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for the degree of Doctor of Philosophy

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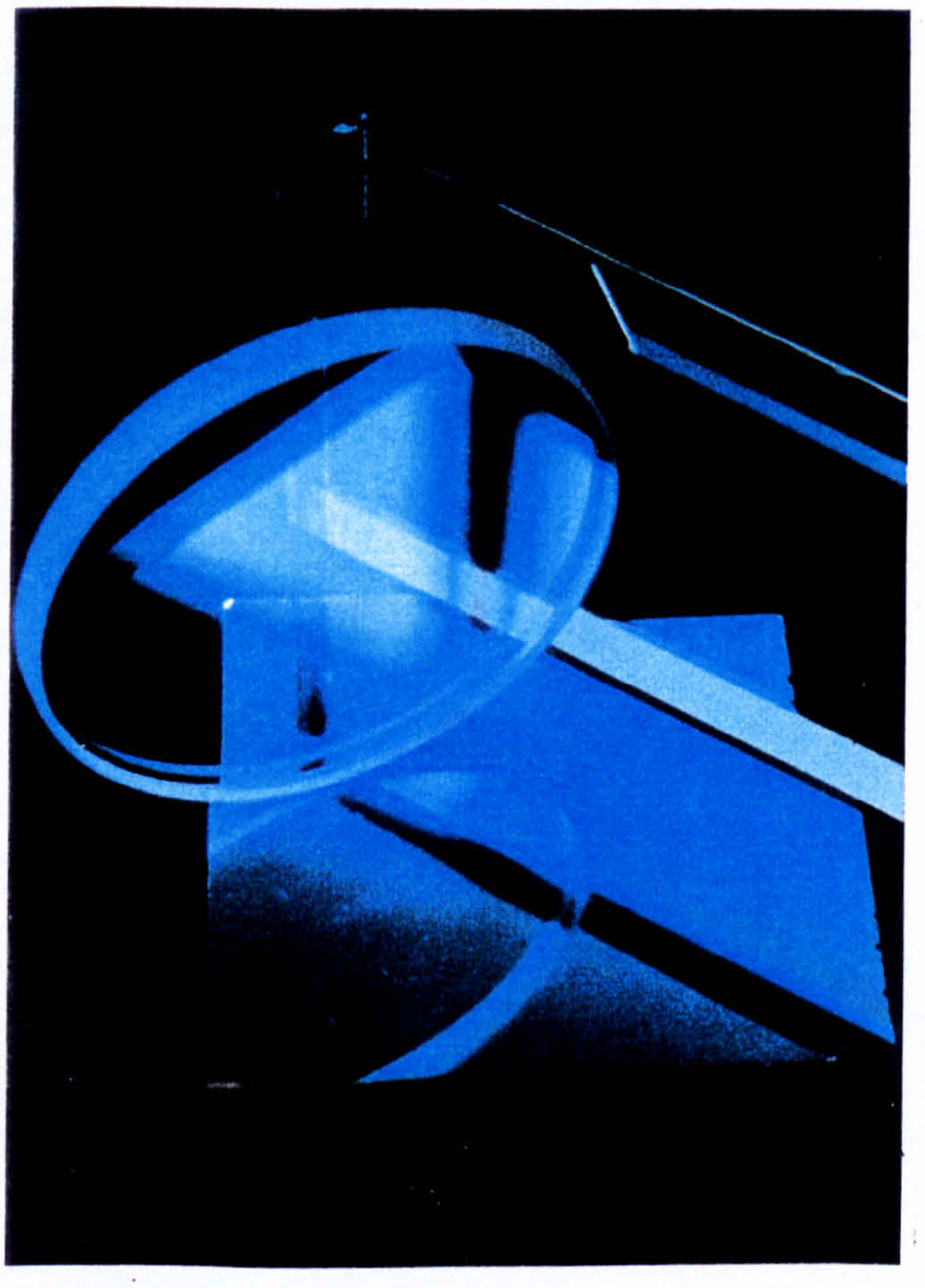

The Innovative Application of the Coated Glass Surface in Architecture

This research programme was carried out with
the assistance of Pilkington Research Laboratory
as co-operating establishment.

