of the calciner, the specification for this area should not be changed. At the feed end, where the lining failures occur, it is recommended that a material with a either a lower PLC or higher expansion coefficient, or combination of the two, be chosen for future relines. The lining stresses should first be checked using the PC based analysis technique developed in this study.

5.7 CONCLUSIONS

The analysis methods used in this study were based on a simplified approach, that sought to obtain order- of - magnitude values for the lining stresses, rather than exact values. The approach is therefore applicable to owners of equipment, in an effort to increase the lining life by improving on the previously adhered to method of trial and error. The simplified approach has been ratified as being of value by Wygant and Crowley (1964), Fowler (1987), and Shacht (1986).

5.8 FUTURE RESEARCH

The subject of monolithic refractory concretes is a complex issue that requires significant ongoing research. Refractory concretes, unlike Portland concrete, usually fall under the auspices of ceramic or materials scientists, and the structural strength of the material is normally considered secondary to the materials heat, chemical and abrasion resistant properties.

This study has shown that the structural stresses set up in a calciner lining can be of significance in the evaluation of a refractory concretes ability to provide adequate service. The same would be expected to apply to many other applications. In order to increase the understanding of structural properties of monolithic refractories in service, the following are areas requiring additional research.

i) The accurate assessment of thermal profiles through monolithic refractory concrete linings in service.

ii) More work on the relationship between temperature and elastic modulus & Poissons ratio.

iii) The effects of thermal "history" on the engineering properties of monolithic refractory concretes.

iv) Compressive and tensile strength tests of monolithic refractory concretes at temperature, including thermal "history" effects.

