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A STATISTICAL ASSESSMENT OF BRILLIANCE AND FIRE FOR POLISHED GEM DIAMOND ON THE BASIS OF GEOMETRICAL OPTICS

Thesis submitted for the degree of
Doctor of Philosophy
of the University of London

by

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October 1978

ABSTRACT

The polished gem diamond is valued for its colourful optical display. This scattering effect is usually considered to be a combination of three properties; brilliance (the percentage of light that incident on the stone is then scattered out of the crown facets), sparkliness (a measure of the intensity fluctuations in this scattered light) and fire (a measure of the colour difference between the sparkles).

The fifty-eight facet Round Brilliant Cut Diamond is considered as a random scatter of incident light. The diamond as a rotationally symmetric style, is considered to be spinning and surrounded by a hypothetical sphere, and the brilliance, sparkliness and fire are identified with statistical properties of the intensity distribution produced on the sphere. Using a computer model with finite ray tracing methods, the effects on these statistical measures of changing the pavilion half length, the table spread and the crown height are investigated. The results confirm the traditional round brilliant proportions as satisfactory and also go some way to reconciling the many 'ideal' cuts by emphasing the trade-off between maximising brilliance, sparkliness or fire. A new set of proportions is proposed and is shown to be superior to the traditional styles using these statistical measures.

The simplifications and modifications of the Round Brilliant Cut Diamond are also discussed and shown to fall into two families of styles based on 4 fold and 3 fold rotational symmetry and four main derivative classes. Simple trends in the measure of optical goodness are found, the principal conclusion being that stones with eight or more crown and pavilion facets are acceptable but inferior substitutes for the 58 facet

Round Brilliant Cut Diamond, especially for stones of less than 20 points.

The optical goodness of several diamond simulants are also discussed with emphasis on the modern crystals; Strontium titanate, Zirconium Oxide with Cubic structure, Gadolinium Galium Garnet and Yttrium Aluminium Garnet. Strontium titanate is shown to be more attractive than diamond using the statistical measures and in addition the optical goodness is demonstrated to be roughly proportional to the refractive index of the material.

Finally a diamond grading engine is described. The results obtained from the device are compared with those of the computer simulation.

Acknowledgements

I would like to express my thanks to Professor Walter Welford for both his benevolent supervision of this project and with Professor Charles Wynne, for 'the free and learned society' of the coherent optics and optical design groups which I have shared for the past two years. The prevailing group attitude of mutual help and assistance make lists of thanks invidious. However, I am particularly grateful to Mr. Paul Jarvis and Mrs. Prudence Wormell for help with computing, Dr. Tim Williams for assistance with electronics and Mr. Fred Reavell for many useful discussions on the mechanical design of complete optical systems.

I am indebted to the Executive Committee of the Diamond Trading Company (Pty) Ltd. for their generous financial support of this project. Also I would like to thank several of their staff for assistance, Mr. Richard Butler for encouragement and for servicing the secular needs of the project, Mr. Paul Geen ard for teaching me how to 'look at' rough and Mr. Gillpatric Devlin for his interest, useful discussions and organizing the selection and visual grading of the stones in Chapter VI.

Especial thanks for her endurance and support are due to my wife Hilary who not only translated the rough drafts into English but also typed this thesis. Also to Rowena our daughter for sleeping since February from 6.45pm until 7.0 am.

Contents

Brutting: the process of making a stone round by turning it on a lathe against another diamond.

Carat: 1 carat = 200 mg.

Crown: the region formed by the table, kite, star and top half facets, Fig. 4.3, p. 77.

Culet, Collet: the point formed by the eight pavilion main facets, Fig. 2.3, p. 40.

Cut: a particular shape for polishing a diomond, e.g. round brilliant, pear shape.

Dop: a mechanical device for holding a diamond while the facets are ground onto the stone.

GIA: The Gemmological Institute of America.

Girdle: the region between the crown and pavilion, Fig. 2.3, p. 40.

Kite Facet: a crown facet, Fig. 2.3, p. 40.

Maccel: a twin octahedral crystal.

Model: a piece of rough diamond before it is polished.

Paste: a glass diamond simulant.

Pavilion: the region formed by the pavilion main and half facets, Fig. 4.3, p. 77.

Pavilion half facet: see Fig. 2.3, p. 40.

Pavilion half factor: the fraction by which the pavilion half facets extend to the culet from the girdle.

Pavilion main facet: see Fig. 2.3, p. 40.

Point: 1 point = 2 mg = .01 carats.

Scan.D.N.: the Scandinavian Diamond nomenclature, a system for grading polished gem diamond.

Simulant (for diamond): a material used to imitate diamond.

Star facet: a minor crown facet, Fig. 2.3, p. 40.

Style: see cut.

Table facet: the major crown facet, Fig. 2.3, p. 40.

Top half facet: a crown facet, Fig. 2.3, p. 40.

Chapter I

Historical Survey

1.1 Early history

Diamond has been treasured in Europe since the time of Alexander the Great and a regular trade between the Orient and Levant centred on Alexandria was in existence by 300 B.C. By 900 A.D. Venice was a major centre and the European polishing centres based in Ghent and Bruges were established from this centre by the 12th - 13th century. These migrated towards Antwerpen and with the Spanish Fury in 1585 many of the polishers fled to Amsterdam. The 14th century also saw the growth of a centre in Nuremburg. Paris flourished as a centre from the 12th century as the Dukes of Burgundy were traditionally the Lords of Flanders and hence encompassed Bruges, Paris and Ghent.

Let us now trace the development of the round brilliant cut following closely the findings of H. Tillander (1965). A glossary of essential jargon is contained in the Gemmological Institute of America (G. I. A.) Gem Dictionary and the G. I. A. Diamond Dictionary.

1.2 Development of the round brilliant cut up to 20th century

The original gem diamonds were simply perfect octahedra (Fig. 1.1). As many octahedra are found with damaged points it is thought that this stimulated the early diamond workers to 'repair' stones by polishing the broken point into a facet, resulting in the 4-cut stone (Fig. 1.2).

The next major development was an 8-cut stone (Fig. 1.3) thought by Tillander to have become common practice in the 16th century. This was quickly developed into the

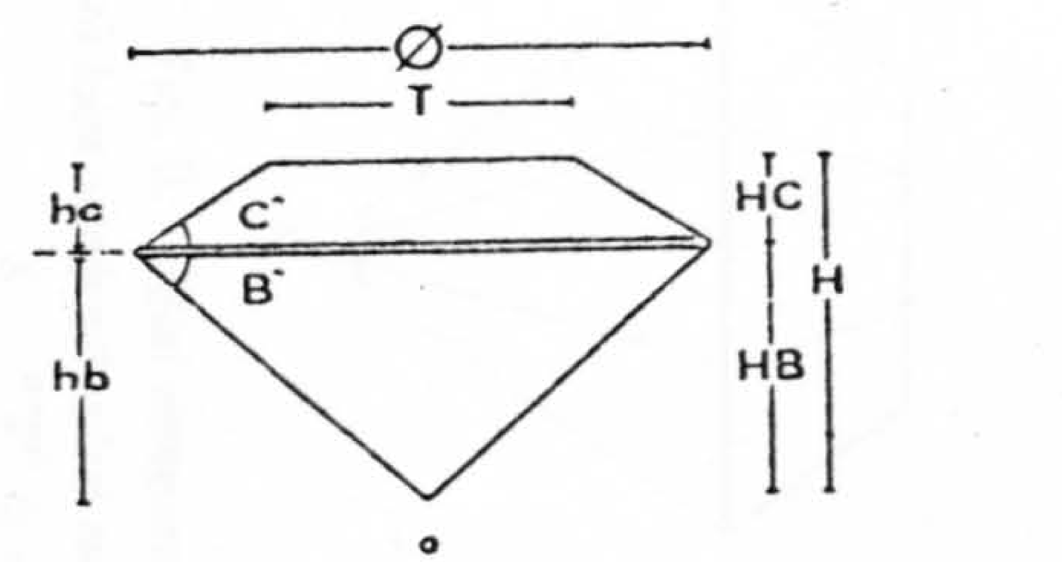


FIG. 4. *Abbreviations and signs used in proportion analyses.*

Ø	*Diameter of stone (usually the shortest)*
T	*Table size (in brilliant-cuts between opposite corners, but in certain other shapes between opposite sides)*
o	*Culet size (measured as the table size)*
hc	*Height of crown x)*
- - -	*Average girdle thickness*
hb	*Height of base (= depth of pavilion) x)*
H	*Total height (from table to culet)*
C^	*Crown angle*
B^	*Base angle (= pavilion angle)*
x)	*without girdle thickness*

Fig. 1.1a. The key to Figs. 1.1-1.11 after Tillander (1965).

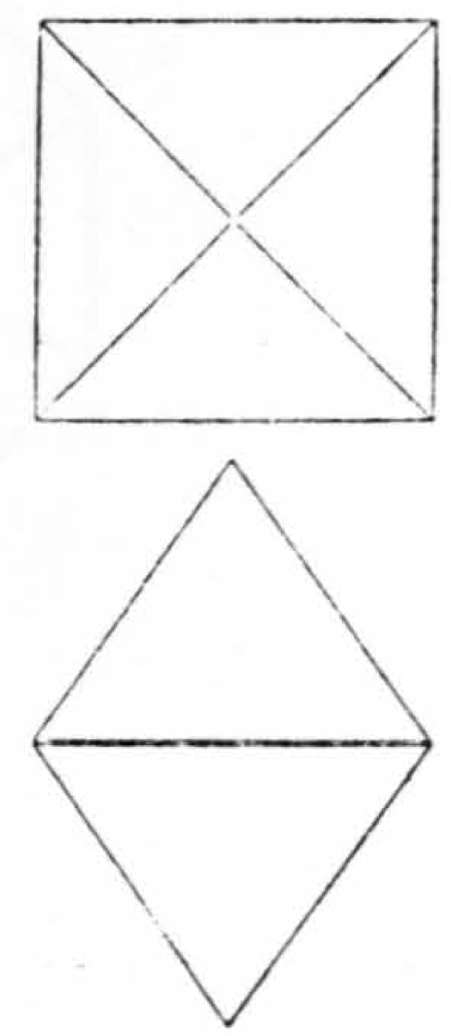


FIG. 5. *The perfect "diamond-point" (4/4)*

hc 70,75% C^ 54°44'8,3"
- - - 1,00%
hb 70,75% B^ 54°44'8,3"
H 142,50%

(With a girdle thickness of 1% the "diamond-point" has a Ø of 99,6% compared with the width of the perfect octahedron. For this reason the depth figures differ from the measures of a crystal without "girdle").

Fig. 1.1b. The proportions of the perfect octahedron, after Tillander (1965).

FIG. 6. *Natural diamond crystals resembling table-cuts. (From "Der Diamant" by Fersman u. Goldschmidt)*

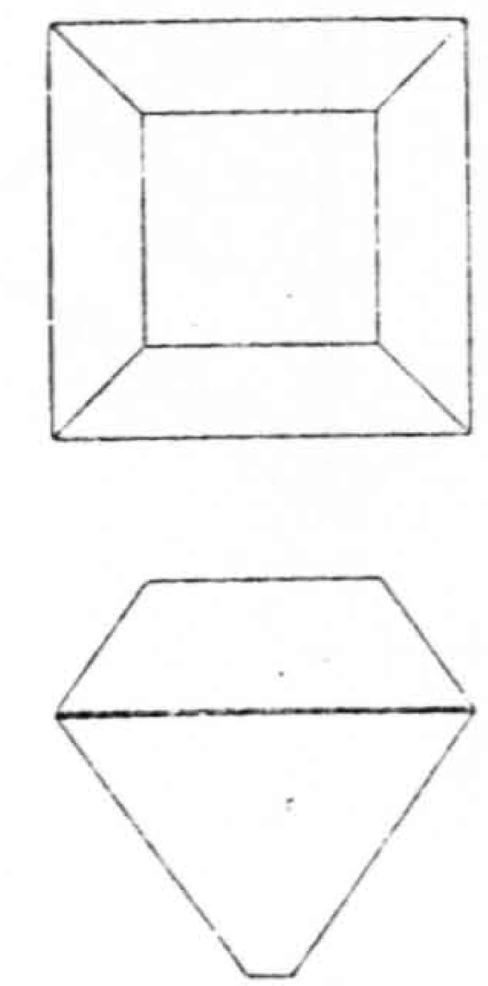


FIG. 7. *The ideal full-bodied square table-cut (4/4)*

T 56,0% *(measured between opposite sides)*
o 11,0% *(square in shape)*
hc 31,2% C^ 54°44' 8,3"
- - - 1,0%
hb 62,8% B^ 54°44' 8,3"
H 95,0%

Fig. 1.2. The 4 cut style after Tillander (1965)

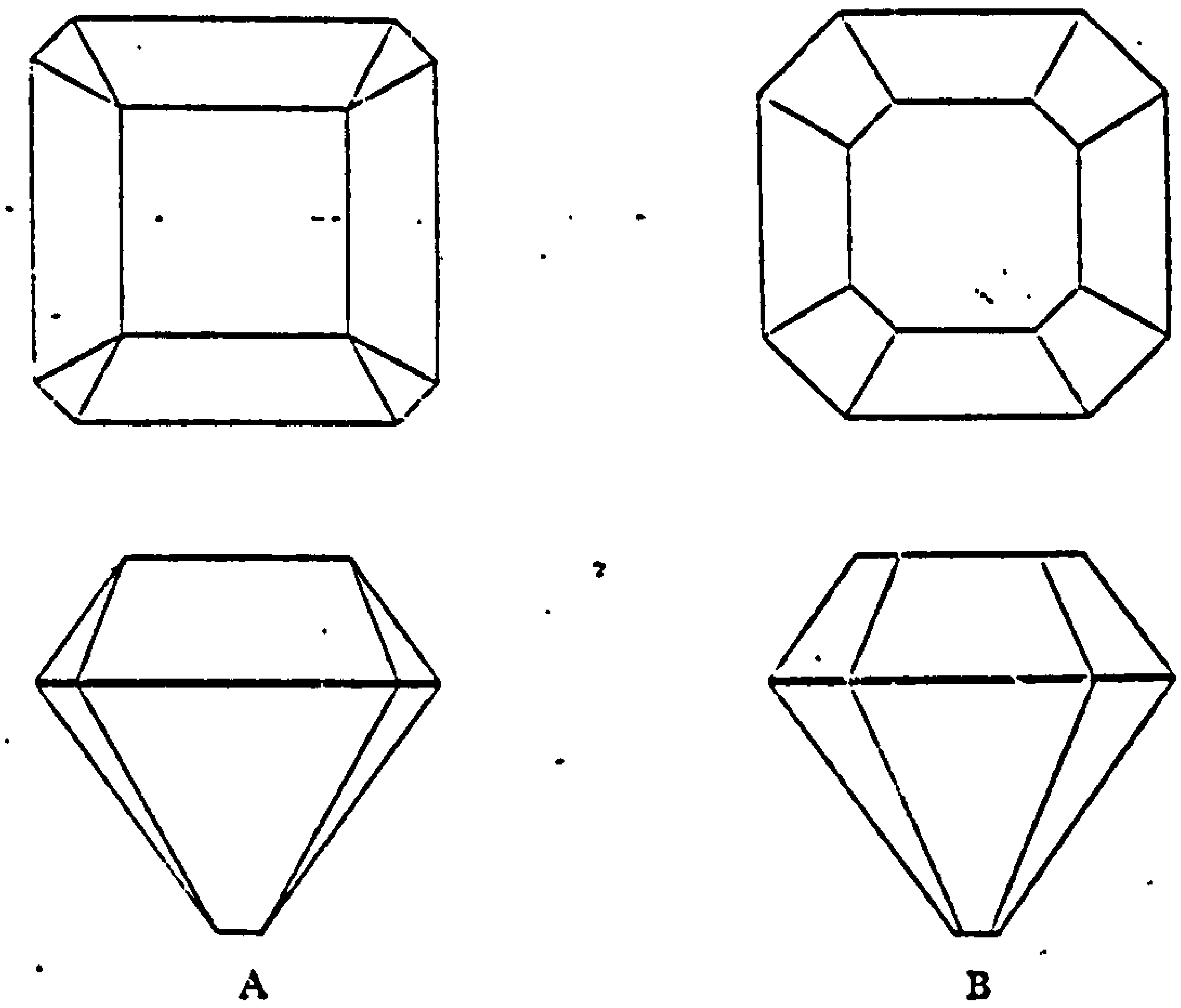


FIG. 8. *Ideal full-bodied octagonal table-cuts* (8/8).

A. *The first step towards the proper single-cut with a square culet and the table size measured between opposite sides. Length of outer edge of main facets is* 80% *of Ø.*

B *A shape, which persisted in mêlée sizes, with an octagonal culet and the table size measured between opposite sides. Length of outer edge of main facets is* 60% *of Ø.*

(*The proportions are equal to those listed under Fig. 7*)

Fig. 1.3 The early eight-cuts, after Tillander (1965)

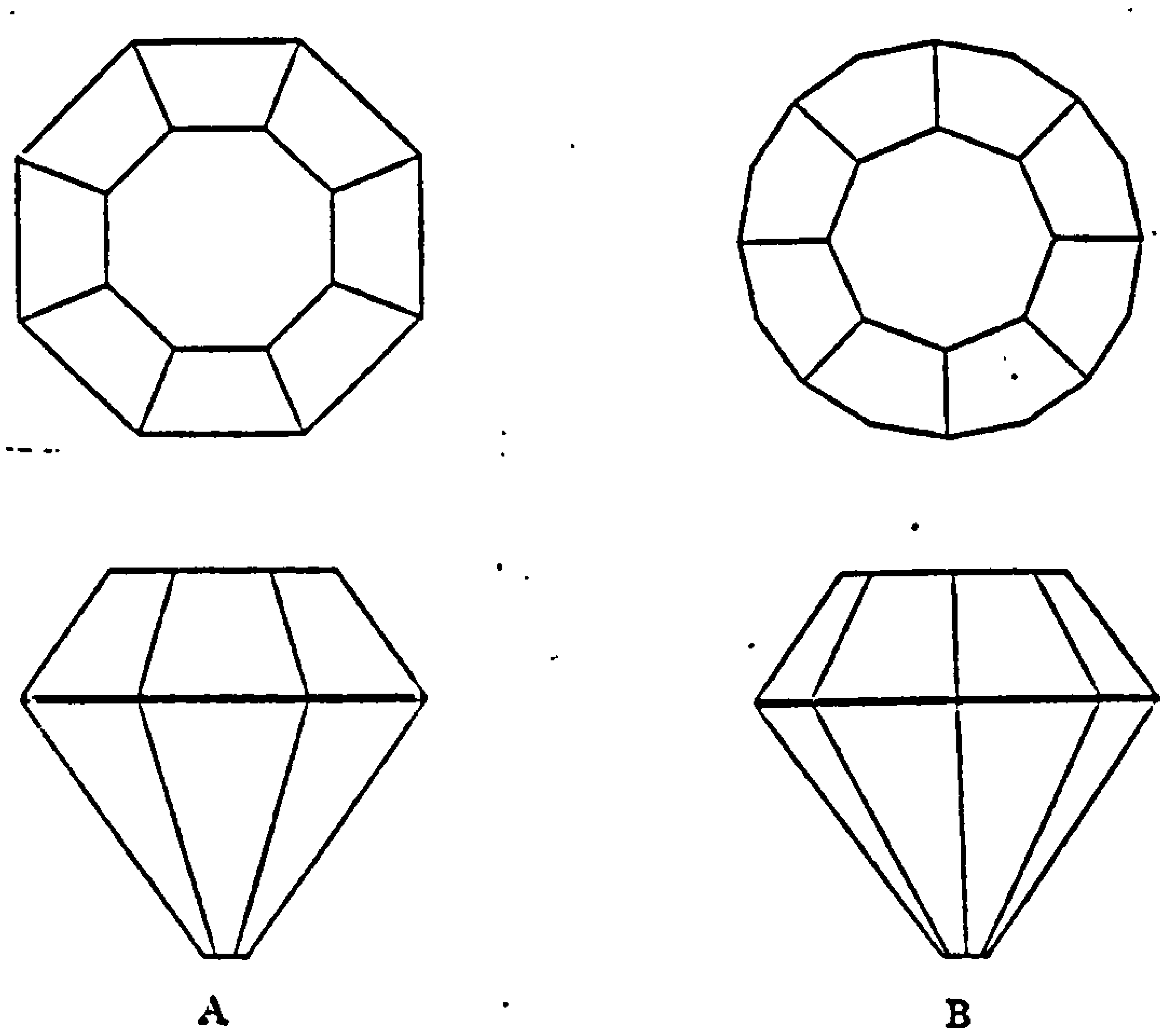
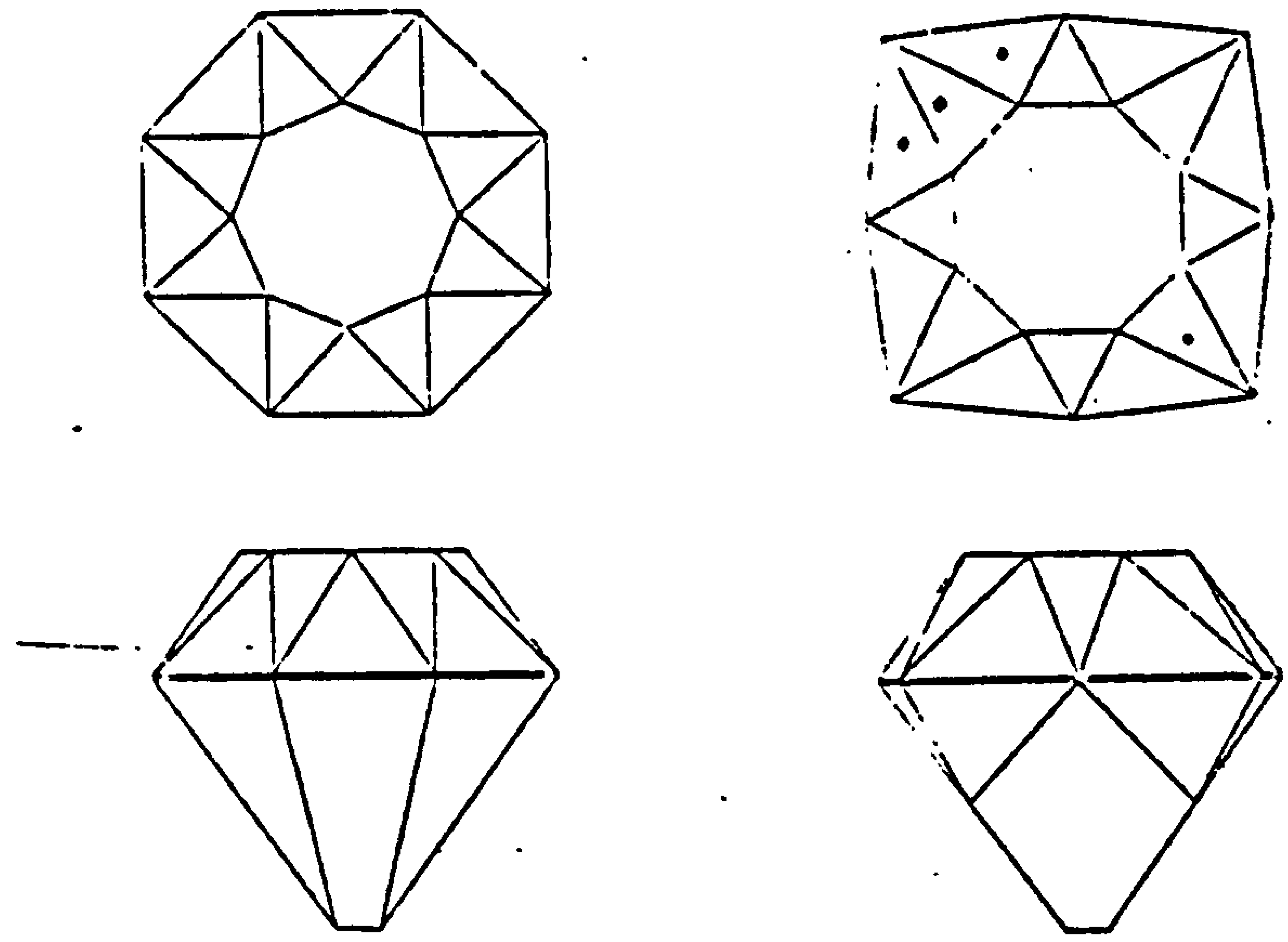


FIG. 9. *Ideal octagonal and rounded full-bodied single-cuts* (8/8)
Both have octagonal culets and proportions equal to those listed under Fig. 7.
A "T" *is measured between opposite sides*
B "T" *is measured between opposite corners*

Fig. 1.4 The rounder eight-cuts, after Tillander (1965).



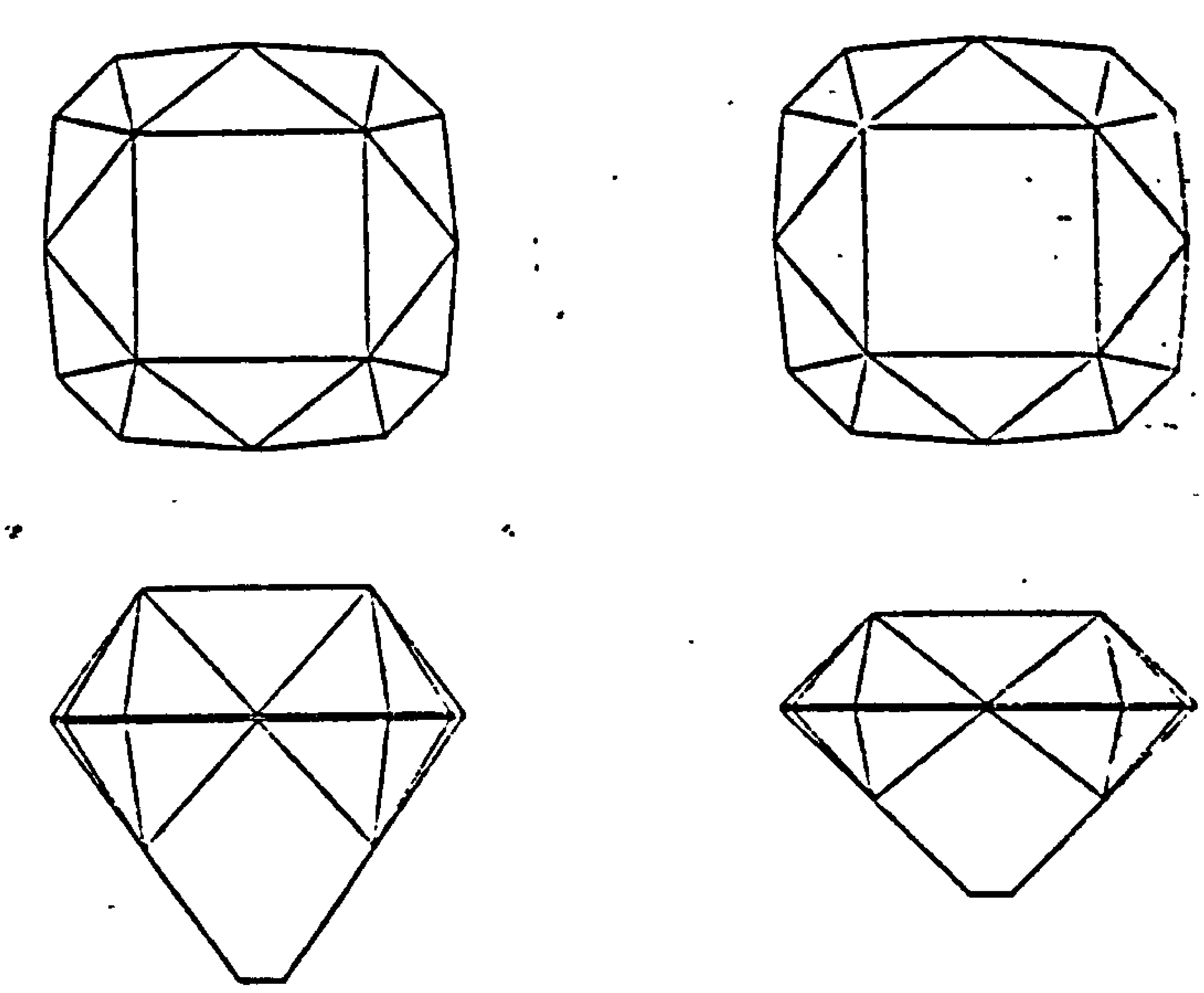
A B

FIG. 10

A. *The ideal full-bodied English star-cut* (16/8)
The culet is square and the proportions equal to those listed under Fig. 7.

B. *The ideal full-bodied English square-cut* (16/12)
The culet is square and the proportions equal to those listed under Fig. 7. The girdle facets in the crown and in the pavilion have the same height, but a different shape. The distance between the "corners" is 90% of Ø.

Fig. 1.5 The sixteen cut, after Tillander (1965).



A *Full-bodied* B *With 45° angles*

FIG. 11. *The ideal Mazarin-cuts* (16/16)

The distance between the "outer corners" is 94% and between the "inner corners" 64% of Ø. The culet is square and the girdle facets above and below the girdle are identical in size and shape.

A. *The proportions are equal to those listed under Fig. 7*
B. *The lower Mazarin-cut has the following proportions:*

T	56,0%		
o	10,0%		
hc	22,4%	C^	45°
---	1,0%		
hb	44,8%	B^	45°
H	68,2%		

Fig. 1.6 The Mazarin sixteen-cut derivative after Tillander (1965)

rounder forms (Fig. 1.4). The 16-cut (Fig. 1.5) was developed almost simultaneously; it was not the 17th century invention of Cardinal Mazarin as popularly thought. Tillander reasonably maintains that this idea propagated from the known preference of Mazarin (Marquis de Racan, 1644) for a 16-cut and his insistence on its superiority to all other styles (Fig. 1.6).

The 17th century was certainly the take-off point for our modern round brilliant cut. In 1644 a stone appeared , now called the Wittelsbach (Fig. 1.7) with 40 facets on both the crown and pavilion sides and a distinctly rounded appearance. The most interesting development is the break-away from an octahedral or 45° pavilion angle which were the norm at this time. In the Dresden collection a stone dating from this period also has the modern proportions. The reason for this departure from tradition is not known.

The major treatise of David Jefferies published in 1750 demonstrated a modern brilliant (Fig. 1.8) and this author also describes the Regent diamond (Fig. 1.9) which has the modern perfect proportions. The model for this stone, which was polished from 1707 - 1717, was a hand sawn piece, an operation taking approximately one year. Although Jefferies was impressed by the optical goodness of the Regent he advocated a pavilion angle of 45° as the ideal.

The 45° pavilion developed into the old mine cut, of which there are two derivatives, the square and round styles (Fig. 1.10). Hence the modern (<u>sic</u>) round brilliant has been known for about 280 years.

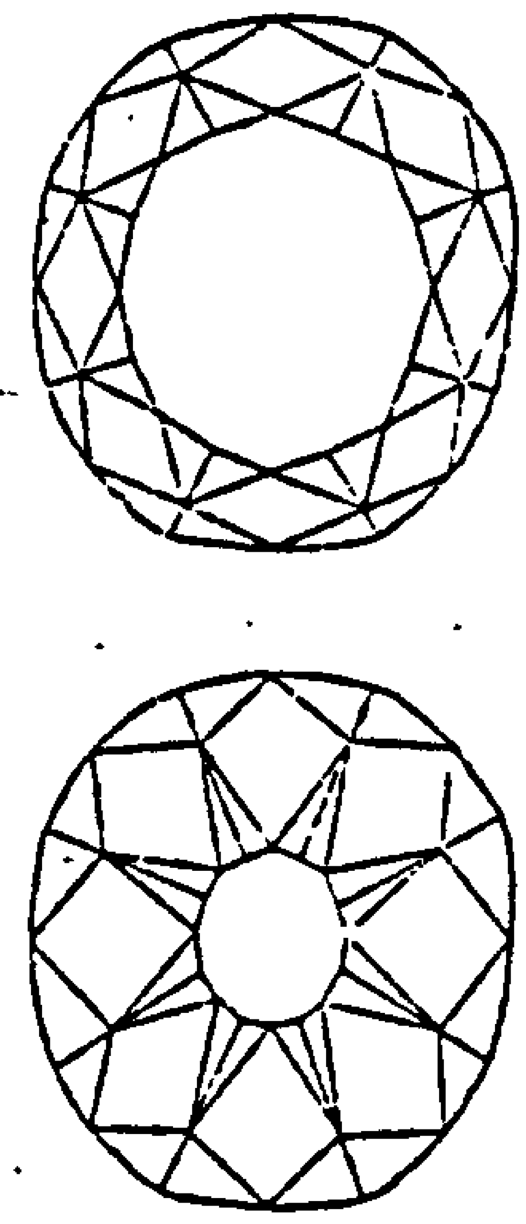


FIG. 12. *The Wittelsbach diamond* (40/40)
(*The pavilion is reproduced as if seen through the crown. The dimensions of the actual stone are* 24,5 × 21,5 *millimeters.*)

T	66,0%		
o	31,0%		
hc	12,5%	B^	36°
---	0,5%		
hb	30,0%	C^	42°
H	43,0%		

Fig. 1.7 The Wittelsbach diamond exhibiting a pavilion angle of 42° after Tillander (1965).

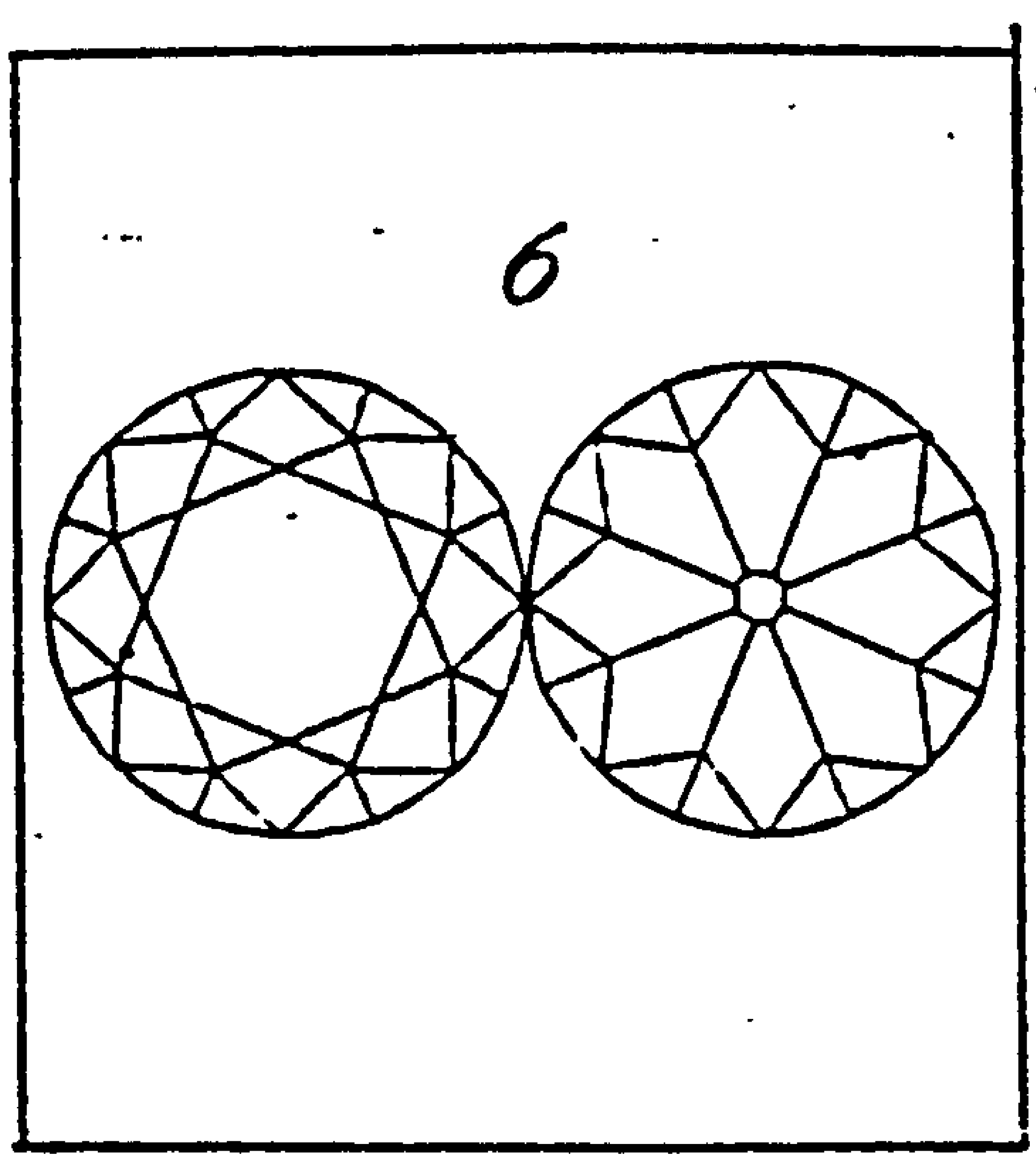


Fig. 1.8 An early example of a round brilliant cut diamond, after Jeffries (1753).

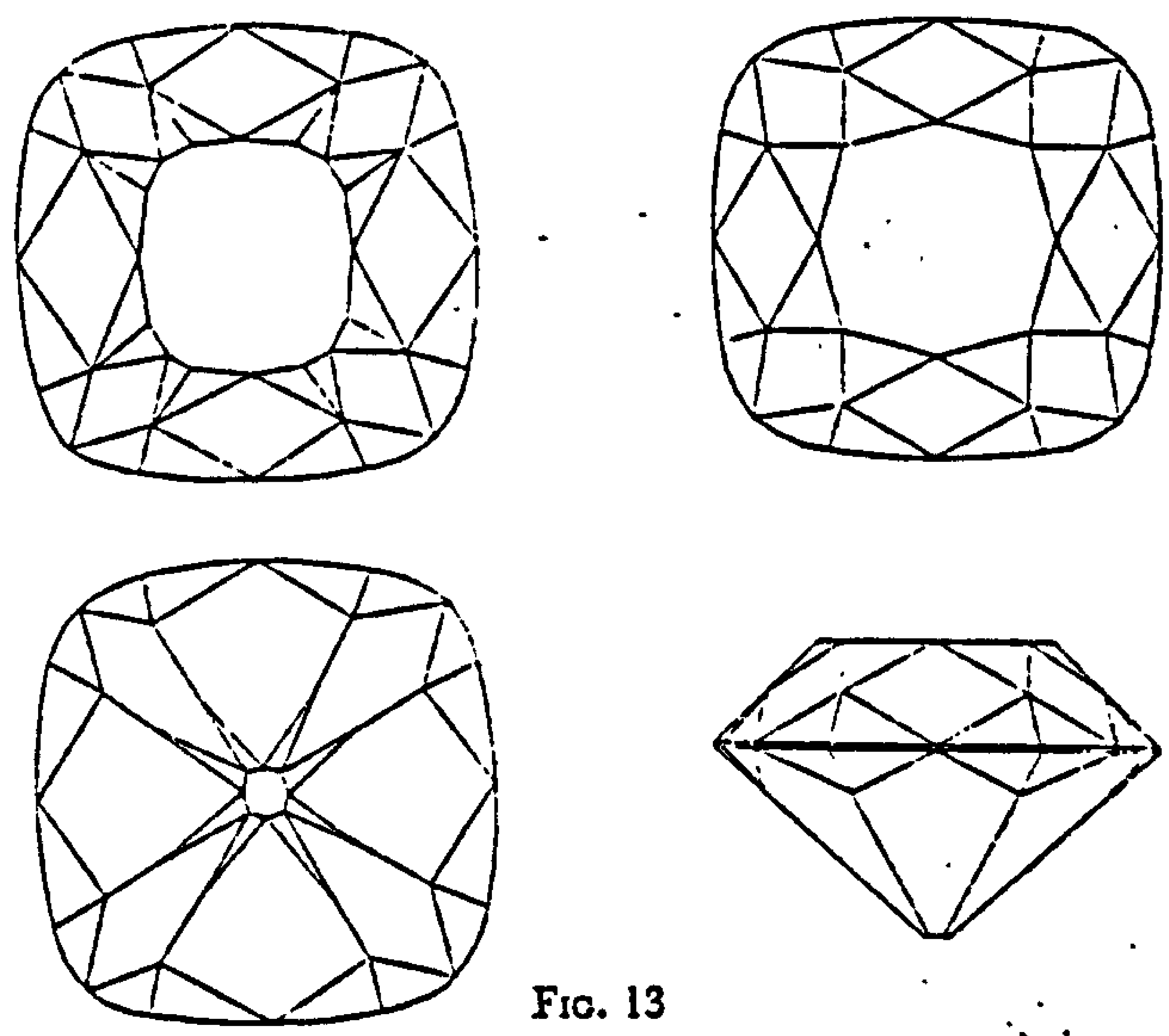


Fig. 14

Fig. 13

Fig. 13. *The Regent diamond* (40/32)
(*The pavilion is reproduced as if seen through the crown. The dimensions of the actual stone are* 30 × 29 *mm*)

T	46,55%	(16-*sided*)	
o	10,35%	(8-*sided*)	
hc	25,90%	C^	45°
---	0,00%		
hb	39,60%	B^	41¾°
H	65,50%		

Fig. 14. *The corrected "Regent-cut" with* 32/24 *faceting.*
This may have been the ideal shape of the earliest brilliant-cut diamonds with four-fold symmetry in the table and 150° *and* 120° *angles. The four larger main facets are symmetrical lozenges, but the girdle facets are of a different size and shape in the crown and the pavilion; the proportion in height is around* 12:10.

T	53,0%		
o	6,0%		
hc	23,5%	C^	45°
---	1,0%		
hb	42,0%	B^	41¾°
H	66,5%		

The distance between the "corners" is 82% *of* Ø.

Fig. 1.9 The Regent diamond exhibiting the ideal proportions, after Tillander (1965).

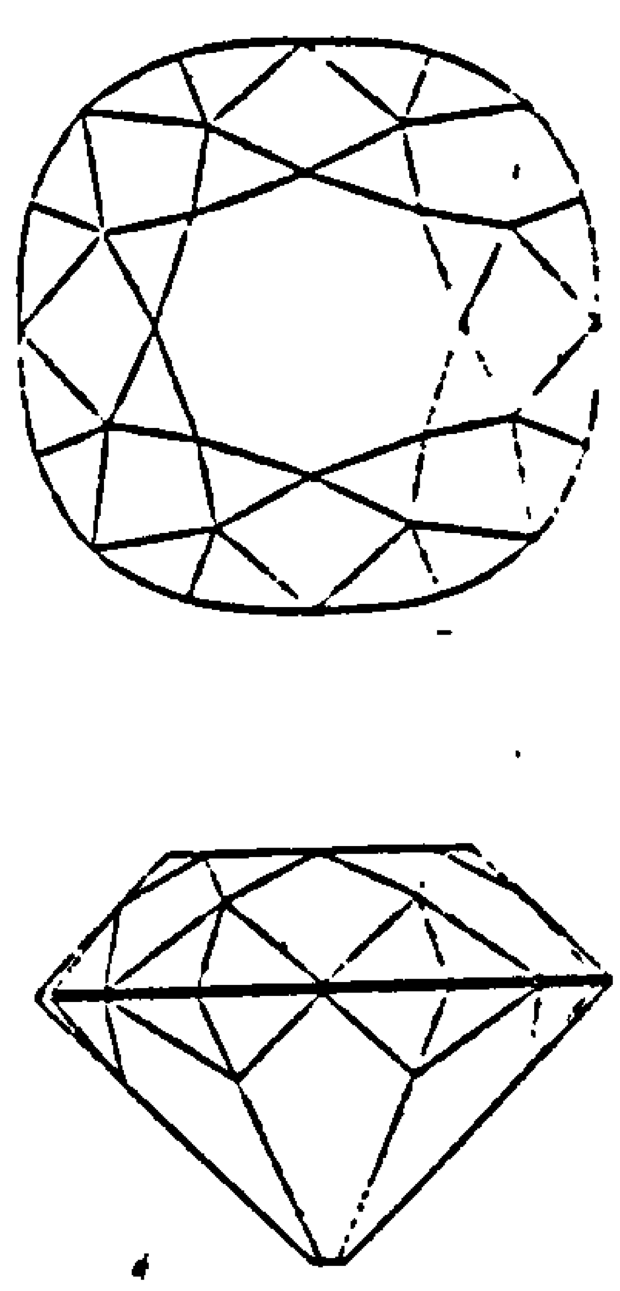


FIG. 15

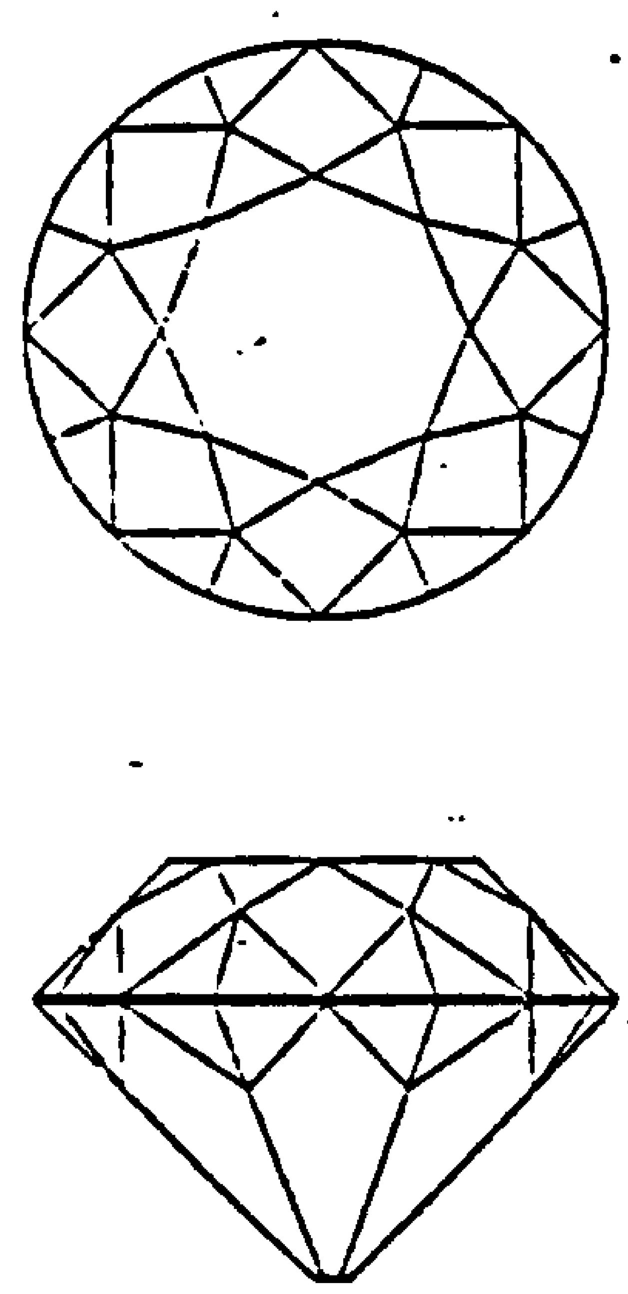


FIG. 16A

FIG. 15. *The almost round early brilliant-cut* (32/24).

This shape is mid-way between Fig. 15 and the completely round brilliant-cut, with a distance between the "corners" of 76% *of* Ø. *The symmetry of the table is still four-fold with angles of* 127,5° *and* 142,5°. *The main facets in the crown are all kite shaped and proportioned to please the eye only. The girdle facets in crown and pavilion have all a height of* 15% *but a slightly different shape.*
The proportion figures are different from the "Regnnt-cut" since the lower pavilion angle of around 41½° *was apparently never generally accepted.*

T	53,0%		
o	6,0%		
hc	23,5%	C^	45°
---	1,0%		
hb	47,0%	B^	45°
H	71,5%		

FIG. 16. *The ideal perfectly round early brilliant-cut* (32/24)

A. *The table has eight-fold symmetry with* 135° *angles. The meeting points of the main facets in the crown are found by drawing a circle mid-way between the corners of the table and the girdle. The girdle facets in crown and pavilion have all a height of* 14½% *and are identical also in their shape.*
The proportion figures are the same as listed under Fig. 15.

Fig. 1.10 The two derivatives of the early brilliant which are the old mine style, after Tillander (1965).

1.3 Tillander's comment on Vincenzio Peruzzi

Vincenzio Peruzzi, the 17th century diamond worker is credited in much of the literature with the invention of the round brilliant cut. The major work of Jefferies (1750) contains no reference to Peruzzi. Tillander points out that if this Venetian existed then a family Peruzzi was extant at the correct time (1640) but in Florence. His first appearance is in a book by A. Caire (Paris, 1833) and Tillander surmises that he may have been a 17th century Parisian diamond worker or even an expatriate working from India. Even after the publication of Caire's book Professor Max Bauer has no entry for Peruzzi in his classic text of 1896 'Edelsteinkunde'. The history of this gentleman once perpetrated has been perpetuated to the present time, The square cut attributed to Peruzzi (Fig. 1.11) has been investigated by Tillander who observed that no contemporary examples of this revolutionary style are extant. The style was relatively easy to produce using the then current technology; this makes their absence from the great collections all the more surprising.

1.4 The 20th century

At the beginning of the 20th century brutting, sawing and the brilliant cut were 200 years old. The revolutionary circular saw was well developed and the perfect proportions long known (Harris, 1710), if not generally used.

The Mediaeval method which evolved the round brilliant from the point cut using trial and error methods was eventually eclipsed by the Renaissance attitude and scient-

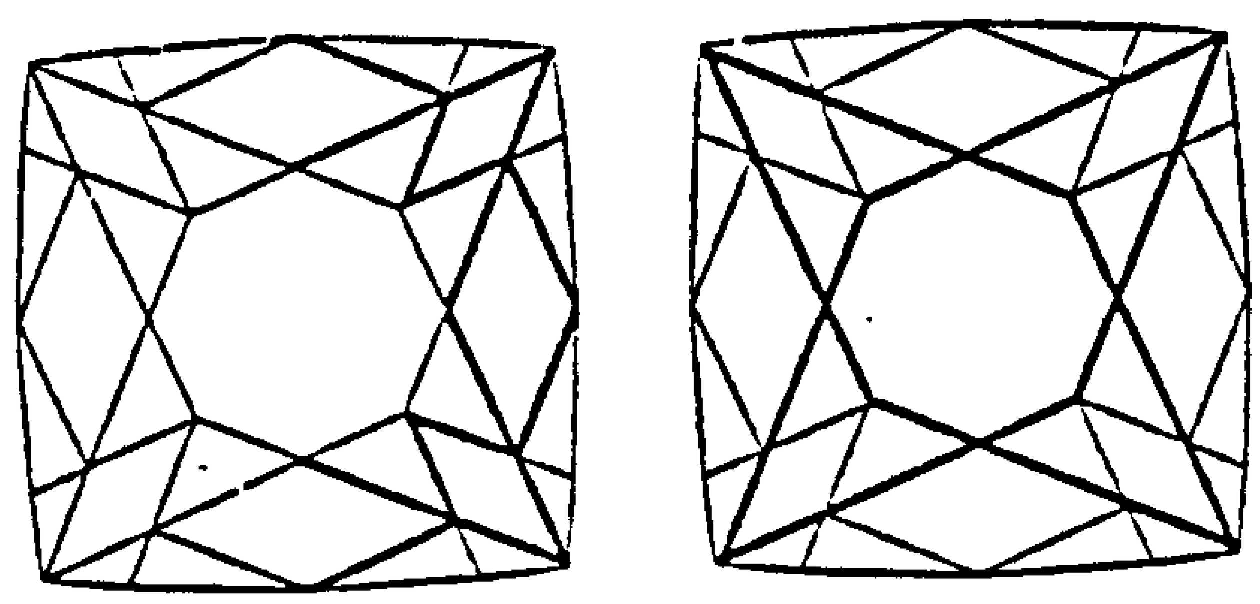
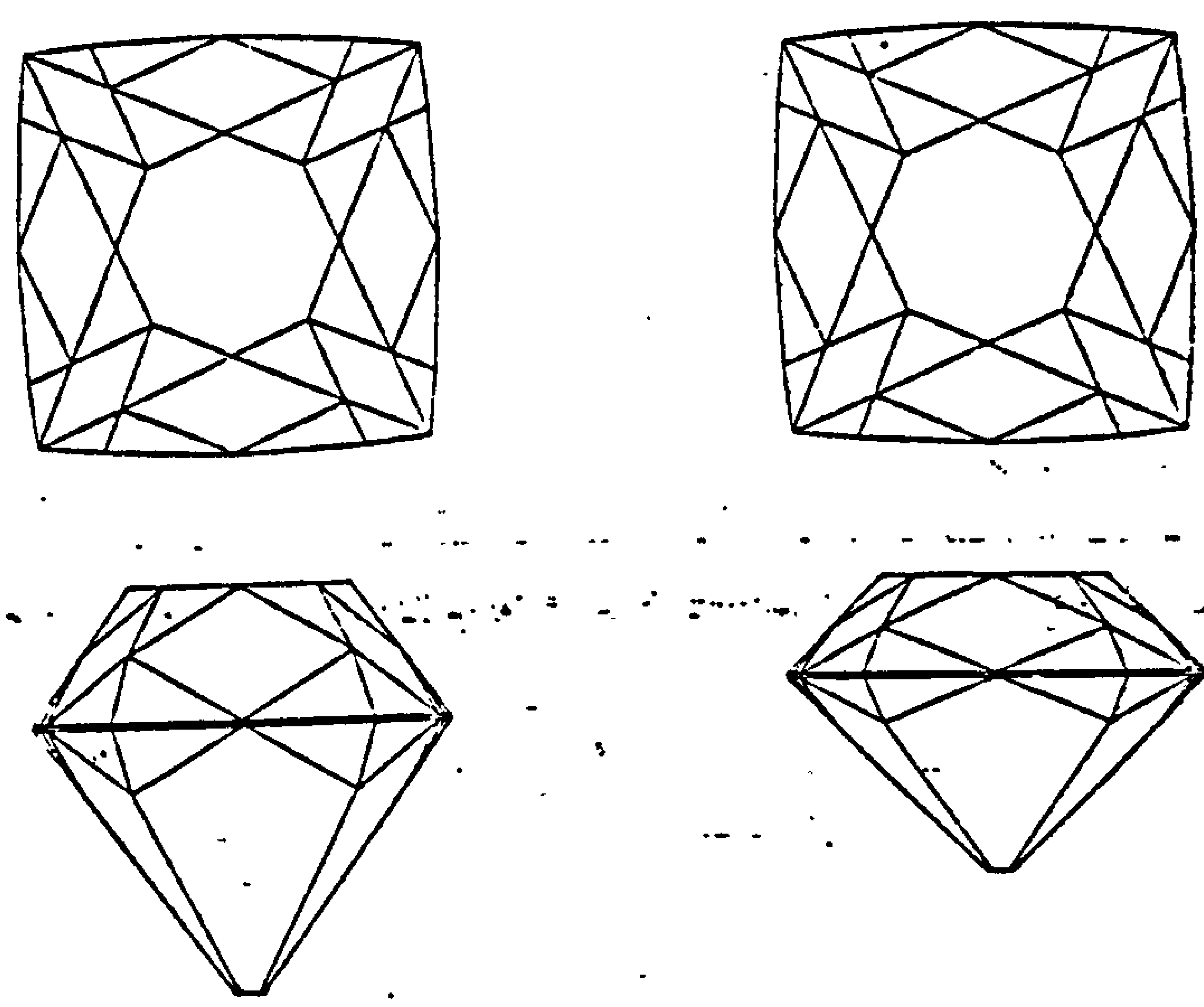


FIG. 21. *Diagrams of the Peruzzi design with the heavier lines drawn to accentuate the elements of symmetry in the crown.*



A B

FIG. 22. *The Peruzzi designs* (24/32)

	A.			B.		
T	53,0%		T	53,0%		
o	7,0%		o	6,0%		
hc	33,0%	$C^{\wedge}$ 54°44′ 8,3″	hc	23,5%	$C^{\wedge}$ 45°	
---	1,0%		---	1,0%		
hb	66,0%	$B^{\wedge}$ 54°44′ 8,3″	hb	47,0%	$B^{\wedge}$ 45°	
H	100,0%		H	71,5%		

Fig. 1.11 The design attributed to Peruzzi, after Tillander (1965).

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tific method. By the early 20th century the scientific method had evolved into the mathematical determinism which approximates real systems by a set of mathematical operations in an attempt to predict the result by theoretical analysis rather than trial and error aided by serendipity.

1.5 The style of Tolkowsky

Tolkowsky, a diamond worker, published a book, 'Diamond Design' in 1919, which was a 'study of the reflection and refraction of light in a diamond'. This was the first attempt to demonstrate the well established result of the 'ideal' proportions by mathematical formalism.

As his starting point he took a simple two dimensional triangular cross section and used simple geometrical and physical arguments to confirm the round brilliant cut with its rotationally symmetrical arrangement of facets as the ideal style for polishing diamond. Tolkowsky also proposed a set of ideal proportions (Fig. 1.12) which were deduced from a merit function for optical goodness. This stated that the optical goodness is the maximum value of the product of the transmitted intensity of a green ray passing from diamond to air and the dispersion of a red and blue ray at the same angle of incidence. During the derivation of this merit function Tolkowsky makes two approximations: The transmitted intensity is approximated by a cosine function. He states that "the amount of light passing through a surface as at AB is proportional to the cosine of the angle of refraction", (page 72 *ibid*) which gives the

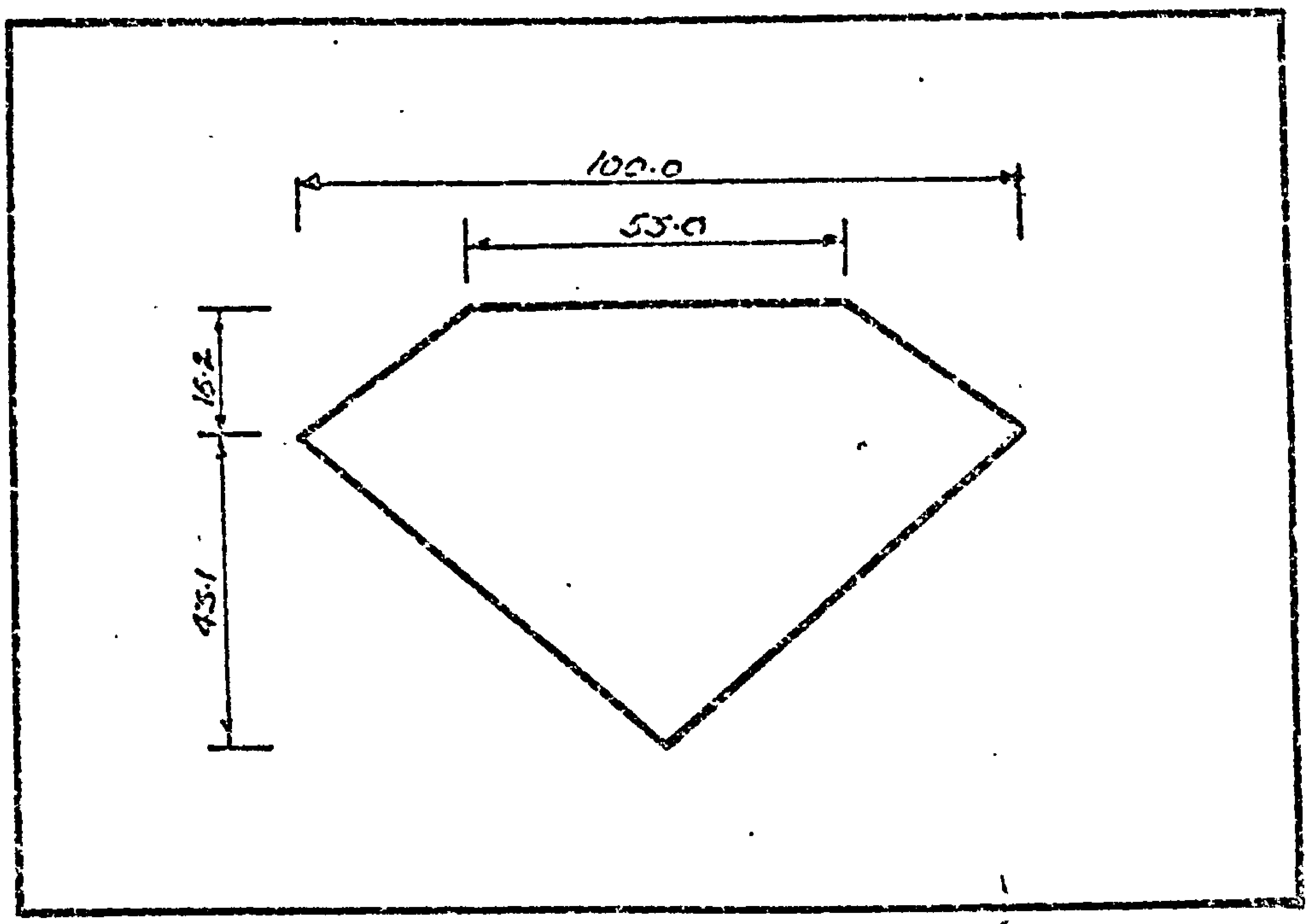

Fig. 1.12 The proportions for the round brilliant cut diamond as calculated by Tolkowsky.

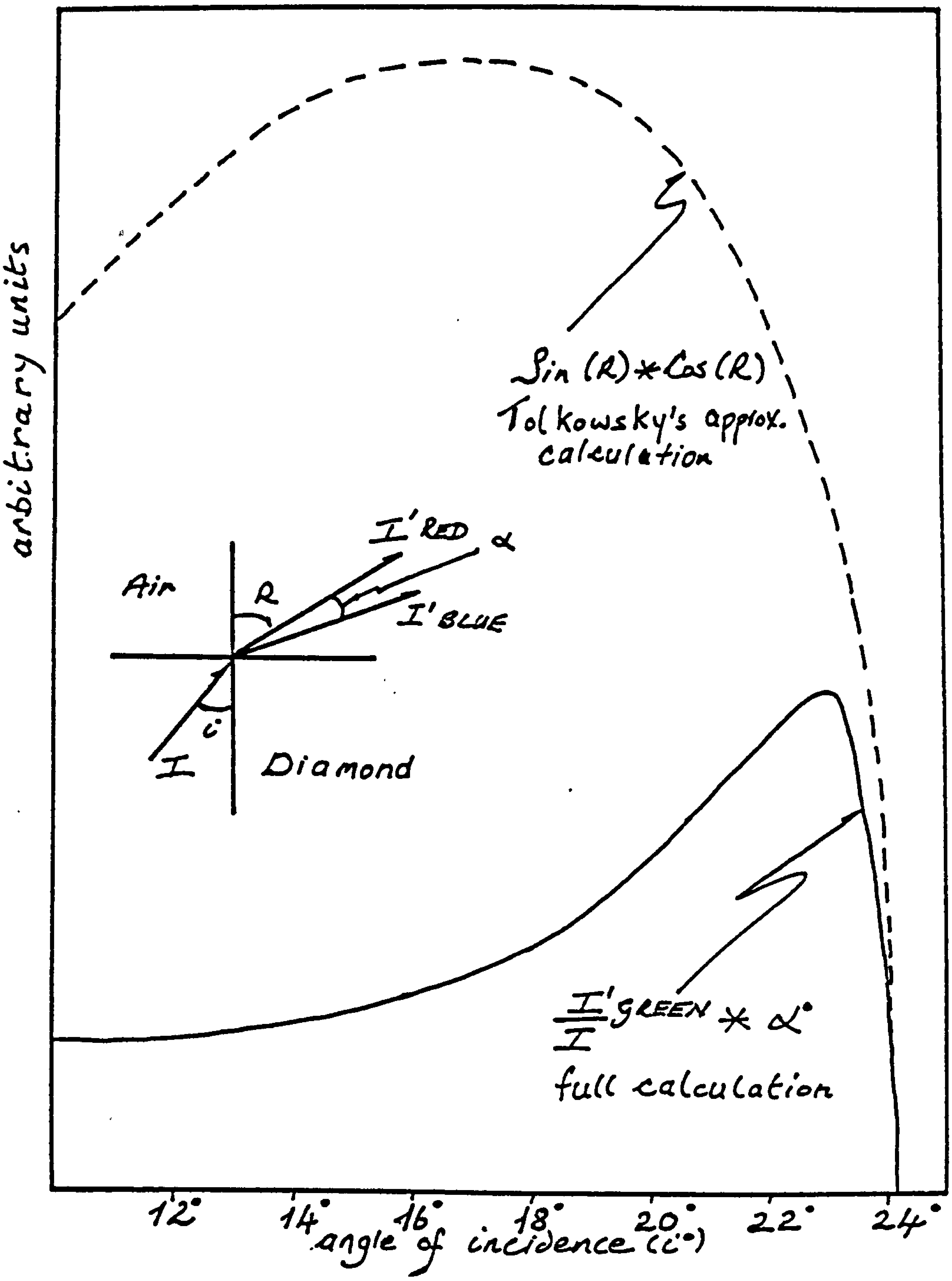

Fig. 1.13 The graph of the merit function used by Tolkowsky.
Dash line (Tolkowsky's approximation)
Solid line (The more exact analysis).

impression that he has confused Lambert's law with Fresnel's equations (1817, 1818). He then approximates the dispersion angle between the red and blue rays by stating (page 72 ibid) "angle of dispersion is proportional to the sine of the angle of refraction." However the angle of dispersion (β) is given by:-

$$\beta = \sin^{-1}(n_{blue} \sin i) - \sin^{-1}(n_{red} \sin i) \qquad 1.1$$

From this it can be argued that the assumption for the dependence of dispersion and transmitted intensity lead to a fortuitous result which is in agreement with the known cutting practice of the time.

If the more exact formulae are used and the analysis of Tolkowsky is otherwise followed (Fig. 1.13) the maximum product is shown to correspond to an angle $39\frac{1}{4}^{o}$ (page 74-75, Equ. 14 ibid) in contrast to his pavilion angle of $40\frac{1}{4}^{o}$

1.6 Work from 1919 - 1960

Tolkowsky's work spurred interest into a more exact mathematical description of the round brilliant cut, which resulted in two important papers (Johnsen, 1926; Krumbhaar and Rosch, 1926). Johnsen used a geometrical approach which was not disimilar to that of Tolkowsky to obtain a pavilion angle of 38^{o} 40' (Fig. 1.14). Krumbhaar *et al*. used a ray tracing technique to produce a set of proportions (Fig. 1.14) with a pavilion angle of 38^{o} 30', essentially the same as Johnsen.

An argument against the wholesale acceptance of the ideal proportions was that they were uneconomic, as a

STYLE	TABLE SPREAD	CROWN HEIGHT	PAVILION DEPTH	CROWN ANGLE	PAVILION ANGLE
Regent(1707)	46.6	25.9	39.6	45	41.75
Wittelsbach	66.0	12.5	30.0	36	42
Jeffries(1753)	58.0	-	-	45	45
Peruzzi (a)	53.0	33.0	66.0	54.7	54.7
(b)	53.0	23.5	47.0	45	45
Wade (1916)	40.0	21.7	43.4	35	41
Tolkowsky	53.0	16.2	43.1	34.5	40.75
Johnsen, Krumbhaar & Rosch	56.0	19.0	40.0	41.1	38.7
Eppler(1939)					
ideal	56.1	19.2	40.0	41.1	38.7
small stones	55.3	16.0	39.9	35.6	38.6
large stones	57.1	14.0	42.1	33.1	40.1
lowest loss	69.0	10.0	44.6	32.8	41.7
Parker(1951)	55.9	10.5	43.3	25.5	40.9
Smith (1962)	44.4	22.2	44.4	46	39
Scan.D.N.	57.5	14.6	43.1	34.5	40.75
GIA.	as Tolkowsky-				
Shigemasa Suzki	58.0	23.0	40.0	48.6	38.9
Eulitz(1972)	56.5	14.5	43.1	33.6	40.8
Elbe (1972)	50.0	14.6	53.7	-	47.5

Fig. 1.14 A table of the many ideal proportions and some historical proportions. All percentages are with respect to the total spread. The angles are in degrees.

diamond is valued on its four Cs, not only cut but also colour, clarity (freedom from internal imperfections and external blemishes, both natural and artifactual) and carat weight (200mg = 1 carat). These new styles required accuracy of workmanship and the additional weight loss and increased time of manufacture militated against their prompt adoption. W.F. Eppler (1934) and co-workers appraised many stones and as a result published a set of practical cuts which went some way to combating the resistance to the 'ideal' styles (Fig. 1.14).

External factors then disrupted the studies of the 'ideal' cuts and it is not until the late 1940's and early '50's that interest was rekindled by Eppler, With R.L. Parker (1951) proposing a stone (Fig. 1.14) with a low crown height, 10.5% of the total diameter.

1.7 The work from 1960 to the present time

Eulitz (1968, 1975) published papers which used essentially the geometrical approach of Tolkowsky and Johnsen to obtain the wellknown results. Tillander (1970) introduced a new practical cut (Fig. 1.15) as part of the Scandinavian Diamond Nomenclature. This grading system for polished gem diamond contains a scheme for grading cut, which is a long process when put into practice. However apart from its small table spread this style is thought by many to reflect the current fashion for proportions in the European market.

M.G. Elbe (1971, 1972, 1973) has produced two important papers. The first deals with the physiological aspects which affect the appreciation of a stone. He also discusses the improvements to the round brilliant

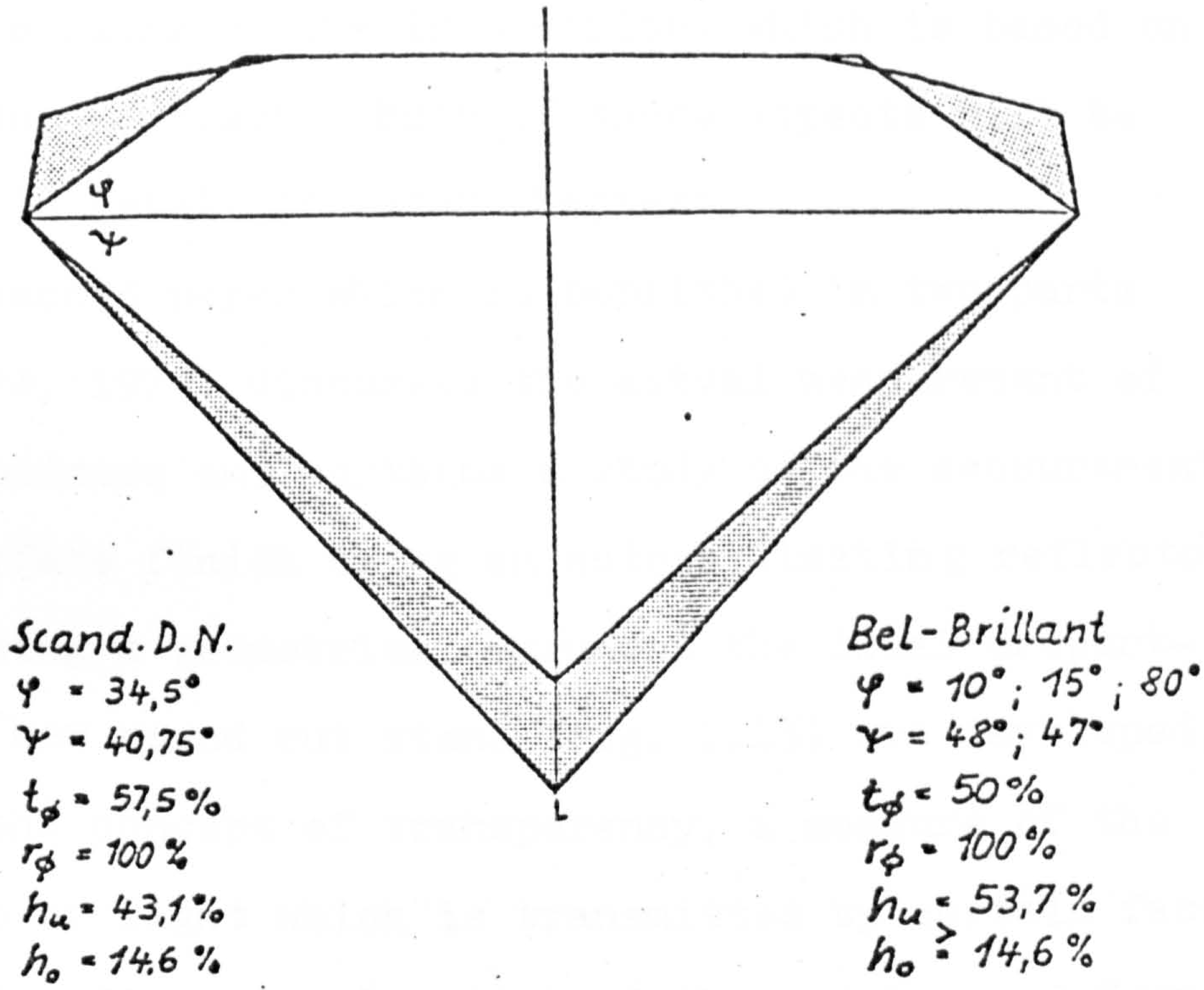

Fig. 1.15 The style of Elbe superimposed on the Scan. D.N. style to show the increased yield, after Elbe (1971).

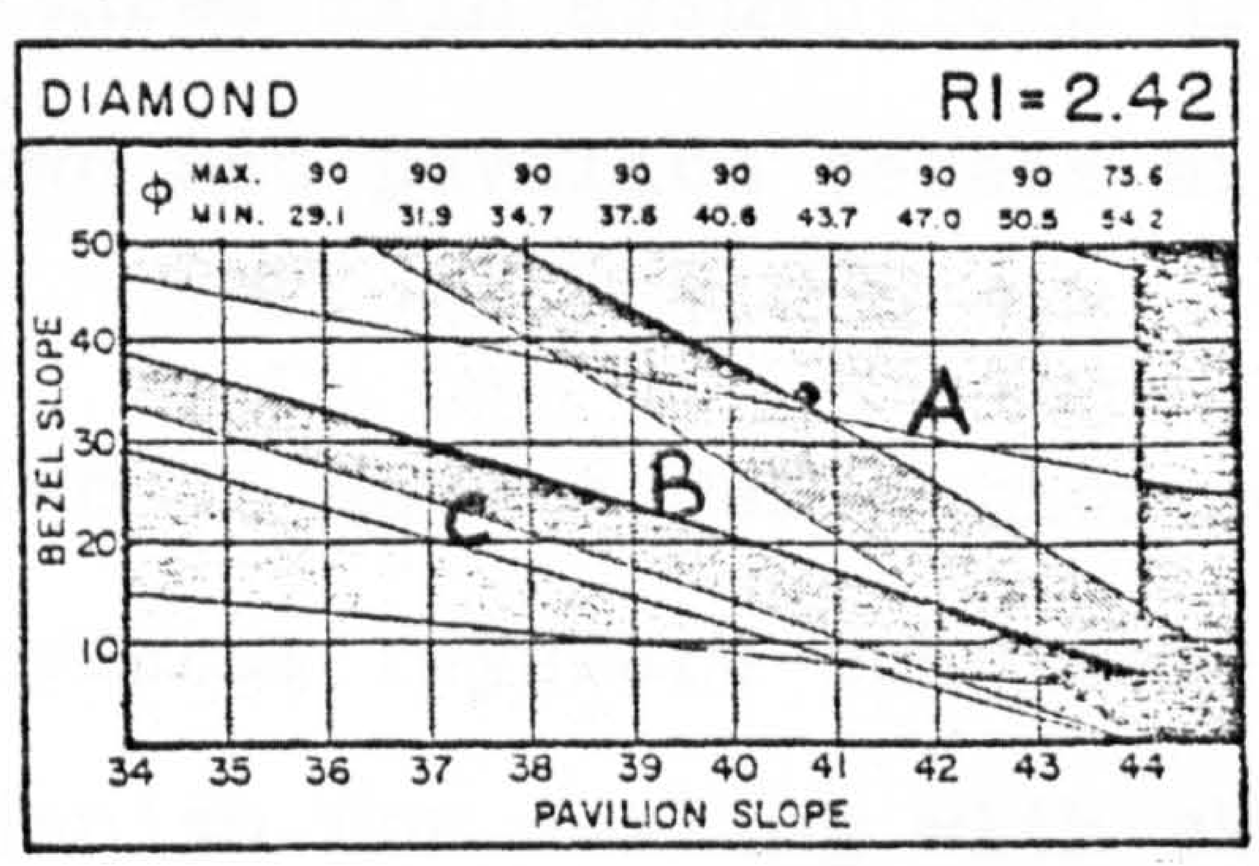

Fig. 1.16 The faceting limits proposed by Harding (1975). The three preferred areas, labelled A, B and C permit a stone to be 'repaired' sequentially starting from A.

cut, proposing three new styles of polishing. Finally a diamond grading engine is described which is based on a method due to Rosch. Both of these aspects will be discussed in detail in later chapters.

The second paper which is published in two parts (Elbe, 1972, 1973) discusses the actual measurement of optical goodness and contains a study of the measurement of the surface finish using an autocollimating reflectometer. Using a geometrical argument the ideal proportions of a new round cut stone (Fig. 1.15) are developed, based on the concept of transparency, a measure of the percentage of light which is transmitted by certain facets.

The two dimensional nature of the models used from Tolkowsky to the present time lead to approximations and implicit assumptions which seem to have been unnoticed by many of the authors.

Harding (1975) published another geometrical argument in which the three main assumptions are clearly stated:-

1. The crown and pavilion bezels are the principal facets.
2. These facets have a reflection symmetry.
3. Only coplanar rays are considered, i.e. there is no mechanism for dealing with skew rays.

In this paper there is also a discussion of the effect of the shadow of the head of the observer and the way in which it will form a central obstruction in the illumination. He requires that the incident light makes an angle of 10^{o} with respect to the stone-head line.

The results are presented as a set of graphs showing the preferred faceting angles for various gem materials. The diamond result is reproduced as Fig. 1.16. Note that he proposes three distinct styles of cutting given areas A, B, and C and if a stone is damaged it is possible to repair a stone from region A into B and subsequently zone C. As a lapidary he sees this as the important finding and not the promulgation of a new ideal cut.

With the increasing realization of the limitations of these studies it became inevitable that a three dimensional model would be constructed using a large electronic computer. N. Stern (1975) has developed a computer program which is a 3D model. Using finite ray tracing methods he traced monochromatic light (636nm) through the diamond. The model was based on the 'Gem Print' of C. Bar-Issac (1973).

Stern proposes a criterion for optical quality which confirms the traditional cuts as satisfactory. This loose proposition is a restatement of a well known preference which will be discussed in Chapter II.

1.8 Aims of the research

As has been seen the ideal proportions are well known, in particular the ideal pavilion angle of 41°. The gross simplifications made by the authors to accomodate the desire for a deterministic model are almost certainly the cause of the discrepancy between the known ideal and the findings of the various mathematical models.

The aim of the present research is to construct a model of the round brilliant cut diamond and the other rotationally symmetric styles using the minimum of geometrical approximations. The principal aims are as outlined below:-

1. To find a non-subjective measure for optical goodness of a polished gem diamond. Diamonds have been and are at present graded by reference to experienced judgement, there being no diamond grading engines for all aspects of optical goodness.
2. To establish a scale of optical goodness.
3. To investigate the optical attractiveness of styles simpler than the 58 facet round brilliant cut diamond.
4. To assess the optical goodness of the diamond simulants, as some of the new crystals have optical properties similar to diamond.
5. To construct a diamond grading engine for optical goodness, based on the measurement of the non-subjective measures of part 1.

Chapter II

The Model

2.1 Introduction

It has been shown that diamond has for several centuries been prized for its pleasing opitcal effect. This optical effect is usually considered to be a combination of three effects: brilliance (the percentage of light entering the stone which is scattered out of the crown facets), sparkliness* (a measure of the variation in intensity of the scattered light field) and fire (a measure of the difference in the colour of the sparkles).

2.2 Factors affecting optical goodness

The non-expert usually observes a diamond set into jewelry with the pavilion obscured by the setting, in diffuse illumination (room lighting) and at a distance of about 50cm (a relaxed arm's length). The observer then moves both the head and stone and the overall brightness, degree of sparkle and chromatic variation in the sparkles are translated into degrees of optical attractiveness.

It would appear that when discusssing optical goodness the observer has in mind several general considerations and some specific likes and dislikes. The

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* Sparkliness is usually called scintillation by the Gemmological Institute of America (1975). However scintillation already has a usage in the fields of astronomy and nuclear physics (Chambers Scientific Dictionary). Sparkliness was also preferred to sparkle as Goodman (1963) used sparkle as a description of coherent noise (now called speckle).

scattered light distribution from the stone should be reasonably uniform. There are two sets of proportions which offend this rule for the round brilliant style. The first is a stone with a pavilion angle of 45° which gives the impression of having a dark table, as the table and pavilion facets are similar to a corner cube retro-reflector with the observer's head forming a dark central obstruction. The other style is a stone with a shallow pavilion angle of 37° or less, where the girdle, which is usually brutted, i.e. it has a frosted appearance, is visible through the table as a white ring. In general terms the greater the number of and the smaller the average size of sparkles the more attractive the stone appears.

2.3 The requirements of a model

If we accept that the model should faithfully describe the diamond this could most easily be achieved using a finite ray tracing programme on a computer. A short calculation will show the effort required in such an approach. The eye has a resolution of about 0.1mm a the near point of vision (25cm). A typical diamond is 5mm in diameter and therefore produces a scene of approximately 625π picture elements (pixels). Assuming that only one ray comes from half the pixels each eye field will require approximately 310π rays. If each primary ray produces 10 secondary rays by partial transmission and total internal reflection at the many facets of the stone, that is, 31π (100) primary rays per eye field.

The number of eye fields at the near point of vision can be estimated by the area of a sphere of 25cm radius divided by the area of the pupil. E.G. for a pupil of 4mm the number of eye fields is approximately 62,500. The total number of rays is then the product of the number of eye fields and the number of primary rays per eye field. This means that at least 6,250,0000 primary rays require tracing to model in some detail an eye's view of a diamond. This corresponds in a typical computer programme to several hours of ray tracing before any analysis of the data is possible (Kidger, 1971).

The purpose of modelling would hence be nullified, since the full calculation would be more expensive than buying the rough diamond crystals and polishing them to predetermined shapes. The complete description is therefore an impossible requirement; what then is the principal requrement for an approximation to the eye's view of diamond? As there are no detectors as versatile in both resolution and colour discrimination as the eye it has been chosen that the principal requirement of the model is:-

That it is realizable as a diamond grading engine for optical goodness of polished gem diamond.

2.4 The reflection spot-pattern technique

Rosch (1927) developed a reflection technique where a polished gem diamond was illuminated by a normal beam of light through the table and the spot pattern produced by the stone's scattered light field was photographed. The purpose was to form a fingerprint of the stone. The argument is that although diamonds are polished to a predetermined set of proportions the individual differences in facet alignment lead to perturbations in the scattered light field, leading to a unique reflection spot pattern of each stone. Two authors have given the analysis of this type of spot pattern some consideration (Elbe, 1972; Stern, 1977).

Stern has modelled the 'Gem Print' of Bar-Isaacs which uses a refinement of a technique due to Rosch to obtain reflection spot pictures. The only difference between Rosch's reflectogram and the Gem Print is that the Gem Print uses a laser light source and in addition a lens to bring the far field diffraction pattern to a convenient image plane. Stern's criterion was that the far field diffraction pattern should contain an even distribution of spots, in fact a special case of the well established preference for an even distribution of sparkles. No chromatic criteria are suggested because of the laser illumination.

Elbe constructed a diamond grading engine based on the technique of Rosch to assess optical goodness. He used a photometer to measure the intensity distribution of a diamond, the stone being rotated while a radial scan in intensity was recorded. A sparkle was defined using physiological optics arguments and all the light falling on a pupil sized aperture at the near point of vision for each azimuthal angle was integrated to form the signal for that angle. This means in terms of the earlier calculation (section 2.2) that each eye field was taken to contain one pixel and not 1,900.

In the resultant distribution, the total number of sparkles was taken as a measure of optical goodness.

This measure, based on a number count of sparkles, only in part fulfills the requirements of a visual grading measure for diamond and as Elbe points out no account was taken of fire (the chromatic variation in the sparkles).

How much information has been lost due to the acceptance of this simplification of the intensity distribution? By using a non-imaging system Elbe has lost one piece of information, that of the position on the stone from which the light came. By the use of this approximation it is not possible to take direct account of the stone's exhibiting a visible girdle or dark table. However there is a saving by a factor of a thousand in the number of rays to be traced. By rotating the stone another assumption is made, that the eightfold symmetry for the round brilliant cut gives little information on the optical attractiveness of the diamond, this being totally provided by the radial scan. However Elbe's simplification of the complex two dimensional intensity distribution to a one dimensional intensity scan, coupled with a technology which makes it possible to obtain intensity scans at several wavelength ranges, yields a technique and data base which are suitable for further analysis. As the principal requirement is now for a realizable diamond grading engine a model based on the method due to Rosch was adopted.

2.5 The diamond grading model for optical goodness

The model was based on the round brilliant cut of 58 facets. A round brilliant cut diamond is surrounded by a hypothetical sphere centred on the table. Rays in several azimuthal and meridional orientations, a form of pseudo-diffuse illumination, are then traced through the diamond using finite vector ray tracing equations. At the same time a note is kept of their fresnel components at each partial transmission or total internal reflection as it is necessary to know both the direction and intensity of the rays. For the rays scattered out of the stone their final position on the sphere is calculated and as the intensity at that spot is known, a map of intensity can be constructed for a given radius of sphere and a particular wavelength of light. By tracing at different refractive indices, the various colours can be modelled. For a good stone the resultant spot pattern is a random scatter of points in the forward hemisphere. When the sphere is rotated the spot pattern merges into a set of concentric rings and it is some property of this radial fluctuation which is required for the measure of optical goodness.

The overall brightness is simple to define:

$$\text{Brilliance} = \frac{\text{Intensity scattered into forward direction}}{\text{Total illumination}}$$

but how to measure sparkliness and the chromatic variation or fire?

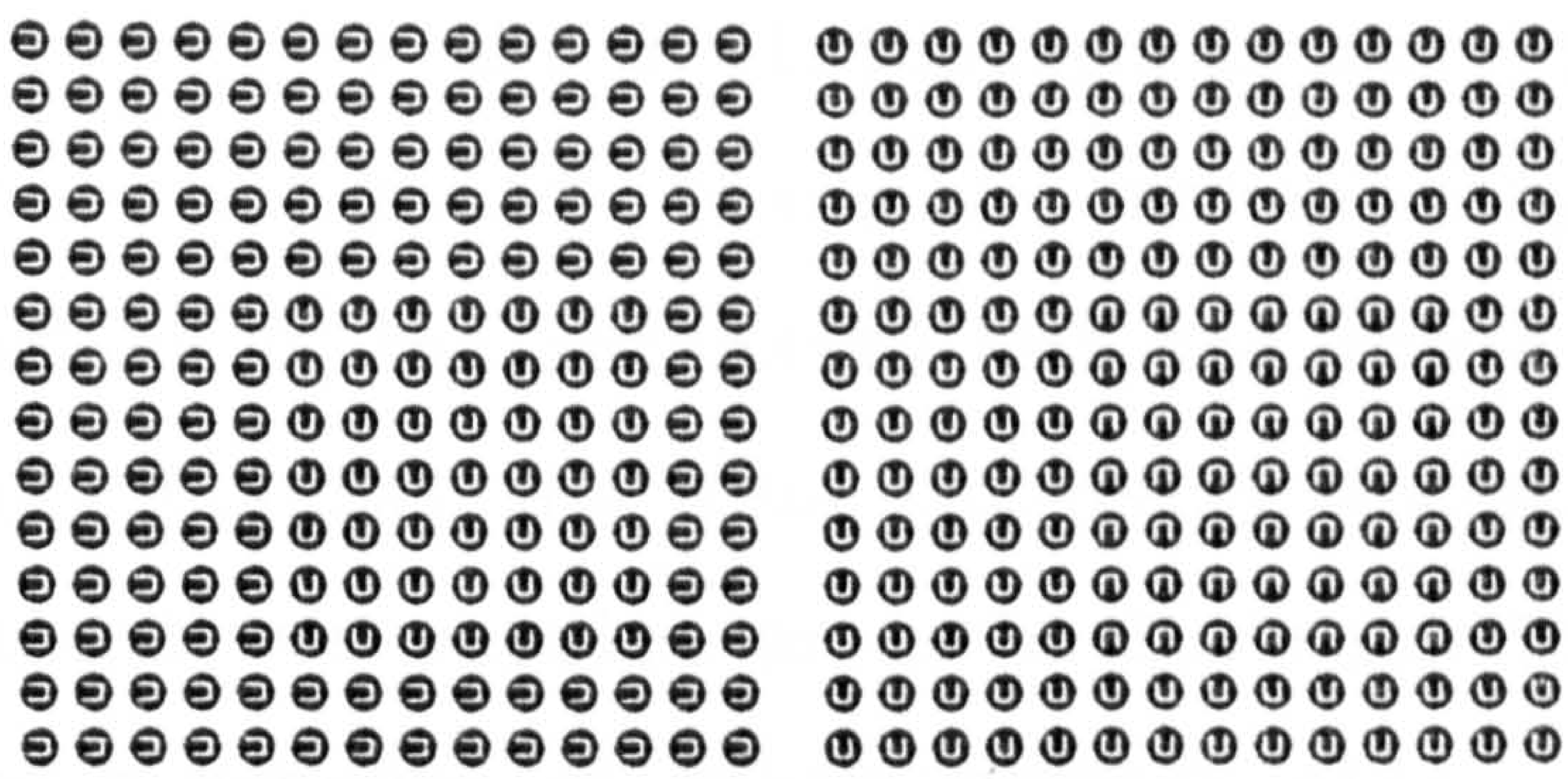
The assumption is made that the radial intensity scan produced by a gem diamond can be considered and analysed as in some sense a random signal, the justification being that the reflection spot patterns of thousands of essentially similar diamonds are unique to the individual diamond. Thus it is a statistical property of this random distribution which the eye-brain system measures as the degree of optical attractiveness. What types of statistical properties is the eye-brain system capable of discriminating?

To the eye-brain system the round brilliant cut diamond presents a 2D scene formed from two elements: a pattern with an eight-fold rotationally symmetric design formed from an elementary random pattern.

Bela Julesz (1975) has shown that it is sometimes possible to discriminate between two scenes which are formed from either a symmetrical array of random elements or from wholly random elements.