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Appendix 1

ABSTRACT

TITLE: *The Innovative Application of the Coated Glass Surface in Architecture*

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The practice-led research is concerned with the changes to the material vocabulary available to the glass artist as a result of developments in technology. Many stained glass artists continue to use a one hundred year old vocabulary in the production of works for contemporary buildings. In this research programme, the potential of a relatively new material - dichroic glass - is explored and an appropriate aesthetic developed. Dichroic glass is selected as focus in the research due to its unique qualities of reflection and transmission of specific wavelengths of light. Thin films technology has resulted in its production and is able to transform standard float glass into a magical material with enormous aesthetic potential.

The approach to the application of the material is essentially a response as an artist to its unique qualities, but this approach is informed by a study of historical precedence and contemporary practice, which sets the context within which the research is carried out. The vital importance of light as the phenomena with which artists designing glass for architecture are primarily concerned, is revealed by this contextual study. The relationship of artist-designed glass to its architectural context is examined and in-depth case studies reveal the approaches of three contemporary artists. Personal practice is thus linked to contemporary practice and historical precedent.

Developments in glass technology are reviewed and the current and developing functions of glass in architecture are outlined. This study establishes the wider context within which the artist, designing glass for contemporary architecture, is working. A study of thin film technology places dichroic glass within its technical framework. In depth analysis of how dichroics are produced and the subsequent production of a range of samples gives valuable insight into the nature of the material.

The research uses a range of methods to address the artistic application of dichroic glass. To utilise the unique qualities of the material, forms are developed both in experimental models and in existing architectural settings. In seeking to enhance the experience of architectural space, the design of forms are developed in response to the particular lighting conditions of the chosen contexts.

The various strands of the research work together to uncover data which would assist artists and designers in their approach to the architectural application of dichroic glass. The methods explored and developed provide useful tools for other practitioners in their approach to design.

I would like to dedicate this research to my Dad, John Johnston (1913-1970), who we all miss and my Mum, Doreen C. Johnston (b.1922) whose strength, support and encouragement has always been fantastic.

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For their technical support, I would like to thank my co-operating establishment, Pilkington Technology Centre, Ormskirk, Lancashire; particularly Jack Brettle and John Siddel whose support and assistance has been of enormous value in gaining an understanding of the material.

Thankyou.

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LIST OF ILLUSTRATIONS.

CHAPTER 1 : INTRODUCTION.

1.1 Outline.

This research programme is concerned with changes to the material vocabulary available to the stained glass[1] artist as a result of developments in technology. A relatively new material - *dichroic glass*, has been selected as focus for the practice-led research and its potential for architectural application is explored. The enormous aesthetic potential of this material led to its selection as focus. Thin film technology has resulted in the production of dichroics which have unique qualities of reflection and transmission of specific wavelengths of light. The effect is magical, creating a glass which appears one colour in transmitted light and yet in reflection, the opposite colour appears. This unique quality has major implications for its potential as an architectural medium for the artist. The material vocabulary used by many stained glass artists designing glass for contemporary architecture, has remained little changed since medieval times. This research aims to examine the application of a new material which can expand this vocabulary and broaden the design potential open to the artist working with glass for architecture.

The approach to the application of the material is essentially a response as an artist to its unique qualities, but this approach is informed by study of historical precedence and contemporary practice, thus setting the context within which the research is carried out. Developments in glass and building technology have resulted in a move away from the window to the development of the glass 'skin' - vast walls of glass which clothe the support structure within. For the glass artist, these developments appear to challenge the very nature of the their medium, stained glass, which has always been concerned with window design. The approach to the application of dichroic glass is, thus, carried out with the acknowledgement of the influence of these issues on artistic practice. Research of these related issues inform practice, enhancing the approach to the challenges of exploring the architectural potential of this material.

Footnotes.

1. The term 'stained glass' over recent years has developed a wider meaning than the strict traditional definition of painted and leaded hand-made glass, being used to refer to any artist-designed glass for architecture. 'Architectural glass' is also used to describe such work and is without the strong associations of the former term. The latter is, however, sometimes used to describe the various manufactured glazing products currently on the market.

1.2 Method

Several areas of study have been brought together in the development of work with the material. In setting the context within which the research is pursued, a historical study has been undertaken which examines the function of stained glass in architecture. This consists of a historical overview, taking as a starting point the incorporation of stained glass in gothic architecture and continuing through to twentieth century application, with reference to developments in building technology throughout this period. The vital importance of light as the phenomena with which artists designing glass for architecture are primarily concerned, is revealed in this contextual study. The work of contemporary artists, whose innovative approaches have broken new ground within the medium has been documented in the form of in-depth case studies. The relationship of artist-designed glass to its architectural context is examined along with the varying approaches of artists to the issue of integration. Personal practice is thus linked to contemporary practice and historical precedence in this contextual study. Influences on current practice are identified and this informs the approach adopted in the application of dichroic glass.

