



THE UNIVERSITY OF
SYDNEY

COPYRIGHT AND USE OF THIS THESIS

This thesis must be used in accordance with the provisions of the Copyright Act 1968.

Reproduction of material protected by copyright may be an infringement of copyright and copyright owners may be entitled to take legal action against persons who infringe their copyright.

Section 51 (2) of the Copyright Act permits an authorized officer of a university library or archives to provide a copy (by communication or otherwise) of an unpublished thesis kept in the library or archives, to a person who satisfies the authorized officer that he or she requires the reproduction for the purposes of research or study.

The Copyright Act grants the creator of a work a number of moral rights, specifically the right of attribution, the right against false attribution and the right of integrity.

You may infringe the author's moral rights if you:

- fail to acknowledge the author of this thesis if you quote sections from the work
- attribute this thesis to another author
- subject this thesis to derogatory treatment which may prejudice the author's reputation

For further information contact the University's Copyright Service.

sydney.edu.au/copyright

**INVESTIGATION OF BEGG 'MINI-SPRING'
LOAD-DEFLECTION CHARACTERISTICS**

BY

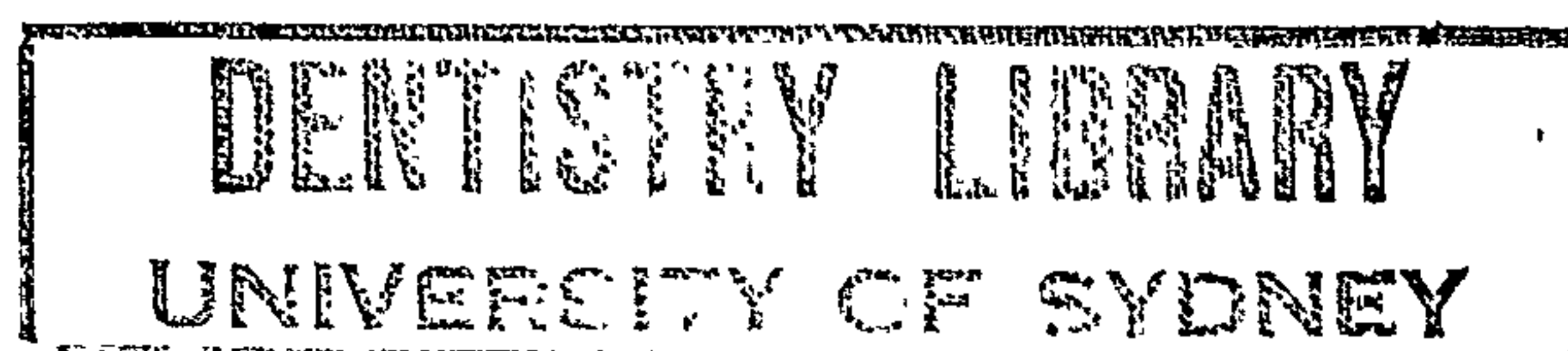
G. R. G. SQUIRES BDS (Sydney)

A thesis submitted in fulfilment
of the requirements for the degree of
Master of Dental Science

Department of Preventive Dentistry

The University of Sydney

January, 1991



ABSTRACT

The load-deflection characteristics of the Begg 0.010" ('Supreme') 'Mini-Spring' (manufactured by A. J. Wilcock Scientific and Engineering Equipment, Whittlesea, Victoria) were investigated to determine what effects significant design modifications (the use of very high tensile, very fine wire in combination with a very small coil diameter and **tangentially** disposed stem or 'leg') may have.

Two aspects of spring performance were investigated:

- a. Stress relaxation over time; and
- b. load-deflection characteristics.

Experimental results indicated **no** stress relaxation effect on spring behaviour **at the loads used**: A constant load was delivered.

Load-deflection characteristics indicated performance levels which were satisfactory with regard to both load delivery and stress-relaxation effects.

When the experimental results are combined with the other clinical advantages of the 0.010" 'Mini-Spring' (in increasing order: improved aesthetics; ease of placement - using lockpins rather than ligation; and facilitation of oral hygiene regimes-because of its very small size) the 'Mini-Spring' may, for the present at least, be regarded as the acme of the Begg uprighting spring armamentarium.

ACKNOWLEDGMENTS

While doubtless unoriginal, it is nevertheless true to say that a thesis project is very much akin to an orchestral work in which the writer/'conductor' is less than redundant in the absence of his/her collaborators/'musicians'.

The present work is no exception to the orchestral analogy and, not to belabour the point, Associate Professor K. Godfrey, Department of Preventive Dentistry, The University of Sydney, is gratefully acknowledged as Supervisor/'Chief Conductor'. His kind, wise and timely counsel has been, and is, greatly appreciated.

The writer has been materially and morally supported by many persons, all of whom qualify for 'First Violin' status. They are acknowledged, alphabetically, with the greatest pleasure:

Associate Professor A. Abel, Department of Civil Engineering, The University of Sydney, provided valuable insights into his research regarding the Bauschinger effect.

Dr. Theo Baisi, post-graduate colleague, contributed greatly to the gathering of literature review material. He also, as always, provided welcome humorous relief in stressful periods.

Professor D. Borland, Mechanical Engineer, The University of Melbourne, was extremely helpful in providing advice and guidance regarding his research into A. J. Wilcock Scientific and Engineering Equipment wires.

Mrs. Catherine Buglio of Ashley Peake Secretarial Services remained calm and collected in the face of seemingly insurmountable odds: converting the author's handwriting into typescript; the quality of her work is tribute to her professionalism.

Dr. Mark A. Cordato, post-graduate colleague, has been unstinting in his enthusiasm for, and support of, this project. He provided much helpful advice and timely practical support.

Dr. R. Earnshaw, Reader Emeritus, Department of Prosthetic Dentistry, The University of Sydney, gave freely of his considerable knowledge and experience, providing valuable guidance.

The validity of any experimental result(s) must surely be a direct function of the design of the experiment. Any credit for validity in the present work must go to Ms. Adrienne Kirby, Statistician, School of Crop Sciences, The University of Sydney. Ms. Kirby's expertise and lucidity made the writer's journey into the world of statistics an edifying and pleasurable experience - a reality at odds with preconceived notions.

Mr. J. K. Kim, doctoral student in the Department of Mechanical Engineering, The University of Sydney, gave much time and provided much insight regarding engineering aspects of the project.

Dr. Barry Mollenhauer, Orthodontist and Editor of the Australian Orthodontic Journal, gave freely of his time and expertise, reinforcing his international reputation for dedication to the scientific advancement of orthodontics.

Professor Y. W. Mai, Department of Mechanical Engineering, The University of Sydney, kindly permitted use of equipment in his Department and was very helpful in discussions regarding the arcane world of Mechanical Engineering.

Dr. T. Mori, Department of Prosthetic Dentistry, The University of Sydney, graciously permitted use of her laboratory equipment.

Dr. Grahame Gerard Christopher Summerhays, friend and colleague, played his usual highly valued 'sheet anchor' role during the difficult periods which attend a project such as this. His support and counsel were indispensable.

Mrs. Julie Summerhays demonstrated her outstanding secretarial and detective skills in the early drafting of this work.

Dr. Sun Shu Hua, post-graduate colleague, gave greatly appreciated practical assistance during the execution of the experiment. His always gentlemanly demeanour provided an oft-needed frame of reference.

Mr. Max Sutherland, Managing Director, Unitek Corporation/3M Australia Pty. Ltd, and his staff (especially Mr. Dimitri Tops) provided, gratis, Begg 'Unipoint' brackets with cheerful efficiency.

Dr. C. Thomas, Head, Department of Prosthetic Dentistry, The University of Sydney, very kindly approved the use of his Department's facilities and expertise - indispensable quantities in the prosecution of the experiment.

Mrs. Margaret Thomas, Secretary, Department of Preventive Dentistry, The University of Sydney, is a woman of many talents but chief amongst them must surely be her calm professionalism and unfailing kindness when dealing with harried post-graduate students.

The kindness and perspicacity demonstrated to all students, undergraduate and post-graduate alike, by Mrs. Joan Thwaite, Head Librarian, Dental Faculty Library, The University of Sydney, ensures library excursions to be always pleasant and, usually, fruitful.

Mr. Ken Tyler, Senior Technical Officer in the Department of Prosthetic Dentistry, The University of Sydney, was responsible for the conception and fabrication of the experimental apparatus. In this he once again demonstrated his extraordinary talent in producing experimental apparatus of the highest standard. Indeed, his work may be truly described as industrial art.

Dr. Peter Powell Vaughan, Orthodontist, Naturalist and friend, should be held accountable for awakening in the author an interest in orthodontics. His practical assistance and advice was, and is, unstinting and always appropriate; his culpability is plain.

Mr. Robert Van Luyen of the Audio Visual Department, Faculty of Dentistry, The University of Sydney, can only be described as a Photographic Artiste. His outstanding technical expertise is evident throughout the present work, and contrasts with the author's amateur efforts in the Wilcock factory.

Dr. Allan Ward, post-graduate orthodontic colleague and computing genius, provided safe passage through the minefield of 'personal'(!) computing which confronts the computing illiterate.

Dr. S. Timothy Wigmore, post-graduate orthodontic colleague, supports the English cricket team, even though an Australian citizen. This aberrant behaviour is, however, transcended by the support he provides his friends. His research efforts on the author's behalf are gratefully acknowledged.

Mr. Arthur J. Wilcock's contribution to the present work has been absolutely outstanding. He gave freely of his expertise and time in equal measure. His assistance has been pivotal in enabling the author to gain an understanding of the engineering principles which underpin high quality orthodontic wire and appliance production. Similarly, his provision of uprighting springs was generous in the extreme.

Last, but not least, Mr. and Mrs. R. K. Squires and Mr. and Mrs. G. F. Woods, parents and parents-in-law, gave to the full of their love and practical support, as did other family members. Their love is fully reciprocated and acknowledged with the deepest gratitude.

This thesis is dedicated to my wife, Sharon Lynette, whose unfailing love and devotion made worthwhile the prosecution of the degree of Master of Dental Science.

It is also dedicated, with much love, to our families.

TABLE OF CONTENTS

		Page
1.	INTRODUCTION	15
2.	CHAPTER ONE	17
	The Roles of Begg Uprighting Springs	17
3.	CHAPTER TWO	22
	Metallurgical Aspects of Wilcock	22
	Orthodontic Wires	
	The Stainless Steels	23
	Iron: The Basis of Stainless Steel	27
	Microstructure and Mechanical	35
	Properties of the Stainless Steels	
	The Elemental Constitution of Stainless	38
	Steels	
	Grades of Stainless Steel	44
	Physical Properties of the '18-8' Stainless	49
	Steels (and their derivatives)	
	Thermo-mechanical Treatments and Wire	50
	Production	
	The Austenite - Martensite	51
	Transformation	
	Wire Drawing	56
	Practical and Theoretical Aspects of	
	Wire Production by A. J. Wilcock	58
	Scientific and Engineering Equipment	

Table of Contents(cont'd)

	Page
4. CHAPTER THREE	73
Begg Uprighting Spring Design and Performance	73
Evolution	74
Begg Textbook - First Edition: 1965	76
Begg Textbook - Second Edition: 1971	80
American Journal of Orthodontics- January, 1977	83
Begg Textbook - Third Edition: 1977	84
Begg Uprighting Spring Design	87
The Begg 'Mini-Spring'	92
Previous Uprighting Spring	104
Investigations:	
Scouler - 1982	104
Hyde - 1988	110
5. CHAPTER FOUR	121
The Experiment	121
Experiment One:	122
Effects of Time	
Experiment Two:	122
Load-Deflection Characteristics	
Experimental Apparatus	122
Experiment One Method	130
Experiment Two Method	131
Statistical Analysis	131
Summary and Conclusions	149
Further Research	151
BIBLIOGRAPHY	152
APPENDICES	
1. Experiment One - Data	157
2. Experiment Two - Data	158

LIST OF TABLES

		Page
Table 2.1	Allotropes of Iron	38
Table 2.2	AISI Austenitic Steels - Type 300	47
Table 2.3	Wire Reduction Sequence	56
Table 3.1	Begg Text Design Second Edition Spring Design Changes	80
Table 3.2	Uprighting Springs 4 x 1st Premolars Extraction Case	85
Table 3.3	Load-Deflection Characteristics - Scouler 1982	107
Table 3.4	Selected Load Deflection Values	116
Table 4.1	Experiment One After Load-Before Load ANOVA	131
Table 4.2	Experiment One Before Load Analysis	134
Table 4.3	Experiment Two During Load-Before Load CRD ANOVA	136
Table 4.4	Experiment Two CRD Means	137

List of Tables(cont'd)

		Page
Table 4.5	Experiment Two Regression Analysis	139
Table 4.6	Experiment Two After Load-Before Load CRD ANOVA	141
Table 4.7	Experiment Two After Load-Before Load Mean Angular Values	143
Table 4.8	Experiment Two During Load-Before Load. R cos Theta ANOVA	146

LIST OF FIGURES

		Page
Figure 2.1	Ferrous Alloys	36
Figure 2.2	The Cr-Fe Binary Phase Diagram	37
Figure 2.3	Schaeffler Diagram	48
Figure 2.4	Stainless Steel and Titanium Wire Schema of Repetitive Dynamic Strain Ageing Process	59
Figure 2.5	Continuous Length Stainless Steel Wire Undergoing' 'Pulse-Straightening'	60
Figure 2.6	Schematic Representation of Bauschinger Effect	64
Figure 2.7	The Manufacturer examining a 'Pulse Straightened' Wire Length Prior to Appliance Fabrication	71
Figure 3.1	Horizontal Bank Spur	77
Figure 3.2	Uprighting Springs - First Edition	78
Figure 3.3	Uprighting Springs - Second Edition	81
Figure 3.4	Uprighting Springs - Self Retaining and Spring -Pin Types	82

List of Figures(cont'd)

		Page
Figure 3.5	AJWSEE Uprighting Springs	93
Figure 3.6	Schematic Representation of Initial Yield Point and Stress Concentration	94
Figure 3.7	Tensile Test Data - Hazel and West (1986)	95
Figure 3.8	Production of Dynamically Strain Aged Orthodontic Wire Appliance Flow Line	96
Figure 3.9	Conventional Uprighting Spring Design Theory	97
Figure 3.10	Wire Diameter and Uprighting Spring Stiffness	98
Figure 3.11	'Mini-Spring' Design Features	99
Figure 3.12	Conventional Uprighting Spring Design Flaws	100
Figure 3.13	'Unipoint' and Conventional 256-500 Begg Brackets	103
Figure 3.14	Graph: Hyde Data (1988) Figure 6.10, 0.012" Short: Re-analysed Data	117

List of Figures(cont'd)

		Page
Figure 3.15	Graph: Hyde Data (1988) Figure 6.10, 0.012" Long: Re-analysed Data	118
Figure 3.16	Graph: Hyde Data (1988) Figure 6.13, 0.014" Springs: Re-analysed Data	119
Figure 4.1 (a) and (b)	Experimental Apparatus	123
Figure 4.2	Projecting Microscope	129
Figure 4.3	Deflection Characteristics Graph During Load - Before Load	138
Figure 4.4 (a) and (b)	MS Coil Distortion Under Differing Loads a. (150g load approximately) b. (550g load approximately)	140
Figure 4.5	Stress Relaxation Graph	142
Figure 4.6	Deflection Characteristics Graph-Bending Moment	147

INTRODUCTION

A recent addition to the Begg orthodontic technique armamentarium, in the form of a new design of uprighting spring, has been introduced by A. J. Wilcock Scientific and Engineering Equipment (AJWSEE) of Whittlesea, Victoria.

The new spring, hereinafter referred to by the manufacturer's designated name of 'Mini-Spring' (MS), incorporates significant design features which differentiate it from its antecedents, viz:

- a. Very small size: approximately 7.0mm in length with an inner coil diameter of approximately 0.7mm;
- b. incorporation of 0.25 mm (0.010 inch) diameter very high tensile ('Supreme' grade) austenitic '18-8' stainless steel wire; and
- c. a fundamental variation in the spring coil design in that the spring stem or 'leg', i.e., that portion which engages the bracket channel is disposed **tangentially** to the coil in contradistinction to conventional springs in which the stem is disposed **radially**.

MOLLENHAUER (1989,1990a) has described several clinical advantages associated with the significant design variations embodied in the MS (which are, in ascending order):

- a. Improved aesthetics;
- b. ease of placement, i.e., securing of the archwire in the bracket slot is effected using lock pins rather than by laborious ligation; and
- c. facilitation of oral hygiene regimes (the MS is 'confined' within the boundaries of the bracket base) resulting in potentially reduced decalcification effects.

The foregoing clinical advantages may be conceded as reasonable and empirically obvious. However, they are of little utility if the MS does not efficiently fulfil its (chief) intended function of tooth uprighting during Stage 3 of the Begg technique.

Therefore, the purpose of this thesis project is to examine, **in vitro**, the load-deflection characteristics of the MS and to compare and contrast experimental findings with those of previous investigations into its conventional antecedents.

The experimental portion will be preceded and supported by a review of:

- a. The roles of Begg uprighting springs;
- b. metallurgical aspects of austenitic '18-8' stainless steel wire, especially that produced by AJWSEE; and
- c. Begg uprighting spring evolution, design and performance.

CHAPTER ONE

THE ROLES OF BEGG UPRIGHTING SPRINGS

OONO and MACHIDA (1968) have described Begg technique uprighting springs as:

'the most important mechanism in the system'.

They go on to observe that uprighting springs:

'provide... the energy to upright the lateral incisor, canines and bicuspid from their extreme axial inclinations to the desirable relationship at the finish'.

PERLOW (1968) has supported the foregoing remarks in his observation that the main function of Stage Three in the Begg technique is to correct the 'excesses' of the first two stages.

Similarly, he concurs with OONO and MACHIDA (ibid) who regarded the application of uprighting springs to canine and premolar root paralleling as the critical step in achieving finished cases of acceptable standard.

However, there are other roles to be played by uprighting springs in the Begg technique including:

- a. Anchorage creation/enhancement in space closure during Stage Two/Three (BEGG - 1961; BARRER - 1963; BARBIERI and BARBIERI - 1972); and
- b. midline control/correction with or without application of appropriate inter or intra maxillary elastic control (SWAIN and ACKERMAN - 1969; CADMAN - 1975b).

In contrast to these positive aspects of uprighting spring use there are negative effects including:

- a. Unwanted crown/root movement including molar buccal flaring in Stage Three (CADMAN - 1975a; and anterior crown/distal root movement during Stage Two (LEE - 1981);
- b. the impeding of bite opening; bite deepening, and the negating of desired tooth movement(s) (BARBIERI and BARBIERI - 1972; HOCEVAR - 1982a, 1982b); and
- c. hindering the maintenance of proper standards of oral hygiene (CADMAN - 1975a).

SWAIN and ACKERMAN (1969) have described the braking and paralleling effects of uprighting springs as 'judo movements' (inasmuch as they resemble judo's use of leverage and resistance) to accomplish desired tooth movements.

CADMAN (1975a) supported the views of SWAIN and ACKERMAN (ibid) in more prosaic terms, noting that the efficiency of the Begg technique was such that requisite tooth movements:

'occur simultaneously with relatively little appliance adjustment'.

This is certainly typified by the use of uprighting springs applied to the simultaneous axial correction of canine and premolar teeth.

The **precision** of the Begg technique was adversely reviewed by STRANG (1964). He observed that in effecting torquing movements with spurred auxiliaries an imprecise 'spring force' was employed. The same view may reasonably be extropolated to uprighting springs if Strang's view is accepted. The implication of these comments is that the use of auxiliaries in the Begg technique is inherently unsafe.

While vigorously supporting the opposite view regarding precision in the Begg technique, BEGG and KESLING (1977a) tacitly acknowledged Strang's comments when they stated:

'archwires and tooth moving auxiliaries still have tooth moving forces in them at the completion of treatment. Therefore, the appliances must be removed before too much overmovement occurs'.

Notwithstanding the foregoing remarks, positive comment is made regarding the separation of root uprighting forces from the archwire (ibid), eliminating untoward reciprocal forces on adjacent teeth. Similar views have been expressed by HOCEVAR (1985).

In addition, BEGG and KESLING (ibid) support the placement of fully activated archwires and auxiliaries, listing their advantages as:

- a. The rates of tooth movement are increased;
- b. reciprocal forces are caused to become more efficient;
- c. variations in both the values and directions of tooth moving forces (changes which retard tooth movement and are inevitable whenever appliances are reactivated) are eliminated.
- d. chairside time is reduced
- e. the total number of appointments is reduced; and
- f. the overall treatment time is greatly reduced.

Regarding braking mechanics, a preliminary report of a current clinical investigation into Begg closing mechanics (Stage 2) was made by WEEKES ('Differential Force Concept - Myth or Moment - 1987).

This continuing trial involves three groups of patients (N = 20) undergoing conventional Begg mechanotherapy.

Three Stage 2 regimes were employed:

- Group 1 : 100g intramaxillary elastic force; free tipping of anterior teeth permitted;
- Group 2 : 100g intramaxillary elastic force, 0.020" braking springs in anterior segments; and
- Group 3 : 45g intramaxillary elastic force; 0.020" braking springs in anterior segments.

At the time the interim report was written only seven patients had completed State 2.

However, the author noted three distinct trends:

- a. Maximum retraction of anterior segments plus minimal mesial molar movement in Group 1;
- b. the 'braking' mechanism employed in Group 2 permitted increased mesial movement of molars and a reduction in anterior retraction; and
- c. the combination of braking mechanics and **light** intramaxillary elastic force, resulted in **some** forward movement of anterior segments (because of the braking springs) nevertheless, the **greatest** amount of molar mesial movement was effected.

WEEKES (ibid) noted that these findings were at odds with the views propounded by BEGG and KESLING (1977a) and lead him to suggest the optimal tactical approach to Stage 2 space closure to be bracing mechanics plus **light** intramaxillary elastics. What is additionally significant and relevant for the present study is that Weekes' bracing springs' may be represented by 'Mini-Springs', although Weekes differed in his approach using what are commonly regarded as springs delivering high forces.

In conclusion, and notwithstanding the potential untoward effects ascribed to Begg uprighting springs, they have nevertheless proved their ability to fulfil their assigned roles of (chiefly) root paralleling, allowing over correction and (secondly) anchorage enhancement and midline correction.

The importance of over correction has been assessed by SIMS (1964) and BEGG and KESLING (1977a) as essential in achieving and maintaining a successful treatment result.

CHAPTER TWO

METALLURGICAL ASPECTS OF WILCOCK ORTHODONTIC WIRES

INTRODUCTION

From the introductory journal series onwards, BEGG (1954) stressed the absolute necessity of employing **light, round resilient** wires to effect those tooth movements required in the correction of malocclusion.

Dr. Begg stipulated the austenitic '18-8' stainless steel round wire produced by A. J. Wilcock Scientific and Engineering Equipment (AJWSEE) of Whittlesea, Victoria as being **the** wire to be employed in his treatment technique.

WILCOCK (1989) has described the long association between his late father, C. A. J. Wilcock (1913 - 1987) and Dr. Begg in the development of a series of orthodontic wires including titanium wire as well as, of course, stainless steel types.

It is certainly fortuitous that the same close working relationship still exists in Australia between the orthodontic and engineering professions, indicative of which is the collaboration between Dr. B. Mollenhauer, Orthodontist, and Mr. A. J. Wilcock Jr. This contemporary association has resulted in, amongst other things, the production of very fine, very high tensile 'Supreme' grade 0.009" to 0.011" diameter wires manufactured, in the first instance, at Mollenhauer's request, for use in lingual orthodontic cases - MOLLENHAUER (1987). (The 0.010" Mini Spring subsequently appeared, again at the suggestion of MOLLENHAUER (1990).)

The availability, over the years, of constantly improving austenitic '18-8' stainless steel orthodontic wire, in various gauges and forms (both straight lengths, or coils and preformed auxiliaries) has been of fundamental importance in realising one of Dr. Begg's treatment aims: the application of **light, continuous** force (BEGG - 1954).

In this chapter will be given an overview of the evolution of the stainless steels, followed by a review of their microstructure and mechanical properties (and specifically, and in detail, the 300 Series '18-8' austenitic steels) concluding with a discussion of the relevance of these properties to the Begg philosophy and appliance.

THE STAINLESS STEELS

The importance to the post-modern world of the stainless steels, as a group, is encapsulated in the words of FISCHER and MACIAG (1977):

'Stainless steels contribute properties and characteristics which are otherwise unavailable within the alloy systems of the various ferrous alloy groups'.

EVOLUTION

COLOMBIER AND HOCHMANN (1967) (in perhaps typical Gallic style?) have indicated that:

'The paternity of the stainless steels, apart from their date of birth, is a highly disputable matter and has given rise to some celebrated legal actions'.

They also relate the apparently simultaneous multinational appearance of stainless steels:

- | | | |
|----|----------------|--|
| a. | U.K. | Brearley (1913) found steels containing nine to sixteen per cent chromium to be highly corrosion resistant; stainless steels were marketed commercially, principally for cutlery; |
| b. | U.S.A. | Haynes (almost simultaneously with Brearley) observed the high corrosion resistance of 'Stellites' (cobalt - chromium and cobalt - chromium - tungsten alloys) even after the addition of iron; |
| c. | Germany | Strauss and Maurer (1914) commented on the resistance to rust and acid of steels containing appropriate concentrations of chromium and nickel (Colombier and Hochmann note that Maurer's work was commenced in France under Osmond); and |
| d. | France | Chevenard (1917-18) filed patents on steels containing fifteen to twenty per cent chromium and twenty to forty per cent nickel. |

A similar chronology was given by MARSHALL (1984):

- a. **1889** Riley of Glasgow found that the tensile strength of mild steel was markedly enhanced through the addition of nickel;
- b. **1905** Portevin (France) observed that steels with a chromium concentration in excess of nine per cent were acid resistant; and
- c. **1912** Strauss, of Krupps, patented an austenitic steel for high temperature applications. Brearley (*vide supra*) independently attempted to prevent erosion and fouling in rifle barrels using ferritic iron-chrome alloys. He found these alloys to be resistant to metallographic etchants and called them 'stainless steels'.

According to COLOMBIER and HOCHMANN (1967) the 'arrival' of the stainless steels in the early years of the twentieth-century came about because of the availability of low-carbon ferrochromium via the thermite-reduction process. Previously, for example, Berthier in 1821 had remarked on the resistance to acid attack of iron highly alloyed with chromium. The then available carbon-rich alloys were, however, unsuitable for commercial application.

The same authors cite the works of Guillet (1904) who published a series of papers in which many of the chromium steels were examined including martensitic and ferritic stainless steels and, in due course, austenitic chromium-nickel steels. Guillet is credited with having determined the micro-structures and mechanical properties of the steels and also with evolving classifications still in use. Portevin and Giesen (UK) completed Guillet's work in 1909. COLOMBIER and HOCHMANN (*ibid*) describe these papers as 'still basic sources'.

Another highly significant worker identified by the same authors is Monnartz (Germany). His accomplishments included:

- a. Being the first to study passivity in the alloy group (1911) and with demonstrating the critical twelve per cent chromium concentration above which it occurs;
- b. identifying the effects of carbon on the stainless steels;
- c. raising the possibility of 'stabilization' (vide infra); and
- d. discovering the beneficial effects of molybdenum (vide infra).

COLOMBIER and HOCHMANN (ibid) summarise their review by quoting C. A. Zapffe who had credited Guillet and Monnartz as being the true 'fathers' of stainless steels:

'The traditional credit accorded to the trio Strauss, Maurer and Brearley' [Zapffe says], 'rather belongs to Guillet, Monnartz, Giesen and Portevin'.

To conclude this introductory historical review and give context to the development and general importance of the stainless steels, the comments of FISCHER and MACIAG (1977) are apposite. These authors indicate that stainless steels were developed because other ferrous alloys lacked sufficient corrosion or oxidation resistance as service (operating environment) temperatures increased. They have provided a definition of stainless steels:

'Those ferrous alloys which contain a minimum twelve per cent chromium for corrosion resistance'.

The importance of stainless steels is encapsulated in their assessment of stainless steels as:

'... a family of alloys which have enabled the advancement and growth of chemical processing and power generating systems upon which our technological society is based.'

IRON: THE BASIS OF STAINLESS STEEL

Introduction

Any exposition regarding stainless steel is predicated upon an understanding of the nature and behaviour of iron and, indeed, of steels in general.

To facilitate this understanding, the following discussion will:

- a. Examine the basic crystallography of iron and the role of various elements in modifying crystal structure; and
- b. review the various strategies which may be employed to effect the strengthening of iron.

Iron Crystallography and Its Modification

HONEYCOMBE (1981) observes that pure iron (which, in its purest form, is very difficult to obtain and, likewise, very weak) exists in two crystal forms:

- a. Body-centred cubic (bcc) known as alpha-iron or ferrite; and
- b. face-centred cubic (fcc) known as gamma-iron or austenite.

The varying crystal-forms are manifested as iron is heated, the former occurring from low temperatures up to 910°C , when the transition to the latter occurs, reverting to the former at $1\,390^{\circ}\text{C}$ which remains stable up to the melting point of $1\,536^{\circ}\text{C}$.

HONEYCOMBE (ibid) notes that the detailed geometry of unit cells of alpha and gamma iron crystals is particularly relevant to (for example):

- a. The solubility in both phases of non-metallic elements, e.g., carbon and nitrogen;
- b. alloying element diffusivity at elevated temperatures; and
- c. general behaviour on plastic deformation;

(The bcc structure of alpha-iron is recorded as being more loosely packed than that of fcc gamma-iron .).

The Roles of Carbon and Nitrogen

HONEYCOMBE (ibid) notes that very small additions of carbon to iron will form a steel, e.g., 0.1-0.2 weight %, approx. 0.5-1.0 atomic %, accompanied by a great strengthening effect.

The same author (ibid) notes that the atomic sizes of carbon and nitrogen are so small that they may be incorporated in the alpha-iron and gamma-iron lattices as **interstitial solute atoms**. This contrasts with metallic alloying elements, e.g., manganese nickel and chromium, whose atoms are much larger, and similar in size to iron atoms. The result is that alloying element atoms enter into **substitutional solid solution**.

While carbon and nitrogen may be incorporated in the iron lattices by means of interstitial solution, it is accompanied by **some** lattice distortion and concomitant generation of strain energy. HONEYCOMBE (ibid) also observes that the larger interstices available in austenite compared with ferrite should, and do, result in greater solubility of carbon and nitrogen in austenite. He notes that: 'These marked differences of the solubility of the main interstitial solutes in gamma- and in alpha-iron are of profound significance in the heat treatment of steels, and are fully exploited to increase strength.'

If tensile testing is interrupted, with a period of rest (at room temperature or for a shorter period at 100° - 150° C) then a new yield point will be observed. Honeycombe refers to this as **strain ageing**.

Yield Phenomena and Interstitial Elements

The dramatic effect of very small concentrations of carbon on yield behaviour has already been discussed. HONEYCOMBE (ibid) also notes the even greater capacity of nitrogen at very low concentrations (0.001 - 0.002 Wt %) to induce severe strain ageing. He attributes the greater potency of nitrogen to its substantially greater residual solubility near room temperature.

(To elucidate satisfactorily the critical role of interstitial elements in yield phenomena, the following discussion is abstracted virtually in toto from HONEYCOMBE (ibid) pages 15 through 20.)

'Cottrell and Bilby first showed that interstitial atoms such as carbon and nitrogen would interact strongly with the strain fields of dislocations [in the crystal lattice(s)]. The interstitial atoms have strain fields around them, but when such atoms move within the dislocation strain fields, there should be an overall reduction in the total strain energy. This leads to the formation of interstitial concentrations or... atmospheres in the vicinity of dislocations, which in an extreme case can amount to lines of interstitial atoms along the cores of the dislocations at the region of the strain-field where there is maximum dilation.

The binding energy between a dislocation in iron and a carbon atom is approximately 0.5eV. Consequently, dislocations can be locked in position by strings of carbon atoms along the dislocations, thus substantially raising the stress which would be necessary to cause dislocation movement. A particular attraction of this theory is that only a very small concentration of interstitial atoms is needed to produce locking along the whole length of all dislocation lines in annealed iron. Consequently, this theory can explain the observations of yield phenomena at very low carbon and nitrogen concentrations.

The formation of interstitial atmospheres at dislocations requires diffusion of the solute. As both carbon and nitrogen diffuse very much more rapidly in iron than substitutional solutes, it is not surprising that strain ageing can take place readily in the range 20°C to 150°C.

[Theoretical consideration of the interaction energy between solute(s) and dislocation(s) indicates that the condensation of atmosphere(s) (and subsequent formation of rows of interstitial atoms along the cores of dislocations) will occur below 700°K.] The yield point should, therefore, be expected to be below 700°K, but it should disappear at higher temperatures when dislocations can escape from their atmospheres as a result of thermal activation. This corresponds approximately with results of experiments showing the temperature dependence of the stress-strain curve of mild steel. As expected, the zone of yielding is well defined at the lower testing temperatures, becoming less regular as the temperature is raised, until it is replaced by fine serrations along the whole stress-strain curve. This phenomenon is referred to as **Dynamic Strain Ageing** in which the serrations represent the replacement of the primary yield point by numerous localized yield points within the specimen.

These arise because the temperature is high enough to allow interstitial atoms to diffuse during deformation, and to form atmospheres around dislocations generated throughout the stress-strain curve. Steels tested under these conditions also show low ductilities, due partly to the high dislocation density and partly to the nucleation of carbide particles on the dislocations where the carbon concentration is high.