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APPENDIX A

SAMPLES OF FINITE ELEMENT ANALYSIS PRINTOUTS

D I R E C T   A N D   S H E A R   S T R E S S E S   I N   E L E M E N T S

COMPRESSION -VE,SHEAR INTO +VE X-Y QUADRANT +VE SHEAR

ELT NO.	ELT TYPE	NODE OR GAUSS POINT	DIRECT STRESS X-DIRECTION N /SQ.M	DIRECT STRESS Y-DIRECTION N /SQ.M	SHEAR STRESS XY-DIRECTION N /SQ.M	MAXIMUM PRINCIPAL STRESS N /SQ.M	MINIMUM PRINCIPAL STRESS N /SQ.M	ANGLE OF MAX STRESS DEGS	MAXIMUM SHEAR STRESS N /SQ.M	EFFECTIVE STRESS N /SQ.M
RELATIVE TO SYSTEM AXES										
8	QPM4	8	-0.102153E+08	-0.569973E+08	0.604945E+07	-0.944567E+07	-0.577669E+08	7.250	0.241606E+08	0.53671E+08
		STRAINS	0.207613E-02	0.100875E-02	0.276048E-03	0.209369E-02	0.991193E-03	7.250	0.110250E-02	
		24	0.774736E+07	-0.393461E+08	0.608971E+07	0.852208E+07	-0.401208E+08	7.250	0.243214E+08	0.449913E+08
		STRAINS	0.207642E-02	0.102688E-02	0.271436E-03	0.209369E-02	0.100961E-02	7.250	0.108408E-02	
		25	0.763755E+07	-0.392363E+08	0.649951E+07	0.852208E+07	-0.401208E+08	7.750	0.243214E+08	0.449913E+08
		STRAINS	0.207398E-02	0.102933E-02	0.289702E-03	0.209369E-02	0.100961E-02	7.750	0.108408E-02	
		9	-0.103243E+08	-0.568883E+08	0.645654E+07	-0.944567E+07	-0.577669E+08	7.750	0.241606E+08	0.536712E+08
		STRAINS	0.207364E-02	0.101124E-02	0.294624E-03	0.209369E-02	0.991193E-03	7.750	0.110250E-02	
		AREA = 0.463824E-03	THICKNESS =1.0000		1.0000	1.0000	1.0000			
RELATIVE TO SYSTEM AXES										
23	QPM4	24	-0.106725E+08	-0.423971E+08	0.410232E+07	-0.101506E+08	-0.429190E+08	7.250	0.163842E+08	0.38851E+08
		STRAINS	0.172826E-02	0.102123E-02	0.182853E-03	0.173989E-02	0.100960E-02	7.250	0.730292E-03	
		40	0.734199E+07	-0.245734E+08	0.412699E+07	0.786701E+07	-0.250984E+08	7.250	0.164827E+08	0.298206E+08
		STRAINS	0.172845E-02	0.103304E-02	0.179847E-03	0.173989E-02	0.102160E-02	7.250	0.718289E-03	
		41	0.726756E+07	-0.244990E+08	0.440476E+07	0.786701E+07	-0.250984E+08	7.750	0.164827E+08	0.298206E+08
		STRAINS	0.172683E-02	0.103467E-02	0.191952E-03	0.173989E-02	0.102160E-02	7.750	0.718289E-03	
		25	-0.107465E+08	-0.423231E+08	0.437844E+07	-0.101506E+08	-0.429190E+08	7.750	0.163842E+08	0.388513E+08
		STRAINS	0.172661E-02	0.102288E-02	0.195160E-03	0.173989E-02	0.100960E-02	7.750	0.730292E-03	
		AREA = 0.471643E-03	THICKNESS =1.0000		1.0000	1.0000	1.0000			
RELATIVE TO SYSTEM AXES										
38	QPM4	40	-0.108631E+08	-0.276890E+08	0.216282E+07	-0.105879E+08	-0.278641E+08	7.250	0.863809E+07	0.24362E+08
		STRAINS	0.139203E-02	0.102759E-02	0.942523E-04	0.139803E-02	0.102160E-02	7.250	0.376435E-03	
		56	0.720131E+07	-0.961528E+07	0.217455E+07	0.747795E+07	-0.989192E+07	7.250	0.868493E+07	0.150911E+08
		STRAINS	0.139213E-02	0.103358E-02	0.927279E-04	0.139803E-02	0.102768E-02	7.250	0.370346E-03	
		57	0.716208E+07	-0.957605E+07	0.232093E+07	0.747795E+07	-0.989192E+07	7.750	0.868493E+07	0.150911E+08
		STRAINS	0.139130E-02	0.103442E-02	0.989702E-04	0.139803E-02	0.102768E-02	7.750	0.370346E-03	
		41	-0.109021E+08	-0.275500E+08	0.230842E+07	-0.105879E+08	-0.278641E+08	7.750	0.863809E+07	0.243617E+08
		STRAINS	0.139118E-02	0.102844E-02	0.100597E-03	0.139803E-02	0.102160E-02	7.750	0.376435E-03	
		AREA = 0.479462E-03	THICKNESS =1.0000		1.0000	1.0000	1.0000			
RELATIVE TO SYSTEM AXES										
53	QPM4	56	-0.107968E+08	-0.125967E+08	232749.	-0.107671E+08	-0.126263E+08	7.250	929584.	0.11807E+08
		STRAINS	0.106668E-02	0.102831E-02	0.992501E-05	0.106731E-02	0.102767E-02	7.250	0.396398E-04	
		72	0.731536E+07	0.550663E+07	233885.	0.734512E+07	0.547688E+07	7.250	934120.	0.661201E+07
		STRAINS	0.106669E-02	0.102893E-02	0.976702E-05	0.106731E-02	0.102831E-02	7.250	0.390088E-04	
		73	0.731114E+07	0.551085E+07	249632.	0.734512E+07	0.547688E+07	7.750	934120.	0.661201E+07
		STRAINS	0.106661E-02	0.102902E-02	0.104246E-04	0.106731E-02	0.102831E-02	7.750	0.390088E-04	
		57	-0.108010E+08	-0.125925E+08	248420.	-0.107671E+08	-0.126263E+08	7.750	929584.	0.118070E+08
		STRAINS	0.106659E-02	0.102840E-02	0.105933E-04	0.106731E-02	0.102767E-02	7.750	0.396398E-04	
		AREA = 0.487281E-03	THICKNESS =1.0000		1.0000	1.0000	1.0000			