1.2.1 Wider developments in glass technology have been studied examining areas currently under research which are influencing contemporary building design. The move away from the window towards the glass curtain wall and the major implications for the form and function of 'stained glass' in such settings is examined. This area of study unites with the historical study of stained glass and the examination of the approaches of contemporary artists, thus establishing the range of issues which influence practice.

1.2.2 In examining the application of coated glass, a study of the processes involved in its production took place during the early stages of the research programme. This involved collaboration with Pilkingtons in the production of a range of dichroic glass samples. This work served to establish an understanding of the process of thin film deposition. Examination of the physics involved in the manipulation of light by thin films provided insight into how the unique visual qualities of dichroics operate. A wider survey of coated glass designed for architectural use took place and the manufacturing process and functions of the applied coatings were documented. Comparative study of the properties of dichroic and other coated glasses established the appropriateness of this material as an architectural element.

1.2.3 Initial work with the material involved the visual recording of the performance of dichroic glass in daylight conditions. This was achieved by constructing a simple white environment within which samples were placed. The shifting influence of the sun, creating changing colours and qualities was recorded photographically. Application of the glass in two live projects took place during the research programme. The nature of these commissioned projects created various constraints which limited the application of the material, yet also created the challenge of applying the knowledge of the material qualities of the glass to 'real' settings. These projects serve as models for further testing of the potential of dichroic glass as a viable material for the architectural glass artist. The design process was analysed in each case, giving insight into the development of a working practice with the material. Design constraints were documented and their influences on the form the works took in each commission were analysed. Further exploration of the materials potential as an architectural medium was undertaken in model form. This method provides freedom from the constraints identified in the live projects. The exploration of a variety of forms was enabled, developing the work beyond the flat planar application demanded in the commissioning of window designs. The process involved in this exploration, using the model as a tool to develop design concepts, has become an established element in the working practice of the artist during the course of the research.

1.2.4 The application of this investigative work within an architectural context forms the final phase of the research. A challenging project is constructed which enables the artist to explore the impact of dichroics within a predominantly glass building. The choice of building for this work is determined by the concerns highlighted in the contextual study and study of developments in building technology. Thus, the issues identified at the start of the research are addressed in the design of a work for a building without windows, one in which the walls and roof are constructed of glass. A scale model of the building is produced and its orientation and solar impact simulated. Within this setting dichroics are applied and tested further, resulting in the design of a glass construction which is integrated into the architecture. Following in the tradition of stained glass, the work enhances the experience of the space through the modulation of light, creating a play of coloured light which shifts in hue and intensity throughout the course of the day and the seasons. The visual qualities of the glass bring with it a further dimension, applied in the design of a form which controls the influence of reflected and transmitted light on architectural space. The design is a response to the material qualities of the glass, the architectural context and the particular lighting conditions within the building.

1.3 Methodology.

In approaching the research problem, methods have been employed which are derived from a number of disciplines. This eclectic, multi-method approach to research is common in this area as no single methodology exists which is appropriate for practice-led research in art and design.

Firstly, in establishing the context within which the work is carried out and identifying associated issues, secondary data was amassed using historical and descriptive methodologies. These methods, derived from the arts and humanities, are text based and are procedures which enable production of the traditional thesis or dissertation. A survey of examples of architectural glass throughout history, along with developments in technology and building design was conducted and is presented in the form of a written study.

Derived from the social sciences, the notion of 'case study' has been employed to achieve in-depth information on the practice of three individual artists. Comparative study of their approach to design has enabled identification of the concerns and influences which guide their approaches to contemporary architectural glass design.

Technological research has employed the methodology of the material scientist in the investigation of the production of dichroic glass and the testing of the properties of the material. This has been achieved by collaboration with researchers at the Pilkington Technology Centre and has resulted in an understanding of the material and the physics involved in the manipulation of light which creates the dramatic visual qualities of this glass.

'Testing' the material has necessitated the construction of methods appropriate to the task. Recording the visual impact of the glass and its influence on environments has taken place through construction of models in which the glass has been placed and photographed. Drawing on the scientific methodology of experiment, the '*what happens if...*' approach to analysis in which tests are carried out within controlled and measurable environs, the visual properties of the glass have been explored and recorded. Implementation of methods used in engineering to ascertain solar impact on architecture has assisted in structuring a simulated time-lapse observation of the influence of the glass within a constructed model, in the final phase of the research.