The phenomenon is often referred to as **blue brittleness**, (blue being the interference colour of the steel surface when oxidised in this temperature range) and has major significance with respect to the stainless steel wire types produced by A.J. Wilcock Scientific and Engineering Equipment, wire types advocated by BEGG (1954d) for use in his appliance and technique, (vide infra).

The break-away of dislocations from their carbon atmospheres as a cause of the sharp yield point became a controversial aspect of the theory because it was found that the provision of free dislocations, e.g., by scratching the surface of a specimen did not eliminate the yield point.

Strengthening Iron

HONEYCOMBE (ibid) lists the following basic mechanisms as the most important in strengthening iron:

- a. Work hardening;
- b. solid solution strengthening by interstitial atoms;
- c. solid solution strengthening by substitutional atoms;
- d. grain size refinement; and
- e. dispersion strengthening including lamellar and random dispersed structures.

He ascribes the most distinctive role to carbon and nitrogen (the interstitial solutes); furthermore, they interact with lattice dislocations and preferentially combine with some metallic alloying elements.

Work Hardening

Detailed comment will be made about work hardening in austenitic stainless steels later in the chapter.

However, and in the context of general comment, HONEYCOMBE (ibid) identifies work hardening as an important strengthening process in steel, especially the high strength levels required in rod and wire (either plain carbon or alloy steels).

Interstitial Atoms and Solid Solution Strengthening

HONEYCOMBE (ibid) notes that the presence of even minute quantities of carbon and nitrogen, eg., 0.005Wt% in iron effects a sharp transition between elastic and plastic deformation in tensile testing and defines it as the **yield point**. This, according to Honeycombe, implies a connection between the effect and the presence of the solute atoms. Furthermore, he asserts that upon complete specimen yielding, general work hardening commences.

An alternative theory was developed which assumed that, once condensed carbon atmospheres are formed in iron, the dislocations remain locked and the yield phenomena arise from the generation and movement of newly-formed dislocations.

To summarize, the occurrence of a sharp yield point depends on the occurrence of a sudden increase in the numbers of mobile dislocations. However, if the dislocations are strongly locked, either by interstitial atmospheres or precipitate, the yield point will result from the rapid generation of new dislocations.

Under conditions of **dynamic strain ageing**, where atmospheres of carbon atoms form continuously on newly generated dislocations, it would be expected that a higher density of dislocations would be needed to complete the deformation, if it is assumed that most dislocations which attract carbon atmospheres are permanently locked in position. Electron microscopic observations have shown that in steels deformed at 200°C, the dislocation densities are an order of magnitude greater than those in specimens similarly deformed at room temperature. This also accounts for the fact that increased work-hardening rates are obtained in the blue brittle condition as compared to tests at room temperature.'

Substitution of Atoms and Solid Solution Strengthening

HONEYCOMBE (ibid) notes that while there may be wide variations in strength, the numerous metallic elements which can form solid solutions in austenite and ferrite invariably form substitutional solid solutions.

Strengthening elements include vanadium, silicon, molybdenum, phosphorous, manganese, nickel and copper, with ambient temperature and concentration modifying their effect(s).

HONEYCOMBE (ibid) relates the degree of strengthening to two factors:

- a. Solute atomic size differential compared with iron (the greater the differential the greater the strengthening effect); and
- b. the elastic behaviour of solute and solvent atoms.

Honeycombe notes that the effect of substitutional atoms is more a 'useful bonus' being 'superimposed on hardening from other sources'.

Grain Size

Grain size manipulation is described by HONEYCOMBE (ibid) as amongst the most important strengthening mechanisms in heat treating steels. The mechanism by which grain size affects yield stress is described by the same author and may be understood by assuming that a dislocation source operates within a crystal causing dislocations to move and eventually to accumulate at the grain boundary. The result is the generation of a stress in the adjacent grain which, upon the achievement of a critical value, operates as a new source in that grain, and so on. Grain size is the critical factor in this process, determining distance traversed and number of dislocations involved. Hence, larger grains lead to higher neighbouring-grain stress concentrations as well as easier yield propagation. HONEYCOMBE (ibid) notes that, practically, (very desirable) higher yield stress is associated with finer grain size.

Summary

HONEYCOMBE (ibid) observes that the strengthening of steels is multifactorial, highly flexible and very potent incorporating as it does the gamma/alpha-phase change with the highly significant modifying effects of alloying elements on the phase change being but one (albeit highly significant) example.

Dispersion Strengthening

HONEYCOMBE (ibid) notes that a further (often potent) strengthening mechanism in steels is the manipulation of the dispersion of phases other than the matrix, e.g., ferrite or austenite, in the microstructure.

An example is the carbide phases which form as the result of the low solubility of carbon in alpha-iron. The same author (ibid) states that other carbides, e.g., chromium carbide in '18-8' stainless steels, replace iron carbide because they (the former) have greater thermodynamic stability. While strengthening **generally** accompanies most dispersions, degraded ductility and toughness may also occur.

MICROSTRUCTURE AND MECHANICAL PROPERTIES OF THE STAINLESS STEELS

Introduction

Before discussing the austenitic stainless steels and, specifically, the '18-8' AISI¹ 300 series, it is appropriate to gain a general understanding of the stainless steels, including a brief review of the categories of stainless steels other than the austenitic group.

The Stainless Steel Family

The general relationship of this group to the family of ferrous alloys is depicted in Fig. 2.1.

PECKNER and BERNSTEIN (1977) amongst others, e.g., COLOMBIER and HOCHMANN (1967); MARSHALL (1984) identify the binary iron-chromium system as the foundation of the stainless steels. They account for the different grades of stainless steels on the basis of variations in '... compositional, microstructural and crystallographic factors'.

The important effects of manipulation of the concentrations of constituent elements may be considered in conjunction with Figure 2.2 - the Cr-Fe Binary Phase Diagram.

1. AISI: American Iron and Steel Institute.

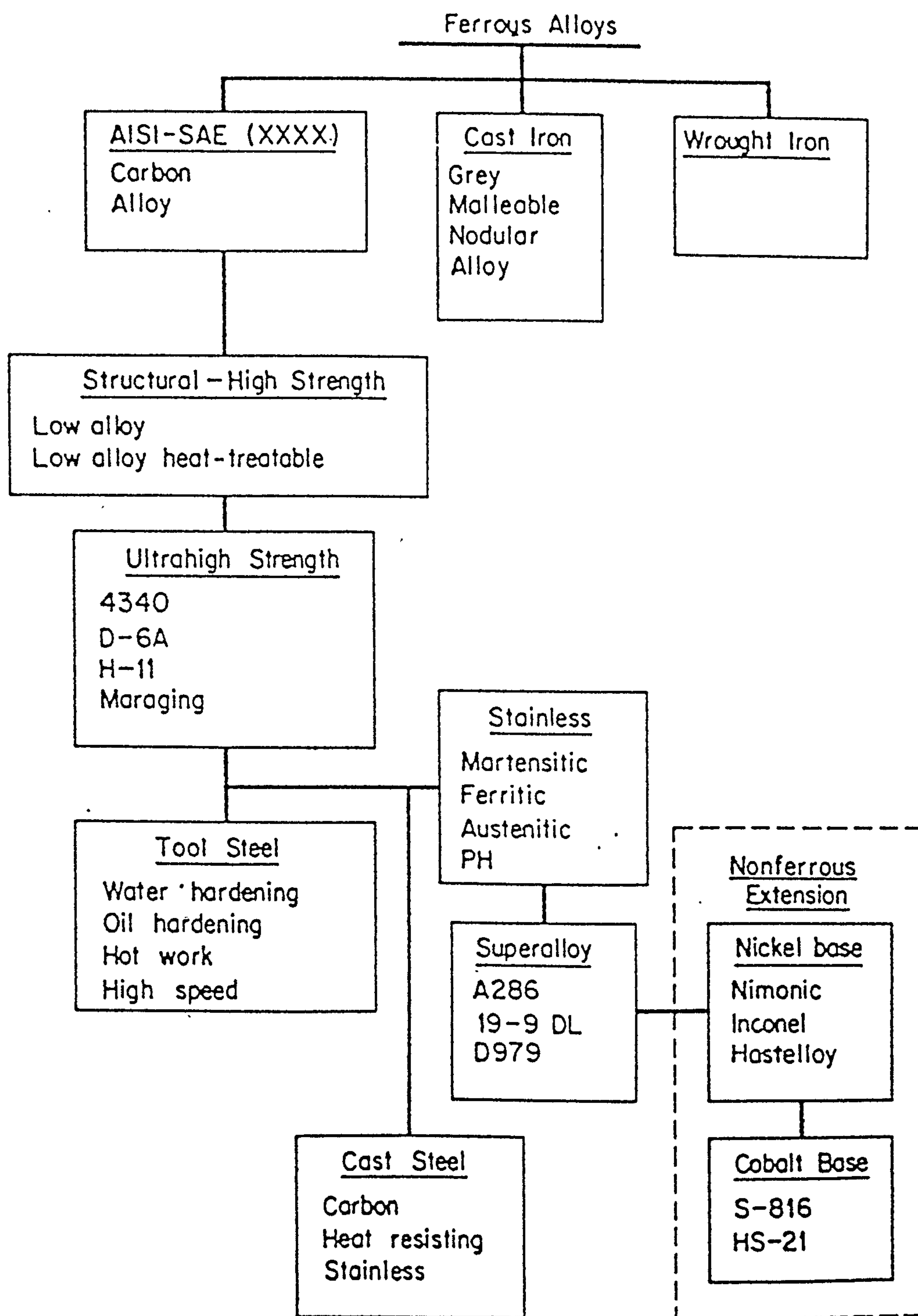


Fig. 1 Relationship of stainless steels to other families of ferrous alloys.

Figure 2.1... (Peckner and Bernstein - 1977)

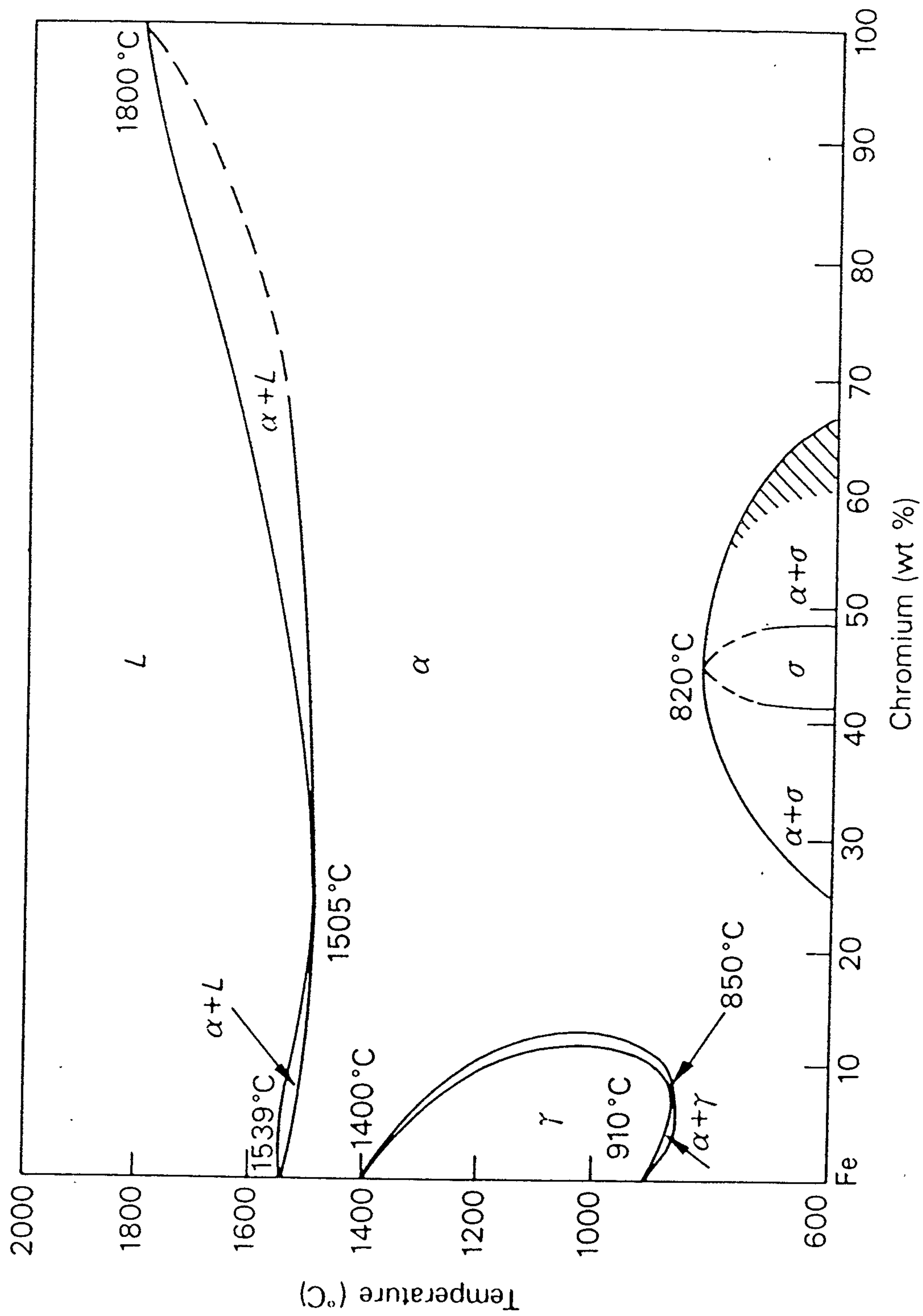


Figure 2.2....(Honeycombe - 1981)

Fig. 11.1 The Fe-Cr equilibrium diagram

THE ELEMENTAL CONSTITUTION OF STAINLESS STEELS

MARSHALL (1984) has described the chief constituent elements of the stainless steels as iron, chromium and nickel:

Iron

Below the melting point of iron ($1\,536^{\circ}\text{C}$) there are three allotropes:

ALLOTROPE OF IRON

Temperature Range ($^{\circ}\text{C}$)	Symbol	Crystal Structure
1 536 - 1 392	δ -Fe	Body-centred cubic(bcc)
1 392 - 911	γ -Fe	Face-centred cubic(fcc)
911 and below	α -Fe	Body-centred cubic(bcc)

TABLE 2.1 (Marshall - 1984)

The phase equilibria of binary and higher, e.g., quaternary systems of iron depend upon whether the added elements are more soluble in bcc or fcc iron. Solid solutions in the fcc and bcc phases are designated gamma and alpha respectively.

Chromium

Chromium is bcc below its melting point which is approximately $1\,900^{\circ}\text{C}$. Solid solutions in chromium are denoted alpha-dash. When the bcc solid solutions in iron and chromium are continuous, as in the case over $1\,000^{\circ}\text{C}$, the symbol is used.

COLOMBIER and HOCHMANN (ibid) describe chromium as the fundamental ingredient of stainless steel and a member of the group of elements known as ferrite formers which extend the alpha phase- field and suppress the gamma phase- field: the 'gamma loop'. (See Figure 2.2)

The Gamma Loop

This loop divides the phase diagram into two zones:

- a. Less than twelve per cent: the alloys, like pure iron, undergo an alpha to gamma transformation on heating; and
- b. greater than thirteen per cent: heating has no effect and the alloys remain ferritic. Similarly, heat treatment cannot affect grain size.

Sigma Phase

This phase is an iron-chromium compound. Its structure is tetragonal and is strongly paramagnetic. The significance of sigma phase is its association with hardening and extreme embrittlement when present in chromium-rich ferrites.

The Effect of Increasing Chromium Concentrations

The gamma loop is seen to contract as chromium concentration increases, the effect being the creation of three groups of chromium stainless steels:

- a. Martensitic steels;
- b. ferritic; and
- c. duplex martensitic-ferritic steels, (vide infra) (COLOMBIER and HOCHMANN- *ibid*).

Nickel

Nickel is fcc below its melting point of 1435°C. Solid solutions are given the symbol δ and are continuous with solid solutions in fcc iron. (MARSHALL-ibid).

COLOMBIER and HOCHMANN (ibid) describe it as an austenite stabilizer with two fundamental effects of:

- a. Extending the austenite stability range; and
- b. increasing the 'hardenability' of the steels by lowering the critical cooling rate; (at around eight per cent Ni, a steel will be martensitic even after very slow cooling).

The same authors indicate that steels already containing chromium will produce alloys with an extremely varied range of structures because of the opposing effects of chromium producing ferrite and the austenite-stabilizing effect of nickel.

For example (and after COLOMBIER and HOCHMANN-ibid): an eight percent nickel concentration will confine the duplex phase field to very high temperatures and very low carbon contents; however, the austenite field will be very extensive. Nickel and carbon in solution combine to stabilise the austenite, which persists at room temperature, and gives the austenitic group of stainless steels, an example of which is the ubiquitous '18-8' group.

Sigma Phase

COLOMBIER and HOCHMANN (ibid) note that the effect of nickel on sigma phase stability is highly significant in chromium containing alloys, the range being displaced to lower chromium contents and higher temperatures.

Carbon and Its Effects on the Phase Diagram

There are two effects brought about by the addition of carbon to iron-chromium alloys according to COLOMBIER and HOCHMANN (ibid):

- a. The austenite is stabilized and its phase field widened; and
- b. special carbides are formed.

The authors observe that, in widening the gamma loop, the effect of carbon is opposite that of chromium and that carbon also suppresses the alpha-phase fields.

The same authors note that the behaviour of chromium steels during heat treatment is complex and, for example, at a concentration of eighteen percent chromium there are three ranges, depending on carbon content:

- a. Less than 0.08% carbon;
- b. 0.08 - 0.22% carbon; and
- c. greater than 0.22% carbon.

In the case of the 0.08 - 0.22% range, (which is the range of values applicable to the 300 series stainless steels used in the wires produced by Wilcock) a duplex austenite-ferrite structure is produced by heating.

Other Additions

As COLOMBIER and HOCHMANN (ibid) note, these are made with the aim of improving either the corrosion resistance in moist surroundings (molybdenum and copper) or the high-temperature scaling resistance (silicon and aluminium).

Silicon

Silicon is an antioxidant and is used chiefly in the 'heat resisting' alloys. It is a ferrite former, contracting the gamma loop and is very similar to chromium in its effect on structure.

Aluminium

Aluminium is used in heat resisting alloys and emulates silicon in its effects. It acts as a hardening agent in the presence of nickel.

Molybdenum

Molybdenum also features in high-temperature applications. It is a ferrite former and stabilizer and extends the passivity and chemical resistance of stainless steels.

Tungsten

Tungsten is a ferrite former and is added to the austenitic stainless steels, especially the '18-8' category to enhance mechanical behaviour.

Manganese

Manganese promotes austenite formation.

Nitrogen

Nitrogen is used in place of nickel when cost is a factor; it stabilizes austenite.

Copper

Copper, while improving corrosion resistance in certain media, cannot act independently to effect austenitic change in chromium steels.

Titanium and Niobium

Both elements are very important in high temperature applications (700°C) suppressing chromium carbide precipitation and hence corrosion (through chromium impoverishment). They may also improve strength in austenite at high temperature.

Cobalt

Cobalt is used in high temperature applications. It does not modify microstructure but it does modify transformation and precipitation behaviour.

Rare Earths

The rare earths (Mischmetal) improve forging properties.

Boron

In trace quantities, creep and rupture strength at high temperatures are improved. (Larger quantities are used in nuclear energy applications.)

Other Elements

The addition of other elements, e.g., sulphur, selenium and phosphorous, is made to improve machinability.

Summary

From the preceding discussion the potential for tailoring alloys to a wide variety of situations and requirements by element manipulation becomes apparent.

GRADES OF STAINLESS STEEL

PECKNER and BERNSTEIN (1977) describe various grades of stainless steel including precipitation-hardenable and austenitic - the grades used for orthodontic purposes (WARE and MASSON - 1975).

These steels can be cold-worked and annealed but not strengthened

Precipitation-Hardenable Grades

The requirement for improved strength and concomitant corrosion resistance led to the evolution of the Precipitation-Hardenable or Age Hardenable grades. A technique used in aluminium, magnesium and nickel-based alloys, amongst others, is employed whereby the re-introduction of carbon and the development of alloys with low-carbon martensite matrices which can be further strengthened by precipitation hardening, is employed.

Within this grade there are three alloy families:

- a. Austenitic;
- b. Semi-austenitic; and
- c. martensitic.

Martensitic grades are based on an '18-8' chromium-nickel austenitic composition with small carbon additions and slight decreases in nickel, chromium and manganese.

-
1. **Martensite** is formed when austenite is cooled rapidly to 400°F or less. It is a supersaturated solid solution of carbon in ferrite and is the hardest and strongest form of steel (SHIGLEY and MISCHKE-1989). It is named for Adolf Martens, a German Metallurgist (ALEXANDER and STREET-1972).

Semi-Austenitic grades are relatively soft, ductile and workable. Strengthening is achieved by first producing martensite by quenching from an elevated temperature and then precipitation of compounds by a subsequent multi-step process.

Austenitic alloys are modified 300 series metals with higher nickel, aluminium and titanium concentrations to produce precipitates. These grades are not as strong as their counterparts within the group but may be used at higher service temperatures.

AUSTENITIC STAINLESS STEELS

FISCHER and MACIAG (1977) describe austenitic stainless steels as:

'...those iron and chromium alloys which have been sufficiently alloyed with nickel or manganese and nitrogen to have an austenitic¹ structure at room temperature'.

Various authors (HONEYCOMBE - 1981; COLOMBIER and HOCHMANN-ibid.) have commented upon the effects of, e.g., nickel or manganese, in extending the gamma loop in the iron-carbon phase diagram.

-
1. Austenite is defined as a solid solution of one or more elements in face-centred cubic iron and was named for Sir William Robert-Austen (1843-1902) a British Metallurgist (ALEXANDER and STREET-1972).

HONEYCOMBE (ibid.) notes that fcc austenite can be preserved at room temperature, either in a stable or metastable condition, with the addition of sufficient alloying element(s). This is because the addition of chromium to a nickel-containing steel retards the kinetics of the gamma to alpha transformation. He further notes that chromium greatly improves the corrosion resistance of the steel through the formation of a very thin stable oxide surface film. The net effect is that this group of steels is the most widely used in a marked diversity of corrosive environments and elevated temperatures. A further bonus is their ease of fabrication and ability to **not** undergo a ductile/brittle transition. (Similar remarks are made by FISCHER and MACIAG-1977).

Carbon and Nitrogen in Austenitic Stainless Steels

As has been noted previously, HONEYCOMBE (1981) identifies carbon and nitrogen as strong austenite formers. They are also the most highly effective solid solution strengtheners available, being interstitial solutes in austenite. HONEYCOMBE (ibid) also observes that nitrogen is more useful than chromium in this regard because of its decreased tendency to cause intergranular corrosion. Concentrations of up to 0.25% are used, resulting in a nearly 100% proof stress improvement of a chromium-nickel austenitic steel.

COLOMBIER and HOCHMANN (ibid) describe the austenitic stainless steels as consisting of a single phase which is capable of dissolving relatively large amounts of carbon at high temperatures and retaining it in supersaturated solid-solution on rapid cooling. The group may contain between eight and thirty percent nickel and are non-magnetic. In addition they are liable to grain growth on high temperature heating and cannot be recrystallized by heat treatment alone; nevertheless they are not subject to embrittlement as are, e.g., the ferritic grades. While they are non-magnetic, cold working will partially transform austenite to martensite, resulting in ferromagnetism.

A range of AISI-grade 300 series '18-8' stainless steels is shown in Table 2.2.

AISI Austenitic Steels-Type 300

FCC, NON-MAGNETIC, NOT HEAT TREATABLE

AISI		Nominal Composition, %			
Type No.	C	Mn	Cr	Ni	Others
301	0.15max	2.0	16-18	6.0-8.0	
302	0.15max	2.0	17-19	8.0-10	
304	0.08max	2.0	18-20	8.0-12	
310	0.25max	2.0	24-26	19-22	

TABLE 2.2 (Peckner and Bernstein-1977)

Note: HONEYCOMBE(ibid) quotes a nitrogen concentration of 0.03wt% in each of the above types; his other values are identical with the exception of manganese which is listed as 1.5wt % in each type. (See Figure 2.3)

Heat Treatment

COLOMBIER and HOCHMANN (1967) emphasise heat treatment as an important consideration when discussing austenitic stainless steels because of its close relationship with the group's physical and mechanical properties.

The (general) sequence described by these authors is as follows:

- Heating to approx. 1 100°C ; and
- rapid cooling (air or water, depending on section (item) size).

The (initial) high temperature is necessary to:

- Erase previous work hardening;
- dissolve all carbides; and
- effect an homogeneous austenitic solid solution.

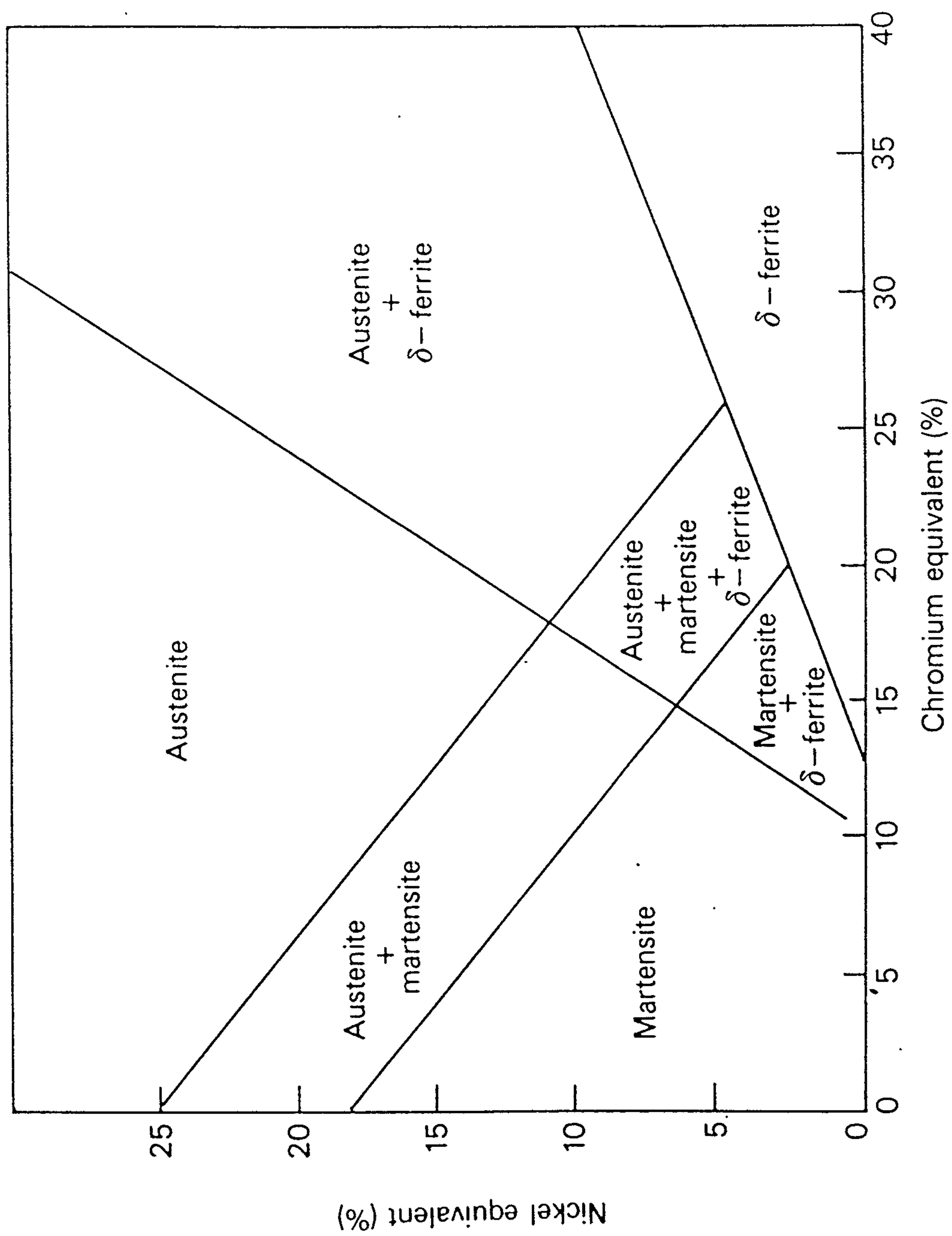


Figure 2.3...(Honeycombe - 1981)

Fig. 11.4 Schaeffler diagram. Effect of alloying elements on the basic structure of Cr-Ni stainless steels (Schneider and Climax Molybdenum Co., *Foundry Trade J.*, 1960, **108**, 562)

The latter rapid cooling ensures carbon is held in solution and not precipitated as carbides. (Precipitation can lead to sensitization and intergranular corrosion.)

PHYSICAL PROPERTIES OF THE '18-8' STAINLESS STEELS (AND THEIR DERIVATIVES)

COLOMBIER and HOCHMANN (ibid) give the melting point as 1 400-1 430°C depending upon carbon content; the addition of two to three percent silicon reduces this to 1 385°C. They also observe that electrical resistivity is increased by cold working and this, in combination with low melting point (effected by the addition of nickel) improves the steels' weldability.

Mechanical Properties

COLOMBIER and HOCHMANN (ibid) note that the Young's modulus is very nearly the same for all steels in the group. An average value of 13,000 tsi at 20°C is apposite and closely approximates that of ordinary steels.

The same authors also comment that the elastic limit of the austenitic stainless steels is: 'often ill-defined' so that values quoted are most commonly the 0.2% proof stress.

Similarly, there is variation in tensile properties within the group.

COLOMBIER and HOCHMANN (ibid) quote the following as typical values at the usual carbon contents of 0.05 to 0.10% carbon:

- | | | |
|----|-------------------|---------------|
| a. | 0.2% proof stress | 13-19tsi; |
| b. | tensile strength | 35-41tsi; and |
| c. | elongation | 40-60% |

Finally, they note the high ductility of the austenitic steels which, unlike proof stress and tensile strength, increases little with increasing carbon content. Conversely, lower elongations are effected by increasing nickel content.

THERMO-MECHANICAL TREATMENTS AND WIRE PRODUCTION

Introduction

In the preceding sections of this chapter a relatively detailed account has been given of the microstructure, physical properties and metallurgical manipulation of the stainless steels in general, and the austenitic '18-8' stainless steels, in particular.

The discussion has, to the present, made general reference to the improvement, e.g., Dynamic Strain Ageing and Work Hardening and occasional degrading, e.g., Work Hardening of physical properties through the application of thermo-mechanical treatment(s). In the first half of this, the concluding section of the chapter, an account will be given of the austenite-martensite transformation which, in combination with the previously described phenomenon of dynamic strain ageing, is applied in the production of the outstandingly high quality wire which is the basis of the Begg 'Mini-Spring'. The section will conclude with a description and discussion of the production of wire by A. J. Wilcock Scientific and Engineering Equipment.

THE AUSTENITE-MARTENSITE TRANSFORMATION

Several authors (COLOMBIER and HOCHMANN-1967; HONEYCOMBE-1981; and MARSHALL-1984) describe the austenite-martensite transformation.

COLOMBIER and HOCHMANN (ibid) comment that, strain for strain, the cold working of austenitic steels produces much greater work hardening than in other steels. They note that while the transformation to martensite through austenite instability is a contributing factor, it is not solely responsible since work hardening occurs in steels with nickel contents of twenty-five percent, the austenitic structure of which is completely stable.

COLOMBIER and HOCHMANN (ibid) attribute the degree of work-hardening to the ratios of carbon to nickel and chromium. They observe that in the '18-8' prototype, increasing work hardening results from raising the carbon content in the range 0.04% to 0.10%. However, above this level, further carbon increases have minimal effect.

Note: Comment has already been made regarding the austenite stabilizing (and hence) anti-martensite transformation effects of increasing concentrations of nickel, chromium, molybdenum and silicon.)

Martensitic Transformation

COLOMBIER and HOCHMANN (ibid) note that martensite can form above the M_s^1 point as a result of plastic strain, and that a temperature, the M_d^1 point, (M_d being greater than M_s) has been defined above which no transformation will occur whatever the plastic strain. Therefore, the proportion of martensite formed is a function of temperature and strain. However, while never reaching one hundred percent, the maximum amount of martensite that can form will increase as the temperature is lowered.

-
1. M_d^1 = deformation induced martensite transformation
 M_s^1 = temperature induced martensite transformation
(MARSHALL- 1984)

On a microstructural level, X-ray crystallographic analysis indicates a new hexagonal phase accompanying the bcc alpha-dash phase. (Heating above 500°C will return the austenitic phase.)

MARSHALL (1984) also notes that austenite transformation can occur in the less highly alloyed austenitic stainless steels in which the M_s temperature is above room temperature, or it may occur during refrigeration in more stable alloys in which M_s is below room temperature. Furthermore, he reiterates the comments of COLOMBIER and HOCHMANN (ibid) that the AISI 300 series steels are quite close to being other than totally austenitic and that phase boundaries may be significantly altered by compositional changes in alloys arising from minor and trace elements normally found in stainless steels.

HONEYCOMBE (1981) supports the remarks of the preceding authors. He notes that fcc metals exhibit higher work hardening rates than bcc metals because of the more stable dislocation interactions possible in the fcc structure (hence the higher work-hardening rates in austenitic steels when compared with ferritic steels).

The same author (ibid) lists two factors influencing work-hardening:

- a. Matrix stacking-fault energy as determined by composition; and
- b. matrix stability.