Discrimination is possible for scenes with similar first order statistics and different second order statistics but not possible for scenes with similar second order but different third order statistics (Fig. 2.1). This leads to the supposition that the attractiveness of a diamond could be expressed by the first order and second order statistics of its intensity distribution.

The analysis of random signals has led to ideas of coherence length and correlation analysis. In particular, the two questions, how sparkly and how fiery is a diamond? are asked in terms of probability theory in the following ways: How different in intensity is each



VISUAL TEXTURE DISCRIMINATION is studied by the author by flashing on a screen images with controlled statistical properties such as these and asking the subject if he can see an area of one texture embedded in an area of similar but different texture. In the image at the left the two textures have identical first-order statistics but different second-order statistics; the difference in textures can be perceived without effort. In the image at the right the two textures have identical second-order statistics in addition to identical first-order statistics. Here discriminating between the two textures requires deliberate effort.

DIFFERENCE IN SECOND-ORDER STATISTICS, which is readily visible here, is exemplified by these two textures, which have identical first-order statistics. The first-order statistics of the textures are identical because each texture consists of the same number of black dots; hence there is the same probability in both textures that a given point will have same luminance. In the left field the dots fall at random. In the right field, however, there are at least 10 dot diameters between dots. Thus if a dipole such as a needle were dropped on the two fields, the probability of both ends' touching a dot would be different in the two cases. Difference in probabilities signifies a difference in second-order (dipole) statistics.

DIFFERENCE IN THIRD-ORDER STATISTICS, which eludes spontaneous detection, is demonstrated in the image at the left. The left and right half-fields in that image have textures that are generated by a Markov process so as to have identical first-order and second-order statistics but to have different third-order statistics based on the sequential arrangement of cells of four different luminance levels: black, dark gray, light gray and white. Only by careful inspection can one see that the left half-field contains a few horizontal stripes of uniform luminance that are formed by three adjacent cells whereas the right half-field contains practically no stripes. In comparison the two textures in the image at the right can instantly be discriminated because they have different second-order statistics, which appear as a difference in granularity. In both textures cells of three luminance levels (black, gray and white) occur with equal probability; hence first-order statistics are the same. In the texture that largely fills the left side adjacent cells are statistically independent of one another in luminance whereas in the surrounding texture adjacent cells are related mathematically by a Markov process. This gives rise to different second-order statistics.

Fig. 2.1 An example of the types of texture discrimination which are possible with the human cognitive system, after Julesz (1975) point in the distribution of light from each other point, and how different is the distribution in red light from those in green and blue? These are answered by the autocorrelation of the intensity and the cross correlation of say, the red and blue intensity scans. In the case of diamond, we require an even distribution of sparkles and a measure of their average size. The average size is given by the half width of the autocorrelation.

In one dimension, the autocorrelation of a constant is another constant; on the other hand, that of a far field speckle pattern from many diffusing elements has the well known gaussian form. Thus in the context of a diamond, these would correspond respectively to no sparkliness, the worst case, and to an even distribution of sparkles.

A suitable measure for sparkliness would therefore be how far the autocorrelation deviates from a constant, the higher the deviation the better, in a sparkling sense, the diamond. Such a possible measure is the variance of a distribution

$$\langle x^2 \rangle - (\bar{x})^2$$

From this it becomes possible to define a sparkliness criterion as the variance of the autocorrelation of the total radial intensity scan, where, as done by Elbe, the diamond is rotated and for a particular azimuth with respect to the table normal all the intensity spots are sampled whatever meridional angle they subtend. Concerning the fire, the intensity distribution is measured for wavelengths in the red, green and blue regions of the spectrum. A similar argument is proposed to that used for sparkliness, the variance of the cross-correlation of the red and blue fields being taken as a measure of fire. However, if the red and blue fields are equal and equal to the green field, this cross-correlation would yield the same result as the autocorrelation. That is, if

$$\frac{R+G+B}{3} \ (=D) = R = G = B$$

then,

$$\int D(u) \times D(u+\Delta)\, du = \int R(u) \times B(u+\Delta)\, du$$

This implies white sparkles. Hence the proposal for a measure of fire is, fire is the quotient of the variance of the cross-correlation for the red and blue intensity scans and the variance of the autocorrelation of the total intensity distribution.

Thus we have a measure for brilliance, sparkliness and fire. Some might prefer a simple single figure for the optical goodness of a gem diamond, instead of a triplet. One such method of assigning a single figure to each point in the intensity distribution is to give the elemental areas colour-coordinates, i.e.

$$\frac{R}{R+G+B}, \ \frac{B}{R+G+B}$$

and then form a colour difference coordinate for each point $\frac{|R-B|}{R+G+B}$. The variance of this factor, which we can call the differential chroma, could then be used

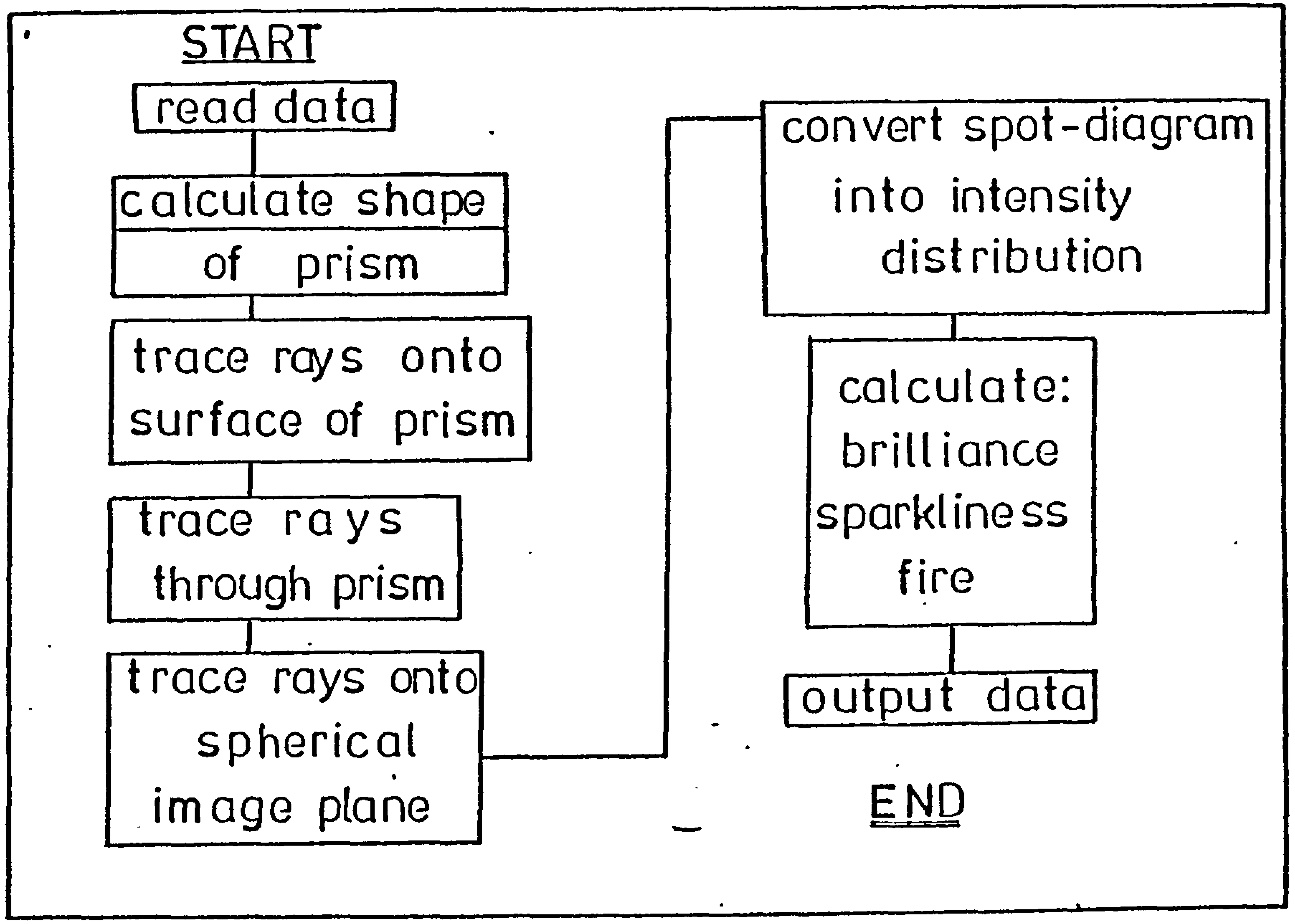


Fig. 2.2 A schematic représentation of the model for the round brilliant cut diamond.

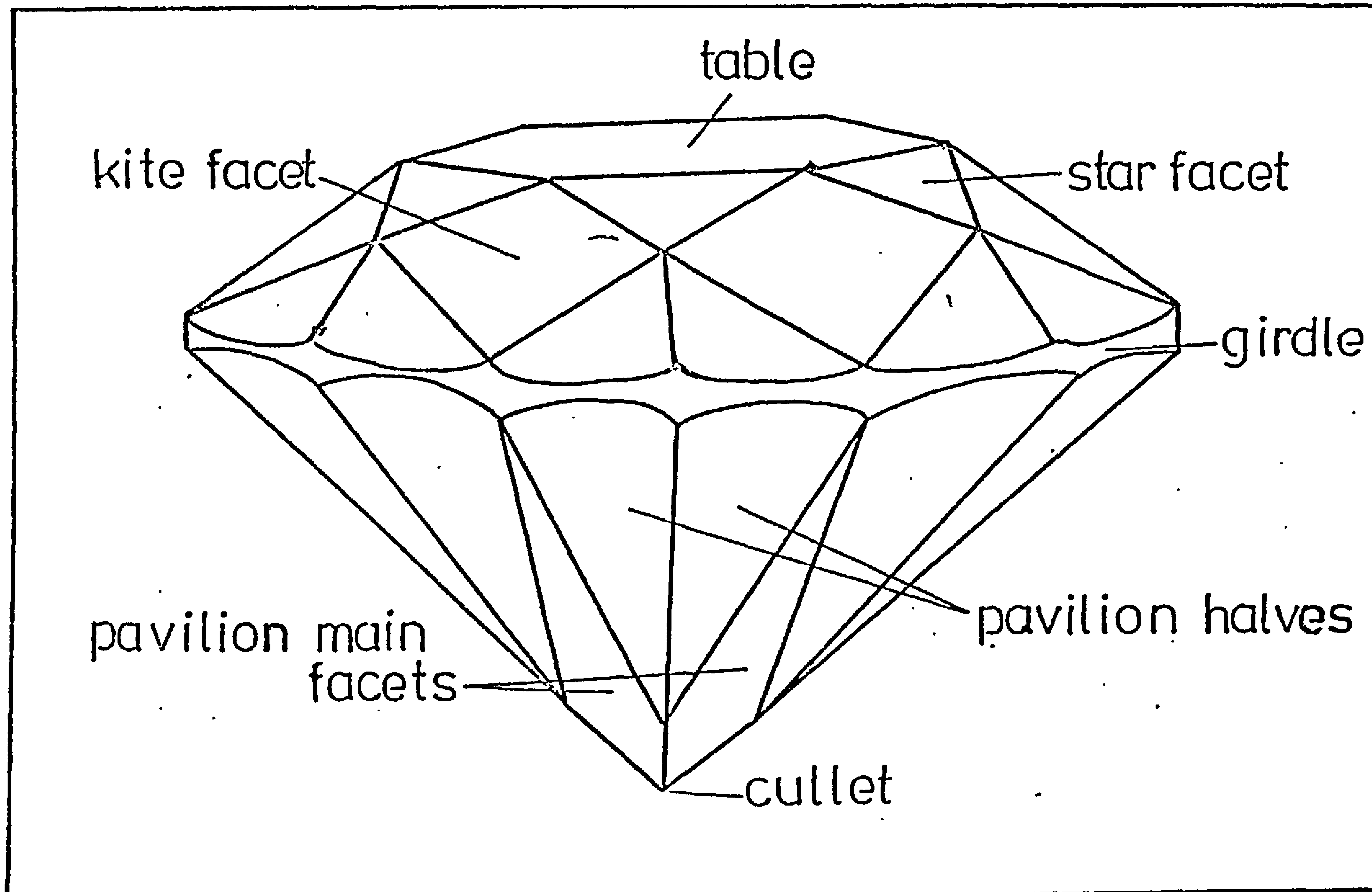


Fig. 2.3 The round brilliant cut diamond showing the facet names.

as simple measure of fire. Similarly for sparkliness, we could take the variance of the intensity distribution. However, with the forward brilliance three factors are again required to obtain a full description of the round brilliant cut diamond and so it would seem naive to expect a single quantity to describe the optical goodness of such a complex effect.

2.6 The computer Programme

A computer program was written to incorporate the details of the model and calculate the statistical measures outlined above. The programme can be split into three major units, the calculation of the shape of the prism, the raytracing of the light through the prism and the statistical analysis of the resultant spot pattern; a schematic diagram of these main elements is given in Fig. 2.2 and flow diagrams of the major blocks are found in Appendix I.

The calculation involved in finding the direction cosines of the normals for the planes that define the prism can be greatly reduced by exploitation of the 8-fold rotational symmetry and mirror symmetry of the round brilliant cut (Fig. 2.3), this resulting solid (Fig. 2.4) having only eight bounding planes. Then by requiring that the table when viewed perpendicularly should form with the stars two interlocking squares it is possible to describe the prism in terms of six factors These are the total spread, the table spread, the crown height, the pavilion depth, the total depth and the pavilion half factor (PHF), the fraction by which the

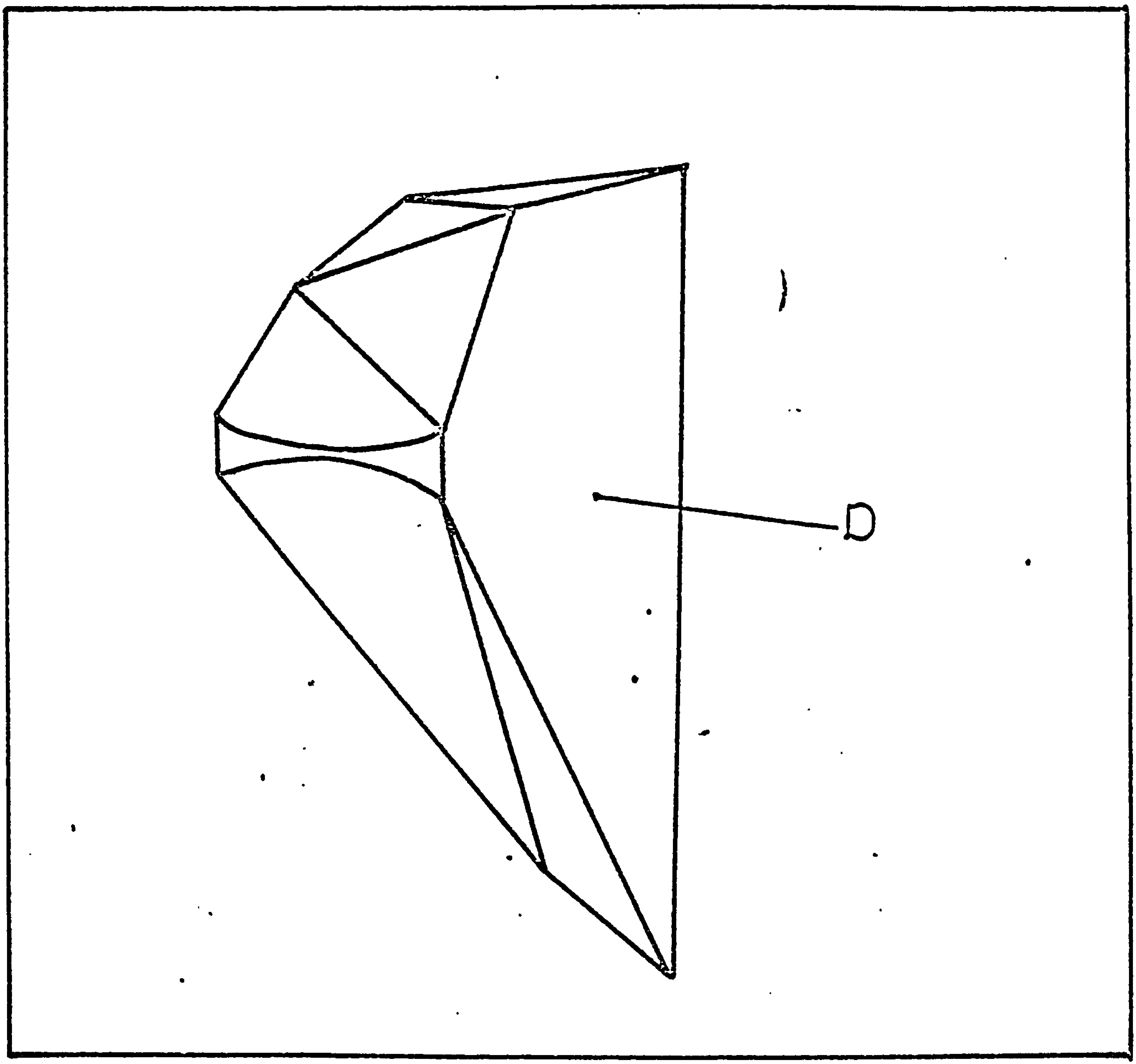


Fig. 2.4 The elemental solid from which it is possible to generate the round brilliant by a reflection and eight-fold rotation. The planes 'a' are the false planes of symmetry.

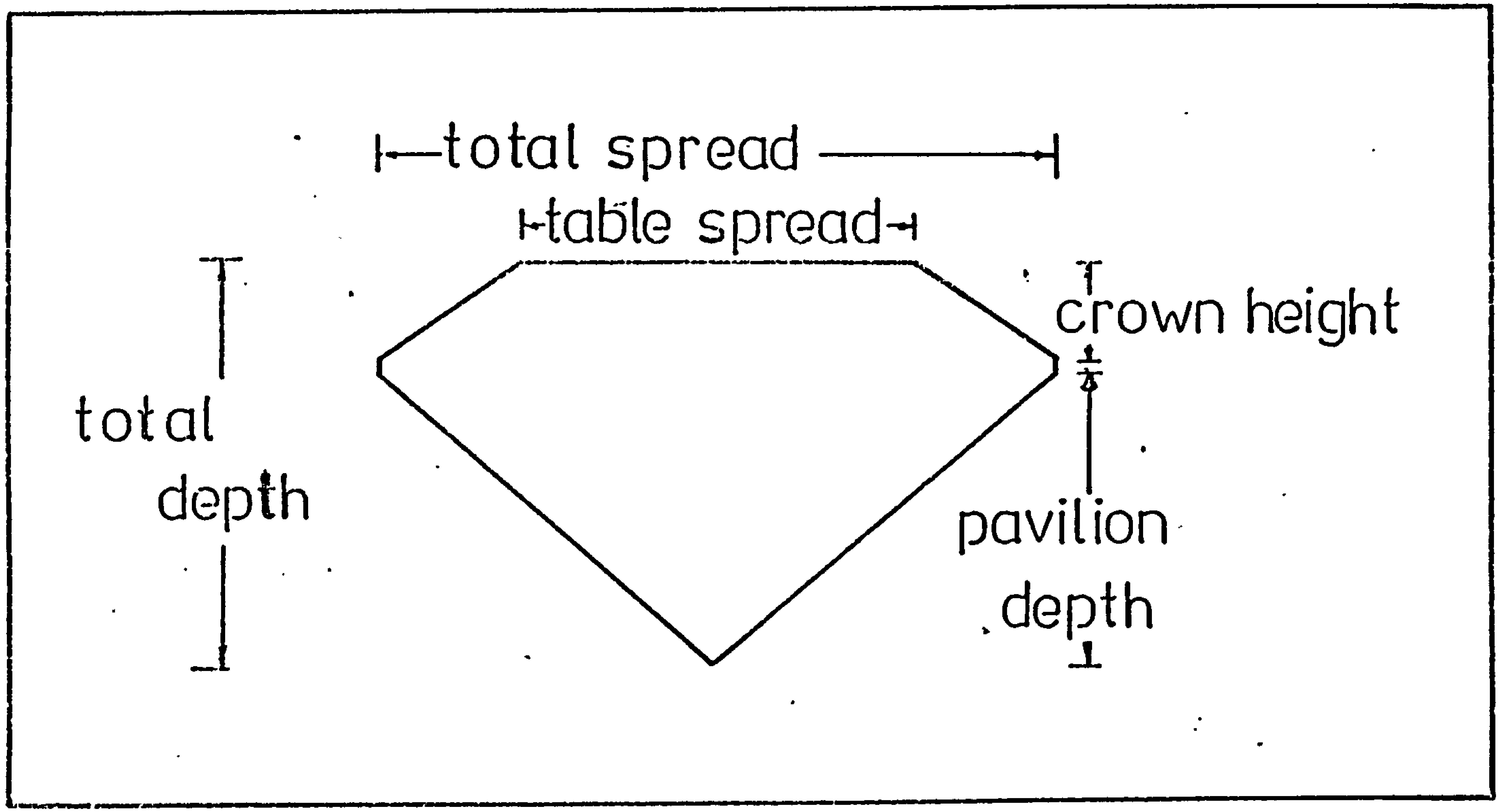


Fig. 2.5 The proportions for a round brilliant cut diamond.

pavilion halves extend towards the collet from the girdle (Fig. 2.5).

The ray tracing section has three subdivisions. The first traces the input rays to the surface of the prism, the second traces the rays using vector ray tracing equations through the prism and finally rays scattered out of the prism are traced onto the hypothetical sphere. Welford (1974) has shown that the rules of refraction and reflection can be expressed by

$$n'\underline{v}' = n\underline{v} + (n'(\underline{v}'.\underline{u}) - n(\underline{v}.\underline{u}))\ \underline{u}$$

when for an interface n and n' are the refractive indices of the present and next space, $\underline{v}$ and $\underline{v}'$ are the unit direction vectors of the incident ray and refracted or reflected ray and $\underline{u}$ is the normal vector to the interface (Fig. 2.6). It can be shown that if $\underline{v}'.\ \underline{u}$ which is the cosine of the angle of reflection or refraction is expressed in the form:

$$\frac{|\underline{v}.\underline{u}|}{\underline{v}.\underline{u}}\sqrt{1-(n/n')^2 \times (1-(\underline{v}.\underline{u})^2)}$$

then the equations of refraction contain only terms in even powers of $\underline{u}$ (the normal to the plane) and hence are independent of the direction of $\underline{u}$. It is also possible to express the Fresnel's equations in vector form. The polarisation perpendicular to the angle of incidence after refraction can be written as:

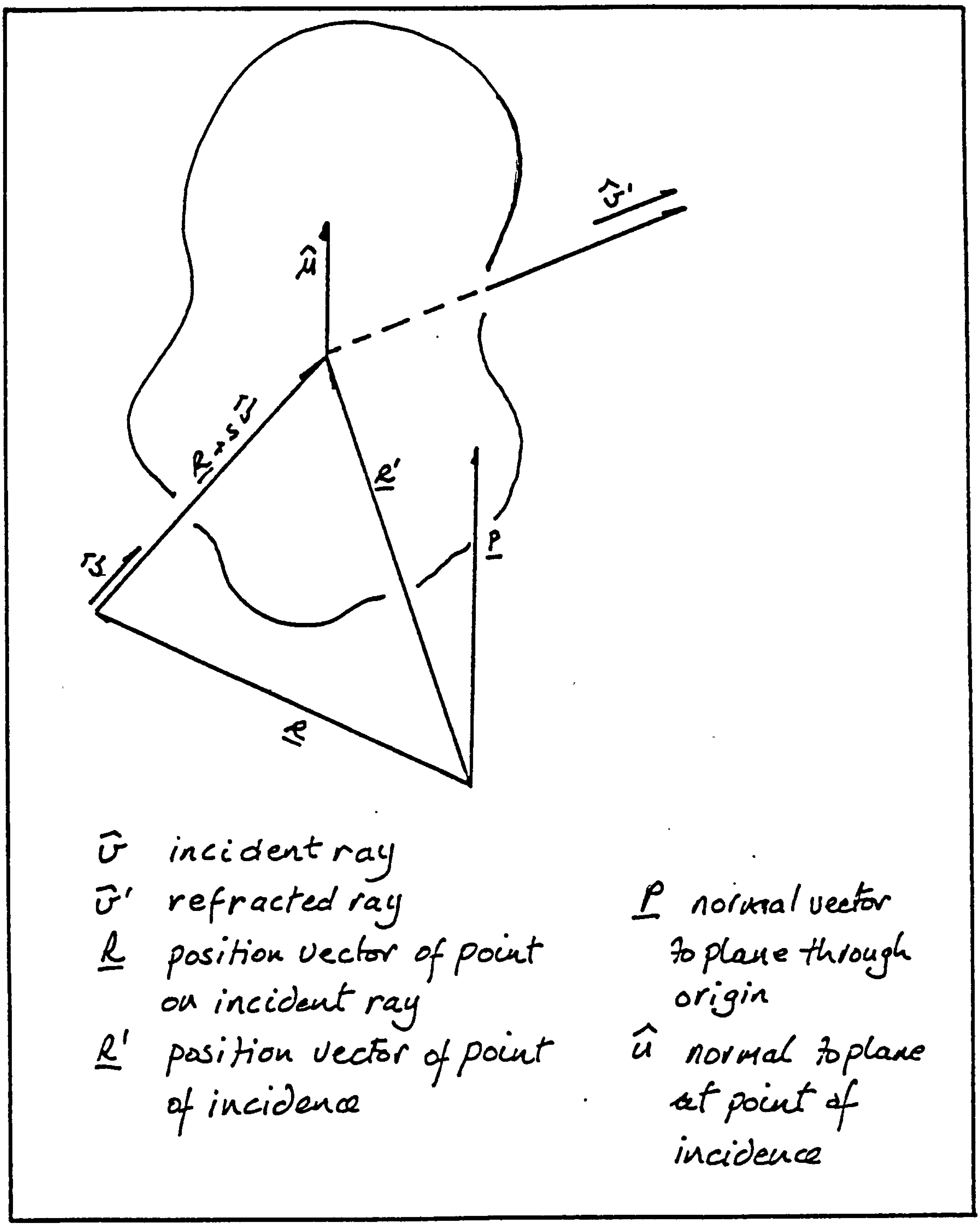


Fig. 2.6 A description of the symbols used for the ray tracing equations.

$$T_{(\underline{ai}.\underline{t})} = \frac{2n(\underline{v}.\underline{u})}{n(\underline{v}.\underline{u}) + (n'(\underline{v}'.\underline{u})} A_{(\underline{ai}.\underline{t})}$$

where for the subscript $\underline{a}_i.\underline{t}$ $\underline{a}_i$ is the unit vector in the direction of polarisation and $\underline{t}$ is a vector perpendicular to the direction of propagation of the ray in the plane of incidence hence $A(\underline{a}_i.\underline{t})$ and $T(\underline{a}_i.\underline{t})$ are the polarisations perpendicular to the plane of incidence before and after refraction. The ray tracing equations and Fresnel's equations are given in Appendix II and III.

It follows from this that it is a simple matter to trace rays in a non-reentrant prism once the forward direction of the ray has been defined.

The only difficulty with such equations is how to start the ray trace. Consider Fig. 2.7 as the raytracing equations can yield all the points of intersection with the planes in a ray's forward direction and the planes extend over all space the start ray would intersect planes 1, 2, 3, 4, and 5. How is it to distinguish plane 4 as the surface of the diamond? As the co-ordinates of the facets are already known from the calculation of the shape of the prism it is possible to calculate whether the ray hits a facet or not as follows.

Consider plane 1 a bezel (Fig. 2.7a). The area of the facet is:

Area of triangle 123 + 134 = A, say,

Similarly for the intersection point P an area

P12 + P23 + P41 = B can be calculated.

$$A < B$$

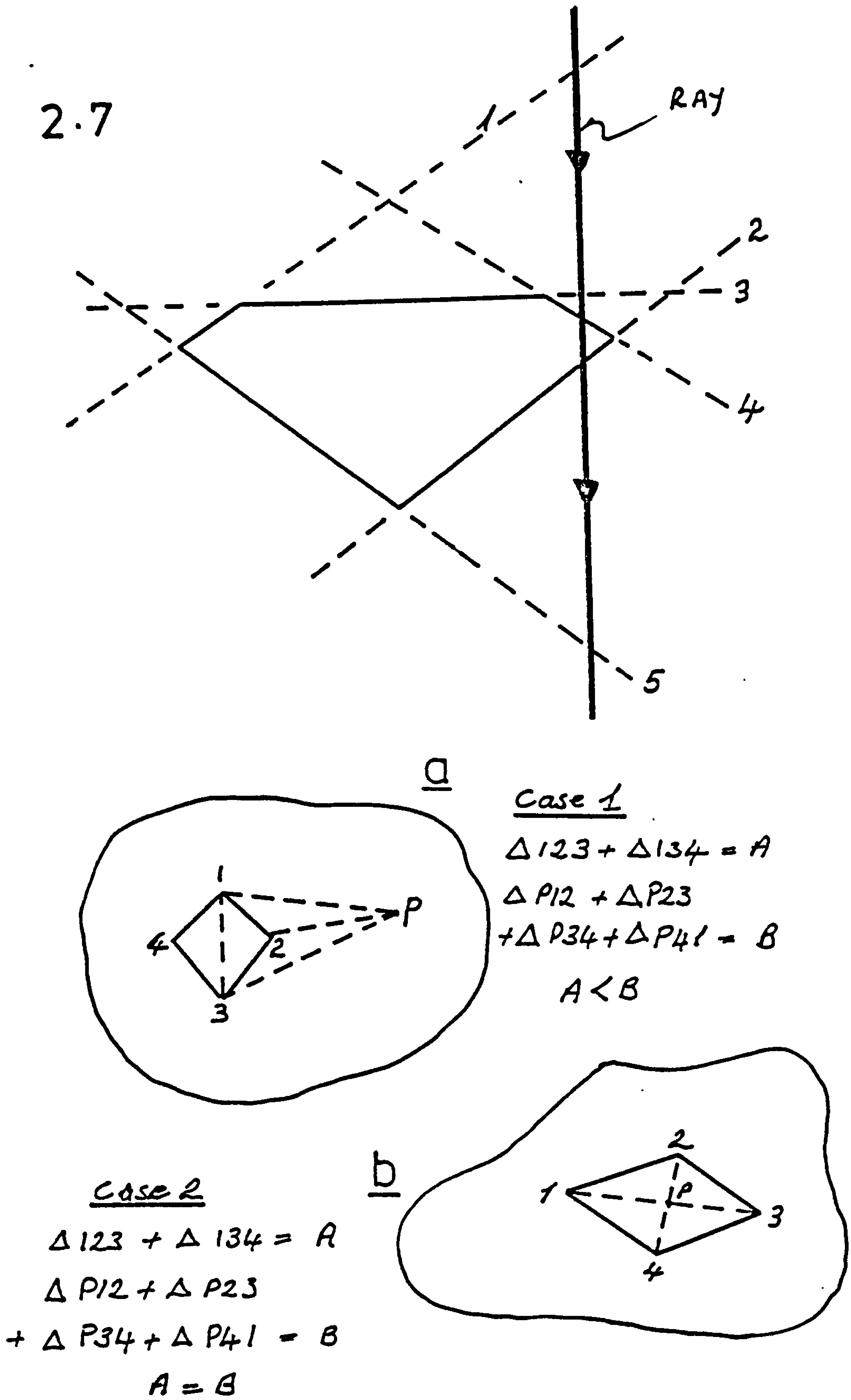


Fig. 2.7 The method used to start the ray trace. By calculation of the intercept of a ray with the facets on the stone. The closest intercept with A=B was the outside of the stone.

For Plane 4 Fig.2.7b a similar operation is carried out:

P12 + P23 + P34 + P41 = B

in this case area A = area B.

Hence the nearest plane with B = A is the surface of the stone. Once inside the stone the nearest plane along the direction of the ray is the next plane on which the ray is incident. Another point to note is that the false planes of symmetry (Fig. 2.4) have special optical properties; The Fresnel's equations are not applied, the false planes are only a mathematical device: all rays are simply reflected whatever their angle of incidence.

Finally, the statistical package calculates the measures for brilliance, sparkliness and fire, both the autocorrelation and cross-correlation being approximated by a serial product. By adopting the photon bucket rather than the more exact imaging system approach the data are divided into pupil width segments along the radial scan. This binning is modelled in terms of a serial form; for a function Q(x) the serial form T(i) is,

$$T(i) = \int_{x+(e.i)}^{x+(e(i+1))} Q(u)\, du$$

where e is the bin width.

For two functios T(i) and S(i) the serial product is defined by:

$$P(j) = \Sigma_i \; T(i) \times S(i+j)$$

For the autocorrelation $T(i) = S(i)$ and the cross-correlation is given by $T(i) \neq S(i)$.

Chapter III

The Symmetrical Round Brilliant Cut Diamond

3.1 Introduction

Of the many approximate calculations of brilliance and fire, only one has used a three-dimensional model and of the two dimensional models many have only considered the classic diamond cross section (Fig. 3.1). These methods have argued that the table, kites and pavilion mains are the principal facets, the stars and halves having a secondary role in optical effectiveness. Historically, the fashion was to polish the table to about 50% of the diameter of the stone and to have short pavilion halves. In this case the argument about principal and secondary facets was probably valid. However, recently, especially in Europe, the fashion has been to polish the table up to 65% of the total spread and to polish the pavilion halves up to 80% of the distance from girdle to collet. In this case, the pavilion halves have an area greater than the pavilion mains, and the 2-d argument breaks down. Some authors have tried to get over this by considering a particular 2-d cross section as in Fig. 3.1. This can be at best considered only a first approximation since the normals to the facets for these cross-sections do not lie in the same plane. Hence the 3-d character of the prism must be considered. The crown heights are also a feature which has changed over the past twenty years. The traditional 15% is still considered ideal with the range down to 10% as an acceptable alternative.

Let us investigate the effect on optical goodness of

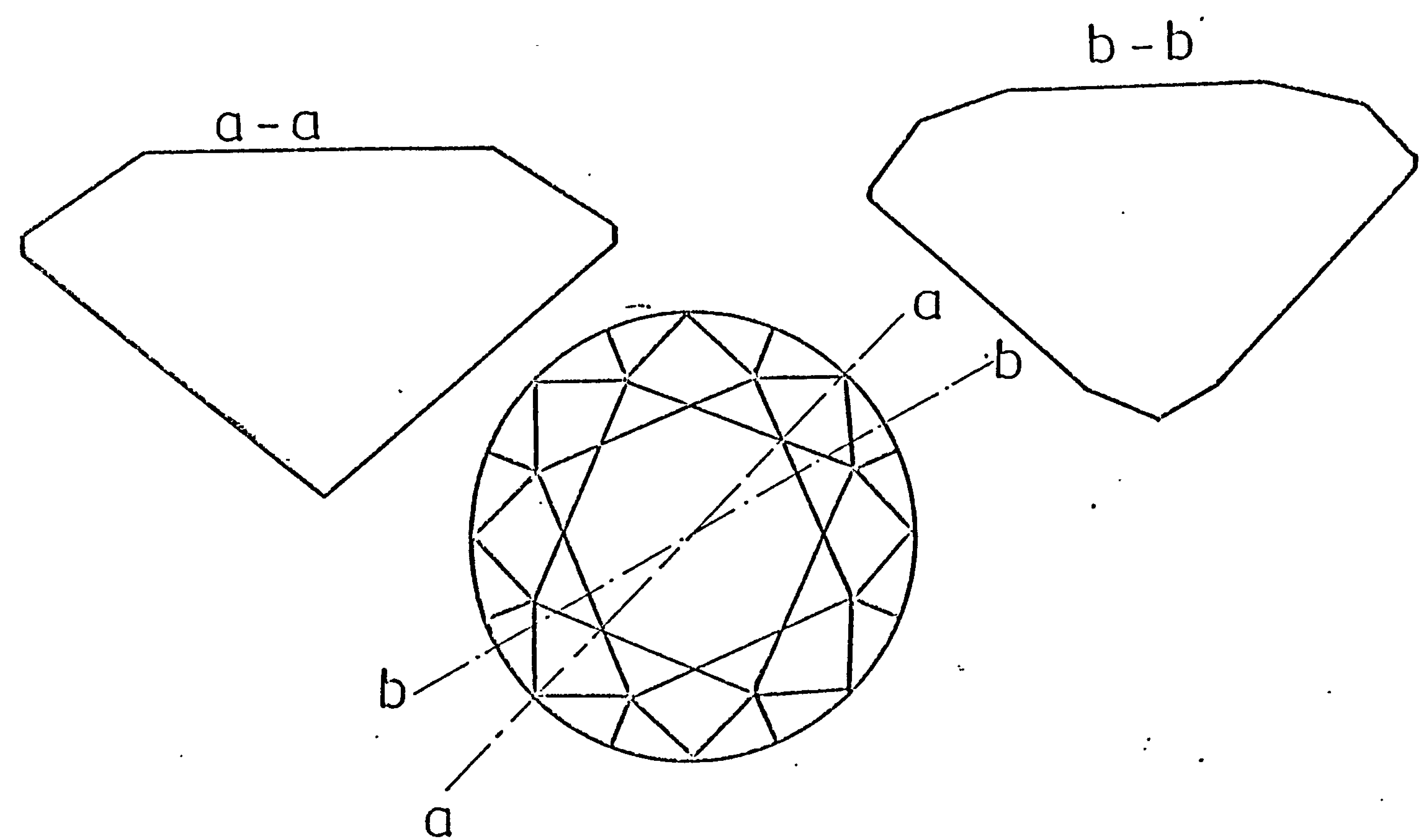


Fig. 3.1 The diamond cross section a-a and an alternative cross section b-b.

varying the crown height, table spread and pavilion half factor, for the round brilliant cut style of 58 facets.

3.2 The effect of varying the pavilion half factor

In the first instance the program was used to investigate the effect of changing the pavilion half factor (PHF) for a round brilliant cut diamond with a crown height of 15% and a table spread of 50%, a style not dissimilar to that of Tolkowsky (1919). In addition the pavilion angle is restricted to a range of 37° - 45°, the range into which all so-called 'good' brilliants fall. The results are presented in Figs. 3.2 - 3.7

The brilliance is fairly constant over the range of pavilion angles and PHF's used, confirming that brilliance alone is no guide to optical attractiveness.

Consider first the simpler measure of optical goodness, the variance of intensity and differential chroma. It is generally accepted that the ideal pavilion angle for cutting a brilliant to give maximum sparkliness is 41°; the variance of intensity has its maximum value centred on 40° and 43° pavilion angles with the maximum values of PHF 0.5 and 0.2 virtually equal. This is also in conflict with the accepted finding that larger pavilion halves increase the sparkliness markedly. A further conflict is the result of peak sparkliness for a 43° pavilion with PHF of 0.8.

The peaks in the differential chroma are all narrow, falling to about half their peak value at $\pm 1^{\circ}$ either-side of their peak pavilion angle. Here again there is disagree-

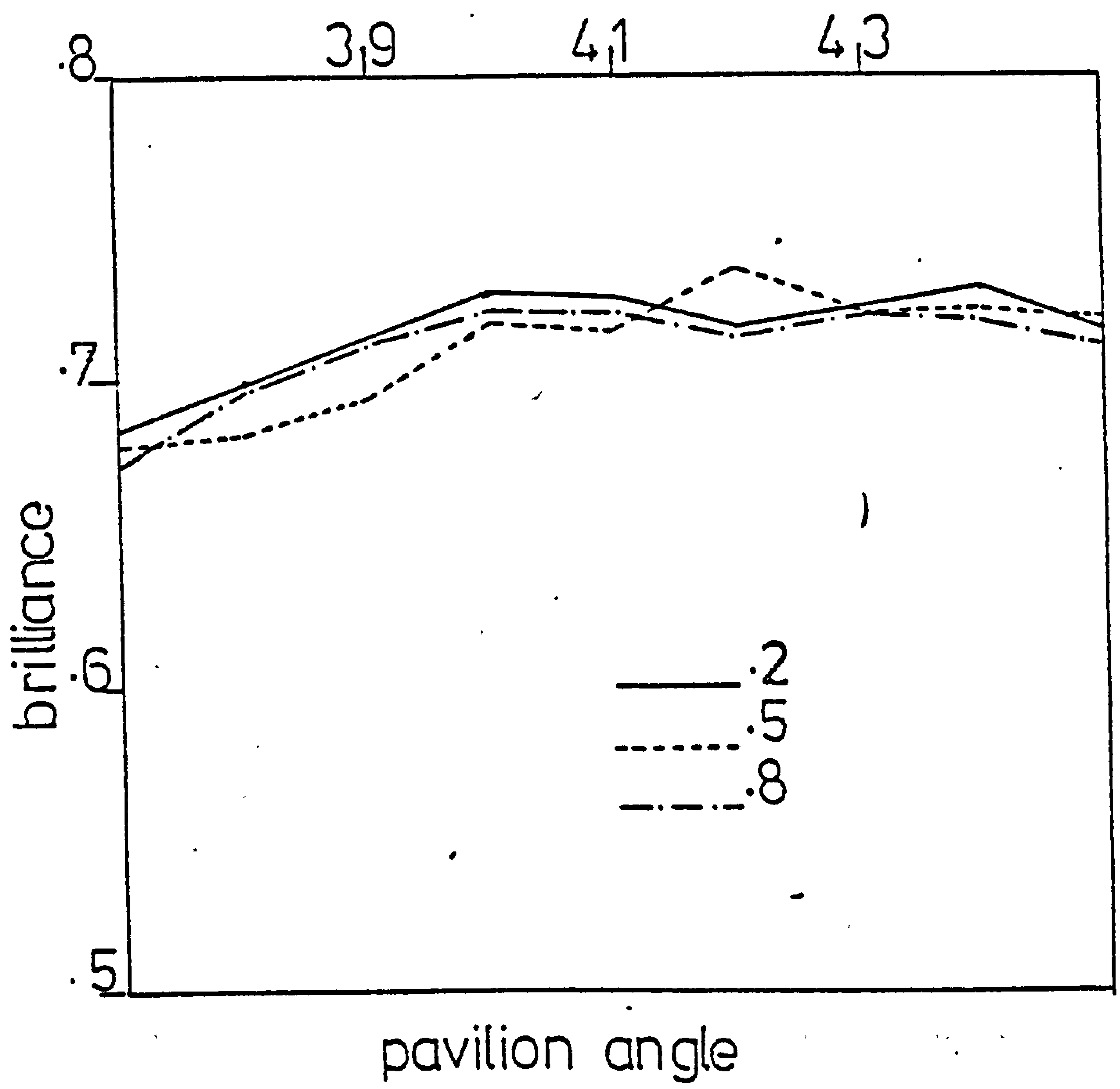


Fig. 3.2 The variation of brilliance with pavilion angle for a round brilliant cut diamond for PHF's 0.2, 0.5 and 0.8.
Crown height 15%
Table spread 50%

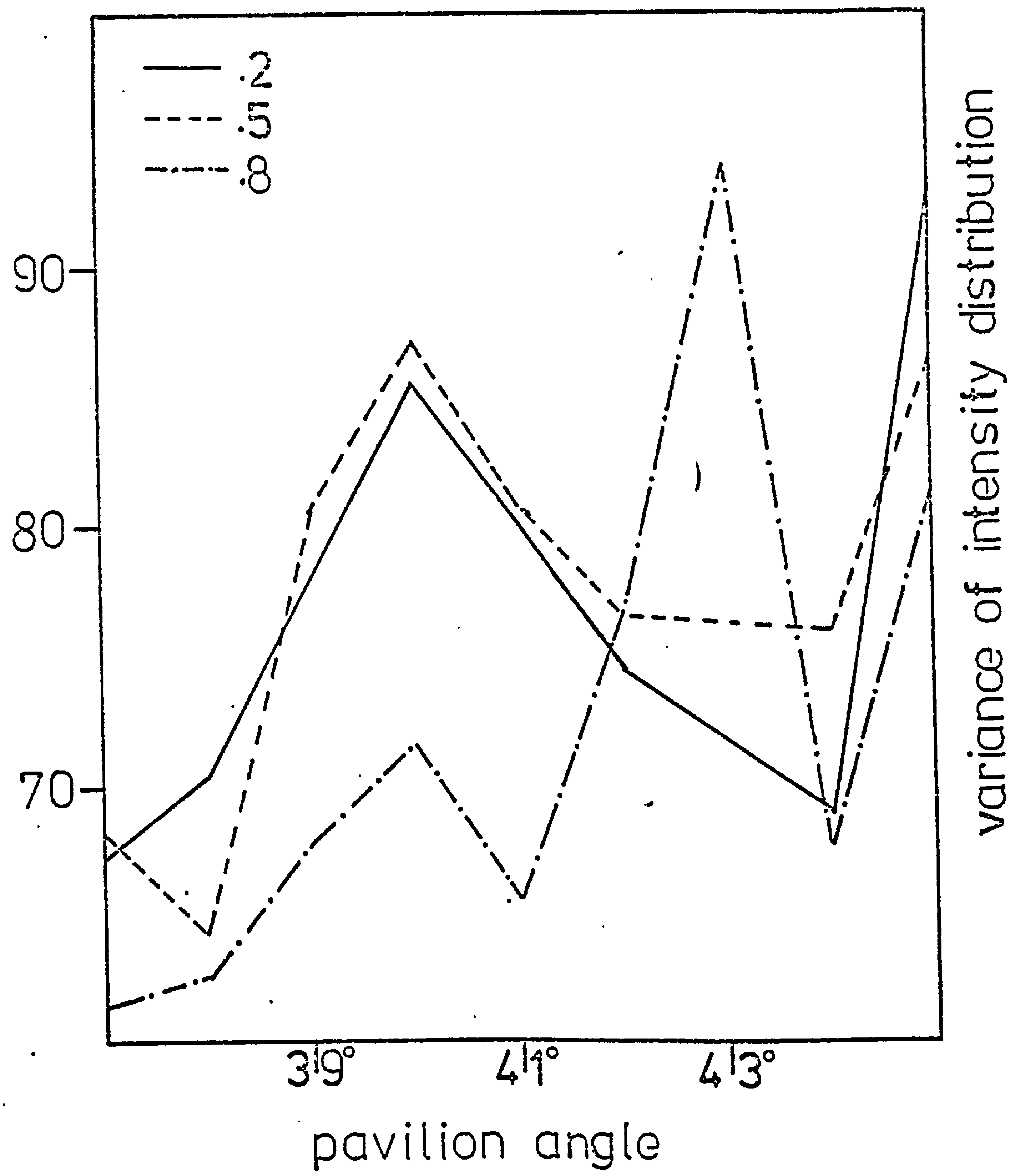


Fig. 3.3 The variation of variance of intensity with pavilion angle for a round brilliant cut diamond for PHF's 0.2, 0.5 and 0.8
Crown height 15%
Table spread 50%

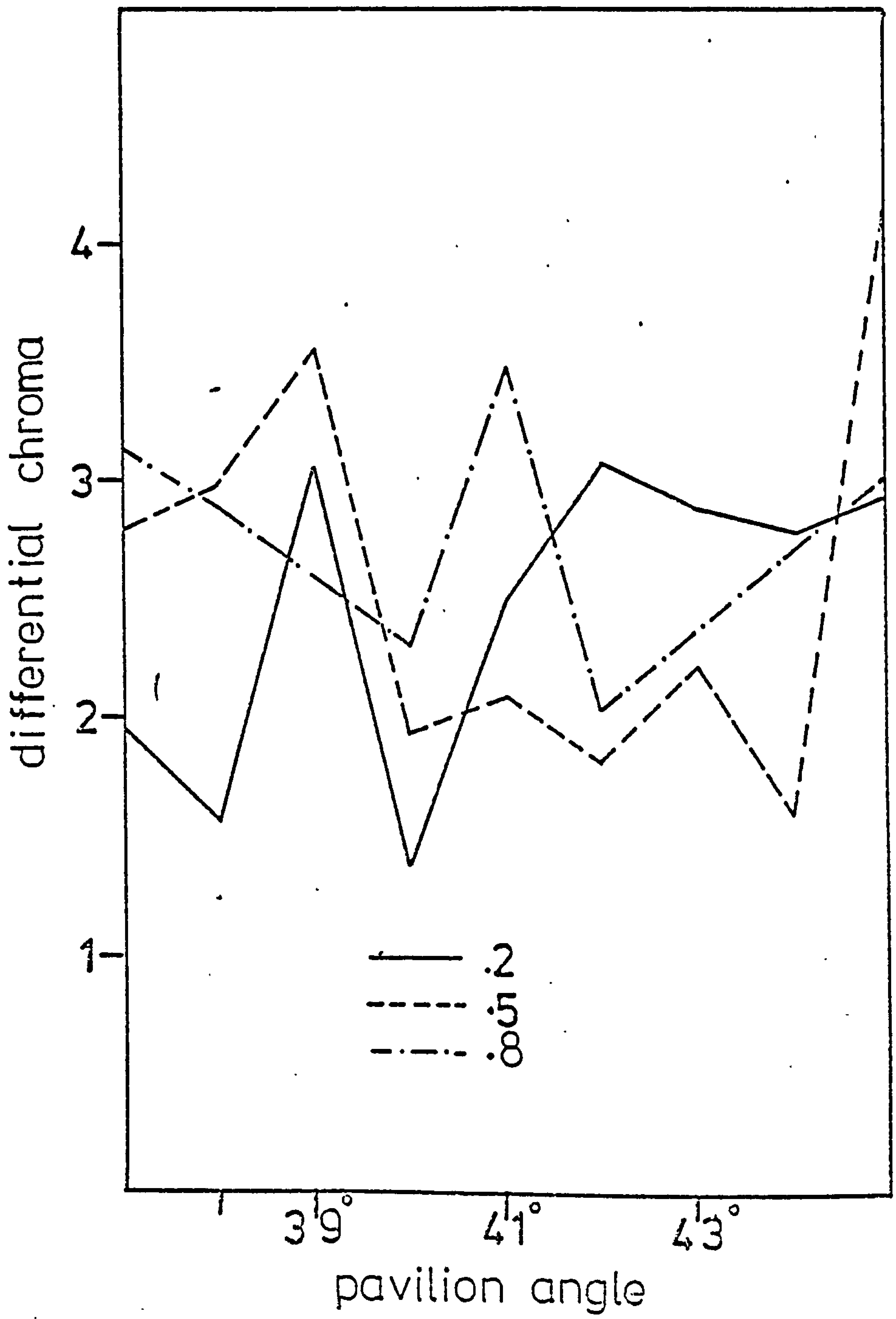


Fig. 3.4 The variation of differential chroma with pavilion angle for a round with pavilion angle for a round brilliant cut diamond for PHF's 0.2, 0.5 and 0.8
Crown height 15%
Table spread 20%

ment with the accepted view that the maximum fire occurs at about a 41^{o} pavilion angle, falling slowly ($\pm 3^{o}$) either side of this value. In addition the old mine cuts which had small pavilion halves were very fiery and this also conflicts with the predictions of the differential chroma. These contradictions with accepted findings and practice lead to the conclusion that the simpler measures,variance of intensity and differential chroma, are not an accurate enough mirror of the psychophysical appreciation of a diamond.

Now consider the two correlation factors, sparkliness and fire (Fig. 3.5 and 3.7). The cross-correlation results (Fig. 3.6) are included for completeness on this occasion. The factor sparkliness exhibits the accepted form for sparkliness, the PHF 0.8 and 0.5 being higher than PHF 0.2 with the major peaks centred on the pavilion angle 41^{o}. The PHF 0.8 again shows a peak at both pavilion angles of 40^{o} and 43^{o}. With regard to the measure for fire the peak values correspond to accepted findings, i.e. with the peaks centred on a pavilion of 41^{o} and the short pavilion half 0.2 having more fire than the modern brilliants. As these two factors provide such a close agreement with the accepted generalizations they were adopted with brilliance as the triplet of measures for optical goodness. The only disagreement with the usual findings and popular belief is that the pavilion factor 0.8 (the current fashion) does not have its peak at 41^{o} in sparkliness, appearing to have more fire and less sparkliness than for a PHF 0.5.

As the normal practice is to keep the pavilion angle

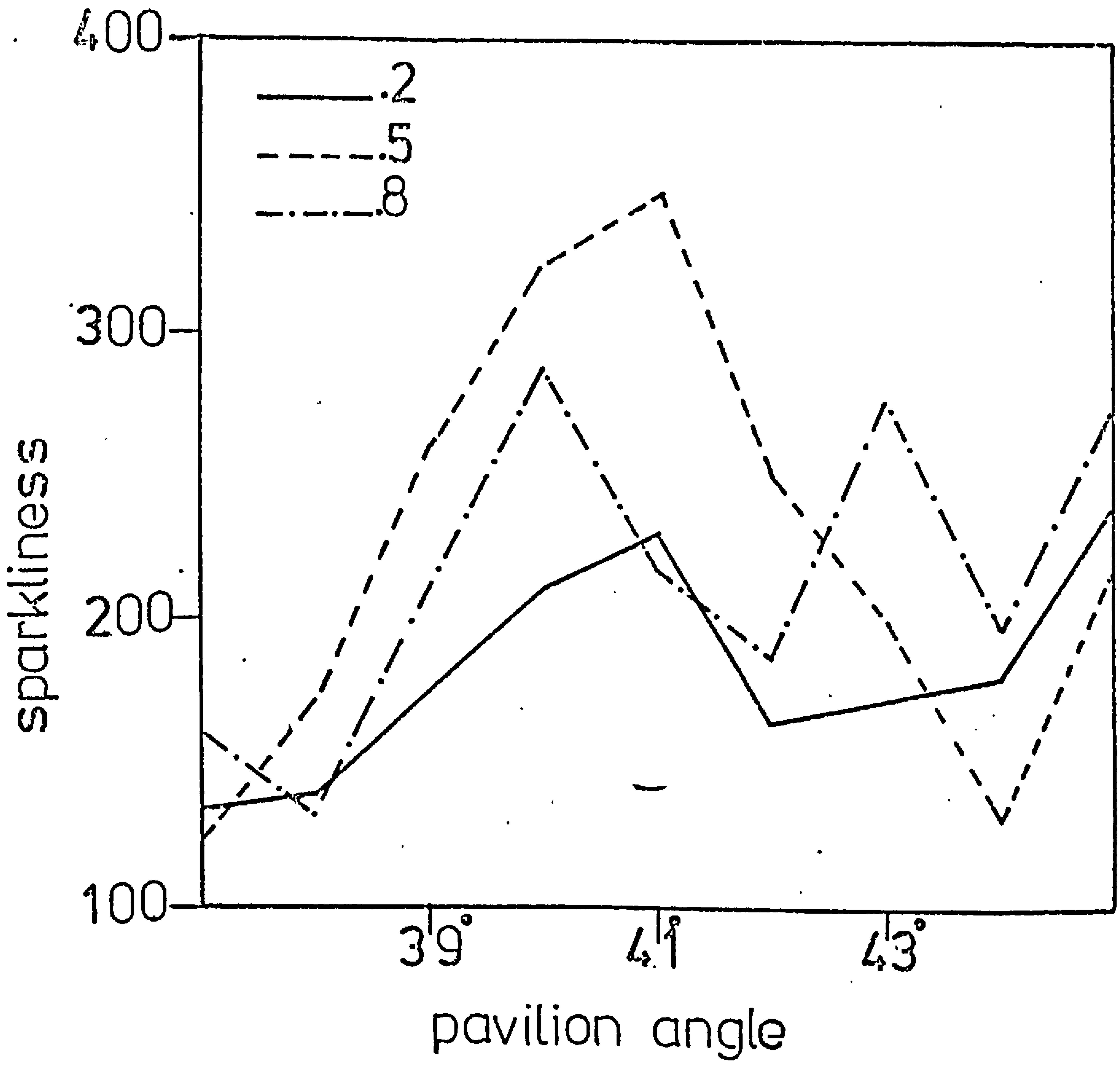


Fig. 3.5 The variation of sparkliness with pavilion angle for a round brilliant cut diamond for PHF's 0.2, 0.5 and 0.8
Crown height 15%
Table spread 50%

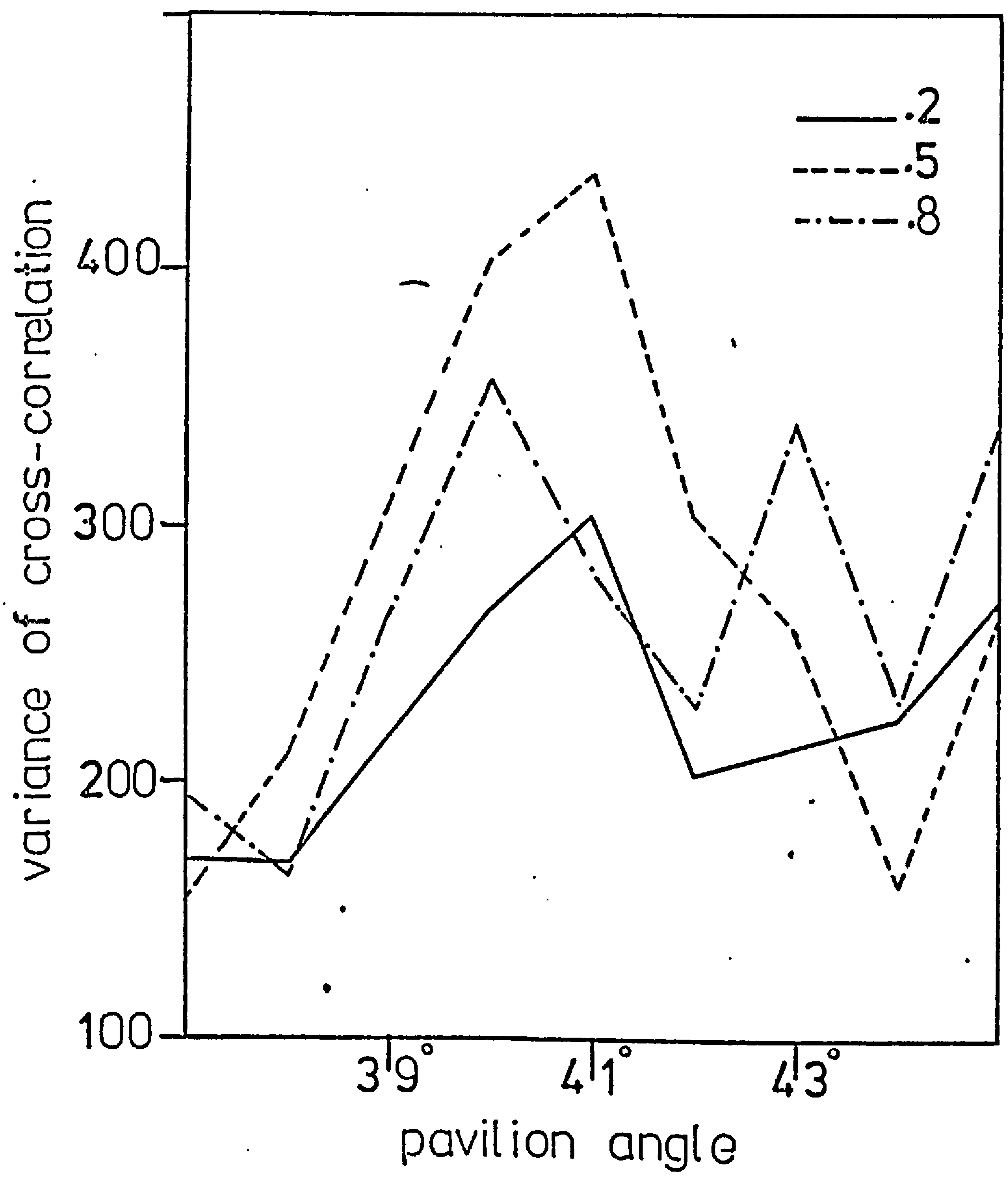


Fig. 3.6 The variation of variance of cross-correlation with pavilion angle for a round brilliant cut diamond for PHF's 0.2, 0.5 and 0.8
Crown height 15%
Table spread 50%

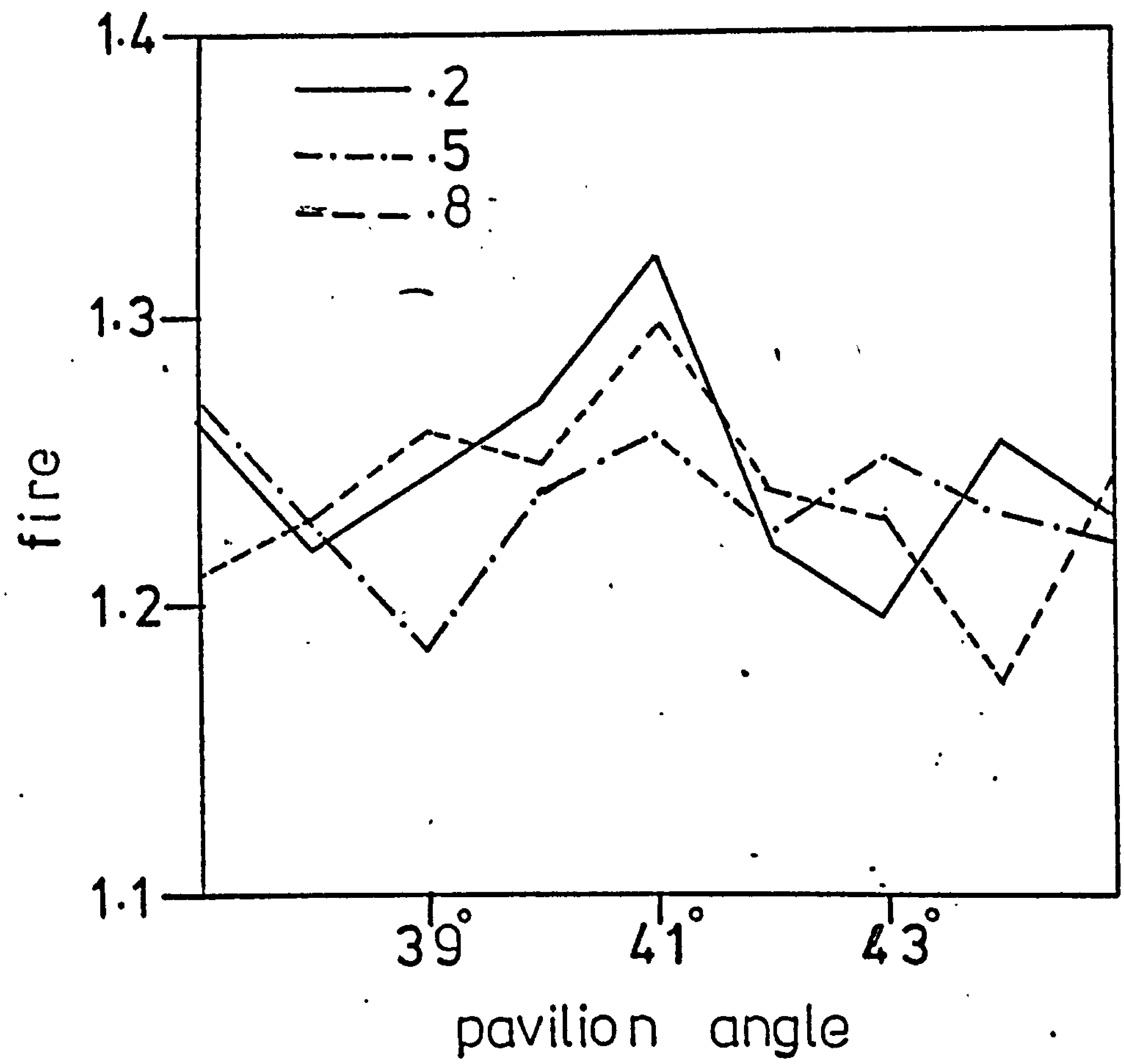


Fig. 3.7 The variation of fire with pavilion angle for a round brilliant cut diamond for PHF's 0.2, 0.5 and 0.8
Crown height 15%
Table spread 50%

in the range 39° - 42° and as it is often possible to gain a higher yield from a piece of thin rough diamond by using a lower pavilion angle, the shallow pavilion style is often encountered.

For a pavilion angle of 39° the statistical sparkliness of PHF 0.5 is still greater than PHF 0.8. However, the fire factor for PHF 0.8 is in the order of 45% higher than the corresponding value for PHF 0.5. Thus the effect of economics of production may have resulted in a stone with lower sparkliness and higher fire, which is acceptable to the current fashion.

3.3 The effect of changing the table spread and crown height

Consider now the other current fashion for polishing stones with larger table spreads and shallow crowns. Recall also the historical preference for polishing brilliants with a pavilion angle up to 54° (the octahedral angle). We choose the pavilion angles to range from 37° - 54°, select a range of crown heights of 10%, 15% and 20% of total diameter and take the table spreads to be 40%, 50%, 60% and 70% of maximum spread, recalling the design of Parker with a 10% crown height and Johnson's with a 20% crown. The pavilion half factor was kept fixed at 0.5 for all the designs. The results are presented in Figs. 3.8 - 3.16.

The brilliance (Figs. 3.8, 3.11 and 3.14) exhibits two trends, that of increasing brilliance with decreasing crown height and for a given crown height increasing brilliance with decreasing table spread. The 60% and 70% table spreads for the 10% crown height have comparable

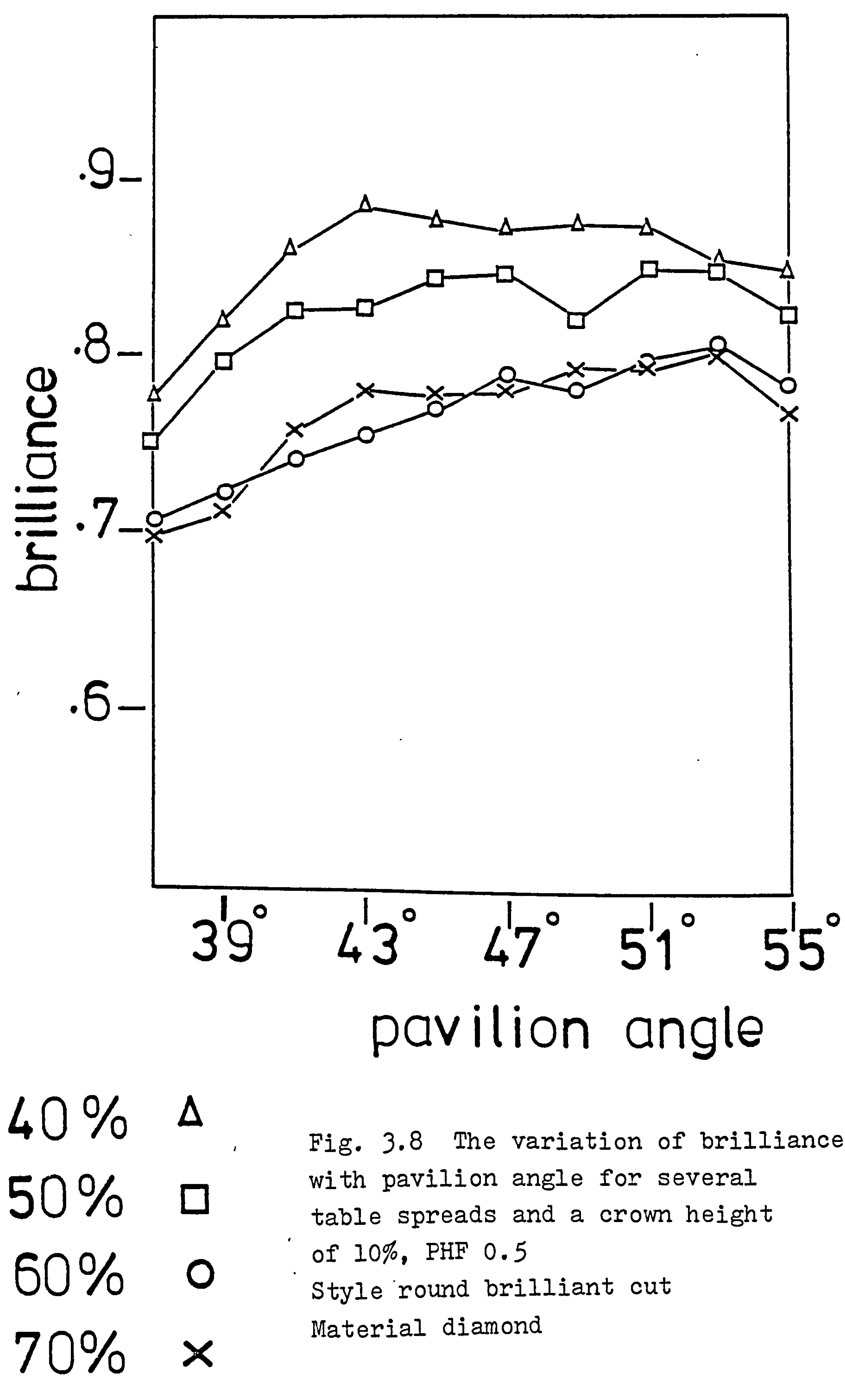


Fig. 3.8 The variation of brilliance with pavilion angle for several table spreads and a crown height of 10%, PHF 0.5
Style round brilliant cut
Material diamond

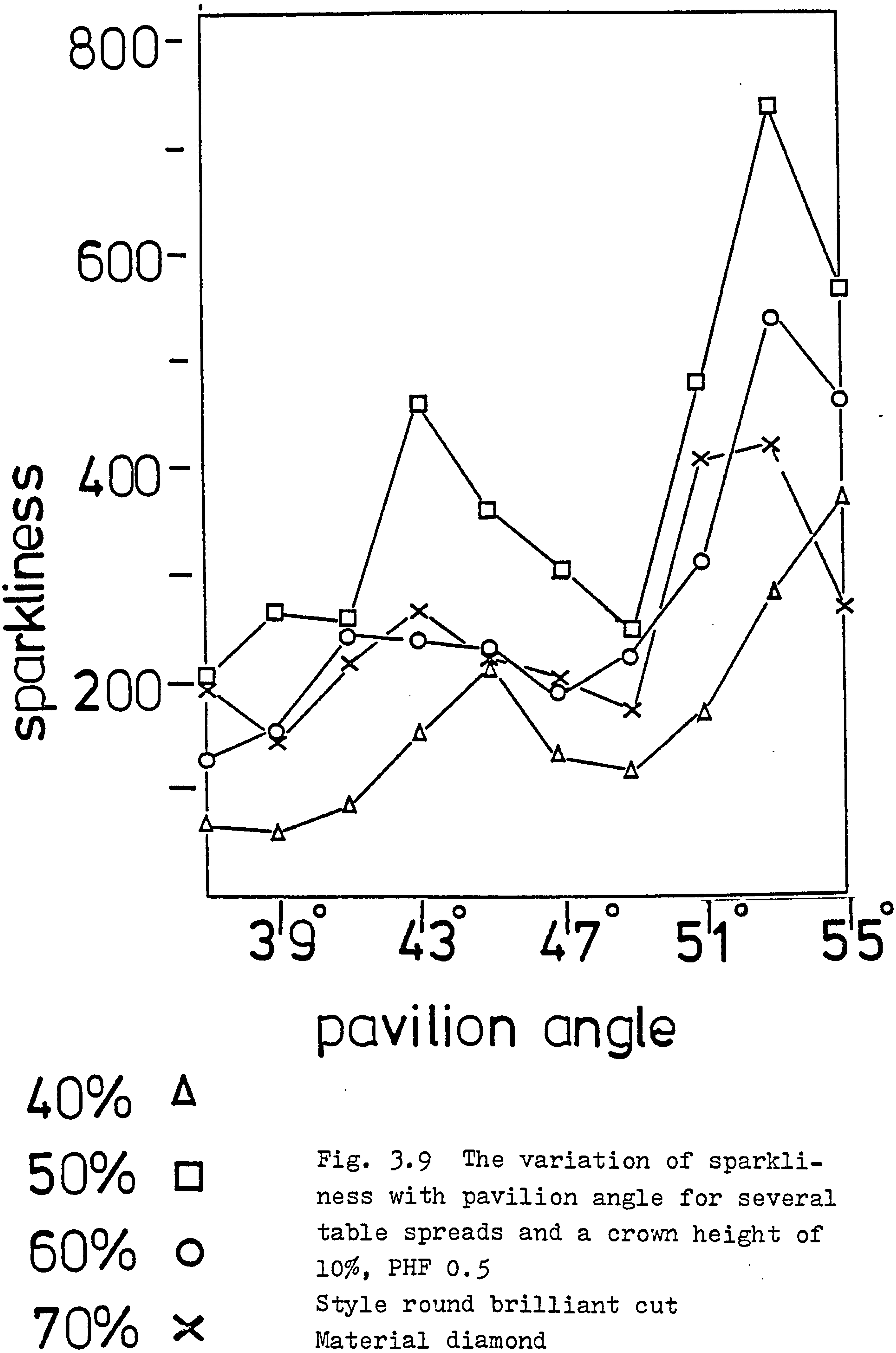


Fig. 3.9 The variation of sparkliness with pavilion angle for several table spreads and a crown height of 10%, PHF 0.5
Style round brilliant cut
Material diamond

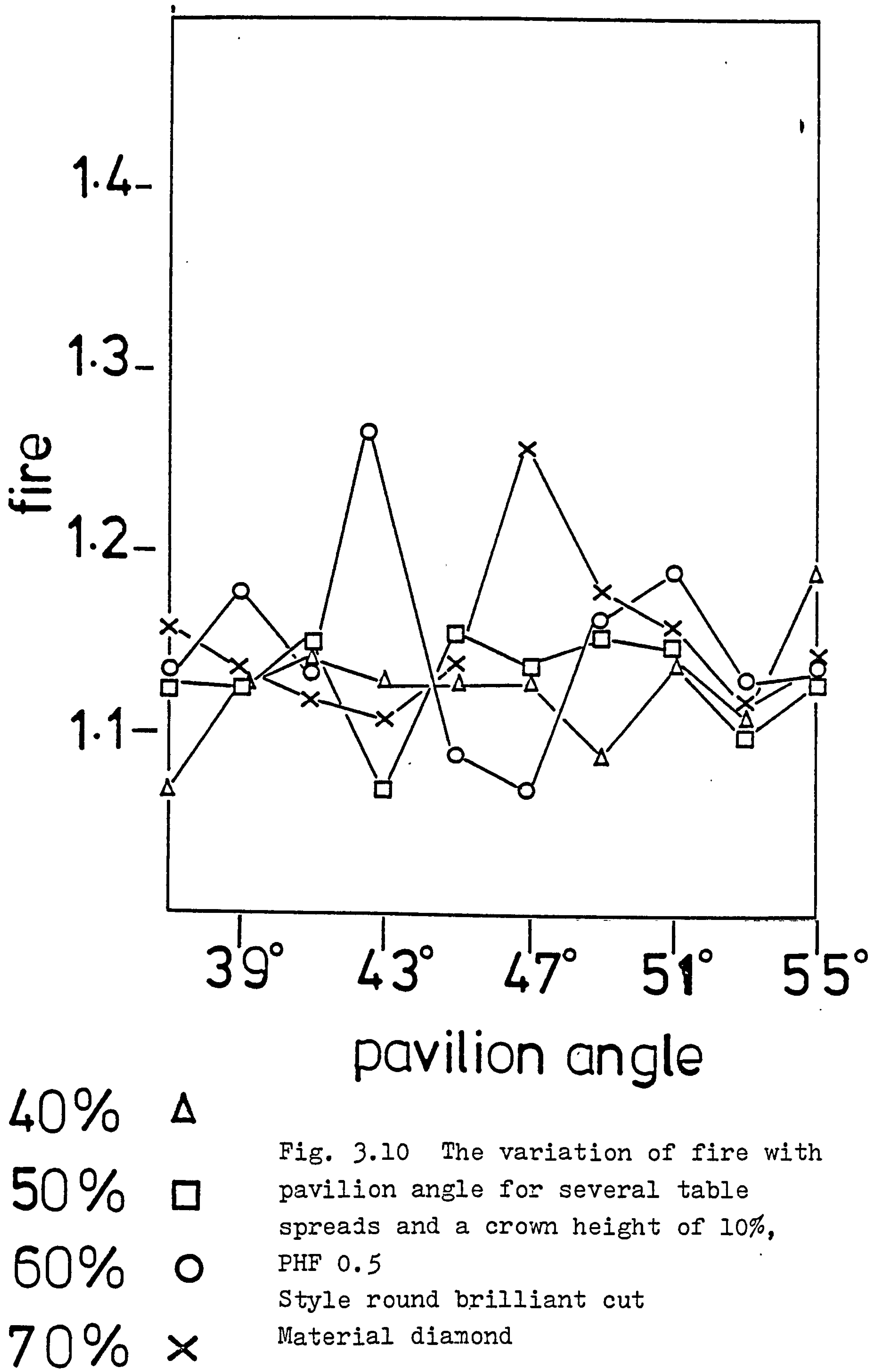


Fig. 3.10 The variation of fire with pavilion angle for several table spreads and a crown height of 10%, PHF 0.5
Style round brilliant cut
Material diamond

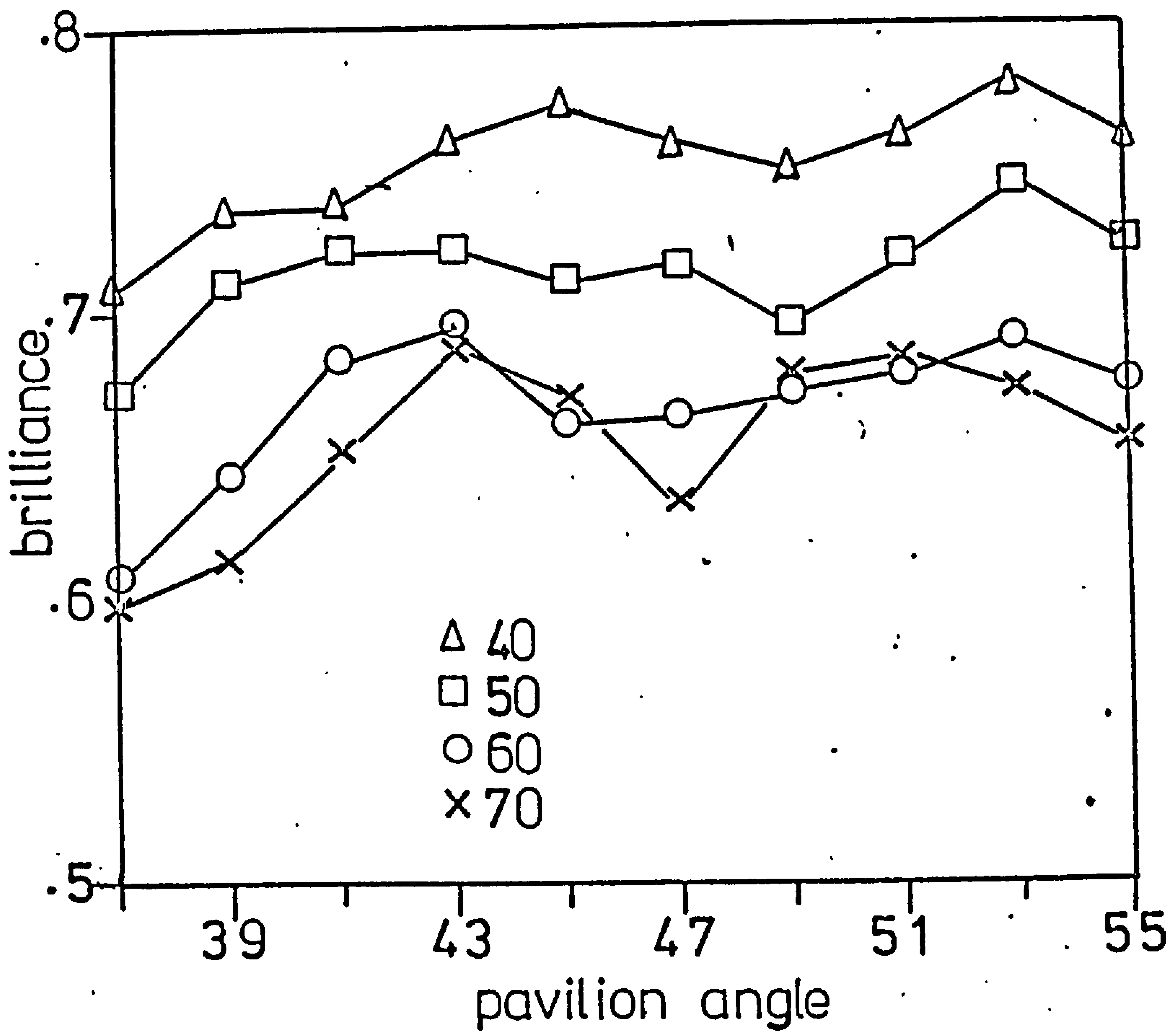


Fig. 3.11 The variation of brilliance with pavilion angle for several table spreads and a crown height of 15%, PHF 0.5
Style round brilliant cut
Material diamond

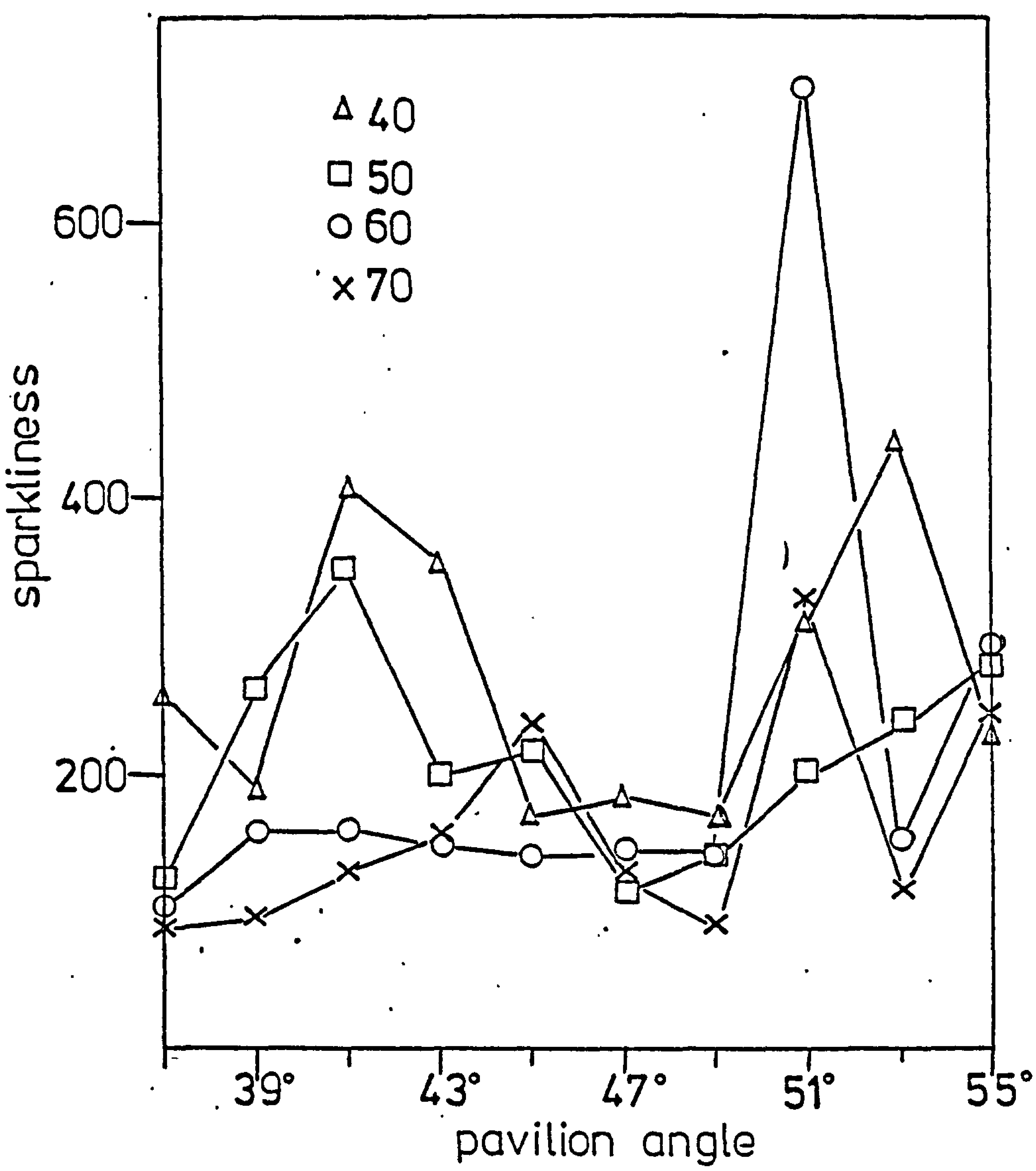


Fig. 3.12 The variation of sparkliness with pavilion angle for several table spreads and a crown height of 15%, PHF 0.5
Style round brilliant cut
Material diamond

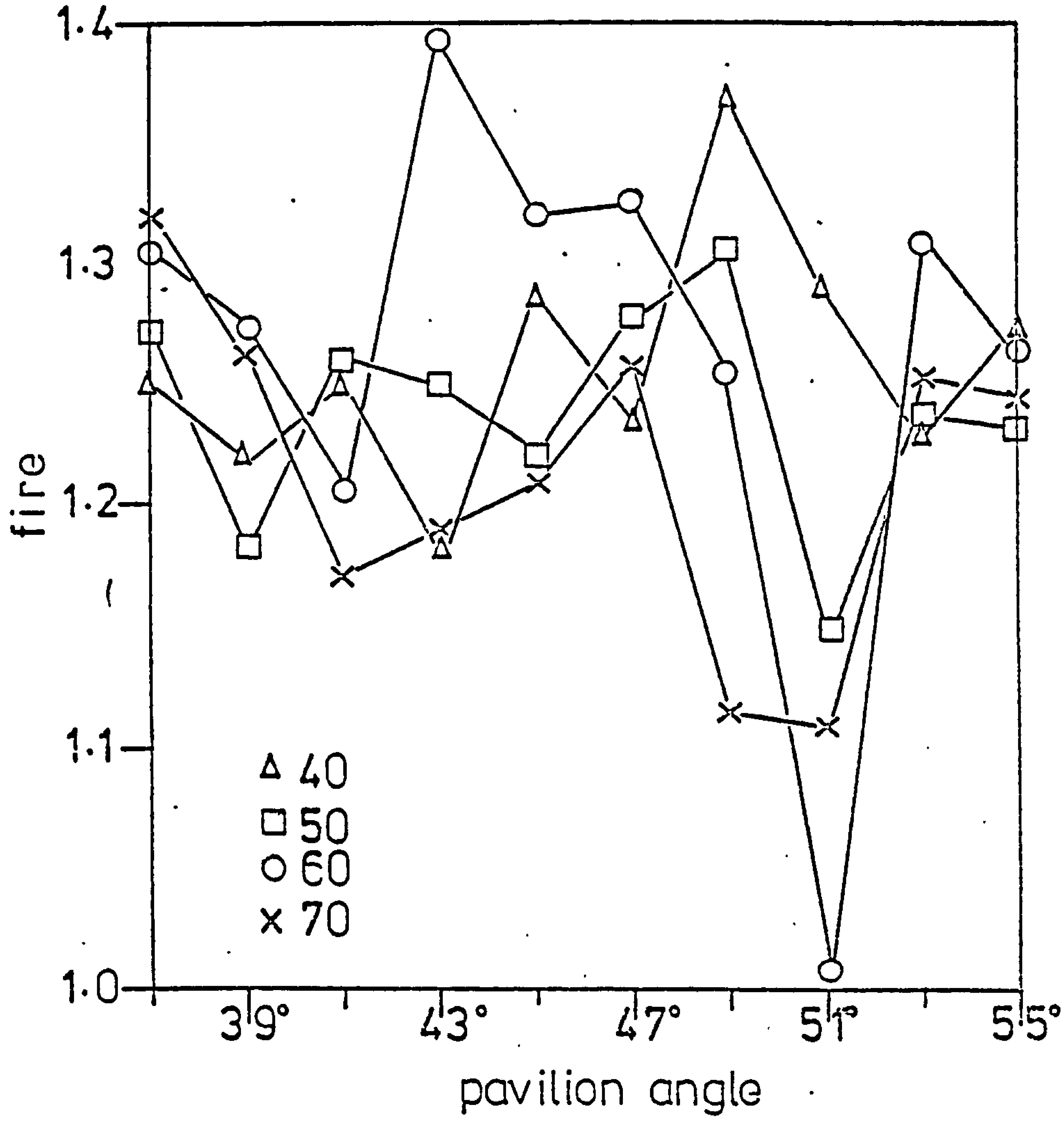


Fig. 3.13 The variation of fire with pavilion angle for several table spreads and a crown height of 15%, PHF 0.5
Style round brilliant cut
Material diamond

brilliance to those designs with 40% and 50% tables and a 15% crown height.

The measure of sparkliness shows one major trend, that of two sets of peaks. A set of maxima centred on pavilion angles of 41° - 43° and a second, generally higher peaks, centred on 51° - 53° pavilion angles.

For the preferred pavilion angles the sparkliness of the 20% crown height is lower than that of the 10% and 15% crowns. This perhaps explains why Johnson's and Rosch's designs were not universally adopted in the late 1920's and '30's in contrast to Eppler's designs. These, which had a 15% crown height were quickly adopted in the late 1930's and as demonstrated in Fig. 3.12, they exhibit the greater sparkliness. An interesting advantage in going from a 15% to a 10% crown height is the increase in performance of those designs with 60% and 70% table spreads. At the ideal pavilion angle (41°), the 50% and 60% table spreads have virtually equal sparkliness.

For fire the stones all appear to perform equally, the only discernable feature being the maximum in fire for a 60% table spread at a pavilion angle of 43°.