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RELATIVE TO SYSTEM AXES
 68 QPM4       72 -0.104830E+08  0.255819E+07 -0.168633E+07  0.277272E+07 -0.106975E+08        -82.750  0.673510E+07  0.12320E+08
        STRAINS  0.751520E-03  0.102382E-02 -0.704210E-04  0.102830E-02  0.747041E-03        -82.750  0.281258E-03
               88  0.767450E+07  0.207728E+08 -0.169371E+07  0.209882E+08  0.745903E+07        -82.750  0.676460E+07  0.184280E+08
        STRAINS  0.751450E-03  0.101948E-02 -0.693174E-04  0.102389E-02  0.747041E-03        -82.750  0.276850E-03
               89  0.770506E+07  0.207422E+08 -0.180777E+07  0.209882E+08  0.745903E+07        -82.250  0.676460E+07  0.184280E+08
        STRAINS  0.752075E-03  0.101886E-02 -0.739853E-04  0.102389E-02  0.747041E-03        -82.250  0.276850E-03
               73 -0.104525E+08  0.252776E+07 -0.179988E+07  0.277272E+07 -0.106975E+08        -82.250  0.673510E+07  0.123201E+08
        STRAINS  0.752155E-03  0.102318E-02 -0.751633E-04  0.102830E-02  0.747041E-03        -82.250  0.281258E-03
      AREA = 0.495101E-03 THICKNESS =1.0000    1.0000    1.0000    1.0000
RELATIVE TO SYSTEM AXES
 83 QPM4       88 -0.993089E+07  0.178562E+08 -0.359307E+07  0.183133E+08 -0.103880E+08        -82.750  0.143506E+08  0.25170E+08
        STRAINS  0.445918E-03  0.101453E-02 -0.147052E-03  0.102388E-02  0.436565E-03        -82.750  0.587320E-03
              104  0.826938E+07  0.361653E+08 -0.360715E+07  0.366242E+08  0.781050E+07        -82.750  0.144069E+08  0.334108E+08
        STRAINS  0.445774E-03  0.100561E-02 -0.144782E-03  0.101482E-02  0.436565E-03        -82.750  0.578257E-03
              105  0.833448E+07  0.361002E+08 -0.385010E+07  0.366242E+08  0.781050E+07        -82.250  0.144069E+08  0.334108E+08
        STRAINS  0.447080E-03  0.100431E-02 -0.154534E-03  0.101482E-02  0.436565E-03        -82.250  0.578257E-03
               89 -0.986605E+07  0.177913E+08 -0.383507E+07  0.183133E+08 -0.103880E+08        -82.250  0.143506E+08  0.251699E+08
        STRAINS  0.447245E-03  0.101320E-02 -0.156956E-03  0.102388E-02  0.436565E-03        -82.250  0.587320E-03
      AREA = 0.502920E-03 THICKNESS =1.0000    1.0000    1.0000    1.0000
RELATIVE TO SYSTEM AXES       *
 98 QPM4      120 -0.345248E+07  0.249079E+08 -0.366723E+07  0.253744E+08 -0.391901E+07        -82.750  0.146467E+08  0.27544E+08
        STRAINS  0.835977E-03  0.101154E-02 -0.454039E-04  0.101443E-02  0.833089E-03        -82.750  0.181340E-03
SHELL         136  0.329425E+07  0.306673E+08 -0.353957E+07  0.311176E+08  0.284397E+07        -82.750  0.141368E+08  0.297976E+0
        STRAINS  0.835876E-03  0.100533E-02 -0.438232E-04  0.100812E-02  0.833089E-03        -82.750  0.175027E-03