Stacking Fault Energy

HONEYCOMBE (ibid) states that chromium-nickel austenitic steels have stacking fault-energies in the range 5-60 mJm⁻². Hence, high nickel content alloys possess the highest stacking fault energy and demonstrate the lowest work hardening. Conversely, the elements silicon, carbon and nitrogen lower austenitic stacking fault energy.

He further notes that heavy plastic deformations produce many fine deformation twins in addition to stable dislocation inter-actions which are contributory factors in the observed high flow stresses of deformed alloys. Therefore, during severe cold working, e.g., wire drawing reductions of up to eighty percent, yield strength of ordinary austenitic steels can be raised to over 1 200 MNm⁻².

Matrix Stability

Martensitic transformation is ranked by HONEYCOMBE (ibid) as having, without question, the greatest effect on work hardening rates. For example, yield stresses of $1\,500\text{ MNm}^{-2}$ can be achieved through transformation. HONEYCOMBE (ibid) also comments that concomitant with the increase in strength is a substantial decrease in ductility and increase in the extent of uniform straining compared with localised straining which a steel will undergo prior to failure.

Controlled Transformation

HONEYCOMBE (ibid) comments that the inherent advantages of the austenitic stainless steels led naturally to the development of **controlled transformation** stainless steels in which the requisite (high) strength levels were obtained after fabrication through one of two means:

- a. Refrigeration - whereby the steel is taken below its $M_{(s)}$ temperature; or
- b. low temperature heat treatment to de-stabilise the austenite.

Refrigeration

The author comments that alloy adjustment should result in almost complete martensitic transformation upon refrigeration.

Low Temperature Heat Treatment

HONEYCOMBE (ibid) states that grain-boundary carbide-precipitation can be achieved by heat treatment around 700°C. The effect is to reduce matrix carbon content and raise the M_{15} so that, on subsequent cooling to room temperature, a martensitic transformation will occur. (Precipitation can be accelerated by manipulating the delta-ferrite volume to provide carbide delta-gamma nucleating sites.)

Further tempering in the 400-450°C range is performed to improve ductility and high proof stress¹. This group of steels is described by HONEYCOMBE (ibid) as complex and demanding of metallurgical processes and hence costly; applications include rocket casings and the skins of supersonic aircraft.

Another example of martensitic transformation resulting from low-temperature plastic deformation of austenitic stainless steels is the TRIP group of steels ('Transformation Induced Plasticity Steels'). However, while the same principle is employed as in the controlled transformation group, **plastic deformation** is employed and a broader thermo-mechanical approach is applied.

These steels are also very expensive and are only used in mechanically highly demanding applications in contradistinction to difficult environmental milieux.

HONEYCOMBE (ibid) makes the very apposite observation that both these examples illustrate how 'a combination of basic principles can be carefully balanced and controlled to achieve outstanding mechanical properties in alloy steels'.

-
1. The term **Proof Stress** has a number of synonyms including **Yield Stress** which SHIGLEY and MISCHKE (1989) note is sometimes taken to correspond with the Yield Point. They observe that some materials have an upper and a lower Yield Point.

Prior to HONEYCOMBE (vide supra) COLOMBIER and HOCHMANN (1967) listed the factors influencing martensitic transformation as:

- a. Composition and prior structure of the steel;
- b. degree, type and rate of strain; and
- c. temperature.

Therefore, and as observed by COLOMBIER and HOCHMANN (ibid), transformation is frequently encountered during the various 'workings' of stainless steels, including:

- a. Deep drawing;
- b. wire drawing;
- c. straightening; and
- d. mechanical polishing.

A feature of the austenitic stainless steels remarked upon by the same authors (ibid) is the very high tensile strengths which can be induced by cold working (up to a limit as high as 100-130tsi).

This increase in tensile strength is accompanied by:

- a. A very marked proportional increase in proof stress (ratios of 85-90% after cold working are typical when compared with proof stress values of 30-45% in the annealed condition);
- b. major reductions in the elongation and impact values: a reduction of only a few percent at fracture in the former while reduction to a tenth the softened condition in the latter are typical;
- c. a reduction in Young's modulus longitudinally with a slight increase in the transverse direction; and
- d. the fatigue limit is found to increase in proportion with the tensile strength. Proportionality is maintained up to tensile strengths of 70tsi.

WIRE DRAWING

(The following description is taken from COLOMBIER and HOCHMANN-1967).

The starting point for small-gauge wires is annealed, hot-rolled rod between 0.2" and 0.8" diameter (5 swg and thicker), in coils which have been quenched in water from 1 050°C to 1 150°C and pickled. A variety of coatings for use as drawing lubricants include lime, lead, copper or chemical oxalate. Drawplate lubricants include soaps, waxes, e.g., beeswax, carnauba wax, synthetic resins (silicones) and special soaps and greases with powdered fillers such as talc, graphite, lime, etc. Soap is still very popular but zinc or aluminium stearates are now also used.

The authors (ibid) note that the total reductions between anneals must be smaller than for other steels, e.g., '18-8' steels:

WIRE REDUCTION SEQUENCE

Die Diameters	Lubricant	Die Material
1. 5, 7 and 9 swg	Soap	}
2. 10 and 12 swg	-	} Tungsten
3. 15 and 17 swg	-	} carbide
4. from 19-24 swg	-	}
in several passes	-	}
5. from 24-42 swg	Soluble oil	diamond
in several passes		

TABLE 2.3 (Colombier and Hochmann - 1967)

The reductions in diameter between dies are 15 to 30%. After each of stages 1 to 4, the wire is annealed by quenching in water from 950°C, which is high enough to soften the steel without damaging its surface excessively. Higher temperatures must, however, be used as the carbon content increases beyond about 0.07%. The final treatment is pickling in a mixture of nitric and hydrofluoric or hydrochloric acids; better still, fused sodium hydroxide can be used.

Wire drawing speeds vary widely, according to the equipment used. '18-8' steels should be drawn at speeds 30-60% lower than would be used for ordinary mild steel wire. COLOMBIER and HOCHMANN (ibid) cite an exhaustive study of wire - drawing in 18-8 austenitic steels published by Francis, the primary aim being to elucidate the effects of lead coating. It was found to be basically a mechanical factor; the lead coating promotes the formation of a stable soap film, and it is then possible to increase the reduction quite substantially. (Soap adheres much less strongly to unleaded wire, hence the difference.)

The results brought out two important points:

- a. The total possible reduction is within limits independent of the number of intermediate passes used, i.e., whether one uses a large number of small reductions or a few larger ones;
- b. the mechanical properties of the wire are independent of the sequence of reductions used, apart from the possible effect of heating if a small number of passes is given. They are unaffected by the use of lead coating.

PRACTICAL AND THEORETICAL ASPECTS OF WIRE PRODUCTION BY A. J. WILCOCK SCIENTIFIC AND ENGINEERING EQUIPMENT

Introduction

The preceding discussion regarding wire drawing, while general in nature, is apposite to the techniques employed by A. J. Wilcock Scientific and Engineering Equipment (AJWSEE). This, the concluding section of the chapter, will be in two parts:

- a. A general description of the wire drawing process employed by AJWSEE; and
- b. a discussion of the theoretical underpinnings of the Wilcock approach to wire engineering.

'Pulse-Straightened' Wire: Production

(The information available for publication regarding wire production techniques is constrained by commercial confidentiality. Nevertheless, the co-operation extended by the manufacturer is gratefully acknowledged.)

The following description should be read in conjunction with Figures 2.4 and 2.5 below:

PROCESS OF REPETITIVE DYNAMIC STRAIN AGEING FOR STAINLESS STEEL AND TITANIUM ALLOYS

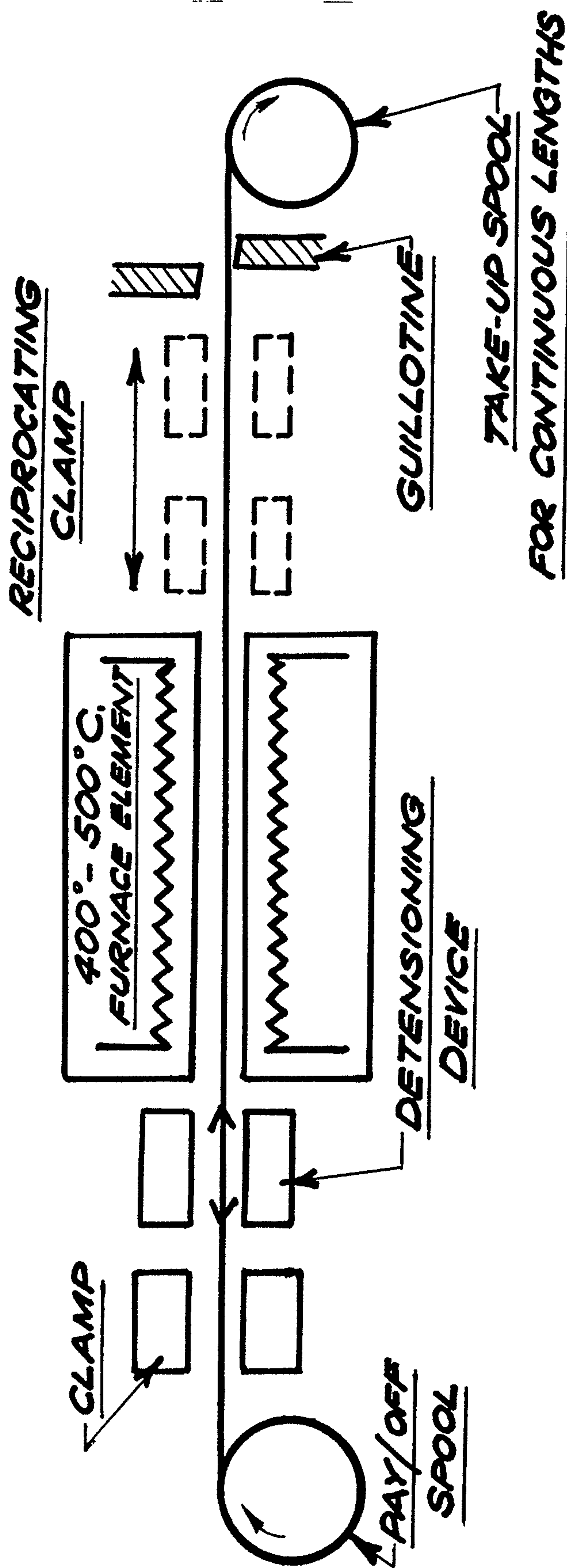


Figure 2.4...(Mr AJ Wilcock Jr.; with permission)

**CONTINUOUS LENGTH WIRE UNDERGOING
'PULSE-STRAIGHTENING'**

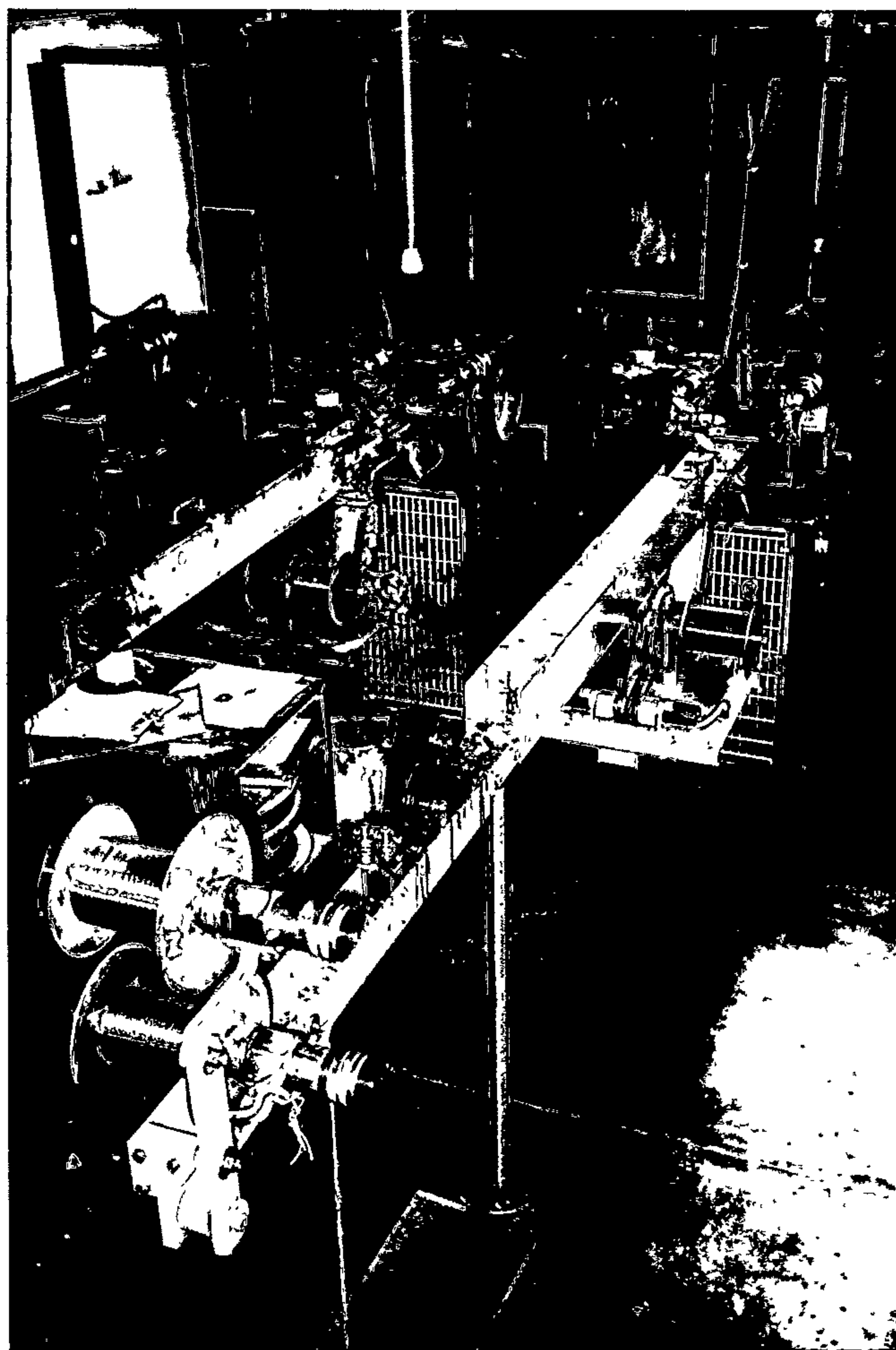


FIGURE 2-5

- a. 'As received' low-alloyed austenitic stainless steel wire is coiled and undergoes preliminary furnace heat treatment;
- b. The wire is then drawn through tungsten carbide dies under tremendous pressure (ensuring hardening to the wire's core - a contrast to THUROW'S (1982) observation that 'drawn wires may be more work hardened near the surface' thereby affecting bending and tensile tests) employing unique lubricants;
- c. Further heat treatment and tensioning in a reciprocating clamp follows with the processed wire then being wound onto a take-up spool or cut into short lengths for arch wire or orthodontic component, e.g., uprighting springs, fabrication.

The wire which results from the above processes has been described by WILCOCK (1988) and later by MOLLENHAUER (1990b) as '**Pulse Straightened**' stainless steel wire or **dynamically strain-aged wire**.

WILCOCK (1990) has attributed the quality of wires produced by AIJWSEE to:

- a. Careful selection of raw materials, paying close attention to chemical and physical analyses as well as size uniformity;
- b. appropriate production methods, i.e., employing the processes described above; and
- c. close attention to quality control, e.g., wrapping tensile tests etc., e.g., HAZEL and WEST (1986); GULLOTTA, WEST and HAZEL (1987).

Pulse Straightened Wire: Theory

Many authors, including BEGG (1954), BEGG and KESLING (1977a) and more latterly PROFFIT (1986) and COOPER and SIMS (1989) have enunciated the desirability of employing **light, continuous** forces to effect orthodontic tooth movement.

PROFFIT (ibid) states that, theoretically at least, there can be no doubt that light, continuous forces are consonant with the most efficient tooth movement.

COOPER and SIMS (ibid) cite PROFFIT (ibid) and remark the apparent continuing contradiction in the contemporary orthodontic literature in the conjunction of the term 'force' with implied physiological orthodontic tooth movement. COOPER and SIMS (ibid) prefer the concept of cell **stimulation** and hence cell survival as the concomitant of light appliance activation. (They conclude with the caveat that '... A clinical demarcation line between pathological and physiological orthodontic tooth loading is yet to be established for Man').

In the translation of theoretical goals to practical reality, AJWSEE has sought to engineer orthodontic wires which will realise, as closely as possible, the goal of light, continuous orthodontic 'force'/'stimulation' delivery.

WILCOCK (1988) has listed the desirable features of orthodontic wire as:

- a. Providing a light, continuous force over large displacements without undergoing permanent deformation;
- b. resisting occlusal forces; and
- c. possessing good formability, bio-compatibility, and zero stress relaxation.

However, WILCOCK (ibid) reiterates THUROW'S (1982) comments that inherently opposing metallurgical properties of flexibility, formability and hardness compromise the full realization of desirable features.

WILCOCK (ibid) has described two methods of straightening wire:

- a. Spinner straightening; and
- b. continuous 'pulse straightening'. (See Figures 2.4 and 2.5)

The latter is the method used by AJWSEE and contrasts with the former (according to Wilcock and others -vide infra), inferior process of spinner straightening which is described by WILCOCK (ibid) as:

'A mechanical process of straightening resilient materials, usually in the cold, hard-drawn condition'.

He continues:

'The wire is pulled through high-speed rotating bronze rollers, which torsionally twist the wire into a straight condition. This can result in severe permanent deformation. If the wire is subsequently subjected to tension, or more particularly to bending, a form of reverse straining, [a manifestation of the Bauschinger effect - vide infra], the yield stress values in tension-compression would be less than that of the "as drawn" material rendering it strain softened.' (Figure 2.6)

The work of BROWN and WATSON (1982) supports Wilcock's contentions. They note that:

'The strengthening of steel bars by cold twisting, ... results in these bars having a low limit of proportionality and very gradual yield behaviour when tested in tension. Paradoxically, this method of "strengthening" may result in lower-than-original proof stresses and even permanent softening, under certain circumstances.'

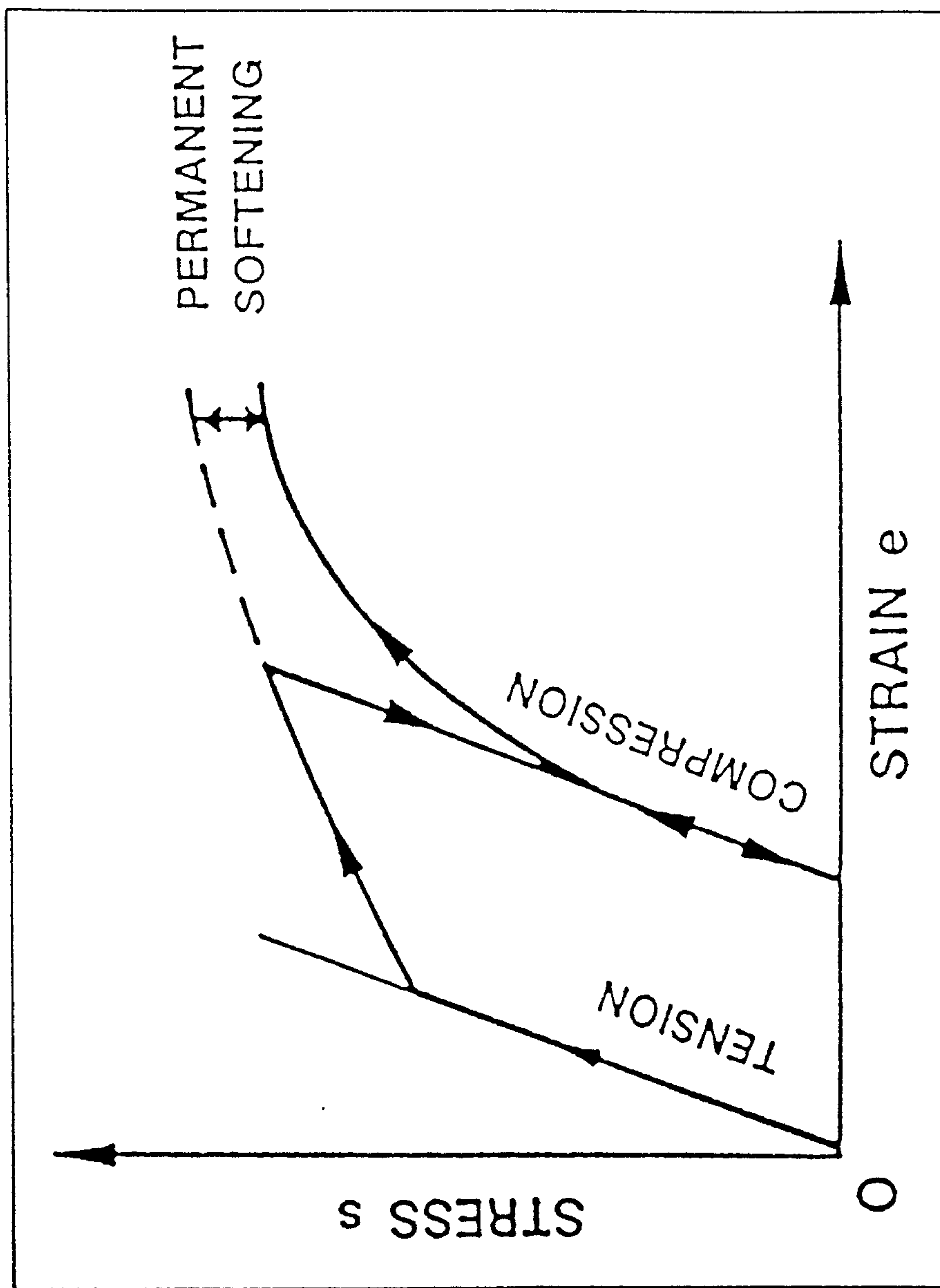


Fig. 4 Schematic representation of Bauschinger effect, where stress-strain curve shows reduced and less defined yield point during compression. Tension-compression sequence can be reversed without changing graph.

Figure 2.6...(WILCOCK - 1988 with permission)

The Bauschinger Effect

DIETER (1986) notes that the tensile properties of wrought-metal products are not the same in all directions and that this property dependence is called **anisotropy**. There are two general types of anisotropy, the one relevant to the present discussion being **crystallographic anisotropy (CA)**; (the other: **mechanical fibreing**). CA results from the preferred orientation of the grain(s) which is produced by severe deformation. The effect of the severe plastic deformation of a poly-crystalline specimen which produces a strong preferred orientation is to imbue the specimen with a degree of anisotropy approaching a single crystal, the strength of which is highly anisotropic. DIETER (ibid) notes that the yield and tensile strengths (the former more than the latter) are the properties most affected and that this type of anisotropy is most frequently found in non-ferrous metals.

ABEL (1987) has observed that:

'Process related anisotropy is introduced, mostly in polycrystals, by welding, forging, rolling or any other means and this anisotropy should influence the designer in making use of fabricated components.'

ABEL (ibid) notes that a further anisotropy may be introduced by prestraining, referred to as 'the Bauschinger effect'¹ after Bauschinger, who reported it in 1886. The author cautions that the effect is complex, involving **both** the initial reverse yield strength **and** the subsequently obtained entire stress-strain relation.

1. Johann Bauschinger, 19th century German Engineer

ABEL (ibid) presents the following as a precise rendering of his understanding of the Bauschinger effect:

'Prestraining in **any** direction, as defined by the principal axis of the strain tension, will introduce an anisotropy for further deformation in **any** other direction. The intensity of this pre-strain associated anisotropy is at maximum when the direction of further straining is opposite to that of the pre-strain.'

Finally, ABEL (ibid), in listing the features of the Bauschinger effect, cites the summary of Bauschinger's paper by Deak (1962), the portions apposite to the present discussion being:

- a. Plastic pre-strain increases the elastic limit of deformation in the same direction as the pre-strain; and
- b. plastic pre-strain decreases the elastic limit of deformation in the direction reverse to pre-strain. If the magnitude of pre-strain is increased, the elastic limit in the reverse direction can be reduced to zero.

The relevance of points 'a' and 'b' to AJWSEE wire is that the former encapsulates the theoretical basis of the manufacturer's thermo-mechanical approach to wire production, i.e., **pulse straightening** (utilizing **repetitive dynamic strain ageing** referred to earlier; the latter is the effect induced by spinner straightening.

The comments of BROWN and WATSON (1982) serve as a summary of the foregoing discussion:

'By using corrections based on Bauschinger stress reversal effects it is possible to account for the full magnitude of the observed lowering of proportionality limit and rounding of the stress-strain curve in the vicinity of the yield point.'

WILCOCK (1989) has observed that this accounts for the reduction in the resiliency of a wire following spinner straightening since the modulus of resilience is proportional to the square of the yield stress divided by the wire's elastic modulus.

(Unpublished test data supplied by AJWSEE (WILCOCK-1990) revealed a loss of tensile strength in 0.016" 'Special Plus'-grade AJWSEE wire of 50,000psi following rotary straightening compared with pulse-straightened wire of the same size and grade - a reduction of approximately thirty seven per cent on the test figures.)

MECHANICAL PROPERTIES OF ORTHODONTIC WIRES

Resilience

HAZEL and WEST (1986), notwithstanding the use of the term 'force', have stated:

'Forces are used to move teeth'.

They subsequently answer their rhetorical question regarding the origin of such force by noting the equivalence of work and energy as:

Force x Distance = Work Done = Elastic Strain Energy = Resilience.

Furthermore, the elastic strain energy of a wire is given by the expression:

$$U = 1/2 S^2/E$$

where S = Stress

E = Young's Modulus

Hence, high resilience in an orthodontic wire is associated with:

- a. A high proof stress S ; or
- b. a low value of E ; or
- c. a combination of high S and low E values.

AJWSEE have opted for option 'a' in the manufacture of stainless steel orthodontic wires since there is no practical scope for alteration of Young's modulus.

Flexibility or 'Springback'

HAZEL and WEST (ibid) define flexibility or 'Springback' as:

'the maximum amount of elastic strain that an arch wire can be subjected to without any permanent set.'

They note that the maximum flexibility of a wire is approximately equal to $\text{Proof Stress}/E$.

Hence, maximum flexibility can be obtained from high tensile wires because of their high proof stress values.

Creep and Stress Relaxation

TIMOSHENKO (1941) describes creep of a tensile test specimen under load, in part, as undergoing 'continuous deformation'. Furthermore, and more importantly, the yield point and ultimate strength of metals in tension is very temperature dependent.

TIMOSHENKO (ibid) notes that up to approximately 250° C the ultimate strength of, e.g., steel, increases and thereafter drops off rapidly. Similarly, the yield point becomes less pronounced as temperature increases up to approximately 300° C and then shows little change. Therefore, at body temperature the consideration of creep phenomena is not really appropriate to a discussion of orthodontic wires.

However, the phenomenon of **stress relaxation** is relevant.

It has been described by TWELFTREE, COCKS and SIMS (1977) so:

'In a specimen which has been deformed and held in a fixed position, the stress may diminish with time, even though the total strain remains constant'.

WILCOCK (1988) has stated that in his view, the importance of zero stress relaxation in orthodontic wire (the resultant of the highest possible yield stress) cannot be over-emphasised if light, continuous force delivery is desired.

Uprighting Spring Manufacture by AJWSEE

WILCOCK (1989) has observed that to prefabricate orthodontic appliances, e.g., uprighting springs, wire straightening is a necessary prerequisite. To achieve this AJWSEE employ their (apparently) unique 'pulsing' process.

WILCOCK (ibid) states that the pulsing process permits:

- a. Straightening of the highest tensile strength wires (not possible previously); and
- b. no suppression of tensile yield stress.

The foregoing is important in the manufacture of uprighting springs. Greater flexibility is permitted (flexibility being equal to proof stress divided by Young's modulus).

Furthermore, greater resiliency is permitted since:

$$\begin{array}{lcl} \text{Modulus of} & = & \frac{\text{Proof Stress}}{\text{Elastic Modulus per}} \\ \text{Resiliency} & & \text{Unit Volume} \end{array}$$

**The Manufacturer Examining a 'Pulse Straightened wire length
prior to appliance fabrication.**

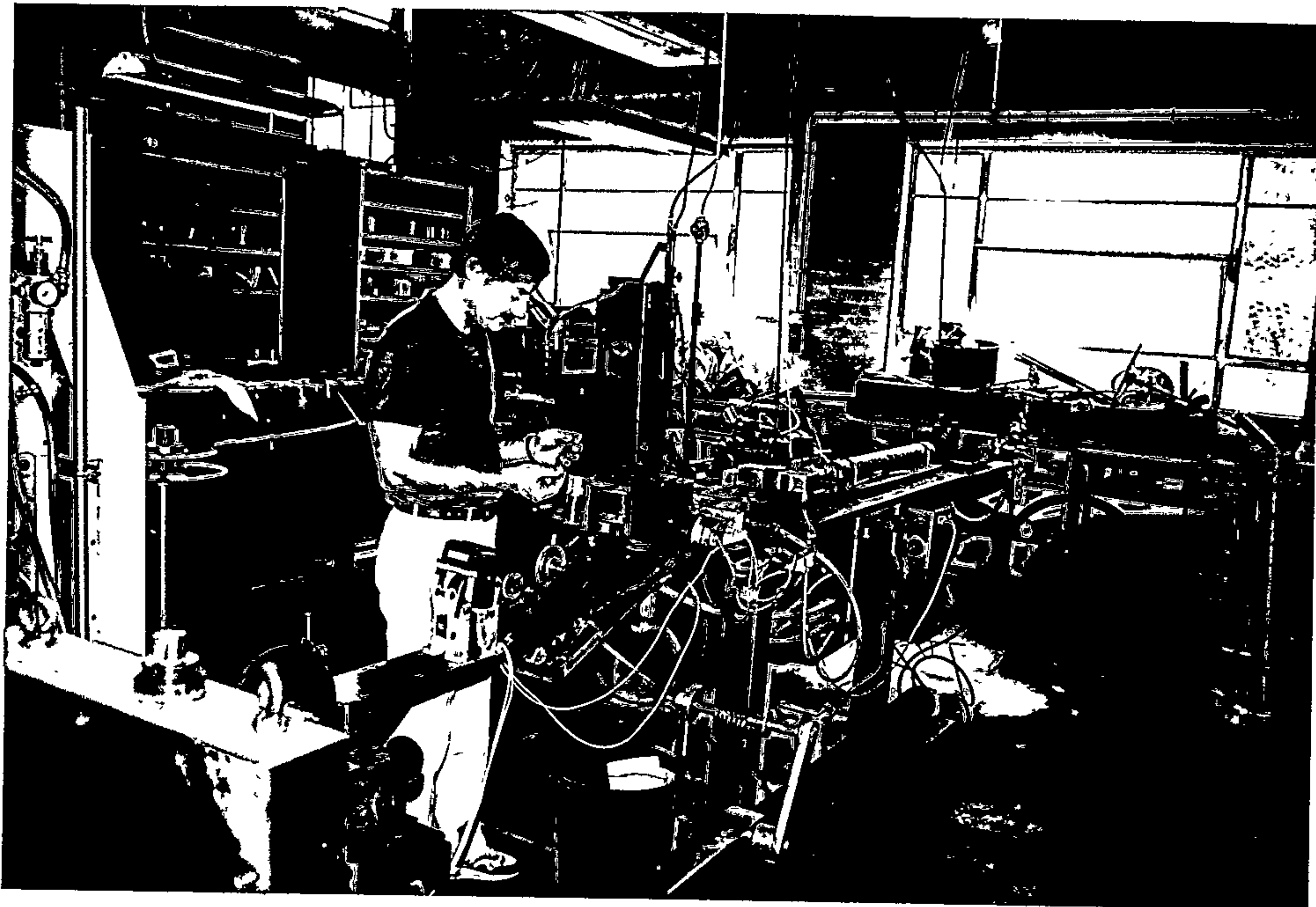


FIGURE 2.7 (Mr. A. J. Wilcock; with permission)

More significantly, however, smaller diameter wires can be used resulting, **theoretically**, in a lighter and more constant load delivery with little or no relaxation. This, according to WILCOCK (ibid), reflects the Begg ideal of light, continuous load-delivery since:

$$\text{Wire diameter (d)} \propto \frac{(\text{Bending Moment})^{1/3}}{(\text{Proof Stress})}$$

assuming:

- a. The number of coils is small; and
- b. coil diameter 'D' with respect to wire diameter 'd' is as large as practicable (generally $D-d > 4$ - See Chapter Three).

WILCOCK (ibid) concludes by noting that the foregoing:

'... has the effect of minimising the reduction in the maximum allowable wire working stress, probably at the point of maximum deformation in the spring which is subject to reverse straining, that is, the "leg to coil" bend'

in 'conventional' uprighting springs.

These theoretical considerations have been employed in the design evolution of the Begg 0.010" Mini-Spring - the subject for discussion in the following chapter.

CHAPTER THREE

BEGG UPRIGHTING SPRING EVOLUTION, DESIGN AND PERFORMANCE

INTRODUCTION

In the Foreword to the Seventh edition of ROBERT'S book 'Spring Design and Calculations' (1954) Terry writes:

'It is no exaggeration to say that Springs are the life blood of modern civilised life, for without springs the great development which has taken place in engineering and mechanical science would have been impossible.' and

'With the ever increasing demands made on spring performance, a great deal of research is being carried out on spring materials, but even the best material will not give satisfactory results unless, in the first place, the spring is correctly designed for the particular purpose it has to fulfil'.