By polishing flatter crowns and tables with greater spreads it is again sometimes possible to obtain a stone with a higher yield from the rough, as was the case with the shallower pavilion angle. The 5% reduction in crown height can be translated into an extra three degrees of pavilion angle. Hence it is sometimes possible to get an ideally proportioned pavilion on an otherwise shallow stone. For example a 36° pavilion showing the girdle

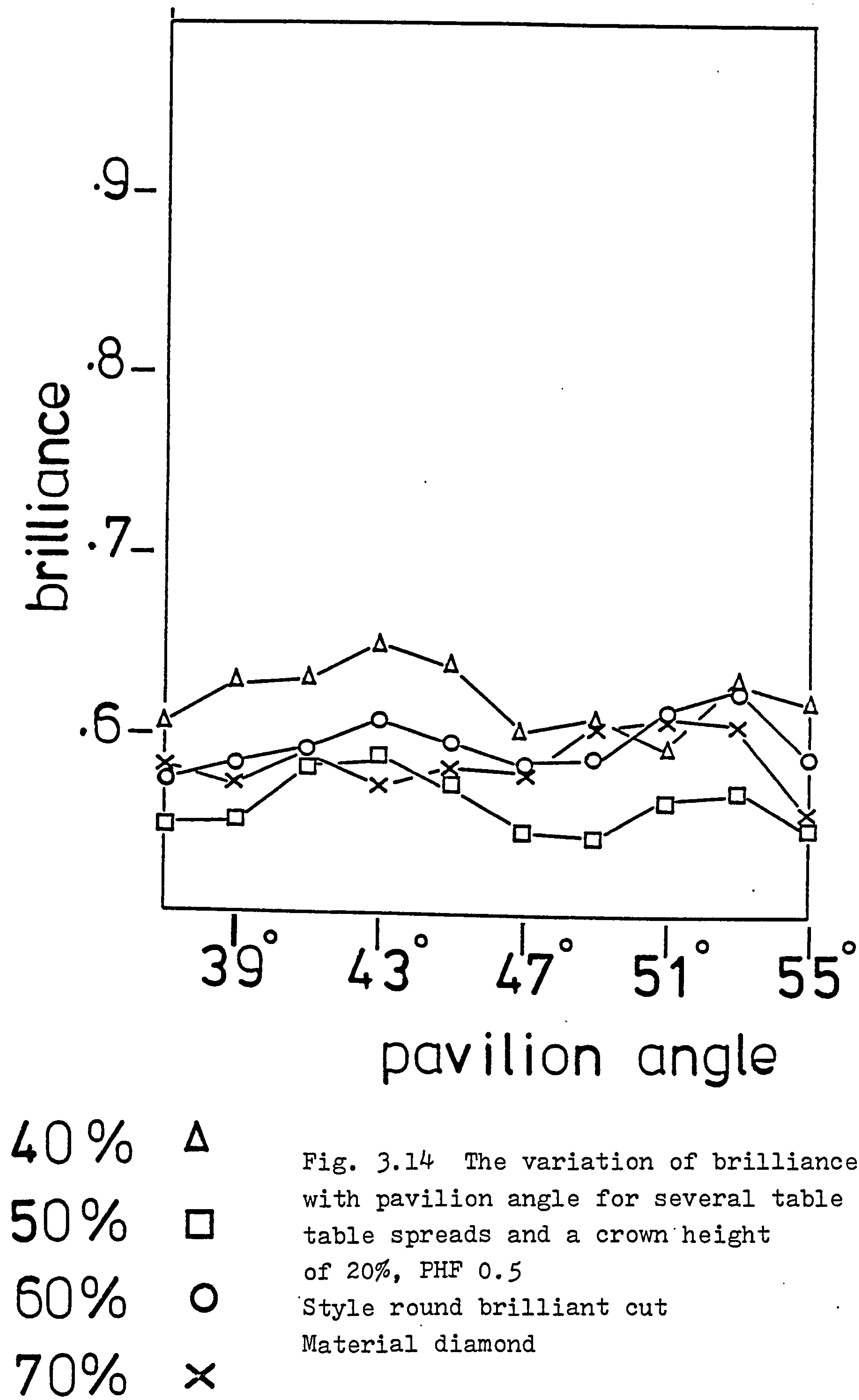


Fig. 3.14 The variation of brilliance with pavilion angle for several table table spreads and a crown height of 20%, PHF 0.5
Style round brilliant cut
Material diamond

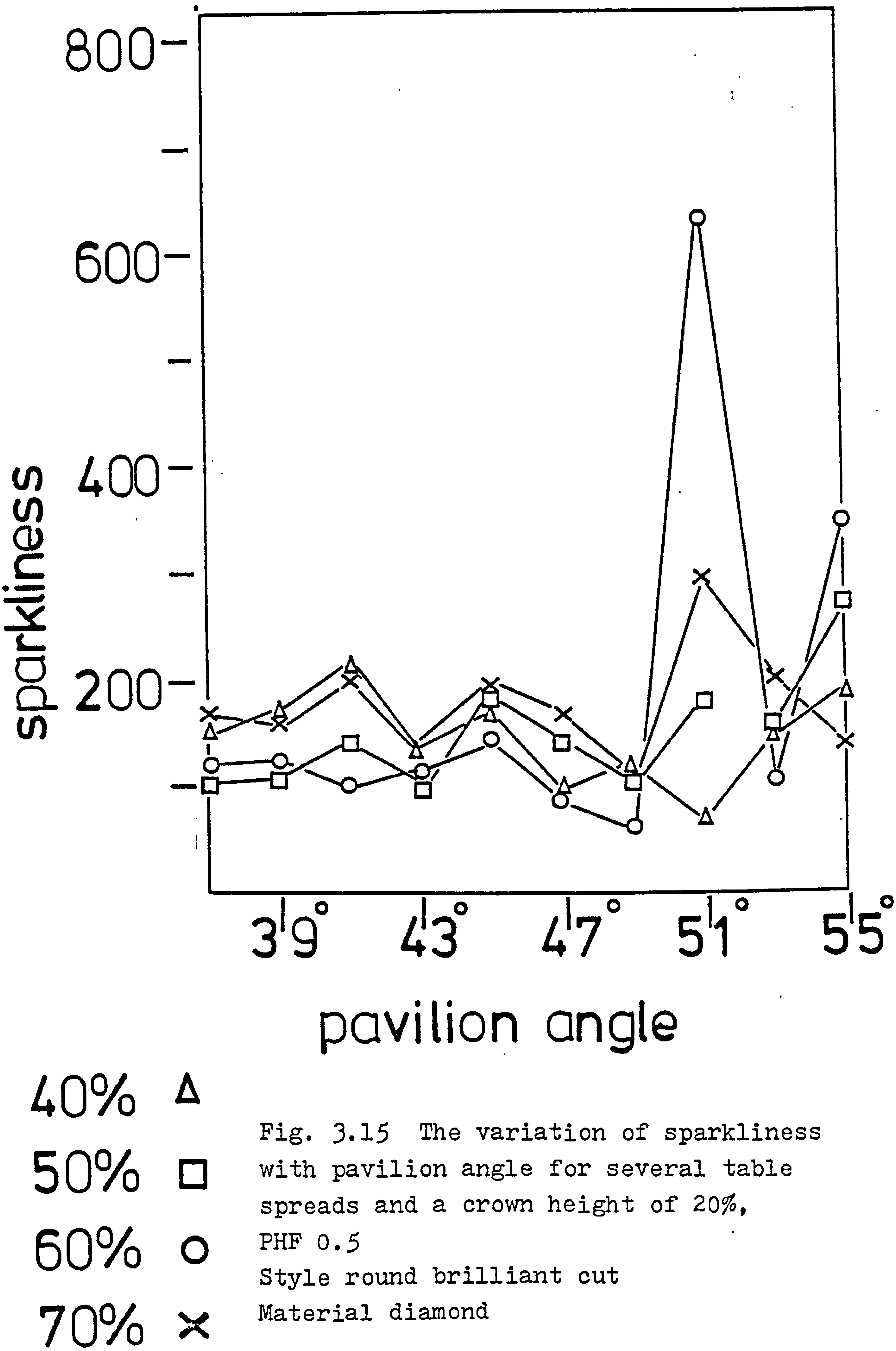


Fig. 3.15 The variation of sparkliness with pavilion angle for several table spreads and a crown height of 20%,
PHF 0.5
Style round brilliant cut
Material diamond

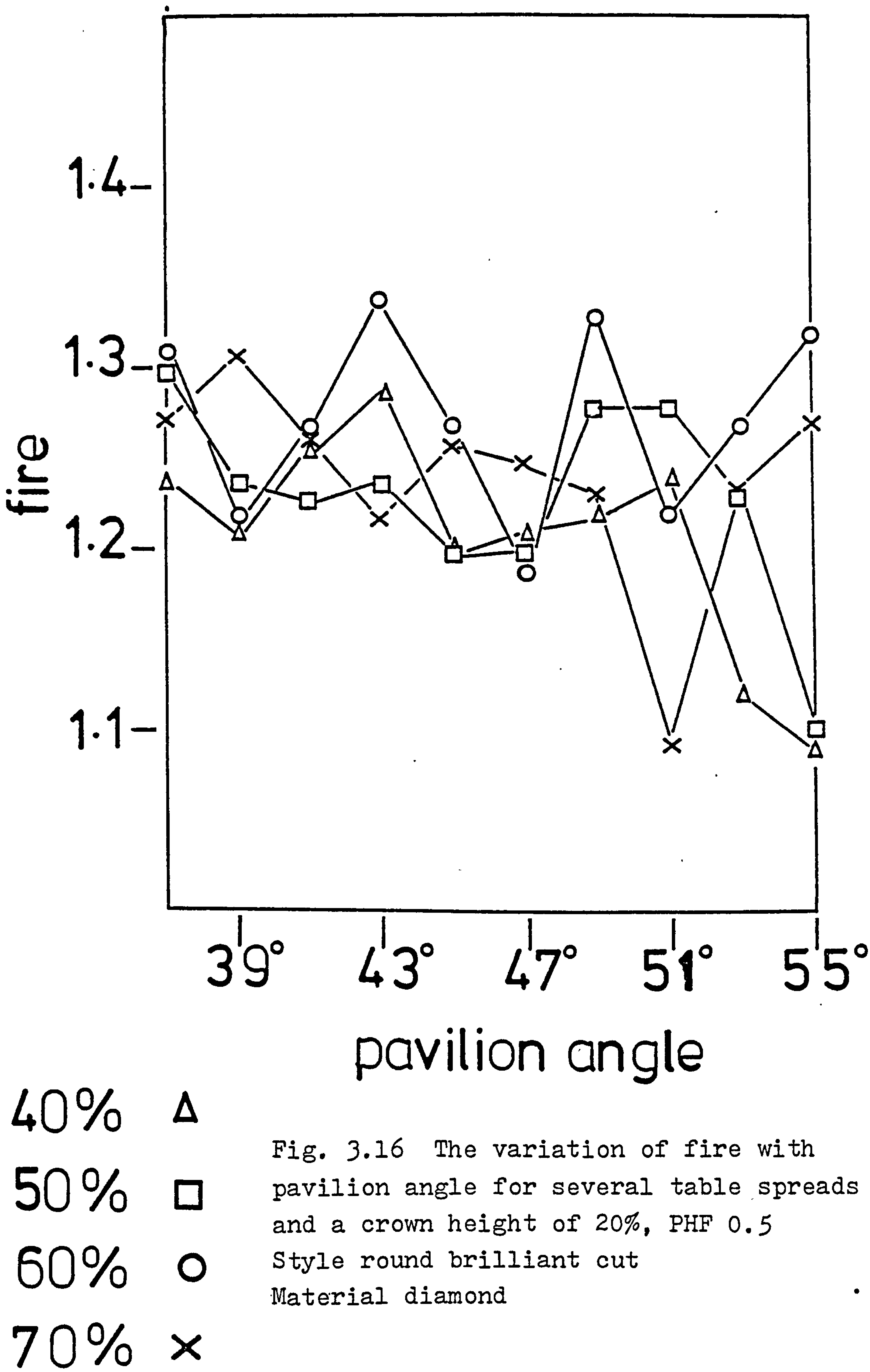


Fig. 3.16 The variation of fire with pavilion angle for several table spreads and a crown height of 20%, PHF 0.5
Style round brilliant cut
Material diamond

ring effect can be changed into a 39^{o} marginal but acceptable pavilion angle, or the marginal 39^{o} into an ideal stone 41^{o}. The pavilion angle is generally accepted as the most important parameter by the polisher.

The effect of dropping the crown height to 10% for a 60% table (this can be shortened to 60/10) was to increase the brilliance to that of a 50% table, 15% crown design (50/15). Couple this to the previous argument, that an increase in chromatic effect for the 60/10 stone will compensate for its lower sparkliness when compared with the 50/15, and it is possible to account for the current fashion in terms of economic expediency.

3.4 Summary

The modern practice of polishing shallower crowns, large tables and longer pavilion halves can be accounted for in some measure by the economics of polishing from the rough influencing a caprice of fashion (more fire, less sparkliness). The statistical measures for sparkliness and fire confirm the traditional proportions as correct and go some way to reconciling the differences between the many ideal sets of proportions. This is achieved by emphasis of the trade-off between maximizing brilliance, sparkliness or fire. Without a survey of human preference it is not possible to draw definite conclusions as to how much sparkliness is valued above fire or vice versa or what mix of brilliance, sparkliness and fire is psychologically ideal. Tentatively it would appear that brilliance and sparkliness are the two more important factors.

3.5 Another satisfactory set of proportions for the round brilliant cut

The multiple peaks in the sparkliness and fire factors lead to the conclusions that the traditional designs for the round brilliant cut are not the only solution. It is proposed that a design with a table spread of 50%, a crown height of 10 - 15% of the total spread and a pavilion angle of 53° plus a pavilion half factor of 0.5 would look as attractive if not more so than a similar diameter stone in the traditional preferred proportions.

Why has this design been overlooked? It is known from historic stones that brilliants were originally polished with the pavilion facets on virtually the octahedral angle of 54.7° but by the 17th century they were polished on 45°. The transition from the 4 point cut to the more complex cuts was also thought to stem from a desire to remove broken corners and other imperfections in the rough crystals. As the ancient and mediaeval diamonds were from India and hence alluvial they were invariably damaged. After removing the major external blemishes the pavilion angle was probably already below 50° and with a high crown ($\sim$ 20%). It can be appreciated from Fig. 3.15 that a 45° pavilion would have given the best optical effect and highest yield from the remaining rough. Hence historically there was little opportunity to polish stones to these now proposed proportions. In addition, the advent of the 41° pavilion and its vast increase in optical goodness meant that when mined perfect octahedral rough became available in the late 19th century there was no reason to experiment further with the ideal proportions, as these were known and could be mathematically justified.

Chapter IV

The Rotationally Symmetrical Styles of Polishing

4.1 The requirement for a simpler style than the round brilliant cut

Diamonds as we have seen are often polished in the round brilliant cut style of 58 facets. A two carat stone is 7mm in diameter and can be adequately held and worked using a mechanical dop. A half carat stone (diameter approx. 5mm) is still fashioned with a full set of facets as is the 20 point stone (100 points = 1 carat) of which the physical size leads to difficulties in handling. With these small goods there comes a point at which it would be easier to manufacture a style simpler than the round brilliant cut which reduces the number of facets and thereby the degree of optical attractiveness. However two questions must be answered:- how optically attractive are the simpler styles and where can the line be drawn between a too simple and a sufficiently complex style?

4.2 The stages of manufacture of a round brilliant cut

A consideration of the stages in manufacture of the round brilliant cut style will give an indication of the possible simplifications and relative importance of some of the facets.

Diamond often occurs as a natural stone with octahedral habit, (Fig. 4.1a). It is then possible to saw through the crystal producing a cap and the four-point sawn model (Fig. 4.1b). The stone is then worked into

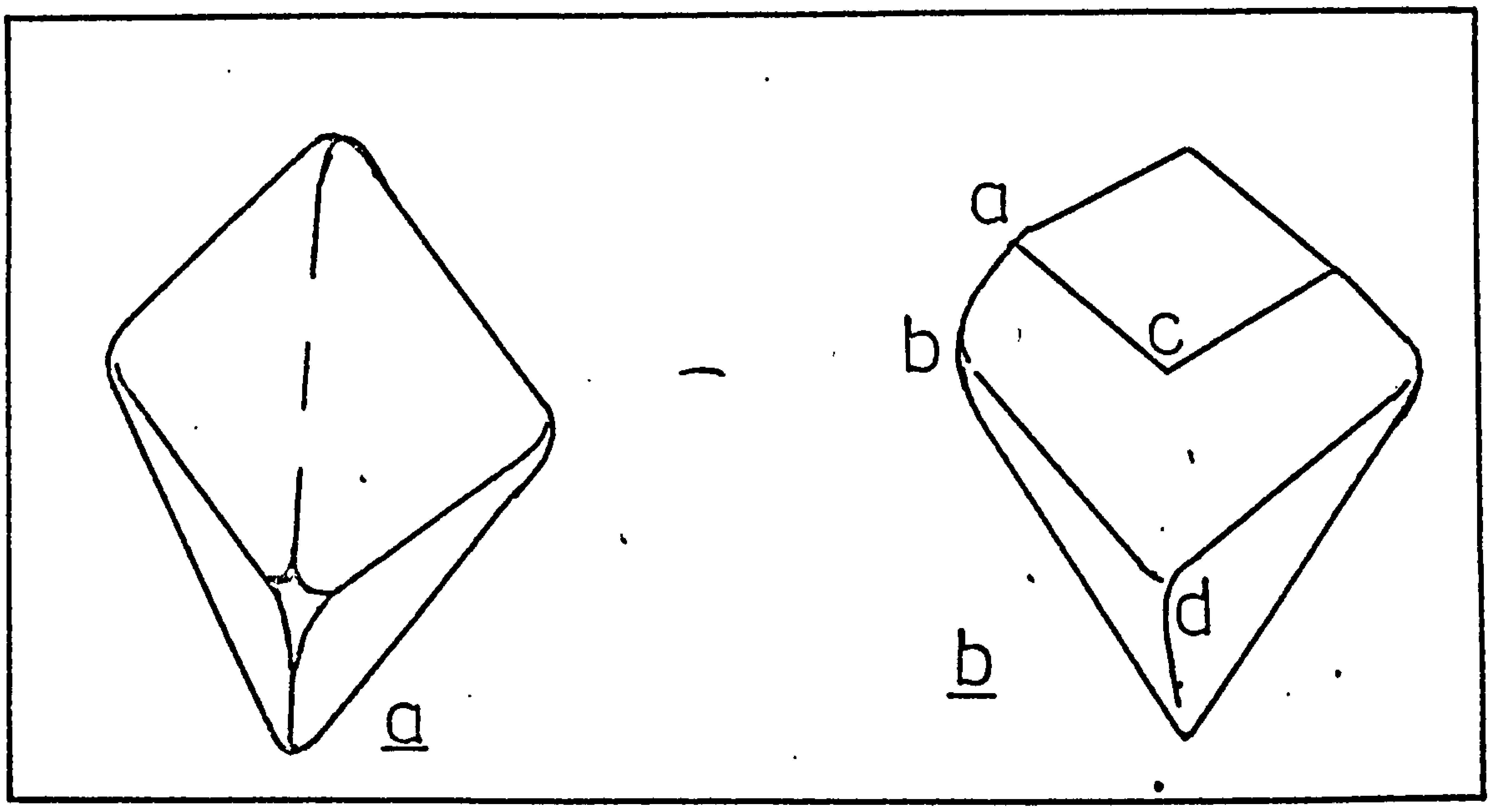


Fig. 4.1 Showing a) an octahedral rough
b) a four point sawn model showing the ribs onto which the four hoeks are polished.

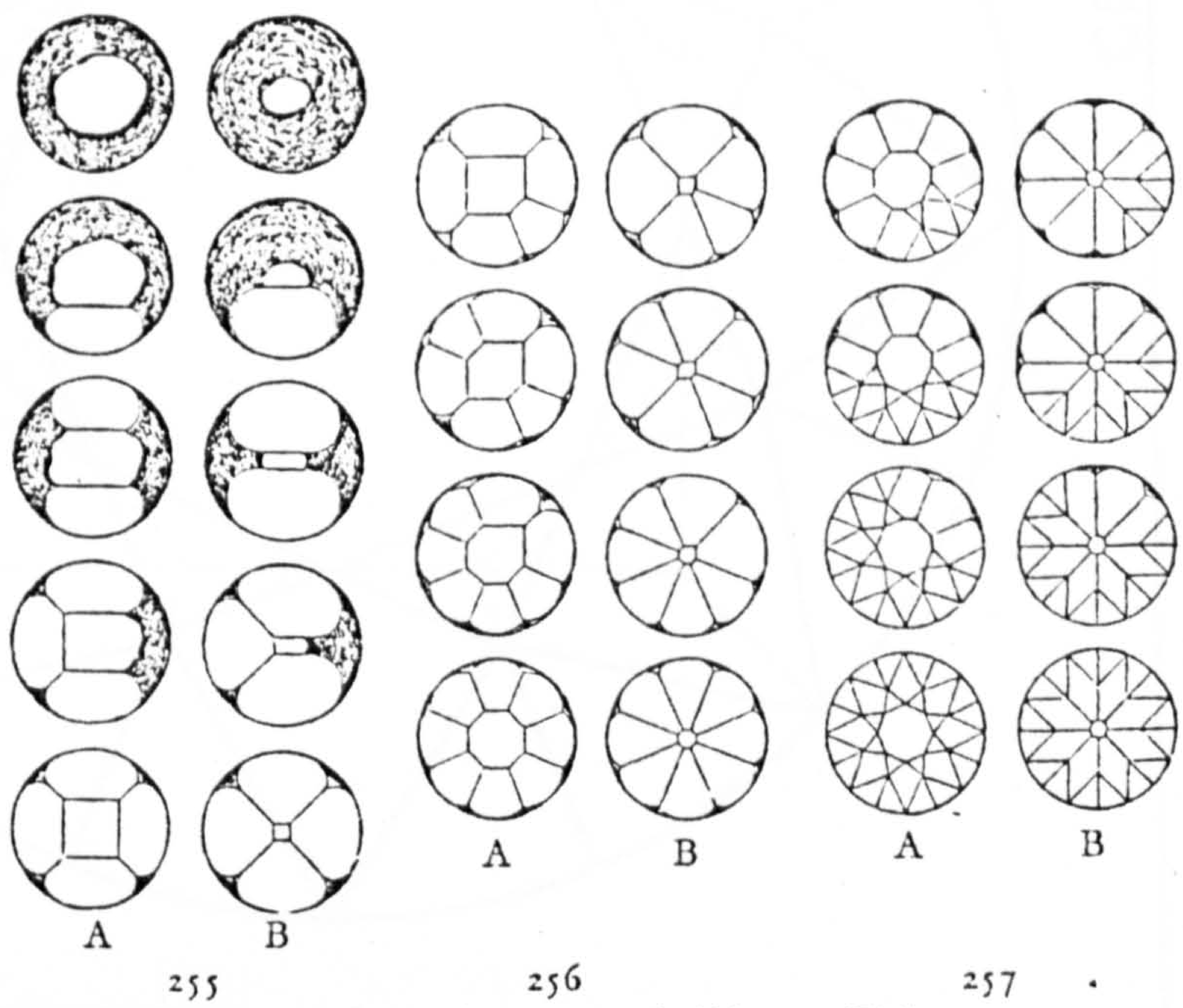


FIG. 255.—Stages in crosswork (A) top, (B) bottom.
FIG. 256.—Stages in "eights" or octagon work (A) top, (B) bottom.
FIG. 257.—Stages in brillianteering. (A) top, (B) bottom. In all cases, operations start on the top, according to W. F. Eppler.

POLISHING OPERATIONS

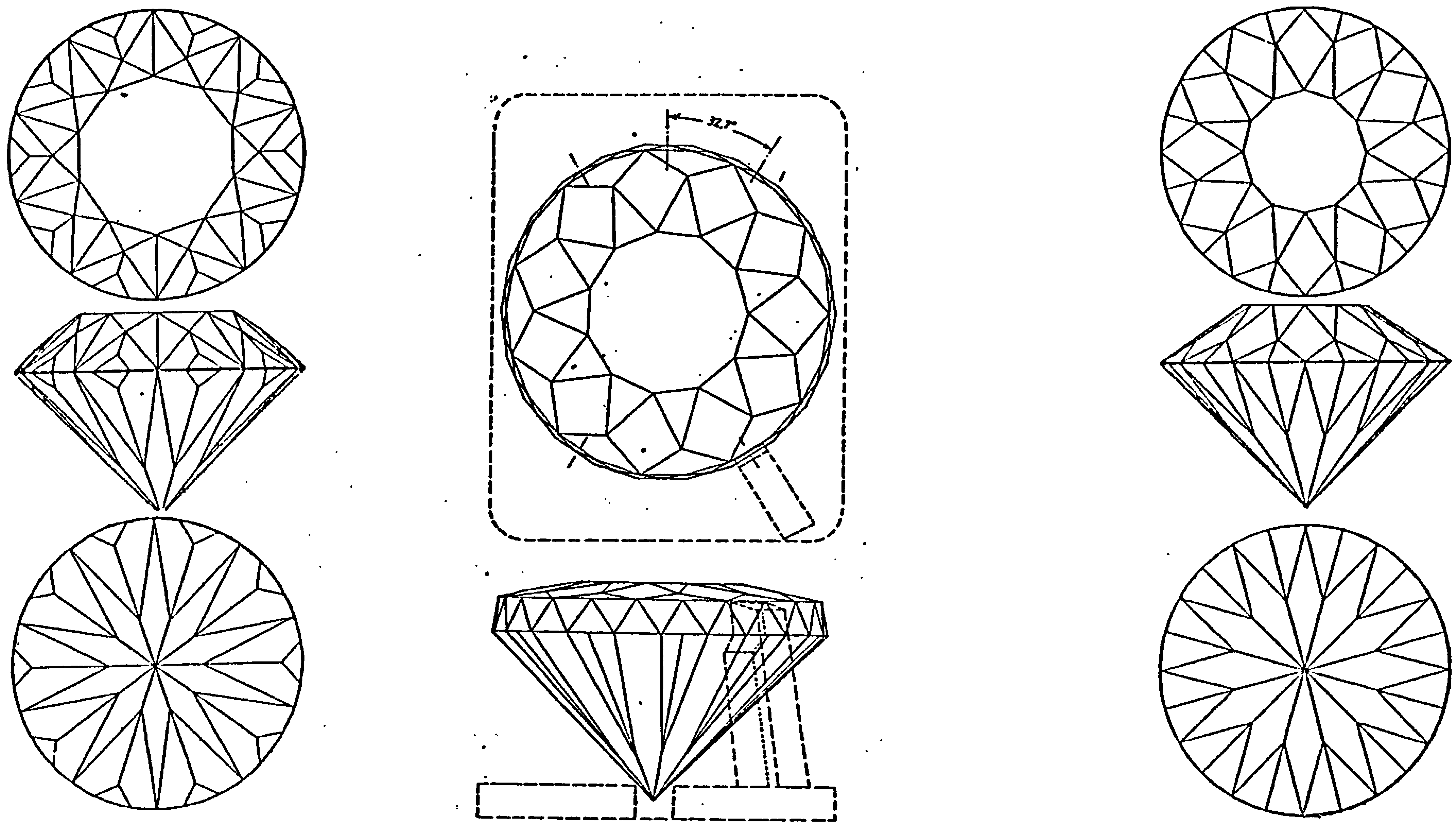
Fig. 4.2 (Fig. 255, 256, 257 in P. Grodzinski - 1952)
Showing the order in which facets are ground onto the round brilliant cut diamond of 58 facets.

Fig. 4.3 a) the crown facets and b) the pavilion facets for
i) dash-dot line the four cut
ii) dash line the eight cut
iii) full line the round brilliant cut diamond

a round cross-section. The diamond polisher uses a 6x magnifying lens and a simple angle gauge coupled with the visual cues of the rough to orientate the facets on the stone. The order of polishing is as follows. The first four facets are polished onto the crown and the pavilion (Fig, 4.2) across the ribs labelled AB - CD in Fig. 4.1b. This results in the four-cut arrangement of facets (c.f. Fig. 1.2 and the dash dot line in Fig. 4.3). The second stage is to polish the remaining crown and pavilion facets, the dashed line facets in Fig. 4.3 & (225b), Fig. 4.2. These two operations are referred to as blocking out the stone or the cross work. The second major stage is known collectively as brilliantering. This involves working the star facets, so that they form with the table two interlocking squares (an eight pointed star). Finally the halves are worked onto the crown and pavilion. The final form of the brilliant is shown in Fig. 4.2 and 4.3. The obvious simplifications are then the four cut and eight cut. If the pavilion halves are extended to the collet (eqivalent to a pavilion half factor of 1.0) a sixteen facet pavilion results. Similarly it is possible to produce a ring of 16 facets on the crown; the resulting style can be termed a sixteen cut. The results thus give a hierarchy for the brilliant cut family based on 4-fold rotation

$$\begin{tikzcd} & & \text{58 cut} \\ \text{4 cut} \arrow[r] & \text{8 cut} \arrow[r] \arrow[ur] & \text{16 cut} \end{tikzcd}$$

with the full 58 facet style a derivative of the eight cut rather than an elaboration of the sixteen cut.



10 fold rotation
Magna cut

11 fold rotation
Style after Elbe

12 fold rotation
King cut

Fig. 4.4 Three fancy cuts exhibiting non 4 fold symmetry

4.3 Methods of improving the optical goodness in diamond

While considering the simplification of the round brilliant cut diamond, it is reasonable to consider the other facet arrangements which may produce increased, brilliance, sparkliness and fire. The round brilliant cut family all have an axis of symmetry with corresponding sets of pavilion and crown facets mirrored in the girdle plane.

Over the past thirty years there have been many patented styles. consideration of these will demonstrate the usual complications which are attempted.

More recently Elbe proposed a cut based on an eleven fold rotational symmetry (fig. 4.4b). An odd rotational symmetry in itself will not result in the girdle reflection symmetry being broken. However the pavilion to pavilion symmetry of reflection will be perturbed to some degree and this will produce an increase in the complexity of the paths followed by rays. The odd rotational styles will mainly result in a great complication in manufacture.

The magna cut (Fig. 4.4a - M. Fine and Son Inc) is based in a 10 fold i.e. 2 x 5 fold symmetry; again there was no attempt to break the girdle symmetry. The main attempt was to increase the number of facets (102) as the popular impression is that this will increase the brilliance sparkliness and fire.

There are no simple methods for producing a stone with 5, 7, 9, 11 and 13-fold rotations using the current hand and eye techniques. Hence a special dop is required to manufacture these types of styles. The only odd-rotation symmetry possible using the standard stone holder is 3-fold.

A rough crystal maccel is triangular in cross-section. Thus using the visual cues of the rough it is possible to produce a three cut and hence a six cut and a twelve cut. The twelve cut was modified by King diamond Cutters, New York, in a similar fashion to the eight cut to produce the King cut (Fig. 4.4c). Superficially, then it would appear that these three styles are equally difficult to produce. However the King cut is easily produced by the traditional cutters and polishers using maccle rough. The simpler styles (lower rotation) of Messers Fine and Elbe require specialist equipment. Thus there is another family of brilliants based on three fold rotation with a hierarchy:

6 cut ↗ The 3 fold equivalent to the 58 cut

3 cut → 6 cut → 12 cut

12 cut ↘ King cut

This family has been fully utilized by Vainer (1978) in London. He has produced a set of triangular styles, the most unusual of which is a star shape after the style of the Mercedes Benz trade mark.

These two families can then be identified as the principal members of the class of rotationally symmetric styles of diamond polishing. The other familial groups requiring specialist equipment for their manufacture are:

5 cut → 10 cut → magna cut

7 cut → 14 cut

9 cut, 11 cut, 13 cut and 15 cut

It would appear that it has been thought unnecassary to go above 16 fold rotational symmetry.

What modifications to a particular style will result in no girdle mirror symmetry or an increase in brilliance, sparkliness and fire? We have seen that adoption of an odd rotation symmetry does not in itself result in the required broken symmetry.

The popular idea that an increase in the number of facets will result in higher optical goodness, is the simplest modification; this can be called an a-type modification.

The two other methods adopted by the diamond designers have a rotation of the crown facets with respect to the pavilion facets and a rotational symmetry with unequal numbers of facets on the crown and pavilion.

Rotation of the crown with respect to the pavilion leads to the notion of 'screw'. The four cut with screw is a four-cut crown with the pavilion rotated by 45° with respect to the crown. Similarly the eight cut with screw has the usual crown arrangement with crown on pavilion rotated by $22\frac{1}{2}^{\circ}$. The screw method of modification will be classed as a b-type modification.

The final method that of obtaining different numbers of facets on pavilion and crown, can be achieved by two distinct methods. The first can be classed a c-type modification and is accomplished by combining the crown of one familial element with the pavilion of a member of the same family; e.g. an eight-cut crown and sixteen cut pavilion giving two pavilion facets below each of the eight crown facets.

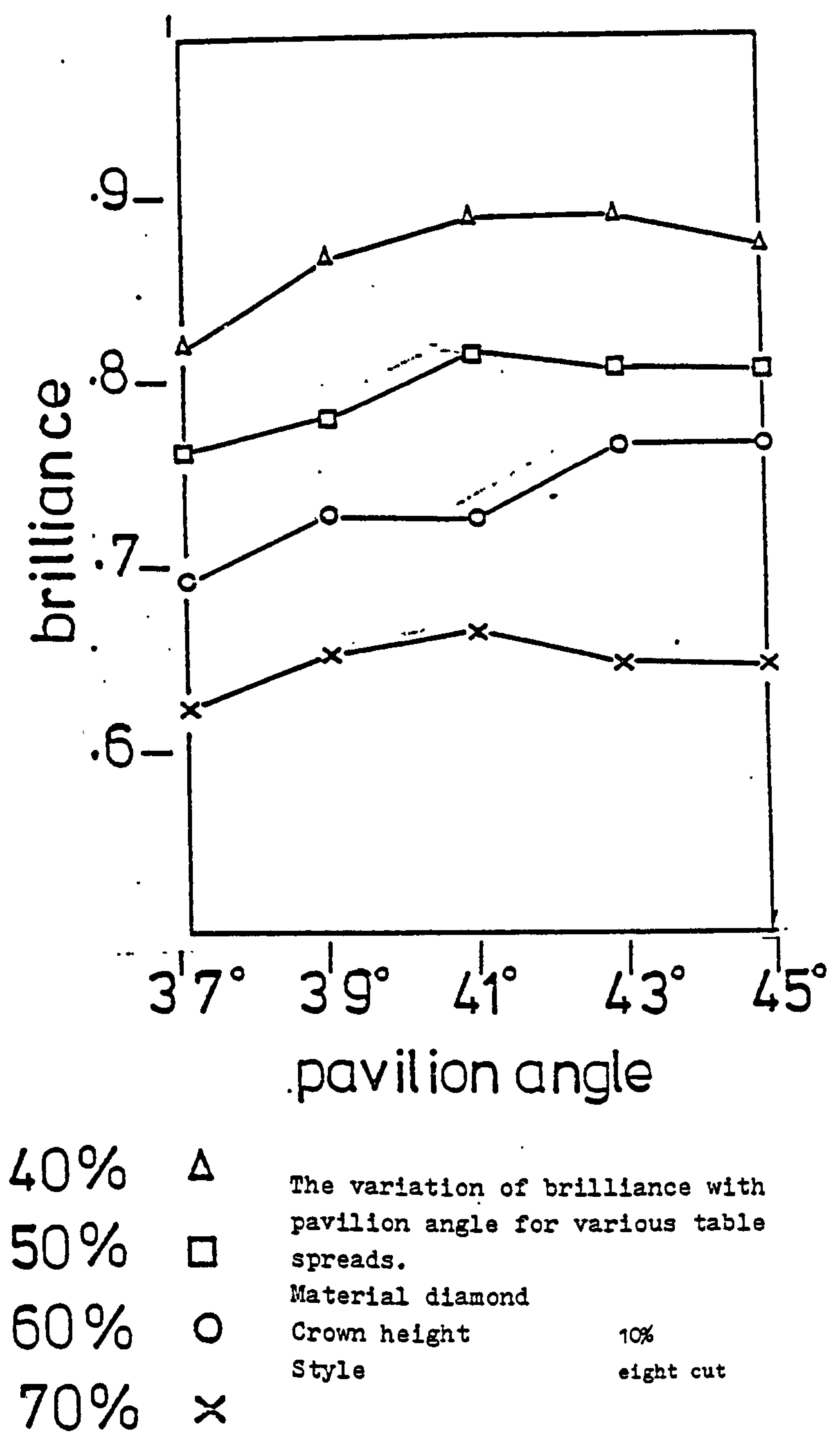
The second modification is to combine the crown of one family with the pavilion of another family. For simplicity we could take a crown from the 4-fold family with the pavilion from the 3-fold family or <u>vice versa</u>, thus breaking the girdle symmetry. This will be referred to as a d-type modification.

Thus there are two basic families of styles based on the four and three fold symmetry and four types of modification to the class of rotationally symmetric styles which require no increase in the diamond polisher's basic skills and more important, mechanisation.

4.4 A system of notation for style description

Tillander adopted a method where the number of crown and pavilion facets were displayed by a slash; e.g. the 58 facet round brilliant cut diamond would be 33/24. In this method there is no way of distinguishing between those stones exhibiting a particular form of modification. The notation therefore adopted is as below. The common styles have special symbols so that the 58 facet round brilliant cut is denoted by 58, and the sixteen cut and twelve cut by 16 and 12 respectively. If the crown and pavilion differ such as in type c modifications the style is denoted by crown type/ pavilion type; for example 8/16 denotes an 8 crown with 16 pavilion. For a d-type 8/6 denotes an 8 crown and 6 pavilion (6-cut pavilion). Fancy cuts such as the King cut and Magna can be described using the method of Tillander with superscripts indicating the rotation symmetry used. Thus the King cut is $49^{12}/36^{12}$) and the Magna $(61^{10}/40^{10})$.

Screw is denoted by the suffix plus sign after the style for the two examples given 4 cut and 8 cut with screw 4+ and 8+ respectively.



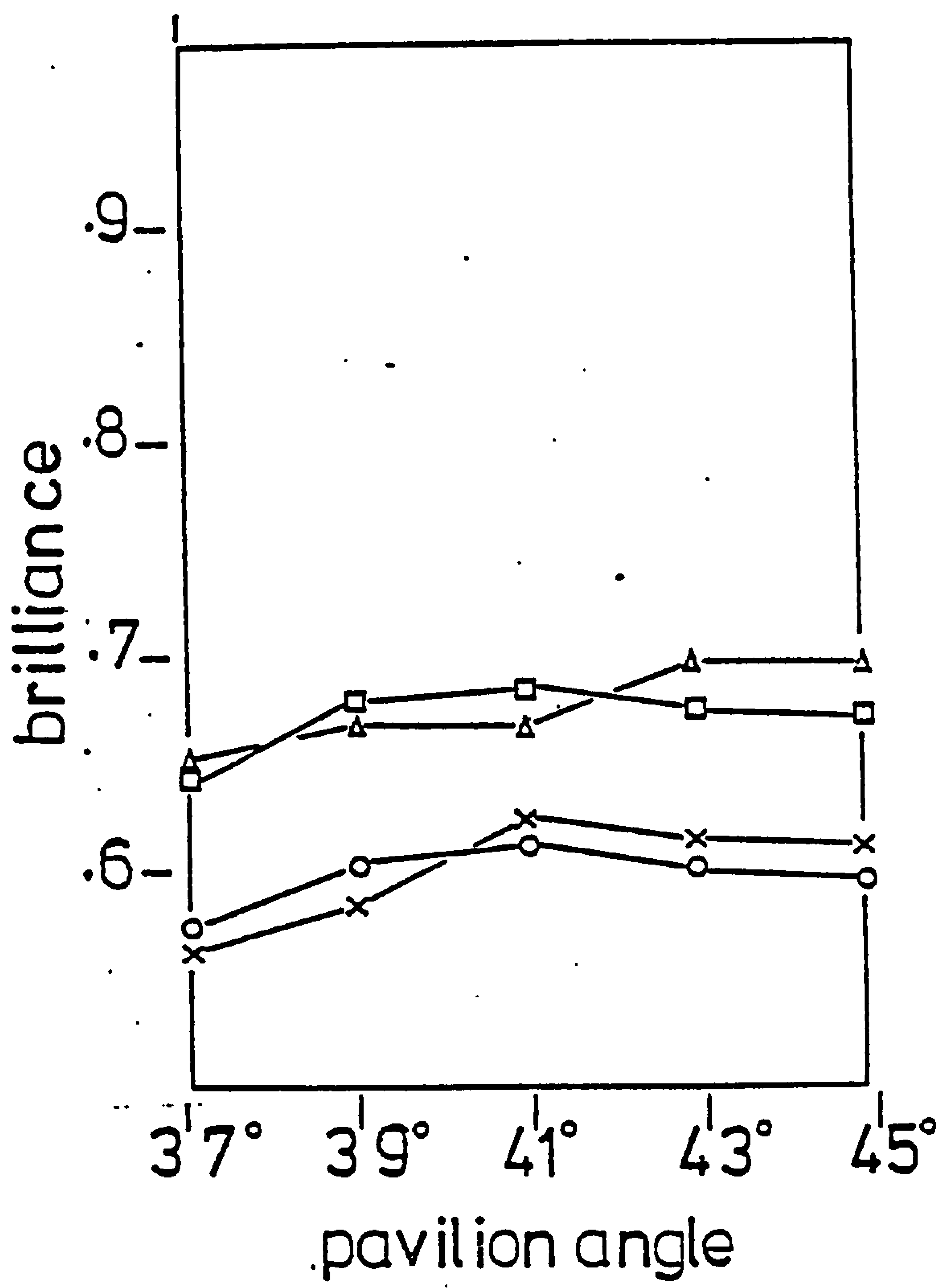
The variation of brilliance with pavilion angle for various table spreads.

Material diamond

Crown height 10%

Style eight cut

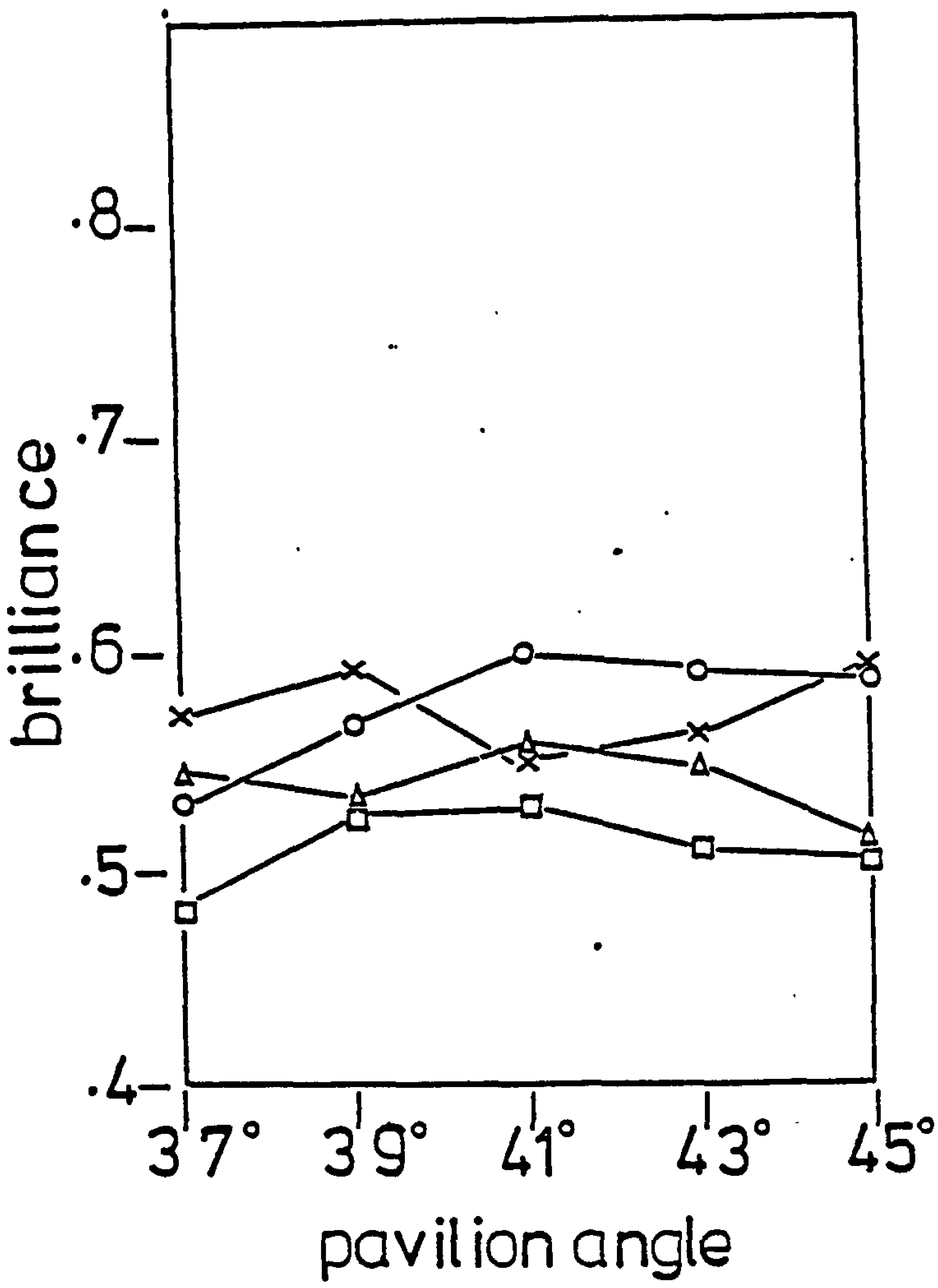
Fig. 4.5



40% Δ
50% □
60% ○
70% ×

The variation of brilliance with pavilion angle for various table spreads.
Material diamond
Crown height 15%
Style eight cut

Fig. 4.6

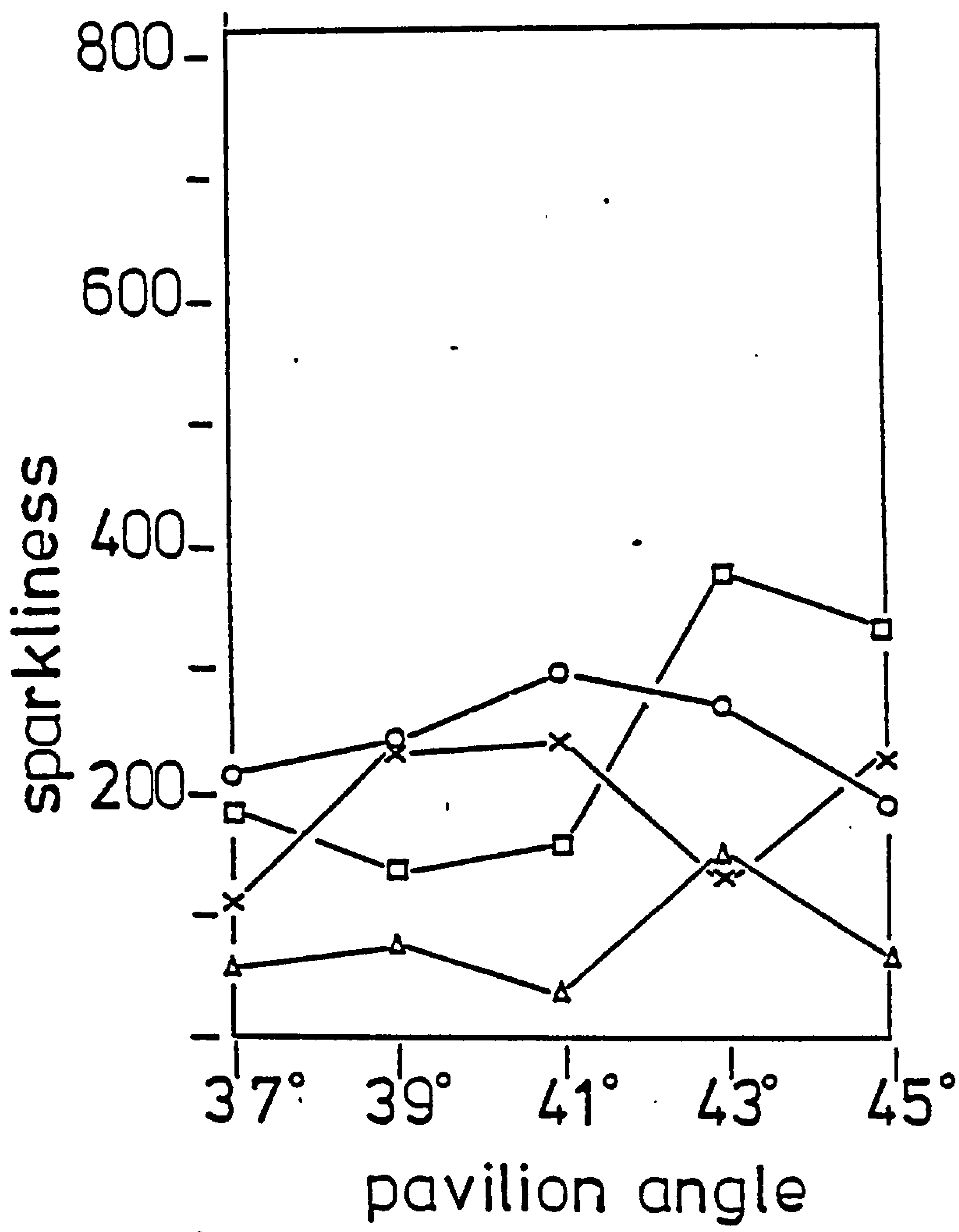


40% △
50% □
60% ○
70% ×

The variation of brilliance with pavilion angle for various table spreads

Material diamond	
Crown height	20%
Style	eight cut

Fig.4.7



40% Δ
50% □
60% ○
70% ×

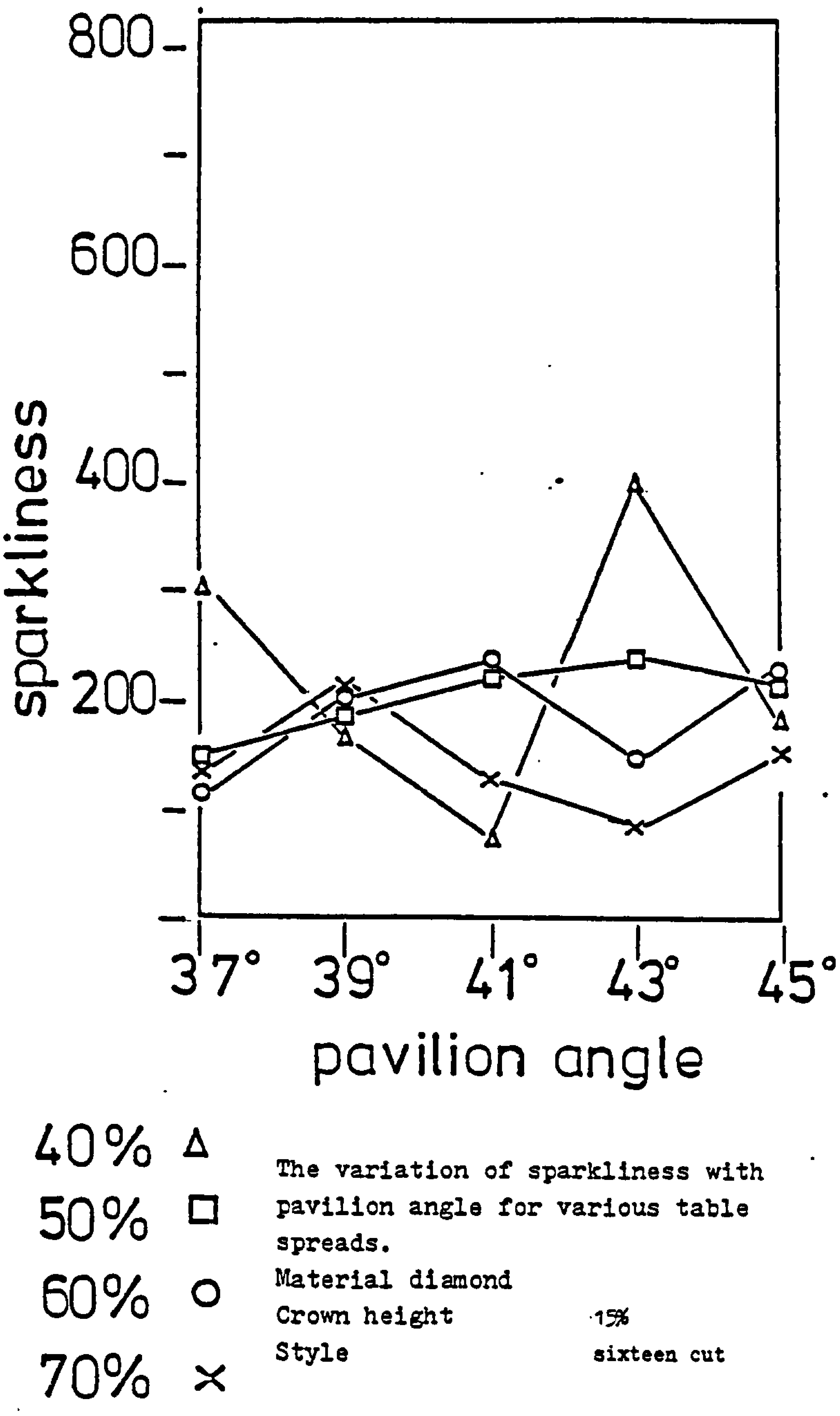
The variation of sparkliness with pavilion angle for various table spreads.

Material diamond

Crown height 10%

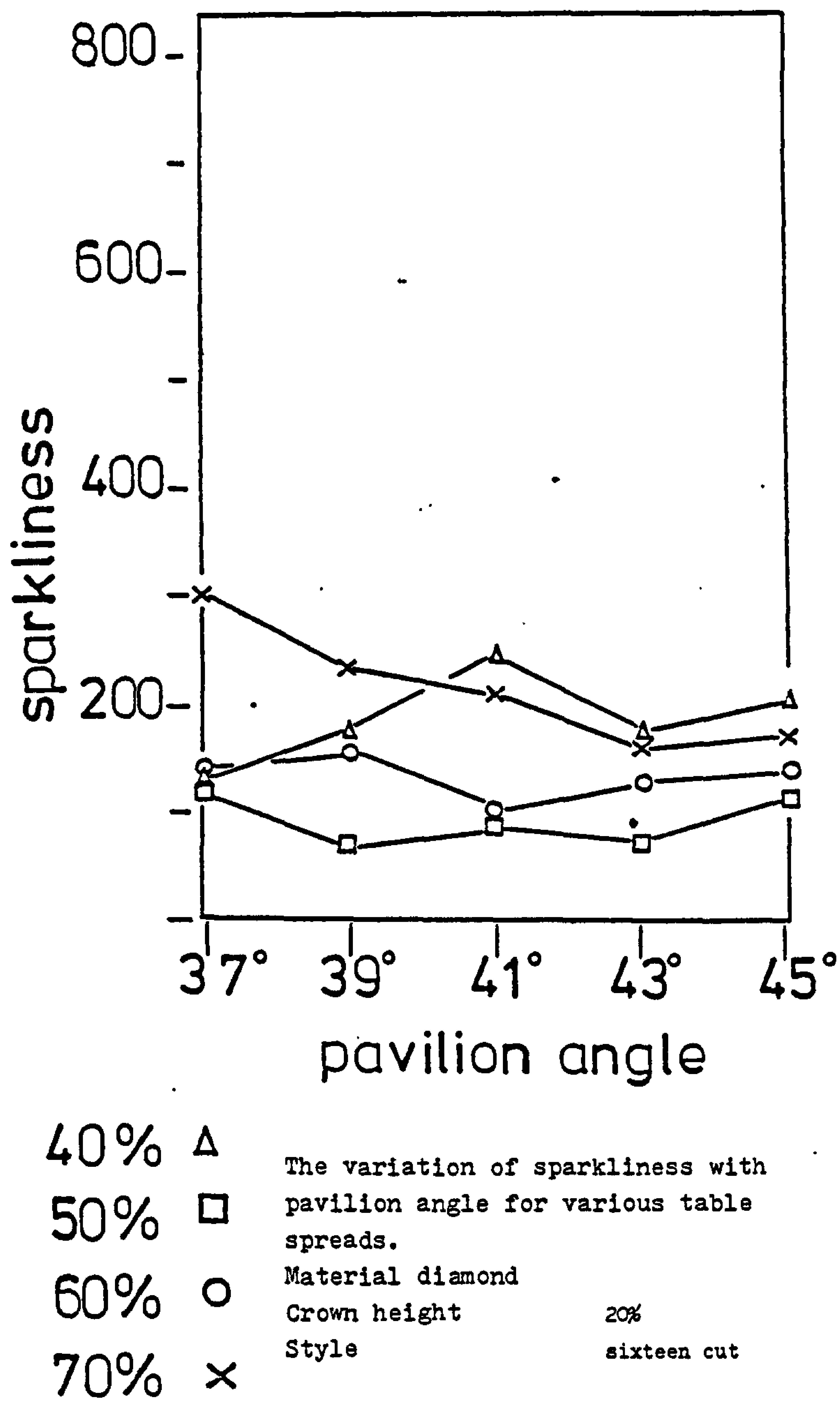
Style sixteen cut

Fig.4.8



The variation of sparkliness with pavilion angle for various table spreads.
Material diamond
Crown height 15%
Style sixteen cut

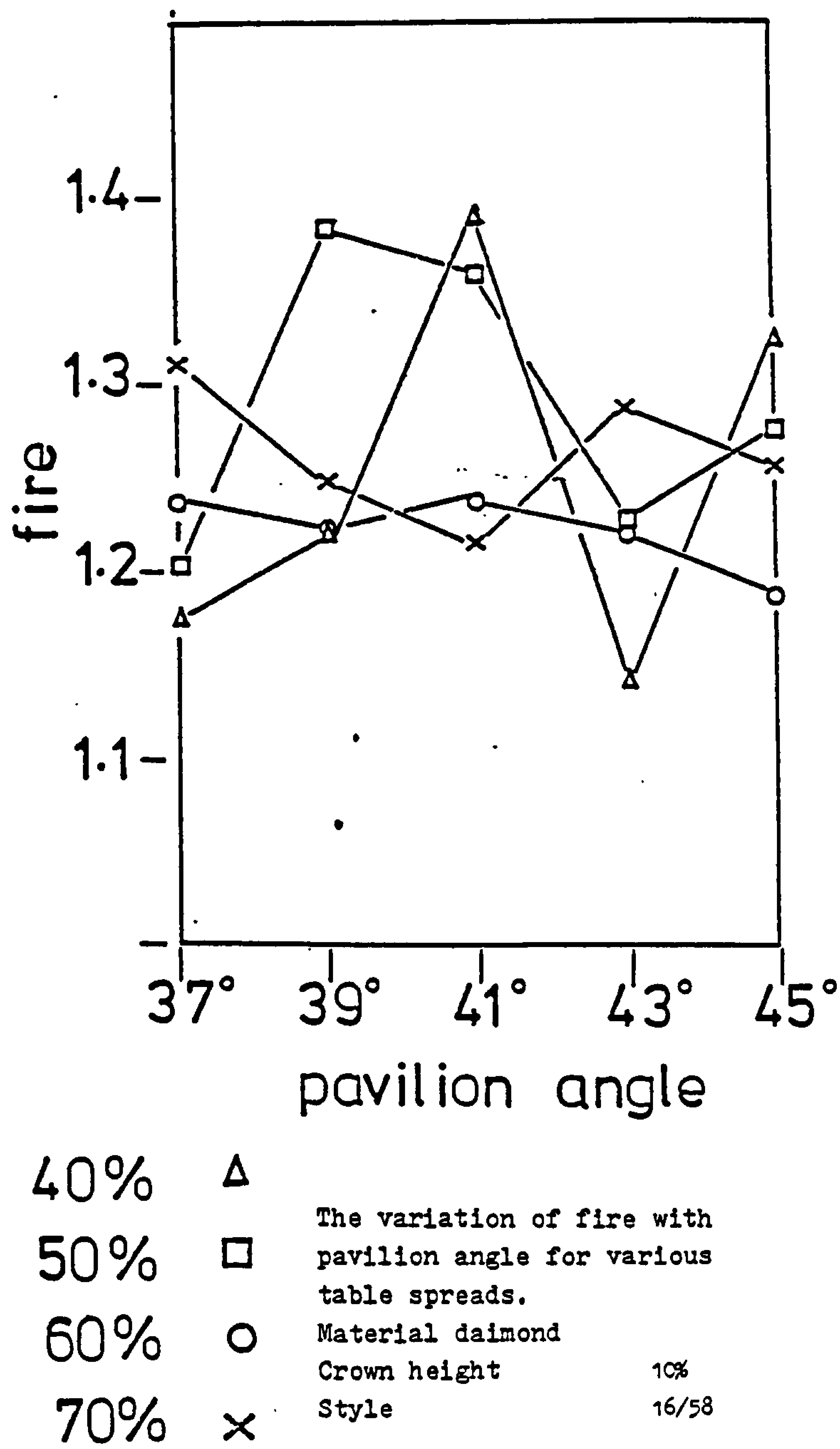
Fig.4.9



The variation of sparkliness with pavilion angle for various table spreads.

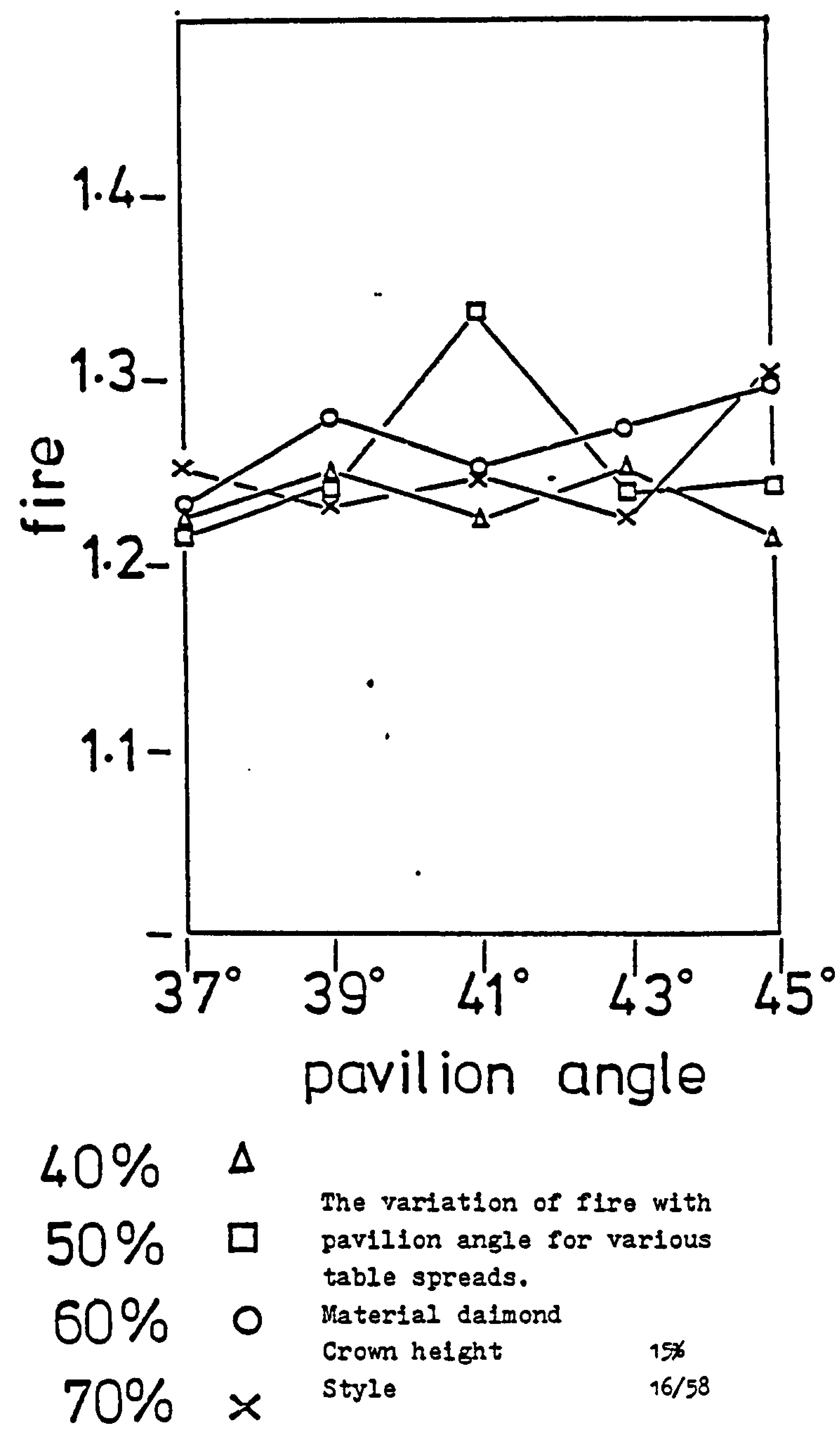
Material diamond	
Crown height	20%
Style	sixteen cut

Fig.4.10



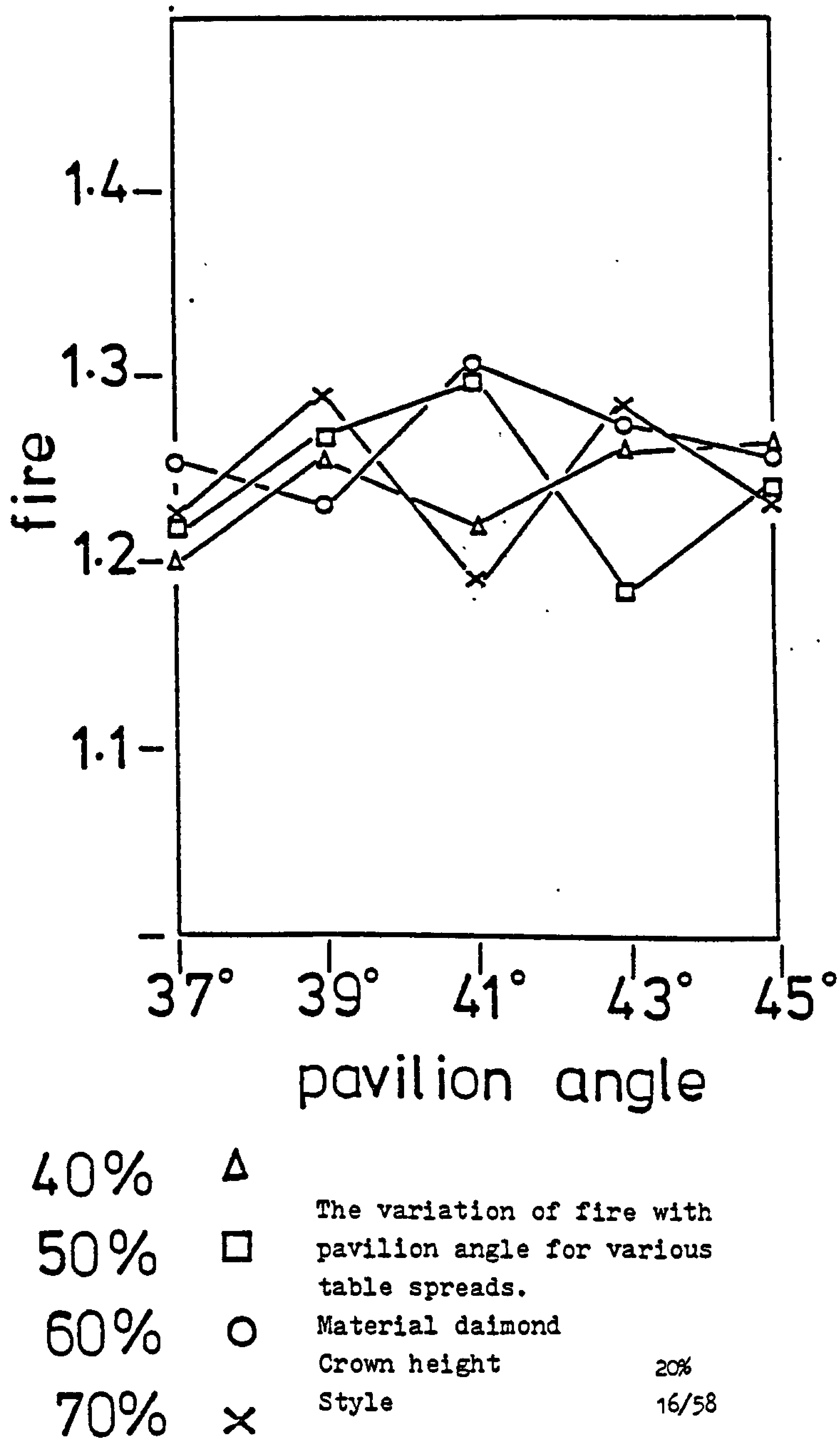
The variation of fire with
pavilion angle for various
table spreads.
Material daimond
Crown height 10%
Style 16/58

Fig.4.11



The variation of fire with pavilion angle for various table spreads.
Material daimond
Crown height 15%
Style 16/58

Fig.4.12



The variation of fire with
pavilion angle for various
table spreads.
Material daimond
Crown height 20%
Style 16/58

Fig.4.13

4.5 The brilliance, sparkliness and fire of some of the modifications to the round brilliant cut diamond

The different types of modifications were investigated by amending the computer program used to investigate the optical goodness of the round brilliant cut diamond. The a-type modification was investigated by taking the four fold family and considering the 4, 8 and 16 cut. The effect of screw in the b-type modification was calculated for the 4+ and 8+ styles. A single example of c-type was investigated at this time.

The pavilion angle was limited to the range 37° - 45° and the crown heights and table spreads were chosen to correspond with those used in the study of the 58 (see Chapter III). For the 16/58 style a PHF of 0.5 was chosen. The results are summarized as Fig. 4.5 - 4.13 and the complete results are presented in Appendix IV.

First consider the trends within the individual styles. All the cuts exhibit similar trends to the full 58 style. As before brilliance decreases with increasing crown height, this being clearly demonstrated for the 8 by Figs 4.5 - 4.7. The decreasing brilliance with increasing table spread for the 10 and 15% crown heights persists.

The 16 cut has been chosen to exhibit the sparkliness trend (Figs. 4.8 - 4.10), with peaks centred on 41° and 43° pavilion angles. The increase in performance with larger table and shallower crown is again apparent. The unsuitability of a 20% crown height is again demonstrated by the lower sparkliness for the 16 cut in agreement with the findings for the 58 cut. As to fire, all the table spread and crown heights perform equally well as demonstrated by the 16/58 (Fig. 4.11 - 4.13).

Thus we see the advantage of Eppler's practical cuts and Parker's design with the lower crown heights 10 - 15% against Johnsen's and Rosch's ideal cuts with a 20% crown.

As the trends are common to all styles the discussion of the various modifications was further confined to the set of typical results from 15% crown heights and 50% table spreads.

4.6 Discussion of a-type modification, the effect of an increase in the number of facets on optical attractiveness

For the a-type of modification brilliance increases with the number offacets (Figs 4.14 and 4.17) in agreement with popular belief. However the effect is not as marked for the 8 16 58 transition as the 4 8 transition. For this example the 4 is some 40% less than the 8, with the 8 and 16, which are comparable, being only some 5% less brilliant than the 58 style.

This lack of performance (for the 4 cut) is further emphasised by the measure of sparkliness. The 4 cut is a factor lower than the 8, 16 and 58 styles (Figs. 4.15 and 4.18). However, the 4 still exhibits a strong peak at the ideal 41^{o} pavilion angle.

Although the 58 is strictly a derivative of the 8 cut it can be considered an admixture of the 8 cut (forming kites and pavilion mains) and the 16 cut (forming the crown and pavilion half facets). This notion is demonstrated by the sparkliness results. The peaks for the 8 and 16 styles occur at 39^{o} and 43^{o} pavilion angles, the 58 having the well known peak at 41^{o}. The form of the sparkliness results also exhibit this 8, 16 mix

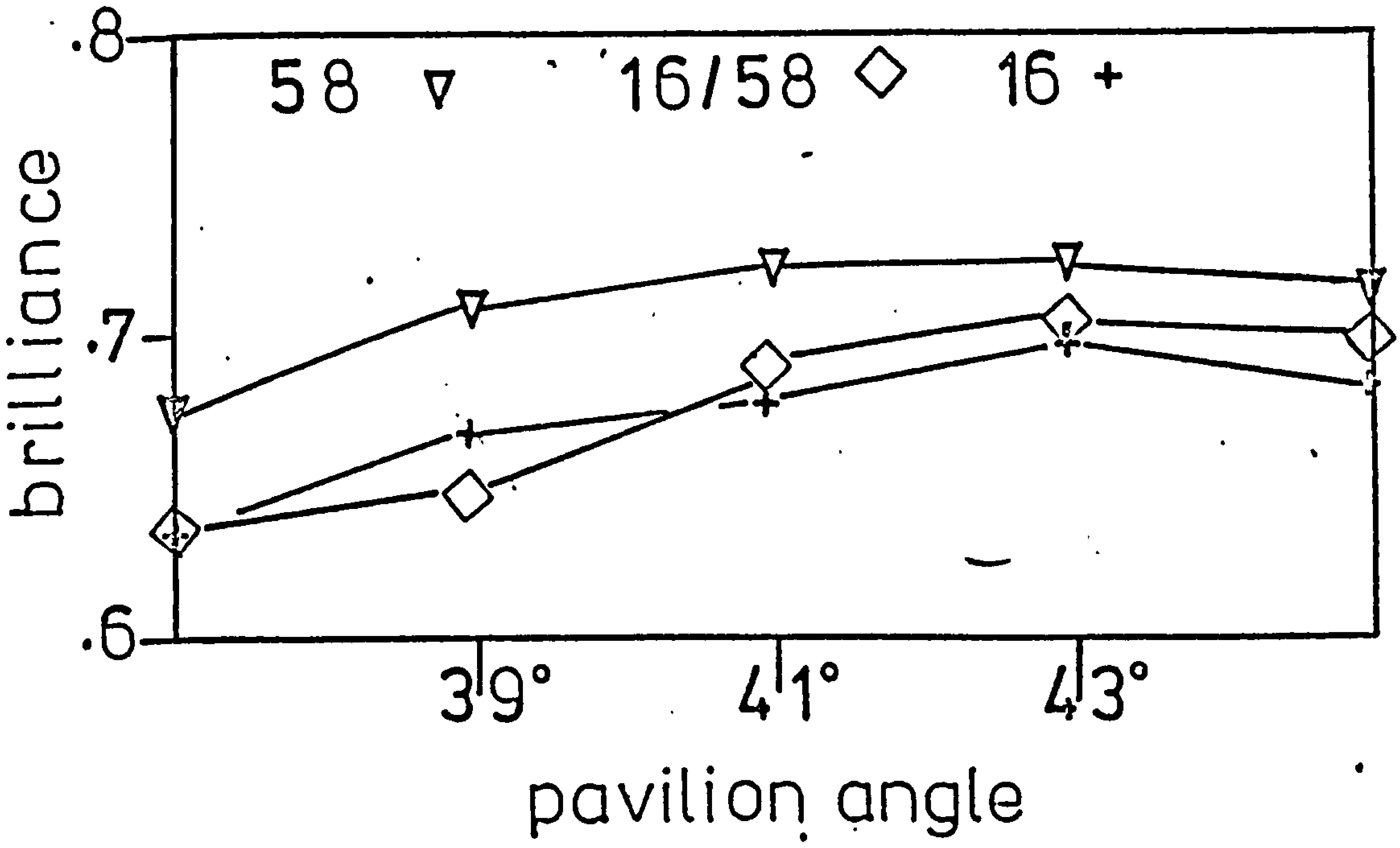


Fig. 4.14 The variation of brilliance with pavilion angle for various styles of polishing
Crown height 15%
Table spread 50%

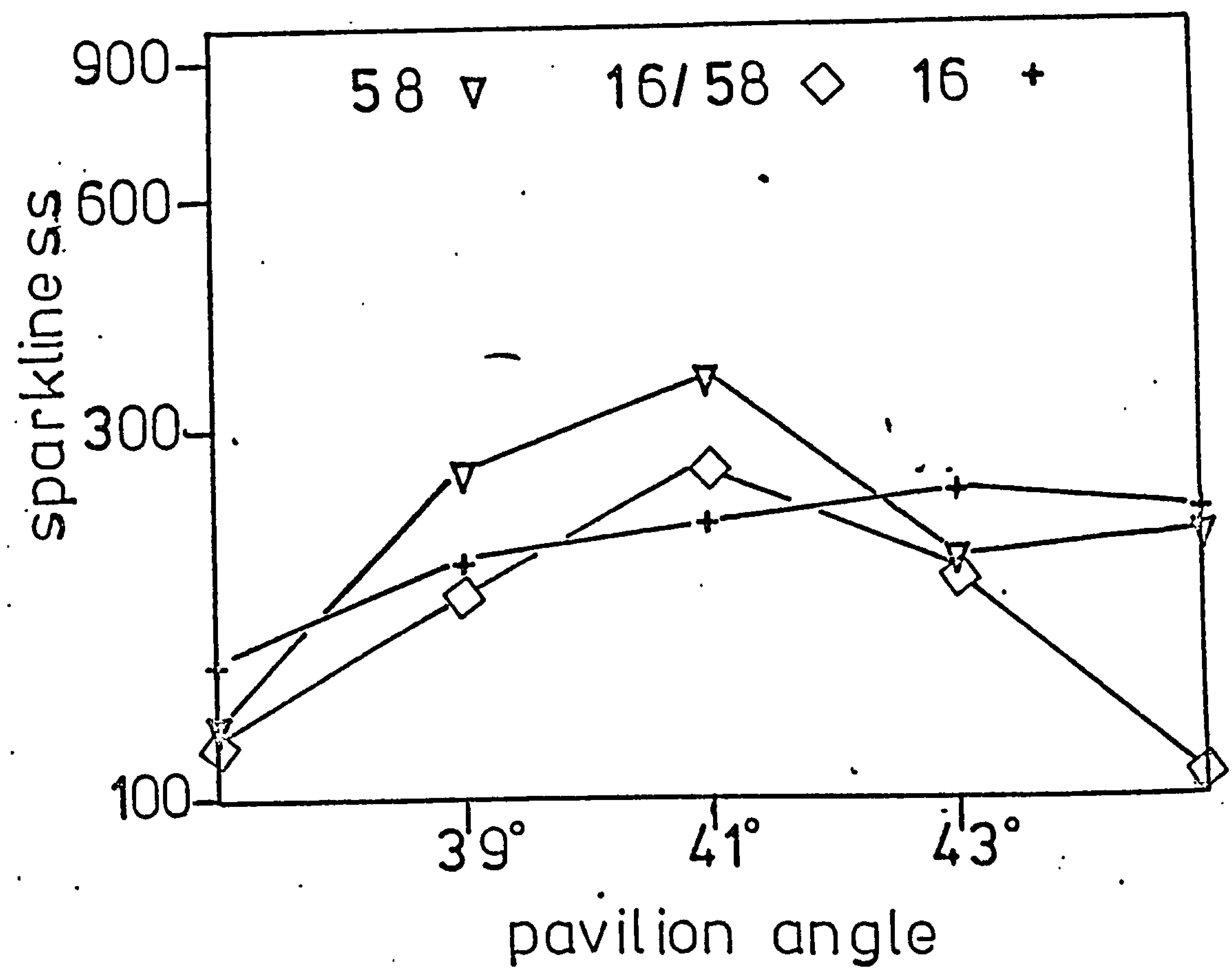


Fig. 4.15 The variation of sparkliness with pavilion angle for various styles of polishing
Crown height 15%
Table spread 50%

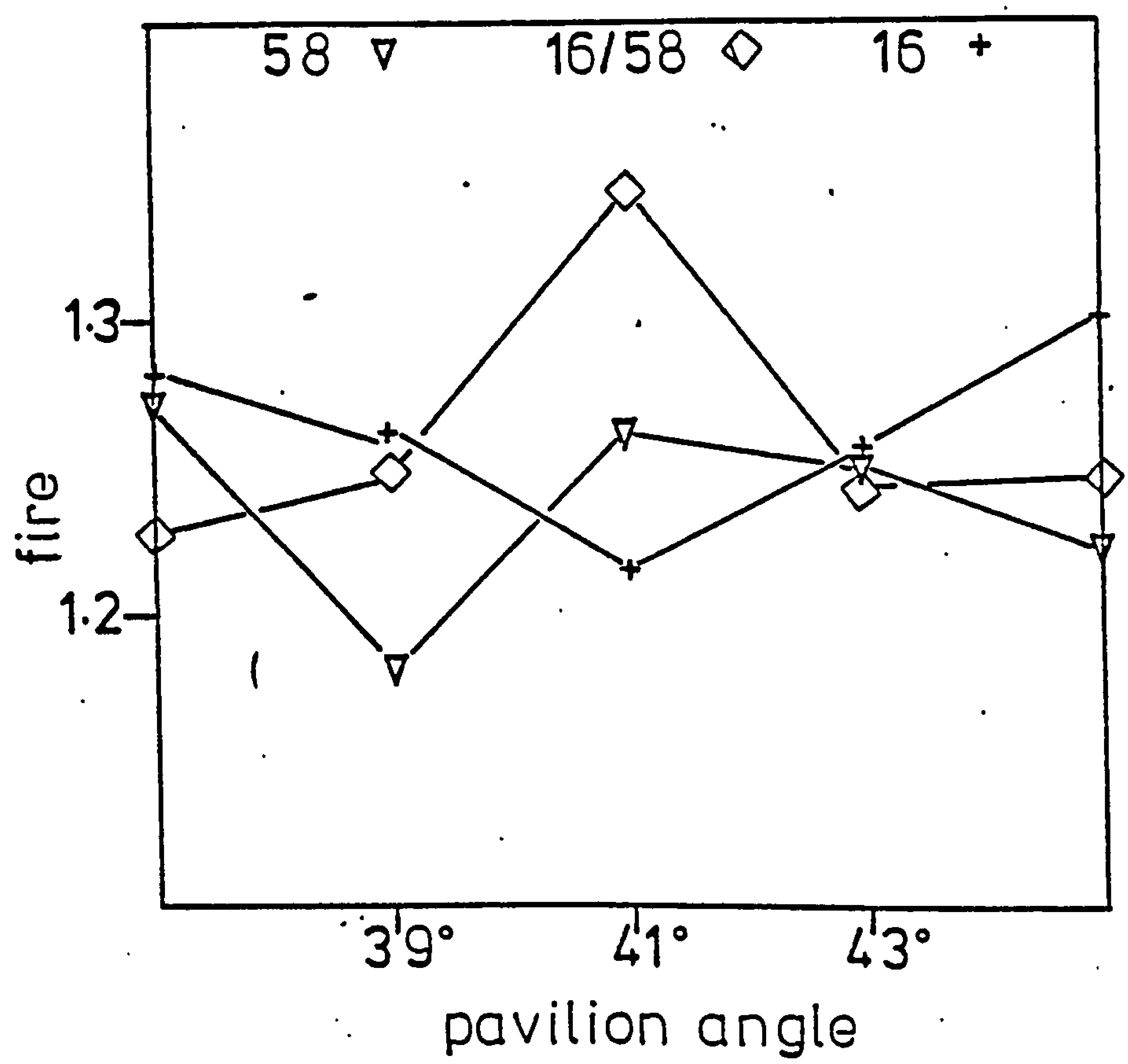


Fig. 4.16 The variation of fire with pavilion angle for various styles of polishing
Crown height 15%
Table spread 50%

the 58 style having a shape which is the scaled sum of the 8 cut and 16 cut curves. When fire is considered there are agian no simple discernable trends.

The advantage in polishing an 8 rather than a 4 cut are therefore apparent (increased brilliance and sparkliness). However this advantage is not carried forward to the 16 style, which can even show a slight decrease in attractiveness with respect to the 8 cut. However, the 58 facet round b rilliant cut again exhibits a consdierable gain in optical goodness over the 8 and 16 styles.

The question arises, why therefore the 16 cut does not exhibit a substantial increase in optical effect over the 8 cut? As mentioned when discussing styles with odd-rotational symmetry, increasing the degree of rotation say from 8 to 16, will not in itself break the girdle mirror symmetry of pairs of crown and pavilion facets. However placing the halves on a 58 style adds facets which are skew to each other (for PHF's less than 1.0), and so increase the chance of rays taking a non-simple path through the stone. Thus the important distinction can be drawn between style modifications which increase the number of facets by 1. addition of skew facets, the preferred scheme and 2. those which gain an increase of facet numbers by symmetry multiplication, which is to be avoided.

4.7 Discussion of b-type modifications, screw

The brilliance (Fig. 4.17) for both the eight cut and eight cut with screw (8+) are reasonably equal over

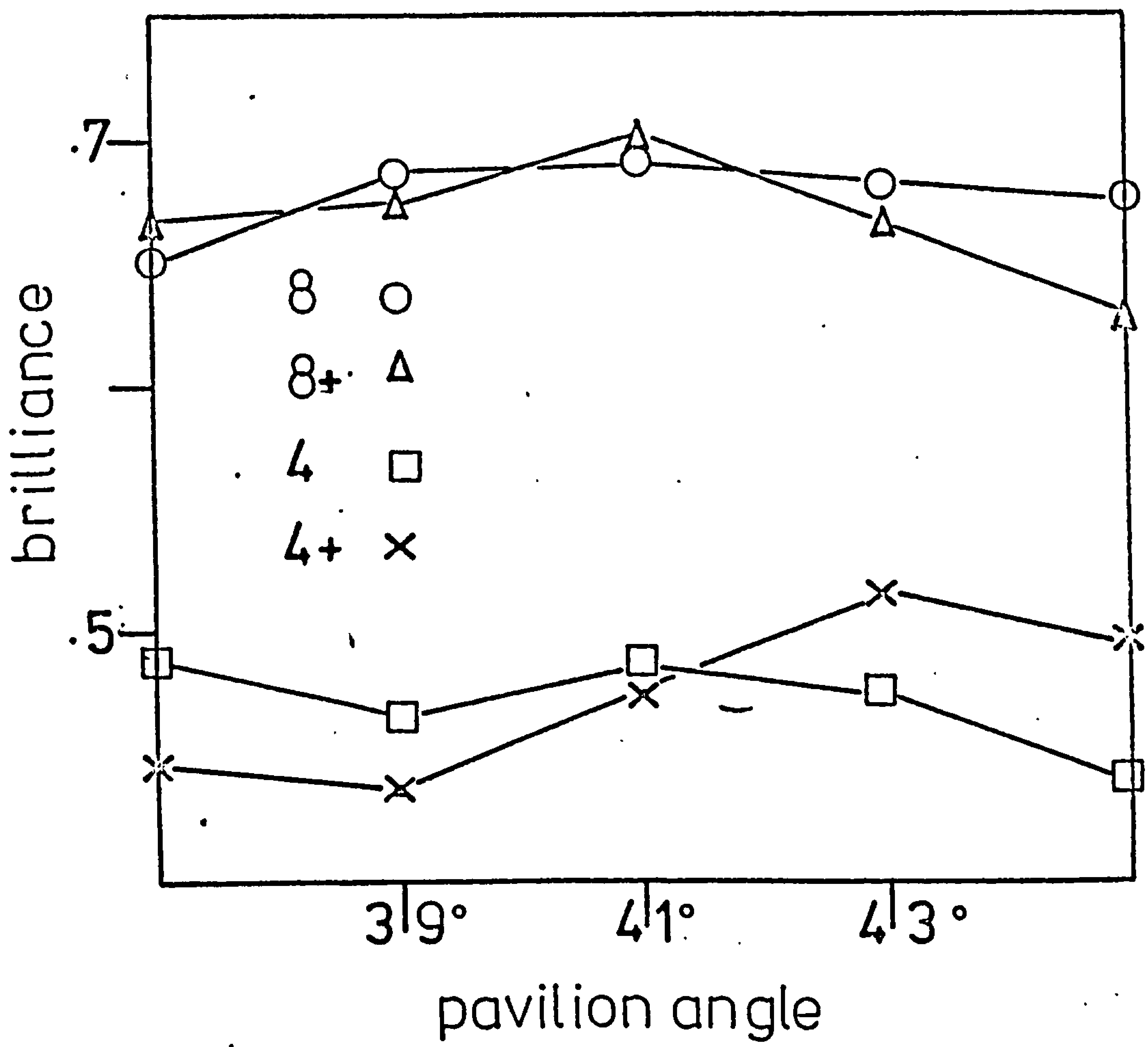


Fig. 4.17 The variation of brilliance with pavilion angle for various styles of polishing
Crown height 15%
Table spread 50%

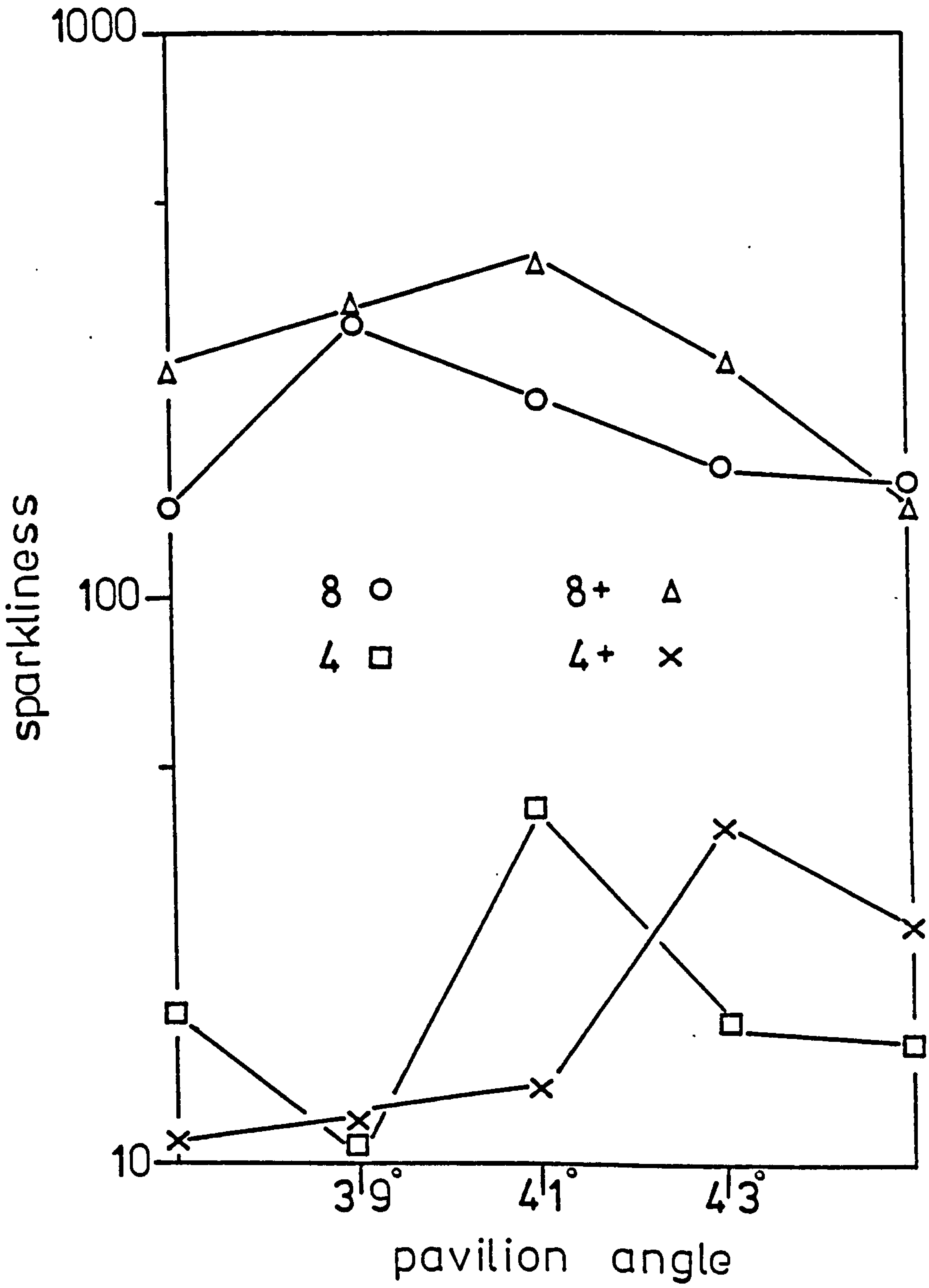


Fig. 4.18 The variation of sparkliness with pavilion angle for various styles of polishing
Crown height 15%
Table spread 50%

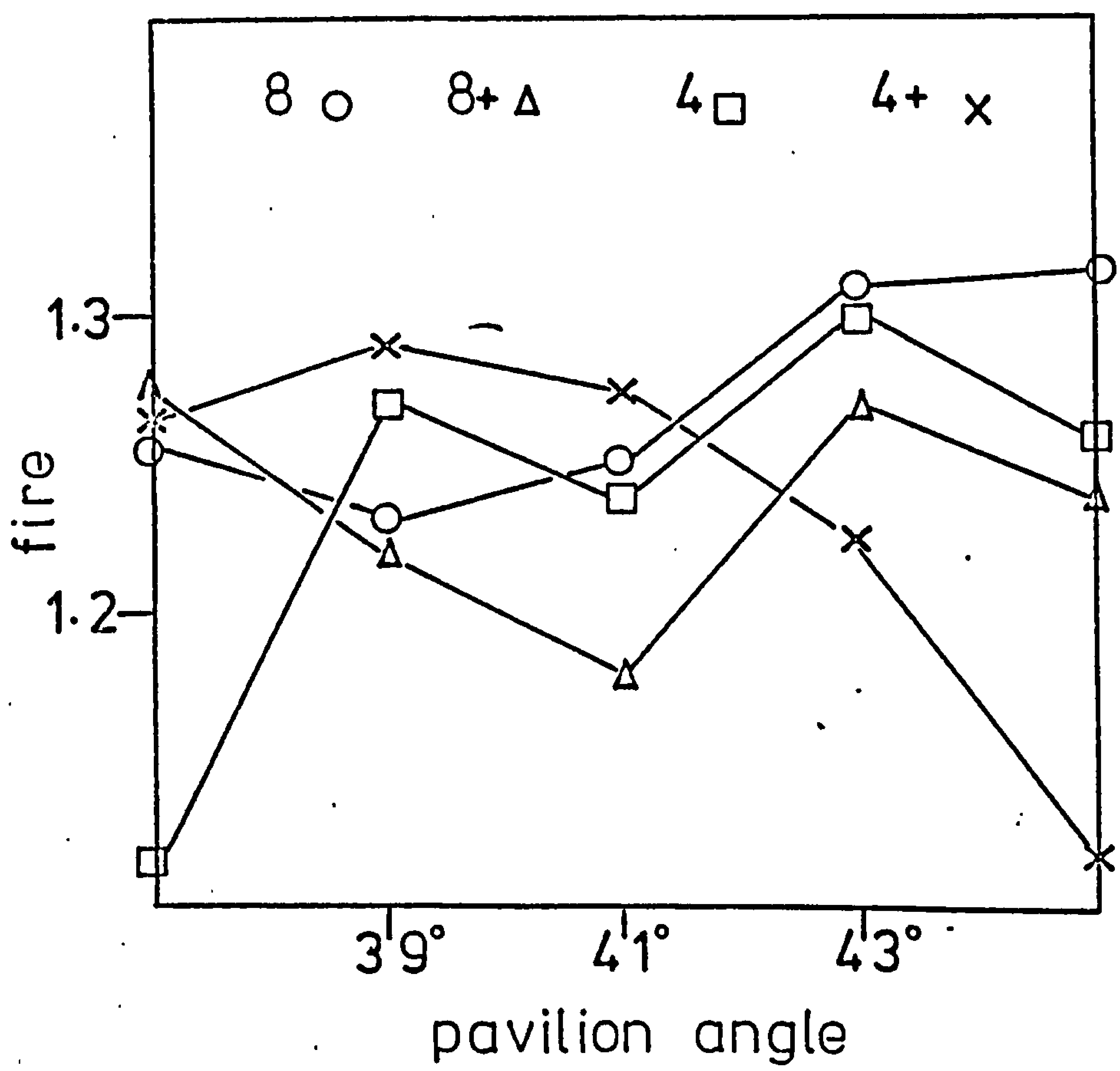


Fig. 4.19 The variation of fire with pavilion angle for various styles of polishing.
Crown height 15%
Table spread 50%

the pavilion range used for all crown heights and the table spreads. This equality is again demonstrated by the 4 and 4+, thus confirming that brilliance is a function of the number of facets, and not their orientation.