              137  0.335812E+07  0.306035E+08 -0.377791E+07  0.311176E+08  0.284397E+07        -82.250  0.141368E+08  0.297976E+0
        STRAINS  0.836272E-03  0.100493E-02 -0.467741E-04  0.100812E-02  0.833089E-03        -82.250  0.175027E-03
              121 -0.338632E+07  0.248417E+08 -0.391418E+07  0.253744E+08 -0.391901E+07        -82.250  0.146467E+08  0.275438E+0
        STRAINS  0.836386E-03  0.101113E-02 -0.484612E-04  0.101443E-02  0.833089E-03        -82.250  0.181340E-03
      AREA = 0.120708E-02 THICKNESS =1.0000    1.0000    1.0000    1.0000
```

* NOTE NON-EQUILIBRIUM CONDITIONS (STRESSES).

D I R E C T   A N D   S H E A R   S T R E S S E S   I N   E L E M E N T S

COMPRESSION -VE,SHEAR INTO +VE X-Y QUADRANT +VE SHEAR

ELT NO.	ELT TYPE	NODE OR GAUSS POINT	DIRECT STRESS X-DIRECTION N /SQ.M	DIRECT STRESS Y-DIRECTION N /SQ.M	SHEAR STRESS XY-DIRECTION N /SQ.M	MAXIMUM PRINCIPAL STRESS N /SQ.M	MINIMUM PRINCIPAL STRESS N /SQ.M	ANGLE OF MAX STRESS DEGS	MAXIMUM SHEAR STRESS N /SQ.M	EFFECTIVE STRESS N /SQ.M
RELATIVE TO SYSTEM AXES										
8	QPM4	8	-0.504579E+07	-0.235290E+08	0.239006E+07	-0.474173E+07	-0.238330E+08	7.250	0.954565E+07	0.21851E+08
		STRAINS	0.977080E-03	0.555369E-03	0.109063E-03	0.984017E-03	0.548431E-03	7.250	0.435586E-03	
		24	0.405915E+07	-0.145469E+08	0.240595E+07	0.436523E+07	-0.148530E+08	7.250	0.960912E+07	0.174500E+08
		STRAINS	0.977196E-03	0.562533E-03	0.107240E-03	0.984017E-03	0.555711E-03	7.250	0.428306E-03	
		25	0.401575E+07	-0.145035E+08	0.256791E+07	0.436523E+07	-0.148530E+08	7.750	0.960912E+07	0.174500E+08
		STRAINS	0.976229E-03	0.563500E-03	0.114459E-03	0.984017E-03	0.555711E-03	7.750	0.428306E-03	
		9	-0.508890E+07	-0.234859E+08	0.255095E+07	-0.474173E+07	-0.238330E+08	7.750	0.954565E+07	0.218515E+08
		STRAINS	0.976096E-03	0.556352E-03	0.116404E-03	0.984017E-03	0.548431E-03	7.750	0.435586E-03	
AREA = 0.463824E-03 THICKNESS =1.0000					1.0000	1.0000	1.0000			
RELATIVE TO SYSTEM AXES										
23	QPM4	24	-0.518932E+07	-0.160788E+08	0.140812E+07	-0.501018E+07	-0.162580E+08	7.250	0.562390E+07	0.14421E+08
		STRAINS	0.802387E-03	0.559698E-03	0.627640E-04	0.806380E-03	0.555706E-03	7.250	0.250674E-03	
		40	0.394431E+07	-0.701064E+07	0.141658E+07	0.412452E+07	-0.719086E+07	7.250	0.565769E+07	0.991862E+07
		STRAINS	0.802453E-03	0.563754E-03	0.617321E-04	0.806380E-03	0.559827E-03	7.250	0.246553E-03	
		41	0.391876E+07	-0.698509E+07	0.151195E+07	0.412452E+07	-0.719086E+07	7.750	0.565769E+07	0.991862E+07
		STRAINS	0.801896E-03	0.564310E-03	0.658881E-04	0.806380E-03	0.559827E-03	7.750	0.246553E-03	
		25	-0.521472E+07	-0.160534E+08	0.150291E+07	-0.501018E+07	-0.162580E+08	7.750	0.562390E+07	0.144211E+08
		STRAINS	0.801821E-03	0.560264E-03	0.669894E-04	0.806380E-03	0.555706E-03	7.750	0.250674E-03	