Identification of the framework within which artists/designers must operate in their approach to commissioned work has been achieved by means of retrospective analysis of the design process experienced in the completion of projects undertaken during the research programme. The visual and technical properties of the material are further 'tested' when applied to 'real' settings, beyond the temporary nature of the model.

The essentially visual nature of the subject of research demands that appropriate methods of documentation and analysis are employed. Emerging computer technologies are providing new tools for the researcher. Utilising the format provided by the *Director* programme, the photographic images recorded throughout the process of research are presented in a format which is accessible and informative. Compilation of the visual imagery with text, within the framework provided by the programme, enables scrutiny of the research in both a chronological linear fashion and a holistic non-linear way. Information is presented enabling cross-referencing of imagery and associated themes/issues. The lateral thinking, inherent in the approach of the artist and designer, is explored and presented in this medium, with links between subjects programmed in and multiple pathways through the data pre-designed by the researcher.

The multi-method approach to the research thus results in an amassing of visual and written material which is presented in the form of a thesis and CD-Rom. This accompanys and records the three dimensional work with the material.

CHAPTER 2 : CONTEXTUAL STUDY.

> *'Stained glass....already has a record, for two centuries at least, of having been dangerously preoccupied with the past. This tendency to retreat into historicism, together with too great a fascination with craft and technique for their own sakes, seem to have bedevilled the art of stained glass in recent years....Neo-Tiffany, post-pop, hyperrealist, and rehashed German work just will not do any longer : flashed rubies and a vegetarian diet are no substitute for works which are determined to explore new possibilities in a medium which is surely capable of being stretched much more than hitherto. The majority of those making stained glass in the USA (and many, of course, elsewhere) appear to be young (under forty years old) : they seem to suffer from a surfeit of 1960's generated hippie/mystical/Zen/nice-liberal/comfy craft apathy.'* [1]

2.1 Martin Harrisons condemnation of the work of contemporary stained glass artists was of influence in the initial questioning of the role of contemporary artist-designed glass for architecture, which has resulted in this research programme. Reconciling the production of works, in a medium which has changed little since medieval times, with building methods of today, is a difficult task. Although there are, undoubtedly, some fine examples of modern stained glass, the 'architectural' nature of a lot of work produced is questionable. In general, artist-designed glass is added to architecture as a decorative feature, after the building has been completed. Commisions for such work are often established with little intention on the part of the architect of achieving true collaborative work. In this climate, the opportunity for integration of stained glass which operates architecturally, is rare and the trend is self-perpetuating. Students of stained glass tend to follow in the footsteps of those before them, producing more of the same. Those architects who are open to the involvement of artists in the making of a building, look around at the work of stained glass artists and see little evidence of exciting collaborative work. As Martin Harrison found, in a discussion with a leading British architect in the 1970's, this leads to a reluctance to commission glass artists for architectural work:

> *'In 1973 I asked the architect James Stirling if, since he had never used stained glass in any of his buildings, he had a particular aversion to the medium. He replied that this was not the case, rather that he had simply never seen any modern stained glass he would consider using.'* [2]

Despite the many examples of successful architectural glass projects, completed since the 'seventies, there is a continuing problem of disconnection between the glass artist and architect. The result is a predominance of commissioned add-on features, leaving the strong architectural works in the minority.

An understanding of the nature of this separation, can be gained through historical study of the development of the visual arts, and the seperation of fine art from the crafts.[3] Much has been written on this subject and there have been many studies compiled which examine the development of stained glass from its origins to present day. Such a comprehensive study is not necessary here, although a brief examination of some major developments is useful in setting the context within which the research is carried out.

> *'I use light abundantly, as you may have suspected;*
> *light for me is the fundamental basis of architecture.*
> *I compose with light.'* [4]

In this statement, Le Corbusier stresses simply his view of the nature of architectural design. Similarly, it is the manipulation of light which has always been the concern of the stained glass artist.