The statistical sparkliness (Fig. 4.18) of the 4+ is altered very little except that the peak value is shifted from pavilion 41^{o} for the 4 cut to 43^{o}. The peak value for the 8+ also exhibits this shifting effect. However, the 8+ peak is significantly higher at 41^{o} than the 8 peak value at 39^{o}. In addition the peak value of the 8+ is greater than that of the 58 style. This confirms that a break in the girdle symmetry can result in an increase in optical goodness. The colour variation (Fig. 4.19) of the 8+ is much lower than that exhibited by both the 8 and 58 styles. However, the higher sparkliliness probably results in an overall increase in attractiveness for the 8+ against the 8 style.

4.8 A discusion of c-type modification

The brilliance (Fig. 4.14) of the 16/58 lies between the 16 and 58 styles in accordance with previous findings except at pavilion 39^{o} where it dips below the 16 cut result.

The commonly held opinion that the pavilion is more important than the crown in determining optical goodness is demonstrated by the sparkliness factor. Here (Fig. 4.15) the peak value for the 16/58 lies between the peak for both the 16 and 58 results, with its form following the results of the 58 cut more closely than the 16 cut; a peak is centred on a pavilion angle of 41° with a steady fall off towards pavilion angles 39° and 45°.

The fire factor (Fig. 4.15) in the pavilion range 39°- 43° shows the 16/58 to be appreciably better than either the 16 or 58. Using the argument invoked in sections 3.2 and 3.3 (that a higher fire can compensate for lower sparkliness) it is possible that the 16/58 is as attractive as the full 58 style.

4.9 Summary and conclusion

Thus there are two main families of rotationally symmetric styles based on 4-fold and 3-fold symmetry and four types of modification.

a) an increase in the number of facets.
b) the rotation of the crown with respect to the pavilion.
c) the mixture of a crown and pavilion from two members of the same family.
d) the mixture of a crown from one family with the pavilion of another style from a family of different degree of rotational symmetry.

Modifications a, b and c were investigated using the 4-fold symmetry family.

Increase in the number of facets was shown to result in an increase in optical goodness. Further, a superior result is obtained by the addition of skew facets in comparison with that resulting from an increase only in rotational symmetry. Screw will either improve a given design or at worst leave the maximum value unaltered.

The mixing of crown and pavilion facets resulted in a stone with brilliance and sparkliness between the two component styles but much improved fire.

This brief survey of the modifications of the 58 facet round brilliant cut diamond, which can be achieved with no increase in the diamond polisher's skills and mechanization has shown that the eight cut with screw has greater sparkliness than the 58. However the lower brilliance and slightly reduced fire of the 8+ lead to a less attractive stone, nevertheless it may be a simple and suitable substitute for the 58, particularly so in the smaller sizes of less than 20 points. The principal general conclusion is that virtually any design with the standard proportions and a rotationally symmetric arrangemetn of facets with eight or more facets on the crown and pavilion will give a reasonable if not an optically ideal stone, which is a suitable substitute for the round brilliant cut in the smaller sizes.

Chapter V

The Brilliance, Sparkliness and Fire of some Diamond Simulants

5.1 Introduction

It is possible to classify gemstones into three distinct groups: i. those valued for their depth of colour such as the titanium-iron doped alumina, blue sapphire and the chromium doped alumina and beryl, the red and green gemstones known as ruby and emerald; ii. those exhibiting peculiar scattering effects including the chatoyant and star stones, whose appearance is the result of scattering from crystallographically orientated asicular inclusions, and the thin film interference of labradorite feldspar. Of this type the most well known is opal, a close packed array of quartz scatterers in a solidified gel giving rise to Bragg diffraction in the visible (the structure was correctly deduced by Brewster, 1840). iii. Those transparent materials polished as complex prisms to exhibit the three effects of brilliance, sparkliness and fire.

Diamond is pre-eminent among this class. The supremacy is attributed to its high refractive index (2.41) and high dispersion (0.044) giving a v value of about 32.

These optical properties coupled with its high resistance to abrasion, its rarity as large optical quality crystals and the difficulty of synthesis conspire to produce an article which can cost in excess of $10 M per kilogram. This has lead to many attempts at both

Fig.5.1 Two sets of faceting limits for polishing the normal diamond simulants.

a) After P. Grodinski (1952). The fig. 266, p403 is equivalent to fig. 2.5

TABLE 44

IDEAL BRILLIANT FORMS OF TRANSPARENT MINERALS

Mineral	Refractive Index n	Limit Angle of total Reflection	Height of		Total Height		Table Diameter		Angles‖ of Main Facets		Angle of Table Facets
			Upper Part	Lower Part	Without Girdle	With 2 per cent. for Girdle	Without Table-Facets	With Table-Facets‡	φ Upper Part	ψ Lower Part	
		Deg.	Per cent.¶	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Deg.	Deg.	Deg.
Diamond*	2·42	24·5	19	40	59	61	56	—	41·1	38·5	—
Zircon*	1·95	30·9	22·0	40·7	62·7	64·7	59·0	—	47·0	38·8	—
Corundum (sapphire)*	1·77	34·5	24·0	40·9	64·9	66·9	60·0	—	50·2	38·9	—
Spinel*	1·73	35·4	24·6	41·0	65·6	67·6	60·5	—	51·0	39·0	—
Topaz*	1·63	37·8	26	41·1	67·1	69·1	61·0	—	53·0	39·1	—
Tourmaline†	1·62	38·1	27·3	40·7	68·0	70·0	59	—	53·1	39·1	(29·50)
Beryl†§	1·59	39·0	27·9	40·7	68·6	70·6	59·4	—	54·0	39·1	(29·10)
Emerald	1·58	39·3	28·1	41·1	69·2	71·2	56·6	47·8	52·3	39·4	(29·0)
Aquamarine†	1·57	39·6	28·1	41·6	69·7	71·7	53·1	41·8	50·1	39·8	(27·6)
Rock crystal	1·54	40·5	27·5	42·9	70·4	72·4	44·2	15·8	44·5	40·6	(24·1)

* Values according to S. Roesch.
† Values according to W. F. Eppler.
‡ For minerals with n smaller than 1·59, to avoid losses in brilliancy.
§ Morganite (pink).
‖ See Fig. 266, p. 403.
¶ The width at the girdle being taken as 100.

b) After Harding (1975). Recall also fig. 1.16 (the recommended faceting limits for diamond), the zones A, B and C have the same meaning. The 'common recommendations' are:- 1) GIA (1975b), 2) Soukup, E.J. (1962), 3) Sinkankas, J. (1962) and 4) Tolkowsky, M. 1919. +A is the crown angle and B the pavilion angle.

P/B	COMMON RECOMMENDATIONS 1 and 2	3	RECOMMENDED PER CHARTS Zone A	Zone B	Zone C*
quartz	43/42	43/40-50	43/37	B/A+	—
beryl	43/42	43/40-50	43/35	40/34	40/18
topaz & tourmaline	39/43	(40/40)	43/33 42/41	40/34 39/37	40/17 39/23
peridot & spodumene	(40/42) 39/43	(40/40)	43/32 42/39	40/32 39/36	39/22 38/27
spinel & grossular	42/37	(40/40,	43/31 42/37	40/31 39/35	39/21 38/26
corundum & garnets	42/37	(40/40)	43/30 42/36	40/30 39/33 38/36	39/20 38/25 37/30
low zircon & YAG	41/40 42/37	(40/40)	43/28 42/34	40/28 39/31 38/34	39/20 38/24 37/28
diamond	40.8/34.5 (Tolkowsky)[4]		43/20 42/26	41/18 40/21 39/24	38/20 37/20 36/20

*Zone C includes the Table as a bezel with zero slope. Experimental cuts in this zone are brilliant but look strange and may not be desirable.

synthesis of diamond and production of a transparent material having the optical properties of gem diamond. These non diamonds are called diamond simulants. Several new crystals have recently been produced by the electronics industry with properties similar to those of diamond. Two questions may be asked about these stones.

1) What is the optical performance of a particular simulant and how does it compare with diamond?
2) Is it possible to place limits on the faceting proportions, such as those given by Rosch, Eppler and Harding, (Fig. 5.1)?

5,2 The diamond simulants

Glass has been the most popular simulant for diamond. The highest refractive indices for glass are typically 1.8 with 'v' values not dissimilar to diamond in the high 20's and low 30's (Fig, 5,2). The Rhinestone, Diamonte and French paste are all glass diamond simulants, paste being the generic for glass simulants.

Natural crystals have also been used, zircon (n = 1.9), sapphire (n = 1.76), spinel (n = 1.73) and even topaz (n = 1.63) which can be easily beaten for optical constants (higher n and lower $\dot{v}$ values) by the SF batch of glasses (Fig. 5.2).

Although these materials exhibit the effects of brilliance, sparkliness and fire to some degree and are passable in jewellery, the stones are easily distinguishable from diamond by direct comparison with diamond or by the applications of simple tests. The interested amateur with a 10x lens and a critical angle refracto-

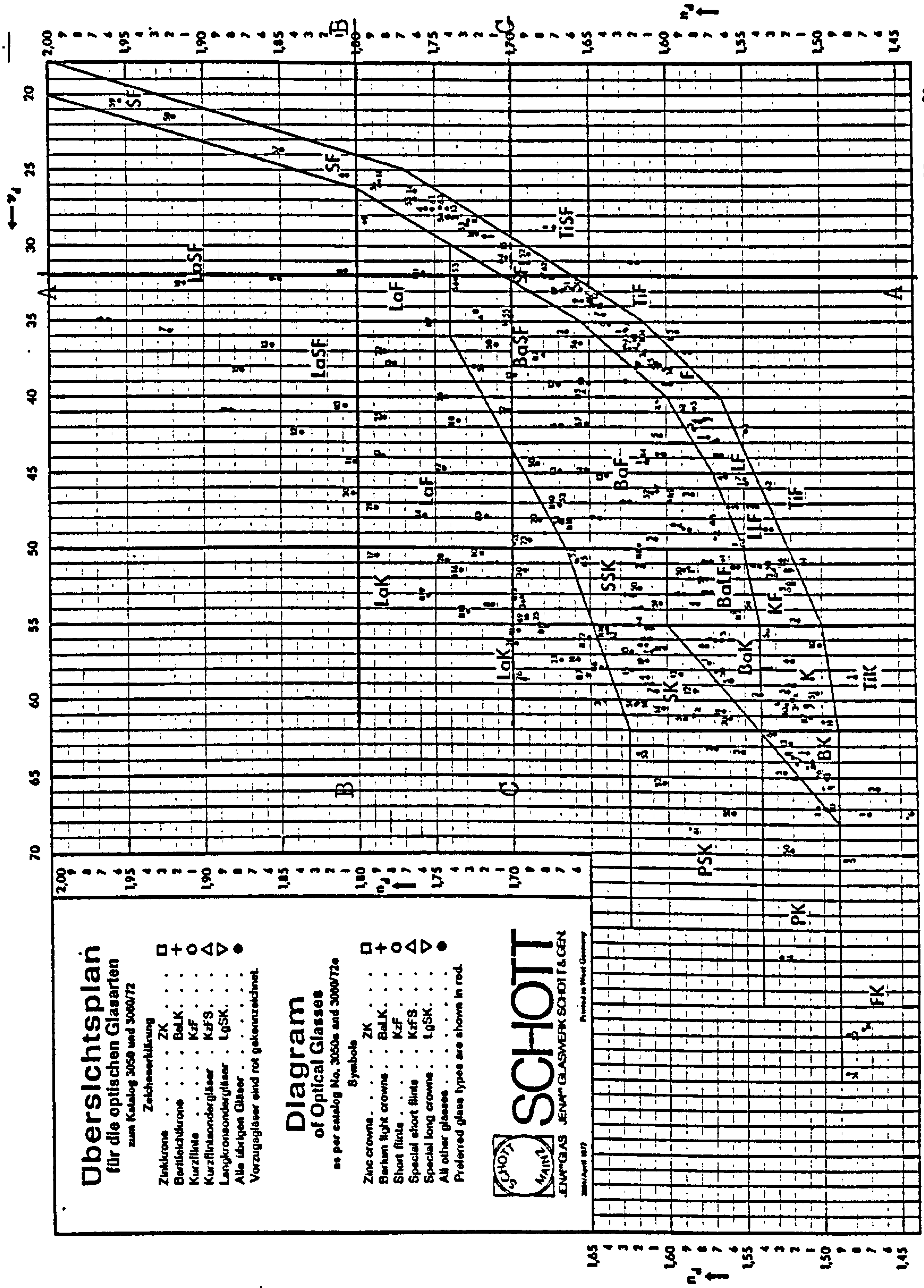


Fig. 5.2 The glass chart of Schott and Gen. (Mainz) Showing refractive index (n_d) plotted as a function of dispersion (v_d) the 'V' value. The line A-A shows the V of diamond (32) higher dispersion is to the right i.e. decreasing V value. The glasses with n 1.7 and V 32 could be considered usable simulants, line C-C. Those with n 1.8, V 32 are useful simulants line B-B.

meter can detect zircon with the lens by its high birefringence, and all these other simulants with a simple critical angle refractometer which measures up to n=1.85.

The notion of a doublet in a gemstone sense can be introduced usefully at this point. As diamond is so expensive, stones are often manufactured as a composite of two gem varieties, usually a diamond crown and a pavilion of some other material (often sapphire). Occasionally diamond-diamond doublets are seen. The detection of a doublet in a set stone is achieved by using the lens to observe the plane of cement; even if it does not contain bubbles the refractive index boundary in the region of 1.35 can be seen.

With the growth of electronics and the semi-conductor industry, exotic crystal growing has become a standard laboratory procedure and it is easy to synthesise naturally occurring materials and novel and curious crystals. Several of these new crystals are highly transparent in the visible, have cubic symmetry, refractive indices higher than 1.8, and comparable colour dispersion to diamond. They are in fact extremely good diamond simulants, not easily detected by an expert with the traditional testing equipment. The most successful of the cubic simulants has been strontium titanate (n = 2.42, v = 9), which is in many ways better than diamond. However the public have preferred materials with higher V values (less dispersion) such as yttrium aluminate with garnet structure (YAG), gadolinium gallium garnet (GGG), and even the birefringent crystal lithium niobate.

Material	Ref. Page No.	Refractive Index	V-value
Strontium Titanate	a 181	2.466	9
ZOC		2.171	38
GGG	a 117	2.02	36
Yttralox	a 118	1.92	30
YAG	a 120	1.84	61
Spinel	a 163	1.73	60
TiF6	b	1.616	31
BK7	b	1.516	64
Rutile	a 155	2.61-2.90	
Lithium Niobate	a 136	2.21-2.30	
Zircon	a 214	1.92-1.98	
Sapphire	a 44	1.76-1.77	
Topaz	a 202	1.61-1.62	
Quartz	a 147	1.54-1.55	
Diamond	-	2.417	32

Fig 5.3 A table of the optical constants of the diamond simulants and some of the birefringent crystals.

a) O'Donoghue(1976)

b) Schott & Gen.(1977)

In the past eighteen months, to this list has been added a zirconium oxide of cubic symmetry, its close relation zircon being tetragonal and as mentioned birefringent. The material is sold under at least three names and as yet no official name; although, the acronym ZOC (zôck) for Zirconium Oxide with Cubic symmetry has been suggested..

Synthetic rutile developed for the paint industry in 1949 (one of the polymorphs of TiO_2, the others being anatase n = 2.5 and Brookite n = 2.6) is the highest refractive index material for normal gems, n = 2.8. Unfortunately it is highly birefringent, $n_e - n_w = 0.287$, but it is still used as an effective simulant.

To overcome the apparent excess of optical goodness in strontium titanate A. Brooks, a lapidary of London, has produced a stone with a clear sapphire crown and strontium titanate pavilion known as a 'Hardtops'. In this way the crown serves two ends i.) in damping down the optical effect and ii.) capping the relatively low abrasion resistance of strontium titanate (Mohs 6) by the hard material alumina (Mohs 9)

5.3 The survey of simulants

As the programme is only applicable to cubic symmetry and amorphous materials, it was not possible to investigate the birefringent crystals. The study was confined therefore to strontium titanate, ZOC, GGG, Yttralox (a General Electric sintered material made from yttrium oxide and thorium oxide), YAG, spinel and TiF6 and BK7, two glasses manufactured by the Schott optical

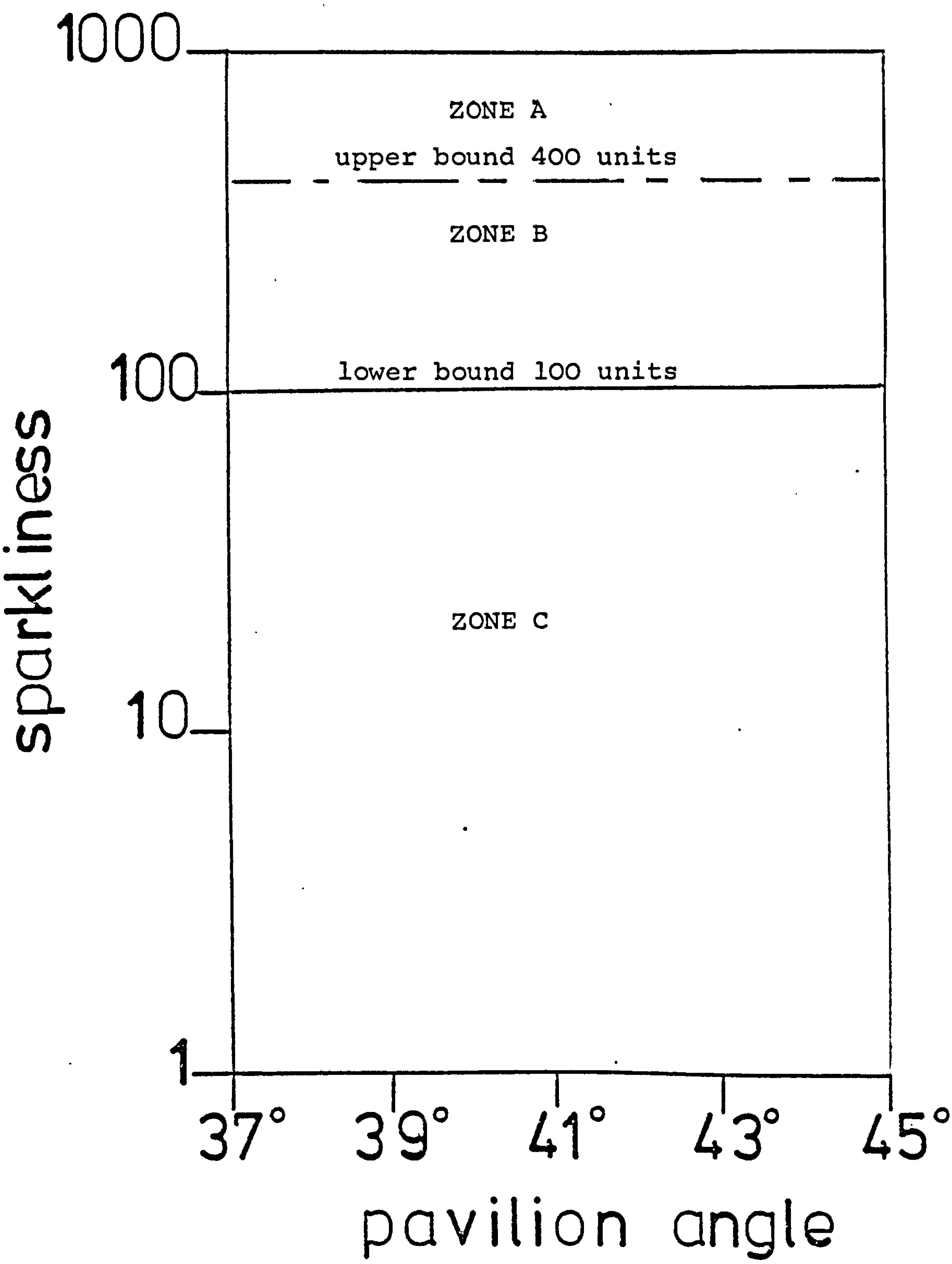
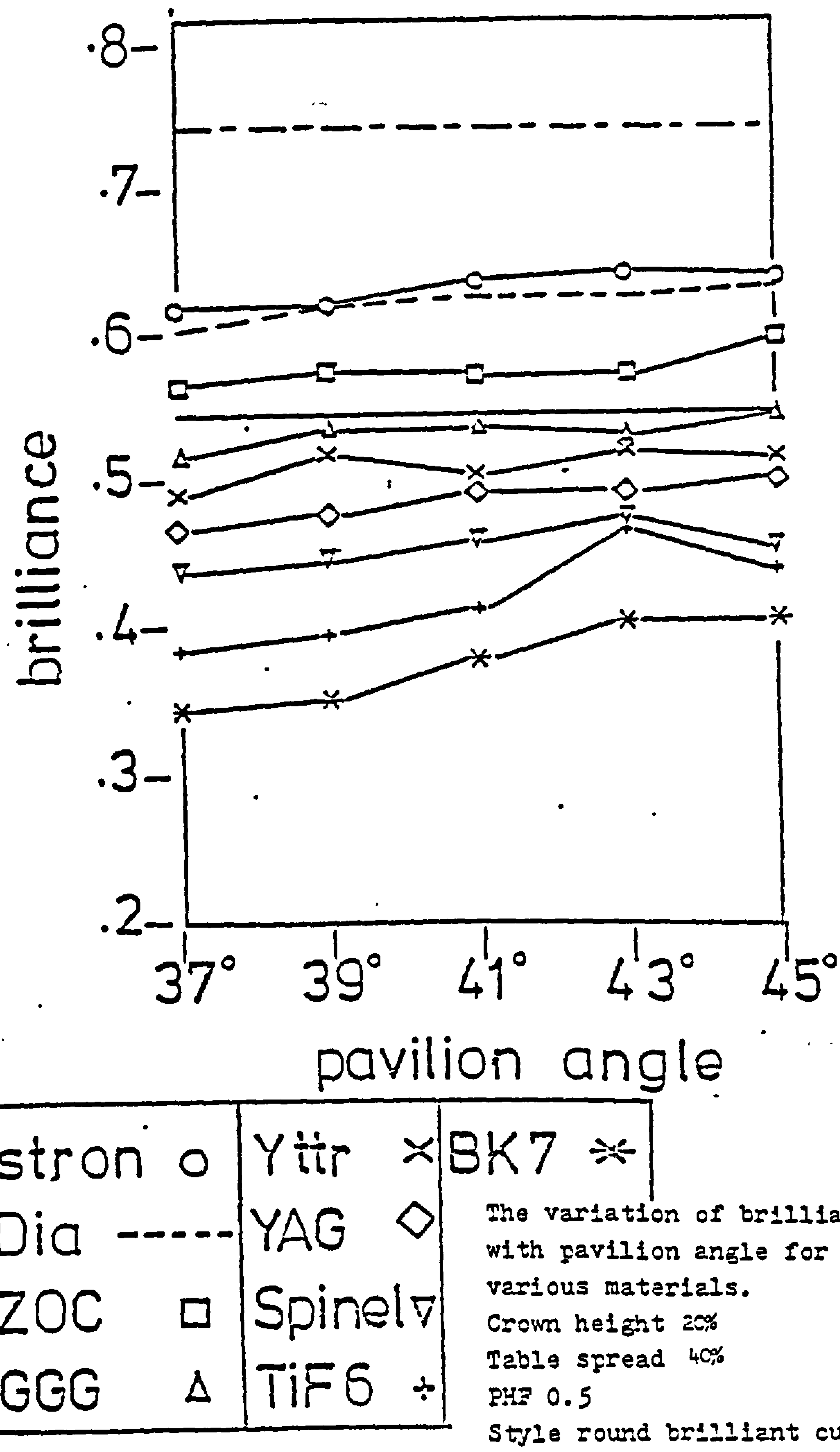
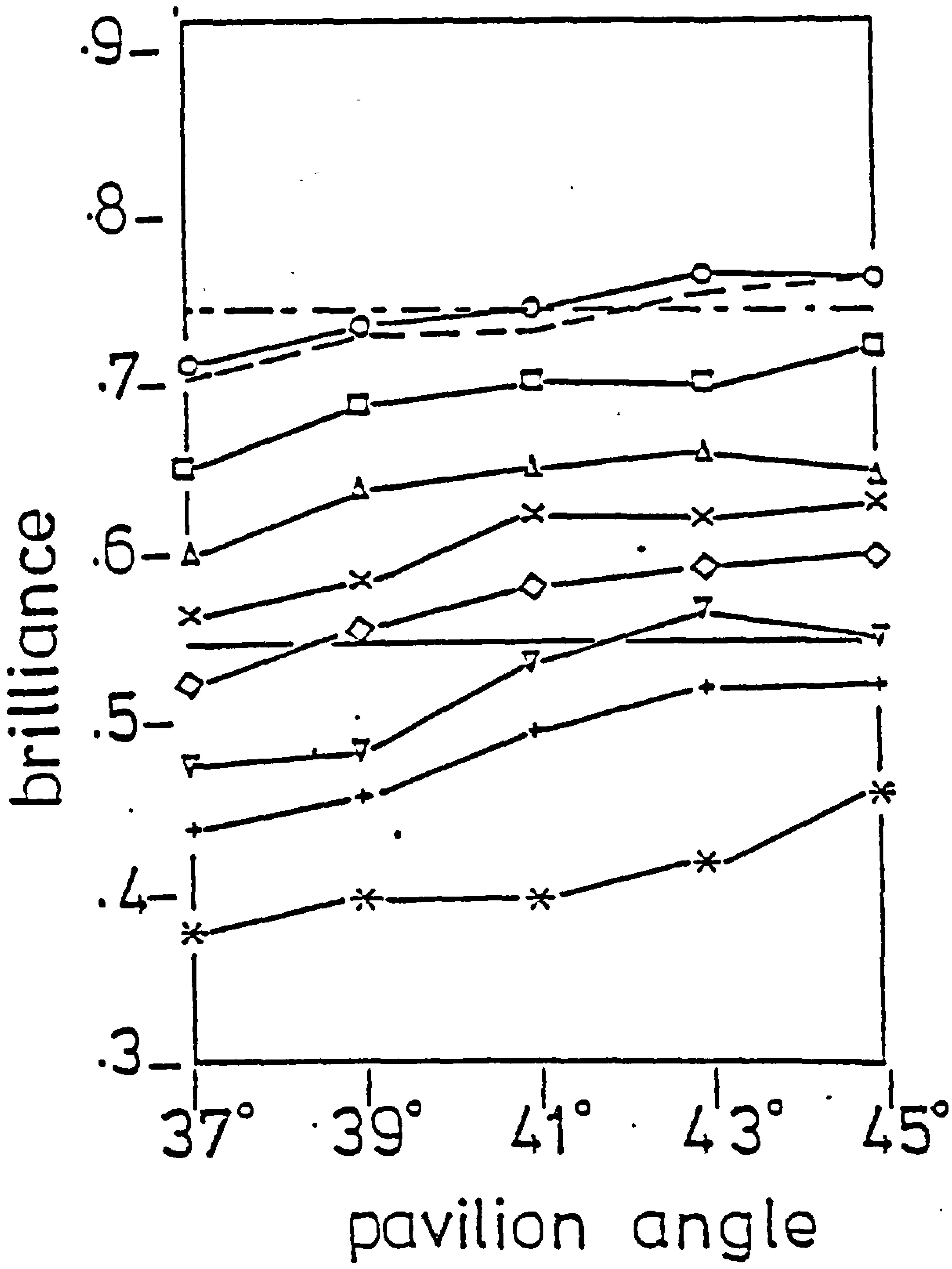


Fig. 5.4 a guide to the graphs of optical goodness,
Zone A better than diamond
Zone B equal to diamond
Zone C worse than diamond



The variation of brilliance with pavilion angle for various materials.
Crown height 20%
Table spread 40%
PHF 0.5
Style round brilliant cut

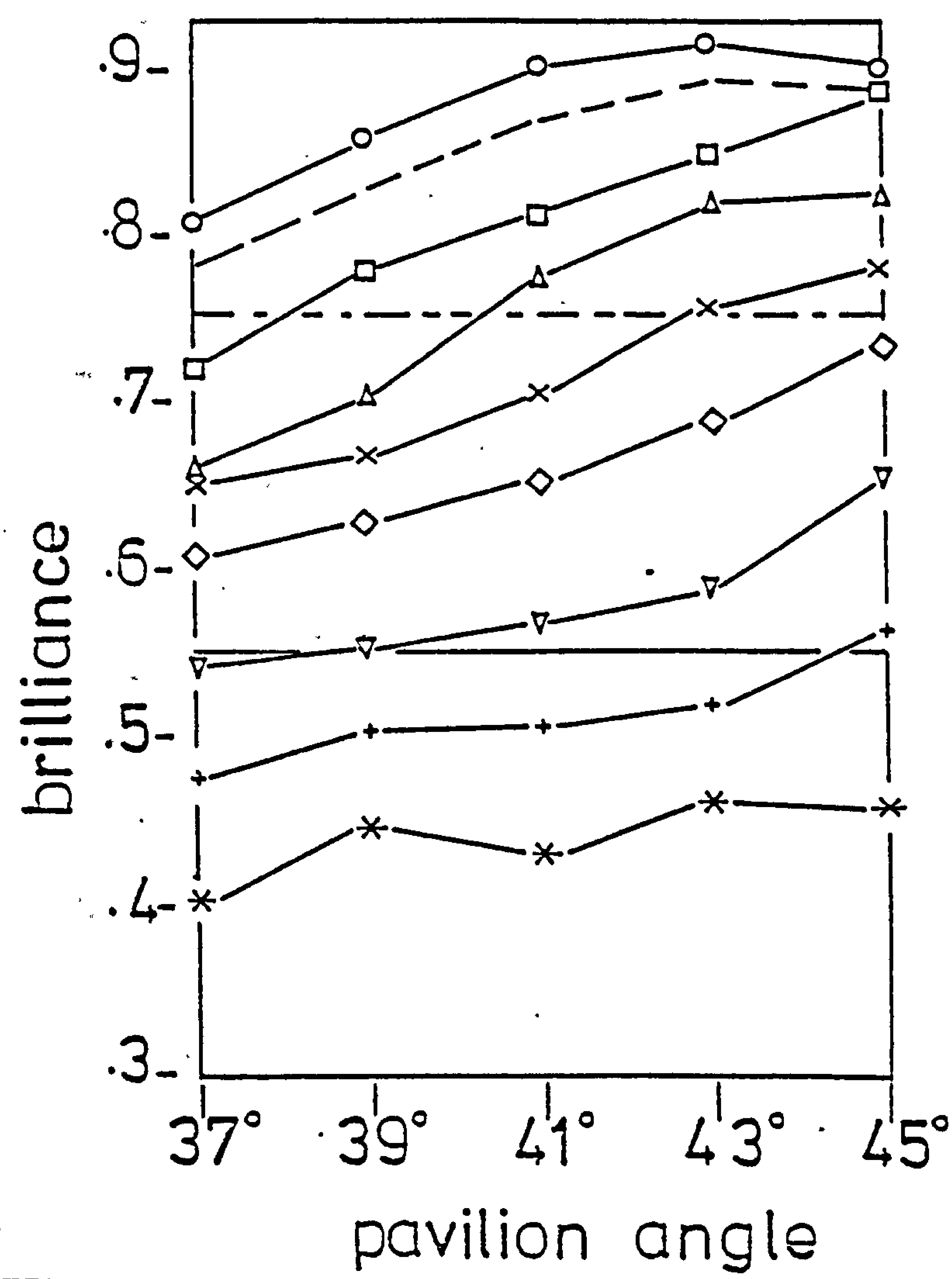
Fig. 5.5



stron o	Yttr ×	BK7 ⋇
Dia -----	YAG ◇	
ZOC □	Spinel ▽	
GGG Δ	TiF6 +	

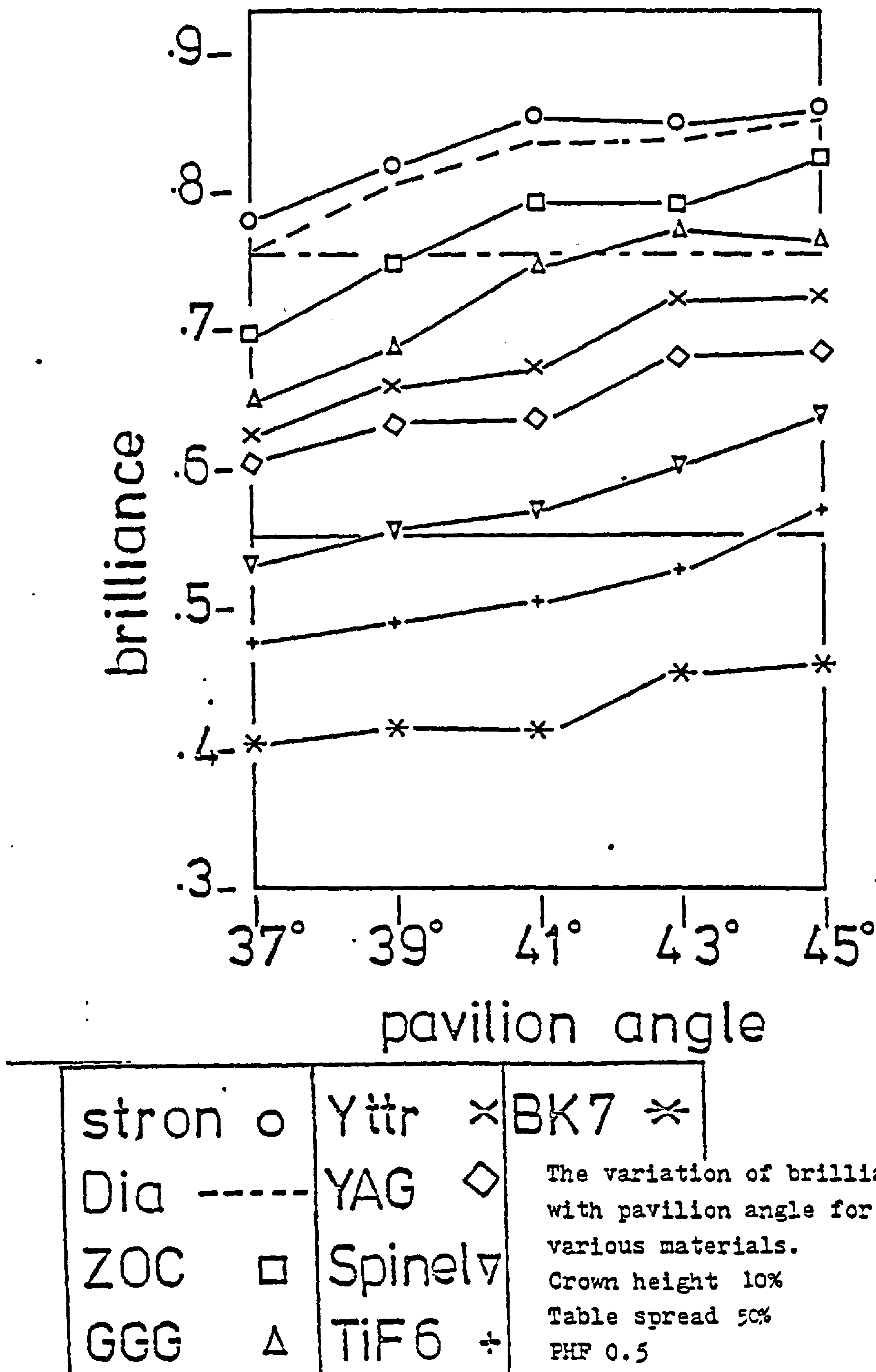
The variation of brilliance with pavilion angle for various materials.
Crown height 15%
Table spread 40%
PHF 0.5
Style round brilliant cut

Fig. 5.6



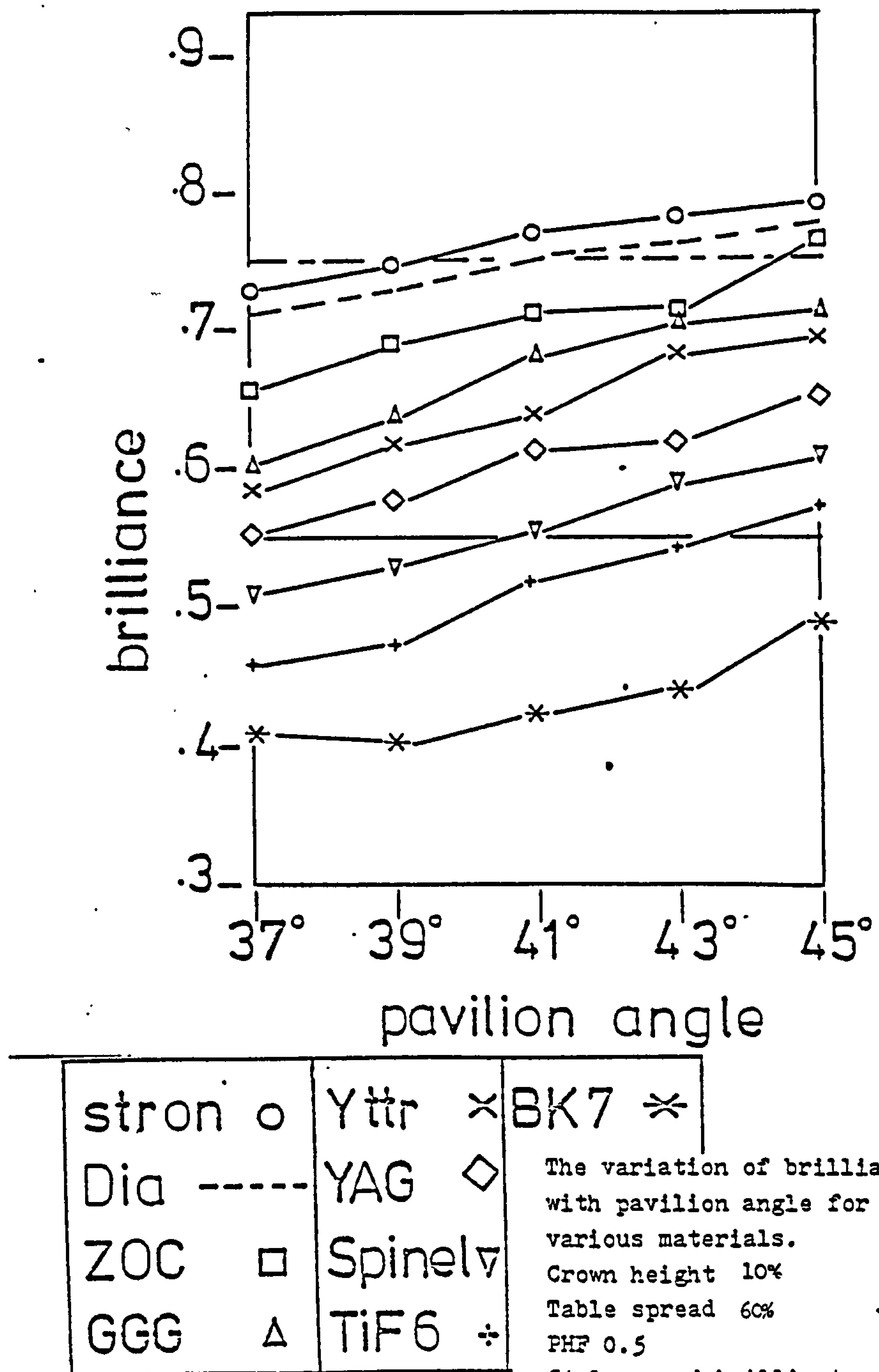
The variation of brilliance
with pavilion angle for
various materials.
Crown height 10%
Table spread 40%
PHF 0.5
Style round brilliant cut

Fig. 5.7



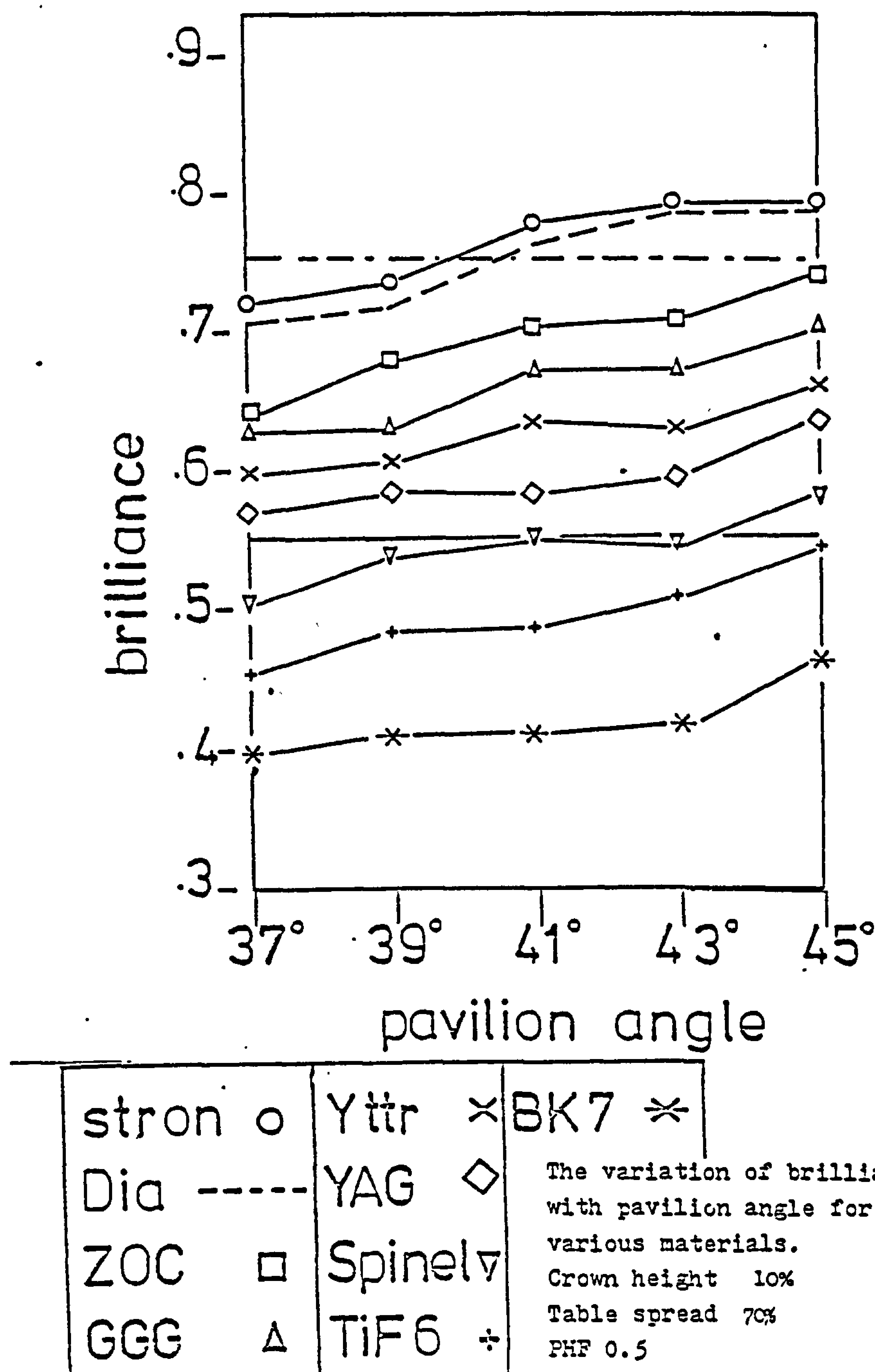
The variation of brilliance with pavilion angle for various materials.
Crown height 10%
Table spread 50%
PHF 0.5
Style round brilliant cut

Fig. 5.8



The variation of brilliance with pavilion angle for various materials.
Crown height 10%
Table spread 60%
PHF 0.5
Style round brilliant cut

Fig. 5.9



The variation of brilliance with pavilion angle for various materials.
Crown height 10%
Table spread 70%
PHF 0.5
Style round brilliant cut

Fig 5.10

glass company, which were included more for completeness than as useful simulants. The optical properties of these materials are shown in Fig. 4.3.

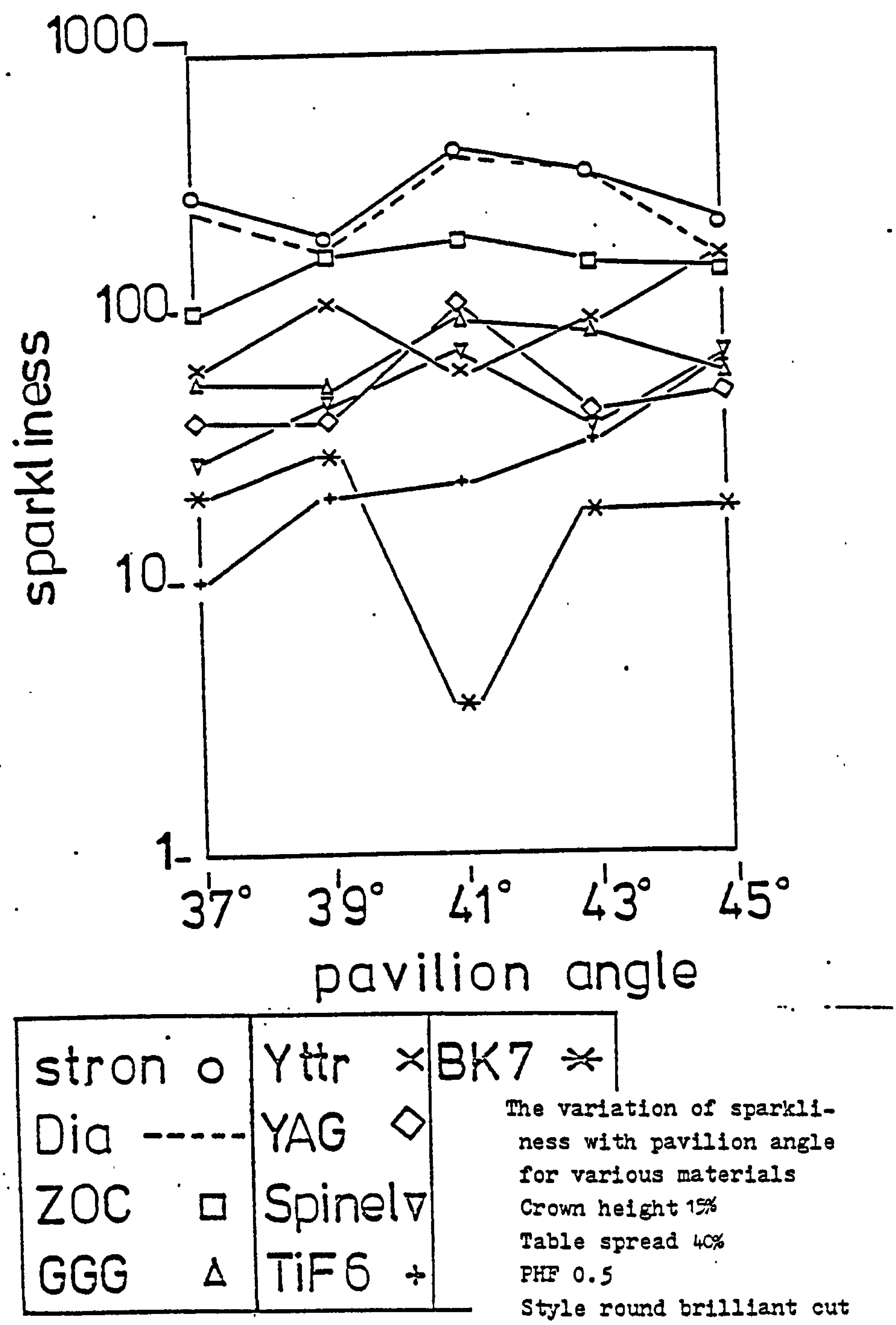
The study was confined to the round brilliant cut style of 58 facets. The pavilion and crown proportions were those used in the study of the round brilliant cut diamond (see Chapter III) with a pavilion half factor of 0.5. The complete results are contained in Appendix V.

The graphs are presented as charts of a particular crown and pavilion combination of all the chosen materials; two boundary lines are given. The upper bound (the dash-dot line) is for sparkliness, the peak value occurs for the 15% crown 40% table style (Section 3.3, Fig. 3.12). The values for brilliance and fire for the same style are plotted on the brilliance and fire results. The lower bound solid line (the old mine style) and again the equivalent values are those used for the brilliance and fire results.

This implies that any material with parameters within these bounds is an acceptable simulant for diamond. Materials above the upper bound are better in some sense than diamond, while below the lower bound they are unsatisfactory as diamond simulants. The three bands will be referred to as Band A $>$ upper bound, Band B, upper bound $>$ Band B $>$ lower bound, and C $<$ lower bound, (see Fig. 5.4).

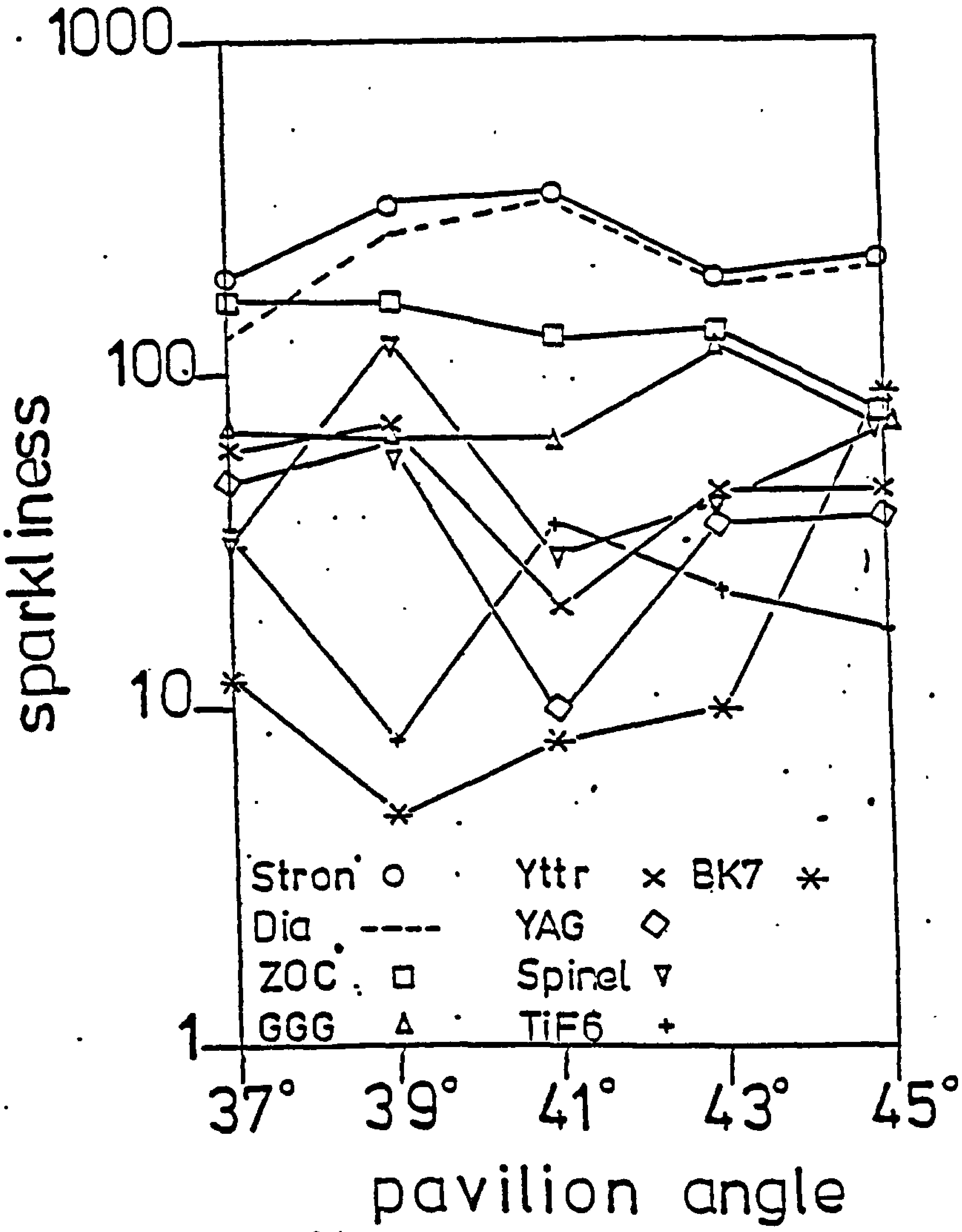
5.4 Results and discussion

Yet again the brilliance exhibits clear trends. Decreasing brilliance with decreasing n for increasing



The variation of sparkliness with pavilion angle for various materials
Crown height 15%
Table spread 40%
PHF 0.5
Style round brilliant cut

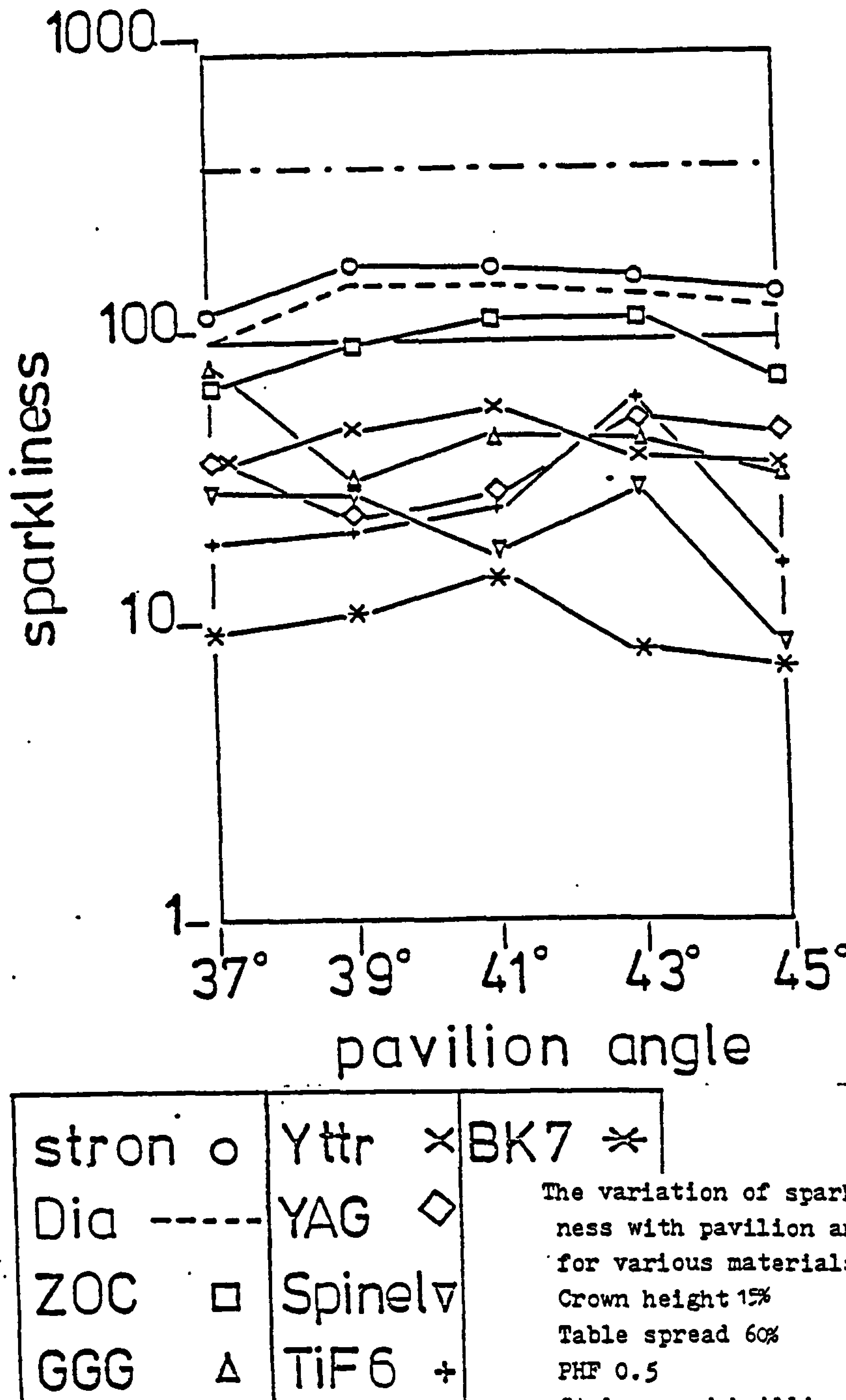
Fig. 5.11



stron o	Yttr ×	BK7 ✳
Dia -----	YAG ◇	
ZOC □	Spinel ▽	
GGG △	TiF6 +	

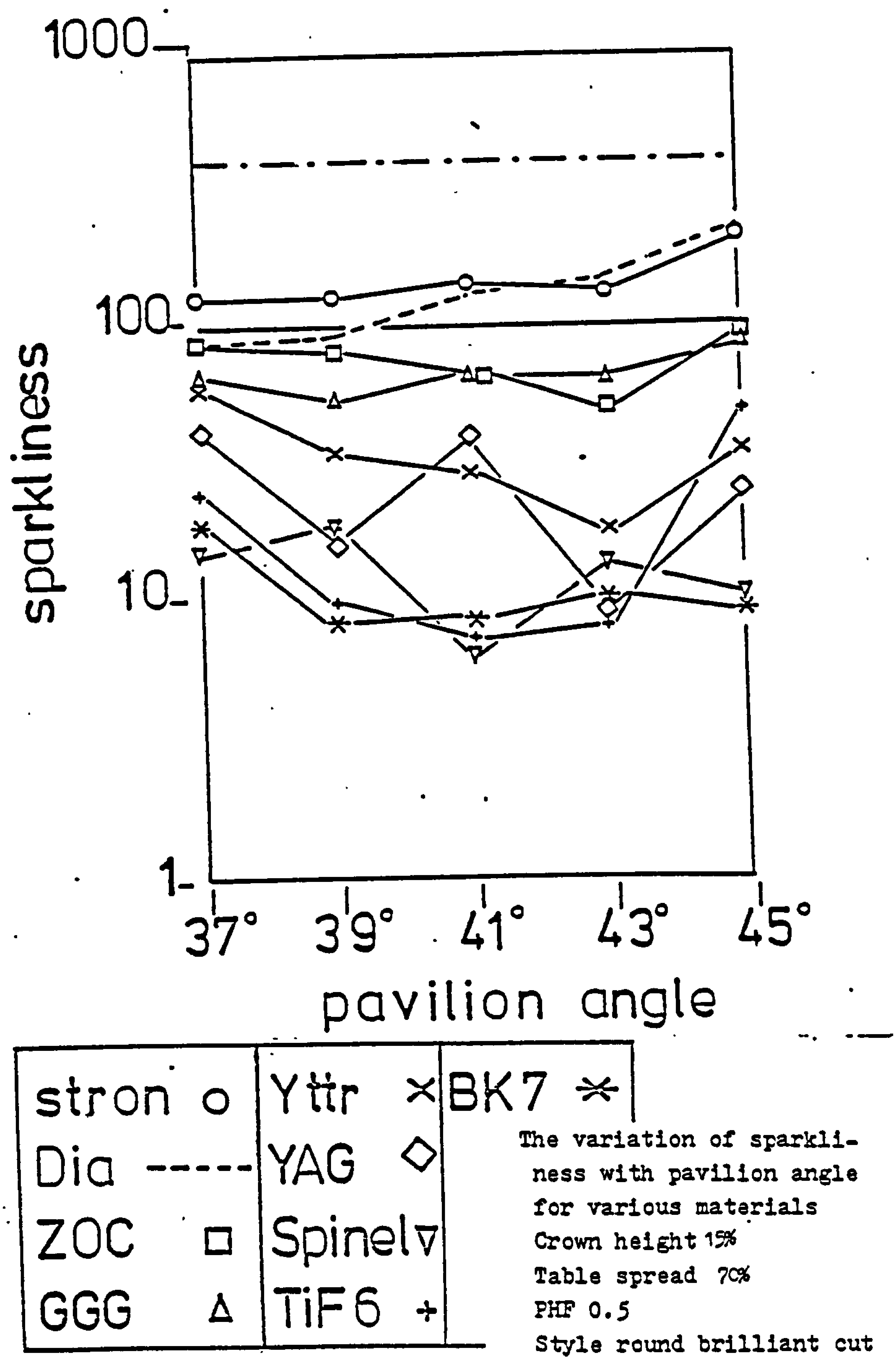
The variation of sparkliness with pavilion angle for various materials
Crown height 15%
Table spread 50%
PHF 0.5
Style round brilliant cut

Fig. 5.12



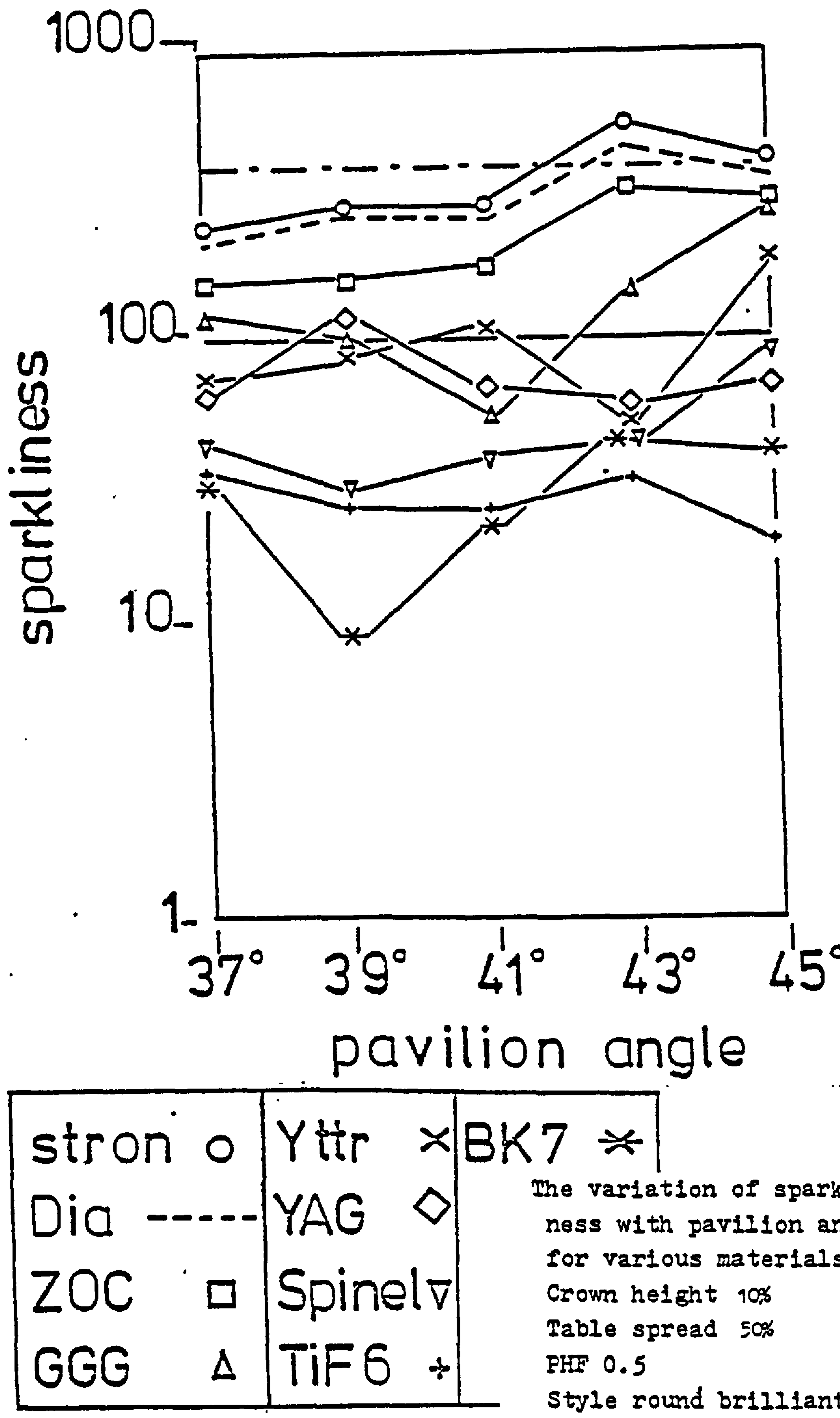
The variation of sparkliness with pavilion angle for various materials
Crown height 15%
Table spread 60%
PHF 0.5
Style round brilliant cut

Fig. 5.13



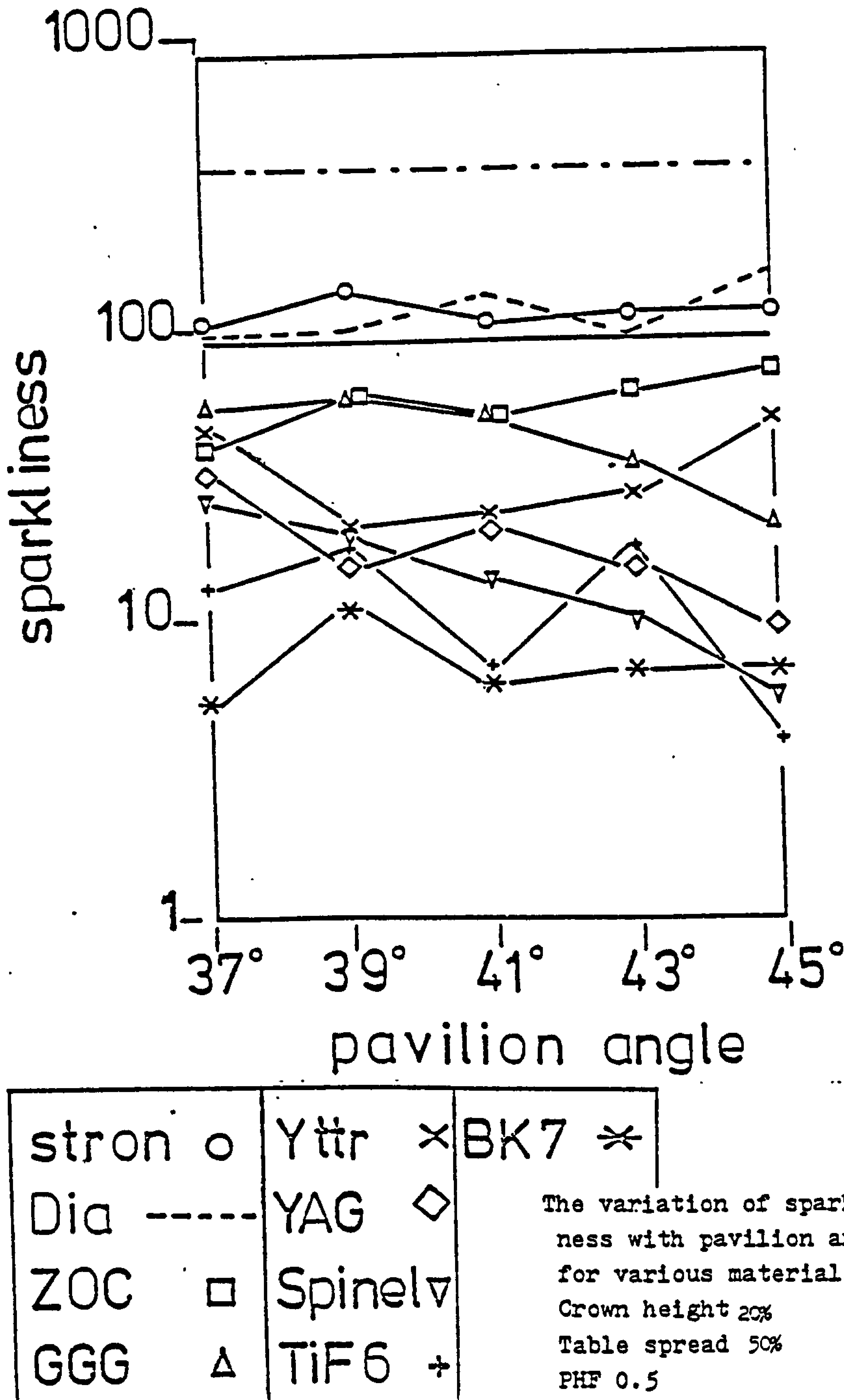
The variation of sparkliness with pavilion angle for various materials
Crown height 15%
Table spread 70%
PHF 0.5
Style round brilliant cut

Fig. 5.14



The variation of sparkliness with pavilion angle for various materials
Crown height 10%
Table spread 50%
PHF 0.5
Style round brilliant cut

Fig. 5.15

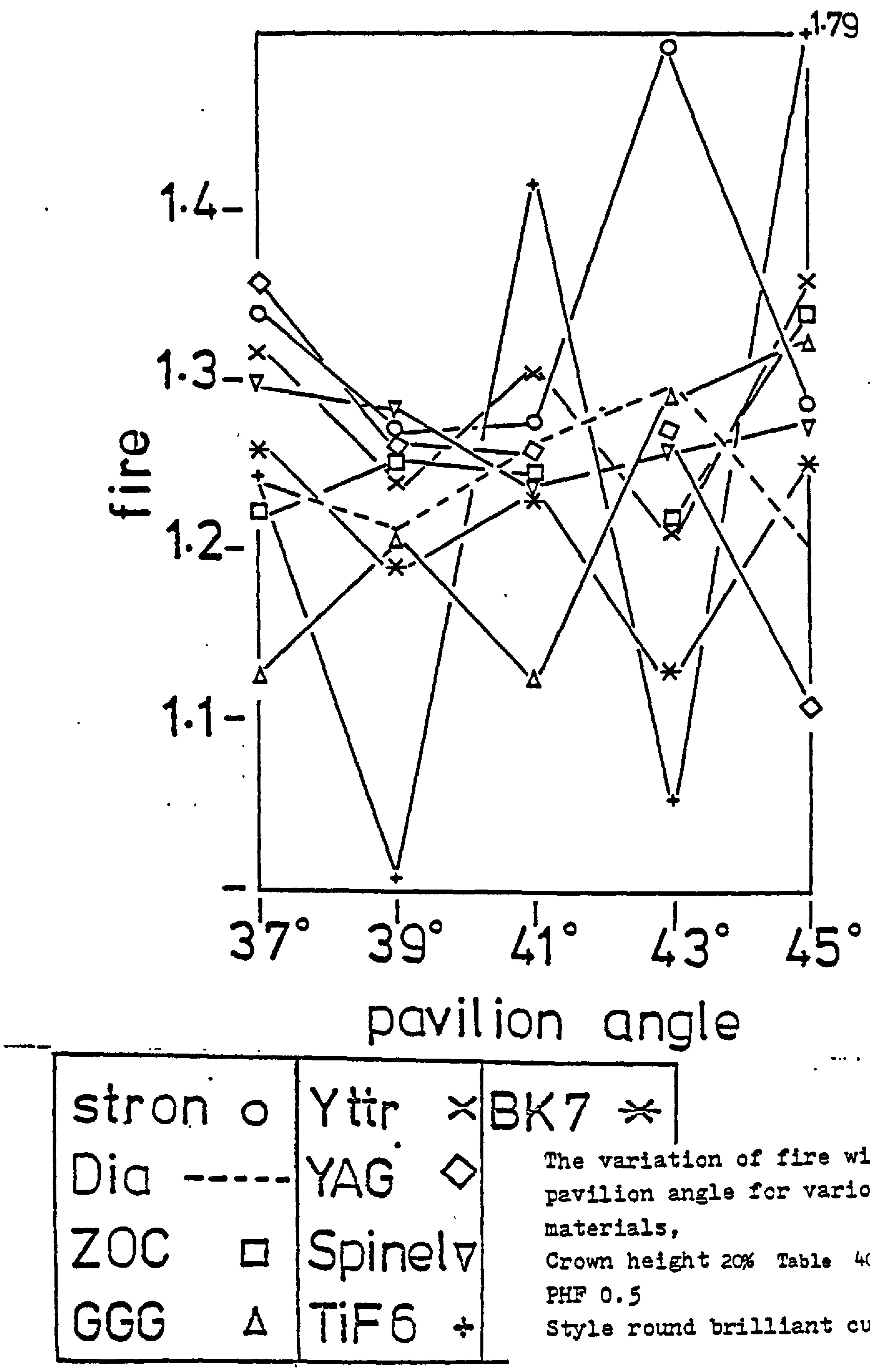


The variation of sparkliness with pavilion angle for various materials
Crown height 20%
Table spread 50%
PHF 0.5
Style round brilliant cut

Fig. 5.16

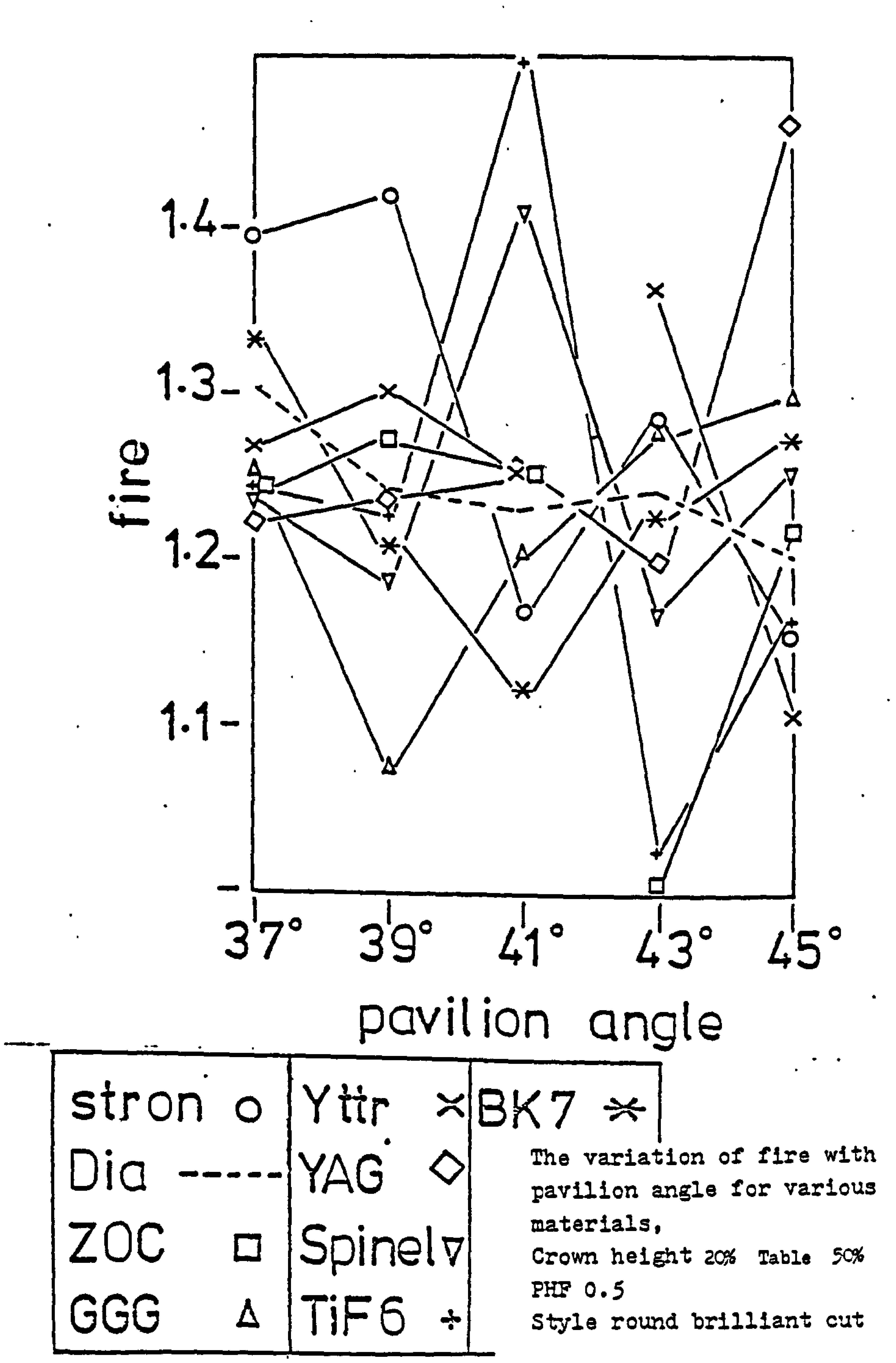
crown height (Figs 5.5, 5.6, 5.7), and decreasing brilliance with decreasing n with increasing table spread (Figs. 5.7, 5.8, 5.9, 5.10). The individual materials behave exactly as the diamond results of section 3.3. The increased brilliance for a 10% crown is clearly demonstrated by the 40% table results (Fig. 5.7). All the materials above spinel (n = 1.73) are in the acceptable region Band B, with GGG, ZOC and strontium in Band A, the higher performance region. However this extra advantage has been lost by the 70% table (Fig. 5.10) with all the materials above spinel in band B except strontium titanate in band A,

It was found in section 3.3 that the sparkliness results for diamond were nearly all contained in the region 100 - 400 sparkliness units. With BK7 (n = 1.51) having values as low as 4 units the spread of values for all materials is some two decades. General trends in sparkliness are discernable but are not as well defined as for brilliance. Considering the 15% crown height results (Figs. 5.11, 5.12,.5.13, 5.14) there is a general fall in performance with refractive index for increasing table spread. In contrast to brilliance none of the materials breaks into band A, but as before strontium titanate is slightly higher than diamond. Thus the superior performance of strontium titanate which should result in a more attractive stone is demonstrated. The apparent dislike of this gem material (its optical effect is considered vulgar by many) must be another caprice of fashion. When the set of acceptable simulants is considered (band B) the individual fall in performance of materials with increasing table spread has a noticeable



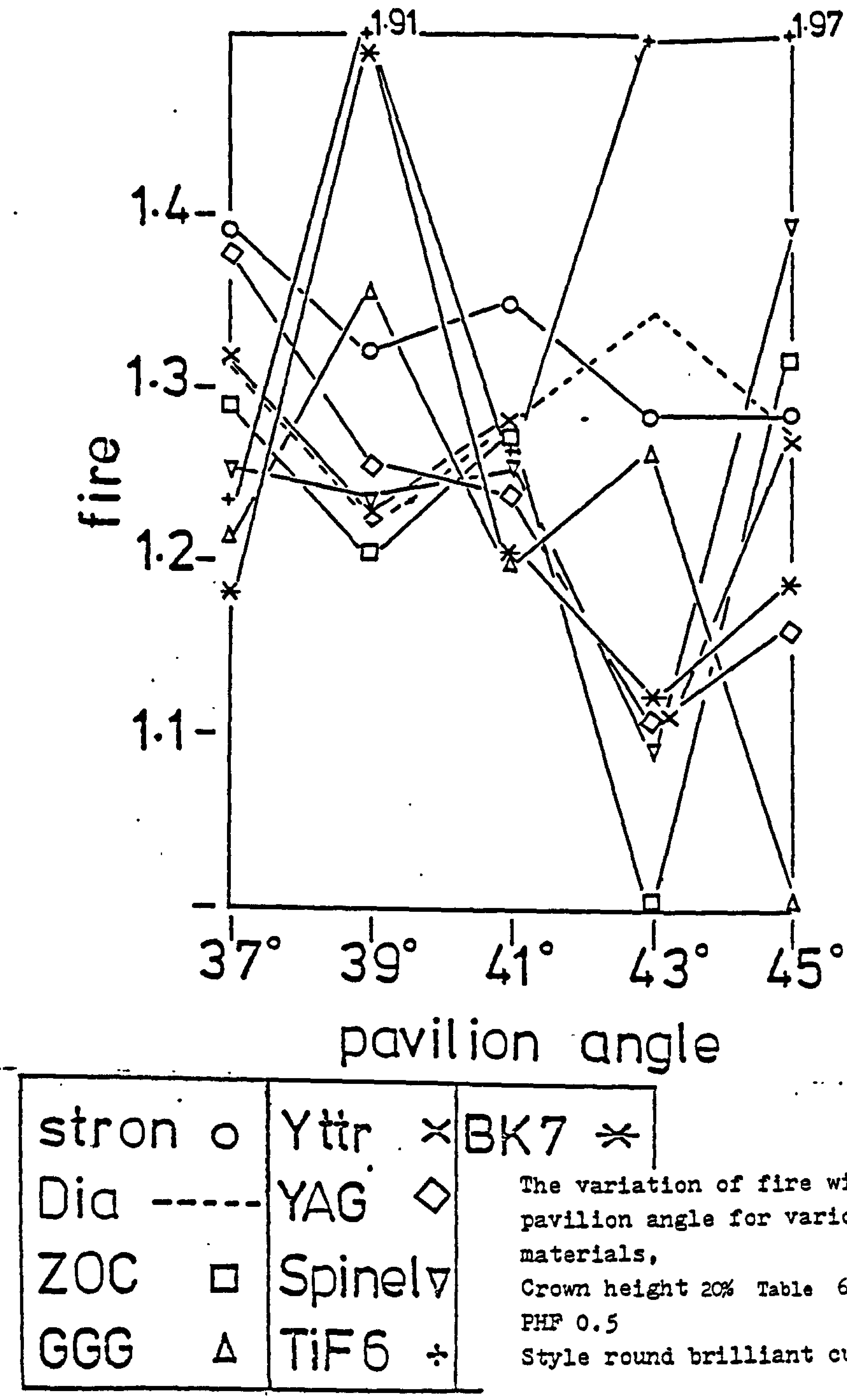
The variation of fire with pavilion angle for various materials,
Crown height 20% Table 40%
PHF 0.5
Style round brilliant cut

Fig. 5.17



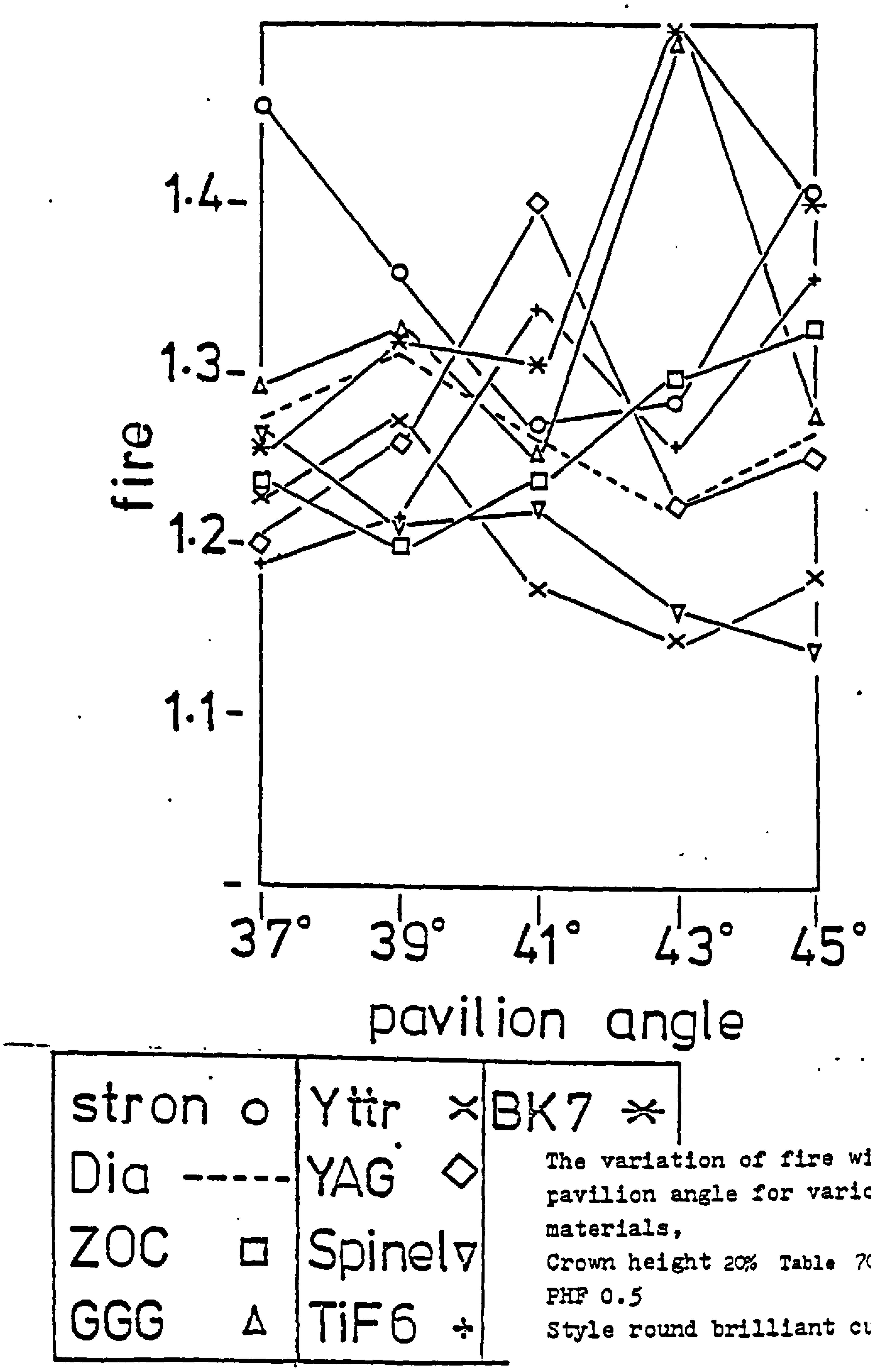
The variation of fire with pavilion angle for various materials,
Crown height 20% Table 50%
PHF 0.5
Style round brilliant cut

Fig. 5.18



The variation of fire with pavilion angle for various materials,
Crown height 20% Table 60%
PHF 0.5
Style round brilliant cut

Fig. 5.19



The variation of fire with pavilion angle for various materials,
Crown height 20% Table 70%
PHF 0.5
Style round brilliant cut

Fig. 5.20

effect. For the 40% table yttralox and above are acceptable, for 50% the lower limit is GGG, 60% ZOC while for 70% tables only strontium and diamond are in zone B.