In the age of the microchip Terry's former pronouncement might now be regarded as slightly dated. However, with regard to orthodontics in particular, and as currently practised, his latter remarks are certainly apposite, the Begg uprighting spring family being a case in point.

In discussing the marriage of the 'best material' with 'correct design' the following will be reviewed:

- a. The evolution of the Begg uprighting spring;
- b. the design variables which may be manipulated to alter its performance, culminating in the advent of the 0.010" 'Mini Spring'; and
- c. previous investigations into uprighting spring behaviour.

EVOLUTION

The observation has been made by MARX (1989) that the contemporary Begg appliance is almost unrecognizable when compared with its original presentation to the profession at large (BEGG - 1954; 1956).

This is nowhere better illustrated in the Begg technique than in the case of the methods propounded by Dr. Begg to effect correct mesiodistal axial root positioning.

Band Spurs

In Begg's earliest papers (BEGG 1954; 1956) tooth movement was effected in a **bodily** fashion via intermaxillary hooks and vertical spurs bent directly into 0.018" stainless steel arch-wires in combination with intermaxillary elastic traction. Mesio-distal root movement occurred by the progressive ligation of horizontally soldered band spurs, labial and buccal, to the archwire.

The 1961 paper (BEGG - 1961) marked a turning point - the introduction of the now universally understood Begg treatment strategy of two-phase tooth movements (crown tipping followed by root torquing and/or uprighting - the classical three-stage treatment sequence) 0.016" stainless steel initial arch wires, **auxiliary** arch wires which included both spurred torquing auxiliaries as well as auxiliary springs ('torquing wires' [sic]) 'to torque roots mesially or distally' (ibid). Horizontal band spurs were still a feature of the appliance to effect mesio-distal torque. Notwithstanding the seemingly evolutionary (if not revolutionary) nature of these changes, they were described as 'minor' by Begg.

Regarding root uprighting, BEGG (ibid) advocated the use of the horizontal 'torquing spur/eyelet combination to upright second premolars; progressive tightening of ligatures threaded through incisor band eyelets and attached to the archwire to upright these teeth; and canine uprighting via 'torquing springs'. BEGG (ibid) also noted that:

- a. Second premolar uprighting boosted anchorage;
- b. labial crown torque of mildly tipped incisors could be effected through the action of the canine 'spring wire'; and
- c. the high resiliency of the arch wires employed results in a great range of tooth movement without the need for reactivation - a feature also shared by 'torquing wires'.

It is interesting (frustrating?) that no specifications were given in the 1961 paper regarding the canine uprighting spring. (However, BRANDT (1962) indicated that he employed a variety of uprighting springs, the wire diameters of which ranged from 0.012" to 0.016".) Furthermore, BEGG (ibid) similarly gave no reason for the necessity of the uprighting spring until the First Edition of his textbook appeared in 1965 (BEGG-1965).

BEGG TEXTBOOK - FIRST EDITION: 1965

BEGG (ibid) stated that horizontal band spurs were used for canine uprighting during the development of the technique. (See Figure 3.1) However, there were untoward effects when this method was employed:

- a. Insufficient distal root movement and excessive anterior crown movement; and
- b. resultant inadvertent mesial dental arch movement.

In other words, the force exerted by this method was excessive.

In contrast, uprighting springs effected desired movements without unwanted side effects.

The precise origin(s) of the uprighting spring remains obscure. However, PERLOW (1968), in an historical review of the Begg technique, notes in his designated third evolutionary stage (post - 1958) the extreme improvement in finished cases (on a par with edgewise treatment) resulting from, amongst other factors, the general employment of uprighting springs.

PERLOW (ibid) also remarks upon the timely advent of the Begg uprighting spring, allowing as it did the correction of the:

"'excesses' of treatment', and that:

'... in 1950 I innovated an exactly similar spring which worked on the same principle.'

Perhaps the quotation which PERLOW (ibid) attributes to Voltaire is, as he says, 'most apropos':

"'originality is nothing but judicious imitation"':

The lack of information regarding uprighting spring specifications continued in the First Edition of the Begg text.

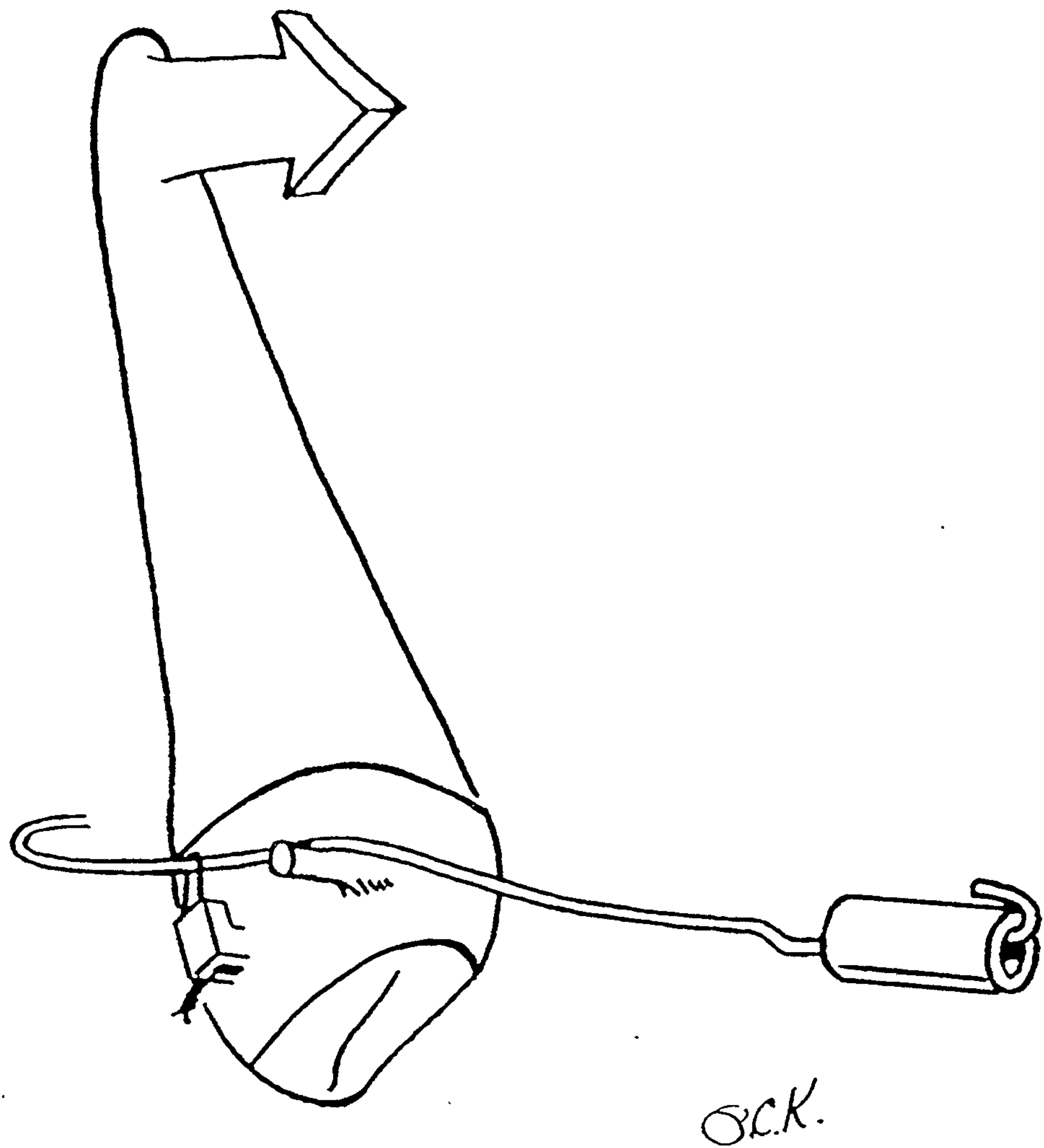


Figure 134. Employment of horizontal band spurs for tipping tooth roots. This method has now been discarded by the author and replaced by employment of root-tipping springs.

Figure 3.1...Horizontal Band Spur (BEGG - 1965)

Figure 3.2...Uprighting Springs - First Edition
(BEGG - 1965)

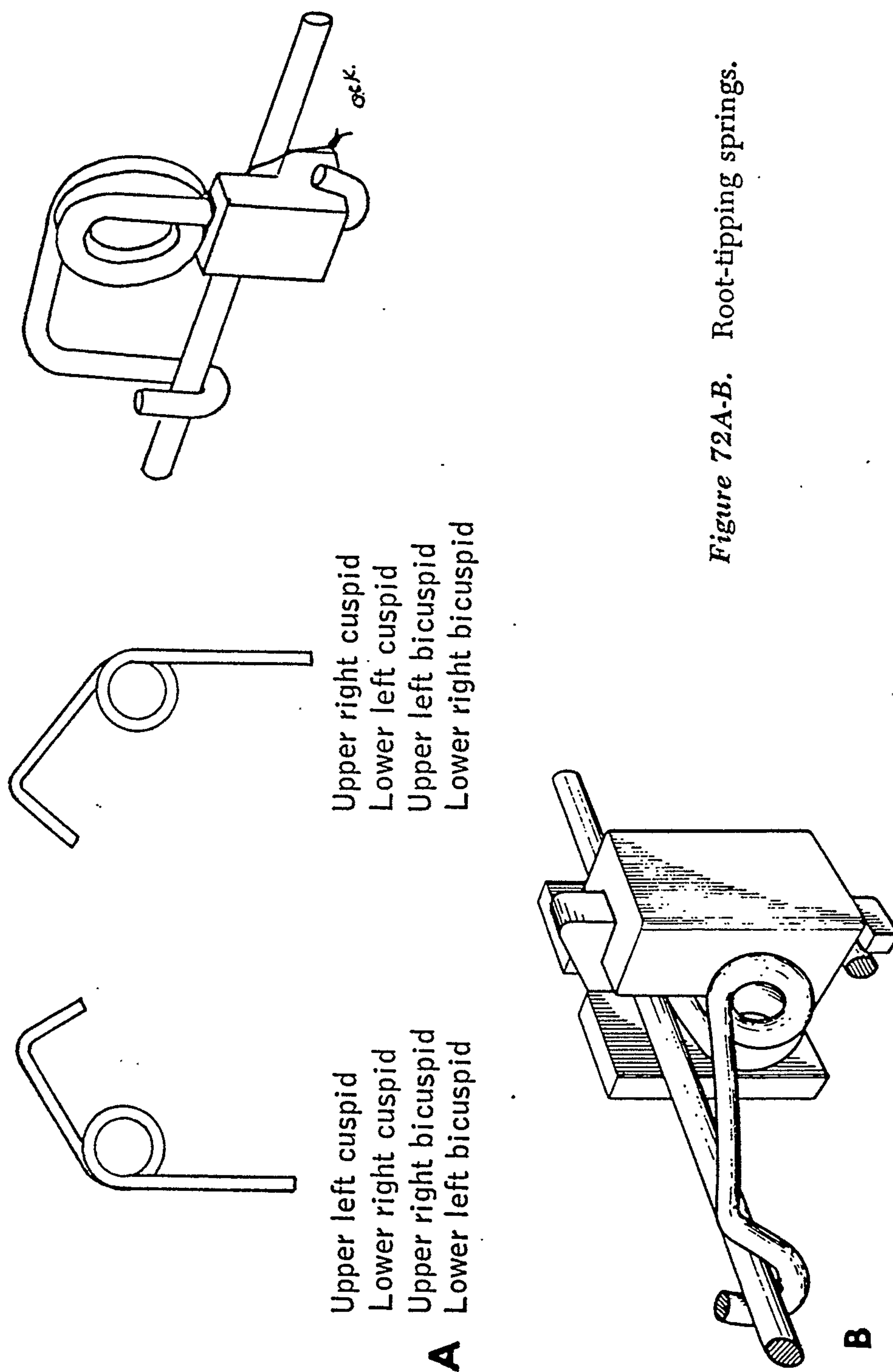


Figure 72A-B. Root-tipping springs.

However, springs of **apparently** the same dimensions **were** now recommended for canine and premolar teeth (pg 87) and Figure 133c (pg 146) indicates that incisors were also uprighted with, presumably, the same springs , pg. 87, 1st Ed. - See Figure 3.2.

The wire diameter of uprighting springs depicted in Figure 133c closely resembles that of the root torquing auxiliary shown in Figure 133b, the diameter of which is stated as 0.016". Therefore, it seems 0.016" diameter uprighting springs **may** have been used in at least **some** cases for, apparently, all teeth. In addition, similarities between uprighting springs depicted in the 1961 paper and the First Edition included:

- a. A tangentially disposed stem/leg;
- b. a relatively long lever arm (although that of the 1961 uprighting spring **appears** the longer of the two); and
- c. self-engagement of the spring in the bracket channel.

BEGG TEXTBOOK - SECOND EDITION: 1971

In the Second Edition (BEGG and KESLING - 1971) the importance of the uprighting spring as an integral part of the Begg appliance was stressed and some information given regarding uprighting spring specifications. 'Refinement' in two design variants was also reported.

BEGG TEXT SECOND EDITION SPRING DESIGN CHANGES

Variable	Original Spring	New Springs
Wire Type	'18-8' Stainless Steel	'18-8' Stainless Steel
Wire Diameter (apparently)	?0.016"	0.014"
Coil Size	'Smaller'	'Larger'
Coil Number (full turns)	Two	Three
Lever Arm	'Longer'	'Shorter'
Stem/Leg Disposition	Radial	Radial
Bracket Engagement	Pin/Ligature	a. Self retaining; b. able to retain archwire also.

TABLE 3.1

Regarding the design variable of stem/leg disposition, the 'old' spring depicted in Figure 151 (pg 129 - Second Edition) does not equate with that shown in the First Edition (Figures 71 and 72, pg 86-87) inasmuch as the stems of the First Edition springs are disposed **tangentially** (as in the 010" Mini Spring), and not **radially** in the Second Edition (Figures 150, 151 and 152, pg 129). (See Figure 3.3) This inconsistency is not explained and, as will be shown later... (vide infra) was, in engineering terms, a retrograde step.

Figure 3.3... Uprighting Springs - Second Edition
(BEGG - 1971)

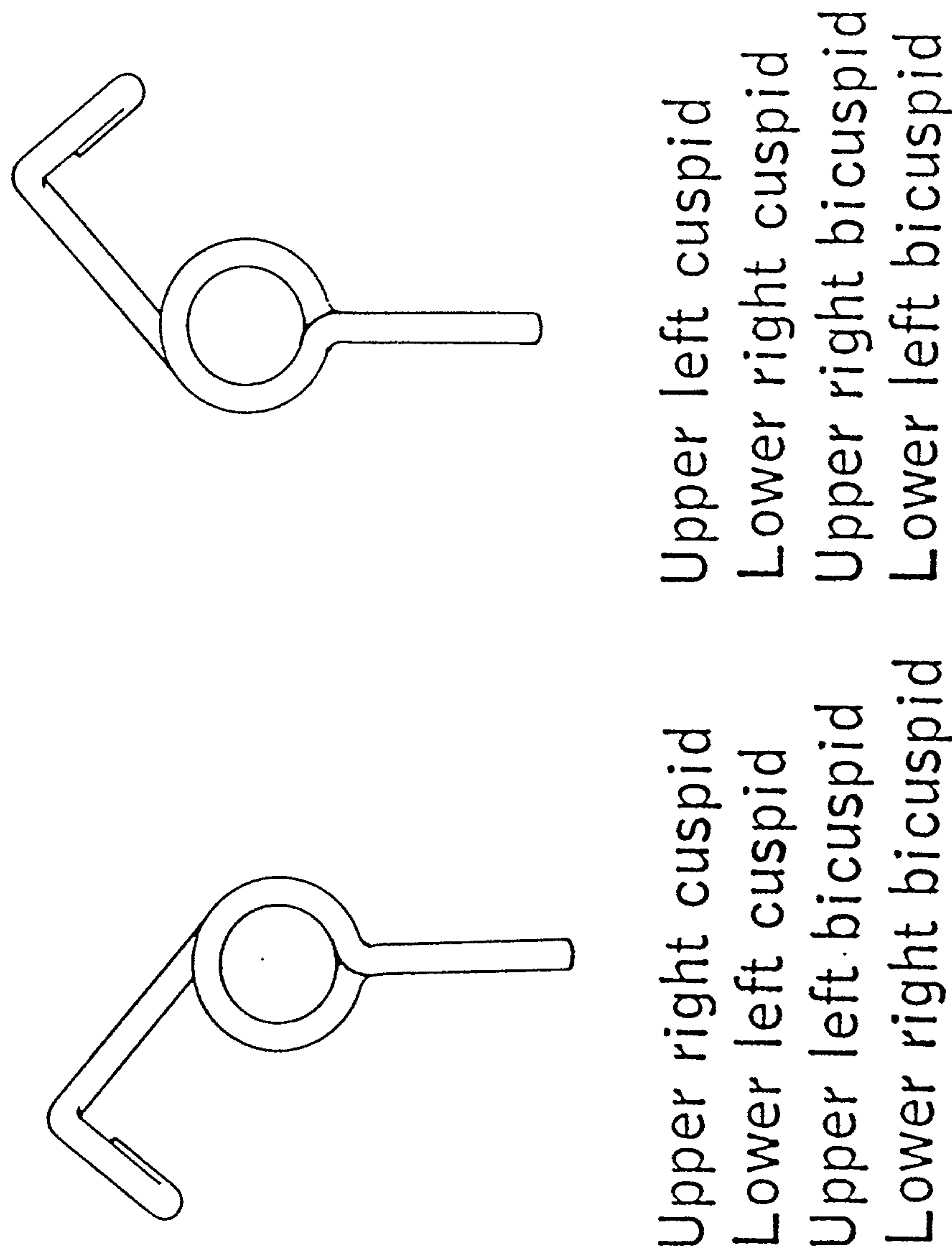


Figure 150. Individual mesiodistal uprighting springs. It is necessary to bend left- and right-hand springs so that the coil will always rest over the arch wire.

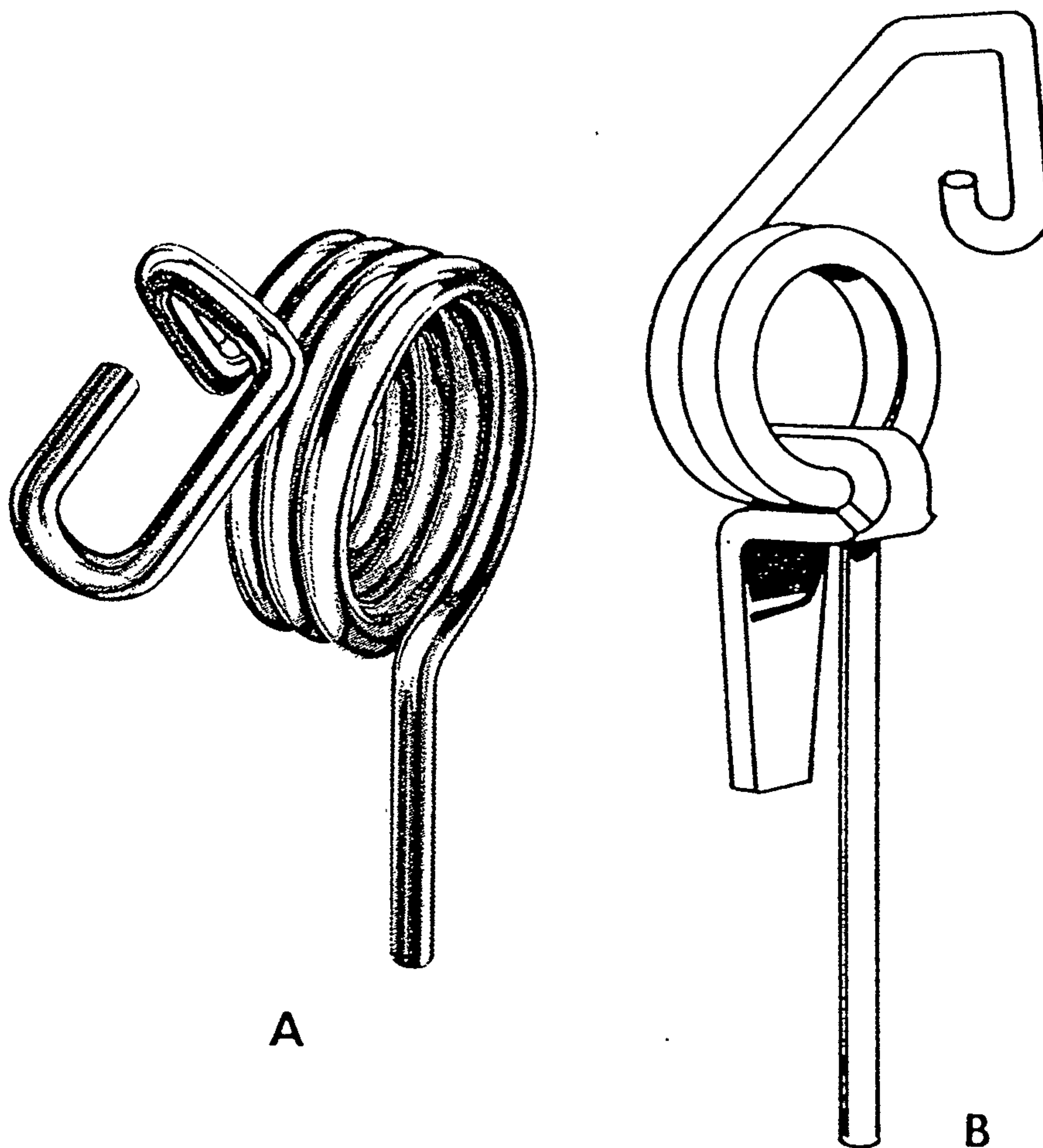


Figure 152A. Self-retaining uprighting spring with three full coils to provide gentle, continuous force necessary to upright teeth without requiring reactivation. **B.** Spring-pin designed to deliver desired force to upright teeth yet positively prevent the arch wire's escape from the arch wire slot.

Figure 3.4...Uprighting Springs - Self retaining and spring-pin types (BEGG - 1971)

BEGG and KESLING (1971) listed the advantages of the 'shorter' uprighting spring designs as including:

- a. Equivalent efficiency through larger, more resilient coils;
- b. self retention/locking-in of the archwire; and
- c. non-interference with adjacent uprighting springs.

AMERICAN JOURNAL OF ORTHODONTICS - JANUARY 1977

BEGG and KESLING (1977a), for apparently the first time, demonstrated a variety of uprighting springs (Figure 24, pg 30) of:

- a. Variable wire diameters of
 - (i) 0.014"
 - (ii) 0.016",
 - (iii) 0.018"; and
- b. the (then and **apparently**) new 'spring-pin' design. (See Figure 3.4)

The qualification 'apparently' is made because these remarks are based upon inspection of the figure and this author's experience - no details having been given by Begg and Kesling.

It would also seem that this is the first time uprighting spring force levels had been published by the authors, viz:

- a. 0.014" - 6 ounces (mandibular incisors);
- b. 0.016" - 14 ounces (mandibular premolars);
- c. 0.018" - 24 ounces (mandibular canines).

BEGG TEXTBOOK - THIRD EDITION: 1977

In the Third Edition BEGG and KESLING (1977b) made similar remarks regarding the advantages of the so-called 'short' uprighting spring and, unfortunately, perpetuated the inconsistency in describing the original canine uprighting spring design (vide supra).

However, the paucity of information regarding 'spring pins' was addressed in the Third Edition.

The authors alluded to the problem of tooth extrusion which can occur during tooth uprighting if an arch wire is not adequately secured in the bracket slot. In addressing this problem the spring pin was developed, thereby combining the advantages of both a lock pin and an uprighting spring (Figure 152B, pg 131).

They extended their 1977 journal recommendations regarding appropriate uprighting springs for different teeth with the following prescription for a four first premolar extraction case, citing it as another example of the concept of differential force.

UPRIGHTING SPRINGS

4 X 1st PREMOLARS EXTRACTION CASE

Tooth	Spring
Maxillary and Mandibular Canine Teeth	0.016" or 0.018", 2 coil
Maxillary and Mandibular Second Premolar Teeth	0.016", 2 coil
Maxillary Lateral Incisor Teeth	0.014", 2 coil
Mandibular Lateral Incisor Teeth	0.014", 3 coil

TABLE 3.2

They further stress (ibid) the essential requirement of using uprighting springs made from '... the hardest Australian wire possible...' to ensure optimum quality by reducing the chance of deformation and guaranteeing '... full activation ... during a greater range of uprighting', with a concomitant reduction in the need for reactivation.

(WILCOCK - 1990) has made the comment that a problem with the spring pin design, in his view, is that the 'pin' portion of the spring effectively reduces, e.g., a three-coil spring pin to approximately one and a half coils, thereby producing an effect opposite to that intended - a reduction in the load-deflection rate.)

Over recent years further additions to the prefabricated uprighting spring range have become available from various manufacturers. A.J. Wilcock Scientific and Engineering Equipment, for one, added 0.012" and 0.014" Premium Plus-grade conventional uprighting springs, i.e., **not spring pins**, to their range during the 1980's. These formed the basis of HYDE's investigation (1988) which will be reviewed in the final portion of this chapter.

Likewise, another manufacturer - TP Laboratories - have an extensive array of uprighting springs, a selection of which were studied by SCOULER (1982), which will also be reviewed.

BEGG UPRIGHTING SPRING DESIGN

Introduction

Much has been written regarding spring design, non-specifically orthodontic, e.g., TIMOSHENKO (1941); WAHL (1944); ROBERTS (1954); SHIGLEY and MISCHKE (1989) and specifically orthodontic, e.g., BURSTONE, BALDWIN and LAWLESS (1961, 1985); PERLOW (1968); LEBSACK, WEIMER and HANNA (1980); and subsequently rewritten in review form, e.g., SCOULER (1982) and HYDE (1988).

Perhaps the landmark article regarding springs, from an orthodontic perspective, was that written by BURSTONE, BALDWIN and LAWLESS (1961), that is if frequency of citation is any guide.

Therefore, the relevant portions of this paper will be related by way of introduction to the writings of SHIGLEY and MISCHKE (1989) whose description of theoretical spring design is embodied in the practical reality of the Wilcock 0.010" 'Mini Spring'.

BURSTONE et. al., - 1961

Burstone et. al., has listed three characteristics for consideration in the design and utilization of orthodontic appliances:

- a. The relationship between force and deflection;
- b. the load at which permanent deformation occurs; and
- c. the range of activation within the elastic limit.

They continue by defining the **Spring Constant** of a spring as derived from Hooke's Law-stress being proportional to strain. They note that the quotient of the load deflection rate or spring constant equals applied force divided by deflection, in units of grams per millimetre or gram-millimetres per radian and that this represents the load necessary to produce a unit deflection.

Burstone et. al., state:

'Springs with lower load deflection rates deliver more constant forces during unloading, since there is less force change from one millimetre of activation to the next'.

Such springs demonstrate a load deflection curve of flatter slope when compared with higher rated springs.

Burstone et. al., also define the following terms:

a. **Allowable Working Load/Maximum Load:**

'... the greatest load that can be applied safely to a wire without permanent deformation'; and

b. **Range of Activation**

'... the greatest distance through which a flexible member can be deflected without permanent deformation'.

They note that orthodontic springs with high levels of 'a' and 'b' above result in an auxiliary with a high range of activation, which is characteristic of a low rated spring '... capable of absorbing considerable energy'.

Mechanical Properties

1. Modulus of Elasticity

Both rate and allowable load may be altered by the mechanical nature of a wire.

Rate is directly proportional to the modulus of elasticity E of a wire and is effectively a constant not affected by physical treatments (work hardening, etc.). Residual stresses induced through cold working may, however, slightly reduce spring rate but can increase the **apparent** proportional limit (a feature around which the MS has been designed - WILCOCK (1990)).

Proportional limit directly determines the allowable working load, the latter being directly proportional to the former. It is affected by:

- a. Grain size
- b. cold working; and
- c. heat treatment.

(Burstone et. al., state that because it is subjected to greater cold working, a small diameter wire will have a higher proportional limit compared with a larger wire.)

3. Cross-sectional Geometry

Burstone et. al., observe:

'The spring constant increases as the fourth power of the diameter of the cross-section of a round wire', e.g., a doubling of a round wire's diameter from 0.010" to 0.020" will induce a sixteen fold increase in the force delivered.

They caution, however, that a reduction in spring rate through wire diameter manipulation (reduction) is limited by the allowable load which changes as the third power of the diameter of a round wire, i.e., a halving of diameter effects an approximately eight-fold reduction in its elastic loading potential.

4. Wire Configuration

A cantilever modified by a coil along its length, i.e., an orthodontic spring, results in a reduced spring rate without any effect on the allowable load; the optimal position for such coil being at the point where the bending moment is greatest.

The load-deflection rate of a 'helix-modified' cantilever, i.e., an orthodontic spring is determined by:

- a. The diameter of the helix;
- b. number of turns in the helix; and
- c. the length of the cantilever.

Importantly, Burstone et. al., state that:

'The elimination of sharp bends enhances the elastic properties of a spring' -this is particularly relevant in the case of the Begg 'Mini-Spring' (vide infra).

Burstone et. al., conclude by observing:

'... in respect to the linear configuration of a spring, it is apparent that optimal design is influenced by the distribution of the wire rather than simply by the total amount of wire utilized.'

5. Spring Activation

Burstone et. al., recommend loading in the direction a spring is wound which is in accord with Bauschinger's findings described earlier (Chapter Two).

Undesirable Spring Design Features

These are listed as:

- a. irritating to the soft tissues;
 - b. unhygienic;
 - c. uncomfortable; or
 - d. overly complicated to fabricate and use,
- none of which features apply to the Begg 'Mini-Spring'.

Summary

Constant force delivery is dependent primarily upon the structural design of the appliance and secondarily on the mechanical properties of the wire. Nevertheless, high quality control and consequent improvements in standardization of wire production (and as is evident in A. J. Wilcock Scientific and Engineering Equipment uprighting spring production, at least - see Chapter Four) would imbue greater confidence in the precision of the estimation of load-deflection rates.

Similarly, wires with consistently high proportional limits simplify spring design and minimize the chances of permanent deformation produced by accidental overloading.

Nevertheless, structural design and not wire quality is the more important factor in the development of an orthodontic appliance.

Burstone et. al., caution that low rated springs can be quite dangerous if activated to excessive force levels. Finally, in referring to the use of the terms 'light' and 'continuous' regarding force application, he recommends against their use in favour of specific force magnitudes and rates of release.

THE BEGG 'MINI-SPRING'

Introduction

Some aspects of Begg 'Mini-Spring' (MS) design and consequent clinical advantages have already been highlighted in the Introduction to the present work.

The purpose of this Section is to:

- a. Complete the description of the MS;
- b. describe theoretical advantages of the changes in MS design; and
- c. comment upon its reported clinical advantages and disadvantages.

MS Design Features

Wire Type: 0.25mm/0.010" diameter 'Supreme'-grade round austenitic '18-8' stainless steel wire. ('Supreme' grade is, to date, the most resilient wire produced by AJWSEE. (HAZEL and WEST - 1986)) See Figures 3.5 to 3.12 .

Size and Conformation:

- a. Overall Length - 7.0mm approximately;
- b. Lever Arm Length - 3.0mm approximately;
- c. Stem/'Leg' Length - 4.0mm approximately;
- d. Number of Complete Coils - 2
- e. Inner Coil Diameter - 0.7mm approximately;
- f. Stem/Coil disposition - Tangential.