AREA = 0.471643E-03 THICKNESS =1.0000					1.0000	1.0000	1.0000			
RELATIVE TO SYSTEM AXES										
38	QPM4	40	-0.519956E+07	-0.852528E+07	430046.	-0.514485E+07	-0.857999E+07	7.250	0.171757E+07	0.74795E+07
		STRAINS	0.633479E-03	0.561014E-03	0.187407E-04	0.634671E-03	0.559822E-03	7.250	0.748490E-04	
		56	0.396156E+07	617809.	432377.	0.401656E+07	562804.	7.250	0.172688E+07	0.376683E+07
		STRAINS	0.633499E-03	0.562206E-03	0.184376E-04	0.634671E-03	0.561033E-03	7.250	0.736383E-04	
		57	0.395376E+07	625609.	461488.	0.401656E+07	562804.	7.750	0.172688E+07	0.376683E+07
		STRAINS	0.633332E-03	0.562372E-03	0.196790E-04	0.634671E-03	0.561033E-03	7.750	0.736383E-04	
		41	-0.520732E+07	-0.851753E+07	459000.	-0.514485E+07	-0.857999E+07	7.750	0.171757E+07	0.747951E+07
		STRAINS	0.633310E-03	0.561183E-03	0.200025E-04	0.634671E-03	0.559822E-03	7.750	0.748490E-04	
AREA = 0.479462E-03 THICKNESS =1.0000					1.0000	1.0000	1.0000			
RELATIVE TO SYSTEM AXES										
53	QPM4	56	-0.508146E+07	-880187.	-543261.	-811075.	-0.515057E+07	-82.750	0.216975E+07	0.47967E+07
		STRAINS	0.469979E-03	0.559555E-03	-0.231660E-04	0.561029E-03	0.468505E-03	-82.750	0.925236E-04	
		72	0.410585E+07	0.832763E+07	-545911.	0.839707E+07	0.403640E+07	-82.750	0.218034E+07	0.727389E+07
		STRAINS	0.469955E-03	0.558106E-03	-0.227972E-04	0.559556E-03	0.468505E-03	-82.750	0.910506E-04	
		73	0.411570E+07	0.831778E+07	-582670.	0.839707E+07	0.403640E+07	-82.250	0.218034E+07	0.727389E+07
		STRAINS	0.470161E-03	0.557900E-03	-0.243323E-04	0.559556E-03	0.468505E-03	-82.250	0.910506E-04	
		57	-0.507166E+07	-889988.	-579841.	-811075.	-0.515057E+07	-82.250	0.216975E+07	0.479674E+07
		STRAINS	0.470188E-03	0.559346E-03	-0.247259E-04	0.561029E-03	0.468505E-03	-82.250	0.925236E-04	
AREA = 0.487281E-03 THICKNESS =1.0000					1.0000	1.0000	1.0000			
RELATIVE TO SYSTEM AXES										
68	QPM4	72	-0.483981E+07	0.684570E+07	-0.151103E+07	0.703793E+07	-0.503204E+07	-82.750	0.603498E+07	0.10501E+08
		STRAINS	0.311545E-03	0.555539E-03	-0.631008E-04	0.559553E-03	0.307531E-03	-82.750	0.252021E-03	
		88	0.437232E+07	0.161090E+08	-0.151765E+07	0.163021E+08	0.417925E+07	-82.750	0.606142E+07	0.146661E+08
		STRAINS	0.311482E-03	0.551652E-03	-0.621119E-04	0.555603E-03	0.307531E-03	-82.750	0.248072E-03	
		89	0.439970E+07	0.160816E+08	-0.161985E+07	0.163021E+08	0.417925E+07	-82.250	0.606142E+07	0.146661E+08
		STRAINS	0.312043E-03	0.551092E-03	-0.662945E-04	0.555603E-03	0.307531E-03	-82.250	0.248072E-03	
		73	-0.481255E+07	0.681844E+07	-0.161279E+07	0.703793E+07	-0.503204E+07	-82.250	0.603498E+07	0.105009E+08
		STRAINS	0.312114E-03	0.554970E-03	-0.673500E-04	0.559553E-03	0.307531E-03	-82.250	0.252021E-03	
AREA = 0.495101E-03 THICKNESS =1.0000					1.0000	1.0000	1.0000			