A similar trend is just discernable for a variation in crown height; the results for the 50% table are typical (Fig. 5.12, 5.15 and 5.16). The fall in performance here is a function of increasing crown height. The 10% crown yttralox and YAG are at the lower bound. With the 20% crown. Only strontium titanate and diamond are in band B. Over the range of acceptable diamond styles, as discussed in section 3.3, the use of YAG, yttralox and GGG and more recently ZOC as diamond simulants is also justified, although these materials give lower performance than a diamond of the same proportions. This is especially true for the modern styles of polishing (lower crowns).

As before (Chapter III and IV) the fire gives complex data from which few general conclusions can be drawn (Figs. 5.17, 5.18, 5.19 and 5.20 are typical). However it would appear that the lower V value materials do give higher fire with the ZOC having whiter sparkles, an advantage in the present styles.

5.5 Summary

The optical goodness of the 58 facet round brilliant cut was investigated when produced in a selection of diamond simulants. Strontium titanate was shown to have optical goodness higher than diamond. YAG, yttralox, GGG and ZOC were shown to be acceptable simulants of diamond with the set of charts (Appendix V) showing the faceting limits. These charts are based on the performance of the typical styles for diamond, discussed in Chapter III. The lower limit was chosen at 100 of the arbitrary sparkliness units, all materials with styles above this bound are considered satisfactory. Materials such as spinel were shown to be marginal.

A correlation between general decrease in optical attractiveness and decrease in refractive index was found. This shows (in general terms) that stones with n above 1.8 are acceptable simulants, while stones in the range n=1.7 - 1.8 are marginal simulants. Below n=1.7 the materials are less useful as simulants, even for their particular ideal properties. As optical goodness appears to be a function of refractive index these general conclusions are also valid for the birefringent crystals, to a first approximation.

Finally, as strontium titanate is considered to exhibit a gross optical effect, ZOC with its whiter sparkliness is the most satisfactory simulant for diamond.

Chapter VI

The Diamond Grading Engine

6.1 Introduction

It is to be remembered that the final value of a diamond is a function of the four factors, colour, clarity, carat weight and cut. Of these, weight and colour can be measured using non-subjective methods and machines. With the recent consumer legislation the requirement for an independent assessment of all four factors has arisen. The Scandinavian Diamond Nomenclature (1969) contains methodologies for the assessment of clarity and cut, and Burr (1974) has also developed a systematic method for grading clarity. As yet there is no direct way of measuring the optical goodness of a diamond such as the round brilliant cut.

There are two approaches to grading the optical goodness of a diamond. The traditional method involves measurement of the proportions of the stone. The ideal proportions are well known and as these constitute the single solution, any stone having these ideal proportions will have the greatest optical effect. The only direct methods of measuring the optical effect of a stone are those based on the method of Rosch (see Chapter II).

6.2 The indirect measurement of optical goodness

When proportion is measured three schemes are usually followed:

i) The traditional shadows technique of the cutters,

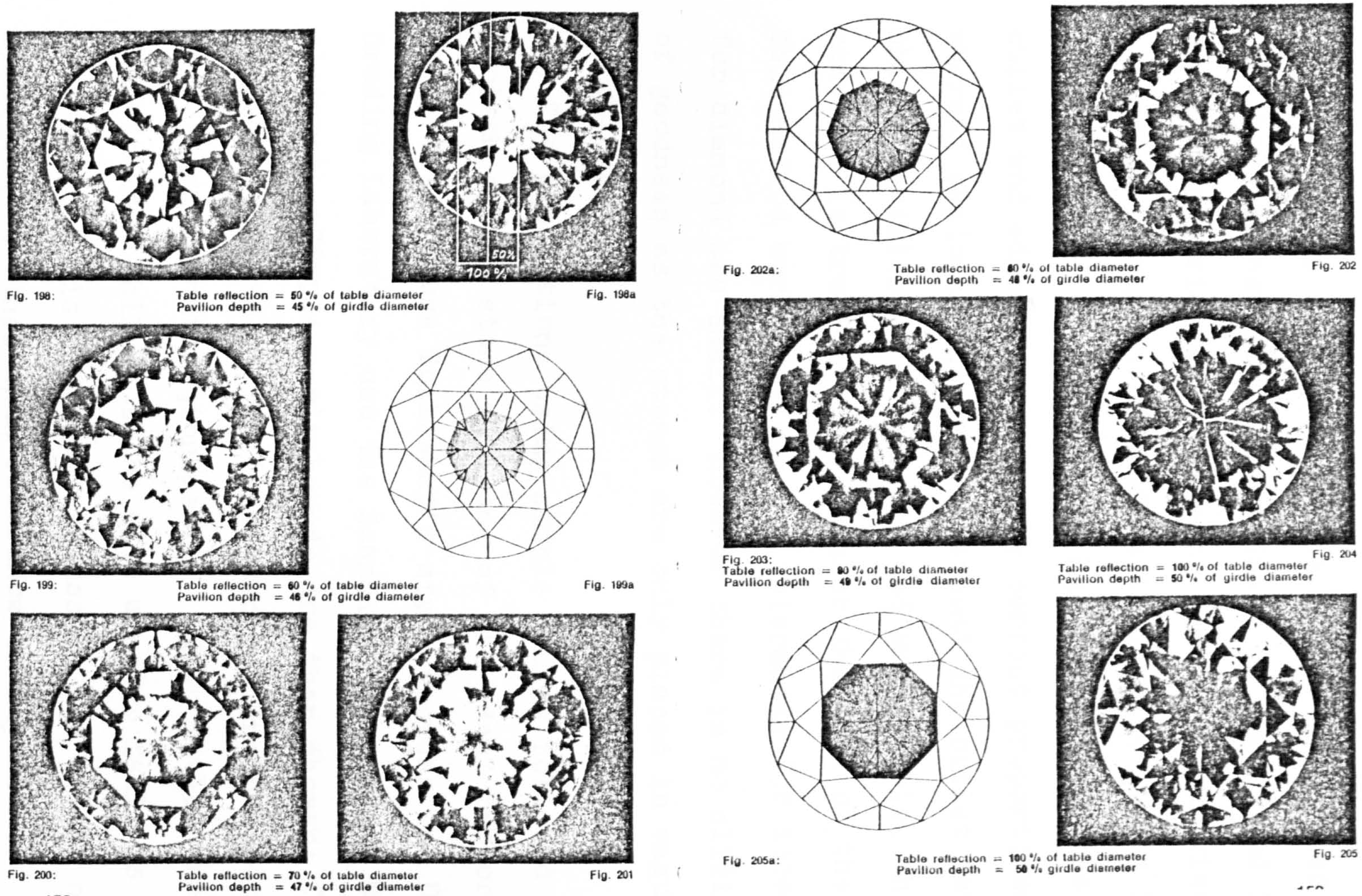


Fig. 6.1 The traditional shadows technique, after Pagel-Theisen (1974).

ii) The use of gauges and measuring devices coupled
with simple merit bounds

iii) The Scandinavian Diamond Nomenclature technique.

i) The shadows technique is the method still used by polishers to estimate the goodness of a gem and is based on experienced judgement. The stone is viewed with a lens and a region of shadows through the table is observed (Fig. 6.1). Shadows halfway between the cullet and edge of table imply correct proportions, whereas shadows concentrated around the cullet imply a shallow pavilion or high crown and small table, the converse is true for shadows near the edge of the table. This method works well as the tolerances for acceptability for diamond are small. However there is no sliding scale of goodness as the stones are only placed in vague groupings.

ii) The proportions using simple gauges followed by comparison of the stone with one of the ideal proportions (e.g. The GIA use Tolkowsky's style whereas The Diamond Grading Laboratory use the Scandinavian Diamond Nomenclature). Simple merit bounds are then chosen; for the stones within x% of the ideal proportions considered good, outside that region medium. This method breaks down in that while a stone with a major fault is assessed as medium, it is difficult to assess the effect of many minor faults other than reference to experienced judgement.

iii) The method of Tillander's committee is a comprehensive method for measuring proportions. The major

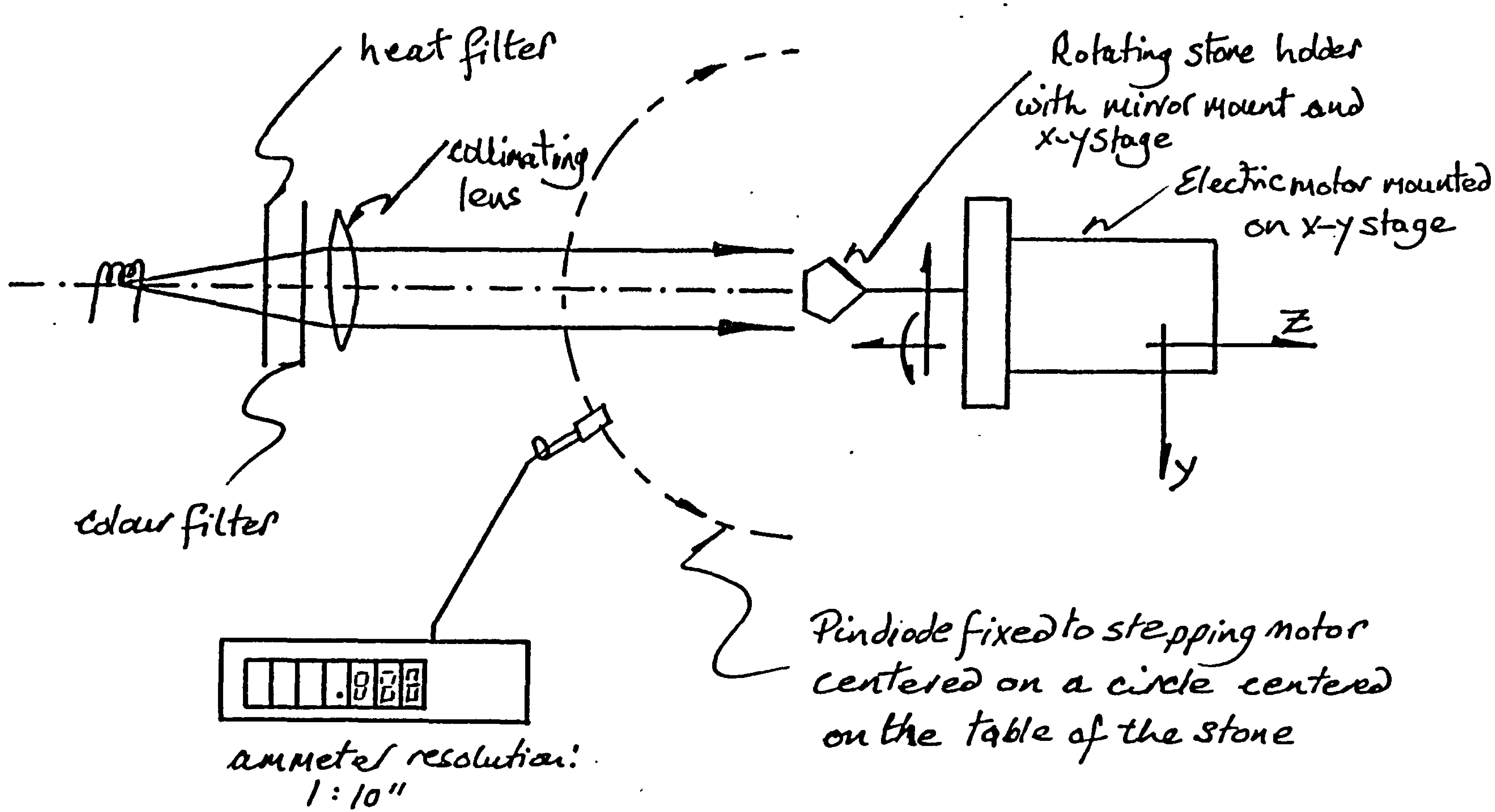


Fig. 6.2 A schematic of the diamond grading engine.

components of make, table spread, crown height are measured as well as minor cutting faults such as off-roundness. Graphs of merit points against proportions and cutting faults are given. This method takes considerable time to put into practice but at least is foolproof.

6.3 The diamond grading engine

This optomechtronic device can be split into four main components:

i) The illuminator comprises a 100 watt tungsten halogen bulb, with regulated current supply, a type Schott KGI heat filter and coloured filter holder. The bulb is focused to produce an f/60 beam at the stone. An alignment laser can be substituted for the illuminator when required. Three gelatin colour filters are used, red, green and blue.

ii) The stone holder comprises a pair of modified five-claw corn-tongs which friction fit into an x-y stage and mirror mount which in turn is mounted onto the shaft of of an 8K rev electric motor. The motor is mounted on a y - z stage with rotation and tilt

iii) The detector is a reverse biased pindiode mounted on the swing arm of a stepping motor, the axis of the motor is perpendicular to the beam axis and the stone. The signal is measured on a Keithly ampmeter which has a resolution of 2×10^{-11} amps over five decades.

iv) The measure of optical goodness deduced from the data were calculated off-line on the computer facility at Imperial College.

The illuminator, stone holder and detector assembly were mounted on a stable aluminium optical table produced by the National Physical Laboratory.

6.4 Setting up the device

The alignment of the three main components falls into four stages:

i) An He-Ne laser was used to define a centre line. The laser was mounted on a standard bench mount and rigidly attached to stops on the base plate.

ii) This is followed by the alignment of the stone holder The motor shaft is adjusted to be collinear with the optical axis, a once and for all adjustment. Light was reflected from the x-y mirror mount and by adjustment of the motors z-y rotation and tilt stage the light was caused to follow its reverse path until it re-entered the window of the laser. This apparently simple alignment device leads to the stone holder being orientated within 0.01° of the optical axis, half the angle the laser window subtends at the stone. The motor and stage assembly was then clamped rigidly to the base plate.

iii) The axis of the stepping motor was adjusted to be co-linear with the plane containing the table of a stone held in the stone holder and the optical axis of the engine. The pindiode was set up in the plane perpendicular to the stone table containing the optical axis.

iv) Finally the tungsten illuminator was set up. This involved replacing the laser with the lamp and again arranging for the incident light to be reflected back to the bulb. In this instance the lamp was adjusted and not the stone holder. The orientation of individual stones uses the same reflection method. The stone is placed in the corn tongs and the axis on the motor stage is adjusted so that the table plane contains the axis of the stepping motor. The x-y mirror mount is then adjusted to return the reflection from the table along its original path even when the stone is rotated. The stone and central portion of the rotating mount are therefore often off-centre. When rotating at typically 1000 revs per minute, this unbalanced situation produced considerable forces and it was found necessary to further construct a rigid cage to stiffen the already rigid stage on which the motor was attached. This damped down the otherwise considerable vibration which was sufficient to give unreliable results due to vibration of the pindiode.

6.5 Discussion of the results

Twelve stones were provided by the Diamond Trading Company for testing and the individual stones will be referred to as 1-12. The intensity distributions in red, green and blue portions of the spectrum were measured using the engine. It was possible to make a base line correction and to normalize the data by comparison of the stones intensity patterns with the reflection from a rotating ball bearing.

Four sets of results are presented as Fig. 6.3.

i) The stones were assessed for optical attractiveness by several diamond experts. The expert observers were requested to divide the stones into groups of equal

1	2	3			4		
experts	SCAN.D.N.	brill	spark	fire	brill	spark	fire
7	29	.700	296	1.185	117	200	1.23
8	44	.703	204	1.289	150	140	1.284
12	90	.710	179	1.201	121	136	1.285
6	66	.708	196	1.260	121	112	1.241
9	78	.651	144	1.289	120	124	1.33
1	172	.672	219	1.232	120	114	1.429
3	118	.665	150	1.22	108	101	1.475
5	162	.648	173	1.208	113	94	1.372
11	69	.712	225	1.29	135	69	1.318
2	51	.619	111	1.201	110	48	1.354
10	118	.719	204	1.196	118	149	1.476
4	202	.663	137	1.240	82	24	2.375

Fig. 6.3 The experimental data: 1) the grouping according to the expert observers, 2)the SCAN.D.N. assessment of make, 3) the brilliance,sparkliness and fire results from the computer program, 4) the brilliance,sparkliness and fire calculated from the diamond grading engine.

optical effect. However, it is to be noted that their usual practice is to assess the optical effect by inference from optimal proportions. The stones were examined with a loupe and not the relaxed arms length of the normal observer.

ii) The Scandinavian Diamond Nomenclature assessment of make was calculated using their charts of demerit. The proportions were measured using a travelling microscope

iii) The measured proportions of part ii were used as the input for the computer model.

iv) The data from the diamond engine were calculated offline using the I.C.C.C. system.

The expert observers placed the stones into five groups with the stone referred to as number seven as markedly superior. As this was an atypical grading methodology for these operatives it would seem reasonable to accept that the errors in assessment could be relatively high and at least $\pm$ 1 group. The Scan. D.N. calculation again placed stone 7 as the best with 4 as the worst. For the other stones there is no obvious trend, although all the stones except 4 are very acceptable makes in a commercial sense. The results of the computer programme and engine again placed stone 7 as the superior specimen with 2 and 4 as the worst in sparkliness. For the programme the stones 10 and 11 have higher brilliance and sparkliness than would be expected from their expert position. While for the engine results stone 11 still exhibits higher brilliance while sparkliness has fallen, the opposite is true for stone 10. However, the general trend of sparkliness is in aggreement with the expert grading. As seen before the fire results fluctuate and appear to follow no clear trend. This sample is obviously too small to draw any conclusions as to the relative importance of brilliance, sparkliness and fire. Although it does appear that brilliance and sparkliness are the major influences as measures of optical goodness.

6.6 Summary and conclusions

It proved possible to construct a diamond grading engine for make based on the technique of Rosch utilizing statistical measures proposed in Chapter II. The suite of twelve stones were examined for optical goodness. The results are in reasonable agreement with the computer predictions and the expert assessment of optical attractiveness. The results are sufficiently encouraging to justify a large scale experiment. This would establish the relative importance of the three statistical measures, as brilliance and sparkliness appear to be the dominant effects with fire playing a profound but as yet obscure rôle in determining the degree of optical goodness.

Chapter VII

General Summary of Conclusions

7.1 Introduction

It has been established that the ideal proportions for the round brilliant cut diamond have been known if not generally used from about 1700. The rise of mathematics as the dominant tool in science and technology lead to the construction of models for the optical effect in diamond. The first of these in 1919 due to Tolkowsky was a simple geometrical argument based on a 2D cross section and has been shown to contain gross assumptions which led to a fortuitously correct result. Subsequent models based on simple 2D arguments failed to give the correct result and it was not until Stern's work that a 3D model was constructed. However his simplistic criterion for assessing goodness was subjective and hence no quantitative results were obtained.

The quantitative measurement of optical goodness was started by Rosch who devised a method of recording the scattered light intensity of a diamond illuminated by a collimated beam of light through the table and crown facets. This method was refined by Elbe to produce a diamond grading engine which measured optical goodness by a number count of sparkles. The present research proposed five goals in the assessment of brilliance, sparkliness and fire of polished gem diamond and these will now be summarised.

7.2 The five aims

i) To find a nonsubjective measure for optical goodness. Work by Bela Julesz has shown that the human cognitative system was less capable of detecting the difference between patterns with different 3rd order statistics but similar 1st and 2nd order statistics. From this it was conjectured that the optical goodness of a gem diamond could be expressed by the 1st and and 2nd order statistical properties of its scattered light distribution. In particular brilliance was associated with the percentage of light rescattered by the crown and table facets versus the incident illumination, sparkliness was defined as the variance of the autocorrelation of the total intensity distribution and fire the quotient of the cross correlation of the red and blue intensity distributions and sparkliness.

A computer 3D model was constructed for the round brilliant cut diamond which incorporated the calculation of the properties of the light distribution. This distribution was calculated using finite vector ray tracing equations. The first investigation was of the effect of changing the length of the pavilion half factor, a procedure which had not been attempted by previous workers.

The results correctly predicted the 41^{o} pavilion as the optimum in sparkliness for a 50% table spread and 15% crown height with a PHF of 0.5. The increase in fire with smaller PHF 0.2 was also correctly predicted. The modern practice of polishing stones with longer pavilion halves 0.8 was justified in terms of higher yield from thinner rough. This style led to a stone exhibiting higher fire and lower sparkliness which was as acceptable as the high sparkliness style of stone. Further examinations of both the effects of variation in crown height and tbale spread confirmed this result.

Two trends appeared in these other studies. These include the effect of increasing brilliance with decreasing table spread and increased brilliance with decreasing crown height. The traditional proportions were confirmed as being the optimum and some reconciliation between the many ideal cuts was possible by realization of the trade-off between high brilliance, or sparkliness or fire. A second set of high optical effect proportions was found based on a pavilion angle of 53^{o}. This was shown (Chapter I) to have been used historically and then discarded when the 41^{o} and 45^{o} pavilions were accepted as ideal in the 1650's and onwards.

ii) To establish a scale of optical goodness

Althought the results quantified the degree of brilliance, sparkliness and fire, it was not possible to assess the mix of the optical measures which although acceptable were not the optimum. An experimental study of the opinion of a sample of the public would be required before the phsychological preference could be established. It has not proven possible to conduct such an experiment.

iii) The modifications of the round brilliant cut diamond

It was found that there were two families of styles based on 4 fold and 3 fold rotational symmetry and four types of modification which did not increase the mechanization of the diamond polisher.

The four fold family (4cut - 58 RBCD) was investigated as representative of a-type modifications. The same general trends in optical performance within particular styles were found as with the 58 facet RBCD. The addition of skew facets was shown to lead to a greater increase in optical effect than that achieved by addition of a similar number of facets by pure symmetry increase.

The investigation of screw showed that this type of modification left brilliance unaffected. However sparkliness was improved or at worst optical performance was left unaffected.

The admixture of one style with another was shown to give a style midway between the two constituents with the possibility of greatly increased fire. It was concluded that any style with more than eight facets on crown and pavilion was an acceptable if not ideal substitute for the full round brilliant cut in sizes less than 20 points.

iv) To assess the optical goodness of diamond simulants

Again this study confirmed the trends of optical performance in respect of crown height and table spread variation which were apparent for the diamond. It was possible to establish a limit of optical goodness at 100 sparkliness units and from this deduce the acceptable diamond simulants. Stones with $n < 1.7$ were found unacceptable, $1.7 > n > 1.8$ were marginal and $1.8 > n$ were assessed suitable diamond simulants. The optical performance was also found to be an approximate function of refractive index.

v) The construction of a diamond grading engine

This proved possible, although the results while confirming the trends were on a small sample. The study of the twelve stones also permitted the first cross-check between visual assessment and the statistical assessment of optical goodness which was encouraging. A larger scale study is now required to assess the performance and ultimate usefulness of the device.

The construction of the prototype has given rise to much future work on both assessment of the technique and improvement of the device.

7.3 Further research

The programme of theoretical work is largely complete on the symmetrical round brilliant cut in diamond and its simulents. However the family of 3fold rotational styles still require investigation as does the admixture of style, the type-d modification. Styles with odd or unusual even degrees of rotation have still to be investigated.

Possibly the most interesting theoretical study to be be completed is a study of the effect of simple cutting faults. A model has been constructed to assess the effect of offroundness, screw, offcentre cullet and of a non-square table-star configuration on the round brilliant cut diamond. As with the 3-fold calculation these results are not completed at the present time.

The requirement of a large scale experiment of public preference has been suggested earlier. If this follows the style of the pilot project described in Chapter VI it would prove possible to establish a scale of optical goodness, as well as clarifying the effect of fire.

The orientation of the stones on the device also proved difficult. The use of a goniometer head such as produced by Stoe and Cie would simplify this adjustment. The offline calculation of data is also tedious and it may prove possible to have the logic control of the stepping sequence and data calculation made by a micro-processing system. If this proved unacceptably expensive J. G. Walker (1978) has constructed and described a correlator which used a hardwired programme to drive a simple calculator.

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Appendix I The flow diagram for the computer programme

Programme THESEUS.

Four basic units that combine to trace rays through a prism of arbitrary shape and then analyse the resultant spot-pattern in a statistical manner.

1) prism   defines the shape of the prism
2) startray   starts the ray trace off
3) trace   performs the ray trace through the prism
4) statpack   performs the statistical analysis

PRISM

ENTER
READ IN PROPORTIONS

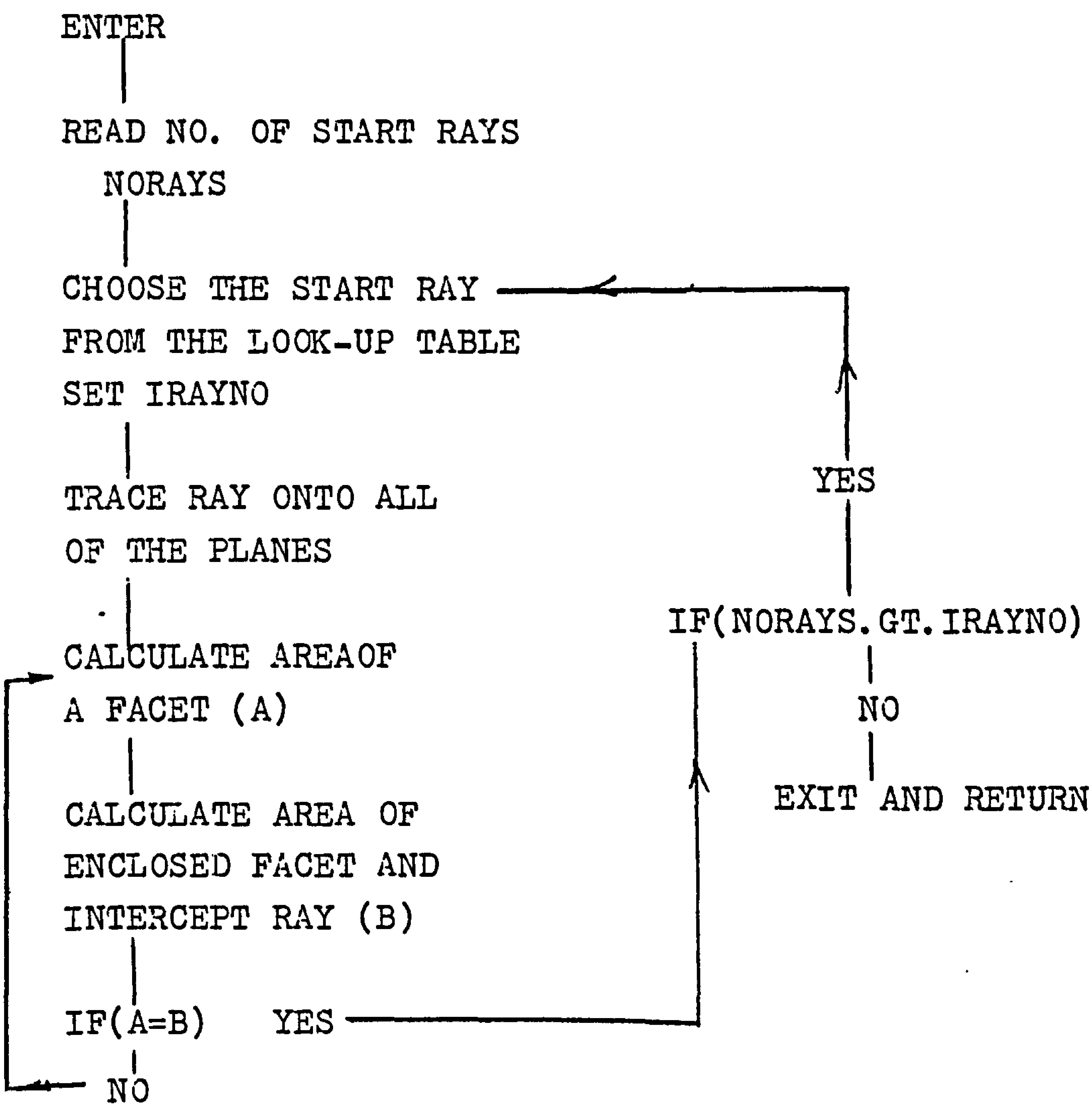
CALCULATE INTERSECTION
POINTS ON THE PLANES

CALCULATE THE DC'S
OF THE PLANES USING
CRAMMER'S RULE

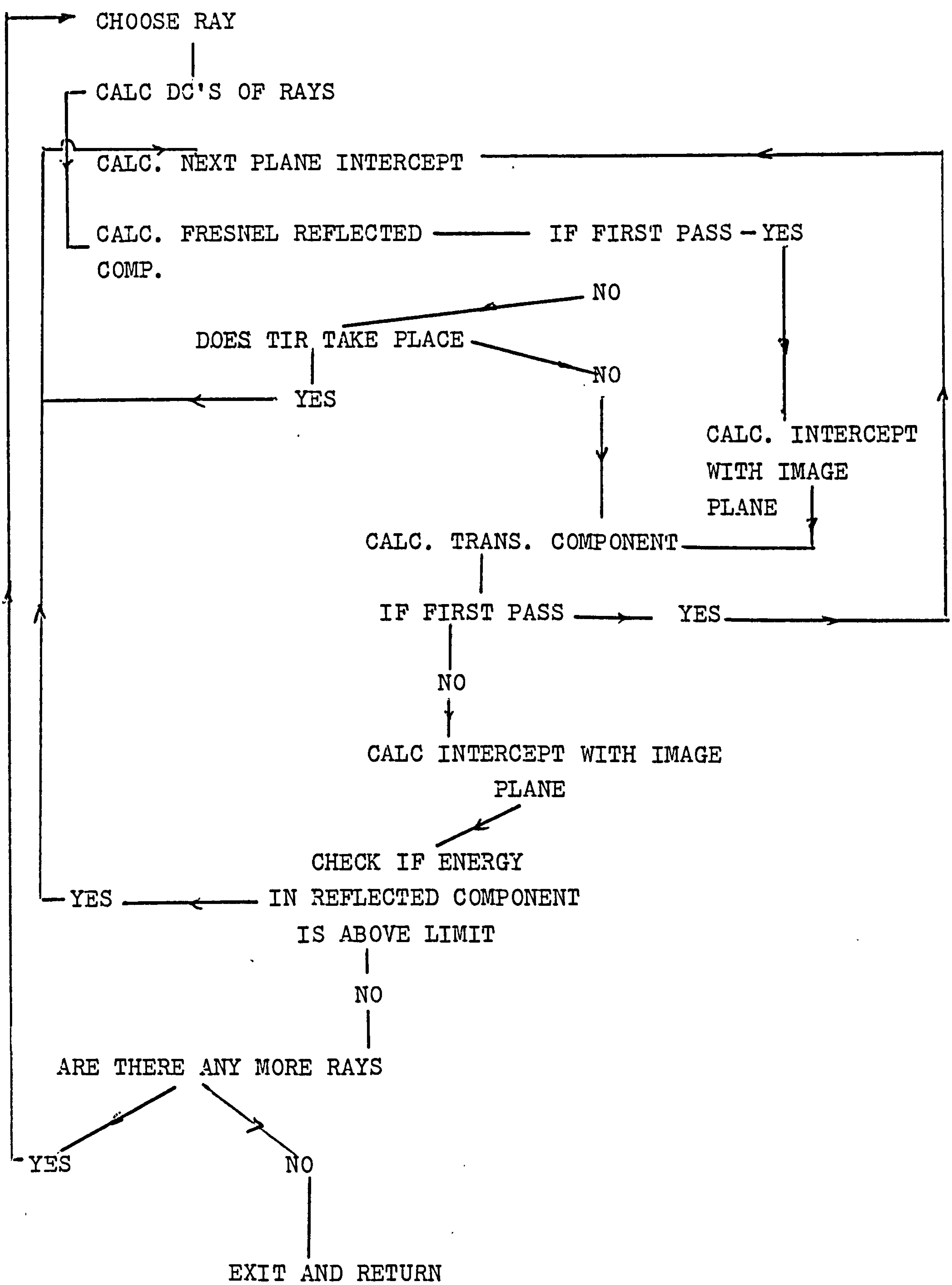
SET UP MATRIX THAT
THEN STORES THE DC'S

EXIT AND RETURN

STARTRAY


ENTER
READ NO. OF START RAYS
NORAYS
CHOOSE THE START RAY
FROM THE LOOK-UP TABLE
SET IRAYNO
TRACE RAY ONTO ALL
OF THE PLANES
CALCULATE AREAOF
A FACET (A)
CALCULATE AREA OF
ENCLOSED FACET AND
INTERCEPT RAY (B)
IF(A=B)
YES
NO
IF(NORAYS.GT.IRAYNO)
YES
NO
EXIT AND RETURN

TRACE


CHOOSE RAY
CALC DC'S OF RAYS
CALC. NEXT PLANE INTERCEPT
CALC. FRESNEL REFLECTED COMP.
IF FIRST PASS
YES
NO
DOES TIR TAKE PLACE
YES
NO
CALC. INTERCEPT WITH IMAGE PLANE
CALC. TRANS. COMPONENT
IF FIRST PASS
YES
NO
CALC INTERCEPT WITH IMAGE PLANE
CHECK IF ENERGY IN REFLECTED COMPONENT IS ABOVE LIMIT
YES
NO
ARE THERE ANY MORE RAYS
YES
NO
EXIT AND RETURN

STATPAC

```
CONVERT IMAGE POINT ENERGY INTO
    MAP OF INTENSITY BY
     BINNING DATA
                |
       CALC. BRILLIANCE AT
          EACH COLOUR
                |
          CALC. SPARKLINESS
            AND FIRE
                |
            OUTPUT DATA
                |
          EXIT AND RETURN
```

Appendix II The vector ray tracing equations

Ray Tracing Equations
c.f. fig 2.6

transfer equation

$$\underline{\ell}_p = \underline{\ell} + \left(\frac{p - \underline{\ell}\cdot\hat{\mu}}{\hat{\sigma}\cdot\hat{\mu}}\right)\underline{\sigma}$$

where: $\underline{\ell}_p$ is the position vector on the plane of incidence
$\hat{\mu}$ is the unit normal to the plane
$\hat{\sigma}$ is the incident direction
and p is the normal distance of the plane from the origin
$\underline{\ell}$ being a point on the ray.

refraction equation

$$n\hat{\sigma}' = n\hat{\sigma} + (n'\cos I' + n\cos I)\hat{\mu}$$

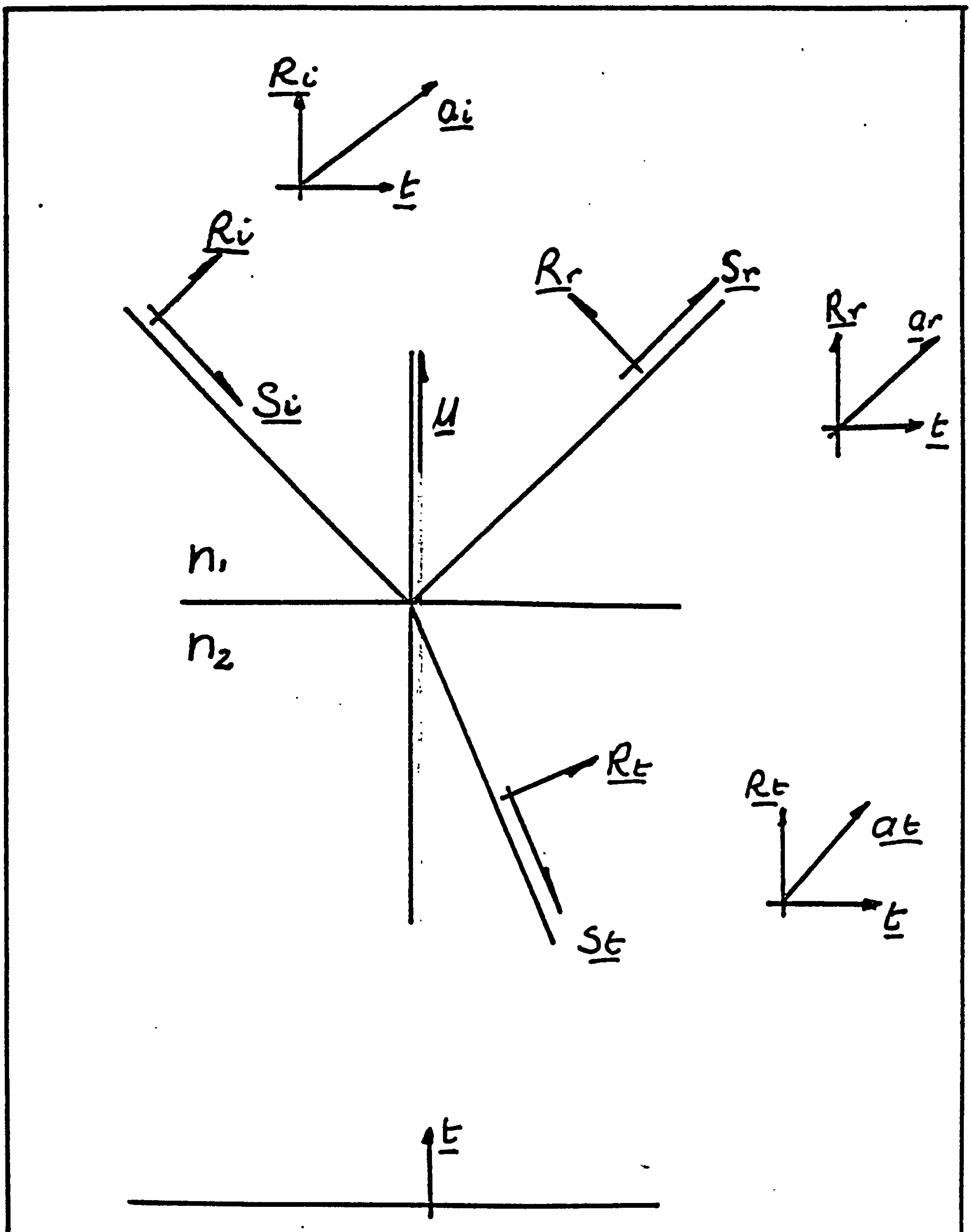
where primed quantities denote refraction or reflection
n is the refractive index of the incident space

$\cos I = \hat{\sigma}\cdot\hat{\mu}$

$$\cos I' = \frac{\hat{\sigma}\cdot\hat{\mu}}{\hat{\sigma}\cdot\hat{\mu}}\sqrt{1-\left(\frac{n}{n'}\right)^2 \times \left(1-(\hat{\sigma}\cdot\hat{\mu})^2\right)}$$

and for reflection $\cos I' = -\cos I$.

Appendix III The vector form of Fresnel's equations



Ri
ai
t
Ri
Si
u
Rr
Sr
Rr
ar
t
n1
n2
Rt
Rt
at
t
St
t

Subscript

- i the incident direction
- t the transmitted direction
- r the reflected direction

Vector

- ax the unit vector in the direction of polorization for the x= i,t and r rays.
- Rx the unit vector in the plane of incidence perpendicular to the i,t and r rays.
- t the unit vector perpendicular to the plane of incidence in the plane of the interface.
- Sx the unit vector in the direction of the x= i,t,and r rays.

n_1, n_2 the refractive indices of the two spaces.

- A the initial energy
- T the transmitted energy
- R the reflected energy

Polarization parallel to the plane of incidence:
for transmitted light,

$$T_{\underline{at}.\underline{Rt}} = \frac{2.n_1^{1}.(\underline{u}.\underline{Si})}{n_2.(\underline{u}.\underline{Si}) + n_1.(\underline{u}.\underline{St})} .A_{\underline{ai}.\underline{Ri}}$$

for reflected light,

$$R_{\underline{ar}.\underline{Rr}} = \frac{n_2.(\underline{u}.\underline{Si}) - n_1(\underline{u}.\underline{St})}{n_2.(\underline{u}.\underline{Si}) + n_1.(\underline{u}.\underline{St})} .A_{\underline{ai}.\underline{Ri}}$$

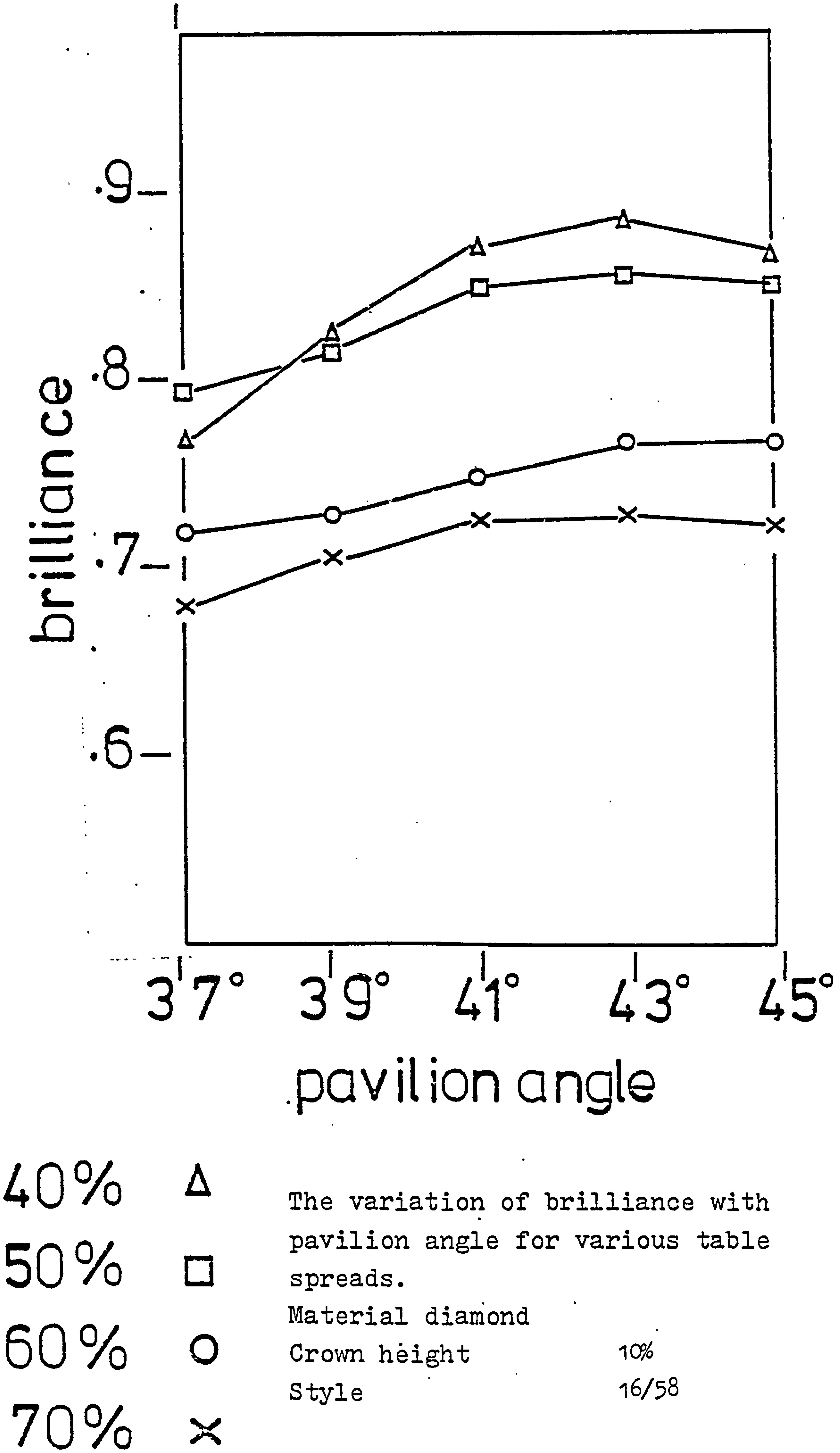
Polarization perpendicular to the plane of incidence:
for transmitted light,

$$T_{\underline{at}.\underline{t}} = \frac{2.n_1.(\underline{u}.\underline{Si})}{n_1.(\underline{u}.\underline{Si}) + n_2.(\underline{u}.\underline{St})} .A_{\underline{ai}.\underline{t}}$$

for reflected light,

$$R_{\underline{ar}.\underline{t}} = \frac{n_1.(\underline{u}.\underline{Si}) - n_2.(\underline{u}.\underline{St})}{n_2.(\underline{u}.\underline{St}) + n_1.(\underline{u}.\underline{Si})} .A_{\underline{ai}.\underline{t}}$$

Appendix IV   The brilliance, sparkliness and fire of several modifications to the round brilliant cut

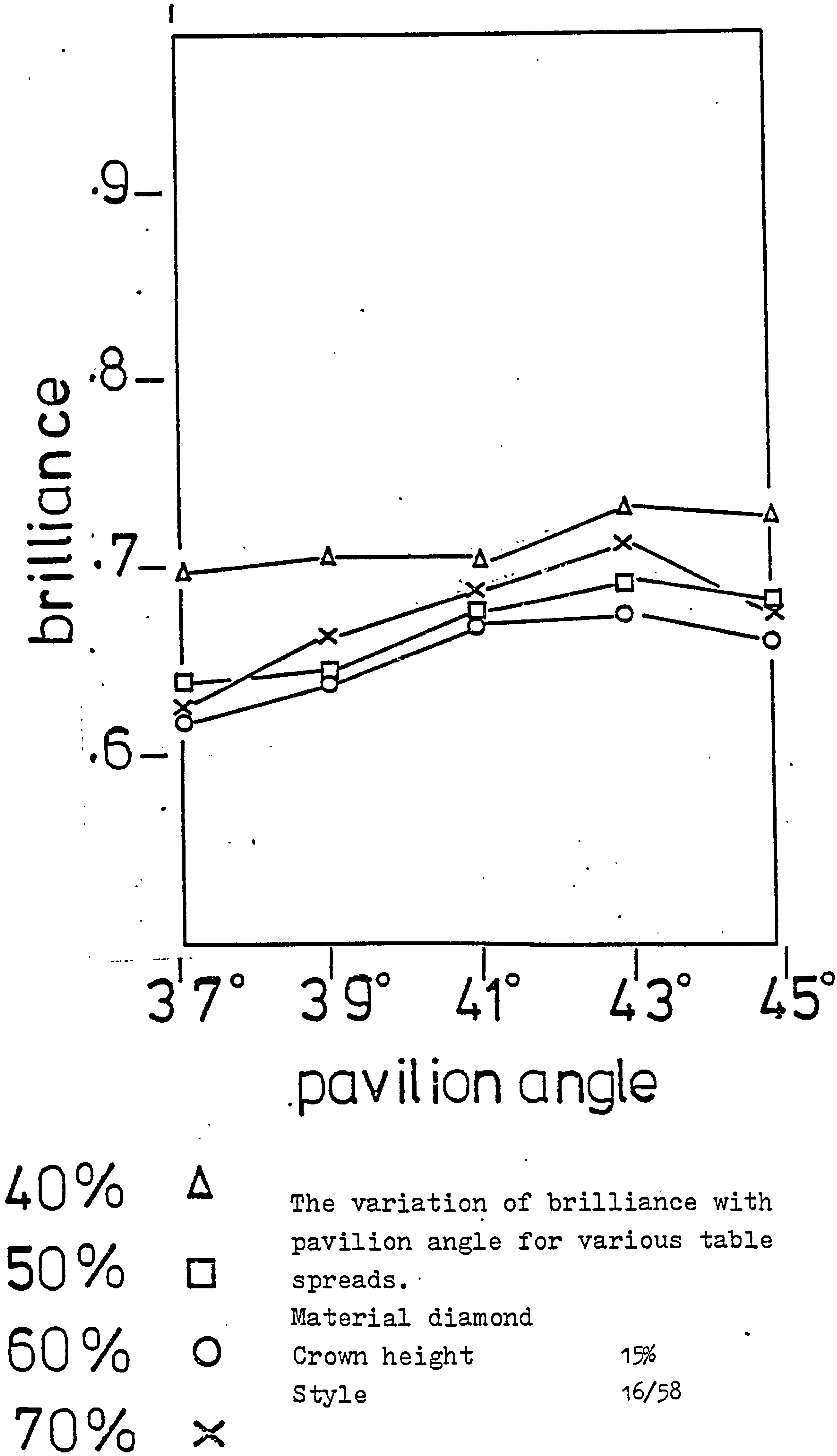


The variation of brilliance with pavilion angle for various table spreads.

Material diamond

Crown height 10%

Style 16/58

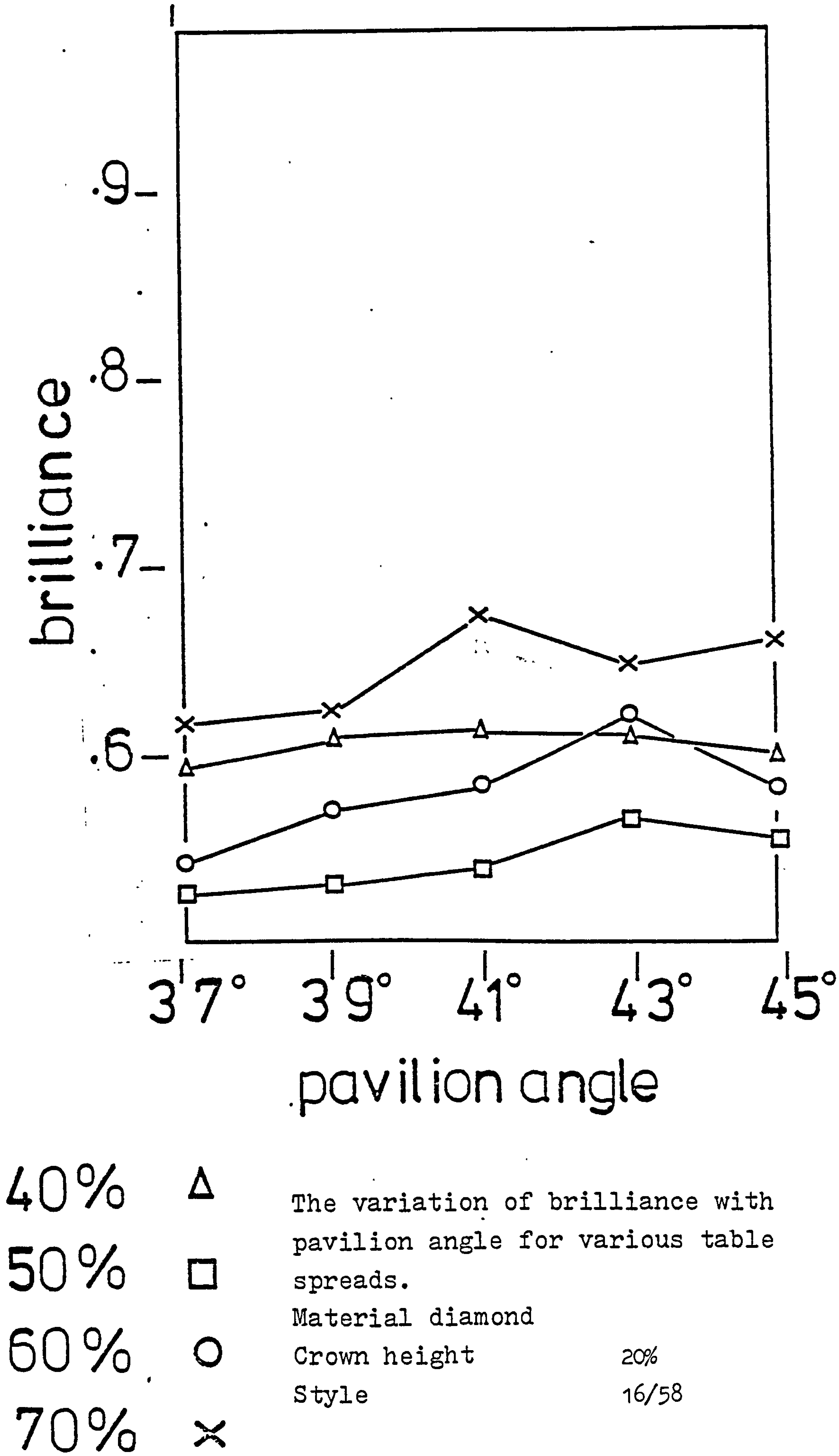


The variation of brilliance with pavilion angle for various table spreads.

Material diamond

Crown height 15%

Style 16/58

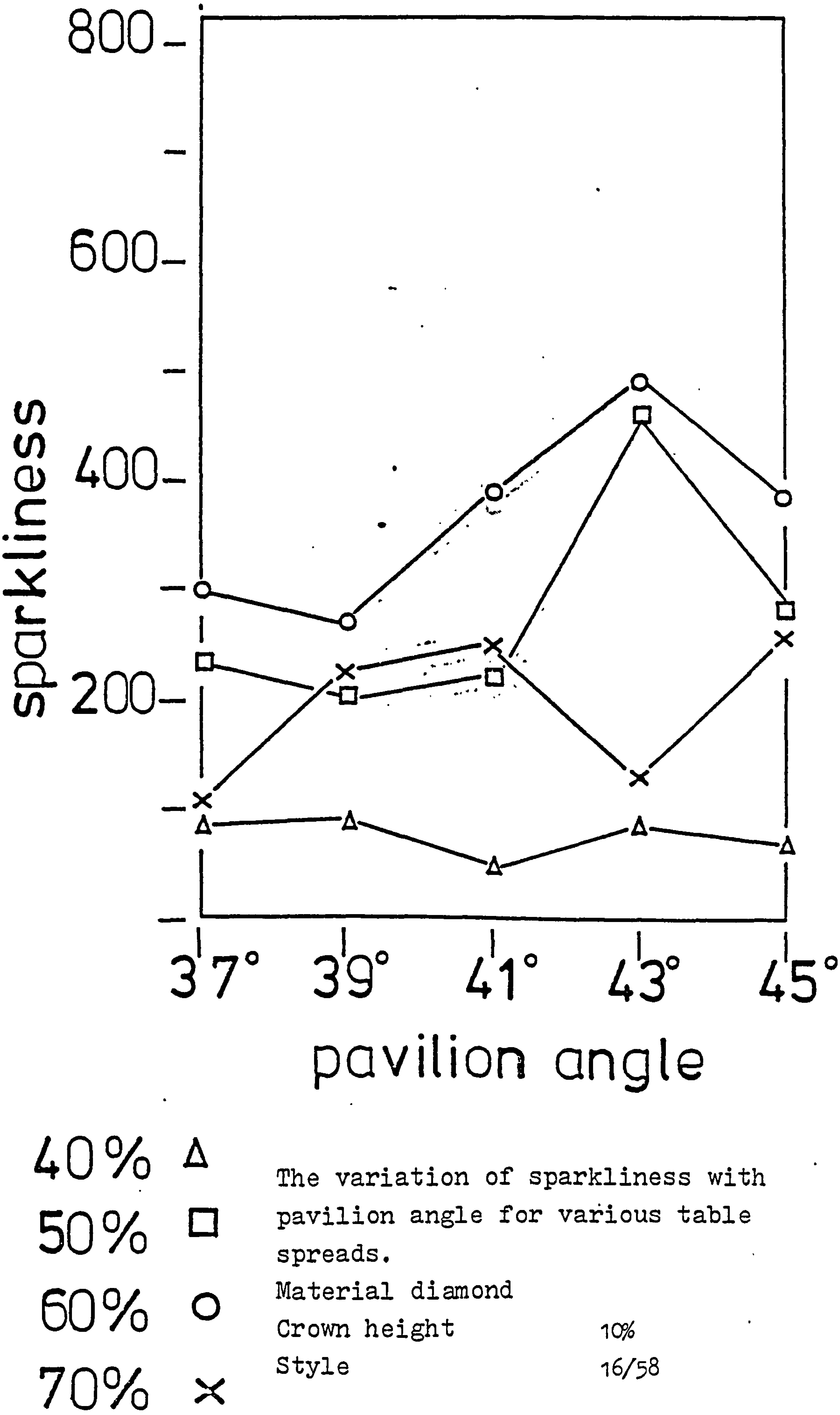


The variation of brilliance with pavilion angle for various table spreads.

Material diamond

Crown height 20%

Style 16/58

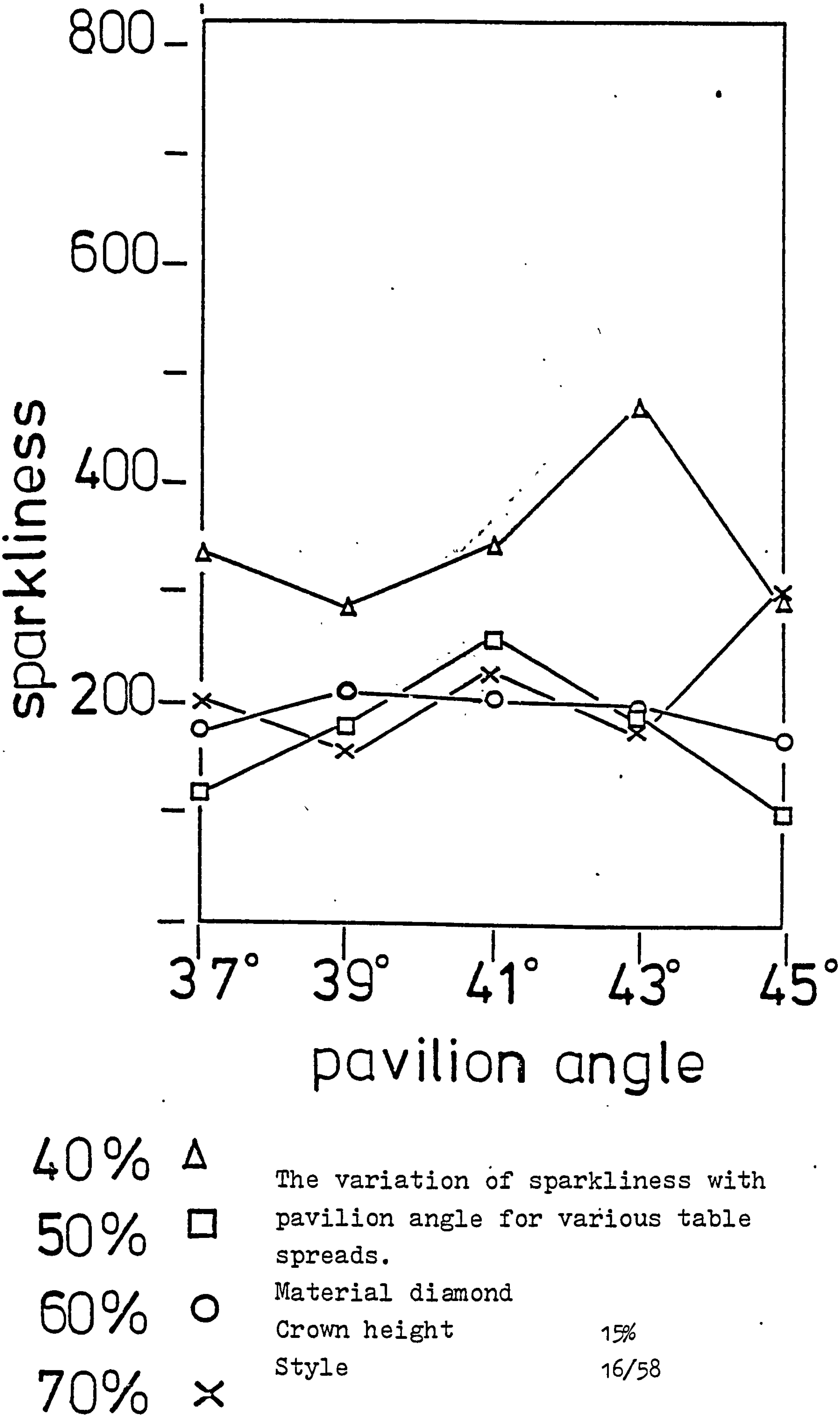


The variation of sparkliness with pavilion angle for various table spreads.

Material diamond

Crown height 10%

Style 16/58

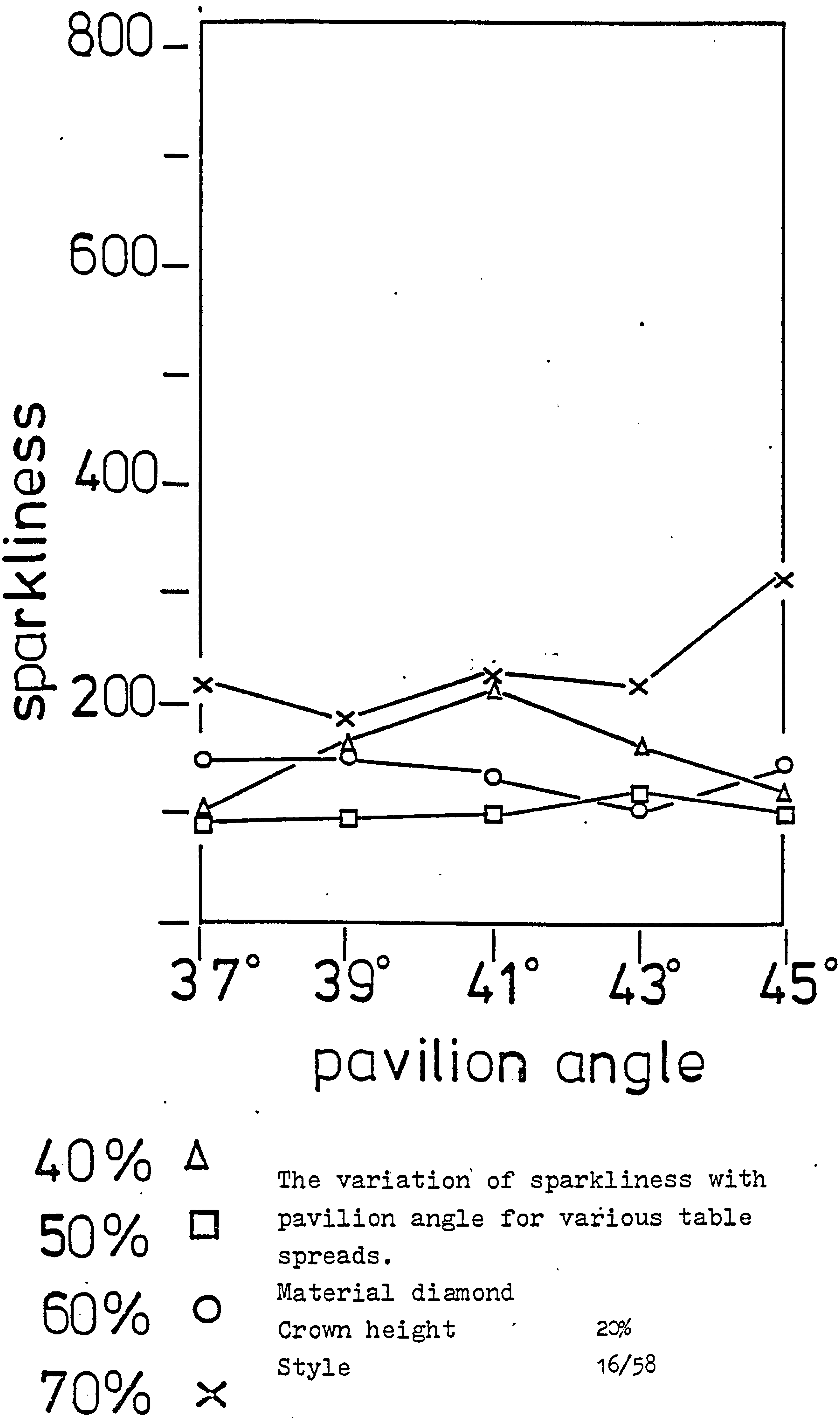


The variation of sparkliness with pavilion angle for various table spreads.

Material diamond

Crown height 15%

Style 16/58

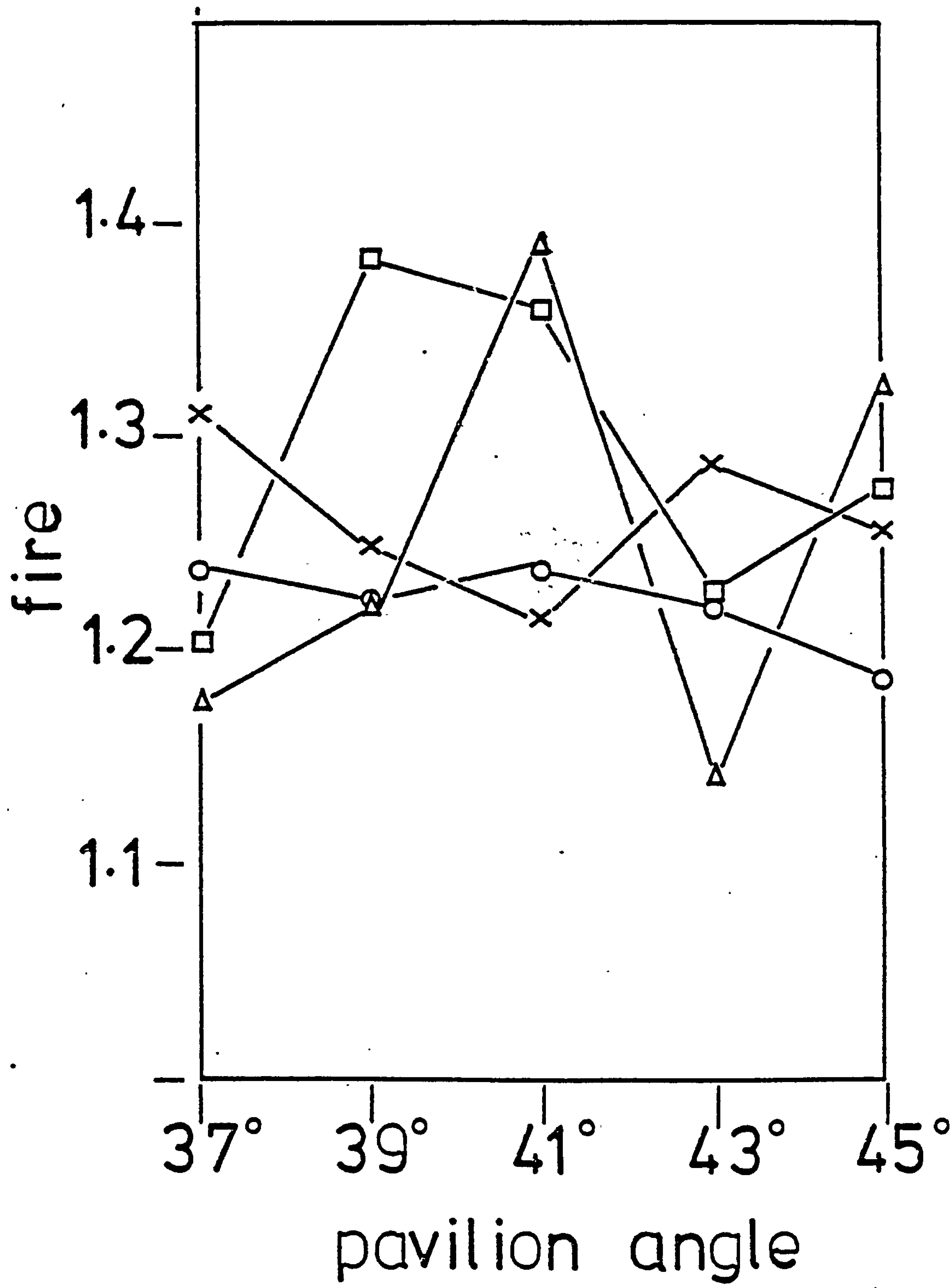


The variation of sparkliness with pavilion angle for various table spreads.

Material diamond

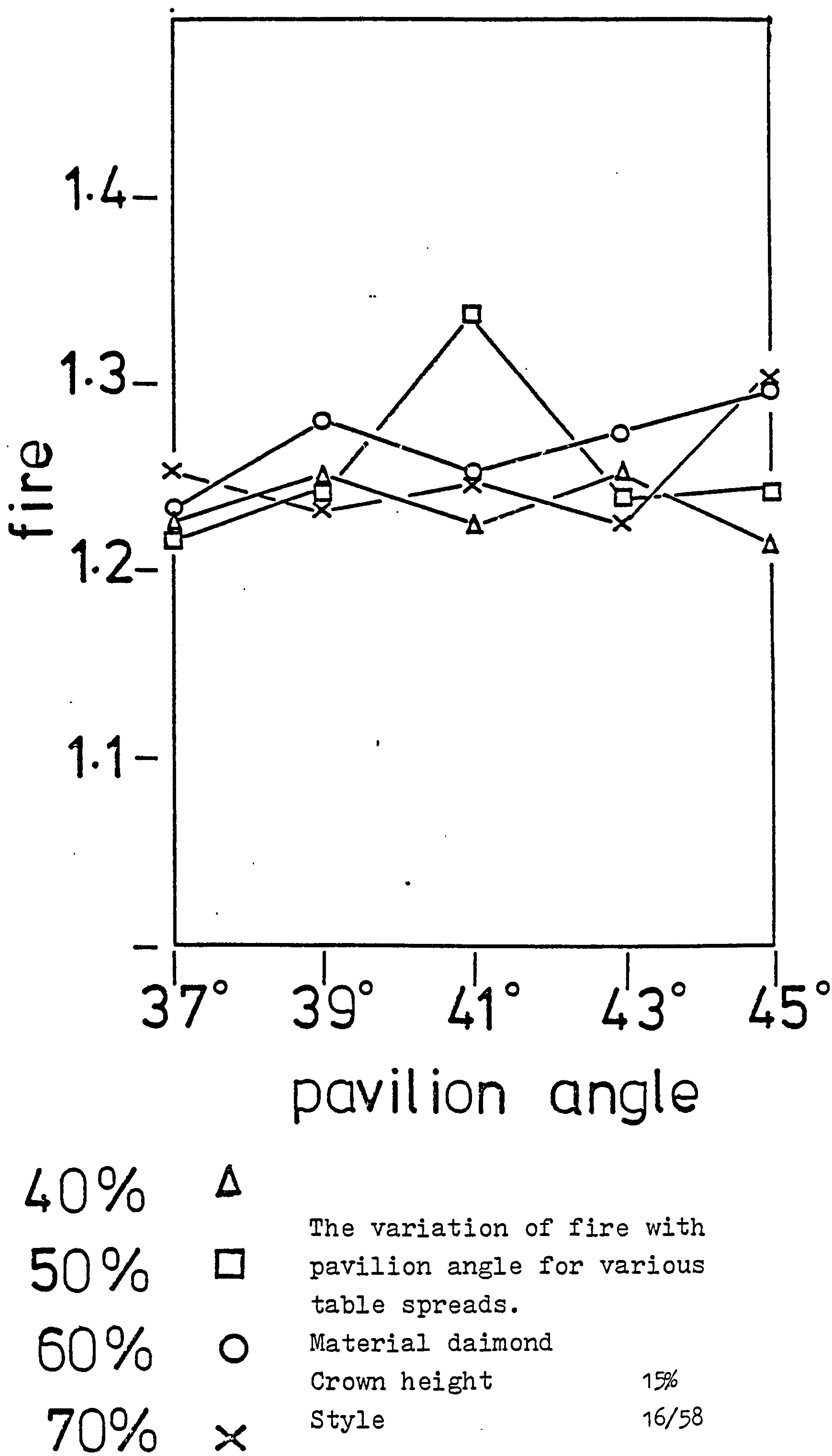
Crown height 20%

Style 16/58



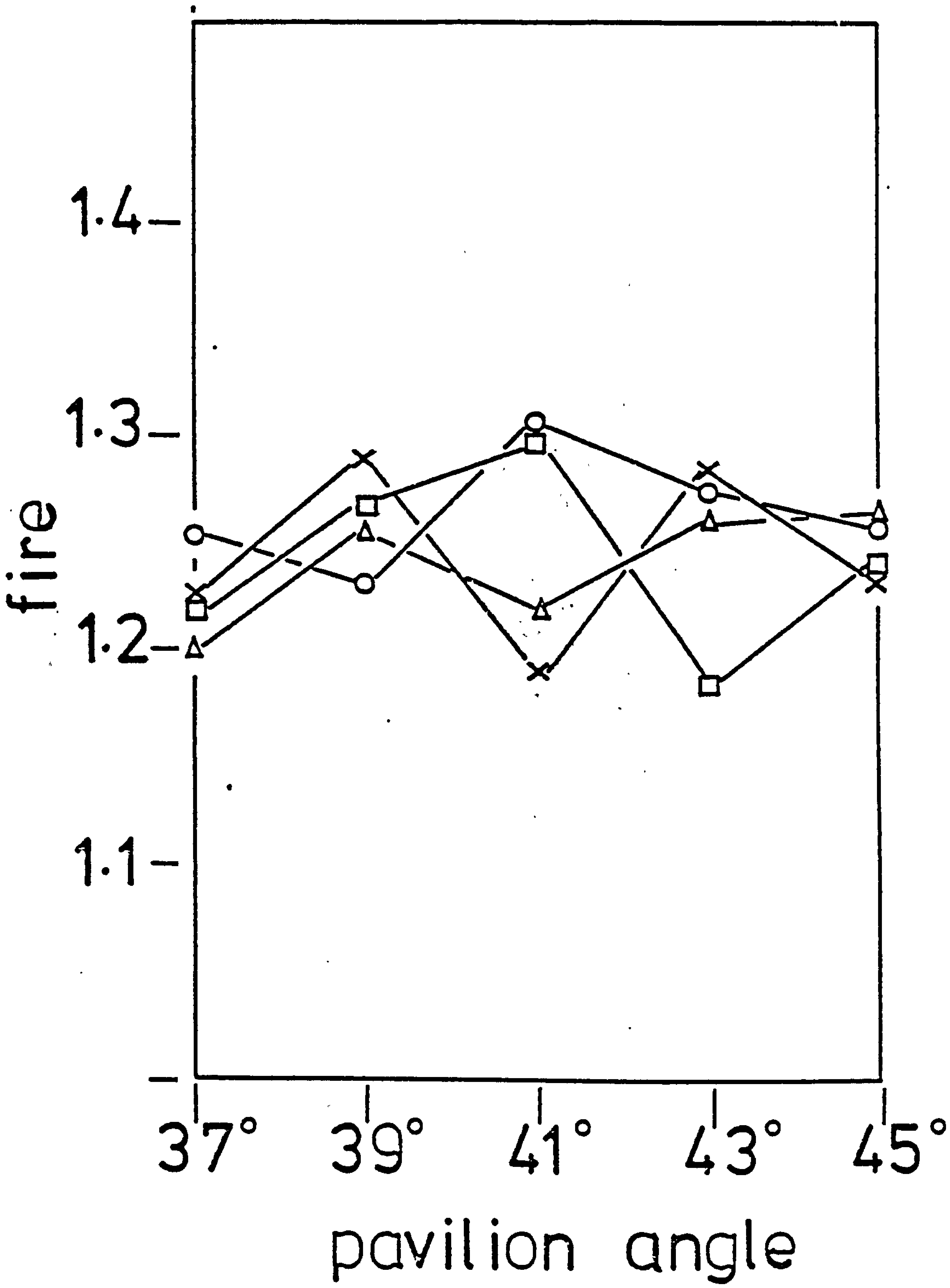
40% Δ
50% □
60% ○
70% ×

The variation of fire with pavilion angle for various table spreads.
Material daimond
Crown height 10%
Style 16/58



The variation of fire with
pavilion angle for various
table spreads.

Material daimond
Crown height 15%
Style 16/58



40% Δ

50% □

60% ○

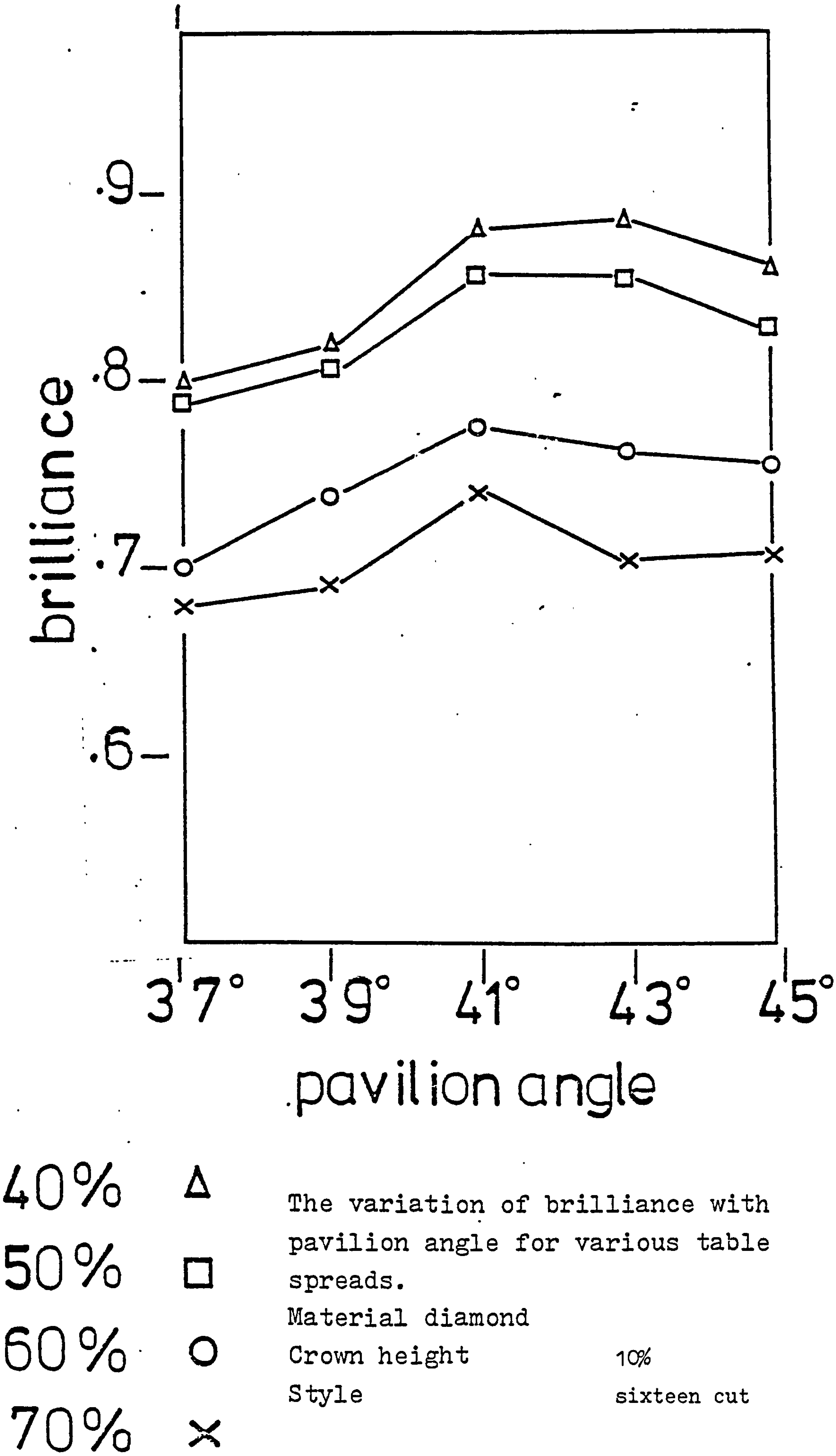
70% ×

The variation of fire with pavilion angle for various table spreads.

Material daimond

Crown height 20%

Style 16/58

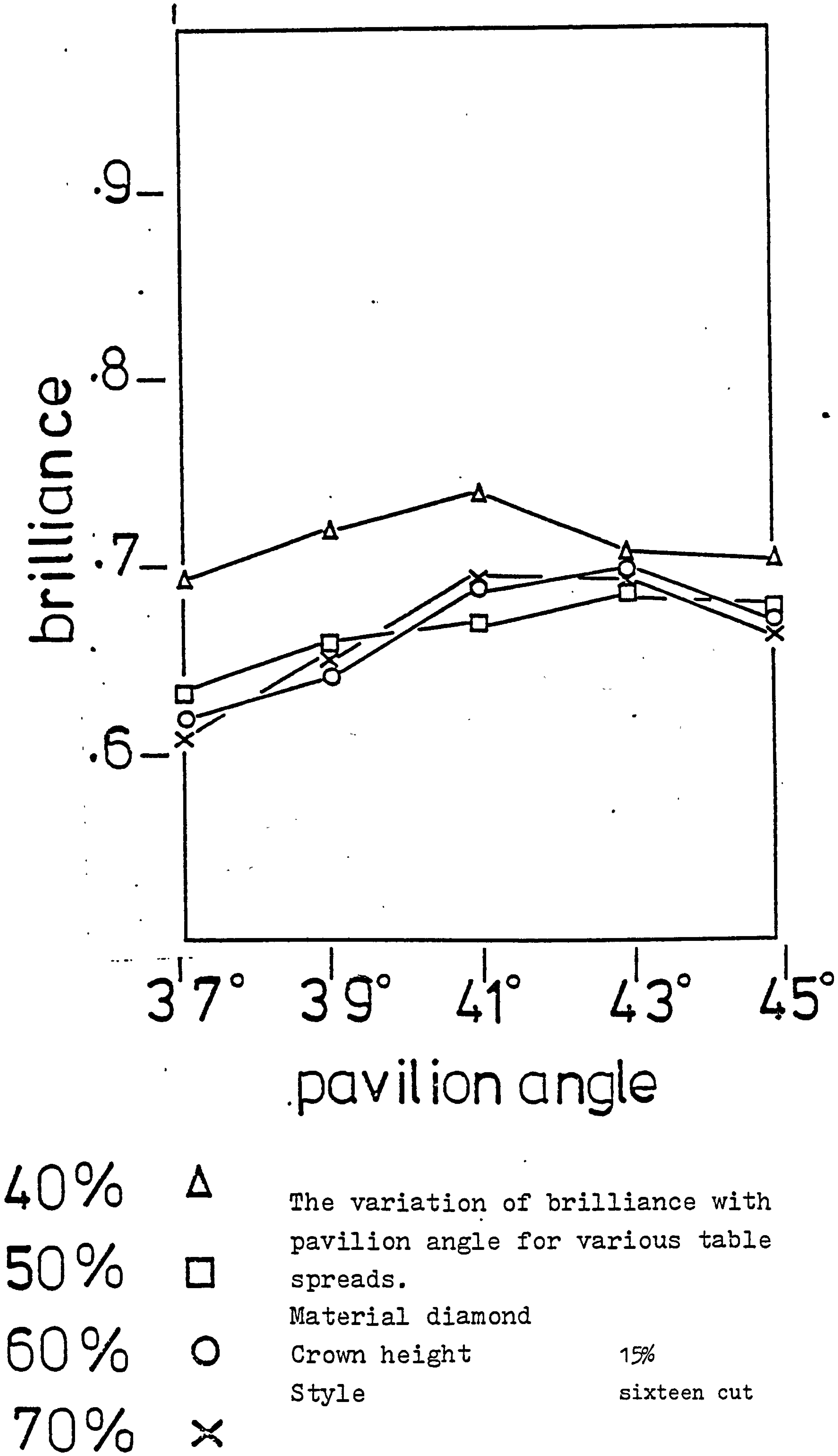


The variation of brilliance with pavilion angle for various table spreads.

Material diamond

Crown height 10%

Style sixteen cut

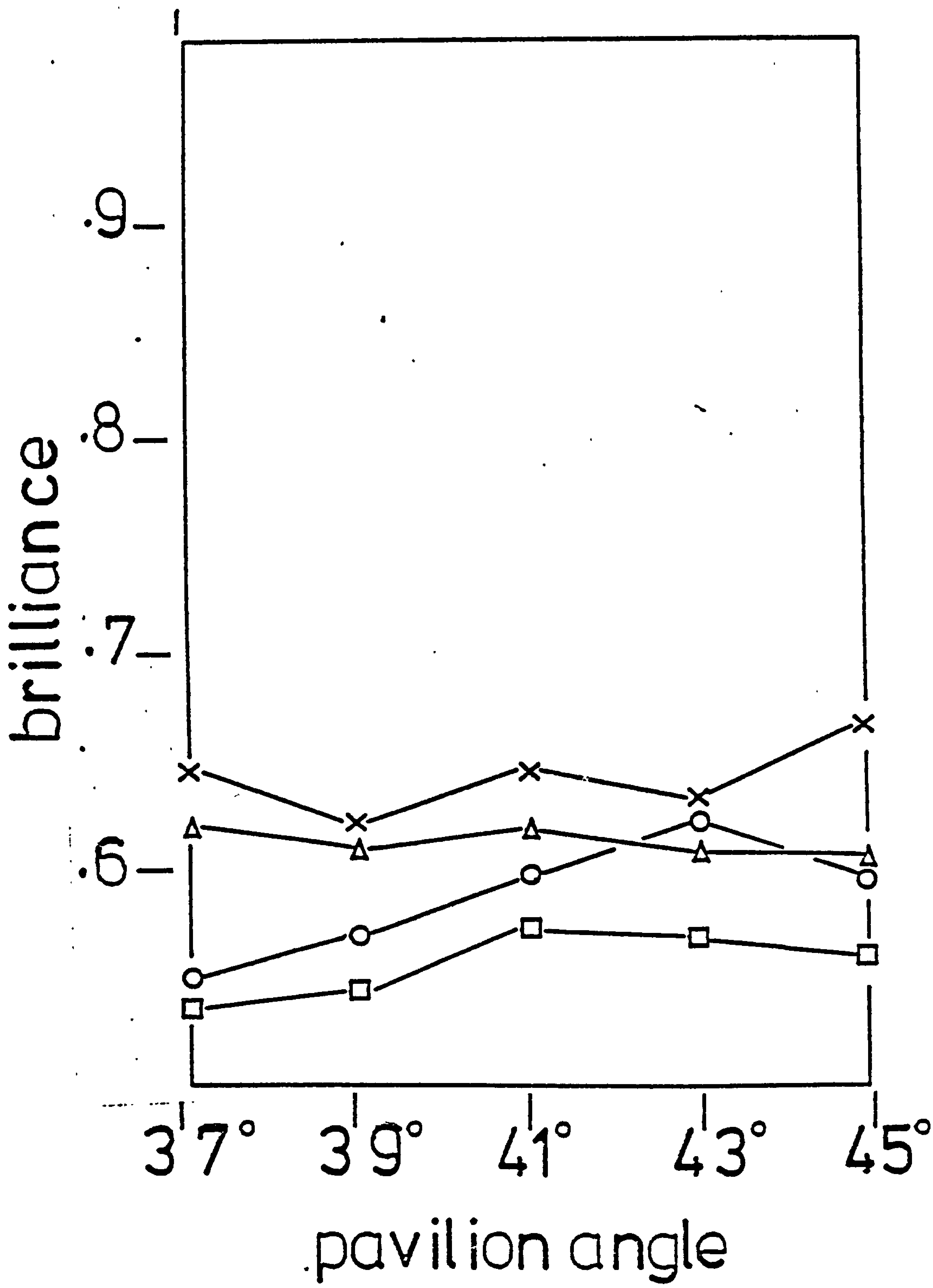


The variation of brilliance with pavilion angle for various table spreads.

Material diamond

Crown height 15%

Style sixteen cut



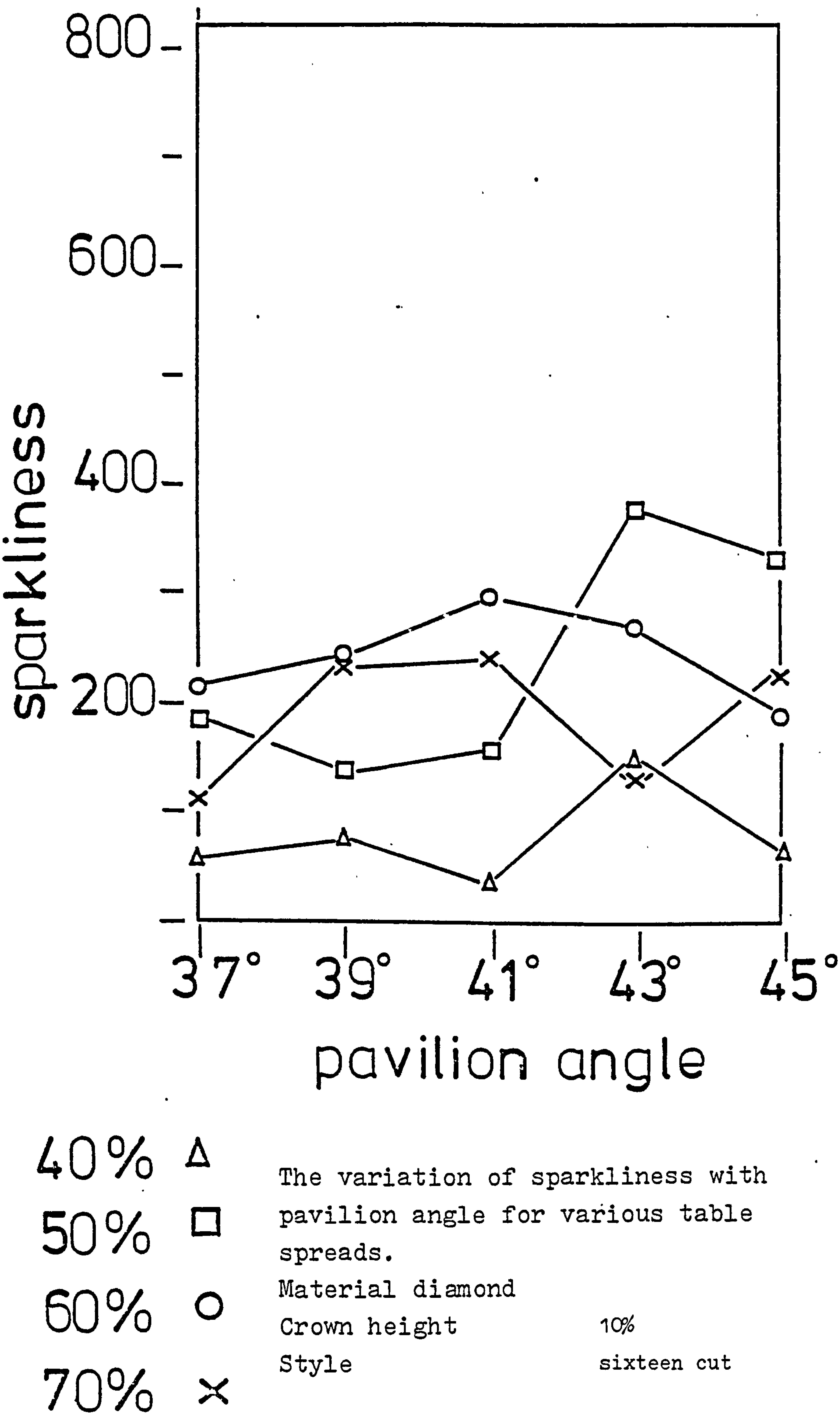
40% △
50% □
60% ○
70% ×

The variation of brilliance with pavilion angle for various table spreads.