John Piper referred to a contemporary 'collective consciousness' about *'the function of stained glass in relation to architecture....This function is, above all, to qualify or alter the light, and hence to create a different atmosphere in a building or a room, and not necessarily to provide a message or even bright colour'* [5]

2.2 This contemporary understanding has its roots in the past. Nowhere has the power of light been more understood than in the construction of the medieval cathedrals. The magnificent transformation of architectural space achieved in Gothic building, can still be appreciated today at Chartres. Although a fire in 1194 destroyed all but the west rose window and the Belle Verriere, the experience created by the existing windows of the 13th century and later, is a powerful one.Although most often documented as 'a bible for the illiterate', the real power of the windows at Chartres lies in their ability to transform the internal environment. (Plates 1 + 2)

In his book, 'The Radiance of Chartres'[6], James Rosser Johnson gives a detailed account of the experience of the building, from the initial response on entering the dimly lit interior, to the full appreciation of the environment, following the gradual adjustment of the eye to the lighting levels.

> *'Most people on entering the Cathedral, are struck by the overwhelming color of the stained glass as it is set off brilliantly against the darkness of the interior....Has color ever been presented with such éclat? Where can one find such brilliance and so much of it, in such a setting? It is not surprising that so many visitors have burst into tears upon experiencing this sight for the first time, as I have witnessed on more than one occasion'.* [7]

The immense power of this place, visited for the purposes of the research in 1994, is not due to the quality of the individual glass panels, in themselves, but to the orchestrated play of light, form and colour which create this environment.

> *'Chartres is one of the masterpieces of Gothic architecture and one which takes the pursuit of light further forward'* [8]

Following the fire of 1194, a rebuilding programme took place and the new cathedral was completed and reconsecrated by 1223. The result was a spectacular embodiment of the aims of Gothic architecture. The structural support provided by the flying buttresses on the outside of the building enabled the creation of immense windows set within the skeletal structure of interior. Subsequent damage and destruction over the centuries to many cathedrals of the 12th and 13th centuries which resulted in the replacement of the original windows with later, incongruent works, has meant that this message is lost. These replacements often consist of clear glass which has the effect of admitting bright light.

> *'Totally white or unglazed windows are not the only offenders: if a deeply colored lancet is in the presence of windows of lighter tonality - especially those with greys and yellows predominating - it will suffer and lose its essential character.'* [9]

On viewing a darker window which has a lighter one adjacent, or even a damaged darker window with an area of white light visible, the human eye adapts to the intensity of the brightest light. The result is that the darker tones are not distinguishable.

> *'It takes only one offending bright area to spoil the effect of the whole ensemble if the rays passing through that area can reach the eye of the observer.'* [10]

The experience of Chartres, then, is outstanding in conveying the original power and the high level of expertise at work in the creation of orchestration of light. The importance of light during this period, was very much influenced by the 6th Century writings of a monk from Constantinople known as Pseudo-Dionysius. This influence was strong throughout Europe during the Middle Ages when there was a great exchange of ideas. Initiated often by church councils, there was a bringing together of churchmen and experts including architects, artists and stained glass makers, which inevitably affected the arts of the time.

Pseudo-Dionysius produced two books entitled; *The Heavenly Names* and *The Celestial Hierarchies.*[11] These works professed the importance of light as the main component of matter.

> *'All was made of light, and the light was the material reflection of the heavenly light, the wisdom of God.'* [12]

Following this, in the 13th century, it was the writings of Robert Grosseteste which further clarified the conviction that it was condensed light which composed all matter. In his book, *de Luce* (*On Light*)[13] he used the scientific method, originating in the Roman Empire, to set out his theories. His works were read and acclaimed all over Europe.

The emphasis on the importance of light influenced its treatment in the design of new buildings in the 12th and 13th centuries. This, along with the Medieval concept of 'claritas', which believed in the influence of the visual world on the human spirit, shaped the approach to building and stained glass of this time.

> *The main quality sought was one of uplift to the eye and therefore to uplift the spirit using transparency, translucency and multiple reflection.*[14]

The Gothic style of architecture, which developed in the middle of the 12th century, aimed to create churches which would achieve this spiritual uplift. In the construction of the Abbey of St.Denis, Abbot Suger was the first to employ flat-bed building techniques, a method observed in the 5th and 6th century buildings of the Near East and Greece. This move away from methods influenced by those used in the Roman Empire, allowed the construction of the characteristic Gothic churches, with their immensely high vaulted ceilings. The walls were constructed completely of dressed stone with little reliance on mortar, thus the result enabled great reduction in the interval between windows. Unlike the preceeding Romanesque architecture, with it's singular windows cut into the thick walls, the Gothic churches enabled much larger areas of glazing and greater relationship between each window. This resulted in a unification of the windows and the architecture which was different to that that had gone before. The stained glass was incorporated into this structure with the intention of manipulating light entering the building and creating an atmospheric effect.