AJWSEE Uprighting Springs
(clockwise from (L) top)
-0.010" 'MS'; 0.012" and 0.014"

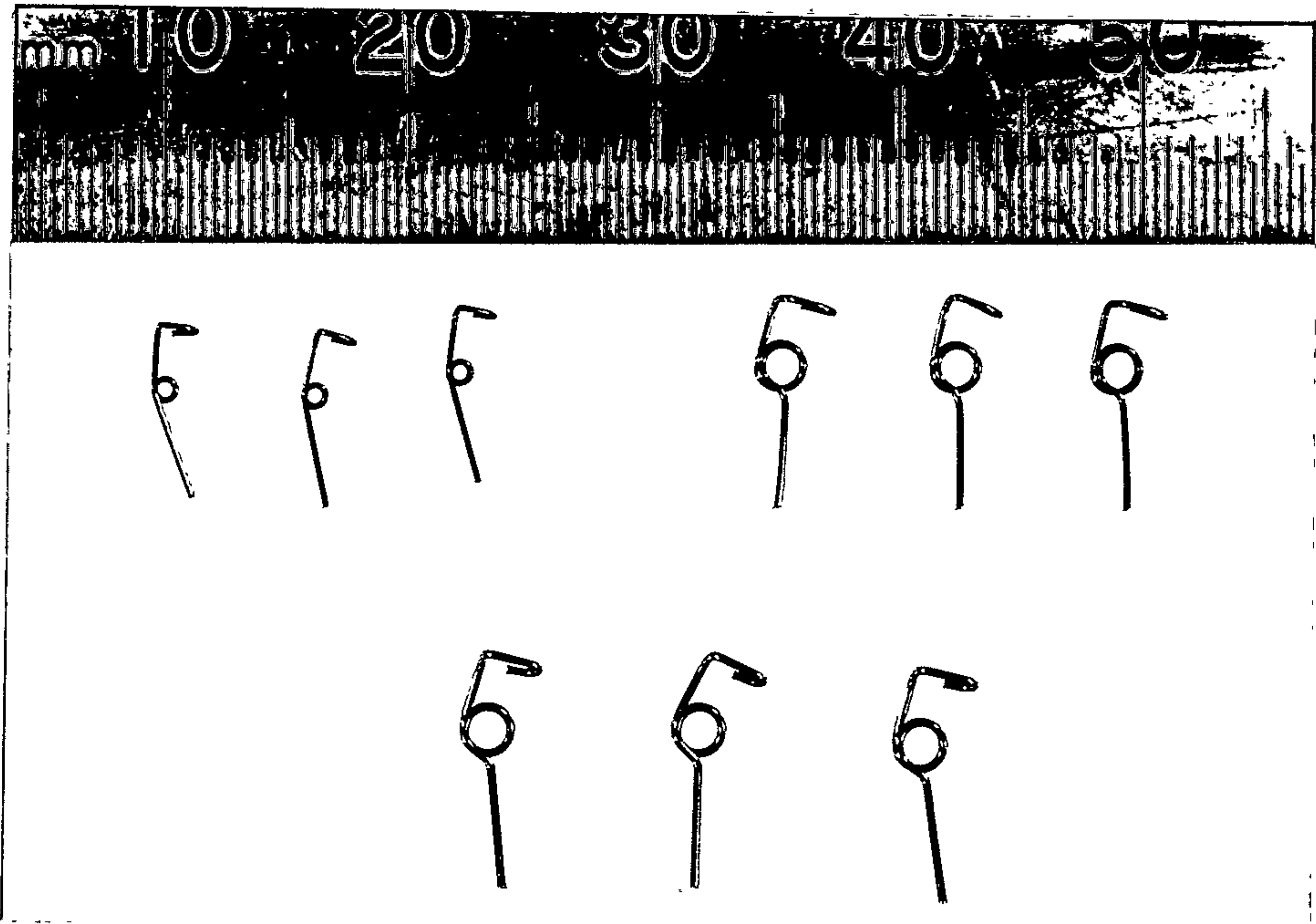


FIGURE 3.5

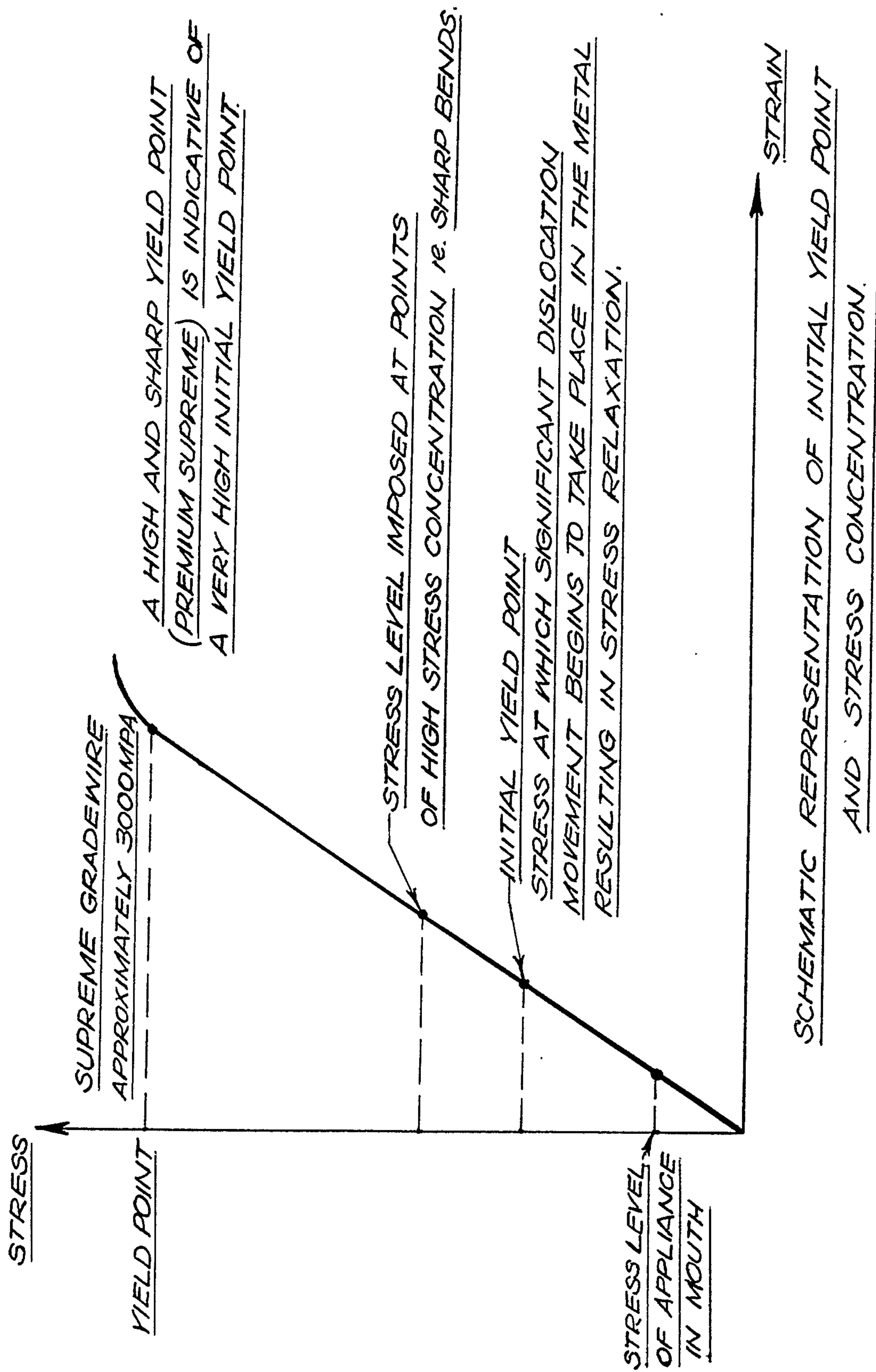


Figure 3.6...(Mr AJ Wilcock Jr.; with permission)

TABLE I - TENSILE TEST DATA

MATERIAL	0.2% P.S. (M.Pa)	U.T.S. (M.Pa)	E (G.Pa)	RESILIENCE $\frac{(P.S.)^2}{2E}$ (M.Pa)	FLEXIBILITY $\frac{P.S.}{E}$ ($\times 10^{-3}$)	STIFFNESS E.I (M.Pa)
A. Stainless Steels						
1. 0.009" Wilcock Supreme	2975	3077	154.7	28.6	19.2	19.5
2. 0.010" Wilcock Supreme	3108	3308	176.7	27.3	17.6	35.3
3. 0.012" Wilcock Special	2654	2859	168.0	21.0	15.8	66.8
4. 0.012" Wilcock Special Plus	2667	2762	170.0	20.9	15.7	67.5
5. 0.014" Wilcock Regular	2269	2483	168.5	15.3	13.5	124.1
6. 0.014" Wilcock Special Plus	2652	2804	174.5	20.2	15.2	128.5
7. 0.015" Wilcock Regular	2282	2527	192.3	13.5	11.9	241.7
8. 0.016" Wilcock Premium Plus	2881	3084	184.5	22.5	15.6	231.2
9. 0.018" Wilcock Regular	2427	2588	163.0	12.1	14.9	328.1
10. 0.018" Wilcock Special Plus	2637	2705	186.9	12.6	14.1	375.2
11. 0.020" Wilcock Premium	2764	2998	160.0	24.2	17.4	490.9
12. 0.015" Unitek Permachrome	1958	2157	151.8	12.6	12.9	190.8
B. Titanium Alloys						
1. 0.018" Ti-6Al-4V Centreless Ground (Wilcock)	1184	1258	90.8	7.7	13.0	182.8
2. 0.018" Ti-6Al-4V Pickled (Wilcock)	1087	1132	88.1	6.7	12.3	177.3
3. Beta - Ti (*)	1169	-	64.6	13.6	18.1	
4. Nitinol (*)	-	1650	33	41.3*	49.5*	
C. Cobalt Base Alloys						
1. 0.016" Square Blue Elgiloy As received (Rocky-Mountain)	1372	1694	189.7	5.0	7.2	404.7
2. 0.016" Square Flexiloy as received (Unitek)	1523	1721	156.2	7.4	9.8	333.2
3. 0.016" x 0.022" Blue Elgiloy As received (Rocky-Mountain)	1447	1767	215.8	4.9	6.7	1196.8
4. 0.016" x 0.022" Blue Elgiloy Flash Paste Heat Treatment	1684	1904	182.8	7.8	9.2	1013.8

(*) Values reported by C.J. Burstone and A. Jon Goldberg, Am. J. Ortho. 1960 Vol. 77 No. 2 : 121.

* U.T.S. values used as P.S. values not quoted.

Figure 3.7...Tensile Test Data - Hazel and West (1986)

PRODUCTION OF DYNAMICALLY STRAIN AGED ORTHODONTIC WIRE

APPLIANCE FLOW LINE

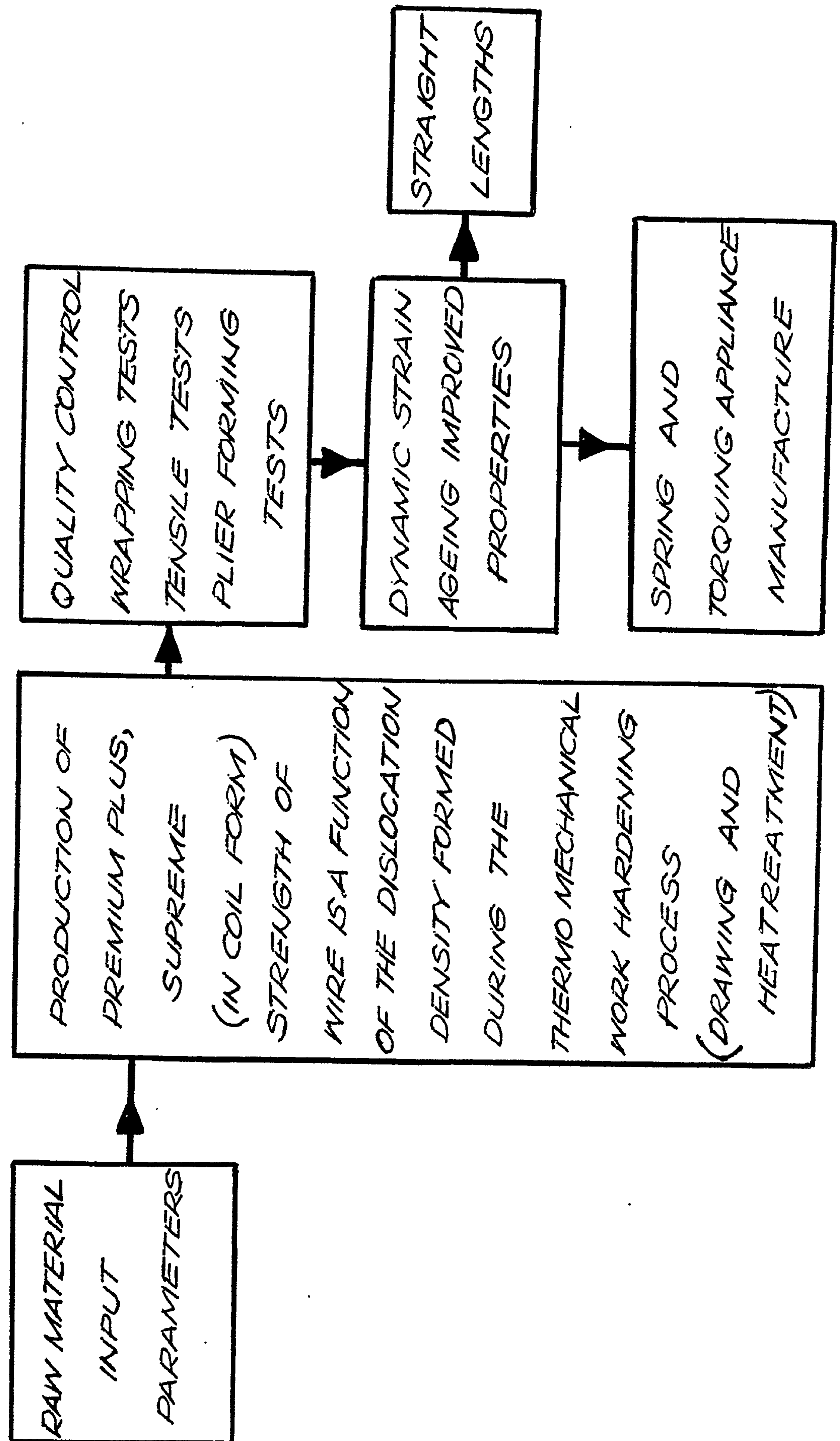
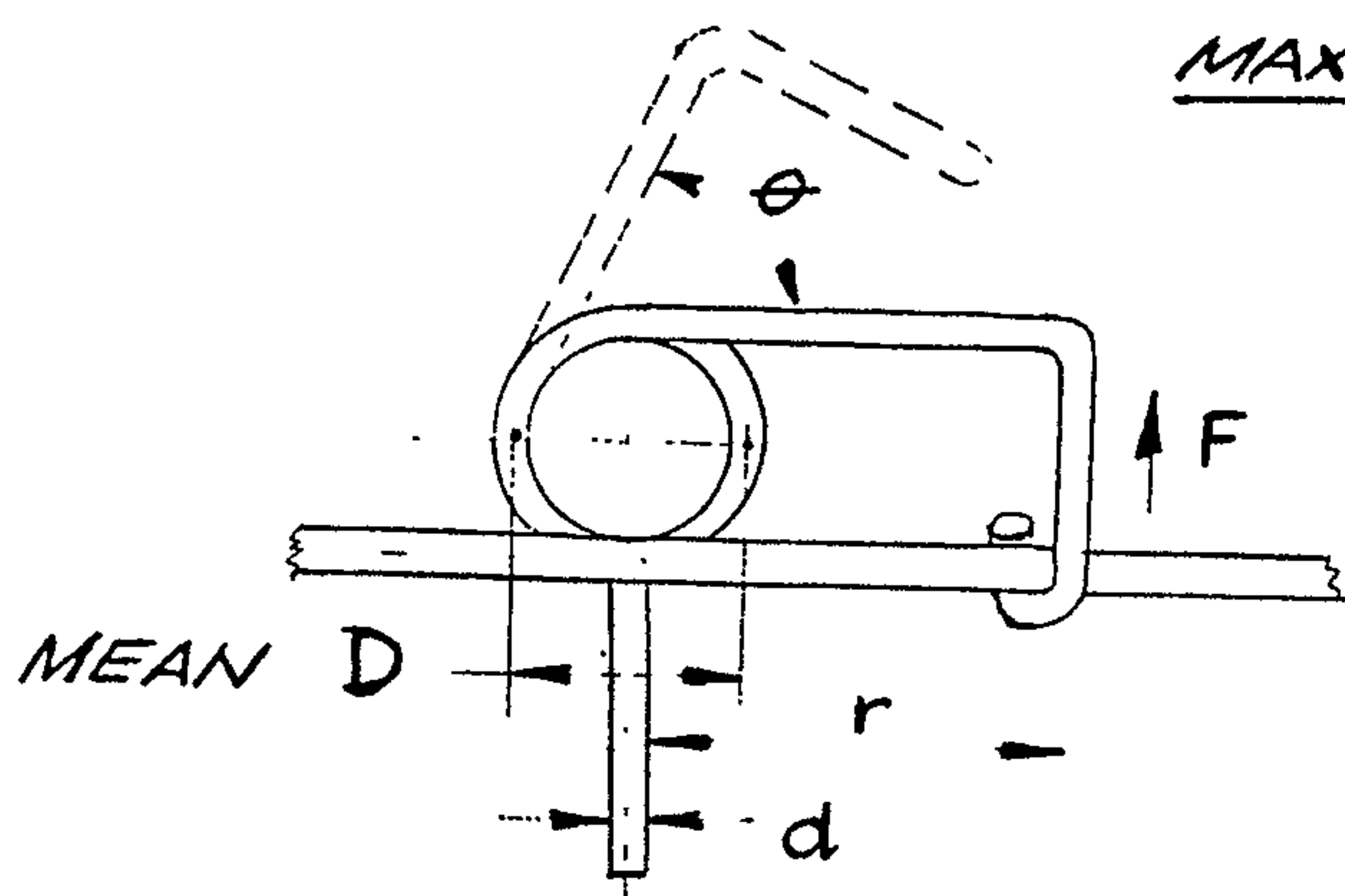


Figure 3.8.... (Mr. A. J. Wilcock Jr.; with permission)



MAXIMUM ELASTIC DEFLECTION

$$\theta = \frac{64 F r D N}{d^4 E}$$

N = NUMBER OF TURNS

MAX. WIRE STRESS = (STRESS CONCENTRATION FACTOR) $\times \frac{32 F r}{\pi d^3}$

$$\therefore d \propto \sqrt[3]{\frac{\text{BENDING MOMENT}}{\text{INITIAL YIELD STRESS}}}$$

BECAUSE OF PHYSICAL CONSTRAINTS PLACED UPON THE SIZE OF AN UPRIGHTING SPRING (ARM LENGTH), THE BENDING MOMENT TO UPRIGHT A TOOTH CAN BE CONSIDERED FIXED FOR A GIVEN WIRE SIZE.

IF WE WISH TO REDUCE THE FORCE LEVELS TO UPRIGHT TEETH IT IS OBVIOUS FROM THE ABOVE EQUATION THAT THE INITIAL YIELD STRESS SHOULD BE AS HIGH AS POSSIBLE.

THIS HAS BEEN ACHIEVED IN SEVERAL WAYS —

- ① USING THE HIGHEST POSSIBLE TENSILE STRENGTH WIRE
- ② DYNAMICALLY STRAIN AGEING THE WIRE (STRAIGHTENING)
- ③ REMOVING ALL POINTS OF REVERSE STRAINING
(BAUSCHINGER EFFECT)
- ④ MINIMISE POINTS OF HIGH STRESS CONCENTRATION

Figure 3.9...Conventional Uprighting Spring Design Theory

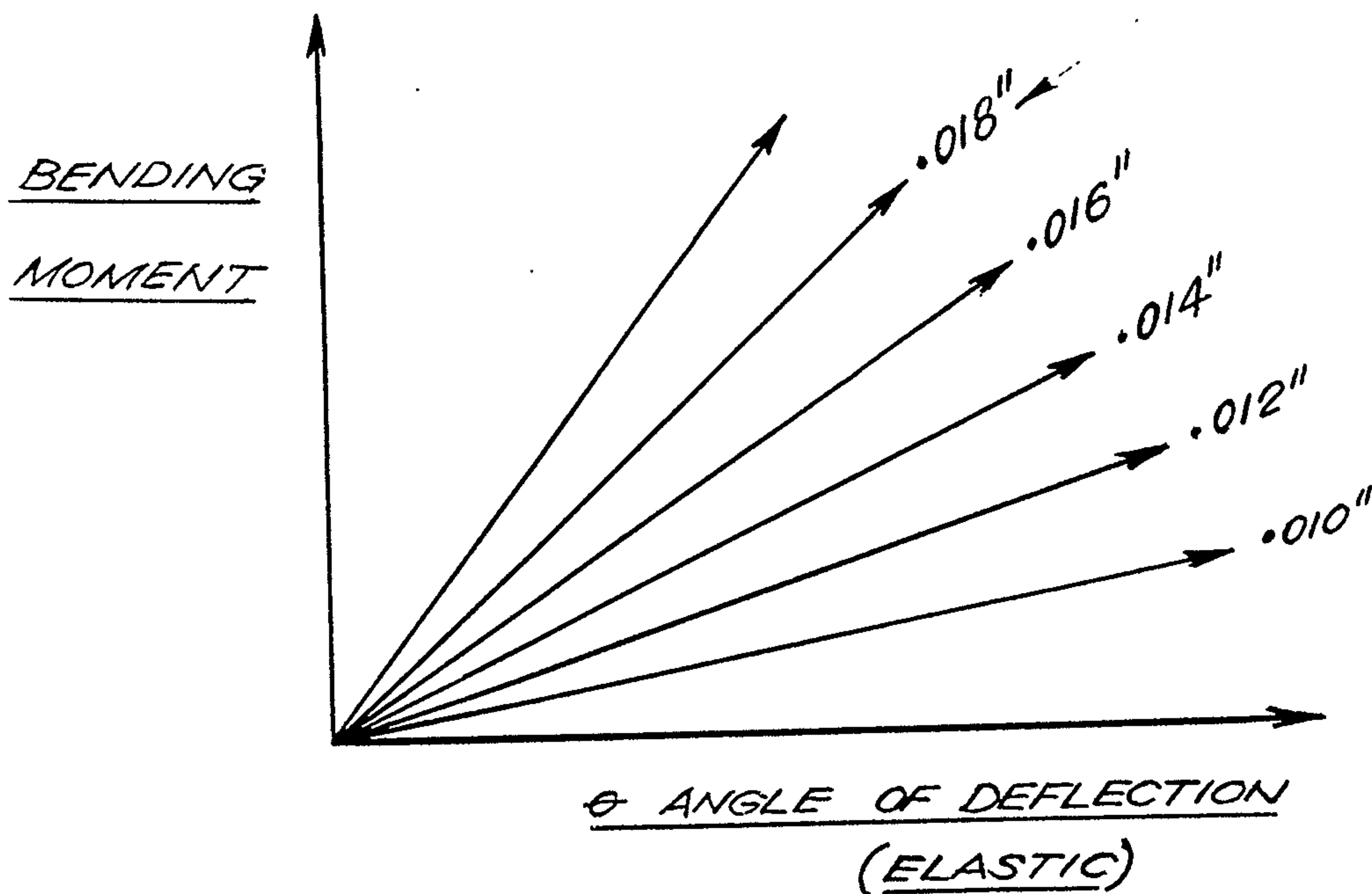
(Mr AJ Wilcock Jr.; with permission)

UPRIGHTING SPRING STIFFNESS

BENDING MOMENT
ANGLE OF DEFLECTION

SCHEMATIC ONLY

.018" DIAMETER OF WIRE



USING A SMALLER DIAMETER WIRE RESULTS
IN A MUCH MORE UNIFORM FORCE FOR UPRIGHTING
OVER A GREATER ANGLE OF TOOTH MOVEMENT

$$\theta \propto \frac{\text{BENDING MOMENT} \times \text{MEAN COIL DIAMETER} \times \text{N}^2 \text{ OF TURNS}}{(\text{WIRE DIAMETER})^3}$$

Figure 3.10...Wire Diameter and Uprighting Spring Stiffener
(Mr AJ Wilcock Jr.; with permission)

SPRING INDEX $C = \frac{D}{d} = \frac{.035}{.010} = 3.5$

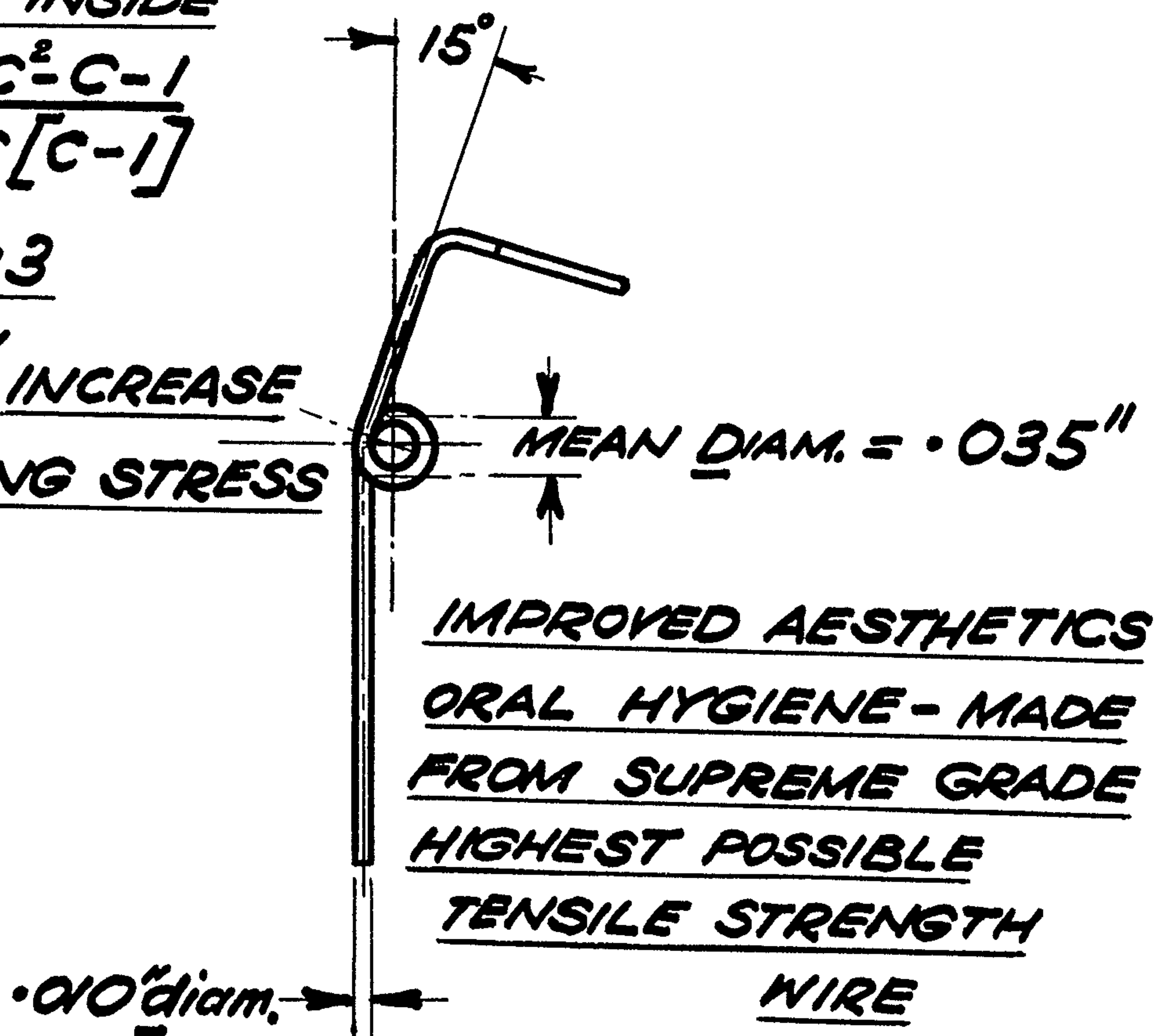
STRESS CONCENTRATION

FACTOR INSIDE

$$K = \frac{4C^2 - C - 1}{4C[C - 1]}$$

$$K = 1.3$$

$\therefore$ 30% INCREASE
IN WORKING STRESS



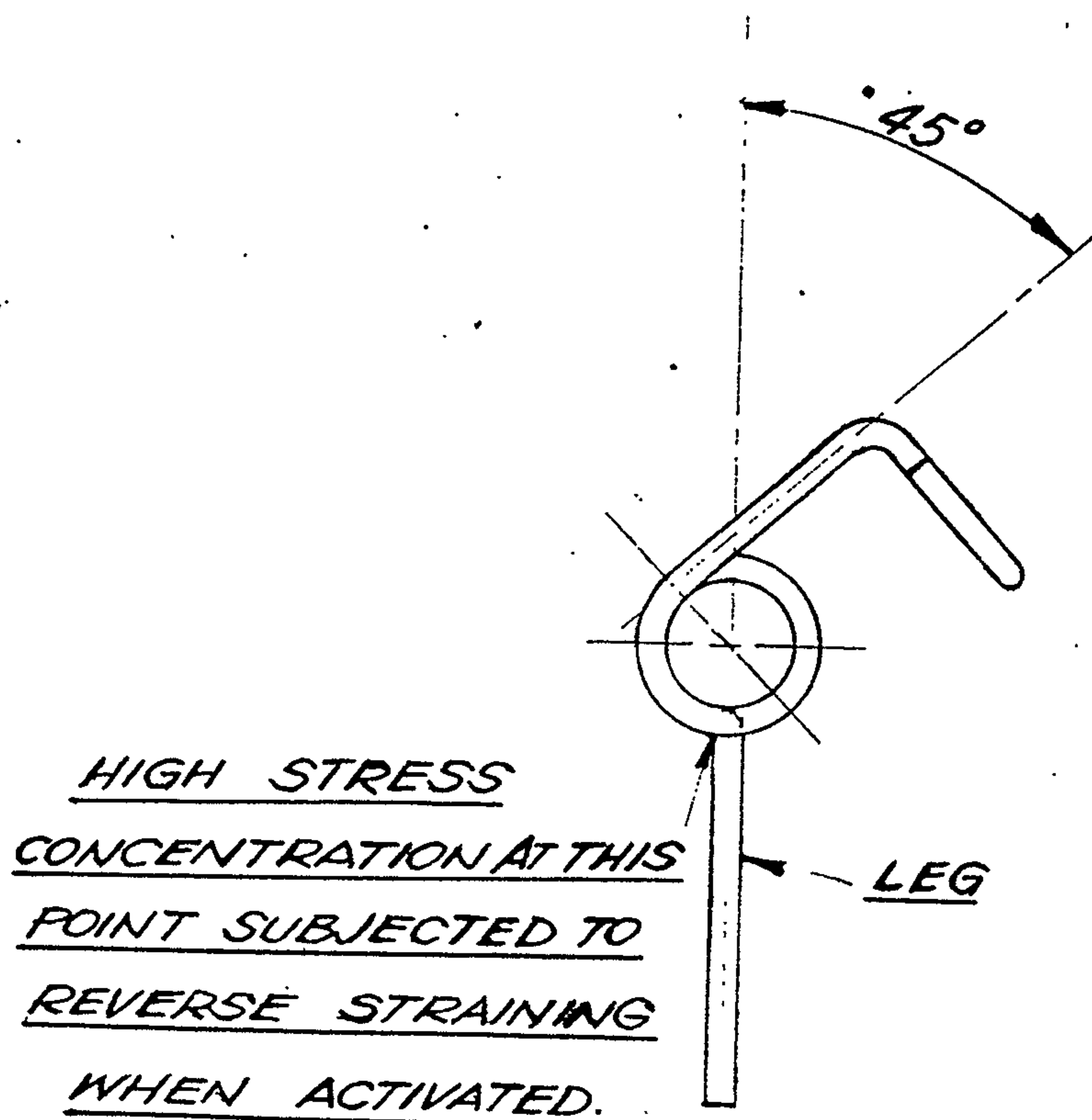
MINI SPRING (TANGENTIAL LEG)

DESIGNED TO ELIMINATE REVERSE

STRAINING WITH LEG TO COIL BEND

Figure 3.11..."Mini-Spring" Design Features

(Mr AJ Wilcock Jr.; with permission)



IF SPRING INDEX

$$C \approx 1.5 \text{ ESTIMATED } \frac{D}{d}$$

$K = 2$ (STRESS CONCENTRATION FACTOR)

IE. THE WORKING STRESS AT THIS POINT

IS DOUBLED IF THIS LEG TO COIL BEND

IS TOO SHARP.

CONVENTIONAL UPRIGHTING SPRING

Figure 3.12

Conventional Uprighting Spring Design Flaws

(Mr AJ Wilcock Jr.; with permission)

MS Design Advantages

SHIGLEY and MISCHKE (1989) describe a spring's **Spring Index**, C

as

$$C = \frac{D}{d}$$

where D = mean spring coil diameter
and d = wire diameter

WILCOCK (1989) has commented that, for commercial steels this has to be of the order $C > 4$.

However, this rule was able to be broken with the MS because of the high tensile nature of 'Supreme' - grade wire. Hence:

- a. The physical size of the MS could be reduced;
- b. the energy storage capacity increased (stored energy is proportional to $(\text{yield strength})^2$);
- c. increase elastic deflection (stress being proportional to bending moment $\times$ diameter^{1/2} where bending moment equals force $\times$ distance - see Chapter Four).

Added to the above in MS design is the **removal** of the sharp bend/stress concentration point where, in conventional uprighting springs, the stem is **radially** disposed to the coil, generating a **reverse** straining effect. This untoward Bauschinger effect is overcome in the MS since the stem is **tangentially** disposed and all straining is '**forward**'. (Similarly, the MS 'arm' can be adjusted by the operator **prior** to insertion if excessive loading is anticipated from the 'as received' condition. This pre-insertion adjustment, which has no effect on spring performance because it is 'forward' straining, eliminates the inefficient tactic of initial lever arm ligation promoted by SCOULER (1982) and HYDE (1988.)

Summary

The MS incorporates many significant design changes which differentiates it from other uprighting springs and should, theoretically, overcome any untoward effects consequent to the use of very fine wire and the breaking of $C > 4$ spring index.

Begg Brackets/MS Assembly

Unitek 'Unipoint' (Unitek Corporation, Monrovia, California) brackets have been recommended (MOLLENHAUER - 1990a) for use with the MS because of the bracket's 'pinched' dual channel configuration (See Figure 3.11). It allows the base archwire to be engaged in the larger channel and the MS to be positioned in the smaller channel closest to the tooth's facial surface, both elements then being secured by a Stage 3 0.016" x 0.022" hook pin (TP Orthodontics Inc. LaPorte, Indiana) or standard Unitek Stage 3 pin (Unitek Corporation).

The MS may also be used with the 'conventional' 256 - 500 Begg bracket (TP Laboratories Inc.) provided an appropriate lock pin, e.g., 0.016" x 0.022" hook pin, is used 'jammed' alongside the MS stem. The most important aspect of MS placements is, however, to ensure that the spring coil is kept away from the vertical slot entrance (MOLLENHAUER - 1990b).