Material diamond

Crown height 20%

Style sixteen cut

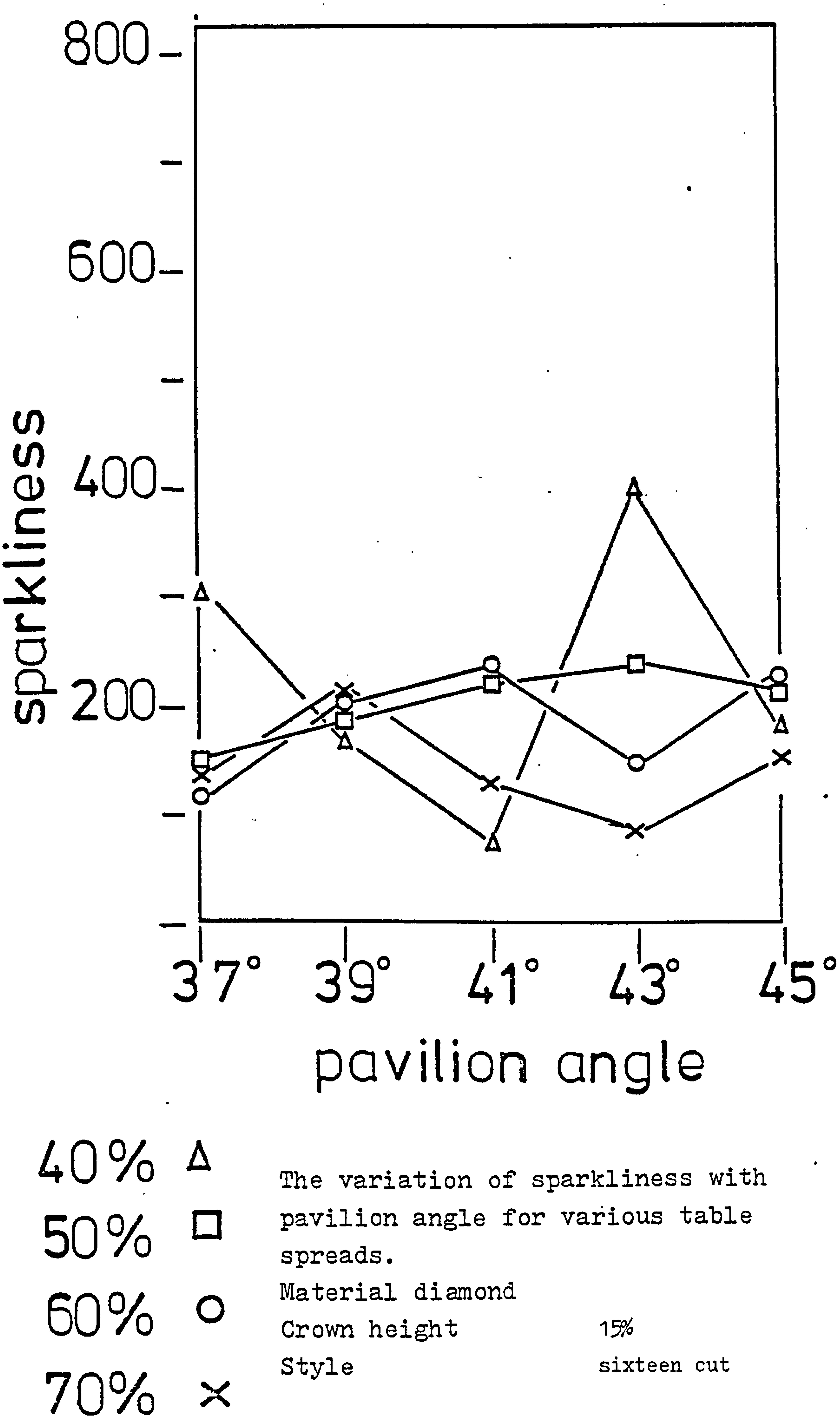


The variation of sparkliness with pavilion angle for various table spreads.

Material diamond

Crown height 10%

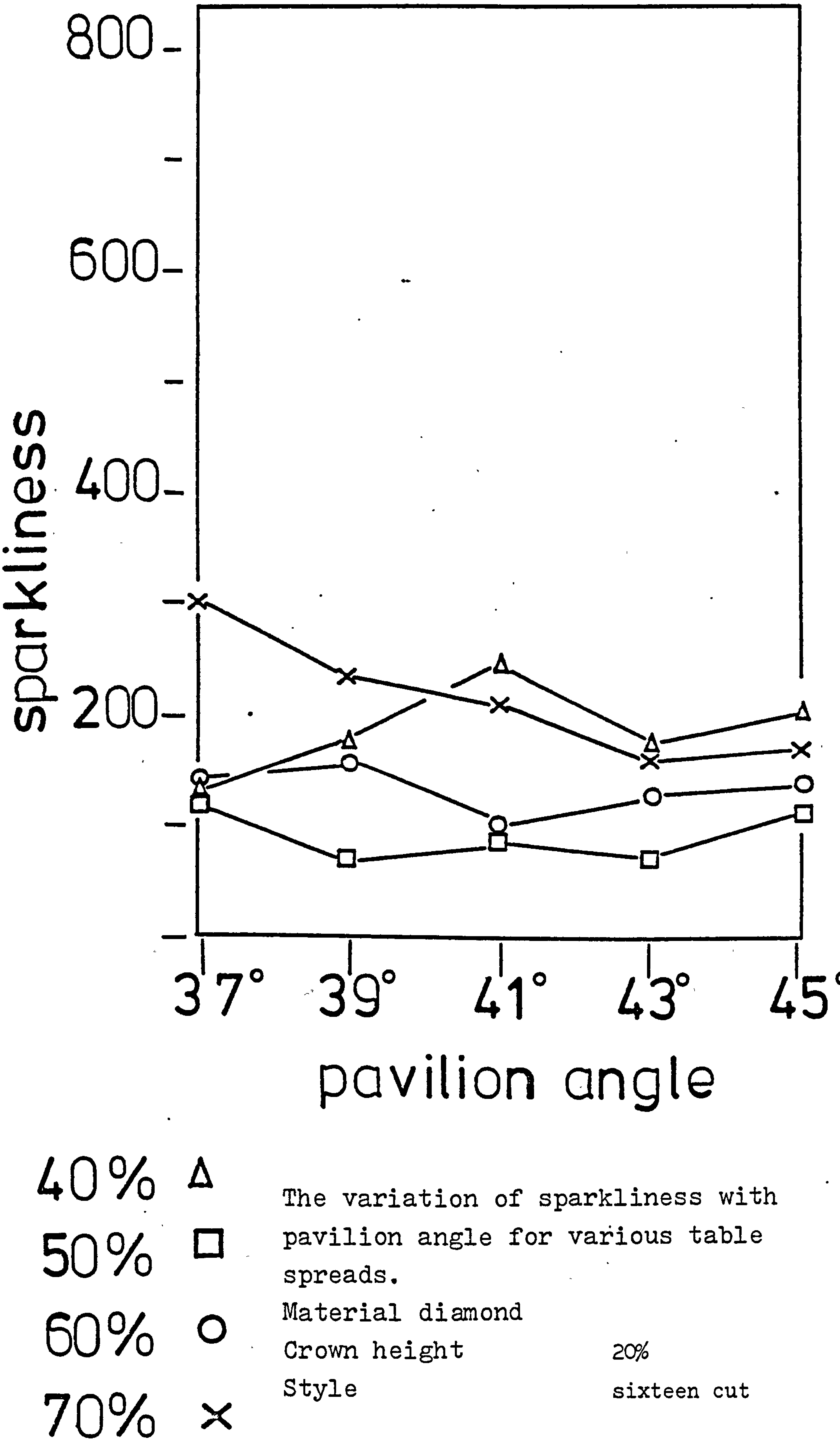
Style sixteen cut



The variation of sparkliness with pavilion angle for various table spreads.

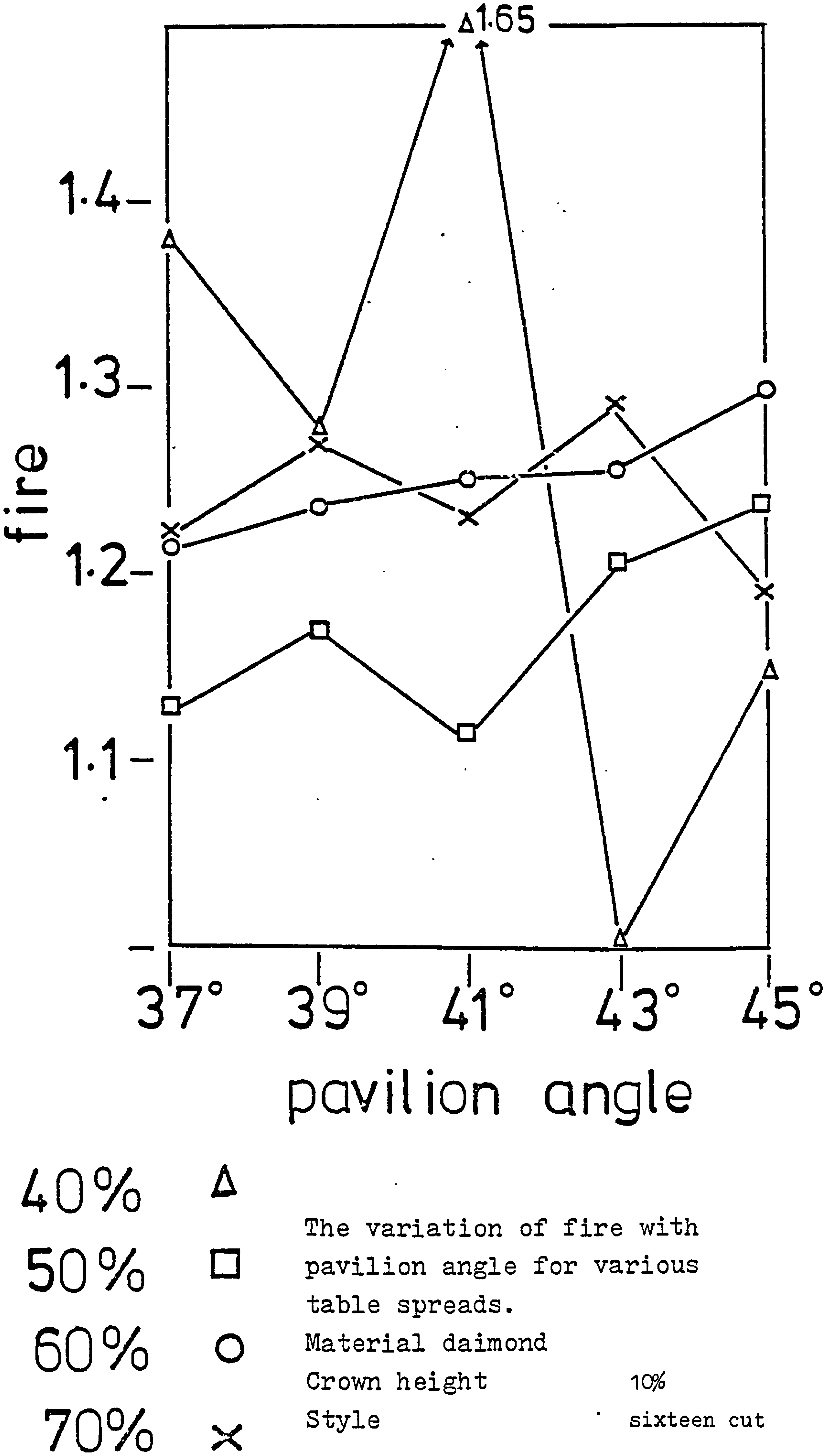
Material diamond

Crown height	15%
Style	sixteen cut



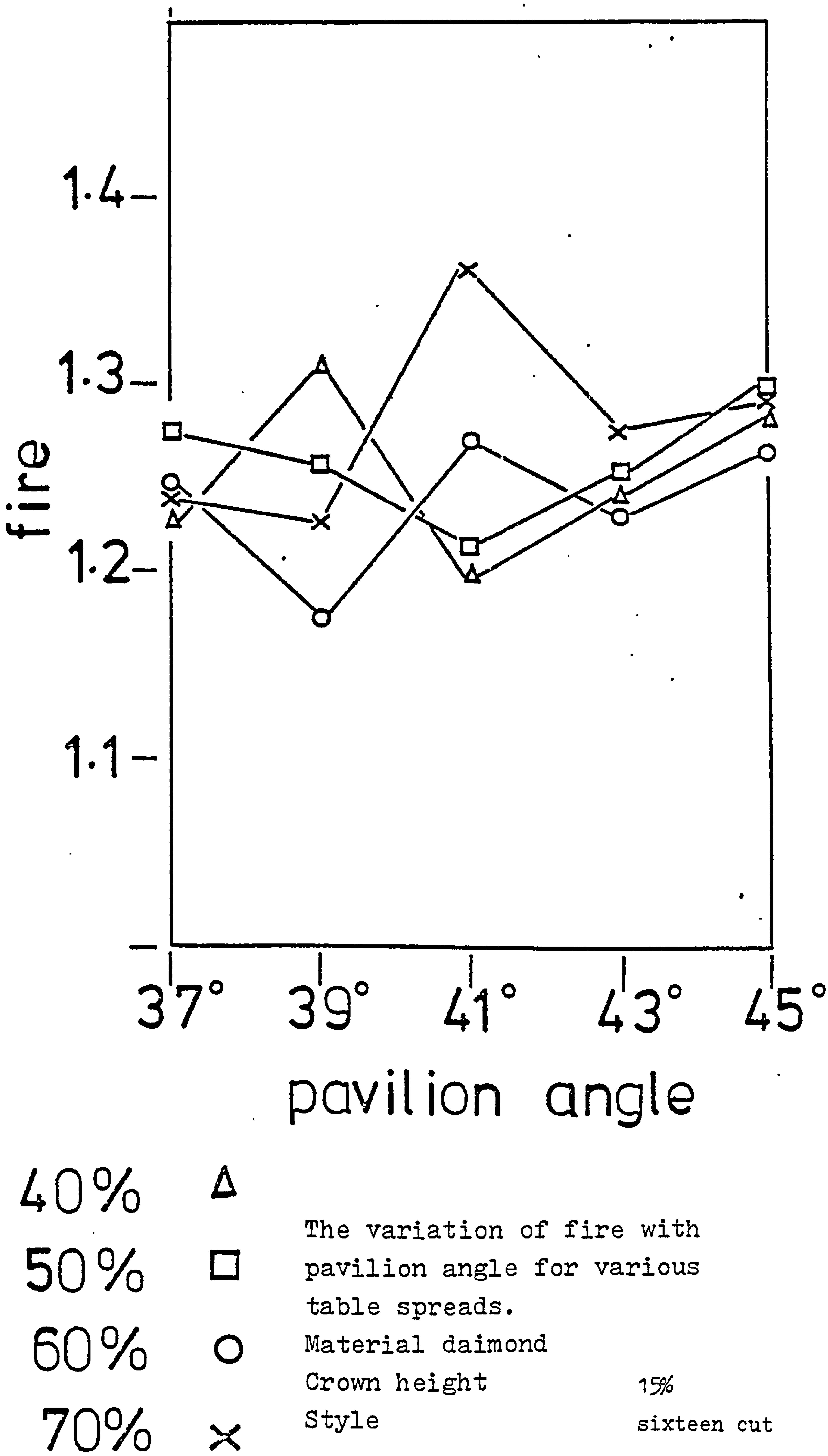
The variation of sparkliness with pavilion angle for various table spreads.

Material diamond	
Crown height	20%
Style	sixteen cut

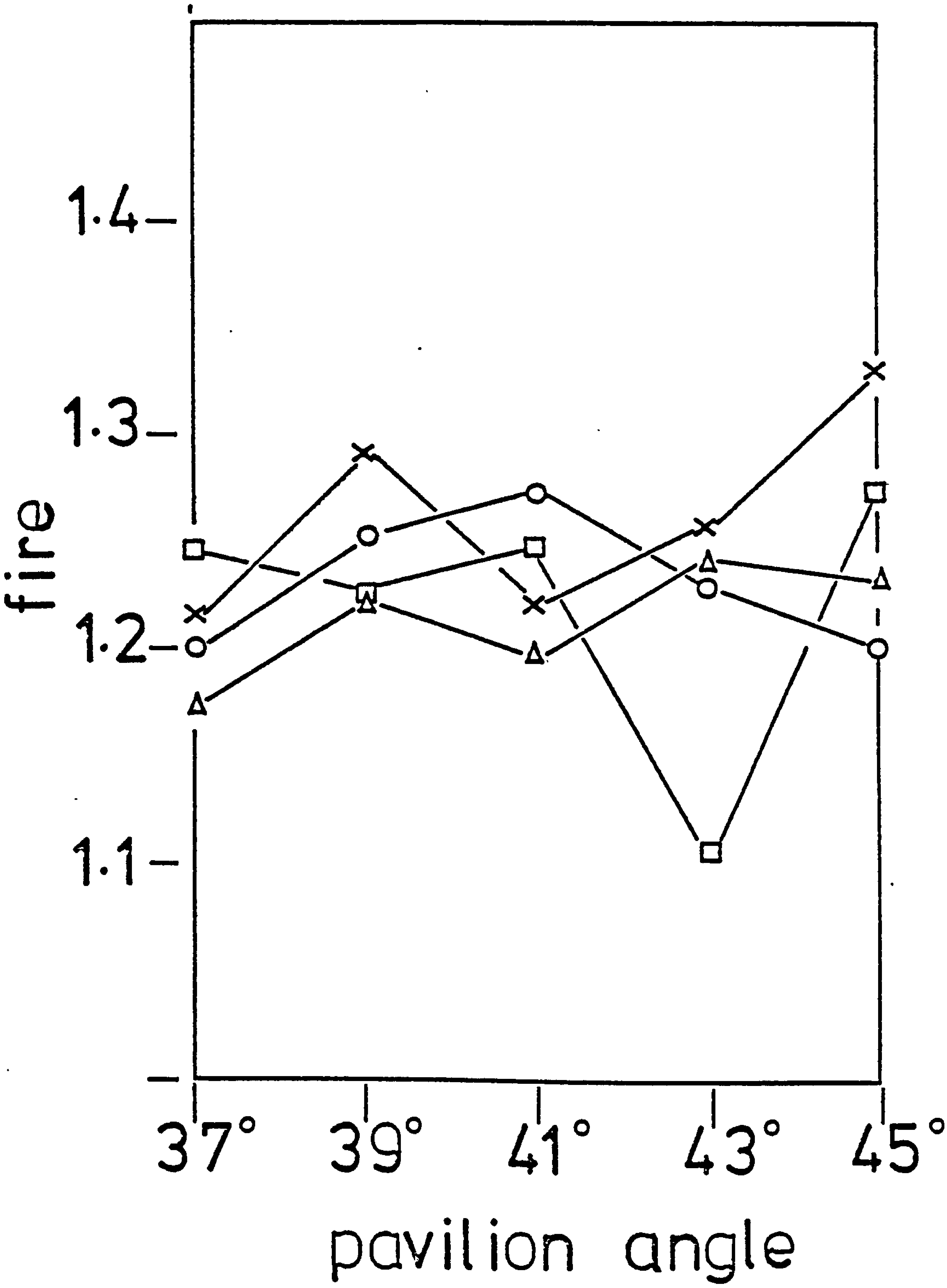


The variation of fire with pavilion angle for various table spreads.

Material daimond	
Crown height	10%
Style	sixteen cut



The variation of fire with pavilion angle for various table spreads.
Material daimond
Crown height 15%
Style sixteen cut



40% Δ

50% □

60% ○

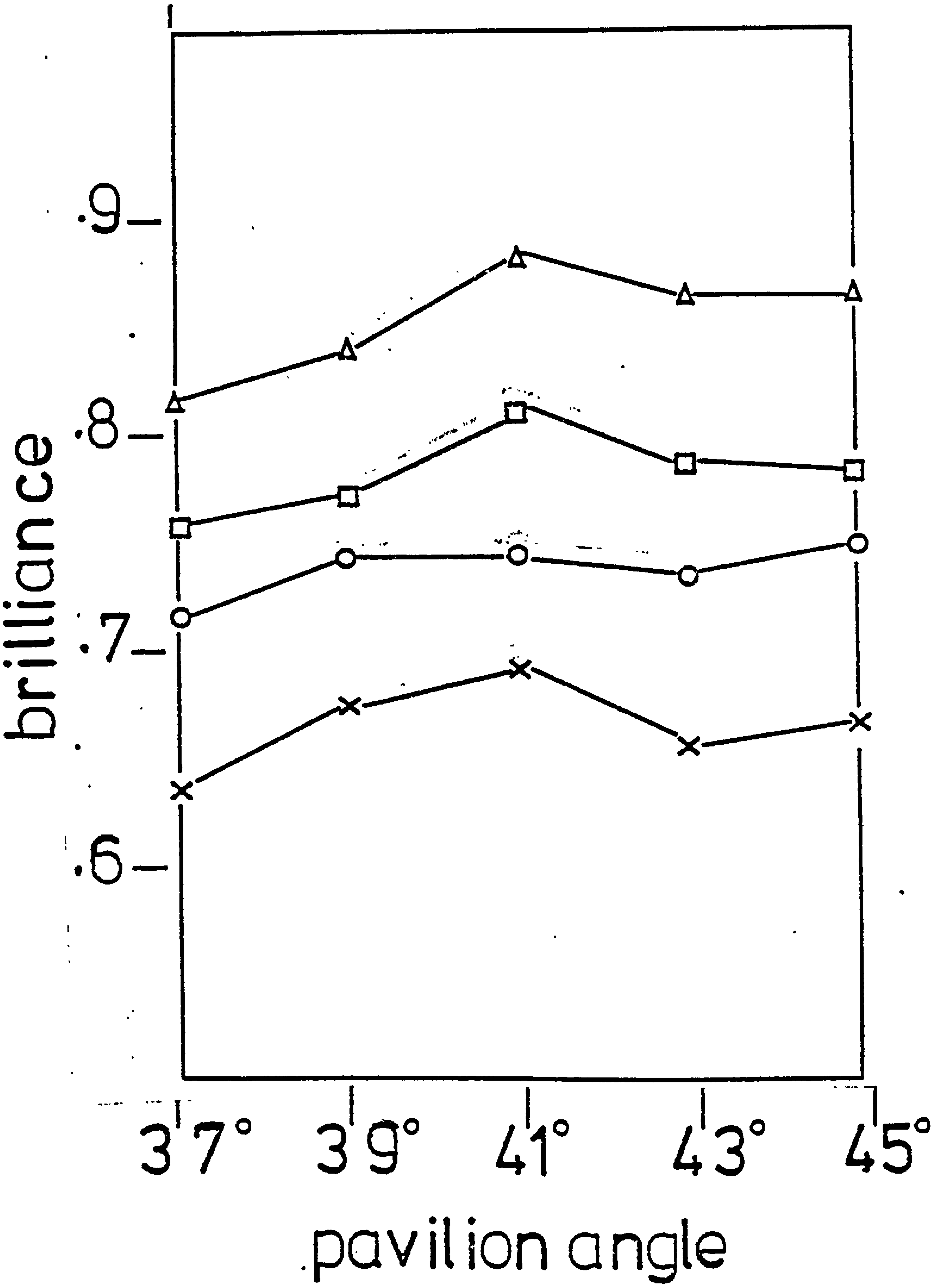
70% ×

The variation of fire with
pavilion angle for various
table spreads.

Material daimond

Crown height 20%

Style sixteen cut



40% △

50% □

60% ○

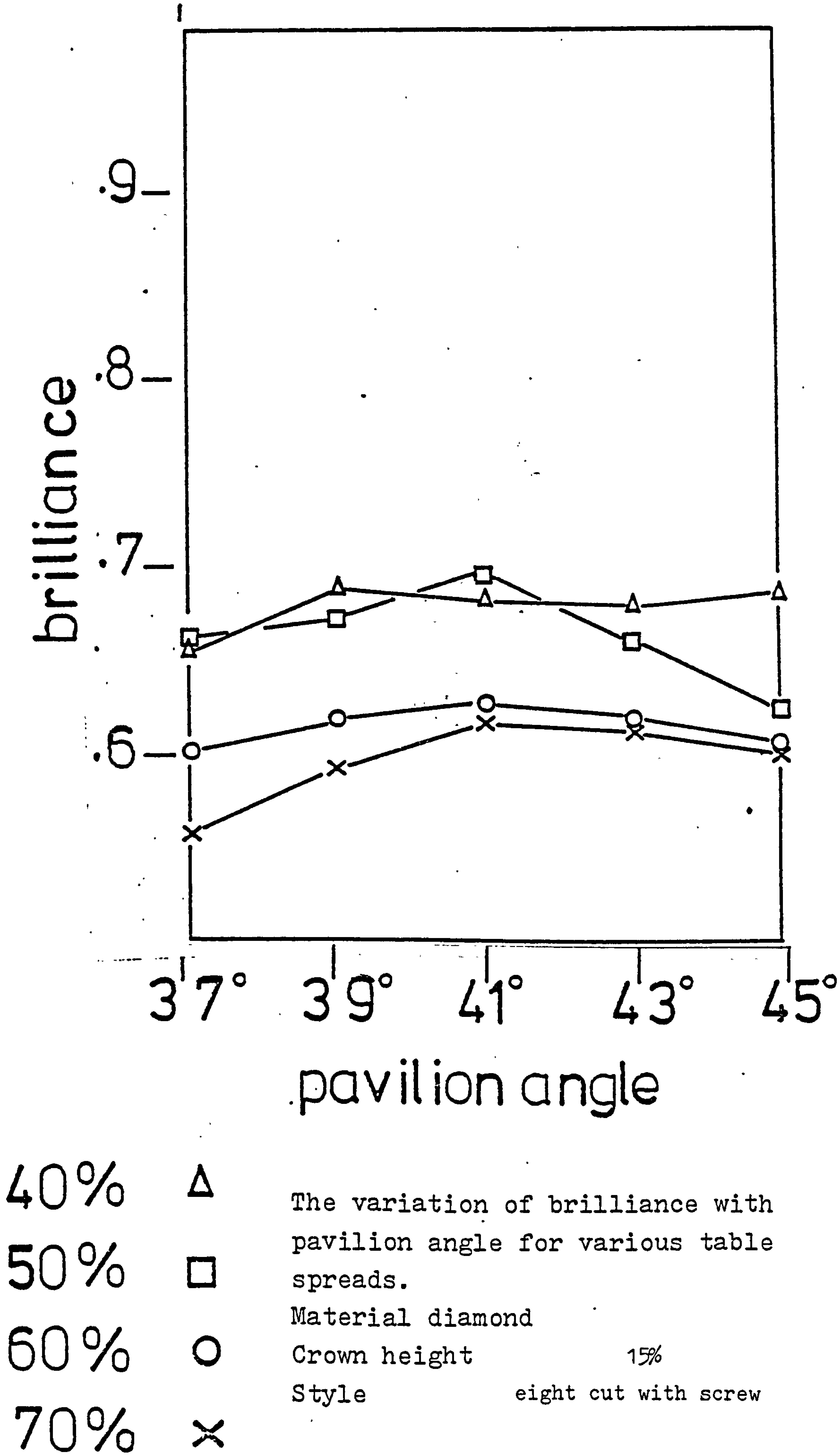
70% ×

The variation of brilliance with pavilion angle for various table spreads.

Material diamond

Crown height 10%

Style eight cut with screw

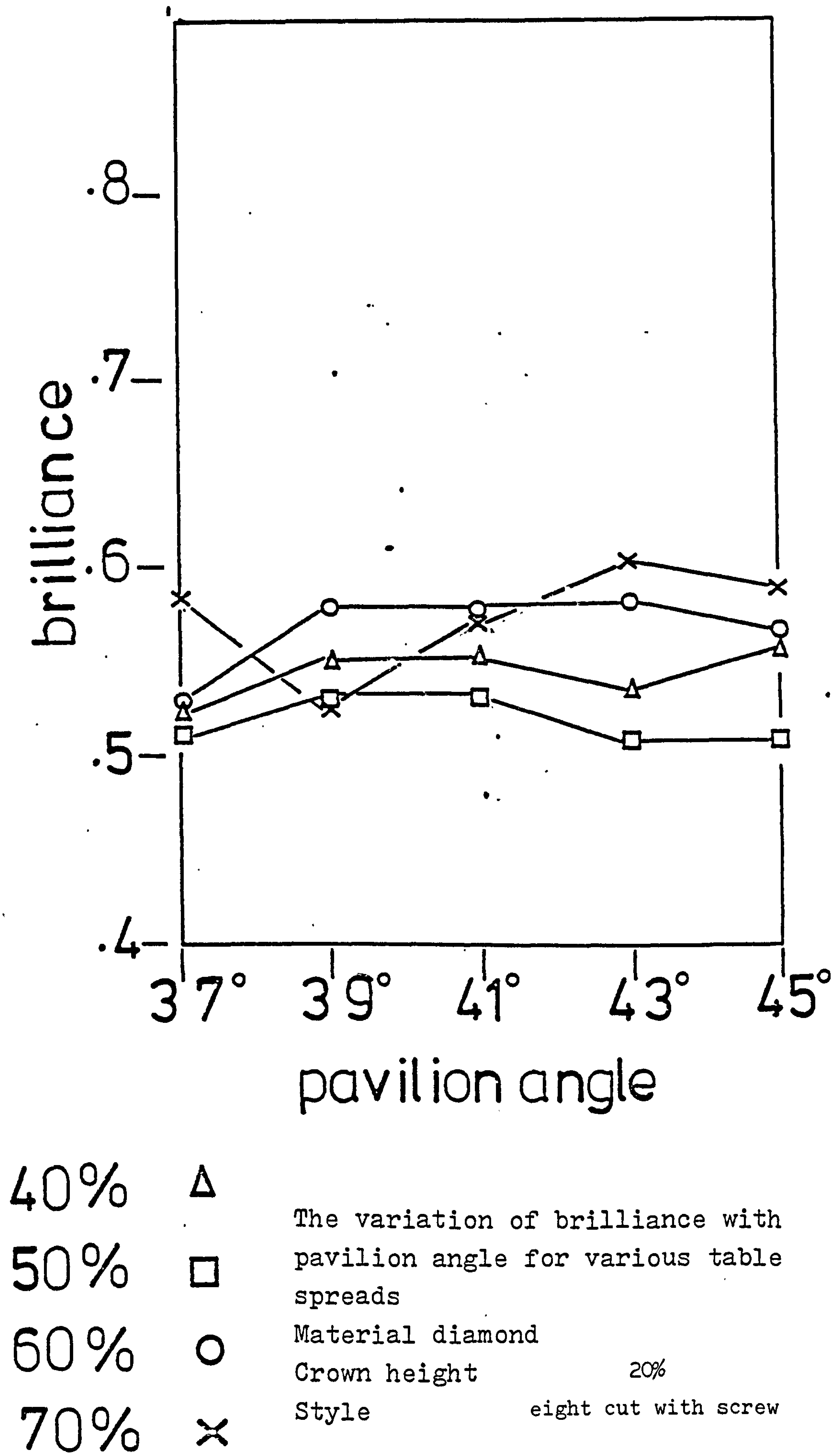


The variation of brilliance with pavilion angle for various table spreads.

Material diamond

Crown height 15%

Style eight cut with screw

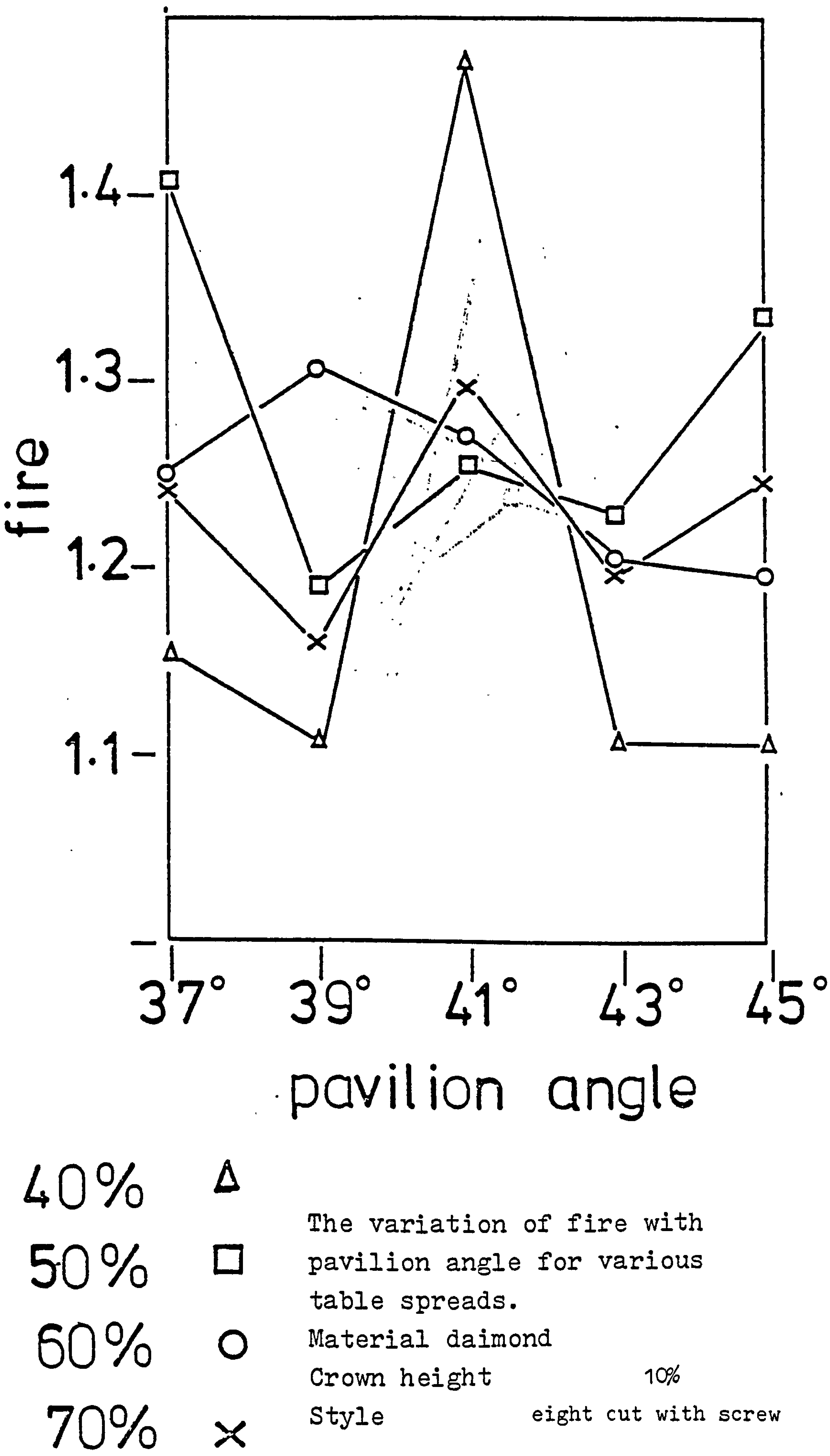


The variation of brilliance with pavilion angle for various table spreads

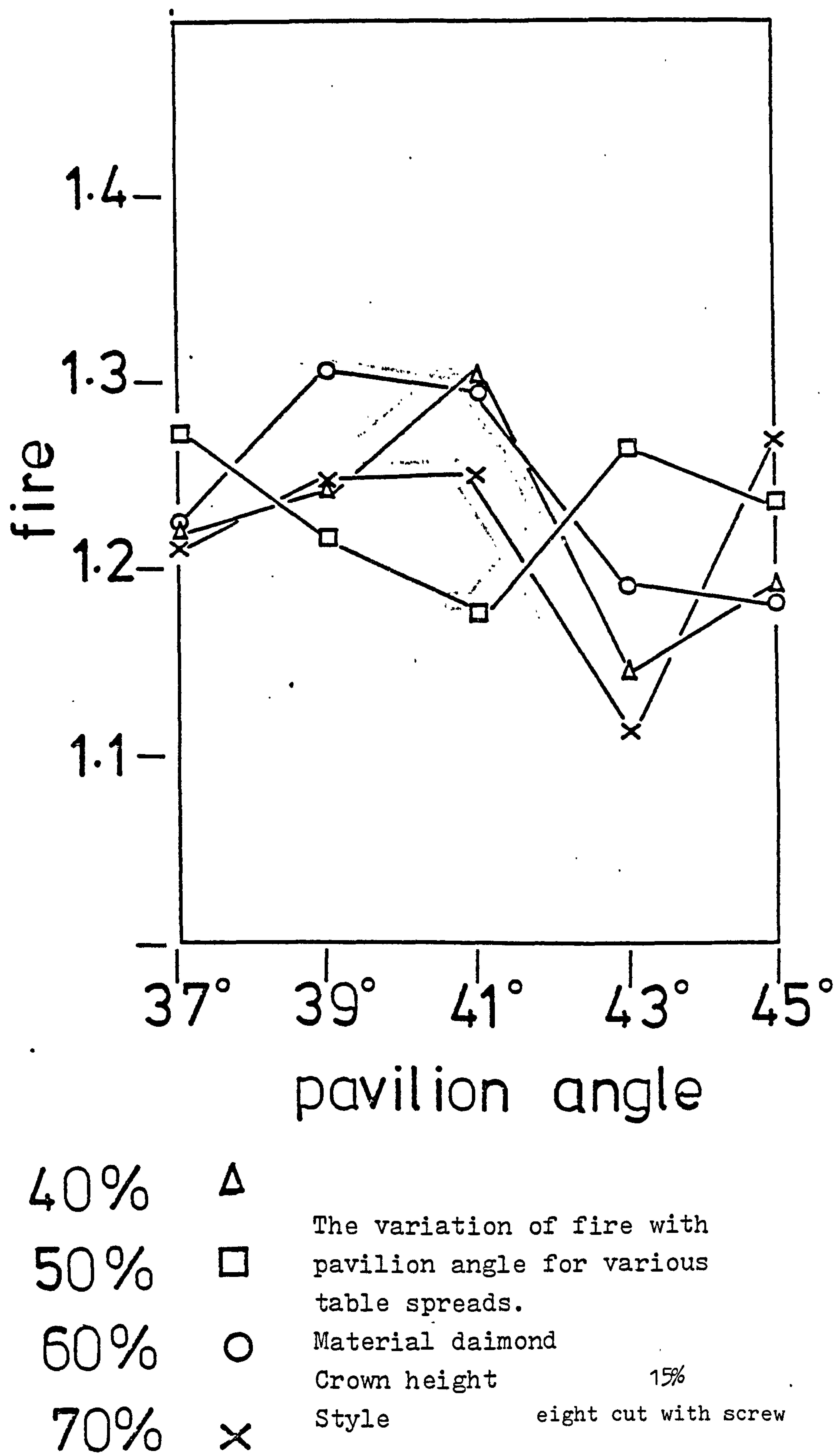
Material diamond

Crown height 20%

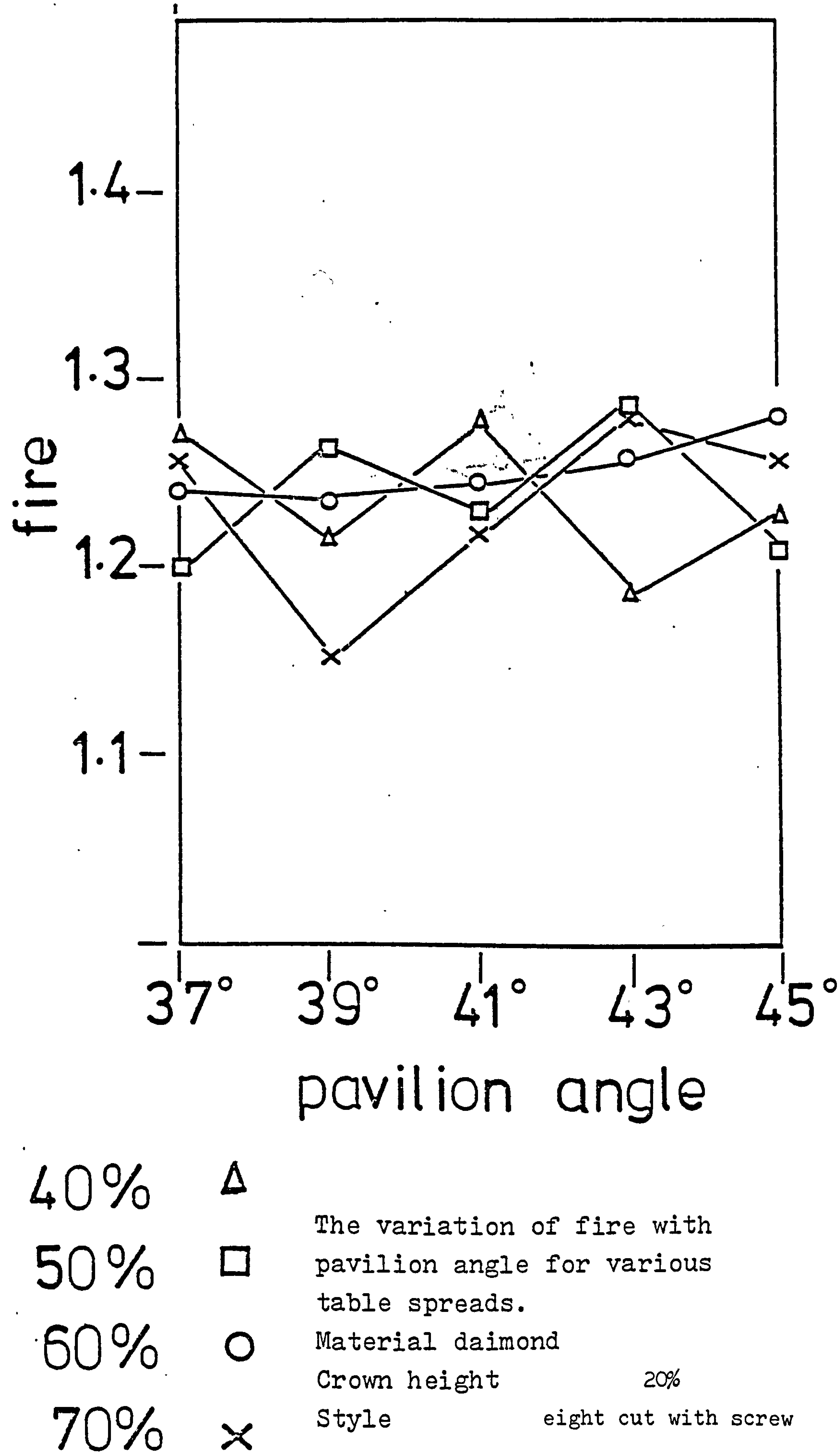
Style eight cut with screw



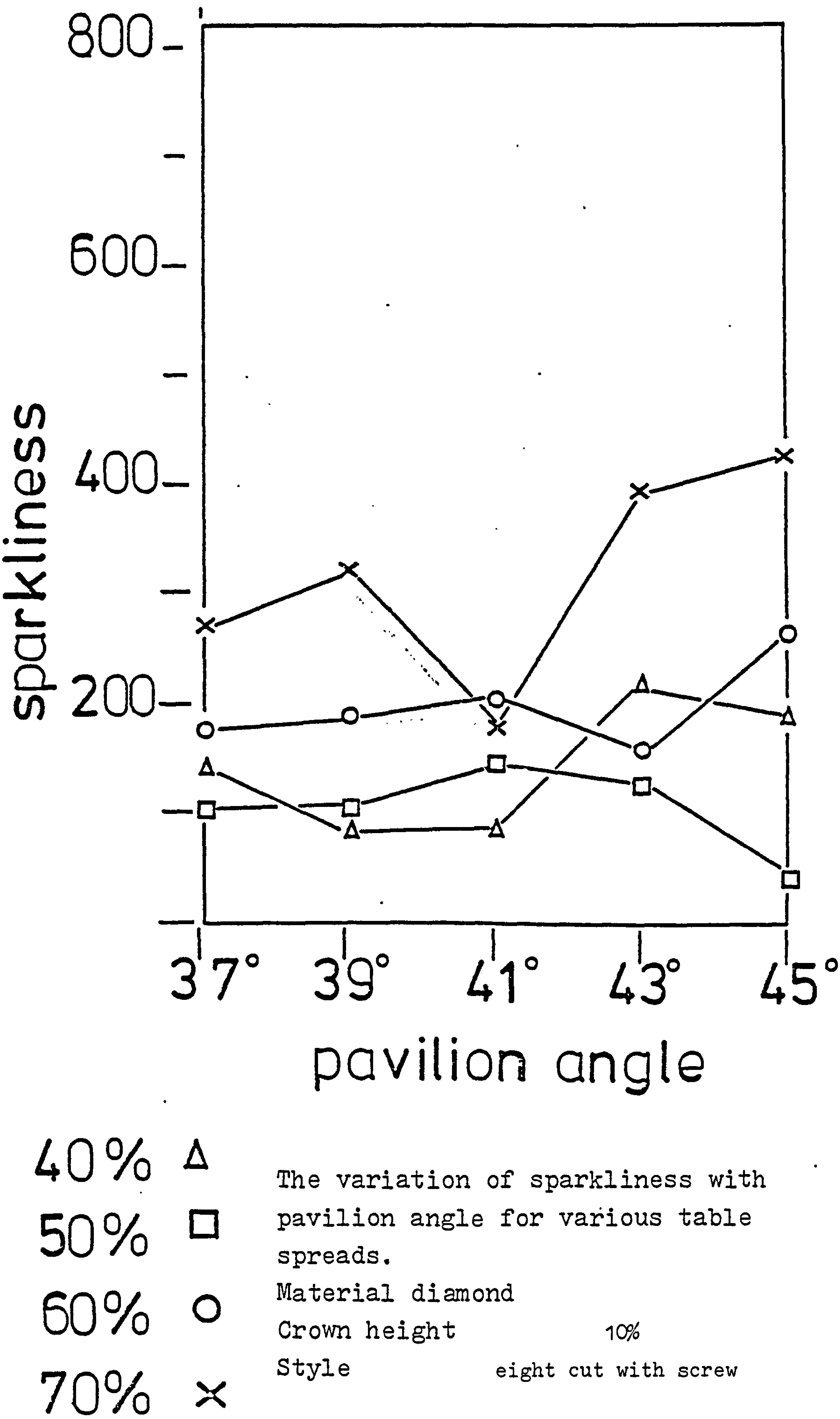
The variation of fire with
pavilion angle for various
table spreads.
Material daimond
Crown height 10%
Style eight cut with screw



The variation of fire with
pavilion angle for various
table spreads.
Material daimond
Crown height 15%
Style eight cut with screw



The variation of fire with
pavilion angle for various
table spreads.
Material daimond
Crown height 20%
Style eight cut with screw

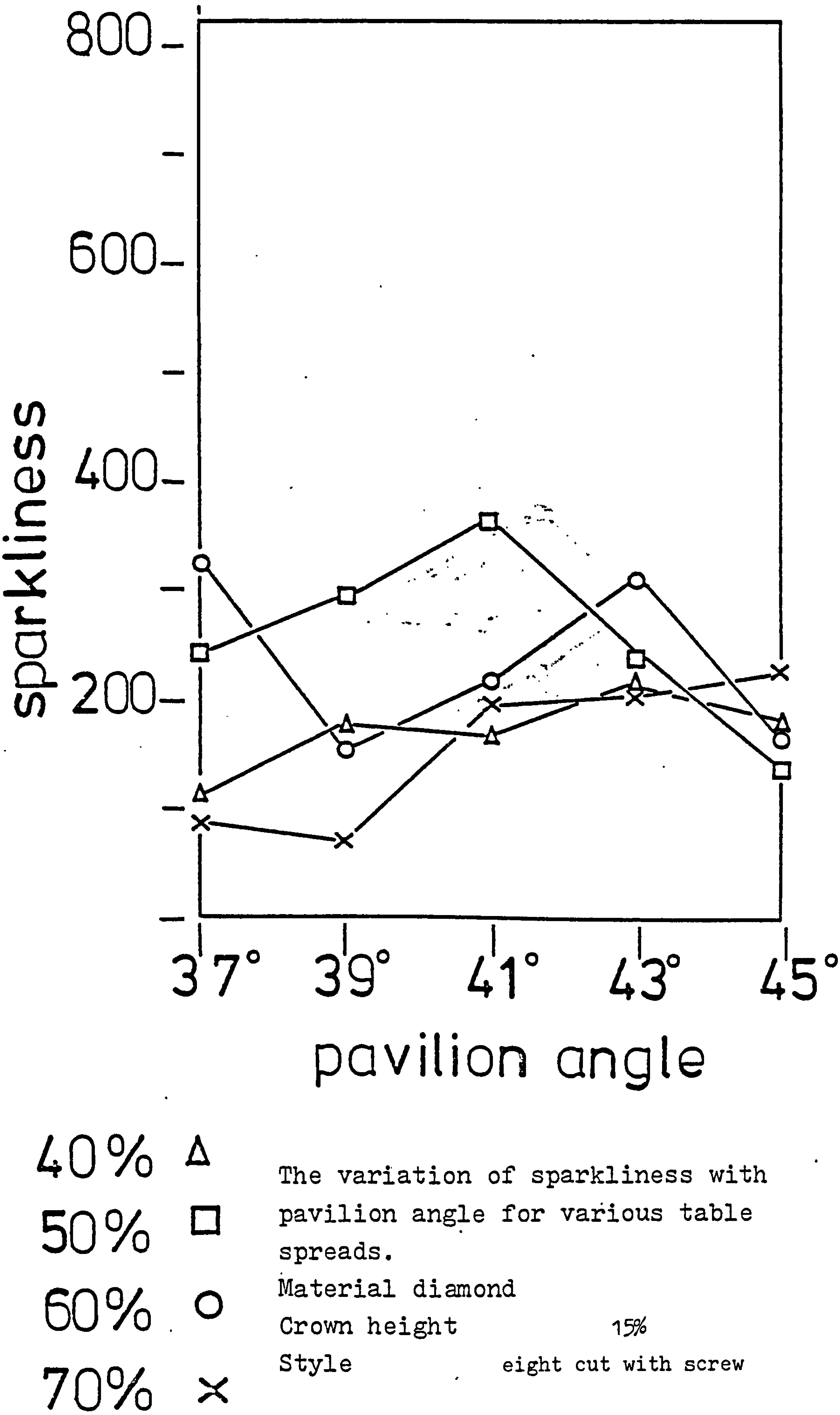


The variation of sparkliness with pavilion angle for various table spreads.

Material diamond

Crown height 10%

Style eight cut with screw

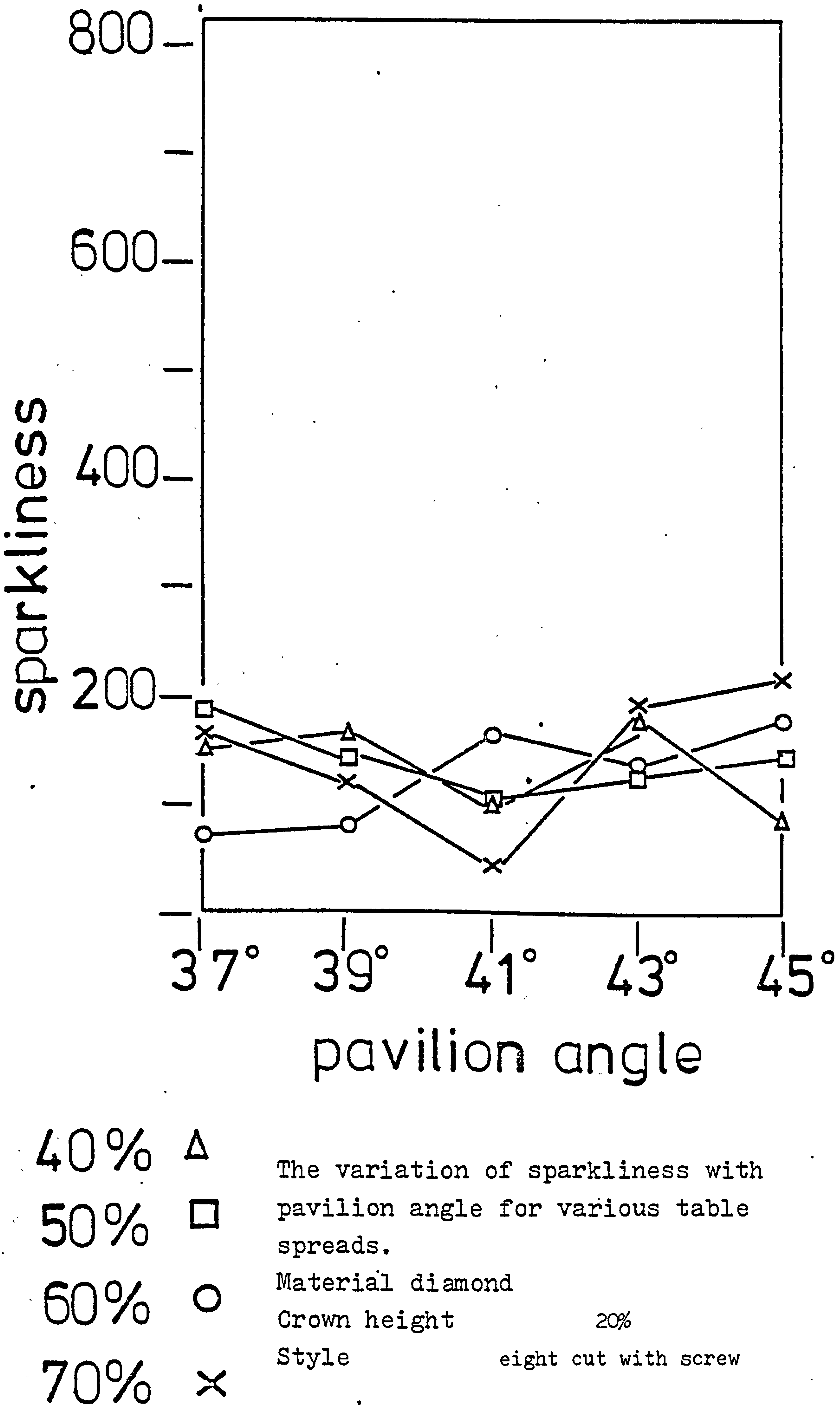


The variation of sparkliness with pavilion angle for various table spreads.

Material diamond

Crown height 15%

Style eight cut with screw

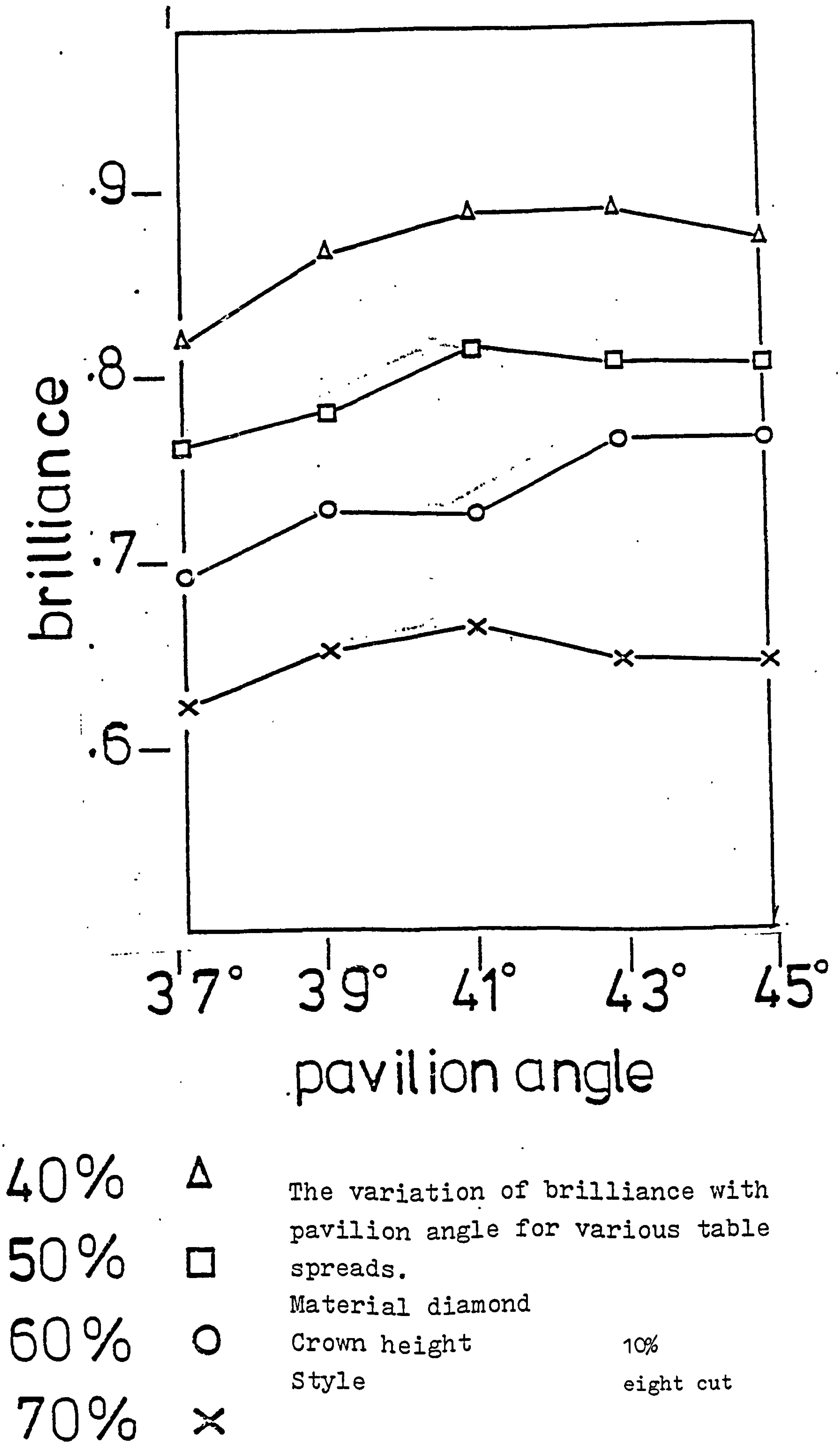


The variation of sparkliness with pavilion angle for various table spreads.

Material diamond

Crown height 20%

Style eight cut with screw

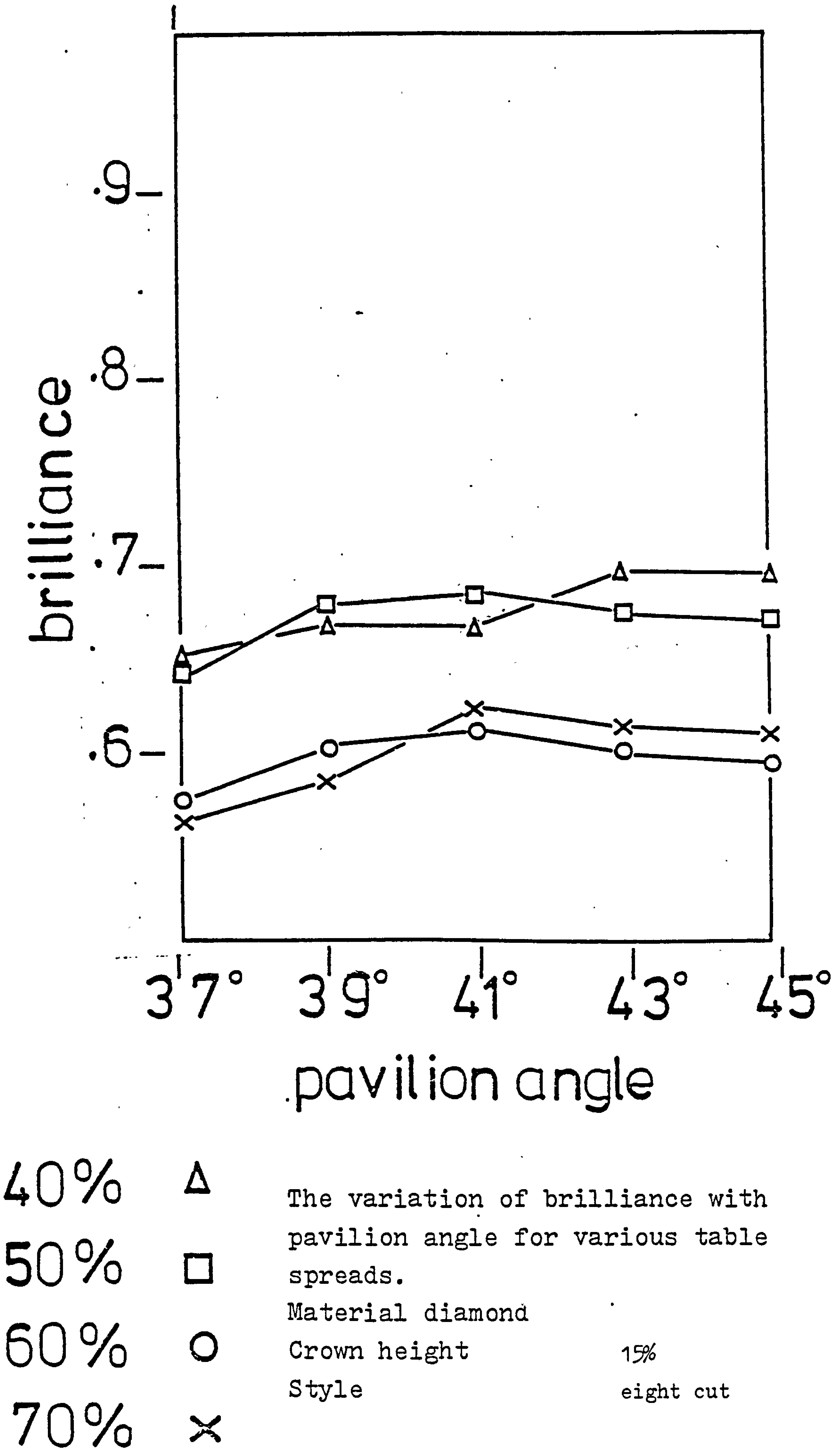


The variation of brilliance with pavilion angle for various table spreads.

Material diamond

Crown height 10%

Style eight cut

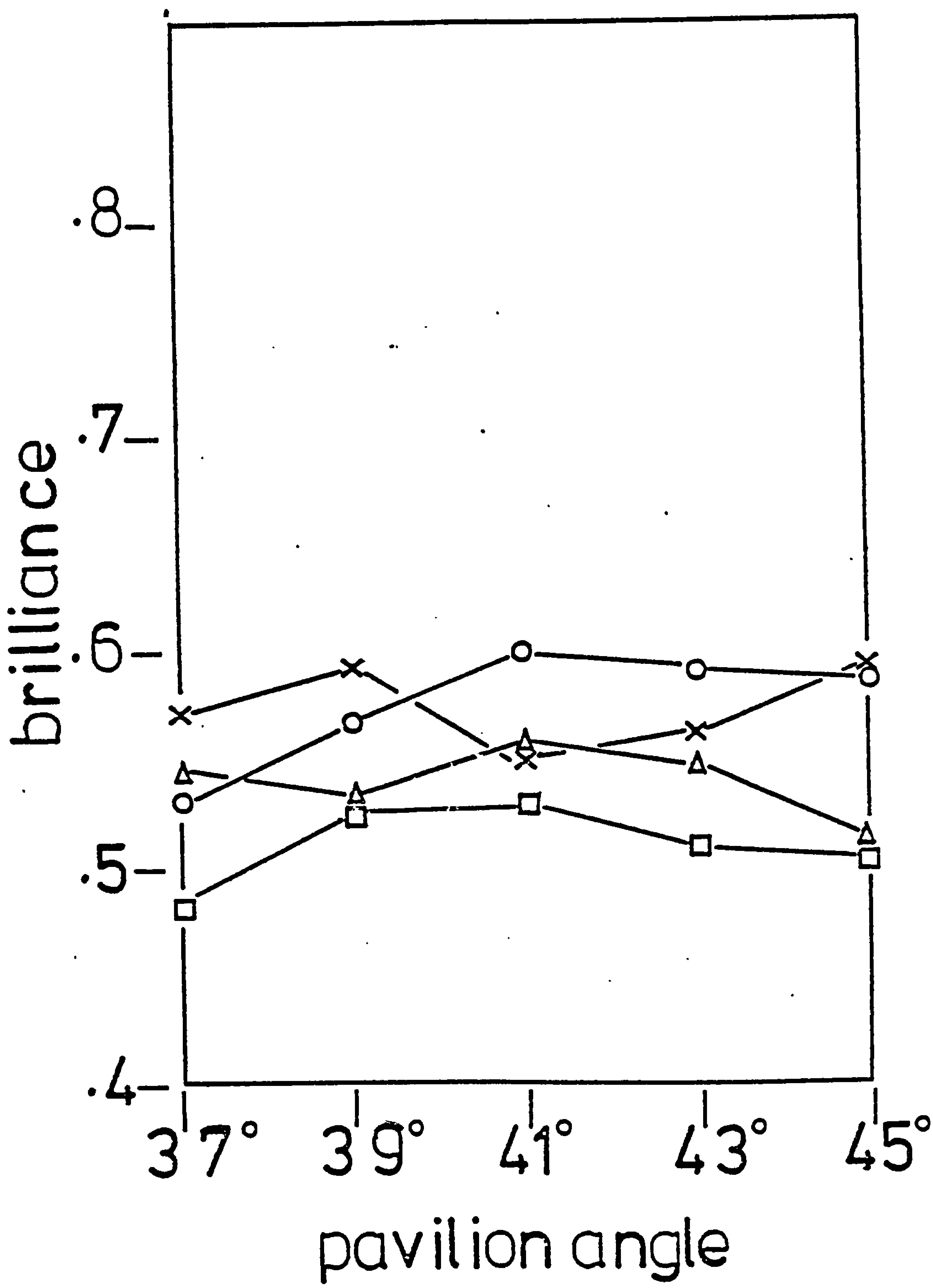


The variation of brilliance with pavilion angle for various table spreads.

Material diamond

Crown height 15%

Style eight cut



40% Δ

50% □

60% ○

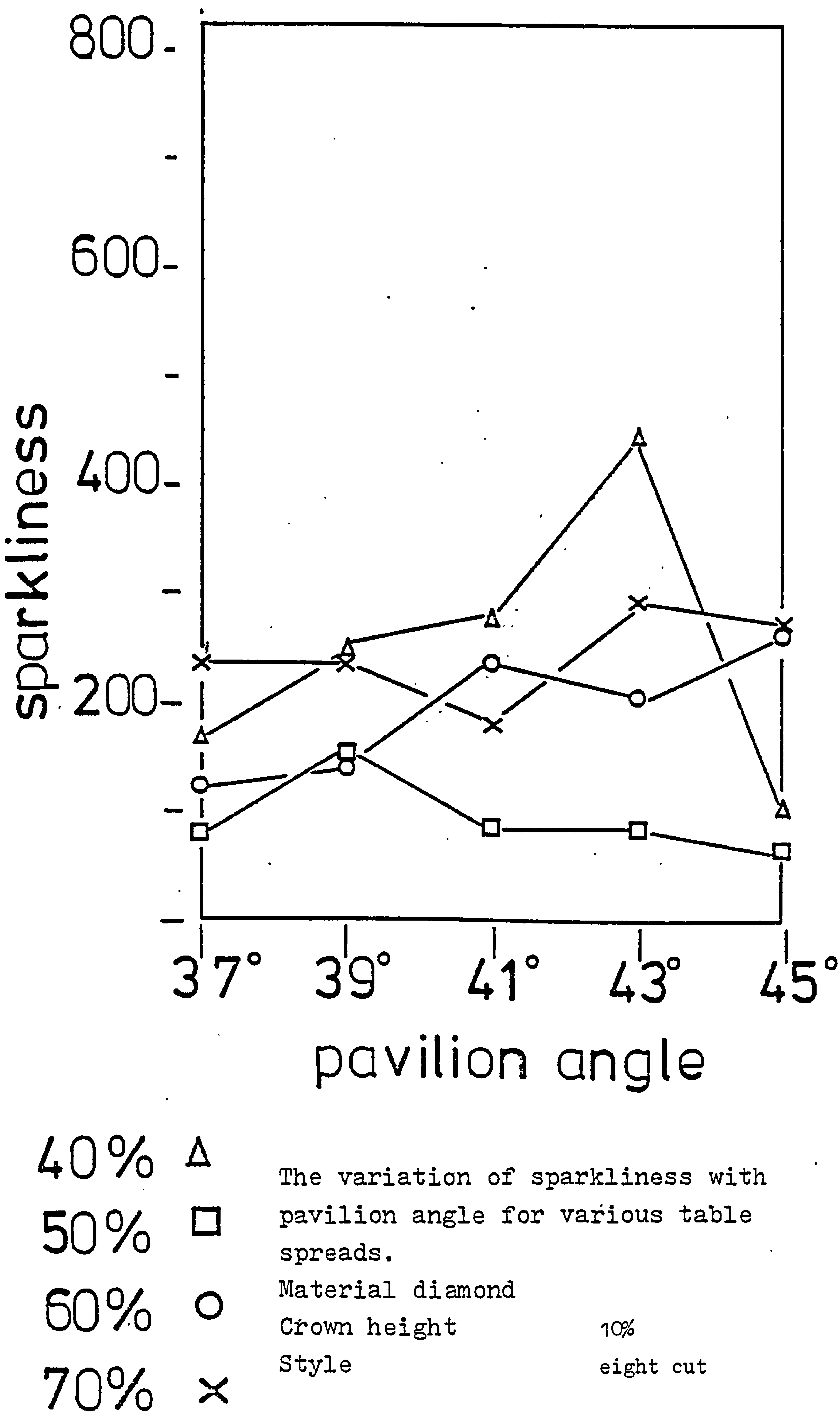
70% ×

The variation of brilliance with pavilion angle for various table spreads

Material diamond

Crown height 20%

Style eight cut

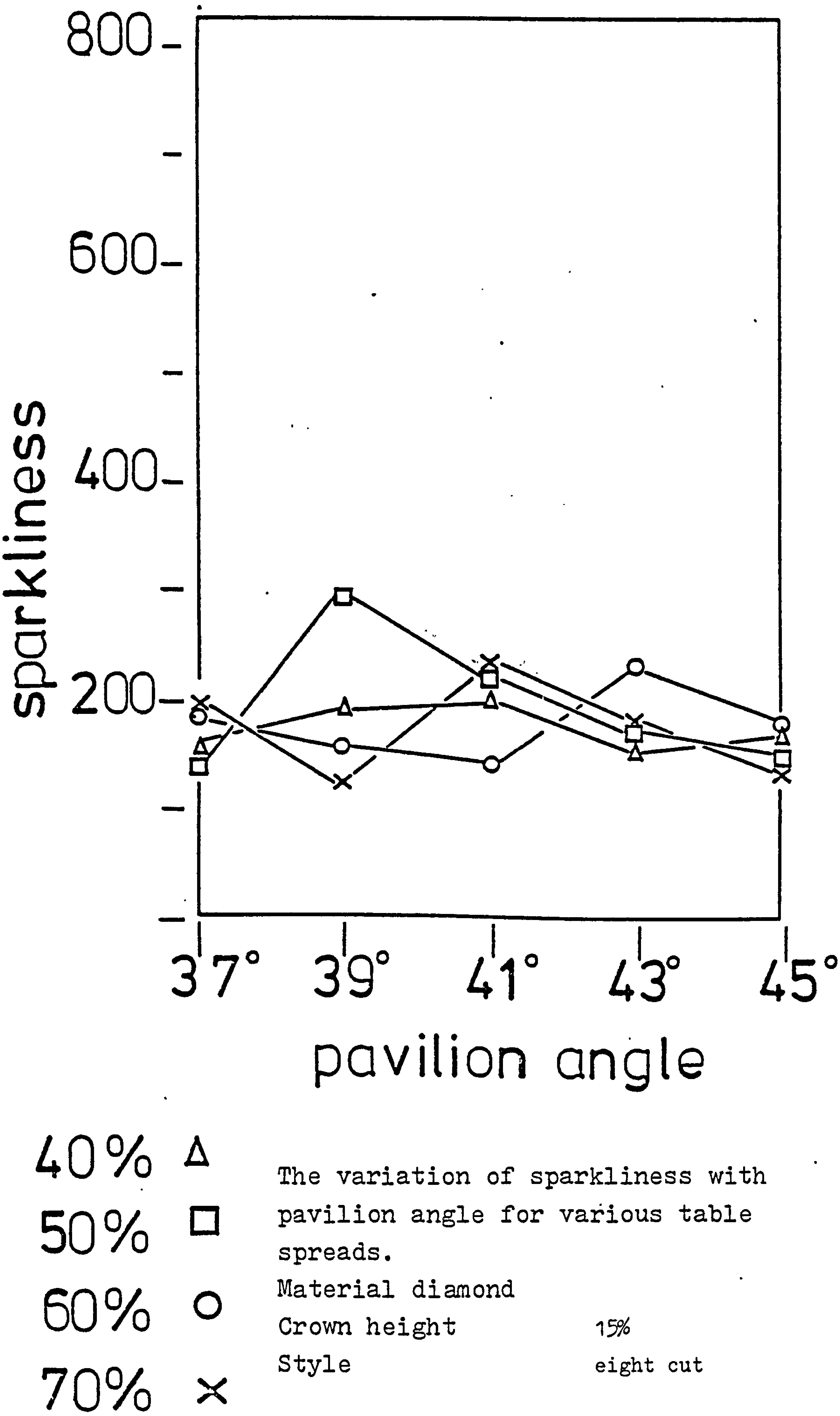


The variation of sparkliness with pavilion angle for various table spreads.

Material diamond

Crown height 10%

Style eight cut

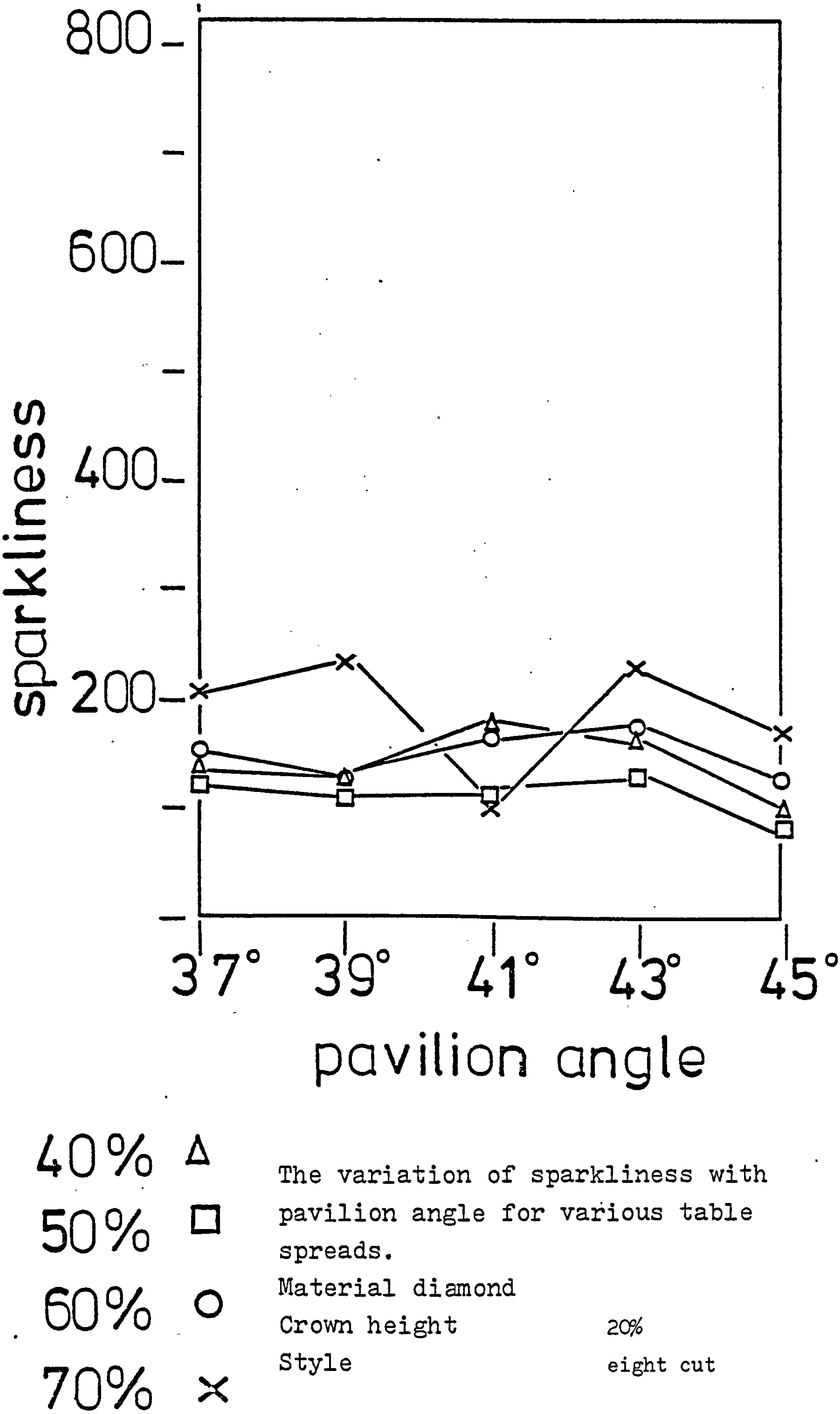


The variation of sparkliness with pavilion angle for various table spreads.

Material diamond

Crown height 15%

Style eight cut

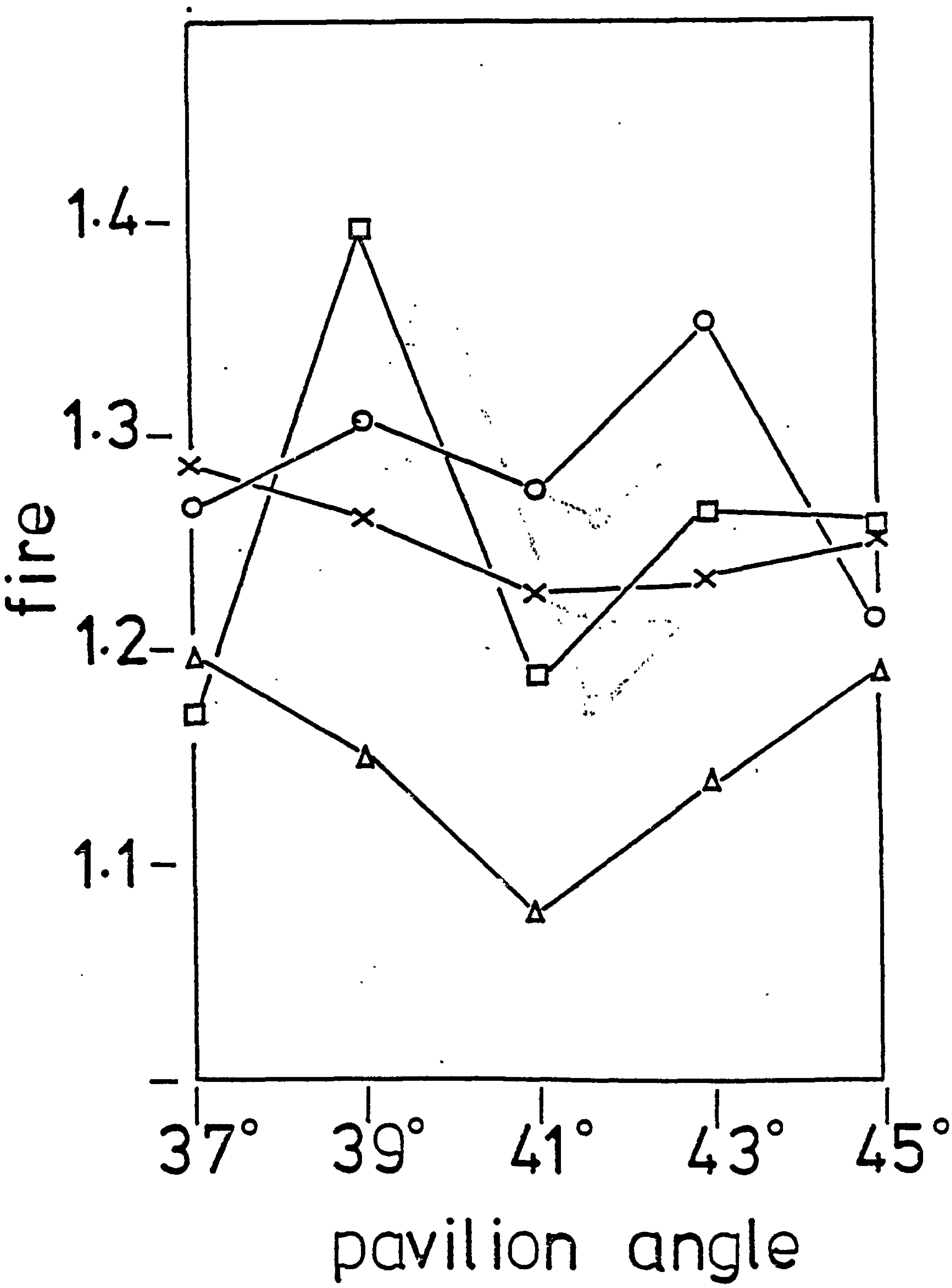


The variation of sparkliness with pavilion angle for various table spreads.

Material diamond

Crown height 20%

Style eight cut



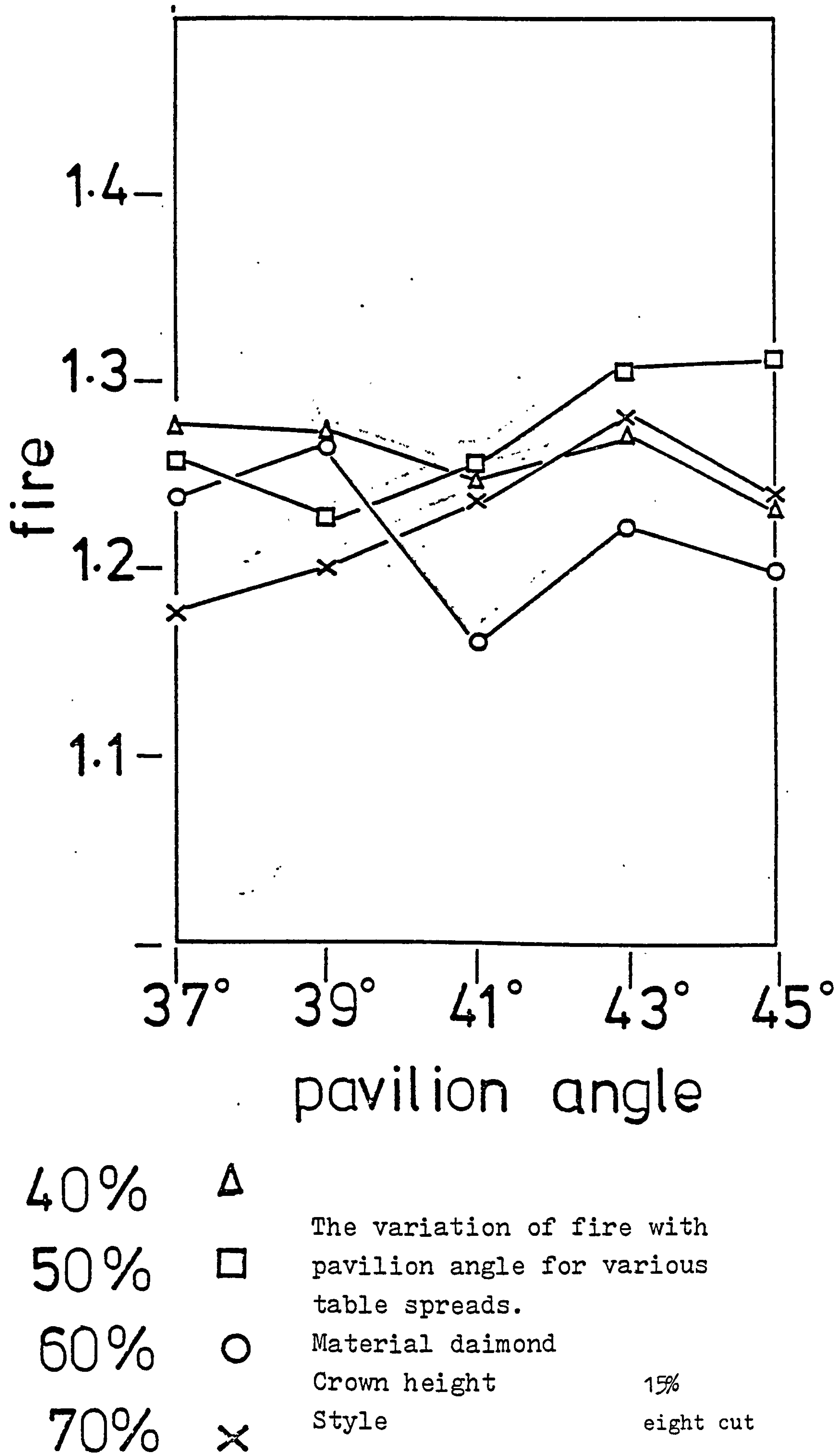
40% Δ
50% □
60% ○
70% ×

The variation of fire with pavilion angle for various table spreads.

Material daimond

Crown height 10%

Style eight cut

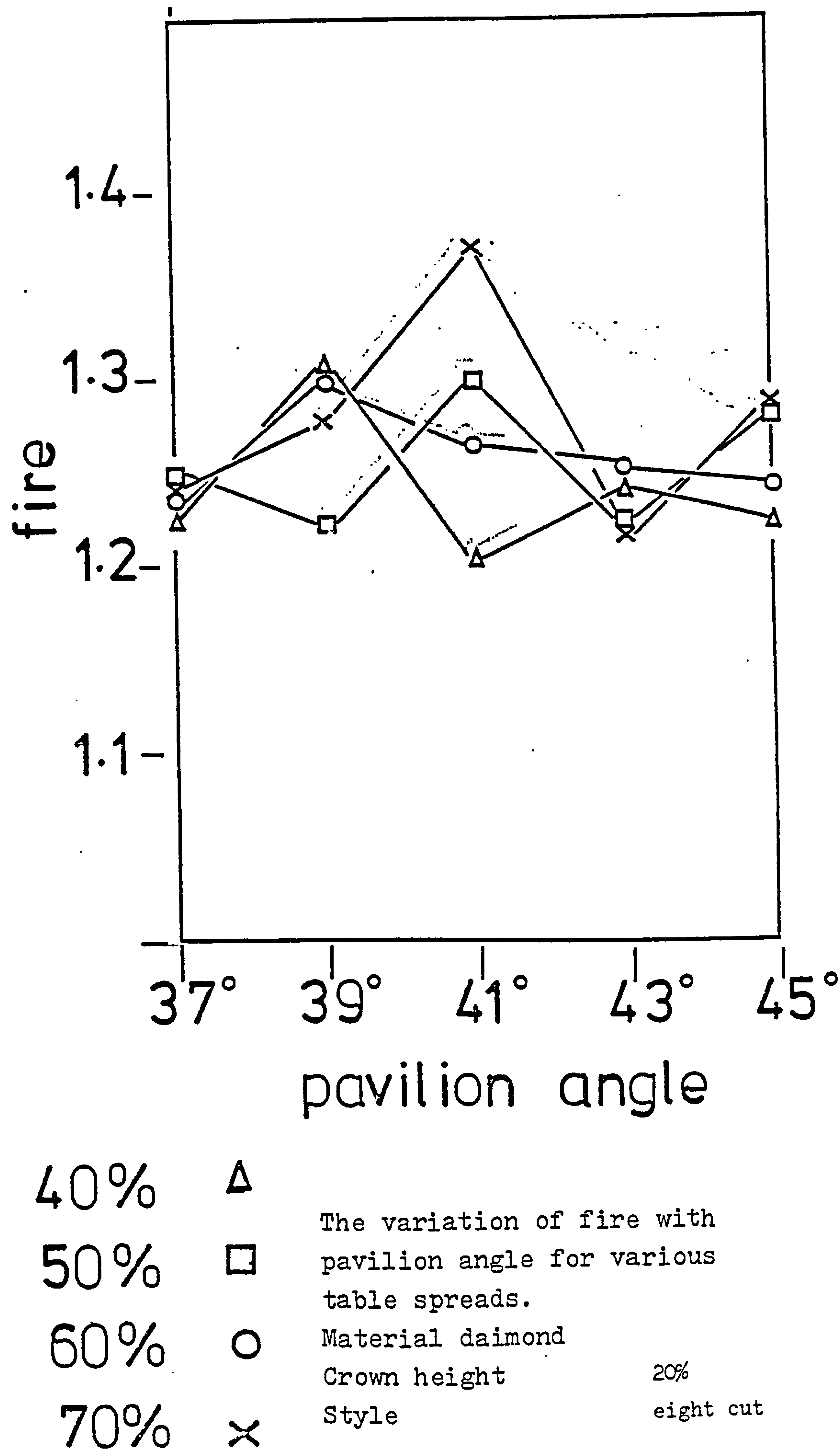


The variation of fire with pavilion angle for various table spreads.