```
RELATIVE TO SYSTEM AXES
 83 QPM4      88 -0.447928E+07  0.146426E+08 -0.247261E+07  0.149572E+08 -0.479383E+07       -82.750  0.987551E+07  0.17844E+08
        STRAINS  0.157868E-03  0.549163E-03 -0.101195E-03  0.555600E-03  0.151431E-03       -82.750  0.404169E-03
            104  0.475624E+07  0.239531E+08 -0.248230E+07  0.242689E+08  0.444046E+07       -82.750  0.991421E+07  0.223815E+08
        STRAINS  0.157768E-03  0.543026E-03 -0.996337E-04  0.549364E-03  0.151431E-03       -82.750  0.397933E-03
            105  0.480104E+07  0.239083E+08 -0.264947E+07  0.242689E+08  0.444046E+07       -82.250  0.991421E+07  0.223815E+08
        STRAINS  0.158667E-03  0.542127E-03 -0.106344E-03  0.549364E-03  0.151431E-03       -82.250  0.397933E-03
             89 -0.443466E+07  0.145980E+08 -0.263913E+07  0.149572E+08 -0.479383E+07       -82.250  0.987551E+07  0.178438E+08
        STRAINS  0.158781E-03  0.548250E-03 -0.108010E-03  0.555600E-03  0.151431E-03       -82.250  0.404169E-03
      AREA = 0.502920E-03 THICKNESS =1.0000    1.0000    1.0000    1.0000
RELATIVE TO SYSTEM AXES
 98 QPM4     120 -0.364149E+07 -0.359961E+07  -5415.43     -0.359892E+07 -0.364218E+07       -82.750   21628.7      0.36207E+07
        STRAINS  0.875802E-03  0.876061E-03 -0.670482E-07  0.876065E-03  0.875798E-03       -82.750  0.267783E-06
            136  0.355784E+07  0.359826E+07  -5226.93      0.359892E+07  0.355717E+07       -82.750   20875.8      0.357823E+07
        STRAINS  0.875802E-03  0.876052E-03 -0.647144E-07  0.876056E-03  0.875798E-03       -82.750  0.258462E-06
            137  0.355793E+07  0.359817E+07  -5578.85      0.359892E+07  0.355717E+07       -82.250   20875.8      0.357823E+07
        STRAINS  0.875802E-03  0.876051E-03 -0.690714E-07  0.876056E-03  0.875798E-03       -82.250  0.258462E-06
            121 -0.364140E+07 -0.359971E+07  -5780.04     -0.359892E+07 -0.364218E+07       -82.250   21628.7      0.362075E+07
        STRAINS  0.875802E-03  0.876061E-03 -0.715624E-07  0.876065E-03  0.875798E-03       -82.250  0.267784E-06
      AREA = 0.120708E-02 THICKNESS =1.0000    1.0000    1.0000    1.0000
```

APPENDIX B

SAMPLES OF PC BASED PROGRAM RESULT PRINTOUTS

Monolithic Lining Stress Evaluation Program

Move to menu selection with cursor keys
Press ENTER to Input data or show results

Quit	
Internal Shell Dia	2743 mm.
Shell Thickness	50 mm.
Youngs Modulus (shell)	206000 MPa
Thermal Expansion Coeff (shell)	1.17e-005 /deg C
Thermal Conductivity (shell)	0 W/M Deg.C
Poissons Ratio (shell)	0.3 --
Lining Thickness	127 mm.
Youngs Modulus (lining)	50390 MPa
Thermal Expansion Coeff (lining)	5.1e-006 / deg C
Thermal Conductivity (lining)	0 W/M Deg.C
NEXT PAGE	

Monolithic Lining Stress Evaluation Program

Move to menu selection with cursor keys
Press ENTER to Input data or show results

PREVIOUS PAGE	
Poissons Ratio (lining)	0.16 --
Ultimate Strength (lining)	95 MPa
Irrever Lin Shrinkage of lining @ shell temp	0.00026 mm/m
Irrever Lin Shrinkage of lining @ op temp	0.0011 mm/mm
Atmospheric Temperature	25 deg C