**'UNIPOINT' BRACKET (L) AND
CONVENTIONAL 256-500 BRACKET (R)**

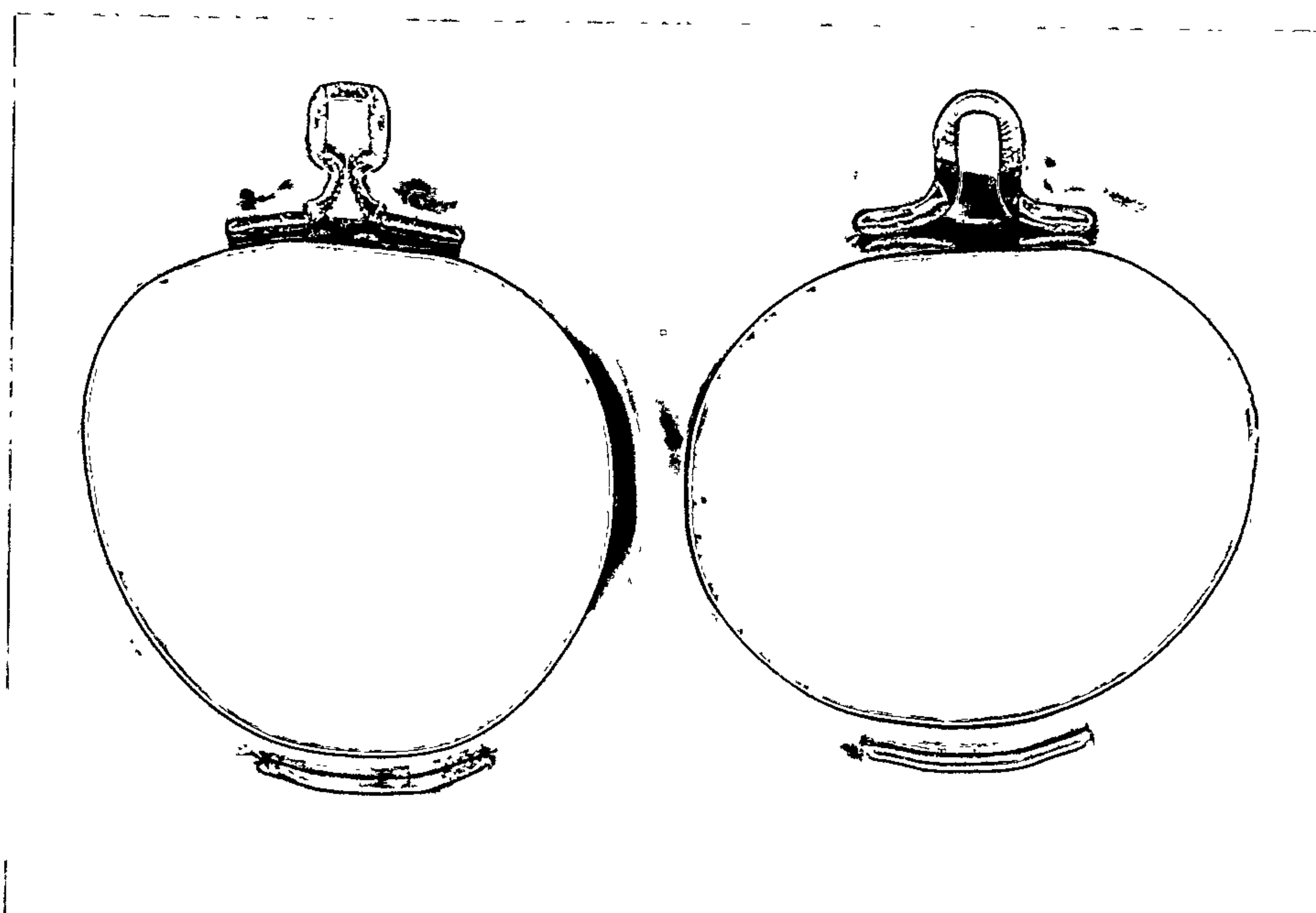


FIGURE 3.13

PREVIOUS UPRIGHTING SPRING

INVESTIGATIONS

Introduction

There have been two previous investigations into the performance of Begg uprighting springs in The University of Sydney; the first by SCOULER (1982) and the second by HYDE (1988).

The purposes of this concluding section are to:

- a. Relate the hypotheses tested by each investigator; and
- b. summarize and critically analyze their findings.

SCOULER - 1982

Hypothesis

SCOULER (ibid) wrote as follows:

'The hypothesis to be tested is that the degree of angular deflection required to activate certain types of uprighting **spring pins** (TP Laboratories Inc.) used in the Third Stage of the Begg technique, may be such that to produce levels of force, greater than those that have been previously proposed as producing optimal physiological tooth movement.

The forces arising from activation of the auxiliary will vary according to the design of the spring-pin under test.

It is anticipated, however, that as the spring-pin bracket combination is subjected to increasing levels of activation, a degree of hysteresis may be observed which could modify these 'expected' levels of force'.

Experimental Aims

Scouler investigated the performance of six types of uprighting **spring-pins** (Figure 3) (as opposed to uprighting springs per se) under load, **in vitro**, examining two areas of spring-pin behaviour:

- a. The force levels generated through **static** spring-pin activation, i.e., no cognizance was taken of the variations in moments produced as the lever or activating arm angle changes during tooth uprighting; and
- b. the role increasing levels of lever arm deflection (and therefore spring-pin activation) may play in generating 'hysteresis' (stress relaxation) effects. A concomitant desire was to try to establish the rate at which this occurred.

Experimental Apparatus and Method

The experimental apparatus consisted of an 'analogue' - type of apparatus whereby direct measurement of spring-pin lever arm deflections was employed. A freely-rotating brass-spindle attached to the lever arm permitted angular changes to be read from a protractor incorporated in the apparatus acrylic base. Each test spring was mounted in a Begg bracket (TP Laboratories: 256-500) along with a length of 0.020" 'Special'-grade Wilcock (AJWSEE) wire.

Weights were added to test springs for five minutes, loads increasing in 50 gram increments. Weights were added until a lever arm deflection approximating seventy-five degrees was achieved. (SCOULER (ibid) cited RAMOS, WEIMER and HANNA (1979) who indicated the maximum deflection one might expect in the clinical situation approximated seventy-five degrees.)

Experiment I: Load Deflection Characteristics

In the first experimental series eight randomly selected spring-pins from each of the six groups were loaded, as described, up to a maximum deflection approaching seventy five degrees.

Experiment II: Spring-Back Characteristics 'Hysteresis'

The same experimental materials were employed in the second series. However, the method varied. In Experiment II the lever arms of spring-pins were deflected manually, by five degree increments, up to seventy five degrees of angular difference from the zero position.

Results

Experiment I

Increases in wire diameter of 0.002" were found to produce an almost doubling of the load required to produce the same deflection from group to group, i.e., 0.014" to 0.016" and 0.016" to 0.018" groupings which Scouler noted was in agreement with the findings of PERLOW (1968) and RAMOS, WEIMER and HANNA (1979).

A selection of experimental findings are given below:

LOAD-DEFLECTION CHARACTERISTICS - SCOULER 1982

	Group	Load (g)	Deflection (degrees)
1.	0.014" two coil ortholoy	180 525	35 70
2.	0.014" two coil Australian	175 440	35 70
3.	0.014" three coil ortholoy	170 460	35 70
4.	0.016" two coil Australian	300 850	35 65
5.	0.016" two coil ortholoy	300 760	35 60
6.	0.018" two coil ortholoy	475 1,050	35 60

TABLE 3.3

and with the exception of the 0.014" groups at thirty-five degrees, are far in excess of the recommended levels.

Therefore, of the spring-pins studied, Scouler recommended the 0.014" three-coil ortholoy group because of its potential for an increased range of activation. However, he was more firmly in favour of 0.012" diameter wire spring-pins as:

'... any type of spring-pin fabricated from 0.012" diameter wire, at any degree of activation, would produce forces that could be considered to be within those proposed as being optimal for physiological tooth movement.'

(Scouler also observed that high quality 0.012" wire would need to be employed to avoid untoward plastic deformation effects.)

Experiment Two

All spring-pin groups demonstrated a variable amount of stress relaxation ('hysteresis') as angular deflection increased through, according to Scouler, either:

- a. Experimental error; or
- b. plastic deformation.

He stated that this last factor lead to an inability to establish a direct relationship between angle of deflection and force generated.

(Comment is indicated regarding the appropriateness of the term 'hysteresis' SCOULER (ibid) used a strictly literal definition (pg 75.):

'coming short, to be behind, etc.' (Oxford English Dictionary).

However, in engineering terms and with regard to uprighting springs 'hysteresis' is a malapropism inasmuch as **repetitive cycling** (loading-unloading-loading, etc.) is required to invoke a true hysteresis effect (TIMOSHENKO-1941). A better term is 'stress relaxation' (and the related phenomenon of creep) and is the term employed in the present work.

There are a few problems with Scouler's research, one of which is relatively serious (and was perpetuated by HYDE (1988) - vide infra). It relates to the incremental loading of test springs-which **must** introduce a strain hardening effect and therefore compromise the experimental results to some degree (INGRAM, GIPE and SMITH - 1986).

Notwithstanding the foregoing comment, and in general, the experimental design was satisfactory, as was the analysis.

Regarding the analysis, a randomized block design (as stated) was used. This means that to repeat the experiment the order in which the springs were tested would need to be known-information which is unavailable; a better design would have been one which was completely randomized.

Similarly, it is difficult to know what effect the manipulation of the apparatus would have had from time-to-time on measurement data and how this would affect the significance levels. However, the foregoing does not necessarily detract from the conclusions.

HYDE - 1988

Introduction

HYDE (ibid) took up SCOULER'S (1982) implicit recommendation and investigated force-deflection characteristics of 0.012" and 0.014" (Wilcock) 'Premium Plus' Begg uprighting springs.

Hypothesis

Part I: Load/Deflection Characteristics

HYDE (ibid) wrote:

'The forces provided by the 0.012" springs should be close to assumed physiological forces even at deflections approaching 60°. The forces provided by the 0.012" L[L = 'long', i.e., long lever arm (described as 'leg' by HYDE) the 'leg' length being 5.0mm] springs should be appreciably lower than the 0.012" S[S = 'short', the 'leg' length being 2.6mm] springs. Both the 0.012" springs should provide much lower forces than the 0.014" springs. [0.014" spring 'leg' lengths were 3mm on average.]

Part II: Hysteresis of Springs

'The springs exhibit no hysteresis, i.e., following loading of the spring it should return to its' (sic) original angulation.'

Experimental Apparatus

The experimental apparatus consisted of a pineboard assembly which was the prototype for that used in the present work except that it allowed for the testing of only one spring at a time. (See Chapter Four.)

Experimental Method

Experiment One

Ten randomly selected springs from each group were tested. The springs were prefabricated by AJWSEE and of 'conventional' design, i.e., radial stem or leg (not Hyde's description) disposition, the 'Long' springs' lever arms being fabricated by Hyde.

The test assembly consisted of a Begg bracket (type unspecified), a length of (Wilcock) 0.020" 'Special Plus' wire ligated into the bracket and the test spring.

'Pilot' springs were loaded to determine what weight(s) would generate a lever arm deflection of at least sixty degrees (after RAMOS, WEIMER and HANNA - 1979). This weight quantum was divided into ten equal increments for application during the test cycle.

Progressive load increments of 30g were added for 0.012" springs and 40g for 0.014" springs; (maximum loadings being 290g and 400g respectively). Weights were left **in situ** for one minute.

Measurement was effected using the photographic technique described in Chapter Four of the present work, photographs being taken before and during loading.

Experiment Two

The same procedures as in Experiment One were employed except loads were left **in situ** for five minutes and photographs taken before load and then **after** load removal.

Loads applied were as for Experiment One but only five springs from each group were tested.

Results

The results from Hyde's work, upon review, demonstrated a series of design and analysis anomalies, casting some doubt over them.

Review

SCOULER (1982) did not make comparisons across weight samples and therefore no difficulties exist in terms of his results or analysis.

However, HYDE (ibid) did make comparisons across groups and in so doing did not take into account the residual effects of sequential loading of the **same** springs (vide supra).

This, as noted in the review of Scouler's work, introduces a flaw into the data for the reason that a work hardening effect is introduced and does not reflect clinical reality - an uprighting spring is loaded to its maximum, **usually only once**, i.e., on initial placement. For the remainder of Stage 3 in the Begg technique the loading of the spring **decreases** as the tooth in question uprights. The inappropriateness of the term 'hysteresis' has already been described in the review of SCOULER'S (ibid) work.

Statistically, the experimental design would have been improved by using:

- a. a fresh spring for each test, thereby eliminating any residual effect ('carry over'); and
- b. a randomized design.

The review of the work of Scouler and Hyde lead to improvements in the design and analysis of the present work.

Statistical Review

If design problems are ignored, the individual experimental results may be reviewed and re-analyzed.

6.5.2 Part One: Deflection During Load (pp 77-79)

The statistical analyses for 0.012" 'Short', 0.012" 'Long' and 0.014" uprighting springs are satisfactory and the conclusions drawn, i.e., that the:

'... change in spring arm angle during load is [as may be intuitively expected] significantly affected by different loads and by variation between individual springs for 0.012" 'Short' and 0.012" 'Long' springs. However, for 0.014" uprighting springs, while loads significantly affect their angulation, they are **not** significantly affected by variations between individual springs.'

FACTORIAL ANALYSIS OF 0.012" 'SHORT' VERSUS 0.012" 'LONG' SPRINGS (pg 80)

The appropriate analysis, which was not applied in this section, is a **split plot** design.

If a valid analysis had been performed then it would have indicated that the estimate of the variance between spring types was approximately eight times that indicated. However, in Hyde's experiment this **true** variation had no effect on the conclusions:

- a. 'The difference in leg length between the springs is significant;
- b. the effect of different loads on the two groups of springs is significant; and
- c. deflections caused by various loads are significantly different between the two groups of springs.'

because of the different nature of the springs and the loads used.

While complaint cannot be made regarding loads or spring-types used per se, this may be significant in any other experiment where differing loads, i.e., loads of smaller interval are used, or in undertaking experiments on the same spring type.

If the differences between the loads had not been as great, then there would have been a better chance of detecting any significant difference between the effects of loads on springs and this is indicated by the **correct error** which is actually **one-half** that reported by Hyde. (The reported value is 15.22 whereas it should be 8.0 - see Error Mean Square Column.)

Reviewing Hyde's conclusions, Conclusion C, (vide supra) does not adequately explain the results inasmuch as it does not address the question of **interaction** and whether or not this is significant.

It may be intuitively expected that the effects of differing loads will be significant and Hyde's work does indicate this to be the case. For example, the difference between low and high loads on 0.012" 'Short' springs is different from the effects of the **same** loads on 0.012" 'Long' springs.

Hyde's conclusion does not address the fact that uprighting spring performance is actually changing with different loads because of the different nature of the springs.

FACTORIAL ANALYSIS OF 0.012" SPRINGS VERSUS 0.014" SPRINGS (pp 81-82)

The same observations may be made for this analysis as have been made in the preceding review, i.e., a Split Plot rather than a Factorial analysis should have been used. However, albeit that an inappropriate analysis was used, the experimental conclusions are not altered (for the same reasons that the conclusions were not altered in the former experimental analysis) i.e., there is a significant interaction between leg lengths, wire diameters and deflection for a given load.

6.5.3 Part Two: Deflection After Load [Stress Relaxation or 'Hysteresis']

ANOVA for 0.012" 'Short' springs, 0.012" 'Long' Springs and 0.014" Springs (pp 83, 84 and 85)

The data in these pages is suspect because of the enormous co-efficients of variation, e.g., 275.4% (pg 83) 230.4% (pg 84) and 167.7% (pg 85). Anything greater than, e.g., 30%, indicates that the subject experimental data should be viewed with concern and 275.4% (pg 83) is certainly in this category.

The question raised by Hyde's data is, naturally, why is it so variable. Could it be that a work hardening effect is being demonstrated through the sequential loading of the **same** springs rather than using different springs for each test? The provisional answer is 'yes'. Nevertheless, Hyde's finding was of **no** stress relaxation in any of the groups.

6.5.4 Regression Analyses (pp 86-93)

A re-analysis of the data using asymptotic regression equations rather than the simple linear regression analysis employed by Hyde generates curves which better fit the data. In each case re-analysis meant the Error Mean Square was reduced. The original and re-worked data curves are shown in Figures 3.14 to 3.16.

A selection from the re-worked data indicates the following force deflection values (Table 3.4):

SELECTED LOAD DEFLECTION VALUES

Uprighting Spring	Load (g)	Deflection (degrees)
0.012" 'Short'	90 Approx.	35
	250 Approx.	70
0.012" 'Long'	49 Approx.	35
	115 Approx.	70
0.014"	140 Approx.	35
	335 Approx.	70

TABLE 3.4

HYDE DATA (1988) fig.6.10
0.012" Short: Reanalysed Data

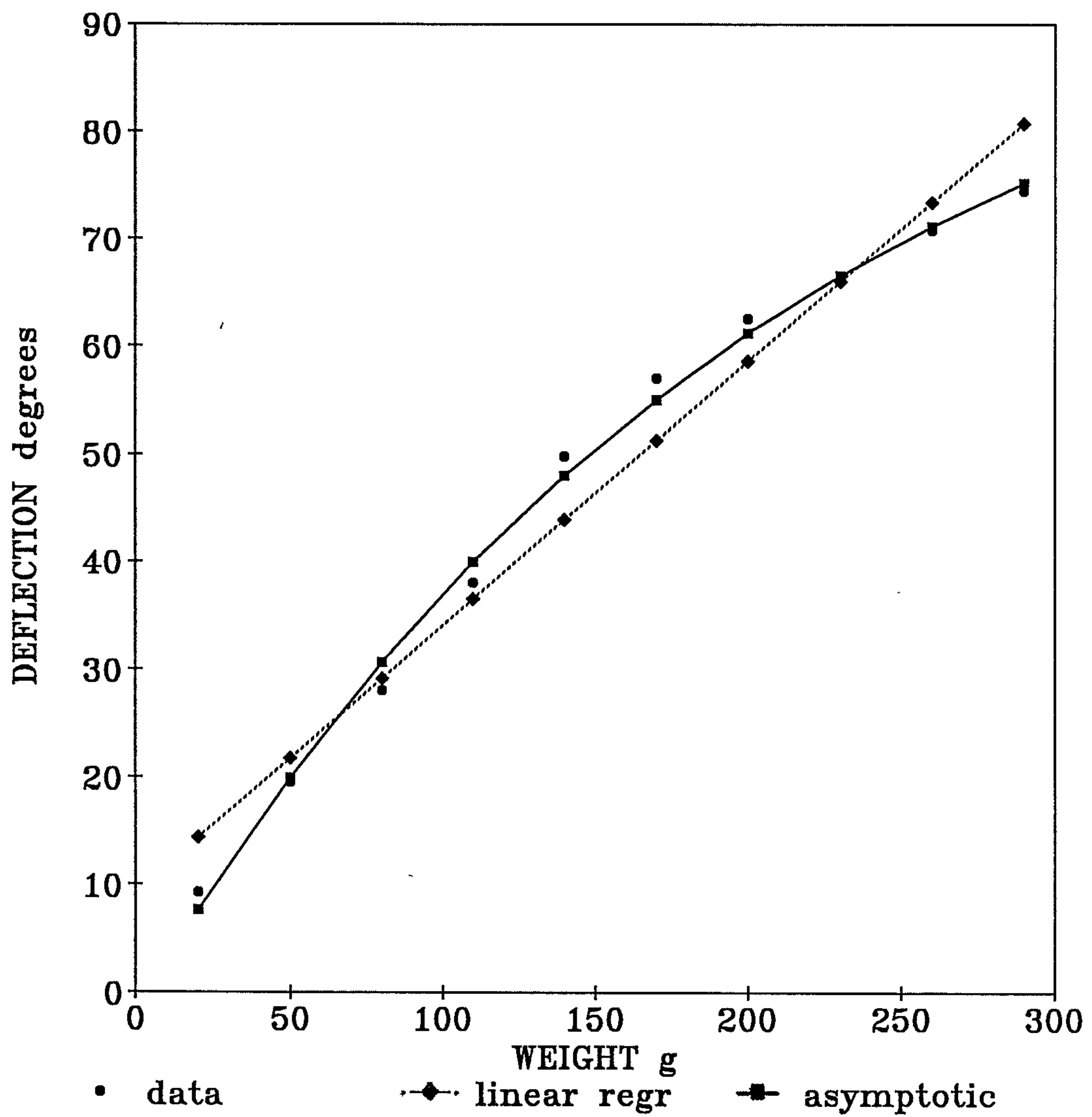


Figure 3.14

HYDE DATA (1988) fig.6.10
0.012" Long : Reanalysed Data

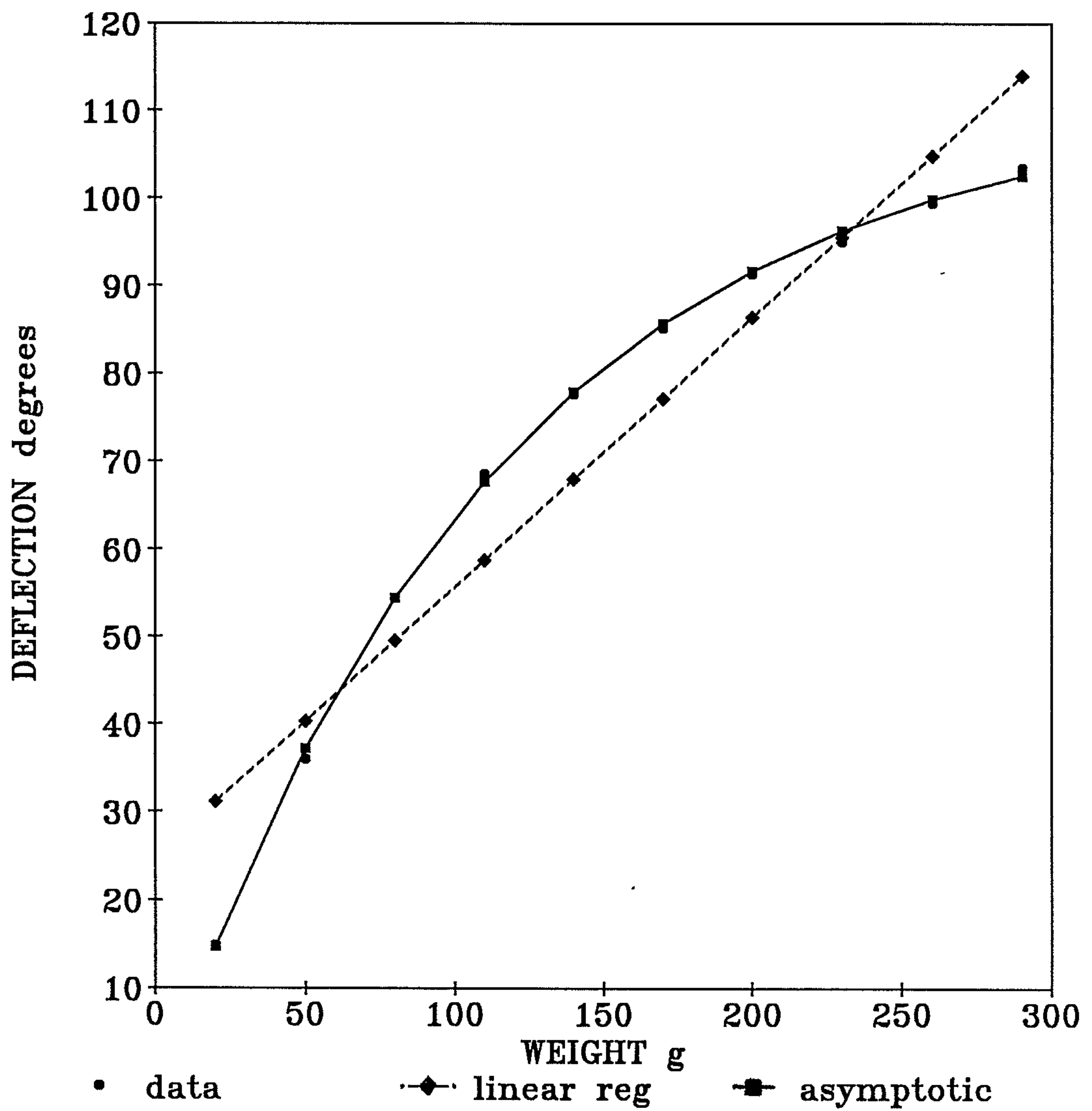


Figure 3.15

HYDE DATA (1988) fig. 6.13
0.014'' Springs: Reanalysed Data

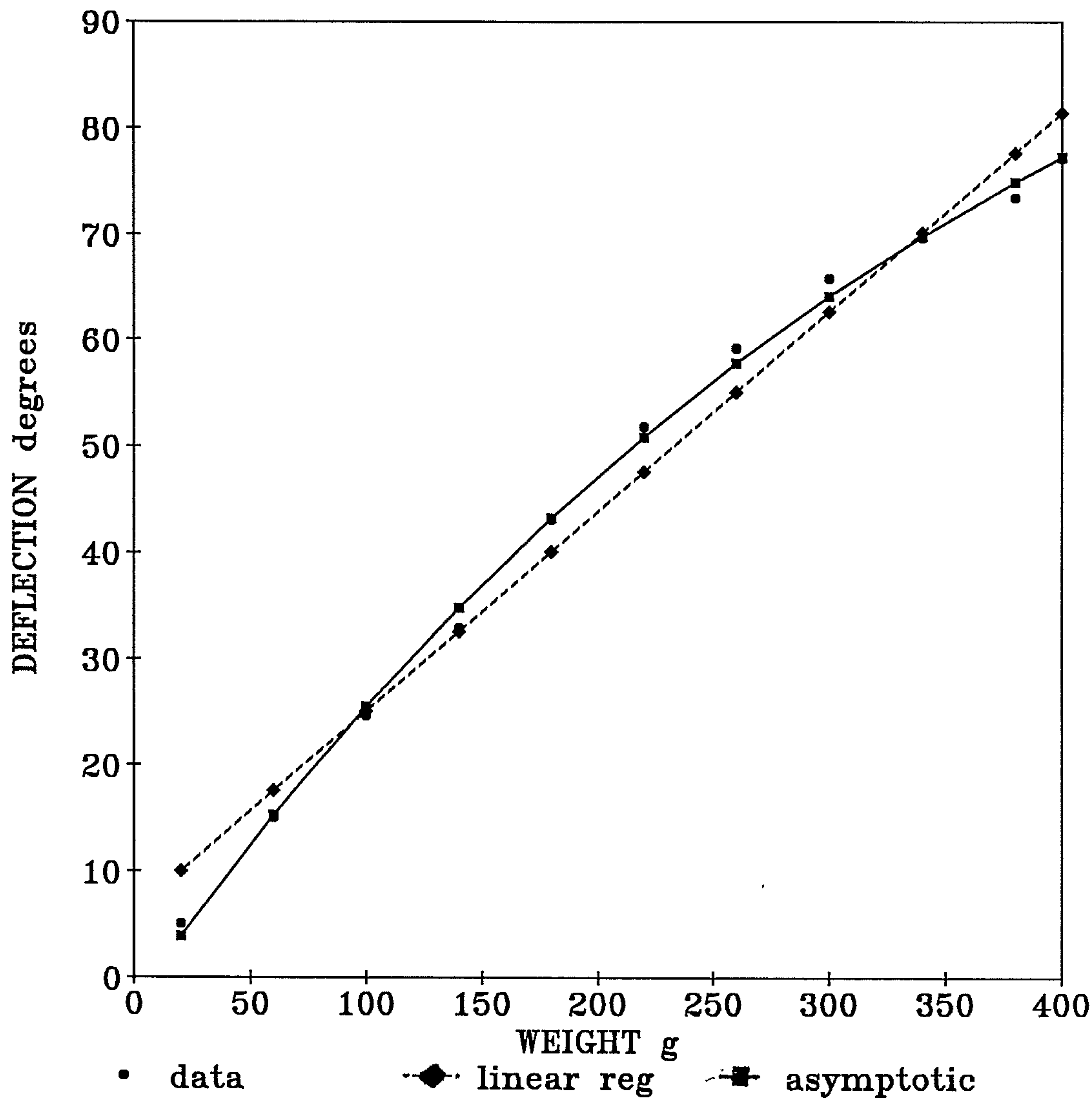


Figure 3.16

Hyde indicated that in his regression analyses he was attempting to establish:

- a. 'the type of correlation between observed data;
- b. a model/function to predict deflection from load within the range of load (interpolation) and outside the range (extrapolation); and
- c. (graphical relationships) between force and deflection in the experimental range'.

He concluded:

'There is a highly significant correlation between deflection **during** load and the applied load for the three groups. The correlation is positive and the regression lines have a positive slope ... thus the change in angle during load is directly dependent on the load, i.e., the heavier the load the greater the change in angulation of the spring. In the case of the deflection after load, for all three groups, there is no correlation nor regression... between the change of angle after load and the applied load.'

Simply put, Hyde has said that as load increases, deflection increases **linearly**. However, when re-analyzed, the data indicated an **asymptotic** relationship, which is consistent with yield phenomena (elastic/plastic behaviour) in orthodontic appliances (BURSTONE and GOLDBERG - 1983). Similarly, his comments on stress relaxation must also be questioned.

CHAPTER FOUR

THE EXPERIMENT

Introduction

In the Further Research Section of his thesis HYDE (1988) suggested two areas for further investigation:

- a. In vivo radicular force levels generated by uprighting springs; and
- b. force/deflection characteristics of proposed 0.011" diameter uprighting springs.

Recommendation 'a'. is probably beyond the scope of an MDSc thesis project and might better form the basis for a doctoral dissertation, considering the complexity of the biomechanical systems involved.

However, regarding the recommendation for a study of the 0.011" uprighting spring, this certainly could be undertaken on a similar basis to the work of SCOULER (1982) and HYDE (1988).

At the time the present work was commenced, the 0.011" spring had been produced by AJWSEE, but in prototype quantities only. The manufacturer was, however, producing and marketing the 0.010" MS.

Effects of Conformational Changes

As noted previously, the MS represents a marked departure in uprighting spring design.

The principal questions to be addressed in the present investigation are:

- a. What effect(s) the conformational changes described may have on spring performance; and
- b. What inference(s) might therefore be drawn regarding resultant tooth movement.

EXPERIMENT ONE

EFFECT(S) OF TIME

Hypothesis

An uprighting spring should show zero or minimal stress relaxation over time for a specified range of loads.

EXPERIMENT TWO

LOAD-DEFLECTION CHARACTERISTICS

Hypothesis

(1) The very small size of the MS, both in terms of wire diameter and overall conformation, should result in low load-deflection values consonant with optimal values obtained from clinical observations; and

(2) following on from (1), the very high tensile wire ('Supreme' grade) used, in combination with a theoretically superior spring design (the spring stem or 'leg' is disposed tangentially to the coil rather than radially) should result in a zero or minimal stress relaxation effect.

EXPERIMENTAL APPARATUS

Introduction

The design of the experimental apparatus was based upon a variation of that used by HYDE (1988). (See Figure 4.1a and b)

Base

The base consisted of a 16mm Corinite™ particle board (Formica Australia Pty Ltd), measuring 595mm x 495mm x 16mm.

Four round rubber 'feet' were affixed at each corner of the base underside to prevent slippage and absorb extraneous vibration.