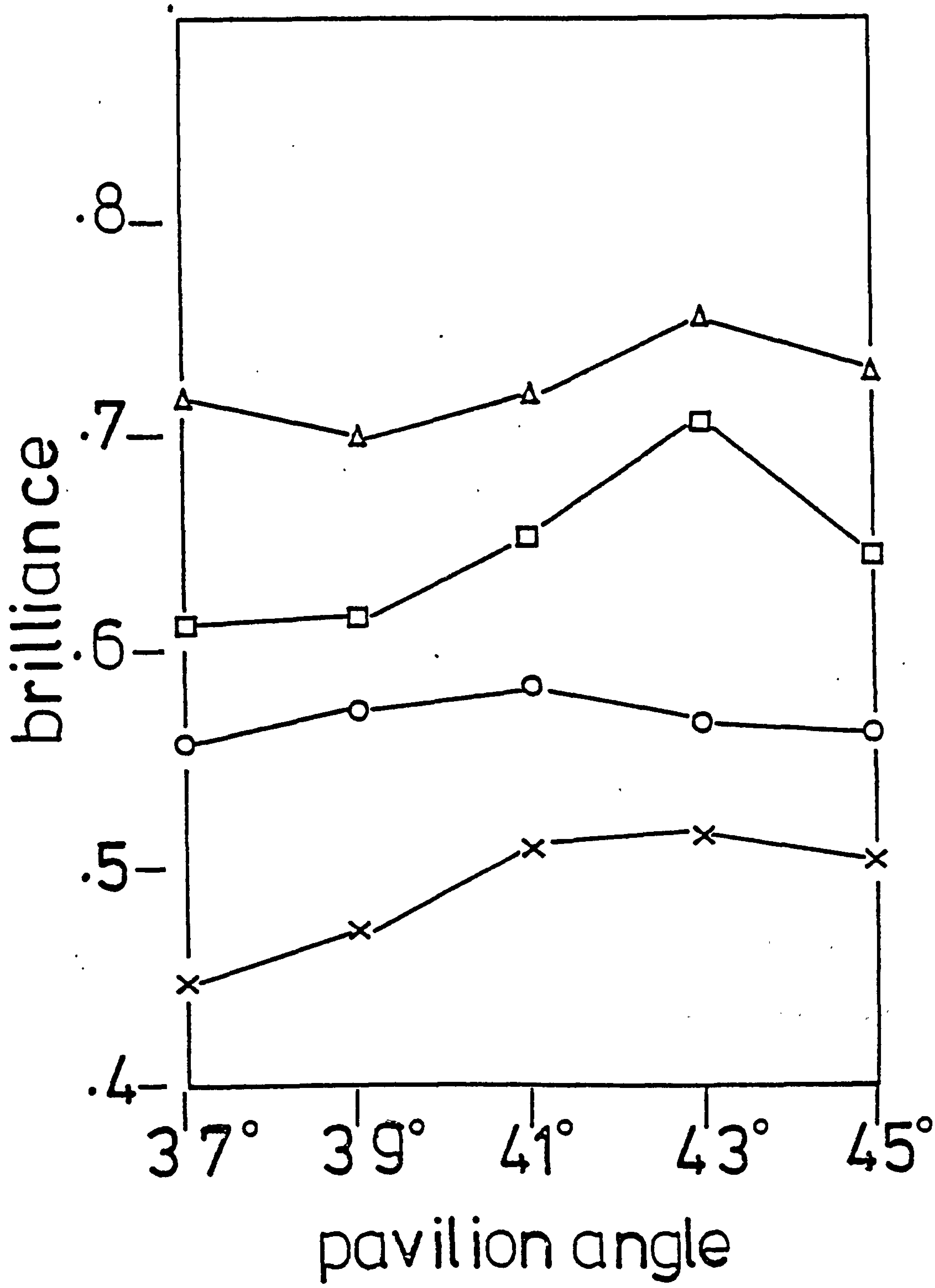
Material daimond

Crown height 15%

Style eight cut



The variation of fire with pavilion angle for various table spreads.
Material daimond
Crown height 20%
Style eight cut



40% Δ

50% □

60% ○

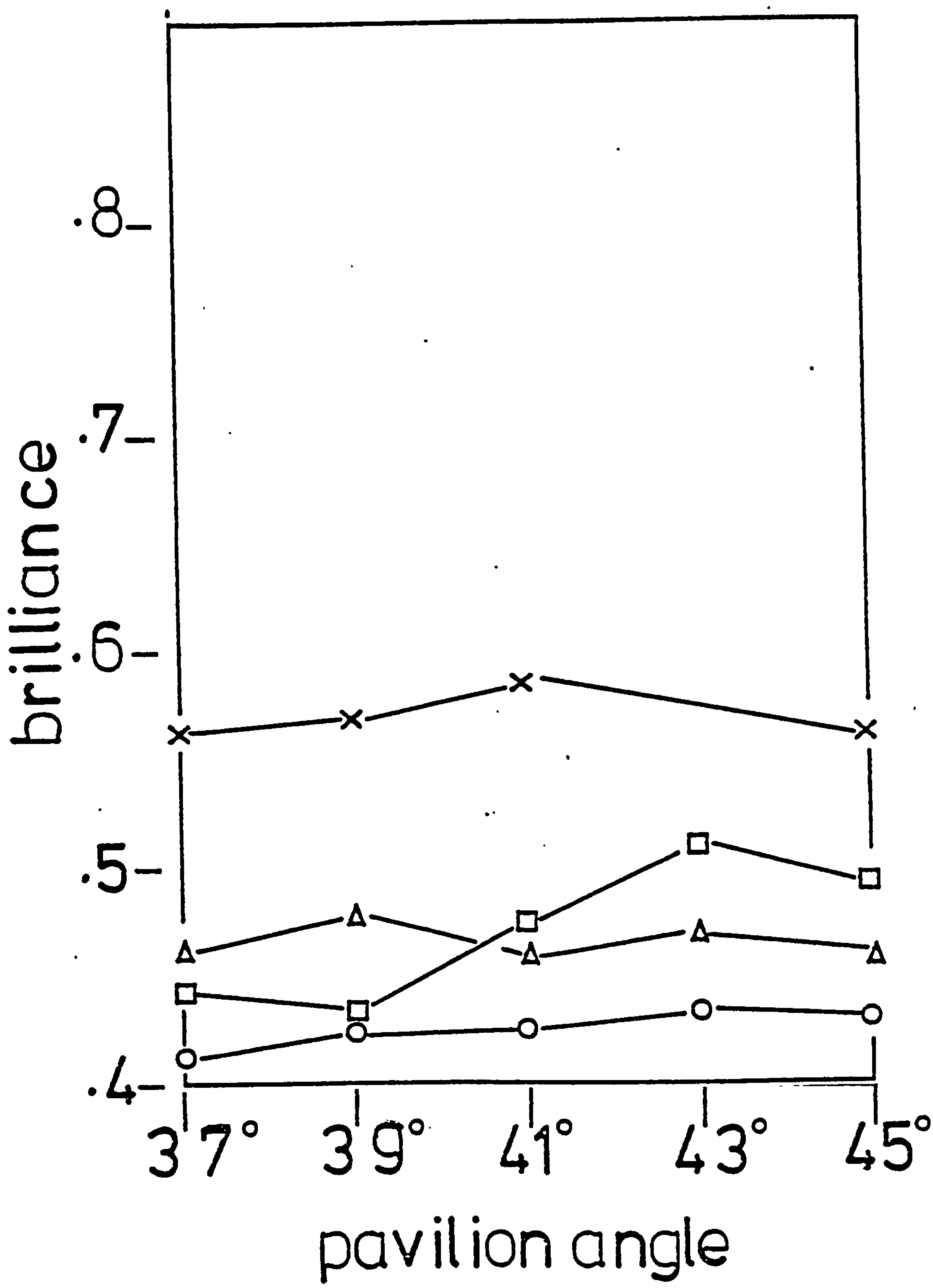
70% ×

The variation of brilliance with pavilion angle for various table spreads

Material diamond

Crown height 10%

Style four cut with screw



40% Δ

50% □

60% ○

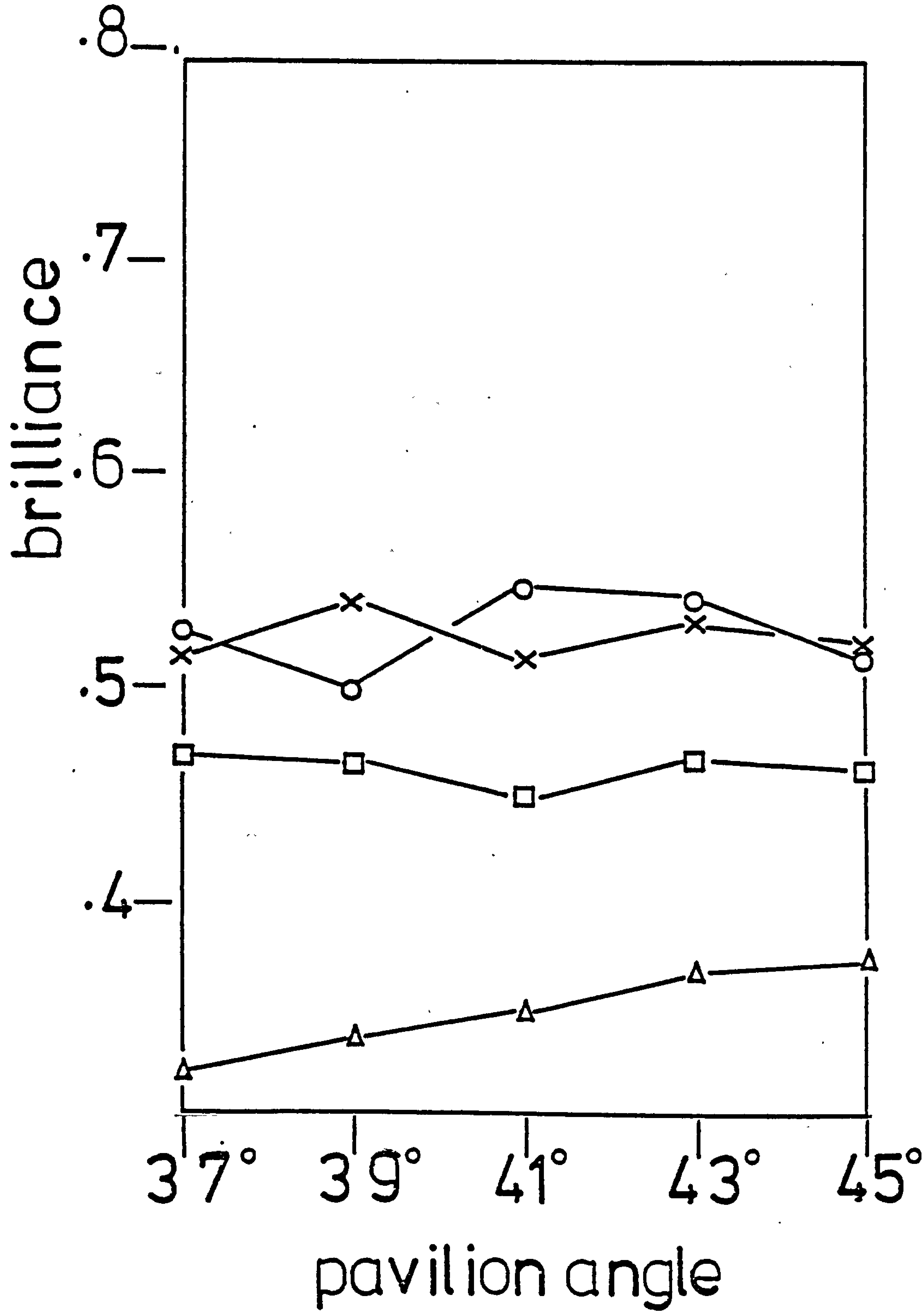
70% ×

The variation of brilliance with pavilion angle for various table spreads

Material diamond

Crown height 15%

Style four cut with screw



40% Δ

50% □

60% ○

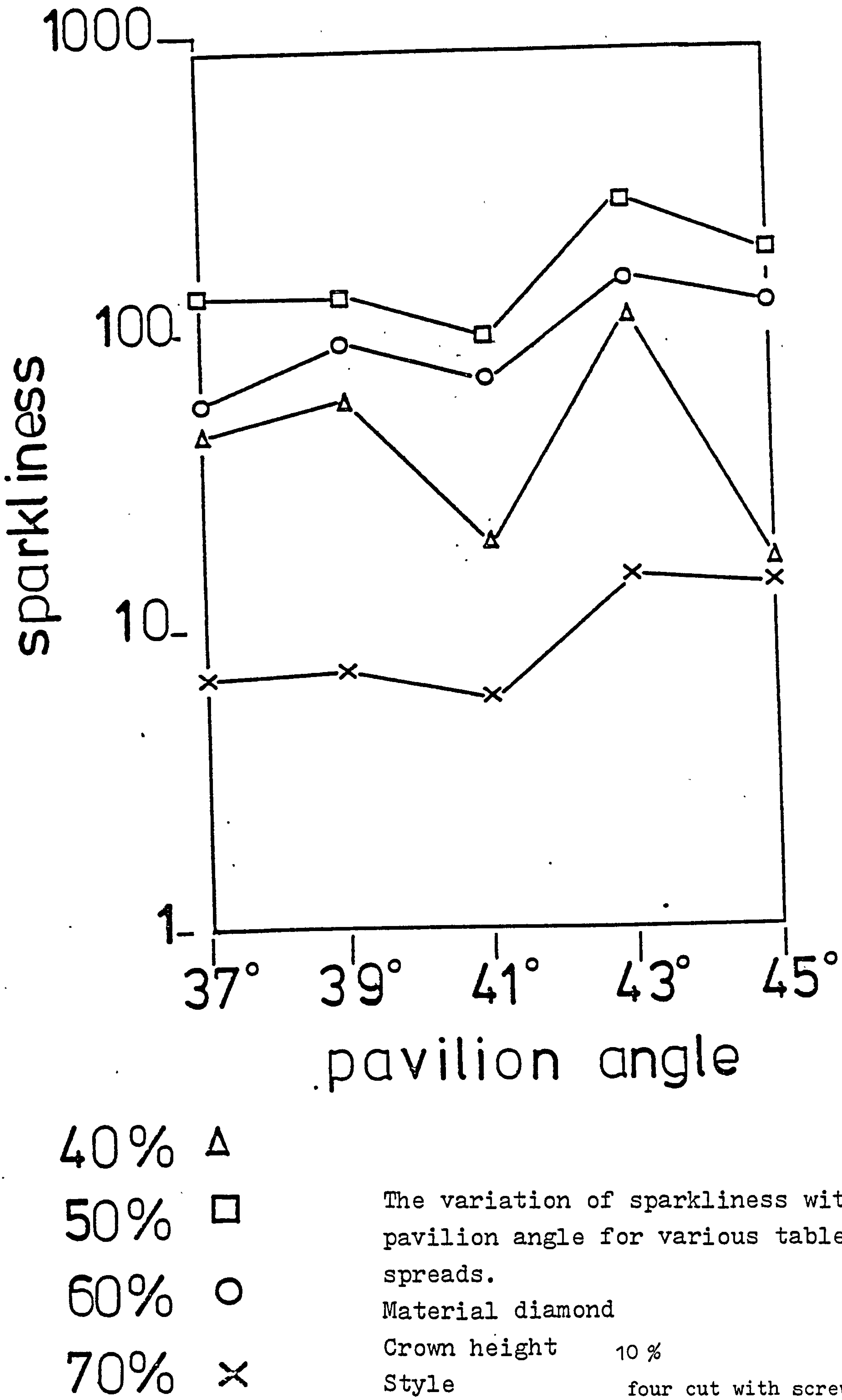
70% ×

The variation of brilliance with pavilion angle for various table spreads

Material diamond

Crown height 20%

Style four cut with screw

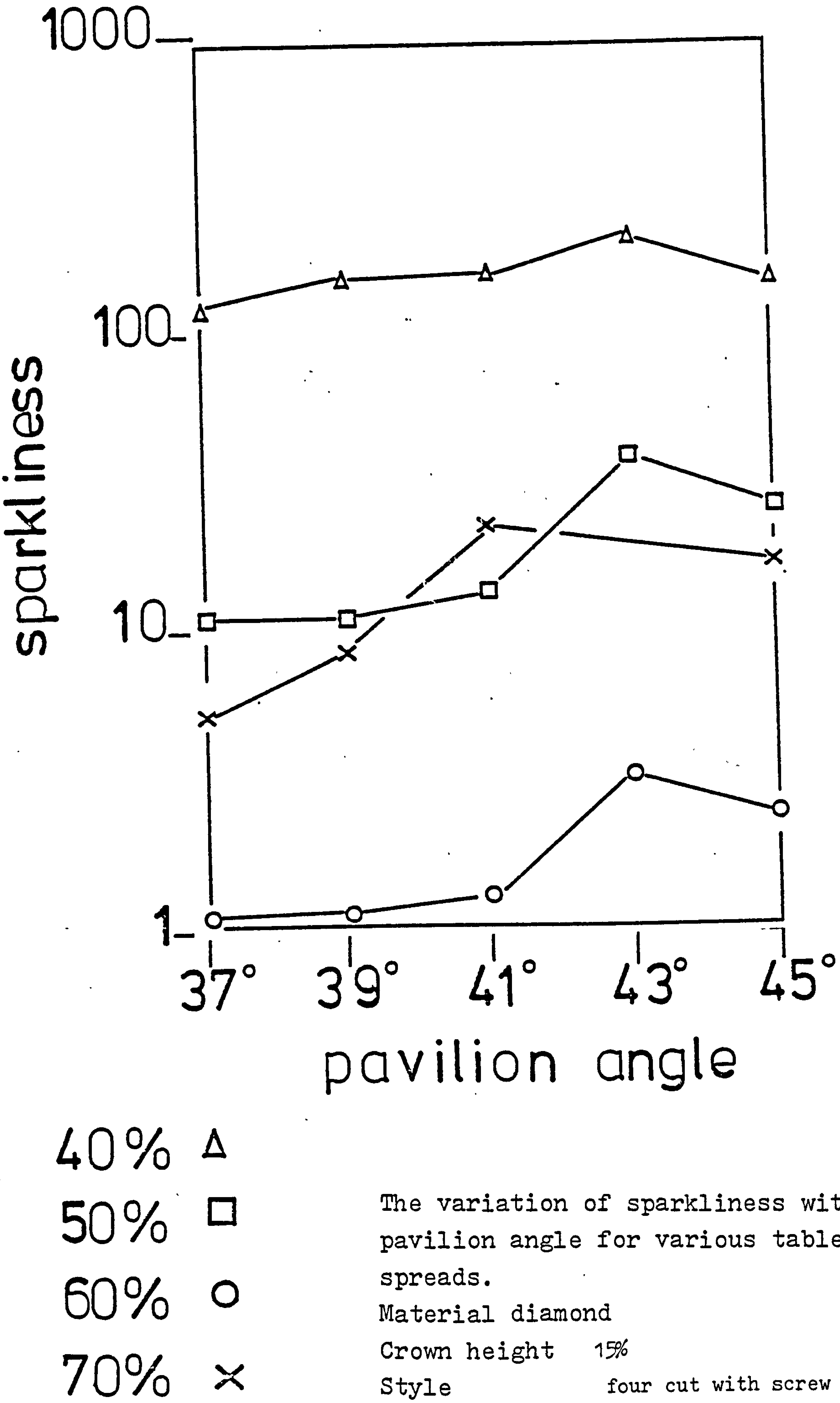


The variation of sparkliness with pavilion angle for various table spreads.

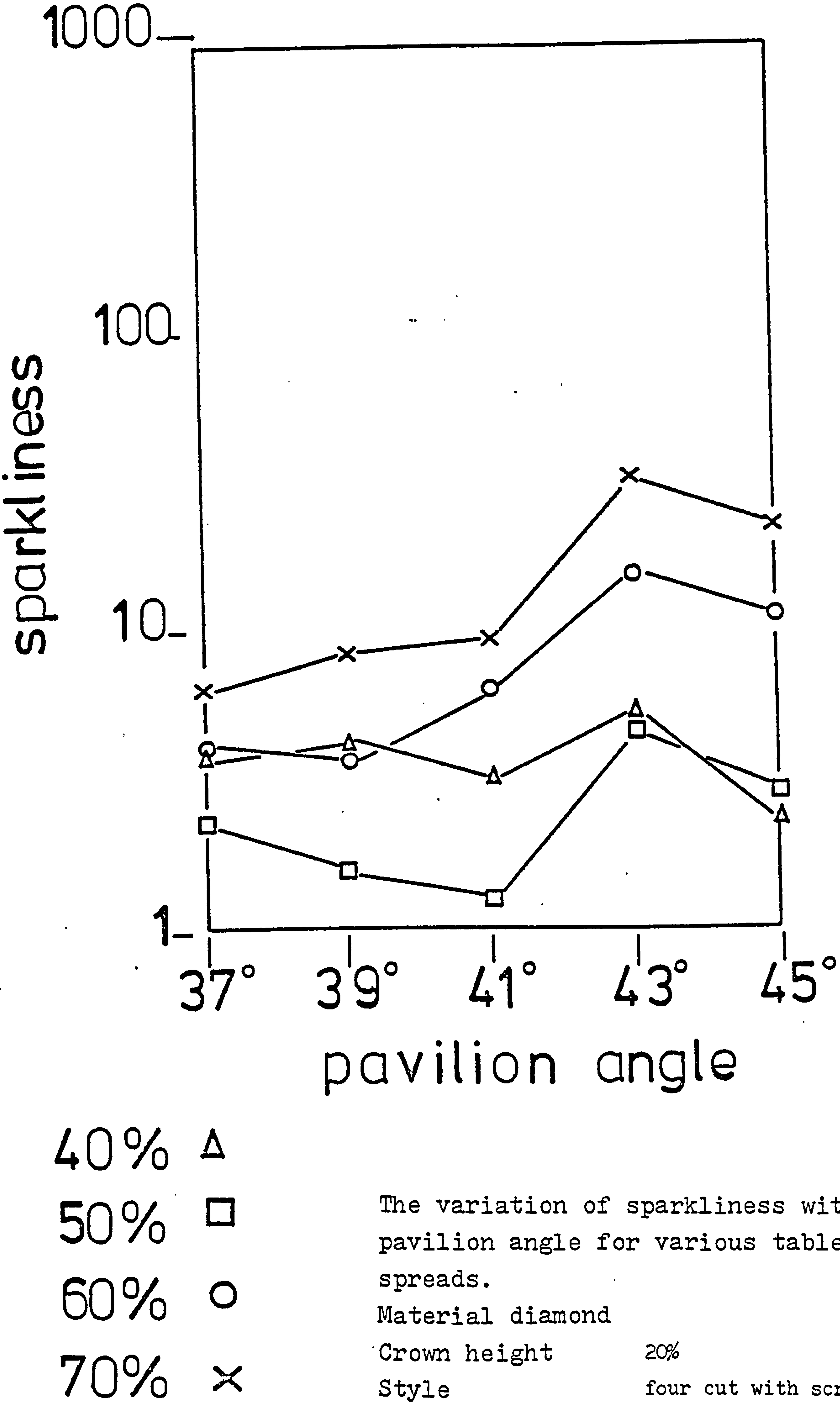
Material diamond

Crown height 10 %

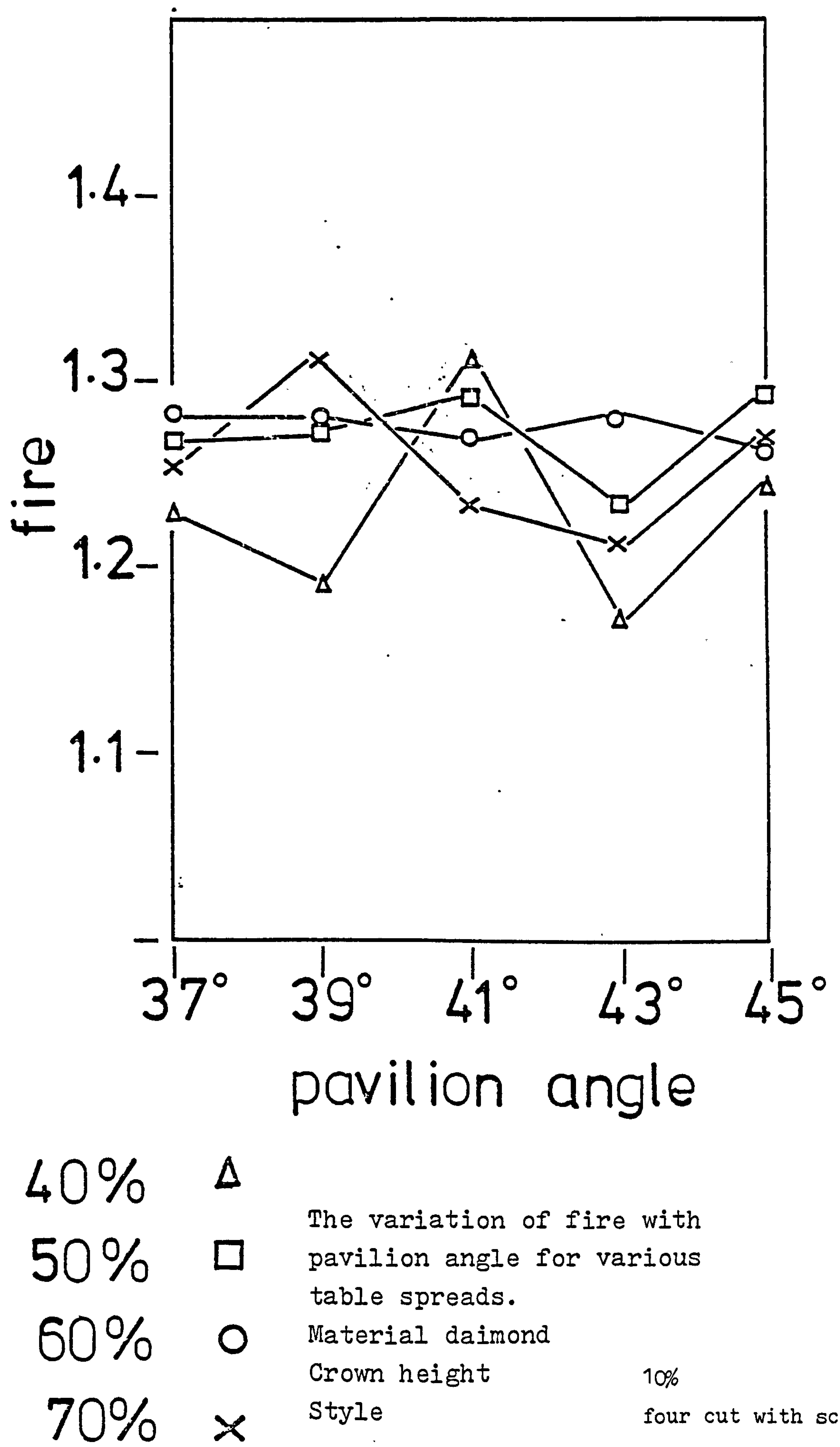
Style four cut with screw



The variation of sparkliness with pavilion angle for various table spreads.
Material diamond
Crown height 15%
Style four cut with screw



The variation of sparkliness with pavilion angle for various table spreads.
Material diamond
Crown height 20%
Style four cut with screw

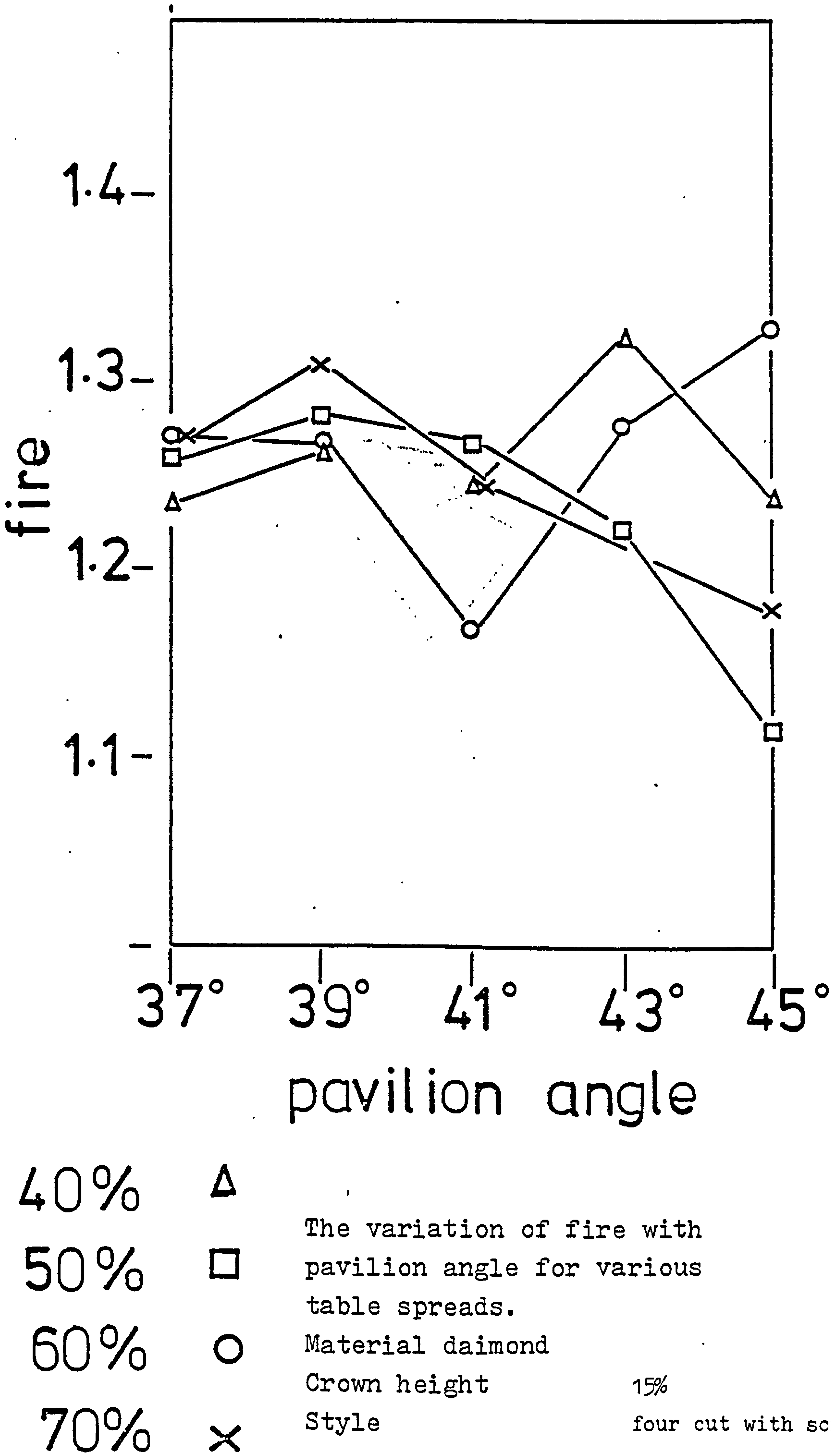


The variation of fire with pavilion angle for various table spreads.

Material daimond

Crown height 10%

Style four cut with screw

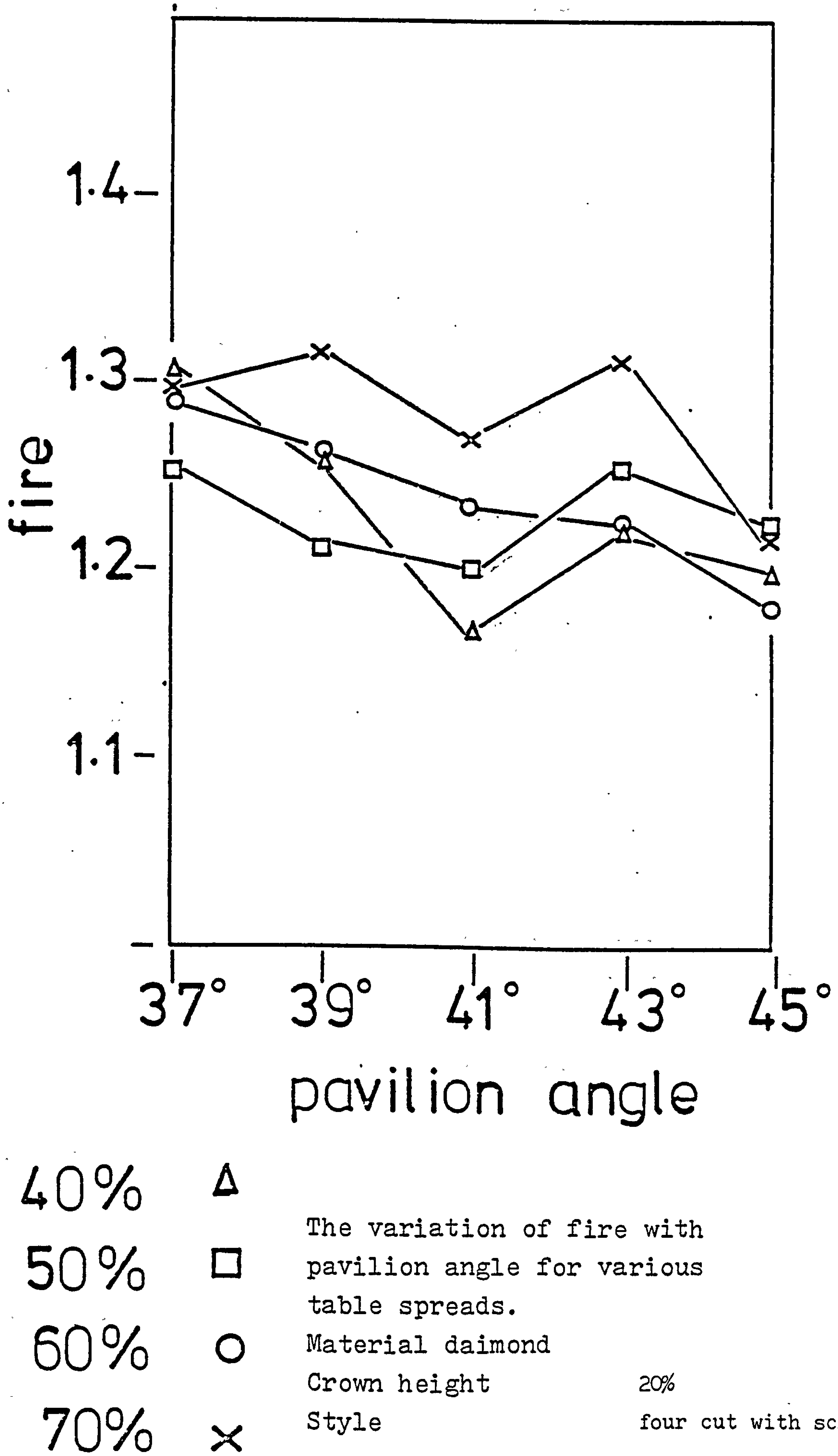


The variation of fire with
pavilion angle for various
table spreads.

Material daimond

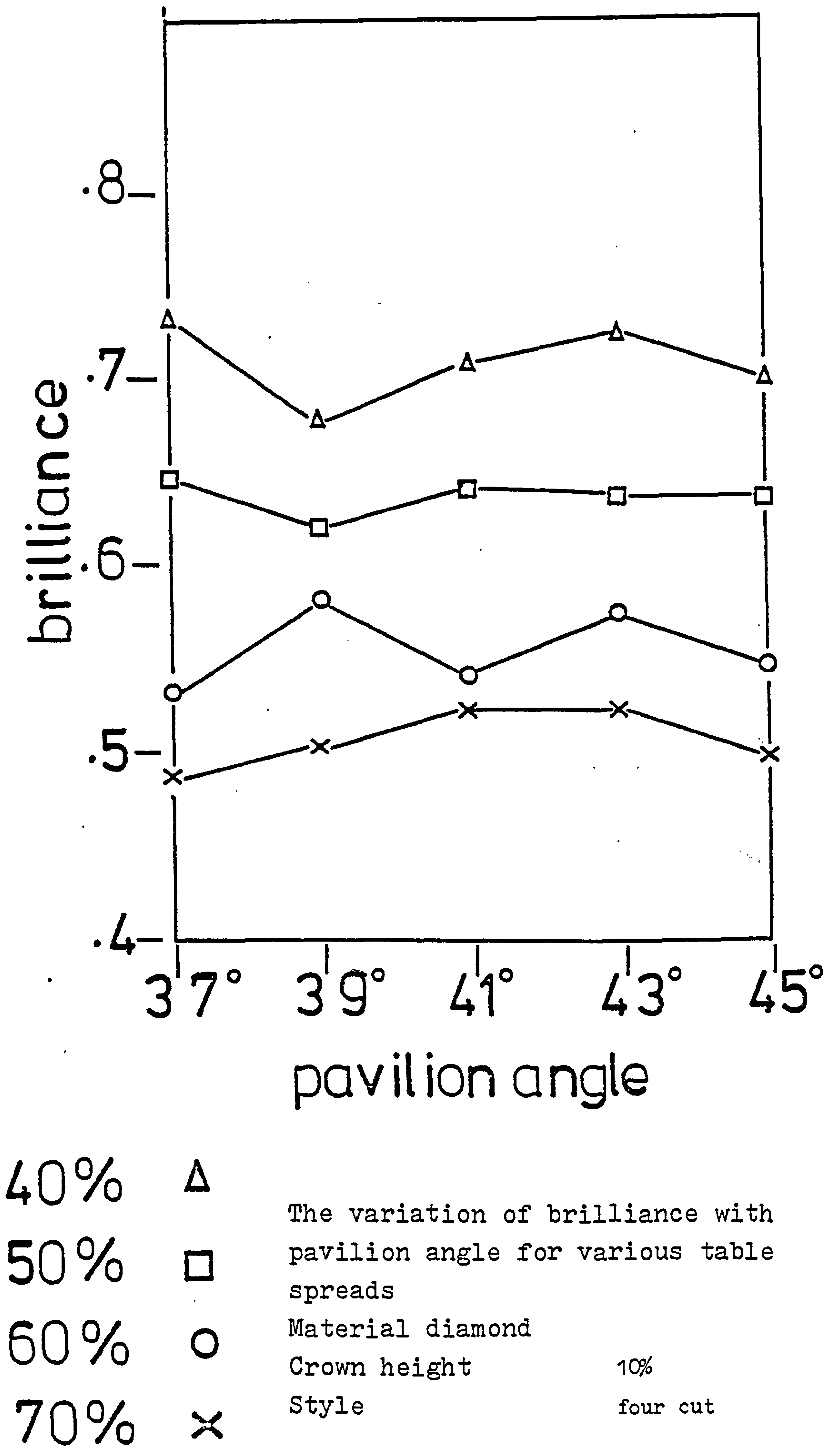
Crown height 15%

Style four cut with screw



The variation of fire with pavilion angle for various table spreads.

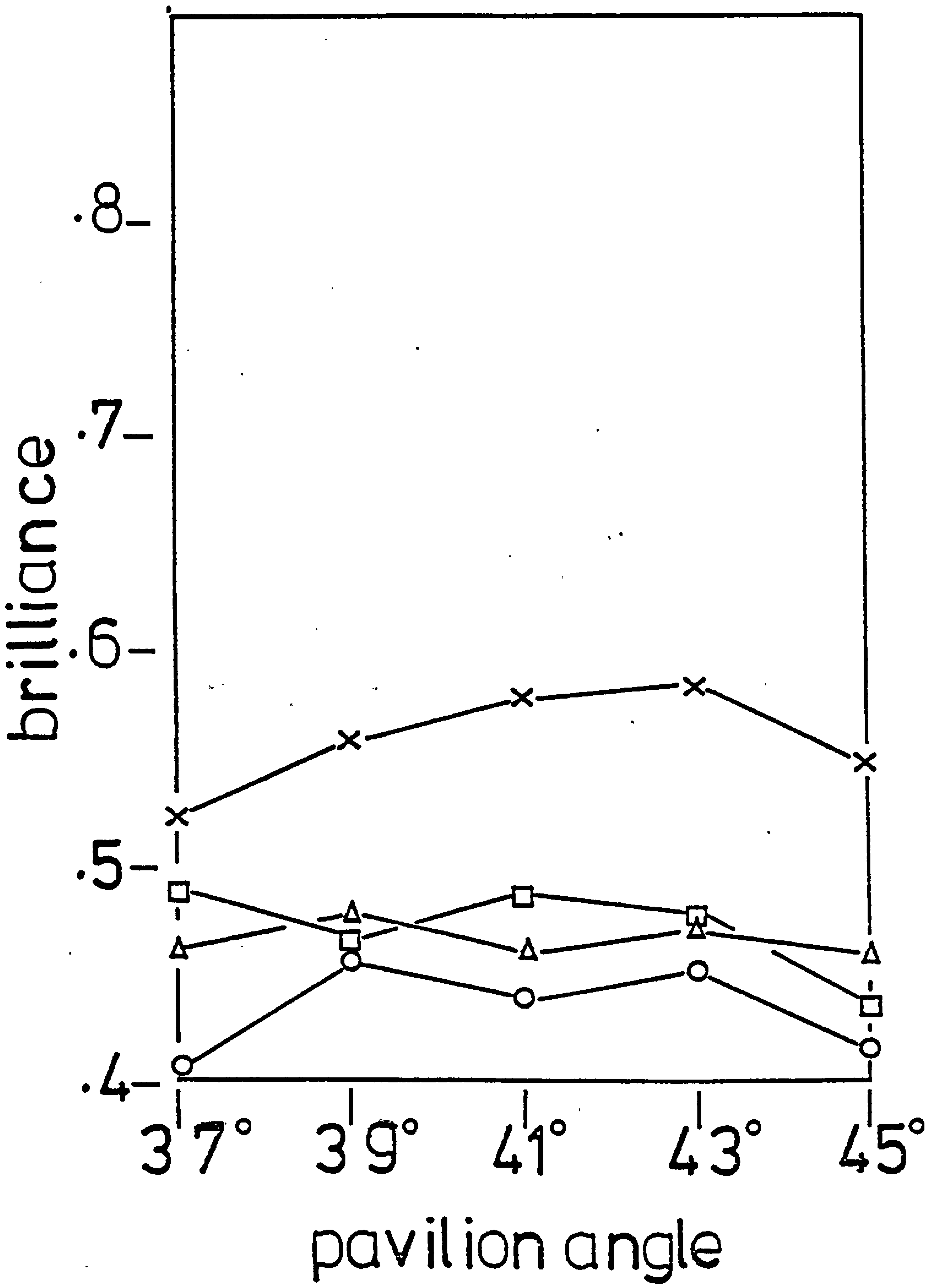
Material daimond	
Crown height	20%
Style	four cut with screw



The variation of brilliance with pavilion angle for various table spreads

Material diamond

Crown height	10%
Style	four cut



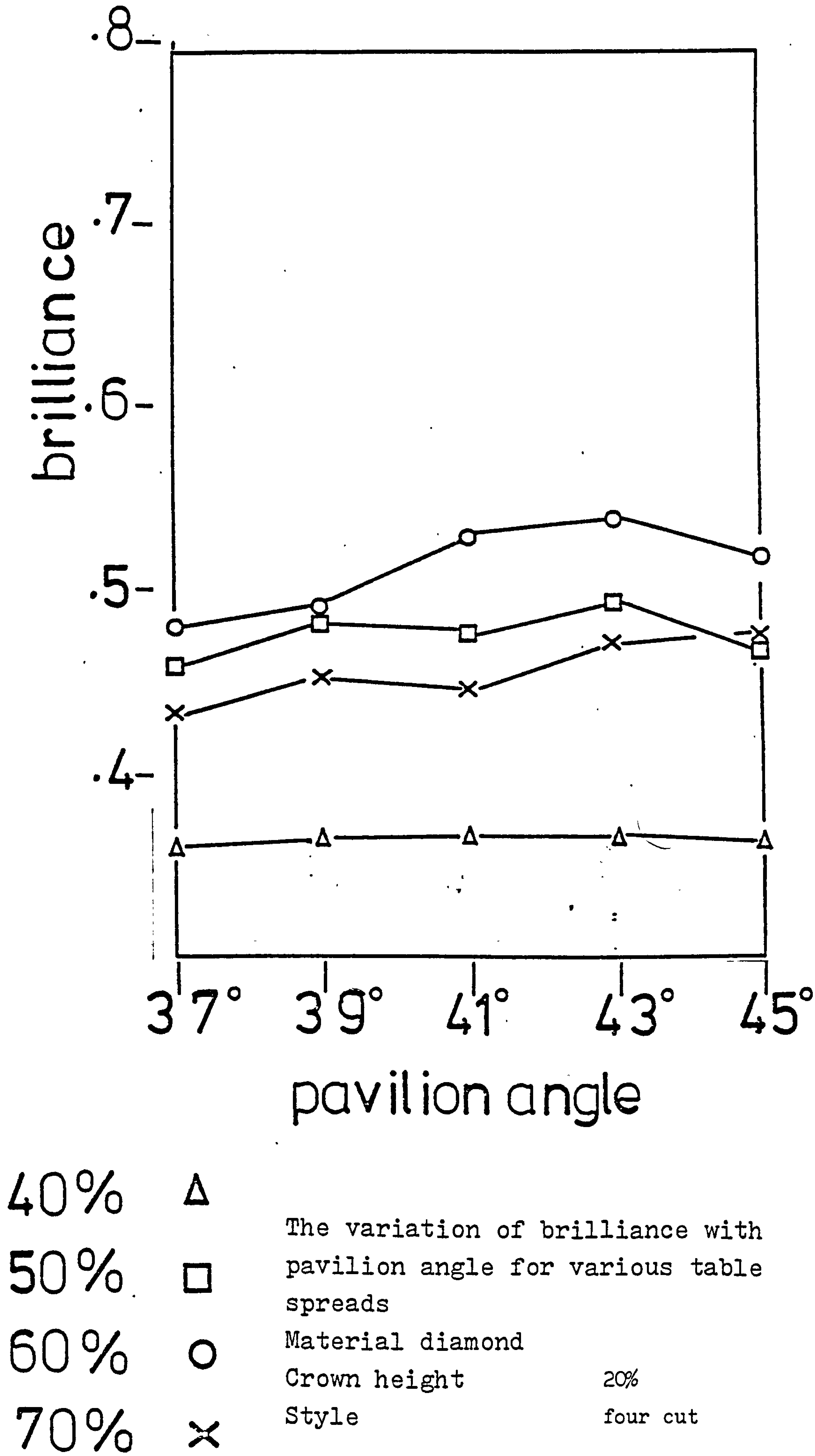
40% Δ
50% □
60% ○
70% ×

The variation of brilliance with pavilion angle for various table spreads

Material diamond

Crown height 15%

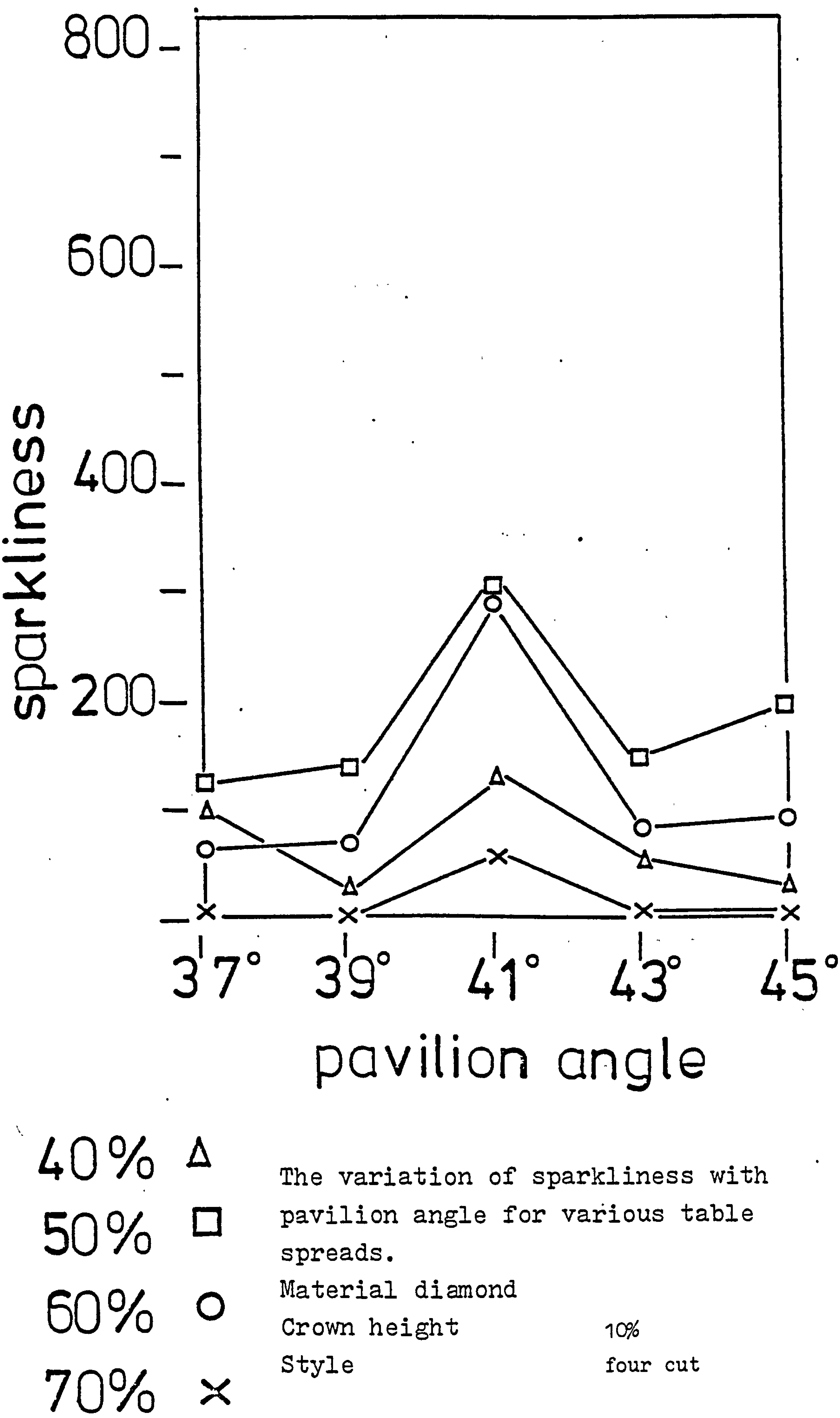
Style four cut



The variation of brilliance with pavilion angle for various table spreads

Material diamond

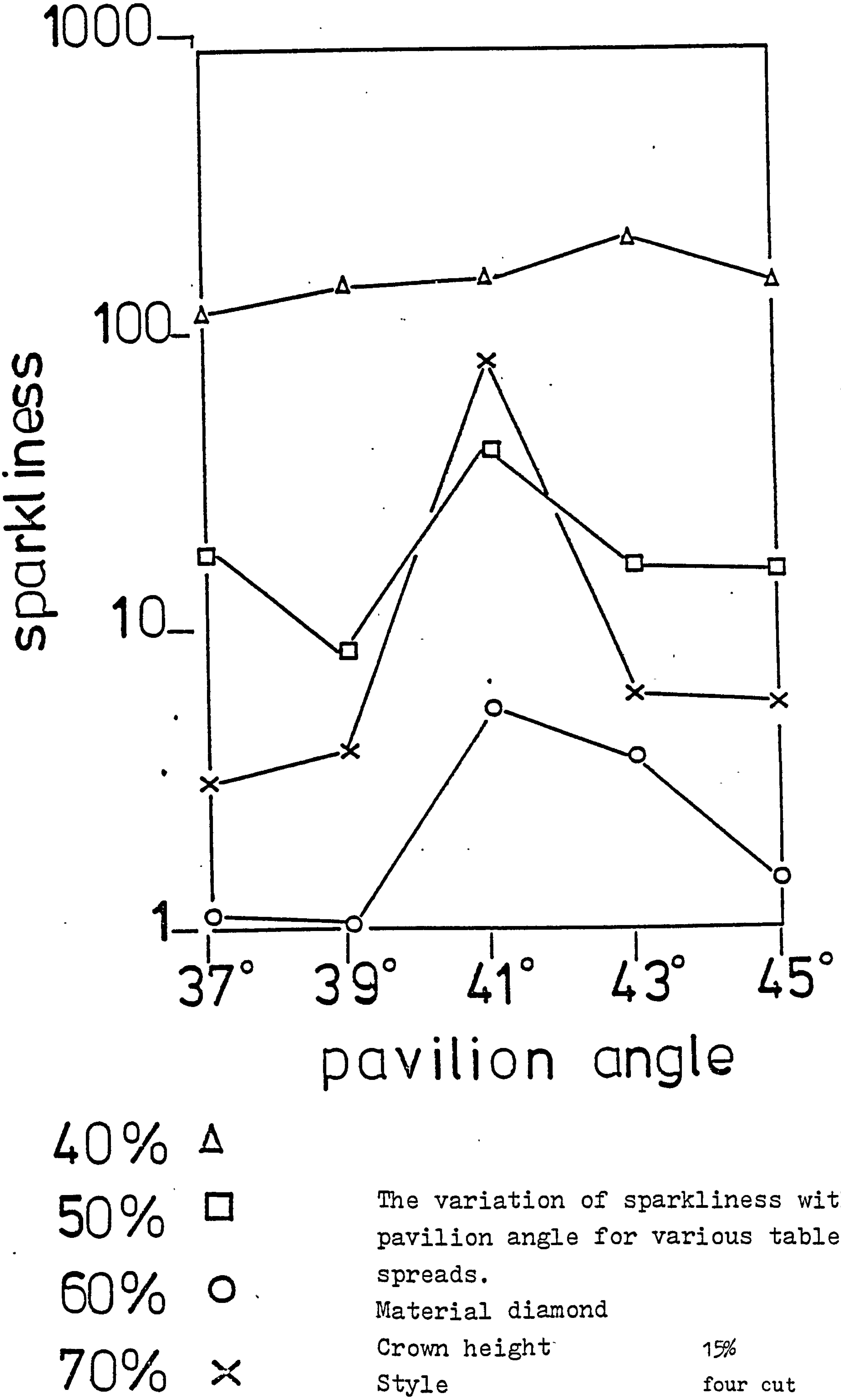
Crown height	20%
Style	four cut



The variation of sparkliness with pavilion angle for various table spreads.

Material diamond

Crown height	10%
Style	four cut

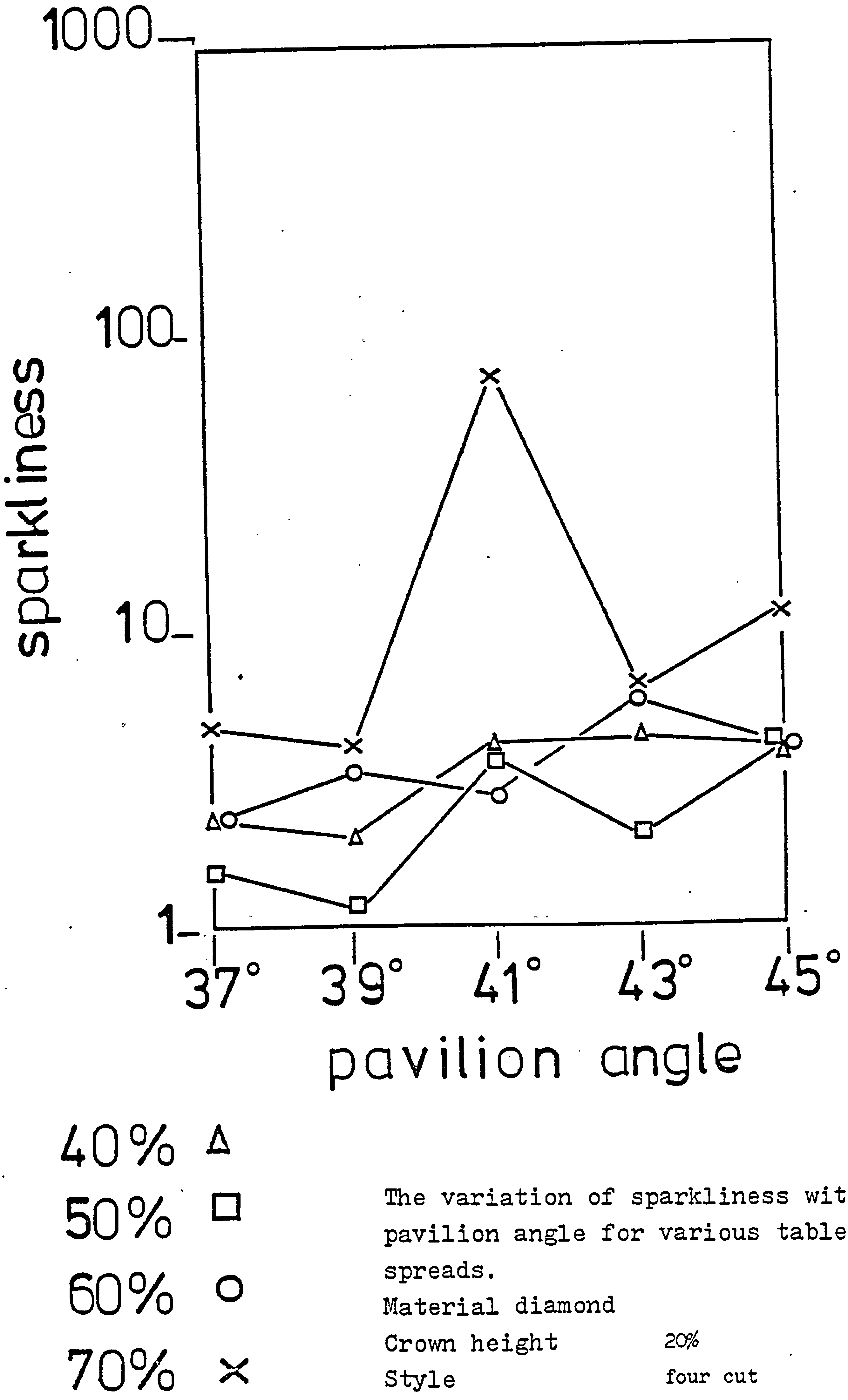


The variation of sparkliness with pavilion angle for various table spreads.

Material diamond

Crown height 15%

Style four cut

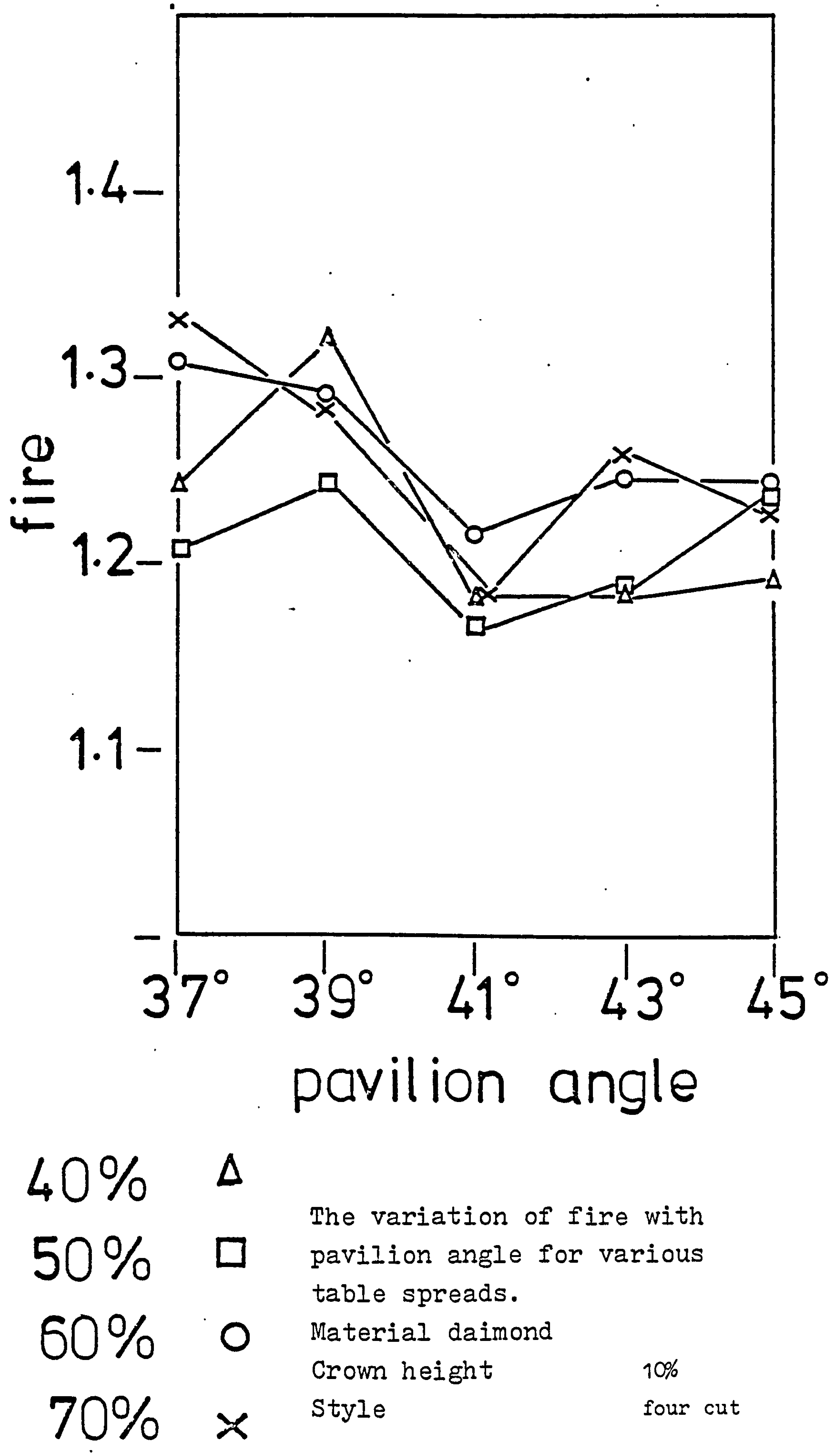


The variation of sparkliness with pavilion angle for various table spreads.

Material diamond

Crown height 20%

Style four cut

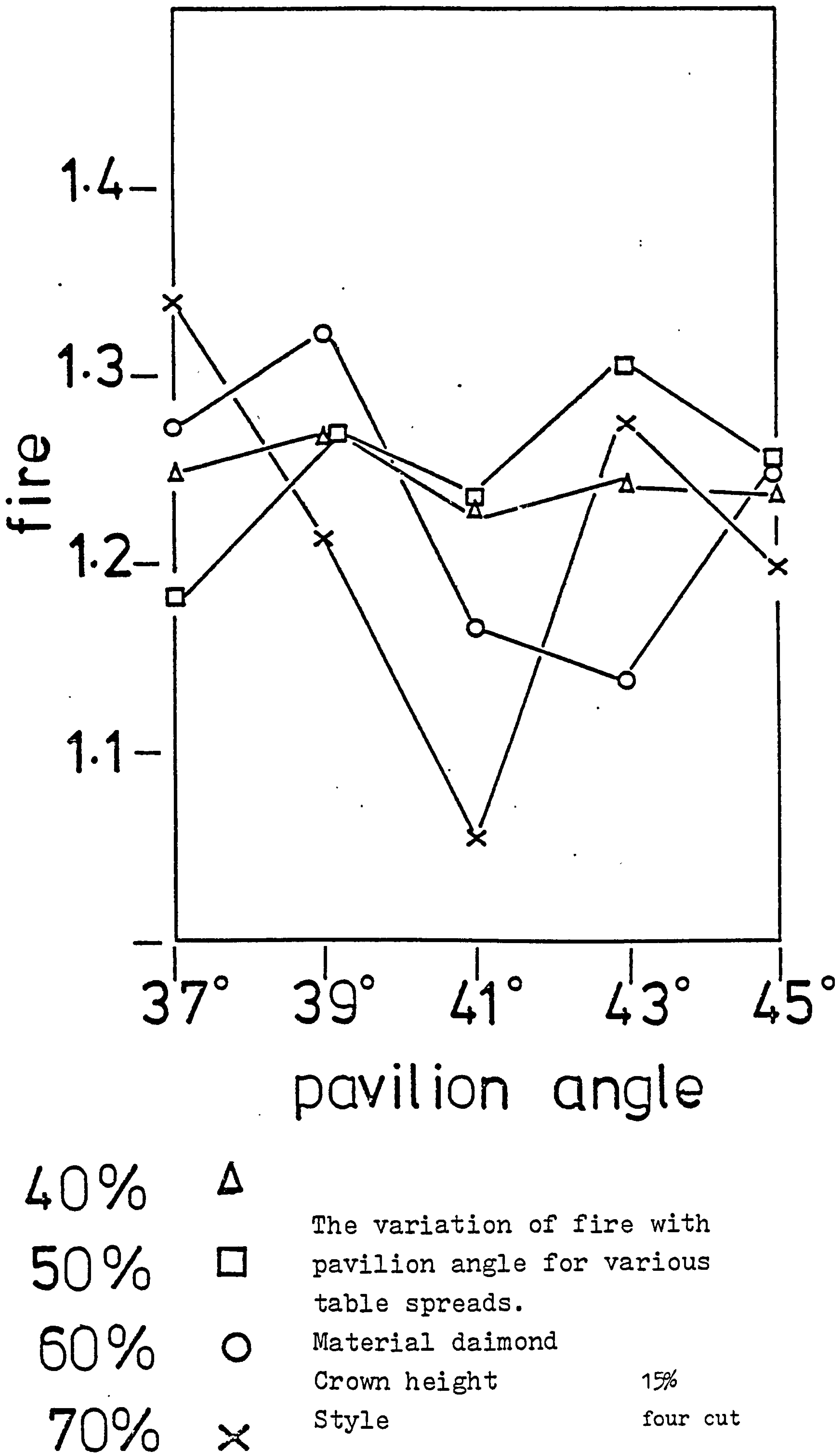


The variation of fire with pavilion angle for various table spreads.

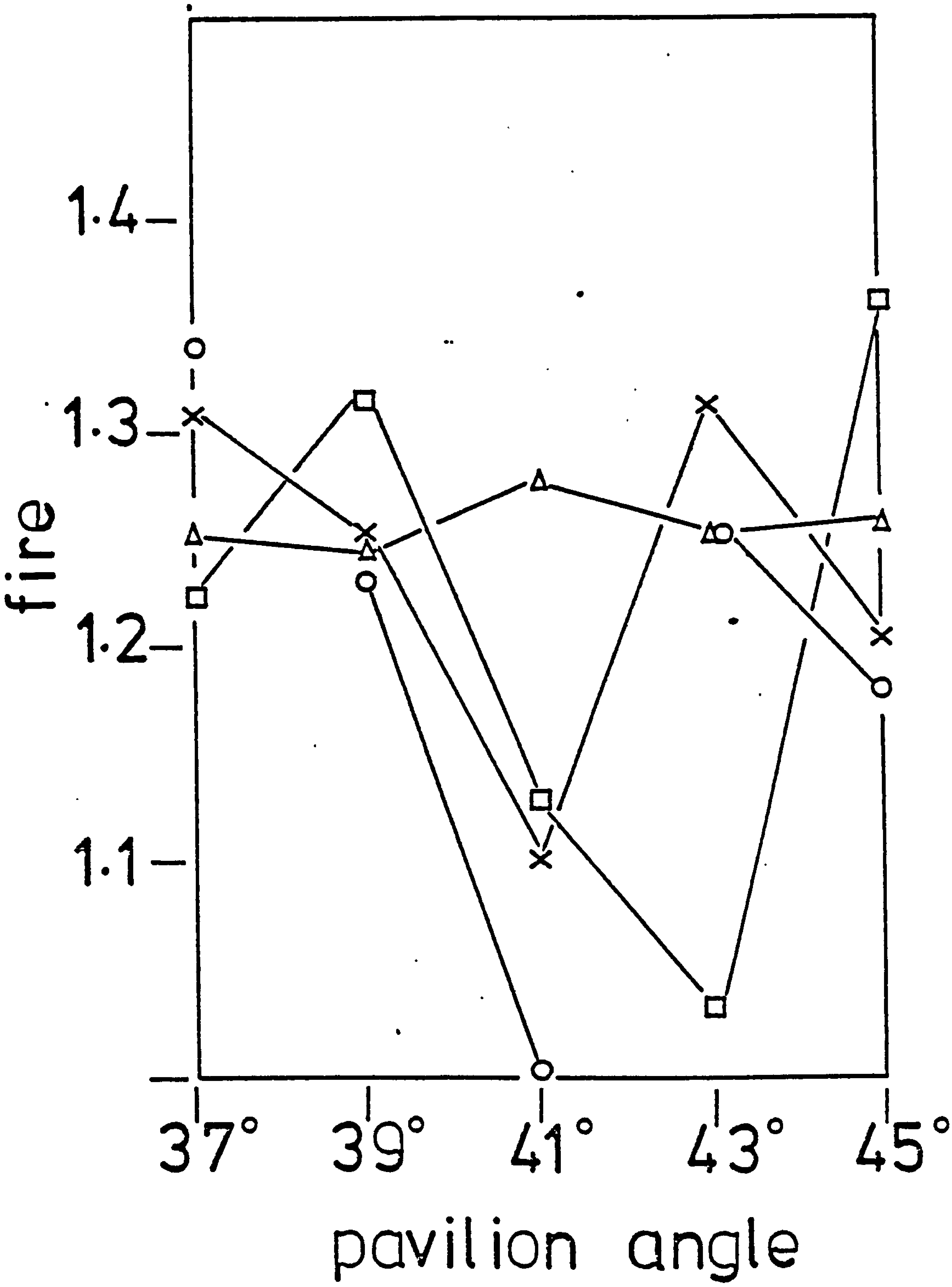
Material daimond

Crown height 10%

Style four cut



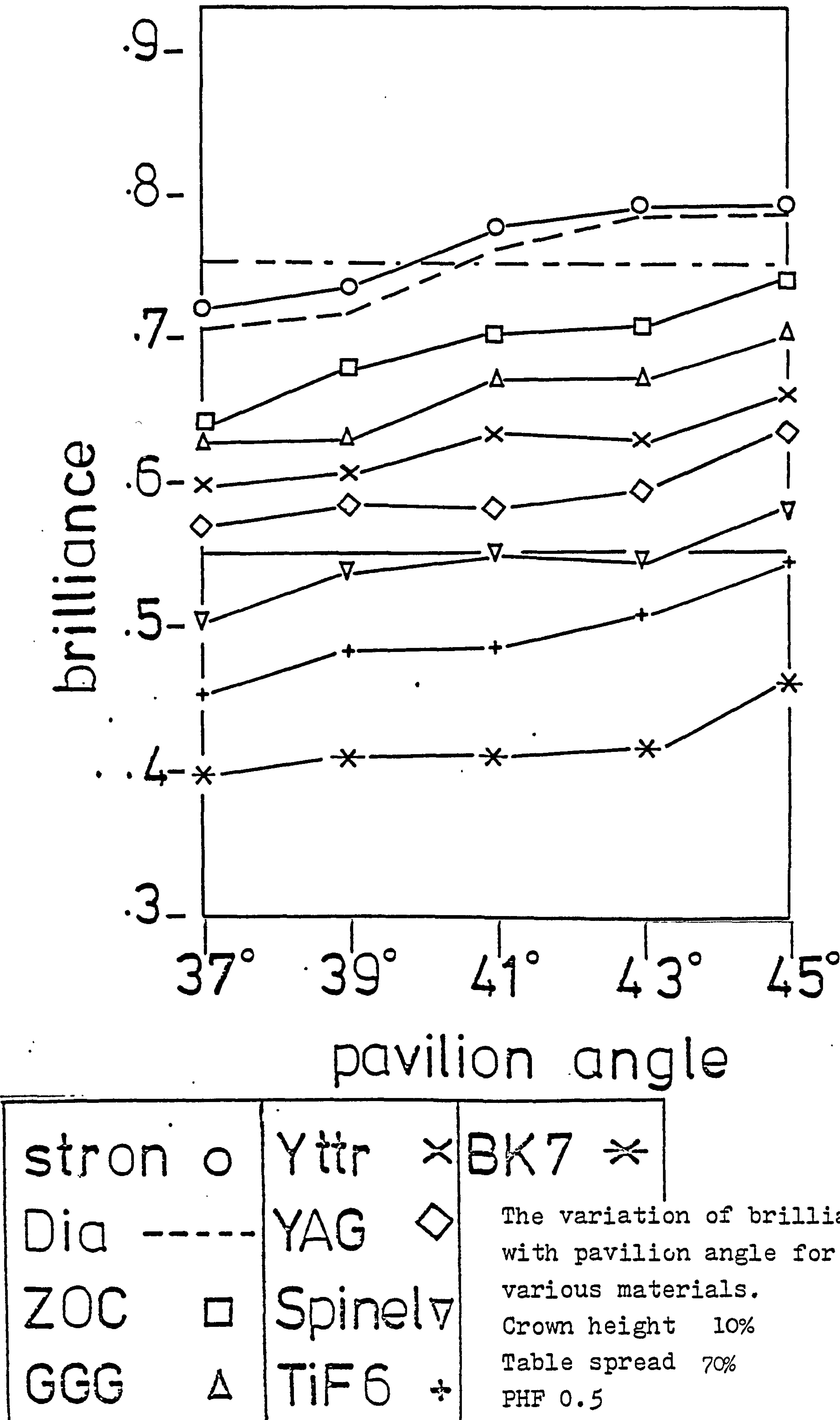
The variation of fire with pavilion angle for various table spreads.
Material daimond
Crown height 15%
Style four cut



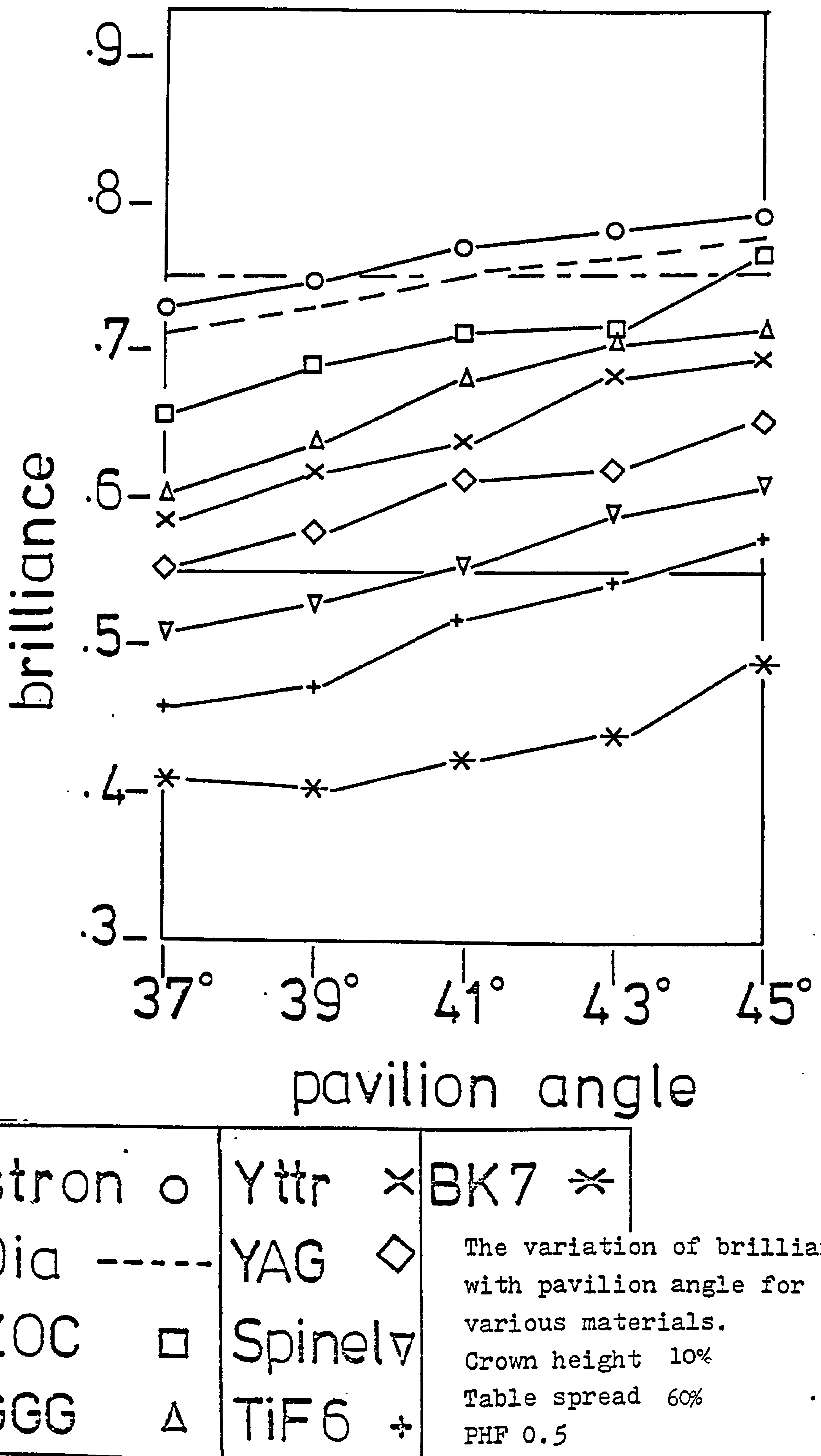
40% Δ
50% □
60% ○
70% ×

The variation of fire with pavilion angle for various table spreads.
Material daimond
Crown height 20%
Style four cut

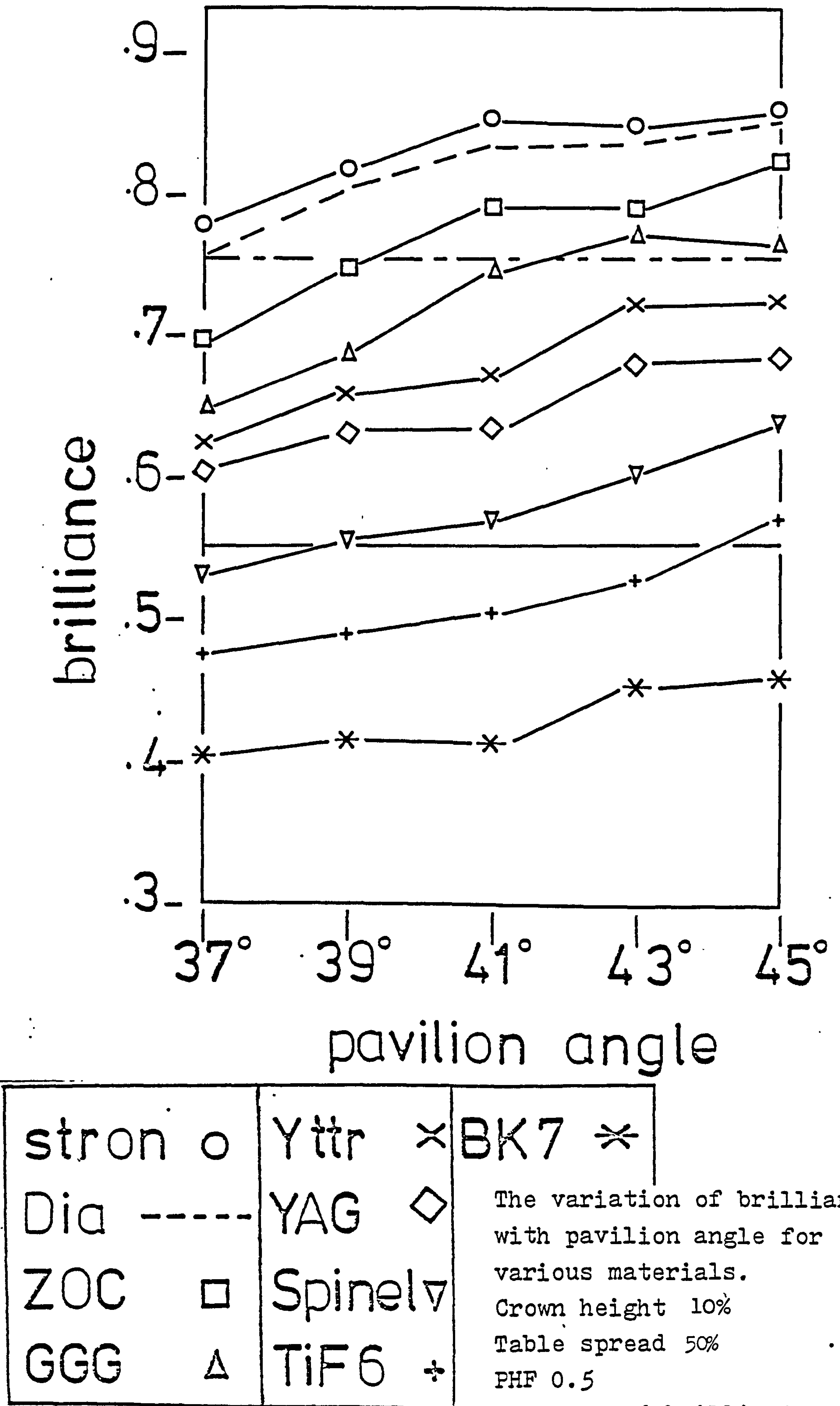
Appendix V The brilliance, sparkliness and fire of several diamond simulants



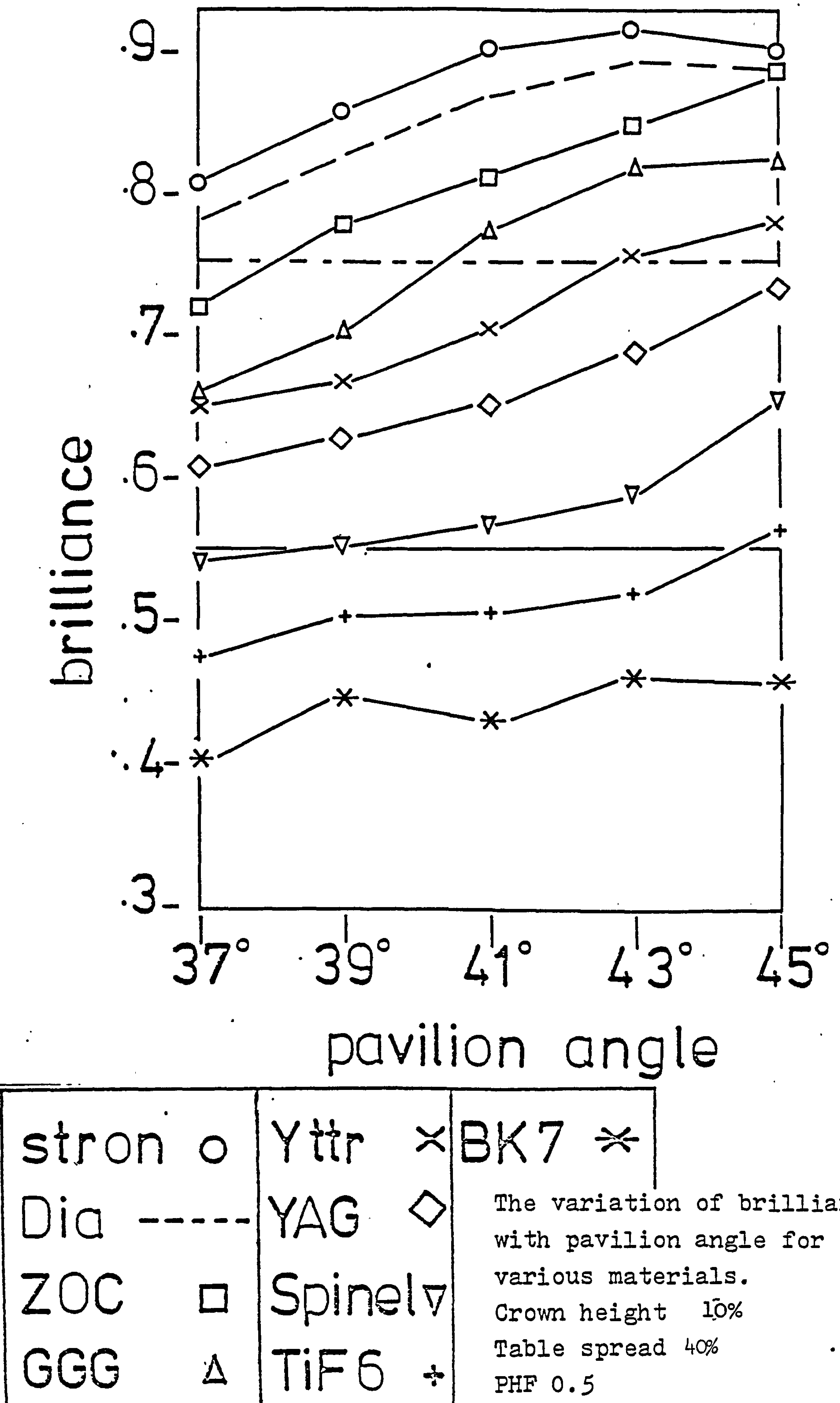
The variation of brilliance with pavilion angle for various materials.
Crown height 10%
Table spread 70%
PHF 0.5
Style round brilliant cut



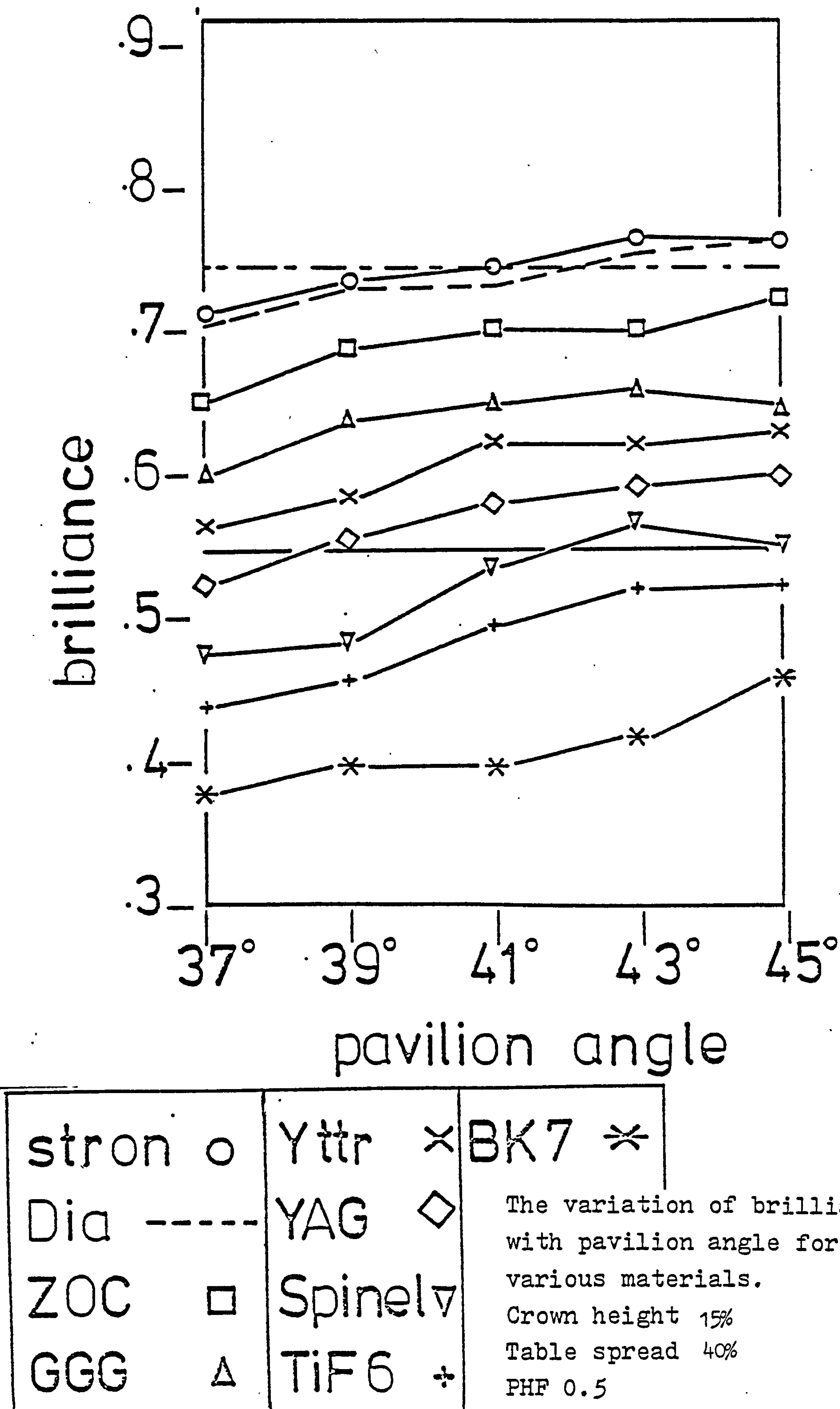
The variation of brilliance with pavilion angle for various materials.
Crown height 10%
Table spread 60%
PHF 0.5
Style round brilliant cut



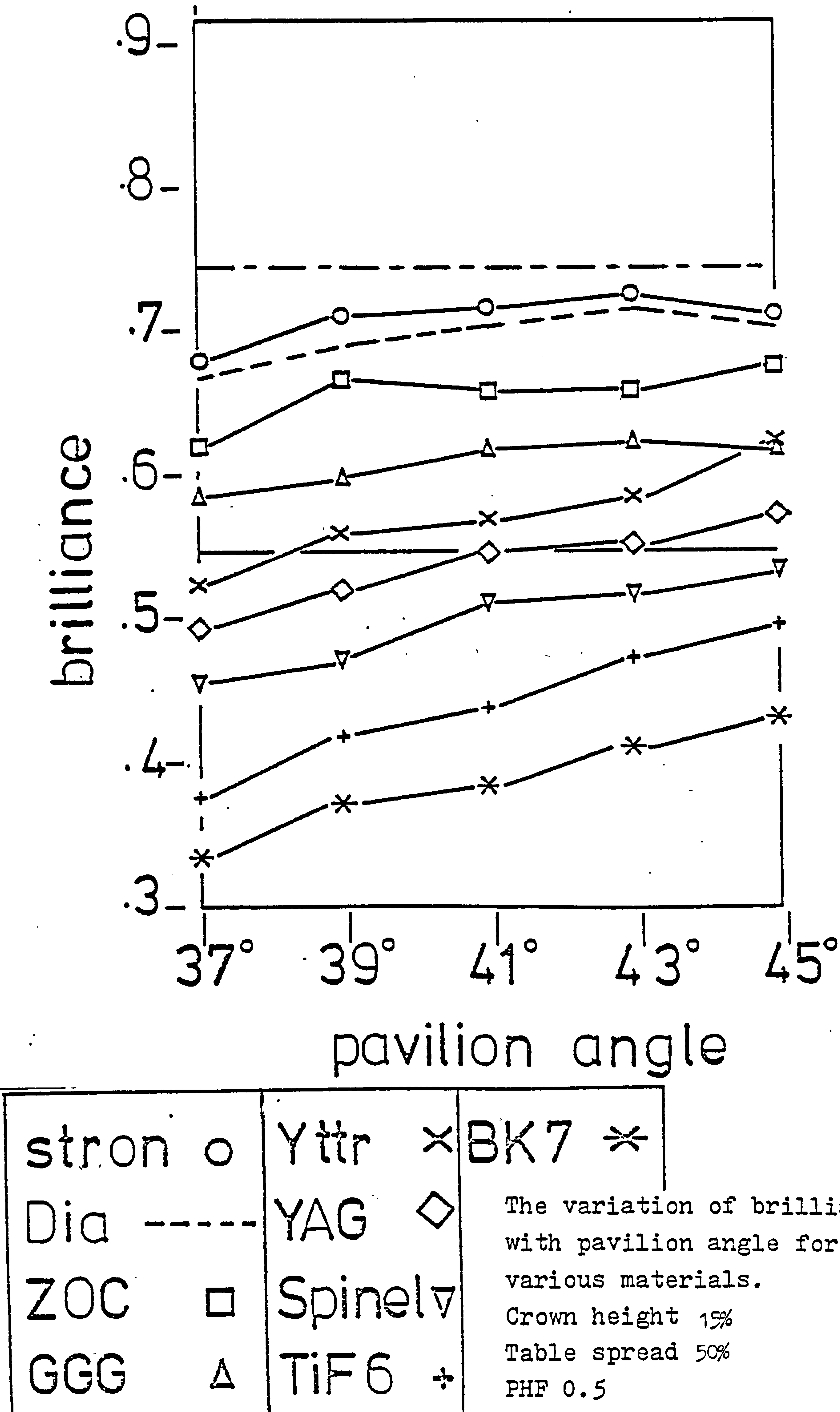
The variation of brilliance with pavilion angle for various materials.
Crown height 10%
Table spread 50%
PHF 0.5
Style round brilliant cut