Themperature of Material @ construction	25 deg C
Operating Internal Temperature	427 deg C
Operating Internal Pressure	0 MPa
Measured Shell Temperature	97 /deg C
SHOW RESULTS	

STRAIN VALUE

'hermal Expansion of Shell____0.0008424
ım

'otal Circumferential Shell elongation____________________________0.0008424
ım

lean Thermal Expansion of Lining__________________________________0.0012087
ım

lean Shrinkage of Lining____0.00068 mm

lean Unrestrained Expansion______________________________________0.0005287 m
ı

let Differential Circumferential Expansion between Shell & Lining__0.0003137
ım

Gap Exists Between Lining and Shell

*** Mean Circum Lining Stress_____________________________________0 MPa**
Stress Diff From Mean @ Hot & Cold Faces Due to Thermal Exp Grad___50.48 MPa
Stress Diff From Mean @ Hot & Cold Faces Due to Shrinkage Gradient_25.195 MPa
*** Circumferential Lining Stress @ Exposed face __________________-25.285 MP
*

*** Circumferential Lining Stress Adjacent to Shell________________25.285 MPa

Additional Stress on Shell Imposed by Lining Stress________________0 MPa

Monolithic Lining Stress Evaluation Program

Move to menu selection with cursor keys
Press ENTER to Input data or show results

Quit	
Internal Shell Dia	2743 mm.
Shell Thickness	50 mm.
Youngs Modulus (shell)	206000 MPa
Thermal Expansion Coeff (shell)	1.17e-005 /deg C
Thermal Conductivity (shell)	0 W/M Deg.C
Poissons Ratio (shell)	0.3 --
Lining Thickness	127 mm.
Youngs Modulus (lining)	50390 MPa
Thermal Expansion Coeff (lining)	5.1e-006 / deg C
Thermal Conductivity (lining)	0 W/M Deg.C
NEXT PAGE	

Monolithic Lining Stress Evaluation Program

Move to menu selection with cursor keys
Press ENTER to Input data or show results

PREVIOUS PAGE	
Poissons Ratio (lining)	0.16 --
Ultimate Strength (lining)	95 MPa
Irrever Lin Shrinkage of lining @ shell temp	0 mm/mm
Irrever Lin Shrinkage of lining @ op temp	0 mm/mm
Atmospheric Temperature	25 deg C
Themperature of Material @ construction	25 deg C
Operating Internal Temperature	427 deg C
Operating Internal Pressure	0 MPa
Measured Shell Temperature	97 /deg C
SHOW RESULTS	

STRAIN VALUE

'hermal Expansion of Shell____0.0008424
ım
'otal Circumferential Shell elongation_____________________________0.0008424
ım
Iean Thermal Expansion of Lining________________________________0.0012087
ım
Iean Shrinkage of Lining____0 mm/mm
Iean Unrestrained Expansion______________________________________0.0012087 m
ı
Iet Differential Circumferential Expansion between Shell & Lining__-0.0003663
'mm

Shell Interferes With Lining Expansion

*** Mean Circum Lining Stress_____________________________________-11.3845 M
*
Stress Diff From Mean @ Hot & Cold Faces Due to Thermal Exp Grad___50.48 MPa
Stress Diff From Mean @ Hot & Cold Faces Due to Shrinkage Gradient_0 MPa
*** Circumferential Lining Stress @ Exposed face __________________-61.8645 M
**
*** Circumferential Lining Stress Adjacent to Shell________________39.0955 MP
*
Additional Stress on Shell Imposed by Lining Stress________________28.9166 MP