EXPERIMENTAL APPARATUS

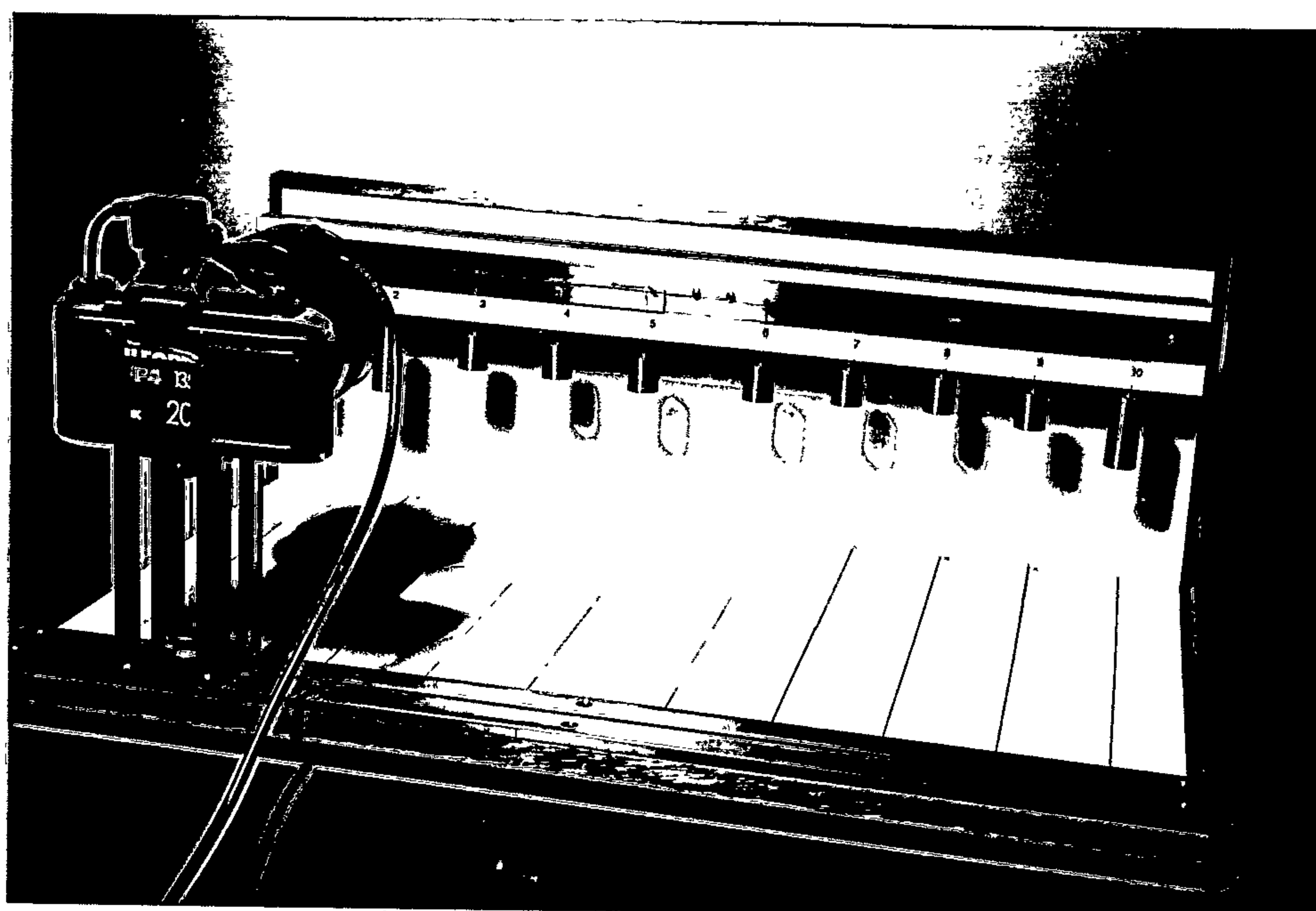


FIGURE 4.1a

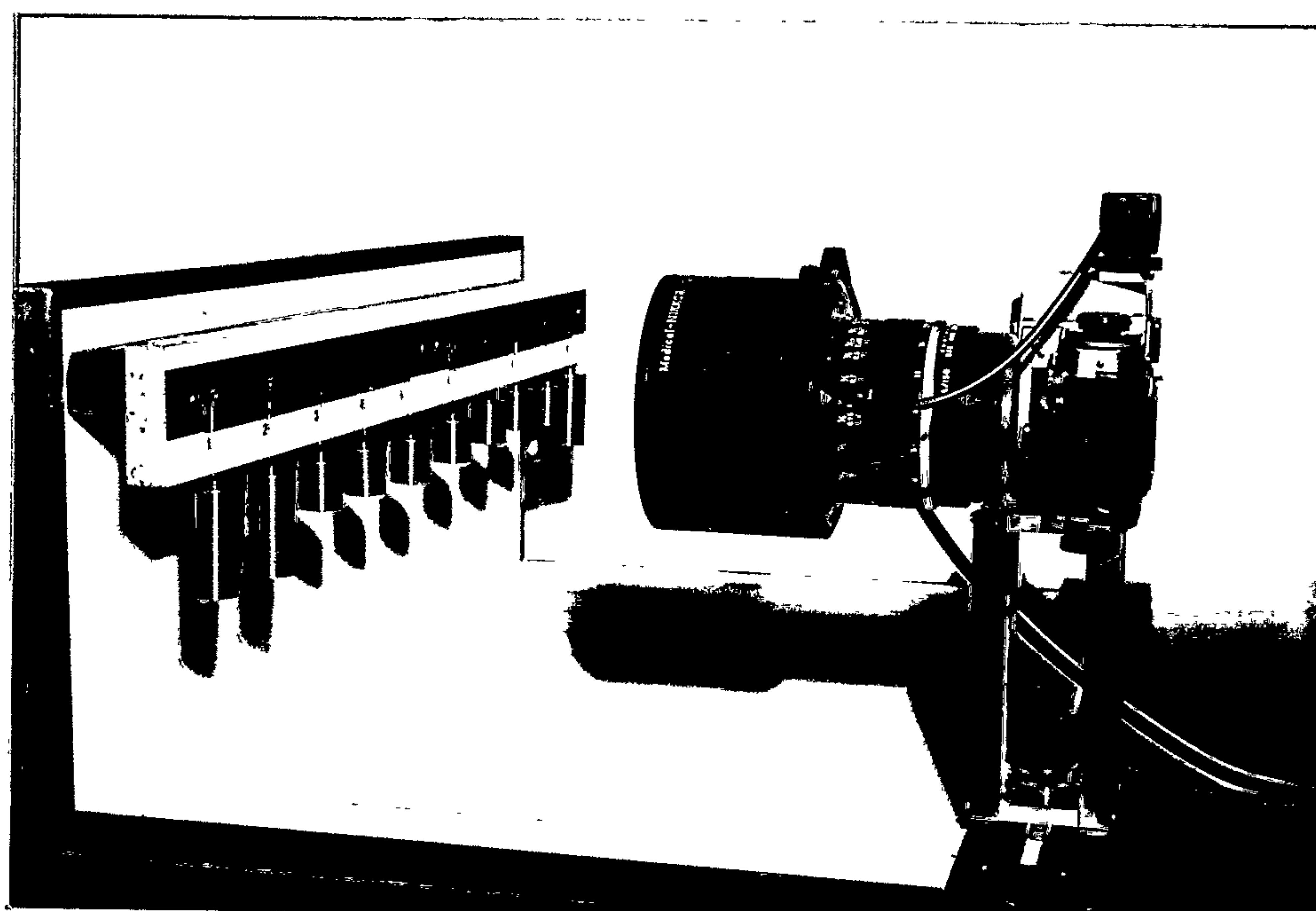


FIGURE 4.1b

Upstand

An upstand, also fabricated from 16mm Corinite™ sheeting, and measuring 595mm x 200mm x 16mm, was screwed and braced to the base board at a distance of 385mm from the base's leading edge.

Face Piece

A Corinite™ face piece, 580mm x 50mm x 16mm, supported by a piece of timber packing, 580mm x 25mm, was screwed to the upstand so that the height of the lower edge of the face piece was positioned 125mm above the base board. The height and depth positions of the face piece, relative to the base board, were predetermined to facilitate:

- a. The unencumbered suspension of various custom-made brass weights, (vide infra), from test springs; and
- b. photographic record taking, (vide infra).

Begg Bracket Mounts

Two pieces of stainless steel strip, 290mm x 25mm x 1mm, were affixed across the Corinite™ face piece. Two additional strips of stainless steel, 230mm x 12mm x 1mm, were soldered to the two larger pieces, parallel with the latters' long axes.

The smaller stainless steel strips were made necessary because Begg brackets (Unipoint™, Unitek Corporation, Monrovia, California), welded directly to the larger strips provided insufficient clearance for unimpeded MS coil function. Welding brackets to the smaller strips gave sufficient clearance, and thereby reproduced the clinical situation whereby natural facial surface crown convexity leaves the MS unencumbered.

Bracket Selection

The selection of the Unipoint™ Begg bracket has been discussed in Chapter Three.

Bracket Positioning

Ten Unipoint™ Begg brackets were positioned along the mounting strips at intervals of 55.0mm, which distance provided sufficient working room for comfortable spring placement and removal during the course of the experiments. This was particularly important in Experiment One, (examining the effects of time on spring performance).

Vertical bracket positions were co-ordinated with the fixed vertical camera position (see later), to place bracket/spring combinations in the centre of the photographic field. The vertical positioning also took cognizance of the requirement for unimpeded suspension of test weights.

Camera Mount

MS lever arm displacements were to be recorded photographically for subsequent measurement on a projecting microscope (see later), employing the method devised by MAI¹ and used by HYDE (1988).

The camera (vide infra) was first secured to a brass mounting column using a standard photographic screw. The column was, in the first instance, designed for, and used by, HYDE (1988), and consisted of brass rectangular angle and plate. (The height of the column, in combination with the recording camera, had determined the vertical positioning of the Corinite™ face piece on the upstand.)

1. Professor Y.W. Mai, Department of Mechanical Engineering, The University of Sydney.

Camera Mount Track

The randomization necessary for spring testing and measurement (in Experiment One at least), necessitated the lateral movement of the camera. To achieve this, a brass track was fabricated and affixed to the leading edge of the base board. The track consisted of a single piece of brass plate measuring 595mm x 50mm x 6mm into the centre of which was cut a groove which allowed the camera column assembly to 'travel' laterally. The column was then able to be secured, as required, along the track, using a knurled brass screw. (The column was machined to allow only lateral movement.)

Photographic Recording Procedure

Accurate and precise measurement was predicated upon the precision of camera positioning. To this end, bracket positions were projected onto the base board's leading edge using technical drawing instruments. Score marks were then placed in the brass track on either side of the centrally positioned mounting column allowing consistent positioning to be achieved.

During use the camera mount was first positioned and locked into position. The camera body was then positioned on the camera mount so that the bracket-spring assembly was centred as closely as possible within the field of view. Finally, sharp focus on the MS lever arm was effected and that position was secured with the photographic screw. This procedure was followed on each occasion to minimise parallax error.

Camera

A 35mm single-lens reflex Medical Nikon Camera with 120mm Medical Nikkor Macro Lens (1:4) was used for recording at 1:1 magnification. The camera lens incorporated a ring flash unit, powered by a 240V mains power source.

Film

Ilford brand FP4 black and white film ISO 125/22° FP4 135 (35mm) film (twenty-four and thirty-six exposure) was used for all recording.

Weights

Custom-made weights were machined from brass rod (19mm and 32mm diameter) to produce ten weights of 50g, ten weights of 100g and a series of twelve weights from 200g to 310g inclusive, increasing in increments of 10g. An 'eye' was machined into each weight's upper surface which allowed weight(s) to be suspended by 0.009" orthodontic ligature wire from the lever arm hook of a MS. (Ligature wire was included in determining each test weight's mass.)

In Experiment One a pair of one 50g and one 100g weight were allocated to each test bracket position and were engraved accordingly, (one through ten).

In Experiment Two weights were assembled with short lengths of ligature wire (plus a 'suspension' wire) to create ten loads of 100g to 550g inclusive, with increments of 50g, and engraved one through ten.

An electronic scale (Mettler Model PC 4400 Delta range) was used for weighing test loads. The scale's measurement error, according to the manufacturer's literature, was $\pm 0.01\text{g}$ for loads up to 400g and $\pm 0.1\text{g}$ for weights greater than 400g. The weights were measured randomly and the procedure then repeated. Averaged values were used for statistical analyses.

Time Keeping

A Seiko-brand quartz digital combination wrist-watch/stopwatch was used for all timing requirements.

'Mini-Springs'

'Mini-Springs' (A.J. Wilcock Scientific and Engineering Equipment, Whittlesea, Victoria: 0.010" Supreme Grade-left; Catalogue: AJW-222-171; Batch Reference: HK.TAL) were supplied by the manufacturer and were randomly selected for use.

Base Arch Wire

To simulate the clinical situation each spring test was conducted with a 0.020" Special Plus-grade arch wire in place.

In Experiment One a single length of arch wire was secured across the face piece via the mount's support screws and engaged in each bracket slot.

In Experiment Two a section of the same arch wire type was positioned so that it was supported, when viewed from the baseboard's leading edge:

- a. In brackets to the right of the test bracket; and
- b. so that the left free-end did not interfere with the vertical movement of the MS lever arm. This was done to facilitate maximum lever arm deflection at the greatest applied load.

'Mini Spring'-Bracket Assembly

The assembly procedure (as recommended by MOLLENHAUER-1990a) was repeated for each test, and was as follows:

- a. Ensure base arch wire **in-situ** in base of bracket slot;
- b. insert MS stem/leg in smaller bracket channel, cinching the stem around the lower surface of the bracket;
- c. introduce hook pin (0.016" x 0.220", brass, Part # 207-341; TP Orthodontics Inc, LaPorte, Indiana, USA) into larger bracket channel and cinch as in b; and
- d. carefully apply test load, as required.

Note: In the clinical situation MOLLENHAUER (ibid) recommended a one movement action whereby the MS is grasped by its lever arm, the stem introduced into the smaller bracket channel, and the lever arm then hooked over the base arch wire. The stem is then cinched and finally the lockpin placed.

Spring Measurement

A Nikon Profile Projector (projecting microscope-PM) Model V-16 was used to measure MS lever arm deflections (See Figure 4.2). The measurement protocol was as follows:

- a. Calibration of the PM bezel prior to each measurement;
- b. central positioning of the photographic negative to be measured on the PM stage; and
- c. careful alignment of the projection screen cross-hairs; firstly the vertical with the midline of the long axis of the bracket slot, and then the horizontal with the bracket base. This protocol was repeated twice in Experiment One to investigate measurement as a source of experimental error.

Note: Because of the design of the MS, i.e., the **tangential** disposition of the stem relative to the coil, the assumption of central positioning of the stem in the bracket slot is reasonable and germane to later force-moment calculations.

PROJECTING MICROSCOPE

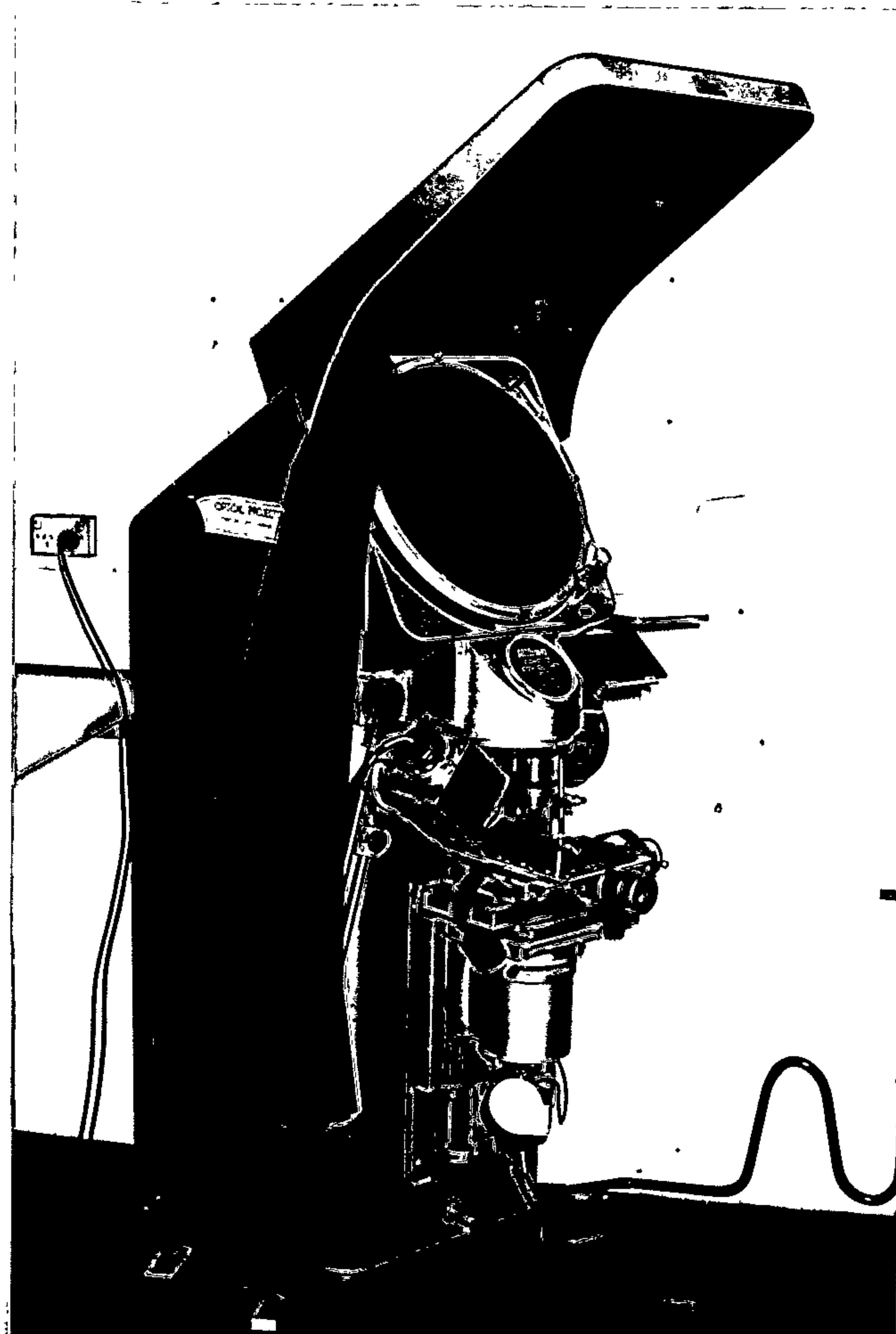


Figure 4.2

EXPERIMENT ONE

EFFECT(S) OF TIME

Method

Loads of 50g and 100g were randomly applied to forty randomly selected 0.010" MS's for pre-determined time intervals,

viz: 1 minute; 15 minutes; 30 minutes; 60 minutes; 12 hours; 24 hours;
1 week; 2 weeks; 3 weeks; and 4 weeks.

Loads selection was based upon:

- a. Literature review of ideal root-uprighting force levels, e.g. , PROFFIT (1986): 75g - 125g;
- b. previous studies of uprighting spring behaviour (Master's theses, The University of Sydney);
- c. a desire **not** to deform springs plastically and thereby ensure any **time** effect only was being taken into account; and
- d. the dynamic (reducing) loading effect which applies in the clinical situation as a tooth uprights. 

Time intervals selected were based upon:

- a. Literature review regarding stress relaxation, e.g., TWELFTREE, COCKS, and SIMS (1977); LEBSACK, WEIMER and HANNA (1980); HAZEL, ROHAN and WEST (1984); and WILSON (1985);
- b. experimental statistical requirements; and
- c. clinically 'relevant' time periods.

Spring lever arm dispositions were determined before load and immediately after load by the measurement of photographic negatives on the projecting microscope.

EXPERIMENT TWO

LOAD-DEFLECTION CHARACTERISTICS

Method

Ten loads ranging from 100g to 550g inclusive, increasing in 50g increments, were randomly applied to fifty randomly selected MS's for a period of five minutes. The same photographic method was used to record and measure lever arm dispositions as in Experiment One. Recordings were taken before, during, and after load.

STATISTICAL ANALYSIS¹

EXPERIMENT ONE

AFTER LOAD - BEFORE LOAD

ANOVA

SOV	df	SeqSS	AdjSS	Adj MS	F	P
Position	9	92.61	79.00	8.75	1.15	0.40
Weight	1	0.02	0.02	0.02	0.00	0.96
Time	9	32.35	41.98	4.66	0.61	0.77
Weight x Time	9	48.86	48.86	5.43	5.43	0.69
Error MS	11	84.11	84.11	7.64		
Measurement Error	40	31.07	31.07	0.77		

TABLE 4.1

Key: See page 132

-
1. All statistical analyses were performed using the Minitab Statistical Program.

Key:

SOV	Source of Variance
df	Degrees of Freedom
SeqSS	Sequential Sums of Squares
AdjSS	Adjusted Sums of Squares
F	Fisher Values
P	Probability or Significance level of test
LSD	Least Significant Difference
AdjMS	Adjusted Mean Square

An Incomplete Randomized Complete Block Design (RCBD) with sub-samples and a factorial treatment structure was used in the design and analysis of this experiment. (Blocks are the bracket positions on the experimental apparatus, each before load/after load event within a block is known as a plot and sub-samples are repeat measurements of the photographic records.) The Analysis of Variance was obtained using a Least Squares regression procedure.

The RCB design is described as '**incomplete**' because to be '**complete**' every time interval/weight combination would have to be used in each block.

The requirement to execute and replicate the experiment in a reasonable period of time meant that a '**complete**' design could not be used. (For example, even using the Incomplete Block Design, MS testing at Block 7 required a period of over seven weeks, and this did not include any allowance for aborted tests.)

The Incomplete Block Design results in the Weight effect and the Time effect being dependent and, so, requiring a non-orthogonal ANOVA. Thus, a Least Squares Regression Analysis was used to calculate adjusted Sums of Squares.

Conclusion

The statistical analysis indicated **no** effect of **time** on spring behaviour **at the loads used** and hence, no graphical trend was evident. Therefore, the springs tested delivered a constant force, i.e., there was **no** stress relaxation effect.

Measurement Technique Reliability

An examination of the variation of Before Load data was made to determine the reliability of the photographic measurement technique employed in Experiments I and II. (This was done using a standard statistical formula.)

BEFORE LOAD ANALYSIS

Mean	22.69
Variance	20.61
Photographic Measurement Error	0.26
Standard Deviation	4.54
Standard Error of the mean	0.72

TABLE 4.2

If Table 4.2 is examined, the Photographic Measurement Error Value is seen to be 0.26. The Standard Error of the mean, i.e., the variability **between** the springs, is seen to be 0.72. In this case, the additional variability attributable to the photographic technique is negligible. Therefore, the analysis indicated the measurement method to be accurate and therefore reliable.

Variability of Lever Arm Dispositions

The same analysis as used for the examination of measurement technique reliability was employed to determine the variability of lever arm dispositions in the as-received condition.

The importance of this examination lies in its significance as an indicator, in part at least, of the confidence a clinician may have in the manufacturer's production and quality control methods. Uniform production standards imbue confidence and subsequently generate clinical efficiency when employing MS's (or any other component for that matter). (See Chapter Three regarding pre-insertion operator adjustment of the MS.)

The data in Table 4.2 have a mean of 22.69 with a Standard Error of 0.72. This means that the 95% confidence interval for the mean is $(22.69 - (0.72 \times 2))$ to $(22.69 + (0.72 \times 2))$.

If a 'normal' distribution is assumed, then 95% of observed values should be within ± 2 standard deviations of the mean. The co-efficient of variation is found to be:

$$\frac{4.54}{22.69} \times 100 = 20\%$$

From the foregoing it can be inferred that lever arm disposition is acceptably uniform, a finding at odds with the comments of OONO and MACHIDA (1968).

STATISTICAL ANALYSIS

EXPERIMENT TWO

Part I - Effect of Load

In Part I an Incomplete Randomised Complete Block Design (RCBD) was used. (The reader will recall that in Experiment One an Incomplete RCBD was also employed.)

When the Least Squares Analysis of Variance (ANOVA) was performed Position was seen to have **no** effect while Weight was seen to have a **significant** effect on spring performance, as one would expect. As the Position effect was not significant, this term was pooled with the error, thus making the analysis a Completely Randomized Design (CRD), resulting in the means having the same variance and facilitating comparisons among the means (Table 4.3).

DURING LOAD-BEFORE LOAD

CRD ANOVA					
SOV	df	SS	MS	F	P
Weight	9	42 900.6	4 766.7	581.17	0.000
Error	40	328.1	8.2		
Total	49	43 228.7			

TABLE 4.3

While both quadratic and asymptotic regression equations could be made to fit the data, the quadratic was the better fit.

The means were plotted against Weight, and the plot examined to determine any trend(s) present (Table 4.4).

CRD MEANS

Weight(g)	N	Angle of Deflection (degrees)
100.0	5	26.38
150.0	5	41.45
200.0	5	57.25
250.0	5	68.40
300.0	5	79.56
350.0	5	87.36
400.0	5	100.83
450.0	5	106.80
500.0	5	112.37
550.0	5	116.26

TABLE 4.4

DEFLECTION CHARACTERISTICS
during load - before load

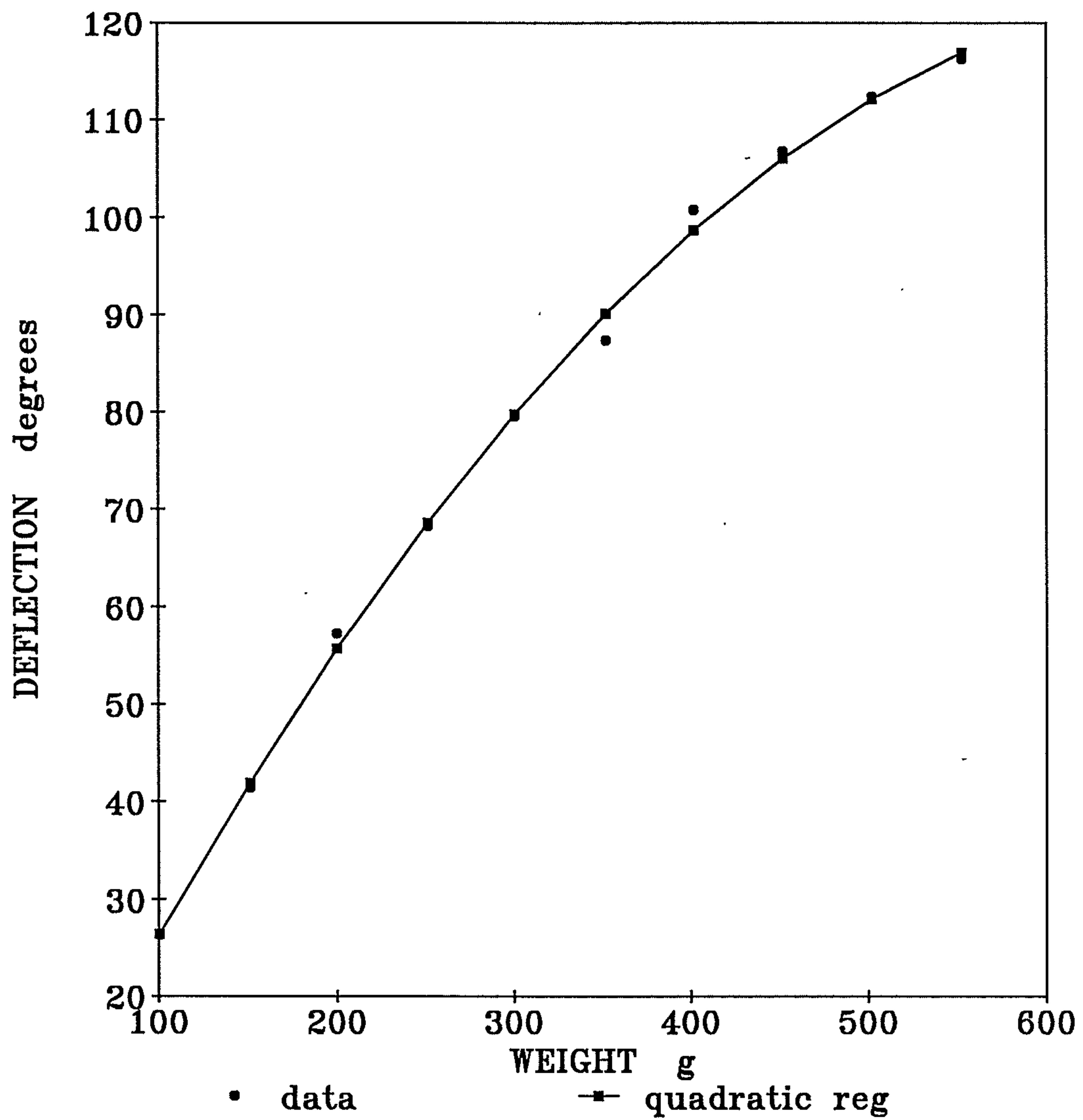


Figure 4.3

REGRESSION ANALYSIS

SOV	df	SS	MS	F	P
Linear	1	8 331.2	8 331	3 787.0	p<.01
Quadratic	1	234.6	234	106.4	p<.01
Error	7	15.6	2 2		
Total	9	8 581.4			

TABLE 4.5

The general form of a quadratic regression equation is:

$$y = a + bx + cx^2$$

$$y = -8.36 + 0.373 \text{ Weight} - 0.000264 \text{ Weight}^2$$

The asymptotic equation which fits the data is:

$$y = a(1 - be^{-cx})$$

$a = \text{asymptote} = 158.883$ which means that the curve would flatten out at approximately 158 on the y axis.

$$y = 158.9 (1 - 1.09e^{-.003x}).$$

The quadratic equation derived from the data, as stated previously, provided the better fit when compared with the asymptotic form. The curve is seen to be 'turning over' and not 'flattening out'. This reflects observed behaviour in which, under heavier loads, i.e., from approximately 450g onwards, the spring helices demonstrated marked distortion. (See Figures 4.4 a and b.)

In comparison with HYDE'S (1988) re-worked data where loads of 90g approximately and 250g approximately corresponded with angular deflections of 35° and 70° respectively for the 0.012" 'Short' Spring, the same angular deflections in the 0.010" 'Mini-Spring' gave load values of 130g and 255g respectively. As expected, these values are much lower than those reported by SCOULER (1982).

MS COIL LOAD-DISTORTION EFFECT

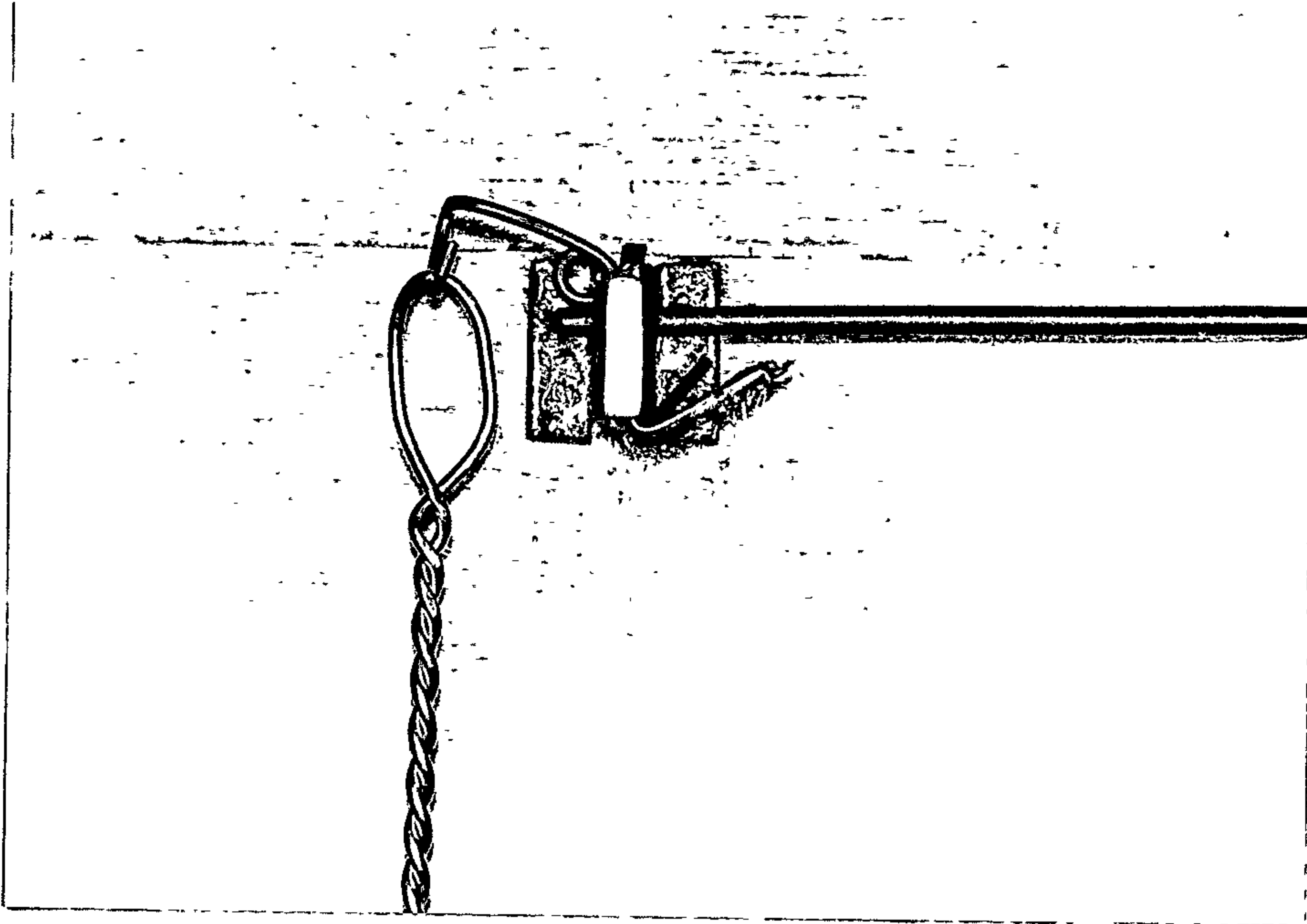


FIGURE 4.4a (150g load)

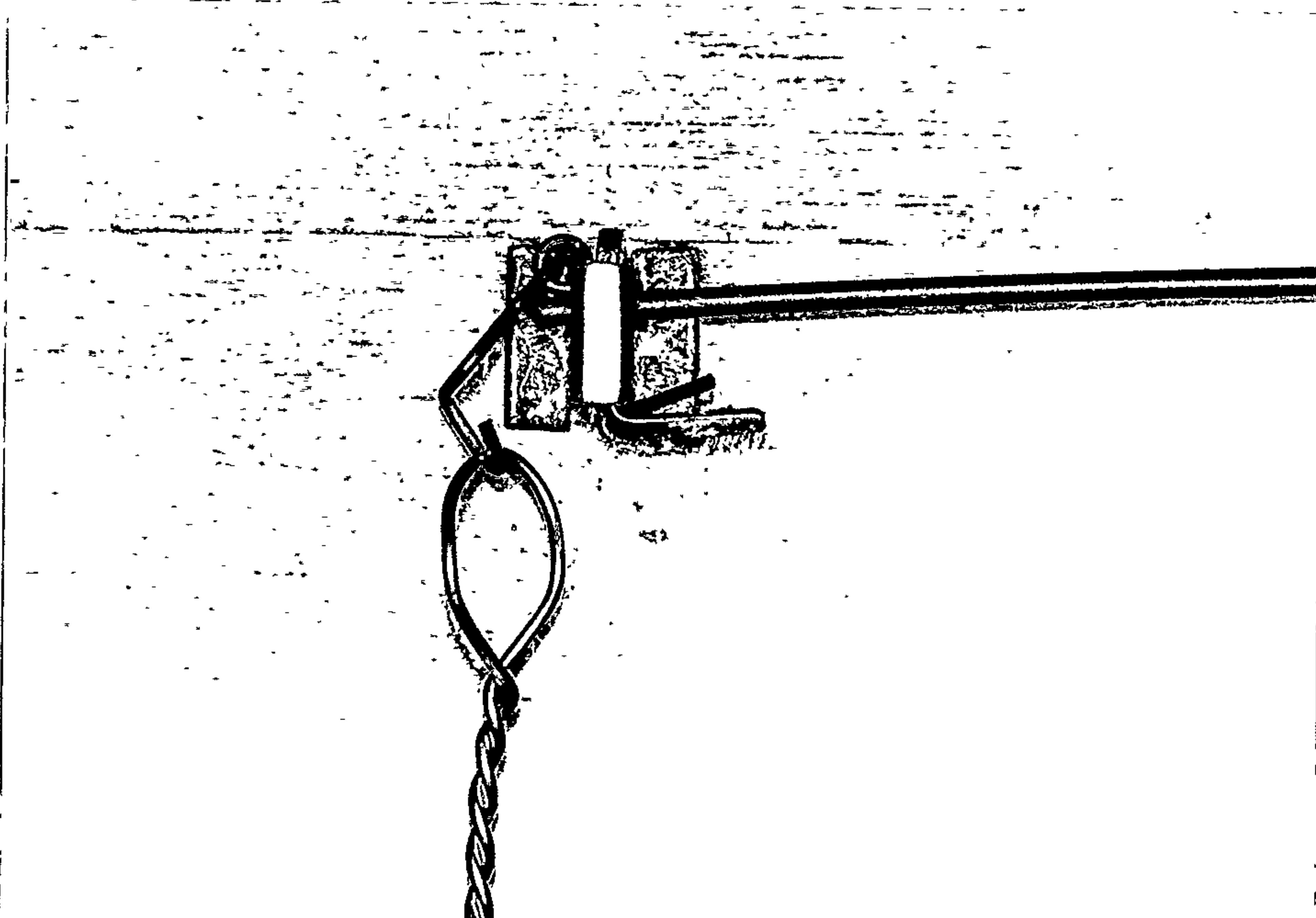


FIGURE 4.4b (550g load)

Part II - Stress Relaxation

The ANOVA by Least Squares method indicated no effect with respect to Position, but a highly significant effect with respect to Weight. Therefore, adopting the approach used in Part I, the analysis was repeated using a CRD (Table 4.6).