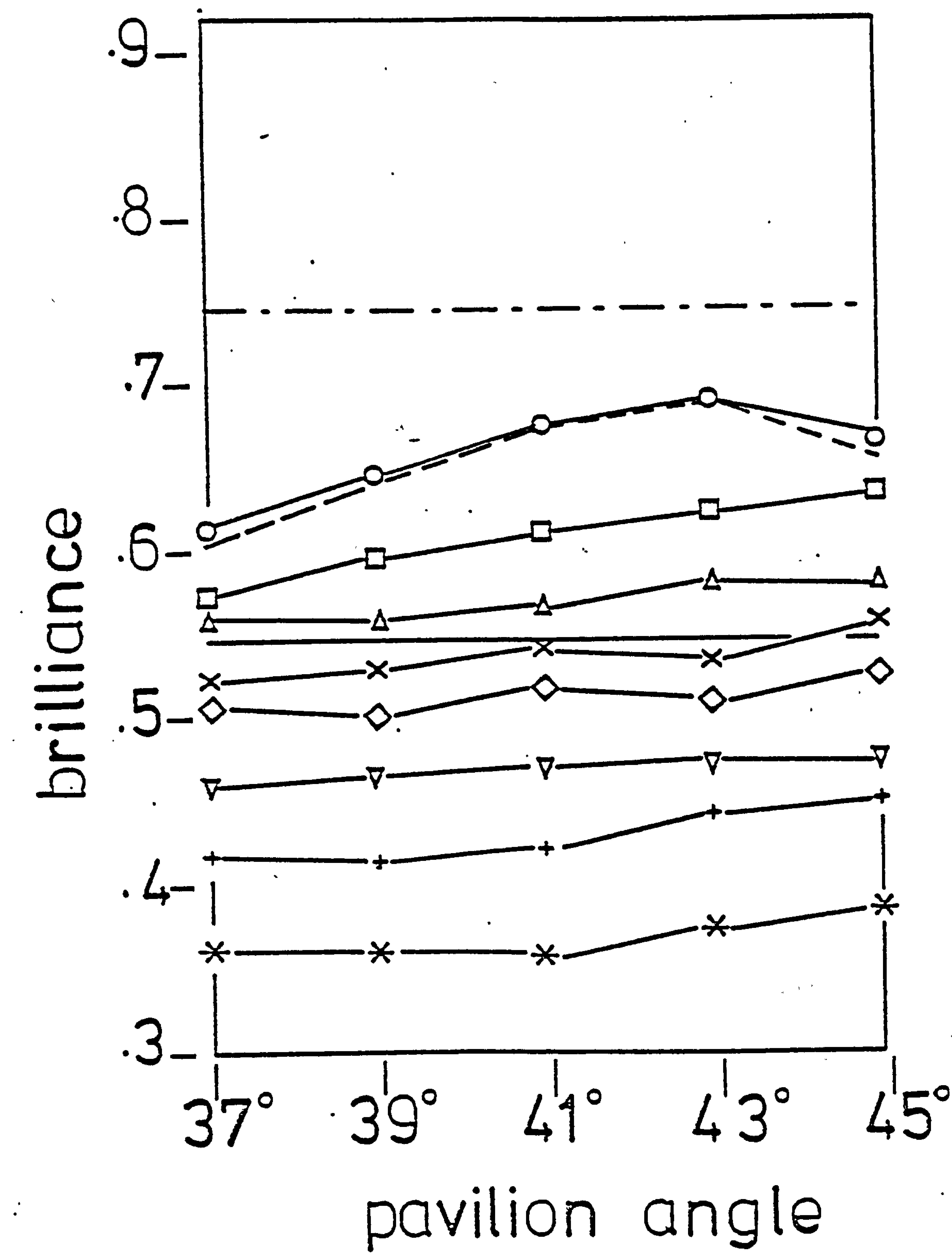
The variation of brilliance
with pavilion angle for
various materials.
Crown height 10%
Table spread 40%
PHF 0.5
Style round brilliant cut



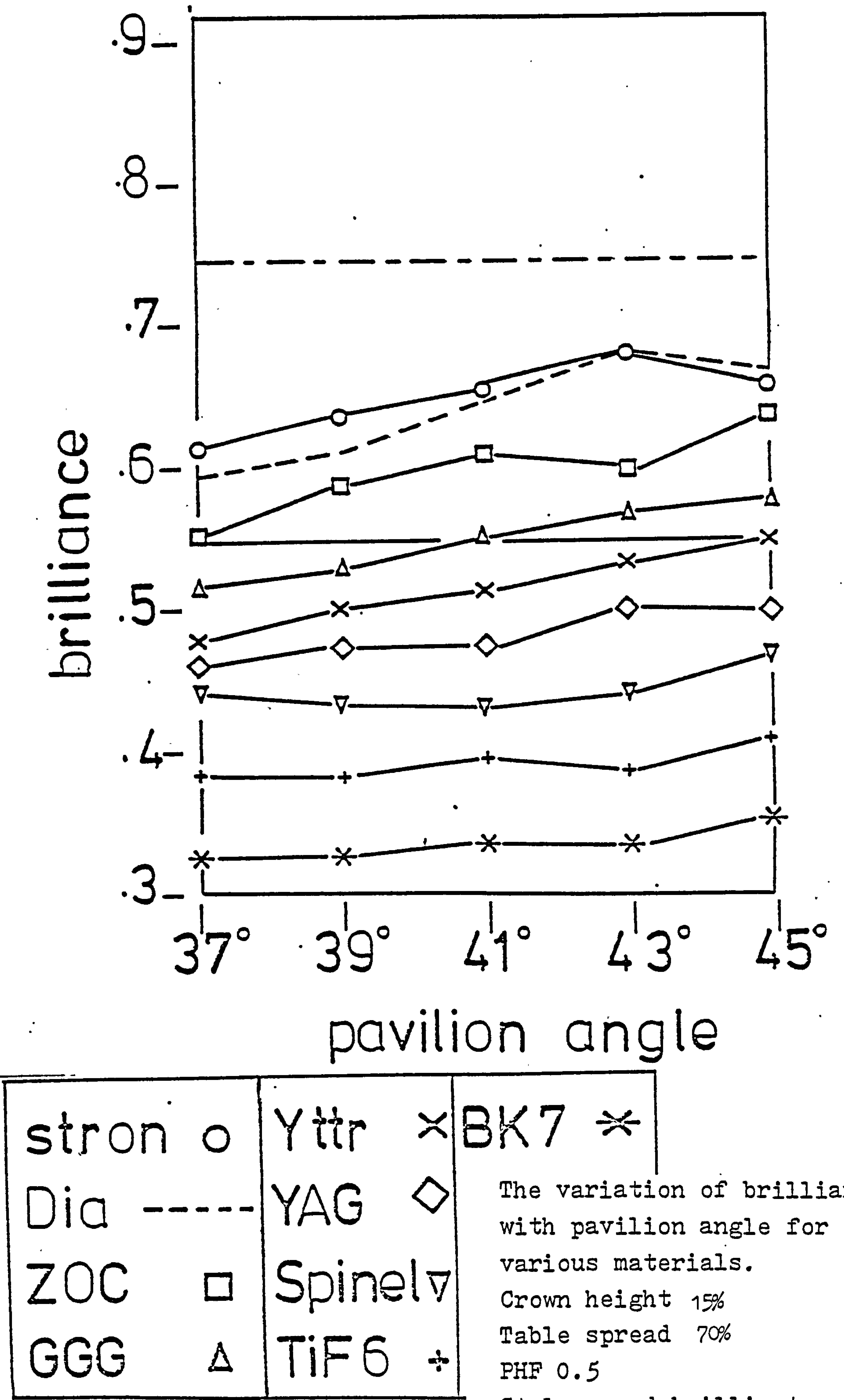
The variation of brilliance with pavilion angle for various materials.
Crown height 15%
Table spread 40%
PHF 0.5
Style round brilliant cut



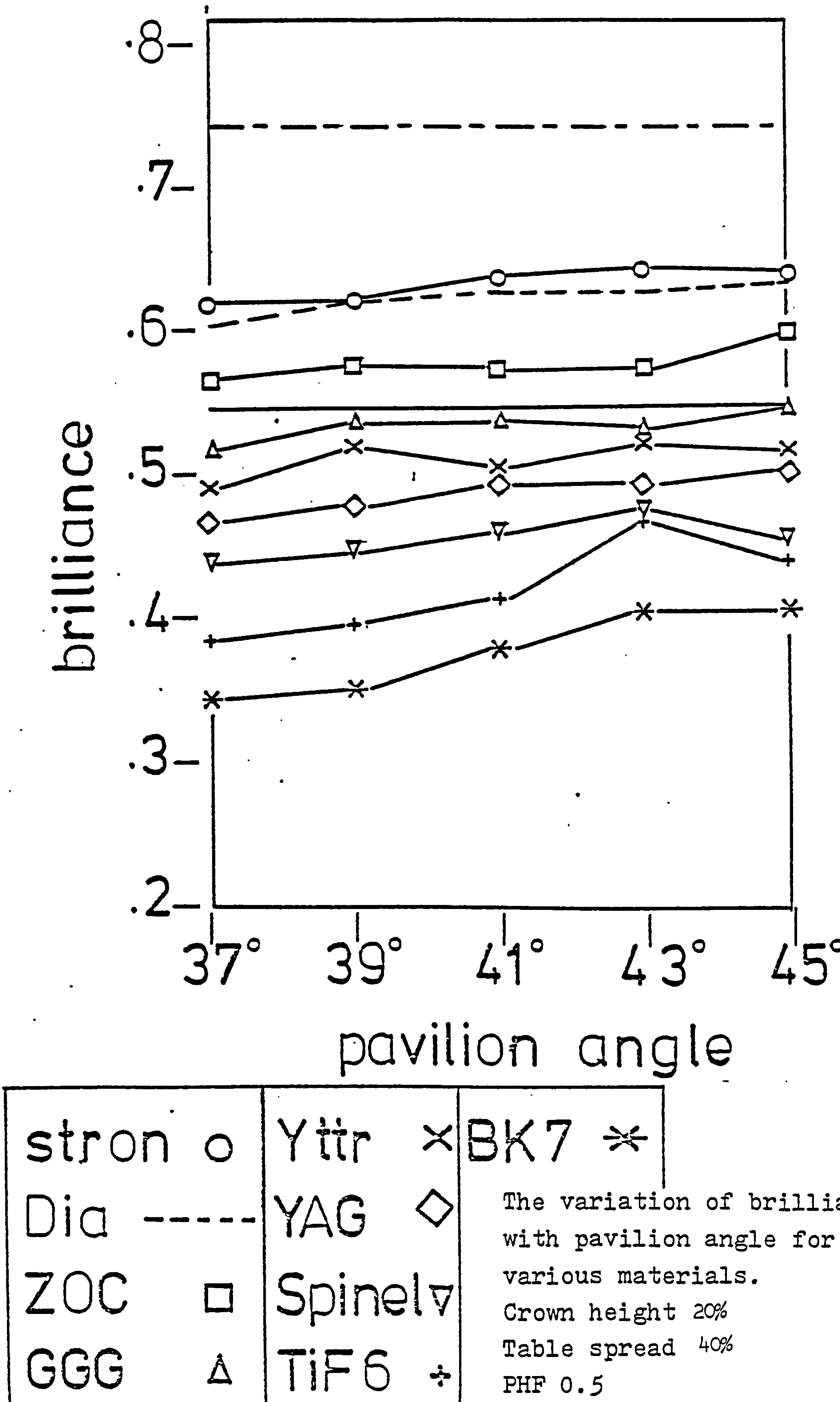
The variation of brilliance with pavilion angle for various materials.
Crown height 15%
Table spread 50%
PHF 0.5
Style round brilliant cut



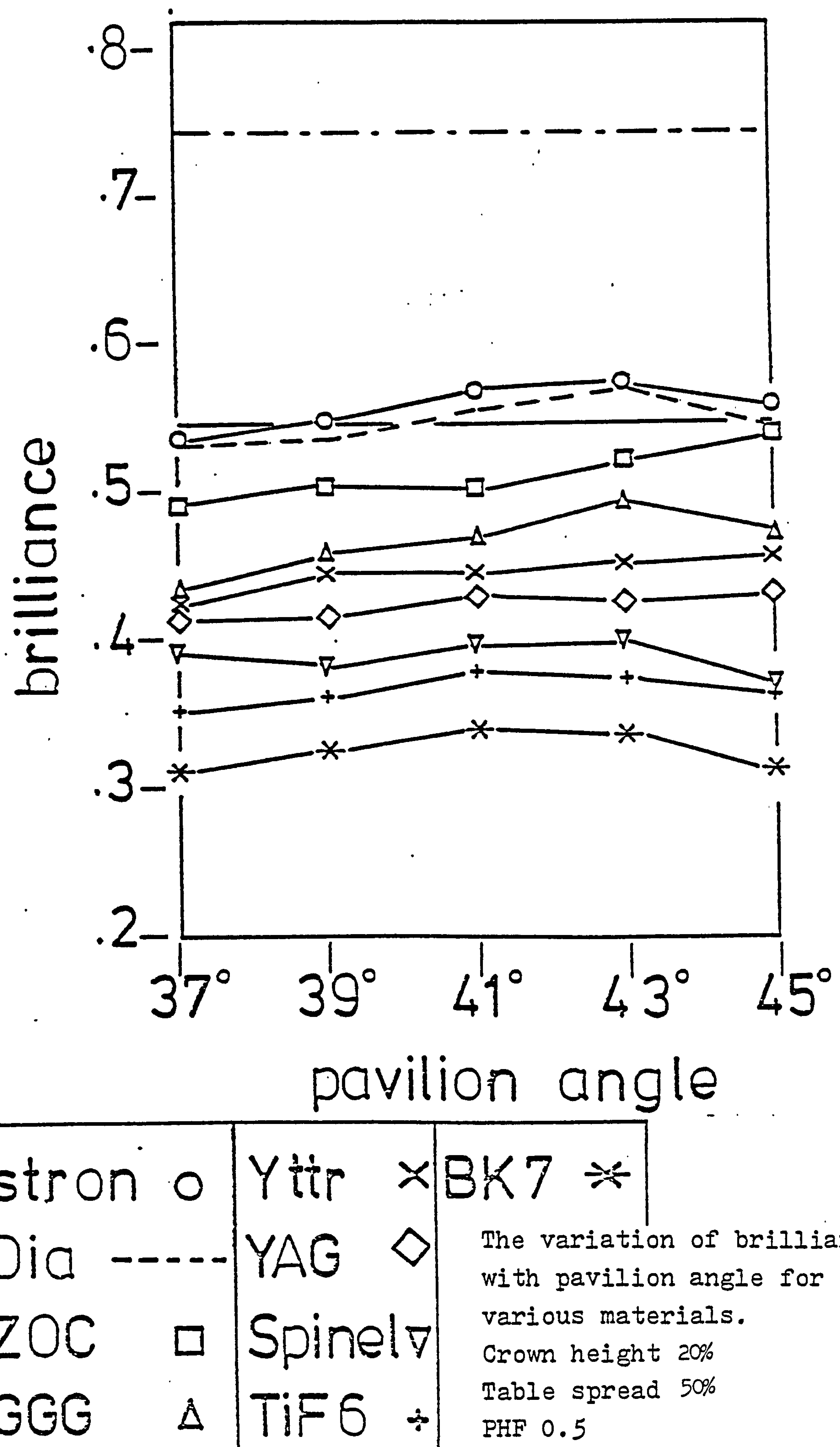
The variation of brilliance with pavilion angle for various materials.
Crown height 15%
Table spread 60%
PHF 0.5
Style round brilliant cut



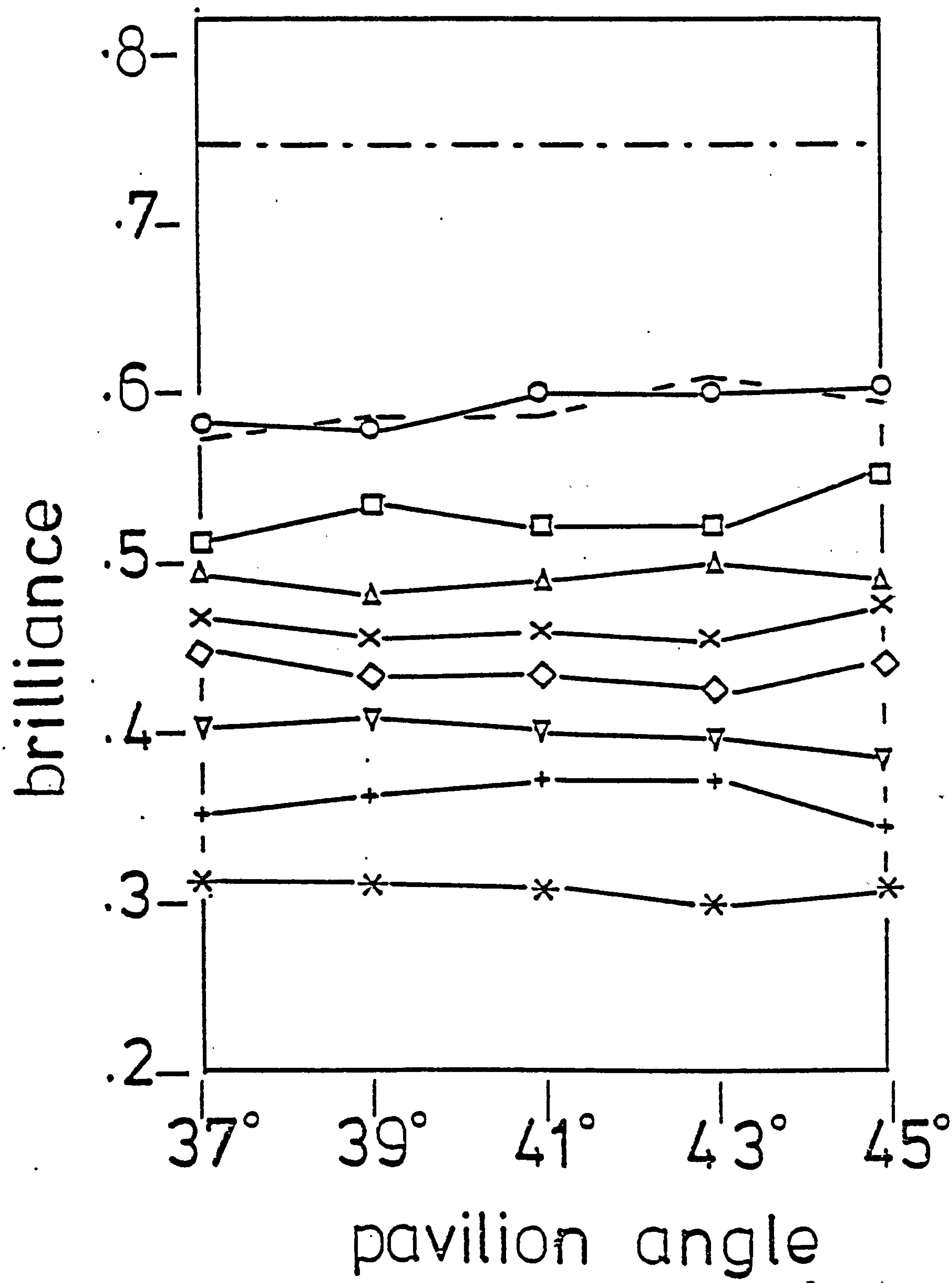
The variation of brilliance with pavilion angle for various materials.
Crown height 15%
Table spread 70%
PHF 0.5
Style round brilliant cut



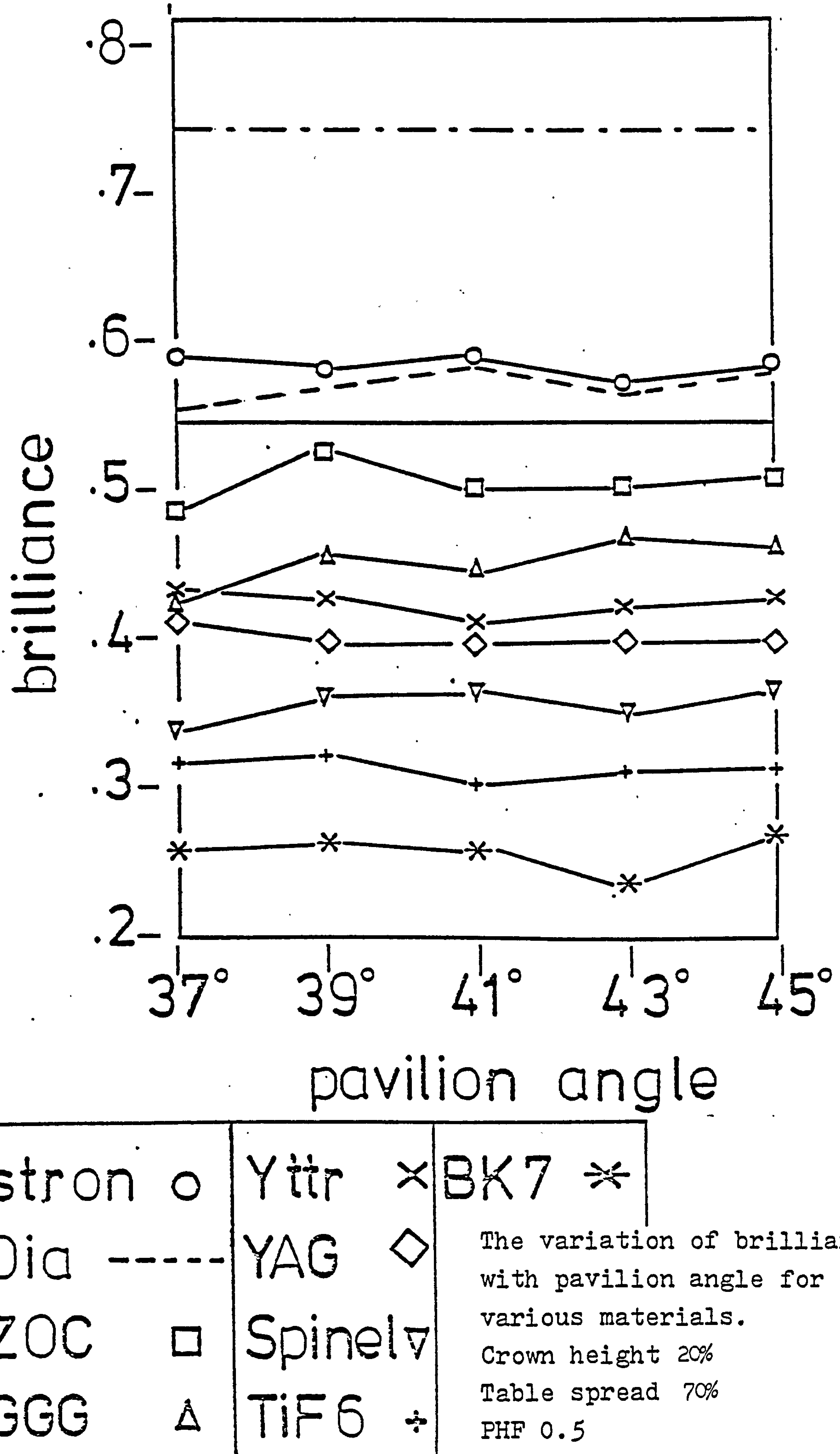
The variation of brilliance with pavilion angle for various materials.
Crown height 20%
Table spread 40%
PHF 0.5
Style round brilliant cut



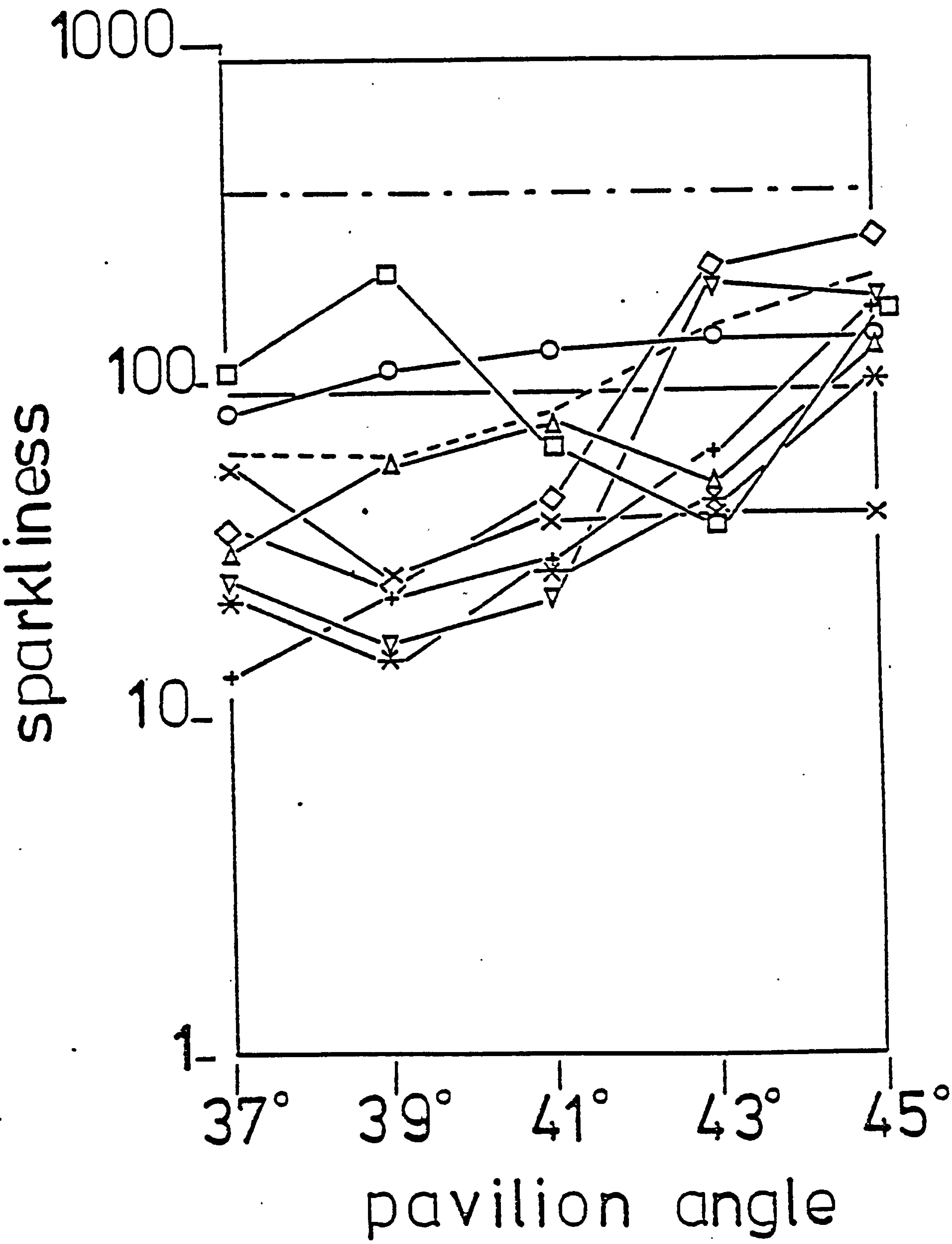
The variation of brilliance with pavilion angle for various materials.
Crown height 20%
Table spread 50%
PHF 0.5
Style round brilliant cut



The variation of brilliance
with pavilion angle for
various materials.
Crown height 20%
Table spread 60%
PHF 0.5
Style round brilliant cut



The variation of brilliance with pavilion angle for various materials.
Crown height 20%
Table spread 70%
PHF 0.5
Style round brilliant cut



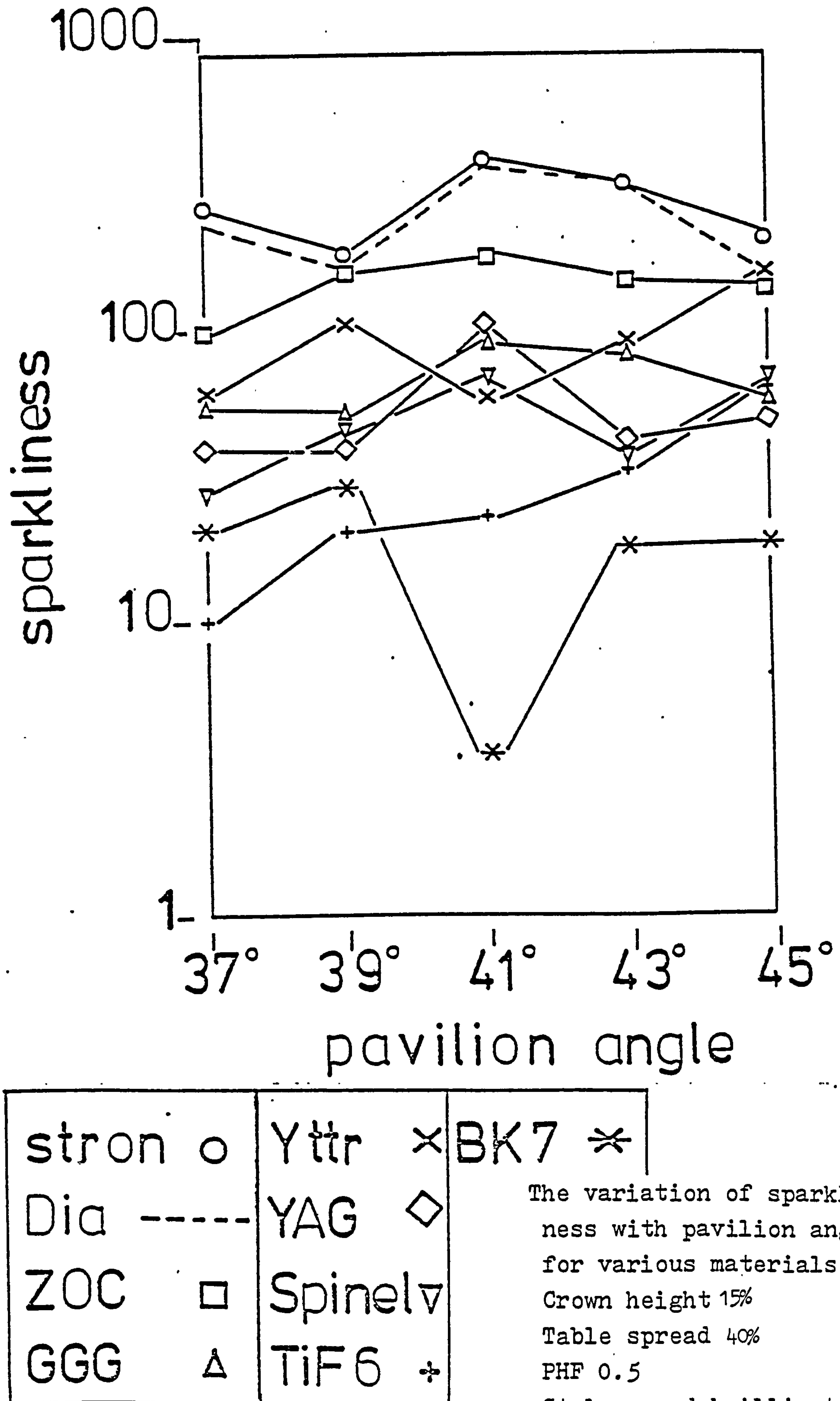
stron	○	Yttr	×	BK7	✳
Dia	-----	YAG	◇		
ZOC	□	Spinel	▽		
GGG	△	TiF6	+		

The variation of sparkliness with pavilion angle for various materials
Crown height 10%
Table spread 40%
PHF 0.5
Style round brilliant cut

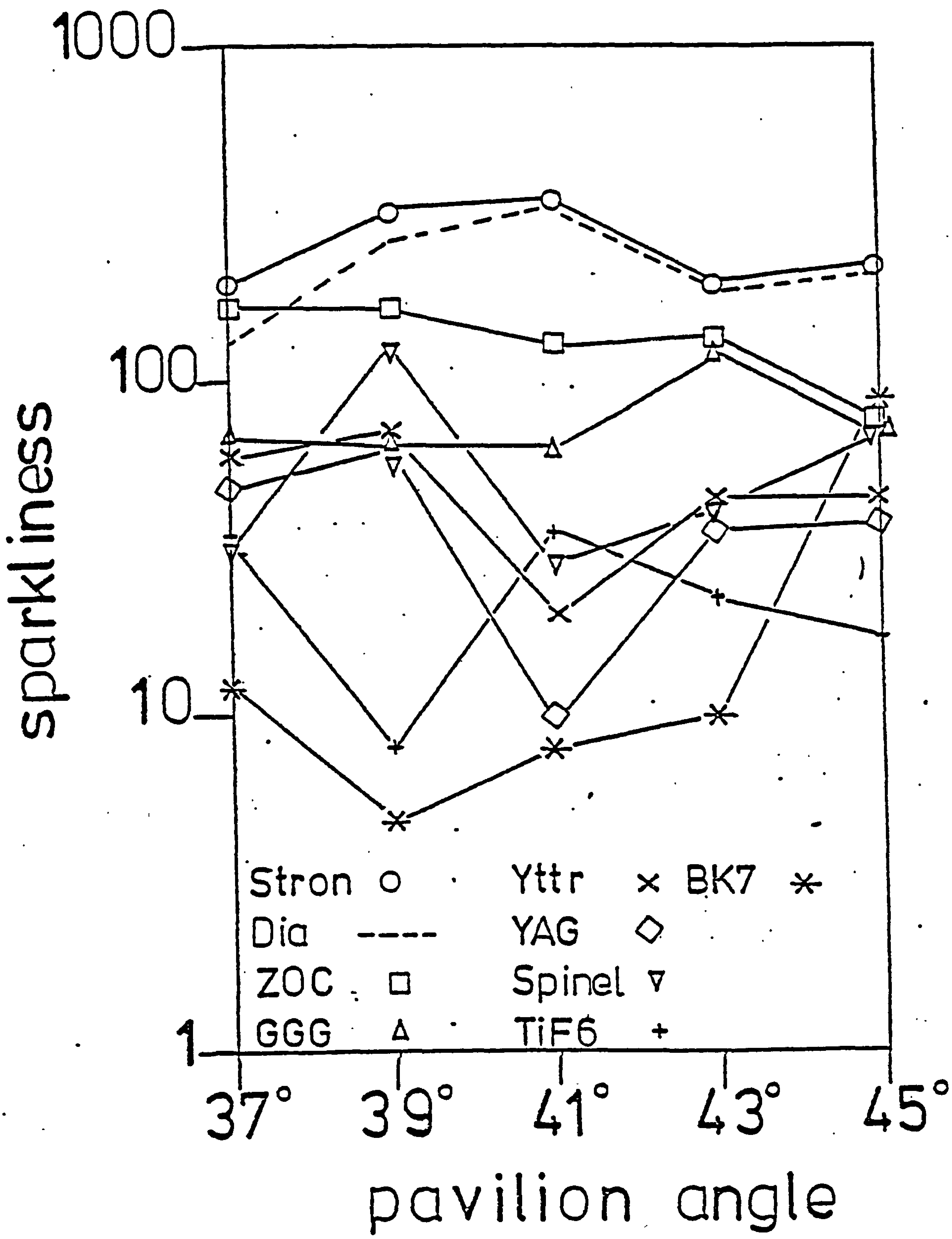
The variation of sparkliness with pavilion angle for various materials
Crown height 10%
Table spread 50%
PHF 0.5
Style round brilliant cut

The variation of sparkliness with pavilion angle for various materials
Crown height 10%
Table spread 60%
PHF 0.5
Style round brilliant cut

The variation of sparkliness with pavilion angle for various materials
Crown height 10%
Table spread 70%
PHF 0.5
Style round brilliant cut



The variation of sparkliness with pavilion angle for various materials
Crown height 15%
Table spread 40%
PHF 0.5
Style round brilliant cut

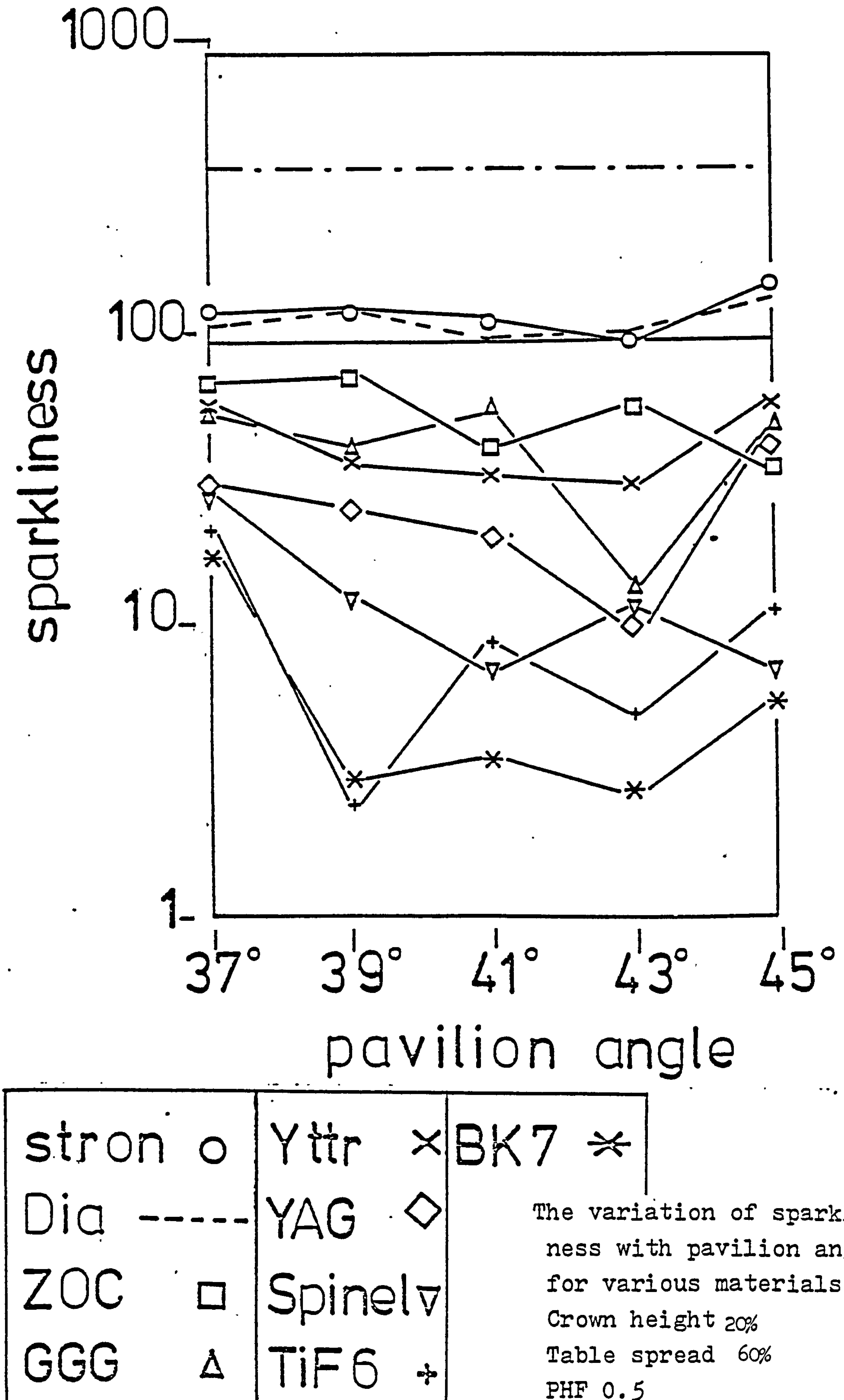


stron o	Yttr ×	BK7 ✳
Dia -----	YAG ◇	
ZOC □	Spinel ▽	
GGG △	TiF6 +	

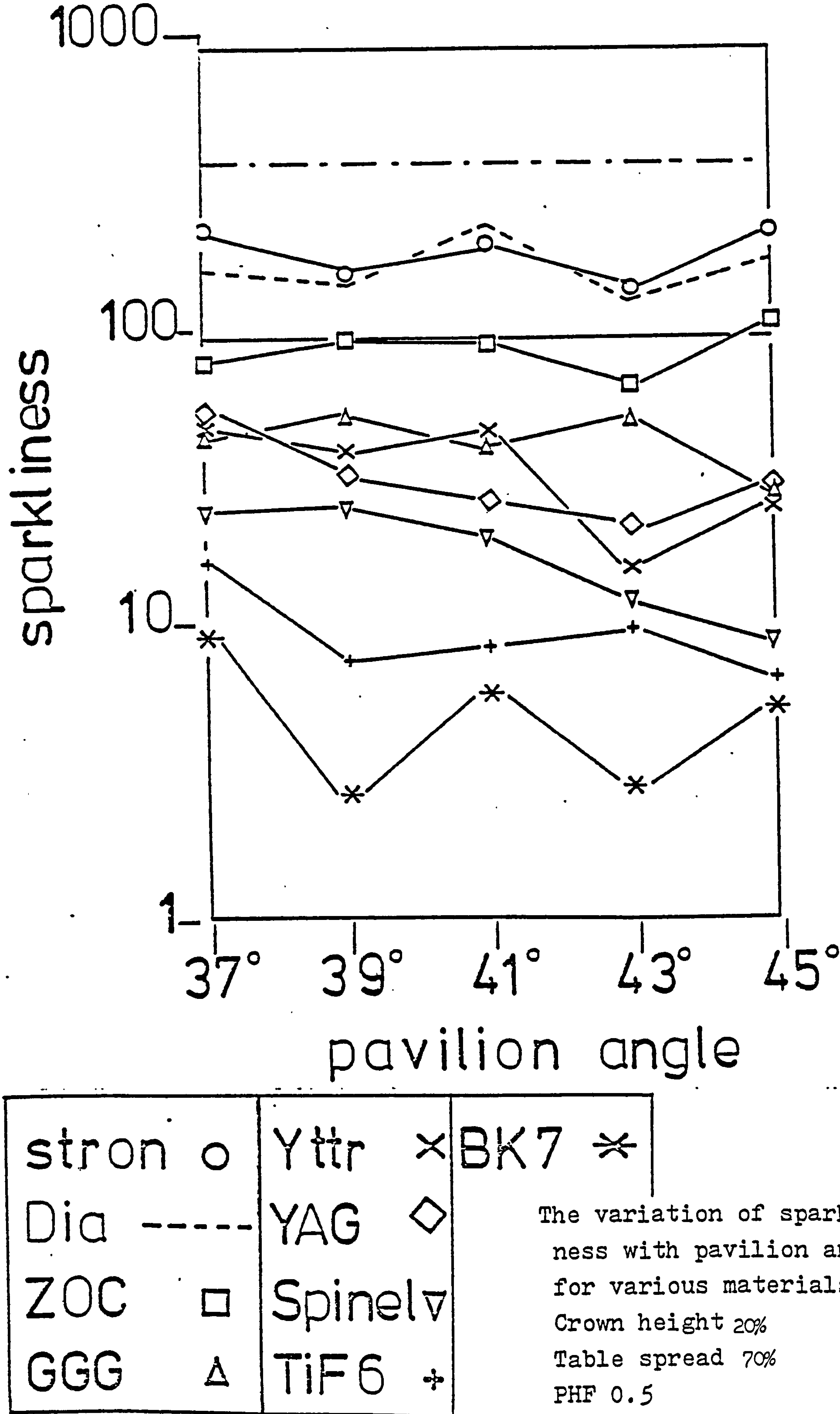
The variation of sparkliness with pavilion angle for various materials
Crown height 15%
Table spread 50%
PHF 0.5
Style round brilliant cut

The variation of sparkliness with pavilion angle for various materials
Crown height 15%
Table spread 60%
PHF 0.5
Style round brilliant cut

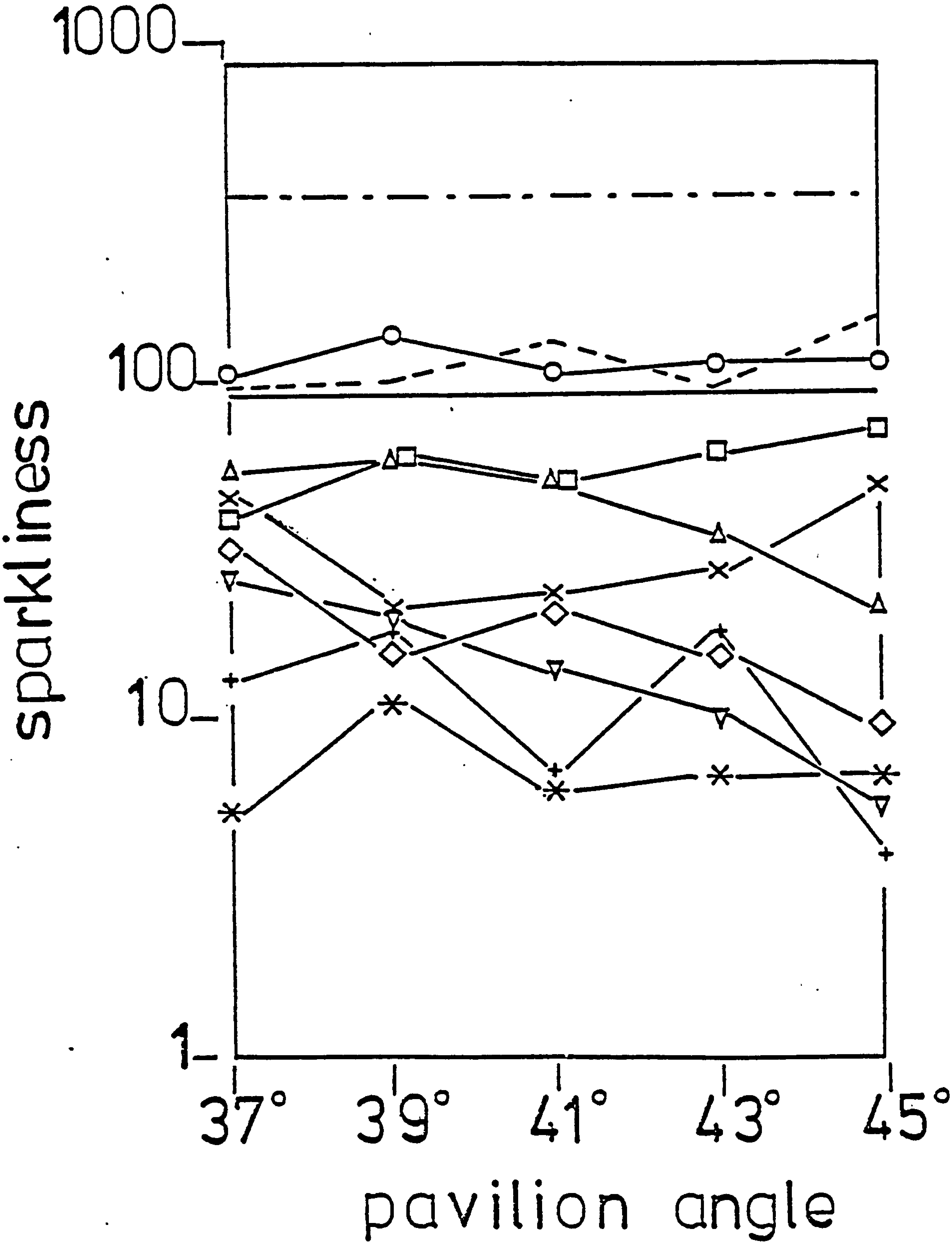
The variation of sparkliness with pavilion angle for various materials
Crown height 15%
Table spread 70%
PHF 0.5
Style round brilliant cut



The variation of sparkliness with pavilion angle for various materials
Crown height 20%
Table spread 60%
PHF 0.5
Style round brilliant cut



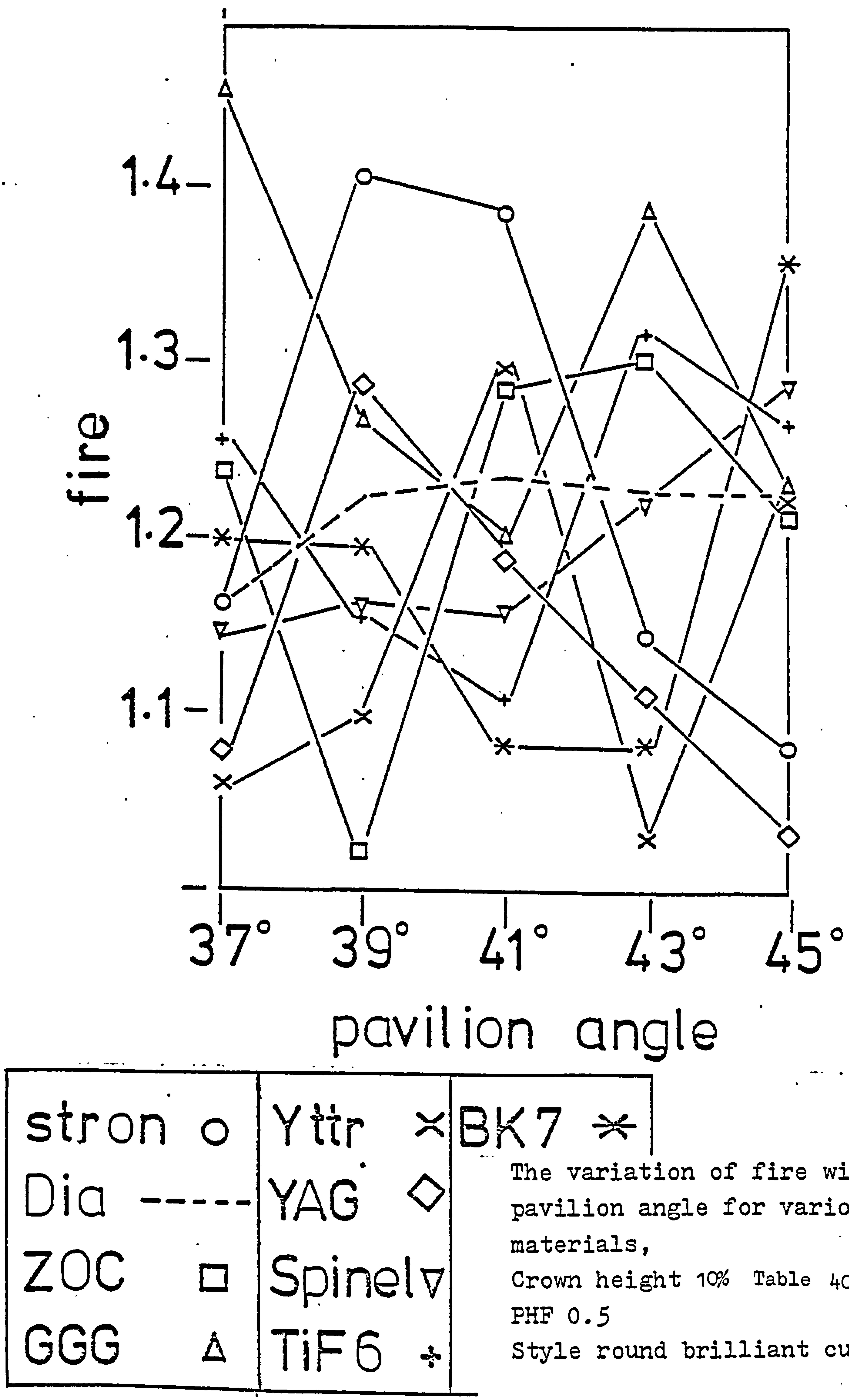
The variation of sparkliness with pavilion angle for various materials
Crown height 20%
Table spread 70%
PHF 0.5
Style round brilliant cut



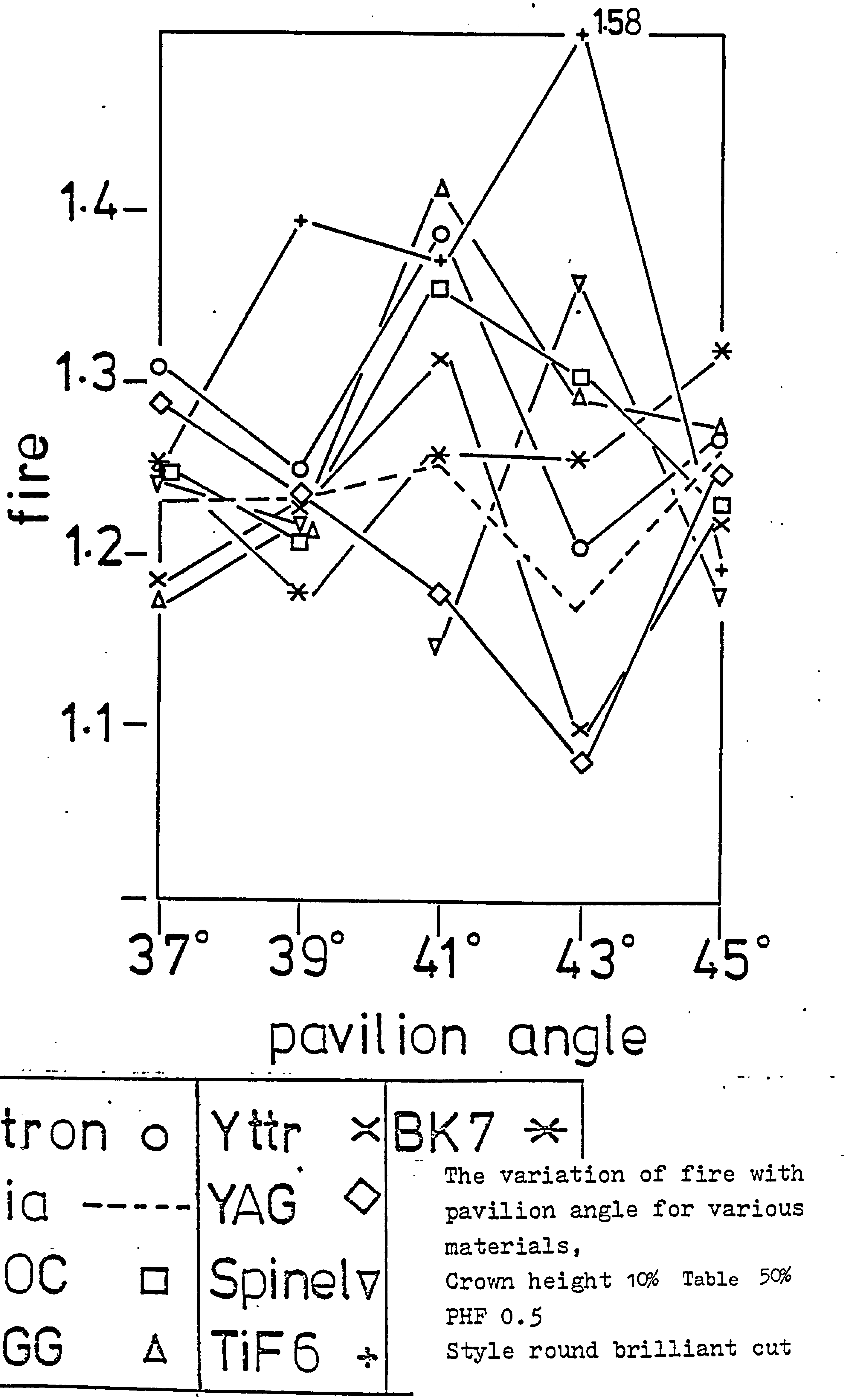
stron ○	Yttr ×	BK7 ✱
Dia -----	YAG ◇	
ZOC □	Spinel ▽	
GGG △	TiF6 +	

The variation of sparkliness with pavilion angle for various materials
Crown height 20%
Table spread 50%
PHF 0.5
Style round brilliant cut

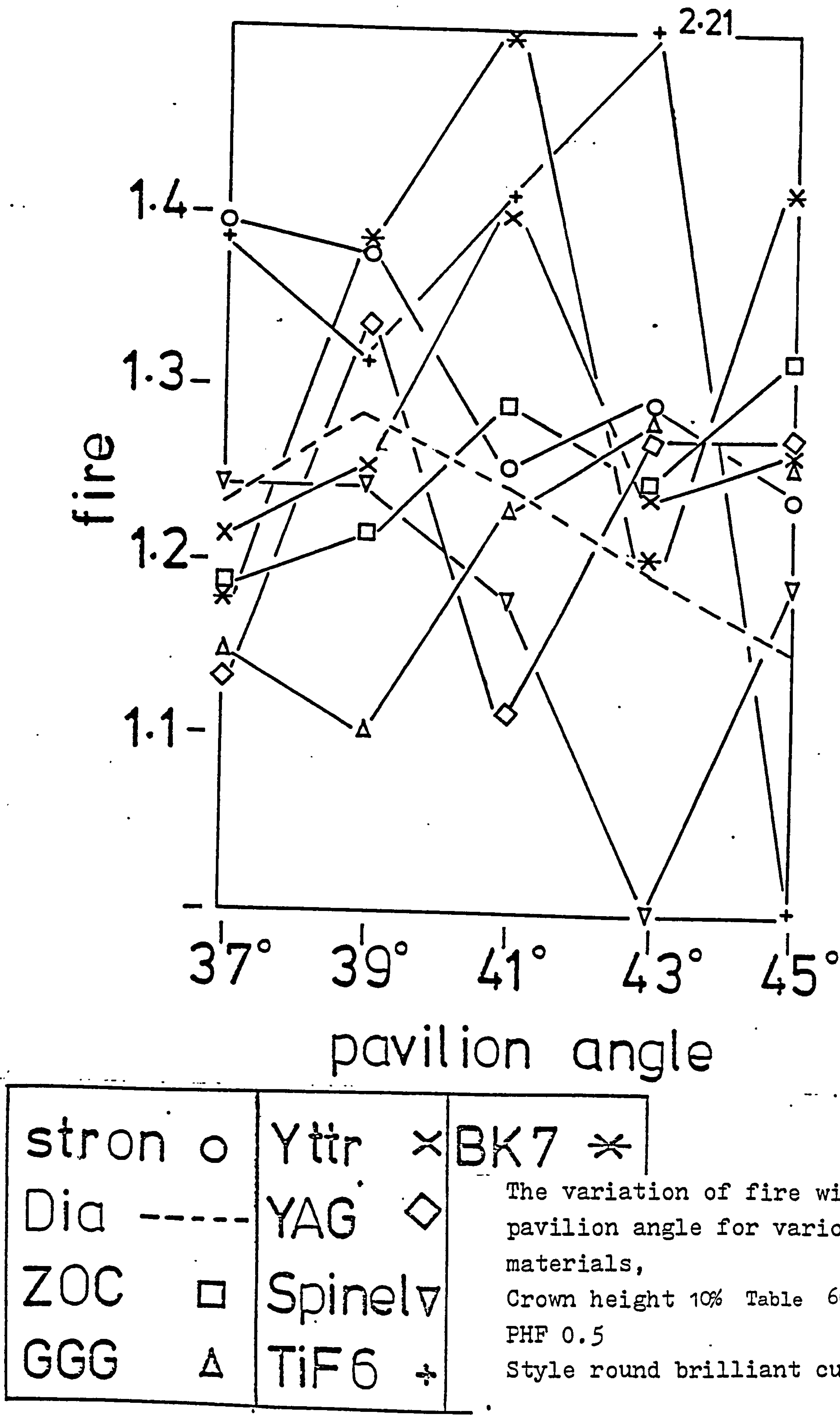
The variation of sparkliness with pavilion angle for various materials
Crown height 20%
Table spread 40%
PHF 0.5
Style round brilliant cut



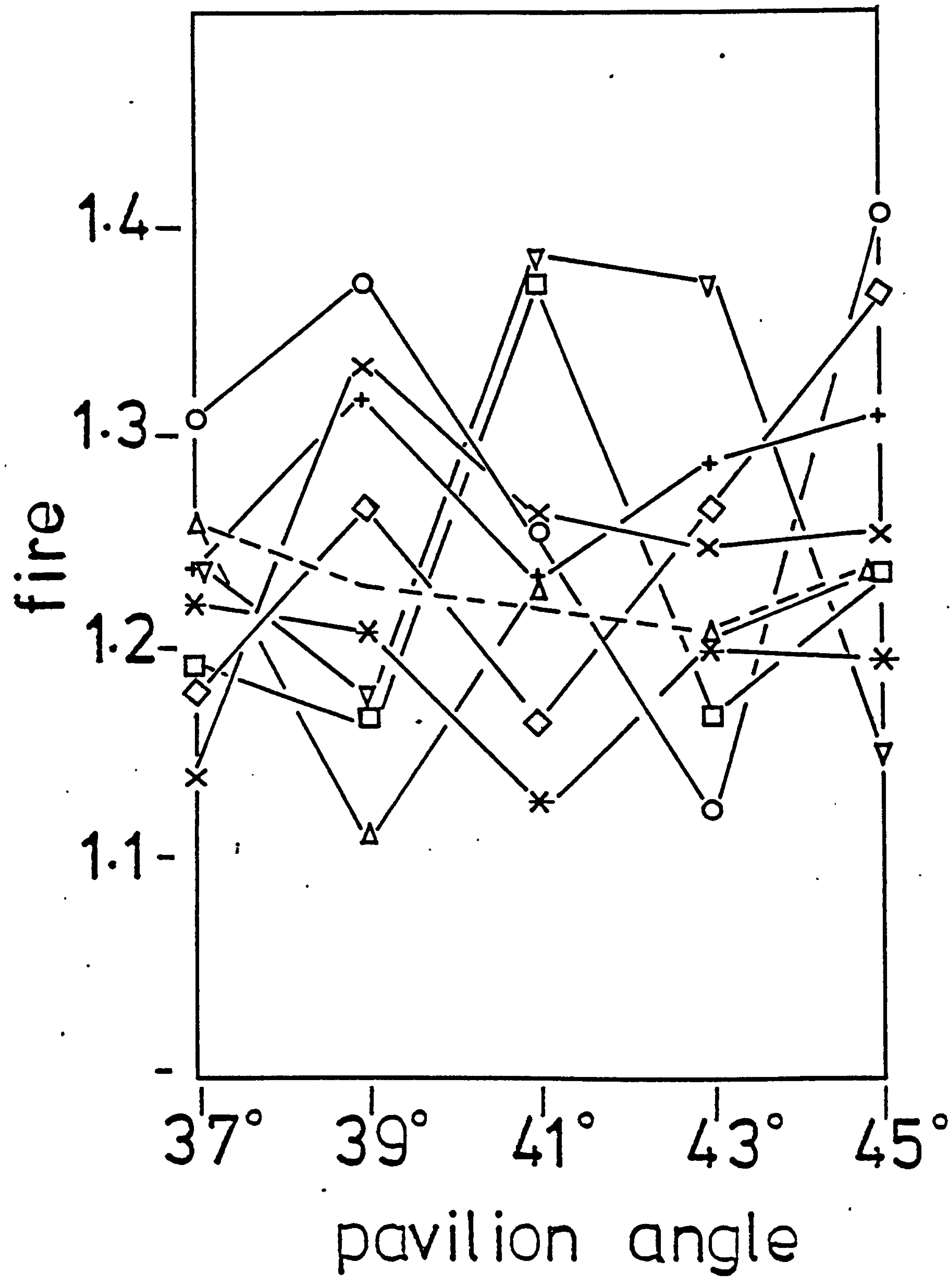
The variation of fire with pavilion angle for various materials,
Crown height 10% Table 40%
PHF 0.5
Style round brilliant cut



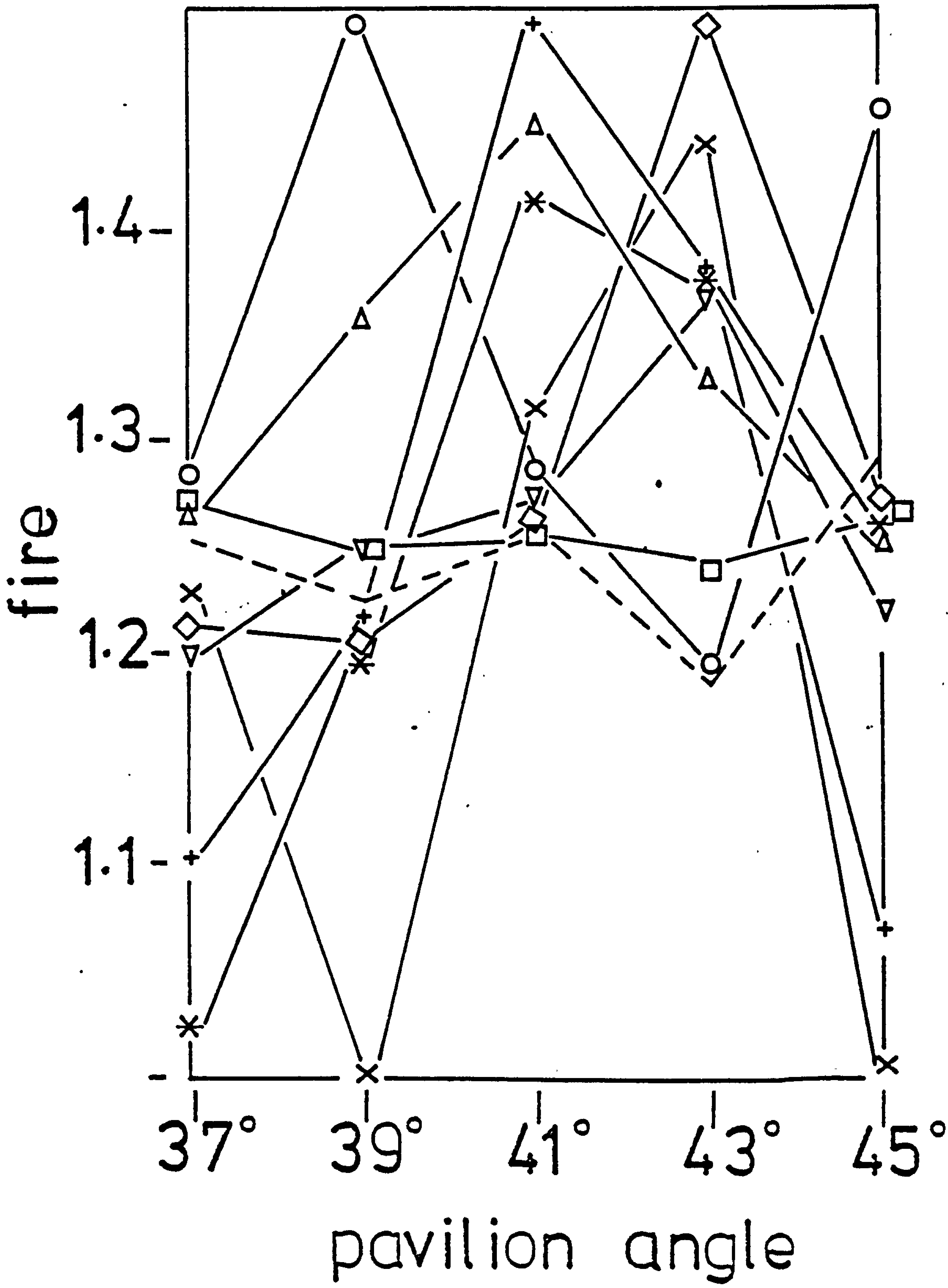
The variation of fire with pavilion angle for various materials,
Crown height 10% Table 50%
PHF 0.5
Style round brilliant cut



The variation of fire with pavilion angle for various materials,
Crown height 10% Table 60%
PHF 0.5
Style round brilliant cut

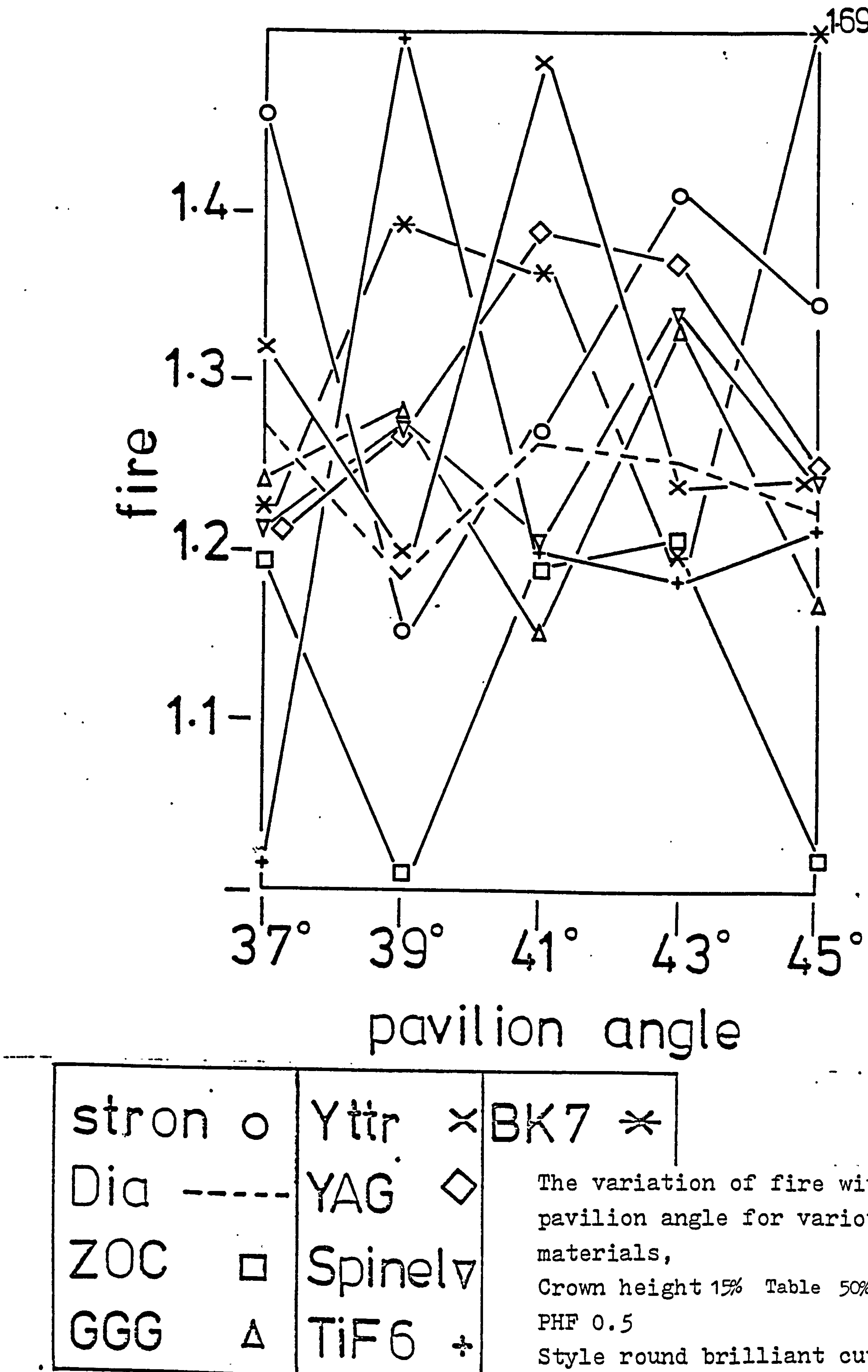


The variation of fire with pavilion angle for various materials,
Crown height 10% Table 70%
PHF 0.5
Style round brilliant cut

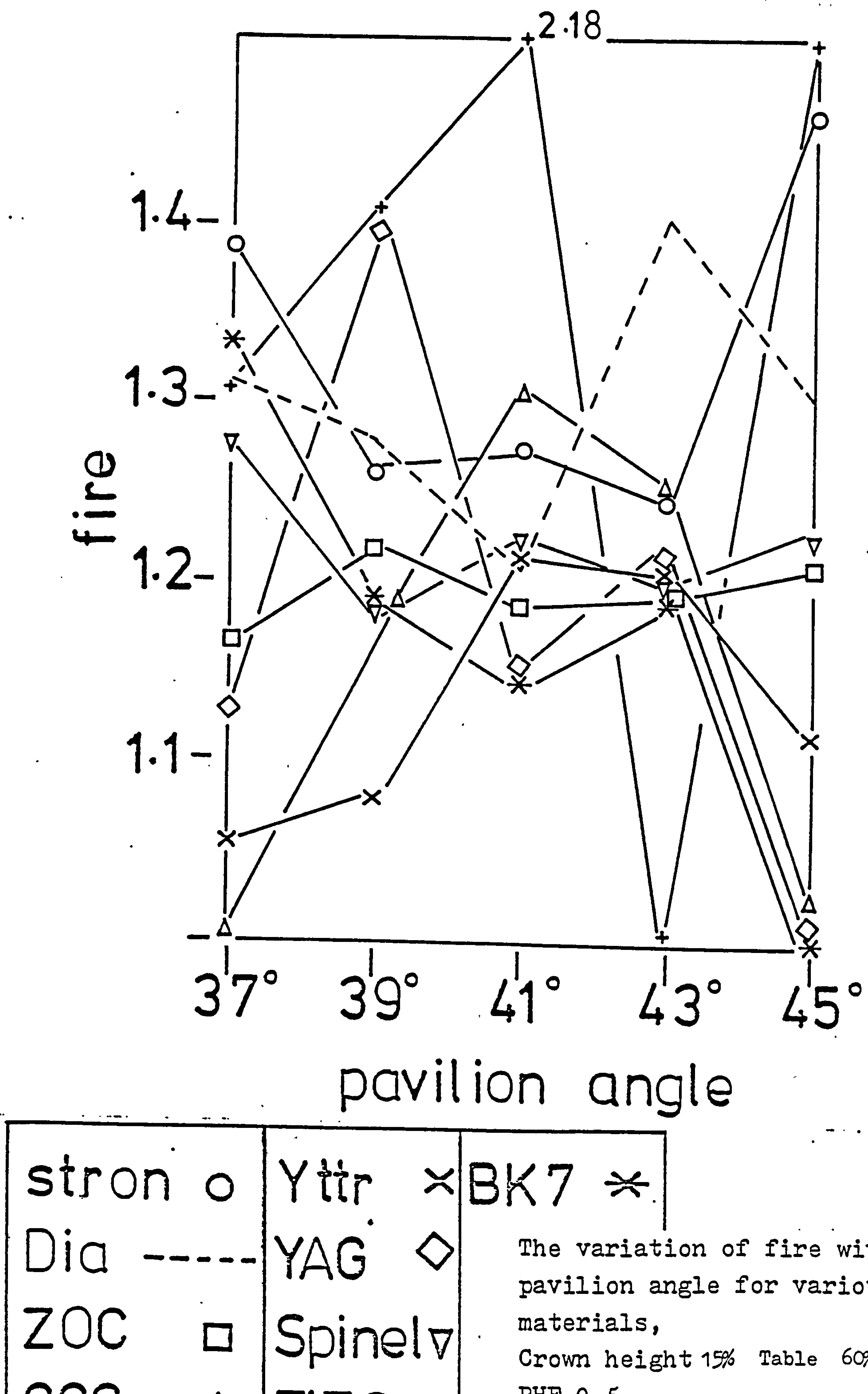


stron o	Yttr ×	BK7 ✳
Dia -----	YAG ◇	
ZOC □	Spinel ▽	
GGG △	TiF6 +	

The variation of fire with pavilion angle for various materials,
Crown height 15% Table 40%
PHF 0.5
Style round brilliant cut

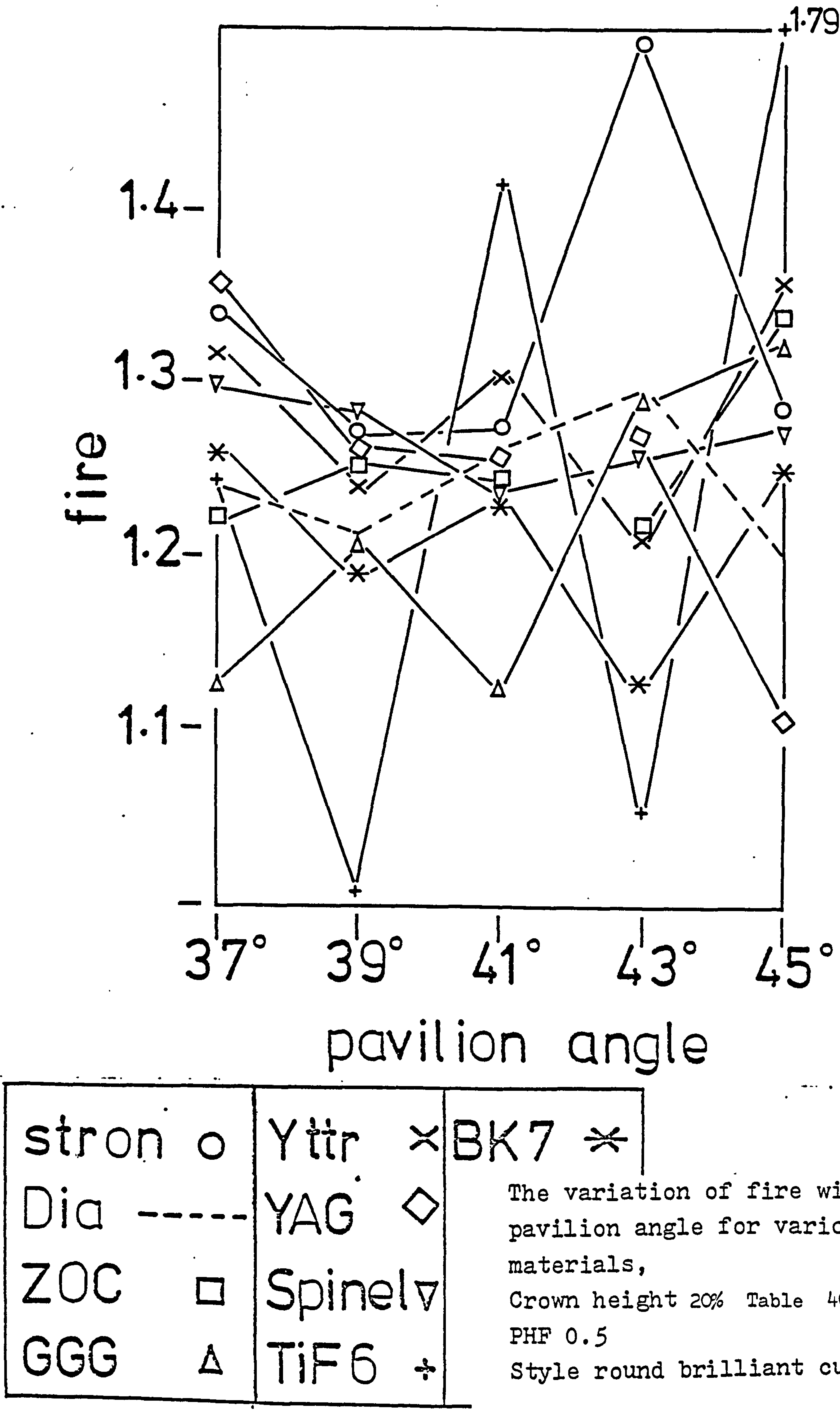


The variation of fire with pavilion angle for various materials,
Crown height 15% Table 50%
PHF 0.5
Style round brilliant cut

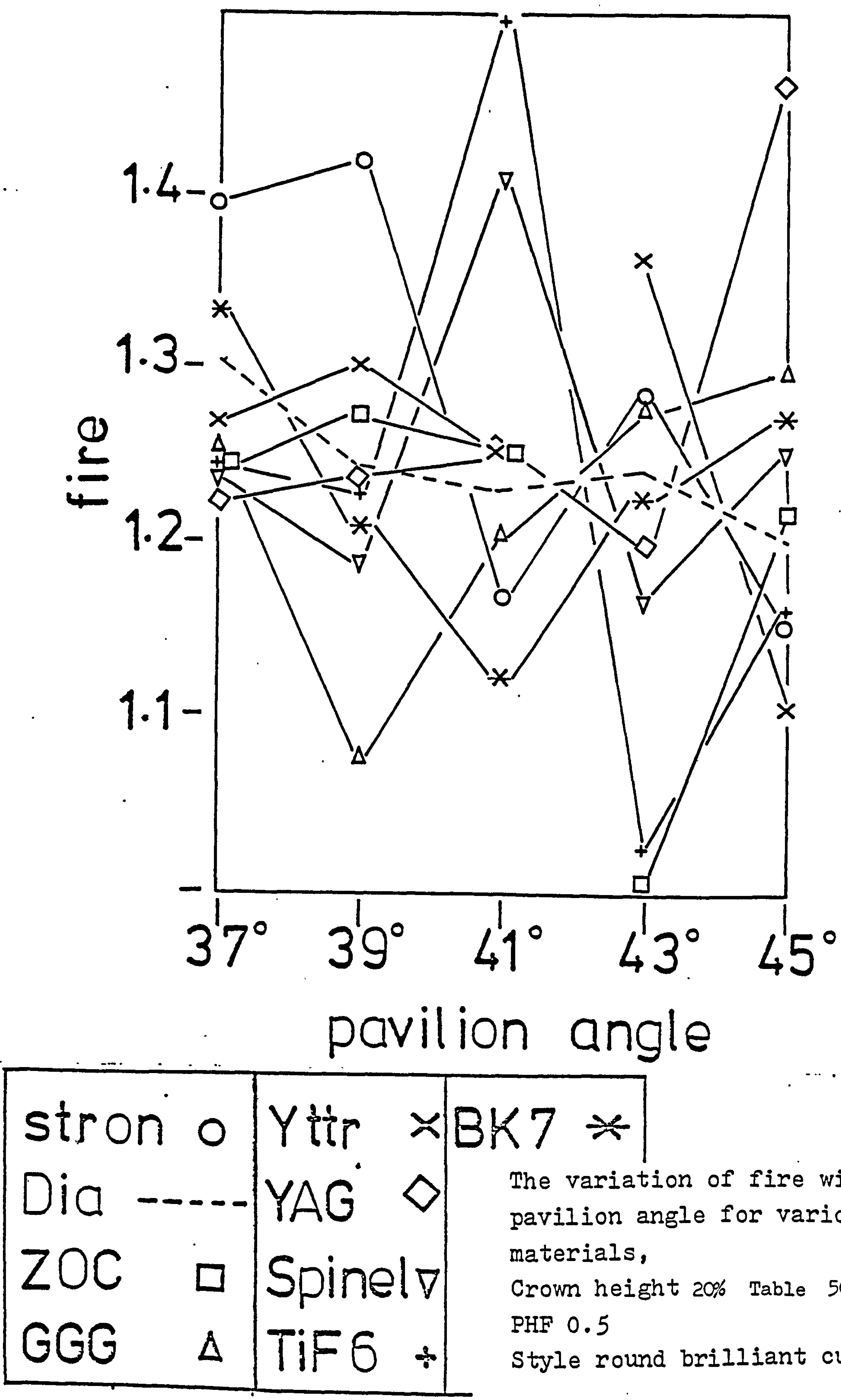


The variation of fire with pavilion angle for various materials,
Crown height 15% Table 60%
PHF 0.5
Style round brilliant cut

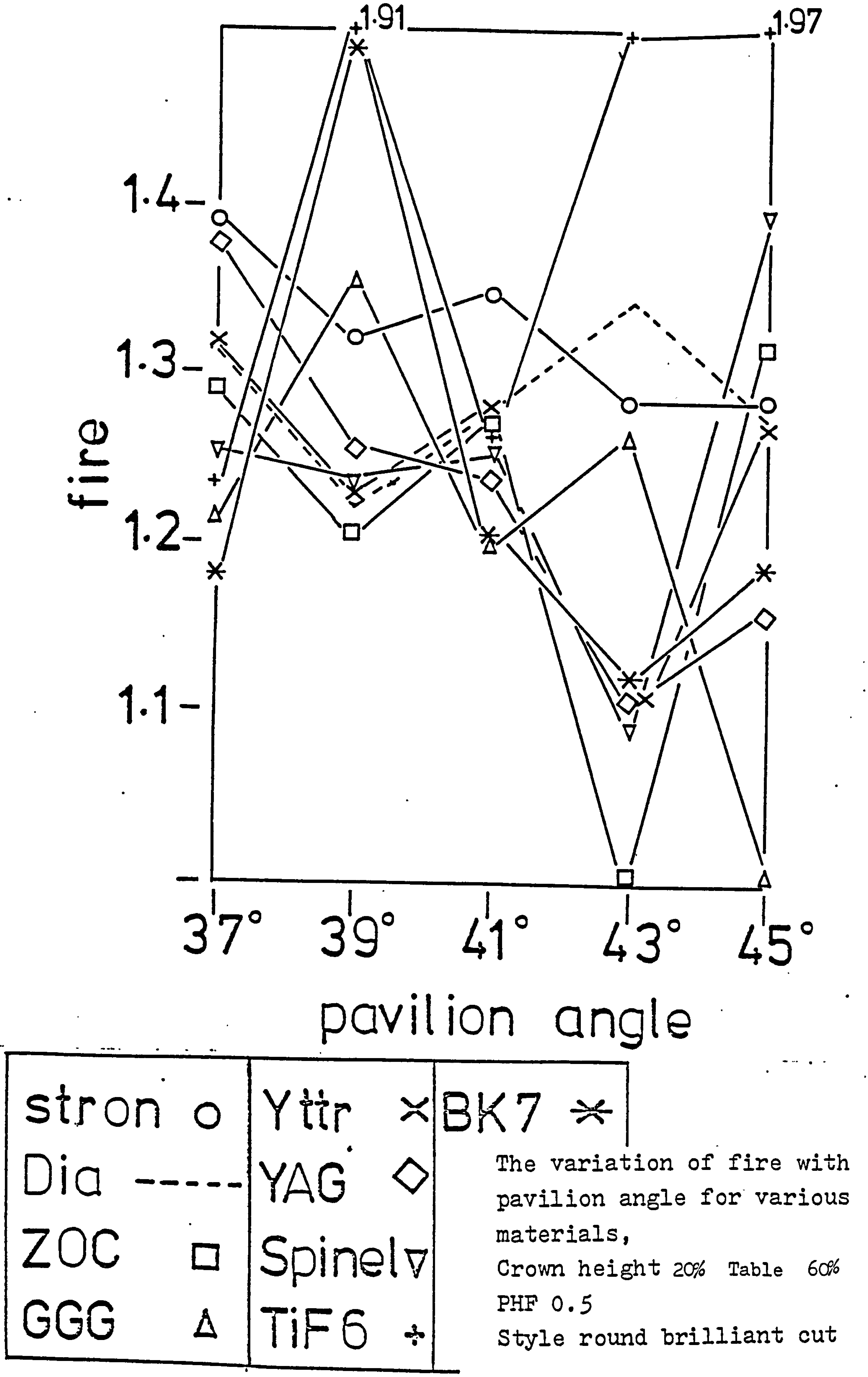
The variation of fire with pavilion angle for various materials,
Crown height 15% Table 70%
PHF 0.5
Style round brilliant cut



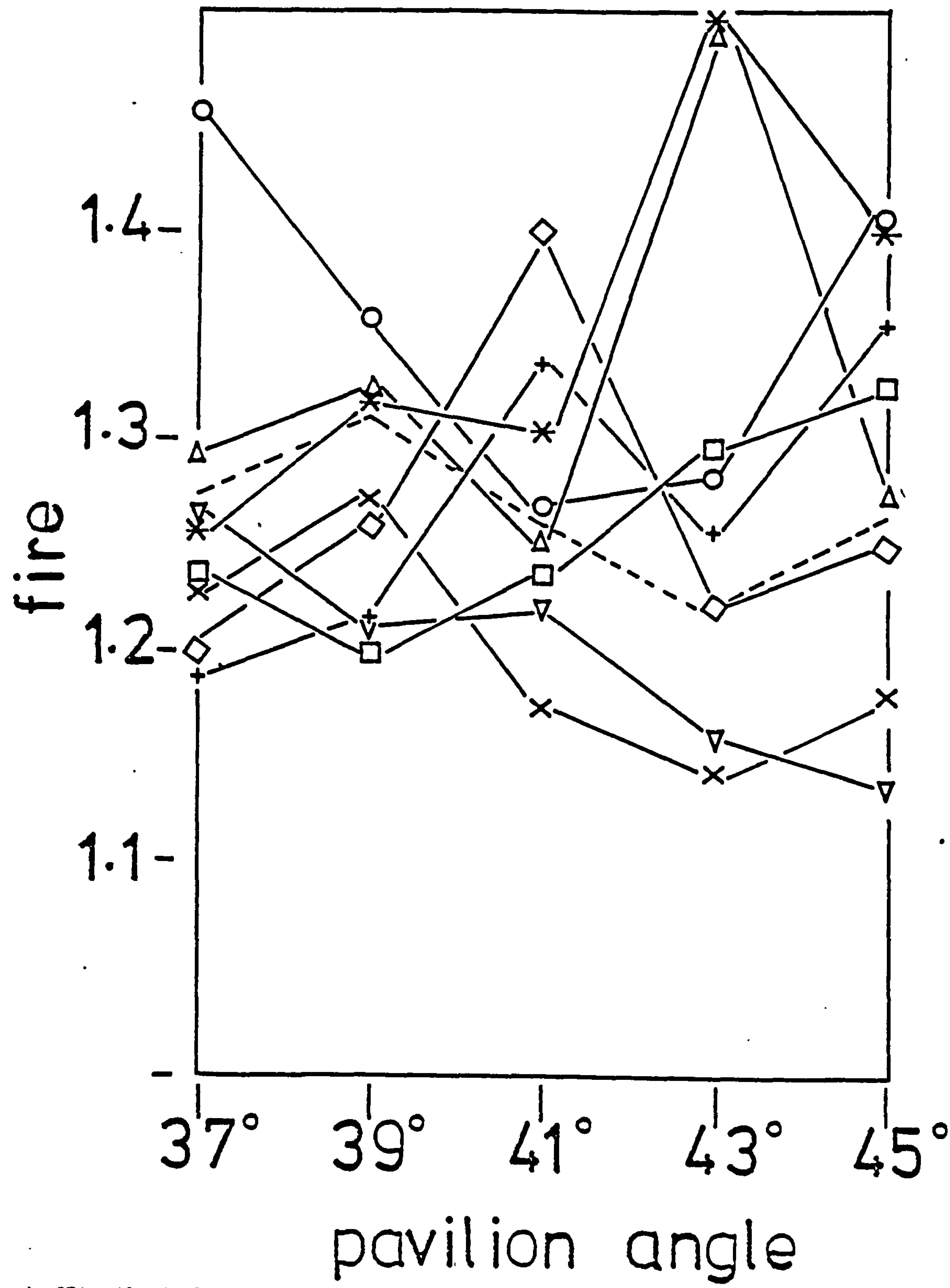
The variation of fire with pavilion angle for various materials,
Crown height 20% Table 40%
PHF 0.5
Style round brilliant cut



The variation of fire with pavilion angle for various materials,
Crown height 20% Table 50%
PHF 0.5
Style round brilliant cut



The variation of fire with pavilion angle for various materials,
Crown height 20% Table 60%
PHF 0.5
Style round brilliant cut



The variation of fire with pavilion angle for various materials,
Crown height 20% Table 70%
PHF 0.5
Style round brilliant cut