AFTER LOAD-BEFORE LOAD

CRD ANOVA

SOV	df	SS	MS	F	P
Weight	9	10 993.2	221.5	127.37	0.000
Error	40	383.6	9.6		
Total	49	11 376.7			

TABLE.4.6

When the means were plotted (Figure 4.5) against Weight a pronounced disjunction was evident and a 'line of best fit' could not be employed - reflecting the marked change in spring behaviour under extreme loads (vide infra).

STRESS RELAXATION (*'Spring Back'*)

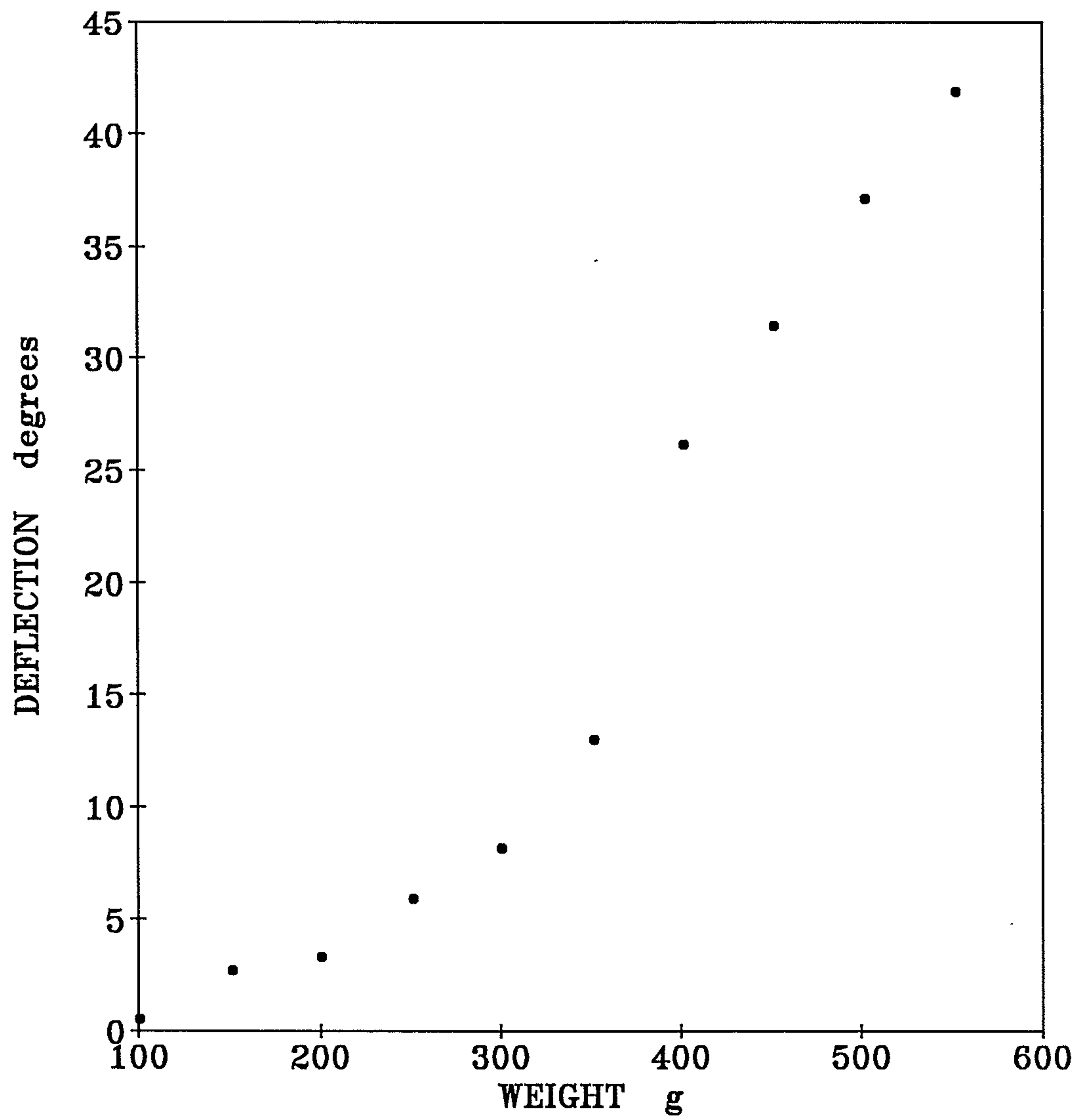


Figure 4.5

Least Significant Difference

The Weight means were compared using the least significant difference:

$$\begin{aligned}\text{LSD}_{5\%} &= t_{40} \times \text{Standard Error of the Difference of the Two Means} \\ &= 2.021 \times \frac{(2 \times 9.6)^{1/2}}{5} \\ &= 3.96 \\ &\text{(i.e., at 5\% level of confidence.)}\end{aligned}$$

Therefore, if the difference between two means is greater than 3.96, then those means are significantly different from each other (Table 4.7).

Weight(g)	After Load-Before Load Mean Angular Values
100.0	0.510 ^a
150.0	2.694 ^a
200.0	3.306 ^a
250.0	5.922 ^{ab}
300.0	8.170 ^b
350.0	12.992 ^c
400.0	26.160 ^d
450.0	31.440 ^e
500.0	37.148 ^f
550.0	41.888 ^g

TABLE 4.7

(In Table 4.7, the same superscript indicates a mean value which is not significantly different.)

The range of **elastic** spring behaviour occurs between 100g and 300g, which is demonstrated in the graph. At 350g spring performance is significantly different at the five per cent level from all preceding means, i.e., spring behaviour is **plastic**, and from 400g onwards there is a very marked plastic effect of Weight on spring performance (which is consistent with Part I).

With regard to angular deflection in the elastic load range, the 300g load value corresponded with an angular deflection value of approximately 80°, which is certainly an acceptable value when considering the degree of tip commonly encountered in incisors, at least.

When considered in the context of Experiment One it might also be reasonably concluded that a minimal stress relaxation effect might be expected over time in the range 0-300g load.

Conclusion

The conclusion may reasonably be drawn that a marked 'stress relaxation' effect does characterise MS performance in a load range which is relatively low when compared with the performance of 0.012", and greater, uprighting springs. The elastic load range is not, however, incompatible with optimal tooth movement, nor certainly with the degree of tooth tip encountered clinically.

Part III - Bending Moment

In Part I the analysis was based upon a direct examination of the effect of increasing load versus lever arm deflection. This was done to allow comparison with the work of SCOULER (1982) and HYDE (1988).

However, this approach is a little simplistic (BURSTONE and GOLDBERG-1983) inasmuch as it takes no cognizance of the precepts of curved bar theory which involves two components (TIMOSHENKO (Part II) - 1941):

- a. A couple in the plane tangent to the cylindrical surface of the radius R , which produces bending of the wire in that plane given by the expression: $M_b \cos \theta$; and
- b. a second component representing a couple acting in the axial plane of the spring: $M_b \sin \theta$, which can be resolved into **torque**: $M_b \sin \theta \cos \alpha$, and **bending moment** in the plane of the coil: $M_b \sin \theta \sin \alpha$.

Hence the element ds undergoes bending by a combined bending moment equal to $(M_b^2 \cos^2 \theta + M_b^2 \sin^2 \theta \sin^2 \alpha)^{1/2}$ and twist by a torque equal to $M_b \sin \theta \cos \alpha$.

TIMOSHENKO (ibid) also notes that, in considering bending of a helical spring by a lateral load not only must deflections produced by bending moment be taken into account, but also deflections produced by shearing force. He states, however, that this effect can be regarded as negligible if the radius R of the helix is small in comparison with the Length l .

However, WAHL (1949) has observed that with proper design, most torsion springs may be considered as subject to a pure bending moment about the axis of the coil. Therefore, the bending moment, M , is given by the expression:

	M	=	$P.R$ (Eqn 4.1)
where	P	=	(in grams or newtons)
	R	=	the radius of the lever arm (in millimetres)

Returning to TIMOSHENKO (ibid), the angle of deflection (in radians) must be taken into account. Therefore, combining the expression $M_b \cos \theta$ and Eqn 4.1 gives the expression:

Bending moment = $PR \cos \theta$ (Eqn 4.2)

in units of either newton-millimetres or gram-millimetres per radian.

Therefore, with this in mind, the experimental data were re-analysed using the bending moment formula, employing an analysis of variance as follows:

DURING LOAD-BEFORE LOAD. $R \cos \theta$

ANOVA						
SOV	df	SeqSS	AdjSS	AdjMS	F	P
Position	9	1 866 765	55 082	6 120	1.78	0.112
Weight	9	7 220 285	7 220 285	802 254	223.85	0.000
Error	31	160 351	106 351	3 431		
Total	49	9 193 401				

TABLE 4 8

This approach to examining uprighting spring behaviour and analysing experimental data is proposed as being more valid and more in keeping with current literature. It therefore provides a satisfactory basis for any future comparative study.

The preceding analyses of load-deflection characteristics (not stress relaxation) were performed in the manner of SCOULER (1982) and HYDE (1988) to provide a basis for comparison in the present work.

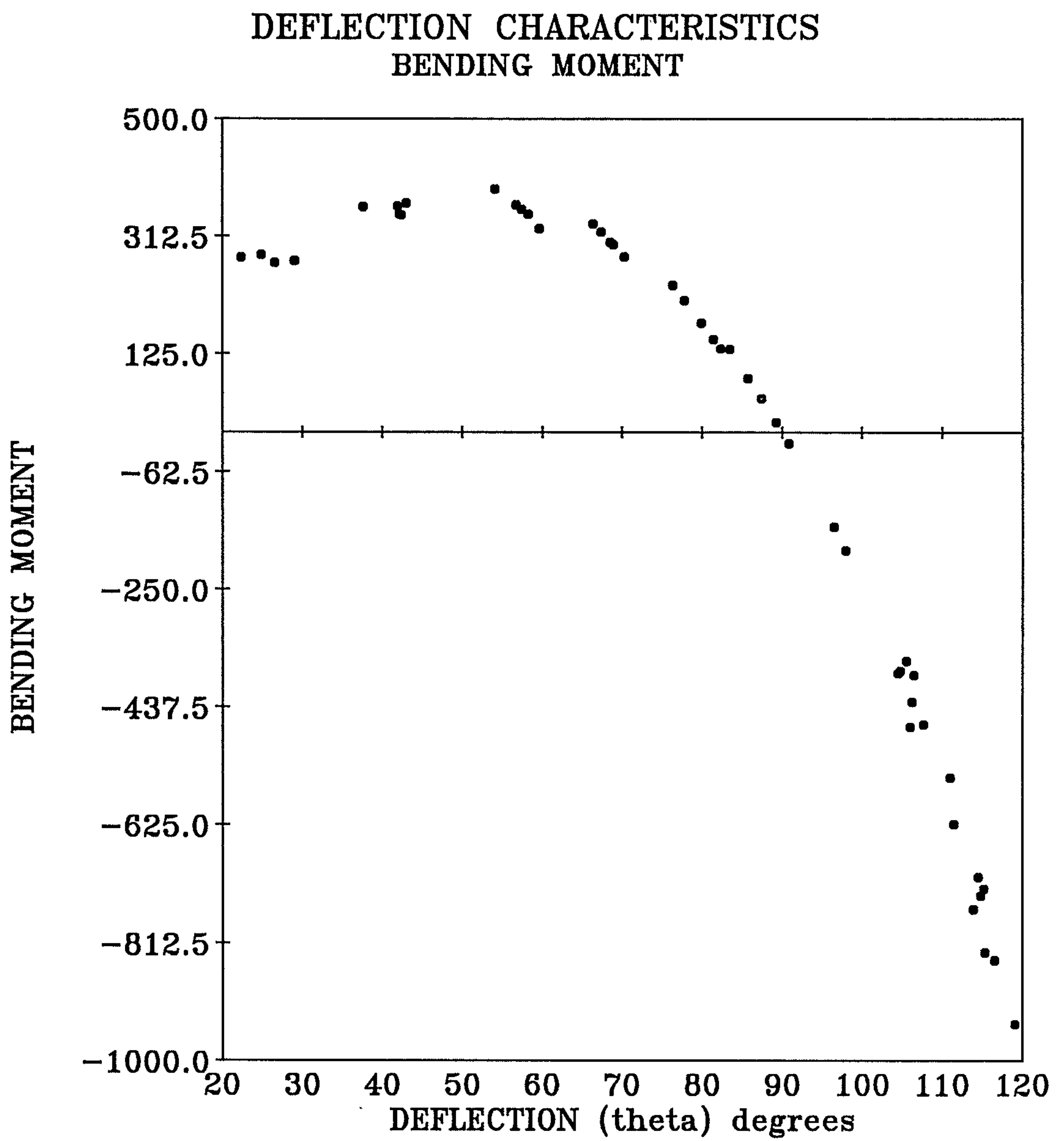


Figure 4.6

In Part II the observation was made that **elastic** MS performance occurred in the loading range 100g to 300g and that this corresponded with an angular deflection of approximately 80° . When bending moments are considered, then the same conclusions may be reached. Figure 4.6 shows the relationship from Eqⁿ 4.2 applied to the data from this experiment, clearly demonstrates that beyond a deflection of approximately 80° MS behaviour is subject to the complications of curved bar theory as alluded to earlier in the comments of TIMOSHENKO (ibid).

Conclusion

Optimal MS performance occurs up to an angular deflection value of approximately 80° .

SUMMARY AND CONCLUSIONS

Summary

The demonstration of significant departures in conventional uprighting spring design incorporated in the Begg 'Mini-Spring', including:

- a. Use of very fine (0.010") diameter, very high tensile ('Supreme'-grade) wire;
- b. Very small size (the resultant of 'a'); and
- c. tangential stem or 'leg' disposition,

invited experimental investigation.

Areas of study included *in vitro* investigation of load-deflection characteristics including stress-relaxation to allow comparison with other elements of the Begg uprighting spring armamentarium.

A review of previous uprighting spring studies conducted in The University of Sydney revealed flaws both in their execution and statistical analysis. Comparisons with the 'Mini-Spring' were therefore rendered difficult and re-examination of those uprighting springs studied, other than the 'Mini-Spring', is indicated.

Notwithstanding comparative difficulties, the 'Mini-Spring' demonstrated:

- a. No stress relaxation effects over varying time periods ranging from one minute to one month at the loads used, i.e., in the **elastic** loading range. It may reasonably be expected, therefore, to deliver a constant load over time within the **elastic** loading range; and
- b. load-deflection characteristics (load-delivery and stress relaxation) compatible with the range of load values proposed as optimal for root uprighting.

Conclusions

The Begg 0.010" ('Supreme') 'Mini-Spring' demonstrated:

- a. No stress-relaxation effects, when loaded elastically, over a period of a month; and
- b. satisfactory load-deflection characteristics (load-delivery values and stress relaxation effects) consonant with proposed optimal performance levels.

When the foregoing is combined with reported clinical advantages of (in ascending order) improved aesthetics; ease of placement (use of lock-pins instead of ligation); and facilitation of oral hygiene regimes (through its very small size) there is reasonable support for the contention that, for the present at least, the 0.010" 'Mini-Spring' represents the acme of the Begg uprighting spring armamentarium.

FURTHER RESEARCH

In view of the design and analysis anomalies demonstrated in previous uprighting spring investigations in The University of Sydney there is scope for review studies of a variety of Begg uprighting springs, including long-term stress-relaxation effects.

A further avenue of study might also include theoretical modelling of expected load-delivery characteristics.

A natural extension to the preceding *in vitro* suggested study areas is *in vivo* studies, the work of WEEKES (1987) being an excellent model.

BIBLIOGRAPHY

- Abel, A., *Historical Perspective and Some of the Main Features of the Bauchinger Effect*, Materials Forum 10:1; 11 - 26 1987.
- Alexander, W. and Street, A., *Metals in the Service of Man*, Hammondsworth, Middlesex, Penguin Books Ltd., 5th ed. 1972.
- Barbieri, A.E. and Barbieri, F.R., *Begg Auxiliaries*, Journal of Clinical Orthodontics, 6:3; 133 - 156 (Mar) 1972.
- Barrer, H., *A Survey of Begg Treatment*, American Journal of Orthodontics 49:7; 494 - 506 (Jul) 1963.
- Begg, P.R., *Stone Age Man's Dentition*, 40:7; 517 - 531 (Jul) 1954.
- Begg, P.R., *Differential Force in Orthodontic Treatment*, American Journal of Orthodontics, 42:7; 481 - 510 (Jul) 1956
- Begg, P.R., *Light Arch Wire Technique Employing the Principles of Differential Force*, American Journal of Orthodontics, 47:1; 30 - 48 (Jan) 1961.
- Begg, P.R., *Begg Orthodontic Theory and Technique*, Philadelphia, W.B. Saunders Company, 1st ed. 1965.
- Begg, P.R. and Kesling, P.C., *Begg Orthodontic Theory and Technique*, Philadelphia, W.B. Saunders Company, 2nd ed. 1971.
- Begg, P.R. and Kesling, P.C., *The Differential Force Method of Orthodontic Treatment*, American Journal of Orthodontics, 71:1; 1 - 39 (Jan) 1977a.
- Begg, P.R. and Kesling, P.C., *Begg Orthodontic Theory and Technique*, Philadelphia, W.B. Saunders Company, 3rd ed. 1977b.
- Brandt, S., *Experiences with the Begg Technique*, Angle Orthodontist 32:3; 150 - 166 (Jul) 1962.

- Brown, G. G., and Watson, J.D., *The Tensile Properties of Pre-torsioned Steel Bars*, Metals Forum 5:4; 195 - 209, 1982.
- Burstone, C.J.; Baldwin, J.J. and Lawless, D.T., *The Application of Continuous Forces to Orthodontics*, Angle Orthodontist 31:1; 1 - 14 (Jan) 1961.
- Burstone, C.J. and Goldberg, A.J., *Maximum Forces and Deflections from Orthodontic Appliances*, American Journal of Orthodontics, 84:2, 95 - 103 (Aug) 1983.
- Cadman, G.R., *A Vade Mecum for the Begg Technique: Technical Principles*, American Journal of Orthodontics, 67:5; 477 - 512 (May) 1975a.
- Cadman, G.R., *A Vade Mecum for the Begg Technique: Treatment Procedures*, 67:6; 601 - 624 (Jun) 1975b.
- Colombier, L. and Hochmann, J., *Stainless and Heat Resisting Steels*, Edward Arnold (Publishers) Ltd., London, 1st ed. 1967.
- Cooper, S.M. and Sims, M.R., *Evidence of Acute Inflammation in the Periodontal Ligament Subsequent to Orthodontic Tooth Movement in Rats*, Australian Orthodontic Journal, 11:2; 107 - 109 (Oct) 1989.
- Dawes, Burton E., *Dental Arch Crowding in Prehistoric Man, and in Indigenous Racial Groups of North America and Australia*, MDS thesis, Sydney; The University of Sydney 1986.
- Dieter, G.E., *Mechanical Metallurgy*, New York, McGraw-Hill Book Company, 3rd ed. 1986.
- Fischer, G.J. and Maciag, R.J., *The Wrought Stainless Steels* in: Donald Peckner's and I.M. Bernstein's *Handbook of Stainless Steels*, New York, McGraw-Hill Book Company, 1st ed. 1977.
- Gullotta, A., West, V.C., and Hazel, R.J., *The Bauschinger Effect in Stainless Steel Orthodontic Wires*, Australian Orthodontic Journal, 10:2; 110 - 113 (Oct) 1987.

- Hazel, R.J., Rohan, G.J. and West, V.C., *Force Relaxation in Orthodontic Arch - Wires*, American Journal of Orthodontics, 86:5; 396 - 402 (Nov) 1984.
- Hazel, R.J. and West, V.C., *The Importance of Mechanical Behaviour in Orthodontic Archwires*, Australian Orthodontic Journal, 9:4; 317 - 320, (Oct) 1986.
- Hocevar, R.A., *Orthodontic Force Systems: Technical Refinements for Increased Efficiency*, American Journal of Orthodontics, 81:1; 1 - 11 (Jan) 1982a.
- Hocevar, R.A., *Orthodontic Force Systems: Individualized Treatment with Open-minded "Begg" Technique*, American Journal of Orthodontics, 81:4; 277 - 291 (Apr) 1982b.
- Hocevar, R.A., *Begg-Edgewise Diagnosis-Determined Totally Individualised Orthodontic Technique: Foundations, Description and Rationale*, American Journal of Orthodontics, 88:1; 31 - 46 (Jul) 1985.
- Honeycombe, R.W.K., *Steels - Microstructure and Properties*, London, Edward Arnold (Publishers) Ltd., 1st ed. 1981.
- Hyde, Michael T., *'Force-Deflection Characteristics of 0.012" and 0.014" Premium Plus Begg Uprighting Springs'*, MDSc thesis. Sydney: The University of Sydney, 1988.
- Ingram, S.B., Gipe, D.P. and Smith, R.J., *Comparative Range of Orthodontic Wires*, American Journal of Orthodontics and Dentofacial Orthopedics, 90: 296 - 307 1986
- Lebsack, D.M., Weimer, A.D. and Hanna, M., *A Study of Force Decay in Uprighting Springs Used in the Begg Technique*, Australian Orthodontic Journal, 6:3, 95 - 101 (Feb) 1980.
- Lee, K.P., *Improving the "Brakes" for the Begg Technique*, Journal of Clinical Orthodontics, 15:3, 124 - 127 (Mar) 1981.
- Marshall, P., *Austenitic Stainless Steels - Microstructure and Mechanical Properties*, London, Elsevier Applied Science Publishers, 1st ed. 1984.

Marx, R., *BJO Interview Richard Marx - Begg Appliance Treatment*, British Journal of Orthodontics, 16:1, 53 - 57 (Feb) 1989.

Mollenhauer, B., *New Approaches to the Begg Technique Part I - Qualitative Aspects*, Australian Orthodontic Journal, 10:2, 67 - 89 (Oct) 1987.

Mollenhauer, B., *Updates of Original Articles*, Australian Orthodontic Journal, 11:1, 55 (Mar) 1989.

Mollenhauer, B., *Personal Communication*, 1990a.

Mollenhauer, B., *Editorial*, Australian Begg Orthodontics Newsletter, 4 - 5 (Jul) 1990b.

Oono, T. and Machida, M., *Uprighting of Cuspids and Bicuspids in Stage III*, The Journal of Japan Orthodontic Society, 27:2, 319, (Dec) 1968.

Perlow, J., *A Critique of the Begg Technique from the Standpoint of Biomechanics*, American Journal of Orthodontics, 54:6, 407 - 431, (Jun) 1968.

Proffit, W.R., *Contemporary Orthodontics*, St. Louis, The C.V. Mosby Company, 1st ed., 1986.

Ramos, D.F., Weimer, A. D. and Hanna, M., *A Study of the Forces Produced by Various Preformed Uprighting Springs*, American Journal of Orthodontics, 76:6, 637 - 645 (Dec) 1979.

Roberts, J.A., *Spring Design and Calculations*, Redditch, Technical Research Laboratory, Herbert Terry and Sons Limited, 7th ed. 1954.

Scouler, Peter D., *'Some Observations Pertaining to the Activation of Spring-Pins.'* MDSc thesis. Sydney: The University of Sydney 1982.

Shigley, J.E. and Mischke, C.R., *Mechanical Engineering Design*, New York, McGraw-Hill Book Company, 5th ed. 1989.

Sims, M.R., *The Begg Philosophy and Fundamental Principles*, American Journal of Orthodontics, 50:1, 15 - 24 (Jan) 1964.

- Strang, R.H.W., *The Value of a Precision Technique*, American Journal of Orthodontics, 50: , 113 - 124 (Feb) 1964.
- Swain, B.F. and Ackerman, J.L., *An Evaluation of the Begg Technique*, 55:6, 668 - 87 (Jun) 1969.
- Thurrow, R.C., *Edgewise Orthodontics*, St. Louis, The C.V. Mosby Company, 4th ed. 1982.
- Timoshenko, S., *Strength of Materials, Part II, Advanced Theory and Problems*, New York, D. Van Nostrand Company, Inc., 2nd ed. 1941.
- Twelftree, C.C., Cocks, G.J. and Sims, M.R., *Tensile Properties of Orthodontic Wire*, American Journal of Orthodontics, 72:6, 682 - 687 (Dec) 1977.
- Wahl, A.M., *Mechanical Springs*, Cleveland, Penton Publishing Company, 1st ed. 1944.
- Weekes, W., *Differential Force Concept - Myth or Moment?* Abstract, Australian Orthodontic Journal, 10:2, 136 (Oct) 1987.
- Wilcock, A.J. Jr., *JCO Interview: Arthur J. Wilcock, Jr., on Orthodontic Wires*, Journal of Clinical Orthodontics, 22:8, 484 - 489 (Aug) 1988.
- Wilcock, A.J. Jr., *Applied Materials Engineering for Orthodontic Wires*, Australian Orthodontic Journal, 11:1, 22 - 29 (Mar) 1989.
- Wilcock, A.J. Jr., *Personal Communication* 1990.
- Wilson, G.G., *Force Relaxation in Matched Light Titanium and Stainless Steel Wires*, Abstract, American Journal of Orthodontics, 88:3, 268 (Sep) 1985.

APPENDIX 1.

POSITION	WEIGHT ± 0.01g	TIME (days)	ANGULAR DEFLECTION (degrees) before load	ANGULAR DEFLECTION (degrees) after load
1	50.49	0.0007	16.45	19.40
1	100.47	0.0400	26.92	25.62
1	50.49	7.0000	21.92	23.33
1	100.47	1.0000	22.77	25.02
2	50.78	0.0210	22.72	26.07
2	100.48	0.0007	22.82	22.15
2	50.78	21.0000	24.80	25.23
2	100.48	14.0000	24.52	25.37
3	51.44	14.0000	28.48	30.30
3	99.95	1.0000	29.53	27.00
3	51.44	0.5000	24.63	24.17
3	99.95	0.0400	16.27	17.03
4	50.62	21.0000	27.48	26.72
4	100.32	7.0000	15.93	17.52
4	50.62	0.0007	22.35	20.98
4	100.32	0.5000	15.73	20.08
5	50.73	1.0000	22.28	24.87
5	99.85	21.0000	20.92	20.67
5	50.73	0.0210	23.83	20.08
5	99.85	0.0110	27.62	25.12
6	51.03	7.0000	23.42	23.92
6	100.64	28.0000	17.23	21.63
6	51.03	0.0400	20.00	23.23
6	100.64	0.0210	26.17	28.00
7	50.77	0.0400	26.75	25.83
7	100.39	0.0110	19.87	19.10
7	50.77	28.0000	24.87	26.75
7	100.39	21.0000	26.83	28.68
8	50.86	28.0000	25.75	26.97
8	100.46	14.0000	26.58	28.42
8	50.86	0.0110	13.67	16.35
8	100.46	0.0007	19.40	21.38
9	50.94	0.5000	22.00	25.37
9	100.43	0.0210	23.05	22.83
9	50.94	1.0000	8.32	7.03
9	100.43	28.0000	26.42	26.25
10	50.88	0.0110	26.13	27.10
10	100.77	0.5000	20.98	21.75
10	50.88	14.0000	19.57	23.18
10	100.77	7.0000	26.20	26.70

APPENDIX 2.

WEIGHT ±0.01gms	LENGTH mm	ANGULAR DEFLECTION (degrees)			THETA (degrees)	BENDING MOMENT
		before load	during load	after load		
151.2	3.0	16.75	54.40	19.73	37.65	359.14
452.1	3.4	18.17	129.13	52.00	110.96	-549.81
251.5	3.3	24.53	93.43	31.62	68.90	298.80
352.2	3.4	25.73	113.17	41.63	87.44	53.52
502.1	3.4	23.58	135.00	59.15	111.42	-623.40
552.6	3.4	22.37	138.90	61.98	116.53	-839.16
100.5	3.0	19.42	46.00	20.32	26.58	269.64
200.3	3.2	22.87	82.50	28.80	59.63	324.07
300.7	3.3	17.58	99.90	26.40	82.32	132.64
402.1	3.4	17.70	124.15	51.63	106.45	-387.10
552.6	3.4	21.52	138.03	65.02	116.51	-838.57
452.1	3.4	22.78	129.00	55.63	106.22	-429.32
402.1	3.4	24.62	122.52	49.22	97.90	-187.87
251.5	3.3	21.62	270.58	27.20	68.57	303.25
502.1	3.5	18.80	133.60	60.10	114.80	-737.07
100.5	3.1	21.20	50.20	22.37	29.00	272.49
300.7	3.3	22.92	100.72	29.77	77.80	209.72
200.3	3.3	20.40	77.88	24.27	57.48	355.35
352.2	3.3	24.07	109.85	35.92	85.78	85.56
151.2	3.1	20.05	62.25	22.20	42.20	347.23
300.7	3.3	16.18	97.62	29.33	81.44	147.72
100.5	3.1	17.62	46.70	18.58	29.08	272.28
452.1	3.3	19.70	124.43	48.73	104.73	-379.30
151.2	3.2	27.88	69.83	29.67	41.95	359.85
552.6	3.4	20.43	134.25	60.00	113.82	-758.74
402.1	3.3	23.27	119.73	41.38	96.46	-149.26
200.3	3.3	28.07	86.33	28.50	58.26	347.73
352.2	3.3	22.13	113.00	35.95	90.87	-17.62
502.1	3.4	18.73	133.23	53.37	114.50	-707.89
251.5	3.3	18.23	88.53	25.58	70.30	279.79
352.2	3.3	25.62	109.12	34.88	83.50	131.60
452.1	3.4	19.00	126.62	49.73	107.62	-465.25
251.5	3.3	24.78	91.22	28.43	66.44	331.75
502.1	3.4	17.92	133.10	61.00	115.18	-726.27
100.5	3.0	15.55	37.93	15.10	22.38	278.79
402.1	3.4	25.40	123.28	50.27	97.88	-187.39
151.2	3.3	26.88	69.95	30.10	43.07	364.51
552.6	3.5	19.97	139.08	66.40	119.11	-940.86
300.7	3.3	25.13	101.48	29.50	76.35	234.20
200.3	3.3	24.95	81.70	27.32	56.75	362.43
452.1	3.4	24.47	128.92	55.23	104.45	-383.53
151.2	3.1	20.47	62.87	23.80	42.40	346.13
300.7	3.3	24.22	104.13	31.88	79.91	173.87
200.3	3.3	23.85	78.00	27.78	54.15	387.13
552.6	3.5	26.42	141.73	66.75	115.31	-826.80
251.5	3.3	23.48	90.88	29.42	67.40	318.96
502.1	3.4	28.88	134.82	60.03	105.94	-468.78
352.2	3.3	22.87	112.10	37.00	89.23	15.65
402.1	3.4	18.23	123.70	47.52	105.47	-364.62
100.5	3.1	24.00	48.87	23.97	24.87	282.66