The positioning of the windows; the division of interior space; the colours of glass chosen, worked together to create an environment in which sculpture and the glittering of warm reflected light on chalices would be viewed.

> *'Light and structure interpenetrate each other, and it seems quite obvious that the two were conceived in unity from the very beginning.'* [15]

2.3 This total integration of glass and architecture faded towards the end of the fifteenth century. The use of illusion and naturalism in panel-painting influenced the other arts and in stained glass the move was towards depiction of landscape and imagery which made the work appear like 'transparent tapestries'.[16] With the emergence of oil painting following the seventeenth century devotion to Renaissance classicism which condemned the 'Gothic' taste as barbaric, there was a decided move away from stained glass. Imagery was to appear on walls, and windows were to allow the illumination of them. Coloured light would interfere with this imagery. With developments in glass technology making the production of clear glass possible, this became the predominant and desirable glazing material.

Although in England there remained a nostalgia for stained glass and later, more widely, the Gothic revival resulted in a return to the medium, with few exceptions, the powerful integration of glass and architecture was not recaptured. The tendency to look to the past and attempt to recreate work, often inaccurately, grew stale towards the end of the nineteenth century.

2.4

> *'The twentieth century opened in a spirit of fervent reaction by the artistic avante-garde against the backward looking decadence of the time.'* [17]

The tendency for stained glass design to reflect trends in painting, which began in the fifteenth century marking its break from true architectural integration, had continued in the nineteenth. This can be seen in the influence of Pre-Raphaelite and Anglo-Japanese styles in work of this time.(Plate 3) With the emergence of impressionism, this influence ceased as it was difficult to interpret in the medium. The result was that avante-garde art and stained glass design took very different paths. Without the injection of excitement at the new, much of the stained glass produced was predictable, rooted in the past, with little in its character to place it in the twentieth century.

Examples of more interesting work emerged at first in the abstract imagery of Glasgow's Charles Rennie Mackintosh, who used much stained glass in his pioneering approach to architecture at the turn of the century. Glass was an integral element in his buildings used to reinforce the decorative style and imagery which appeared throughout.(Plate 4) Similarly, in the USA, the work of Frank Lloyd Wright incorporated large amounts of leaded glass. Again, the work was of pure abstract geometric form, reflecting the style of the building.(Plates 5 + 6) The Modern Movement which had its roots in the work of Mackintosh and Wright, resulted in the production of further abstract works which stretched the potential of the medium. The Bauhaus had a stained glass department, and experimental work was completed by many, including Josef Albers and Paul Klee. Unfortunately, most of the work produced is no longer in existence.

The artist, Johan Thorn Prikker (1868-1932) of Germany, worked extensively with stained glass. Influenced by Wrights work, and the de Stil movement, in which he was a leading member, he moved away from the figurative to produce works of pure abstraction after 1921, including the dramatic 'Orange' in 1931 (Plate 7). Another leading member of de Stil was Piet Mondrian whose work moved from naturalistic painting, to symbolism, then to cubism and further abstraction concerned with 'plastic reality'. Bold primary colours and rectilinear structure characterise this work. The de Stil movement was a collaboration of architects, artists and industrial designers and its greatest influence can be seen in the architecture of the inter-war years. Dedicated to the..

> *"absolute devaluation of tradition...the exposure of the whole swindle of lyricism and sentiment"*[18]

painting, sculpture, architecture and design were practised with emphasis on *"the need for abstraction and simplification"*.[19] For stained glass, then, new imagery was explored at this time reflecting the move towards abstraction in the arts.

2.5 The visionary writer, Paul Scheerbart, inspired an excitement amongst Modernist architects for the potential of glass. He wrote extensively of his dream of the glass building, which he believed would have dramatic influence on the lives and the cultures of peoples who inhabited them.

> *"If we want to see our culture rise to a higher level, we are obliged for better or for worse, to change our architecture. And this can only happen if we take away the 'closed' character from the rooms in which we live. We can only do that by introducing glass architecture which lets in the sun, the moon and the stars, not merely through a few windows, but through every possible wall, which would be made entirely of glass'* [20]

The crystal quality of glass, symbolised clarity and with the introduction of light into the day to day lives of individuals, a new vision and optimism would be established. This resurgence of emphasis on light harks back to the concept of 'claritas' in the 12th and 13th centuries, with the belief in its dramatic influence on the human spirit.

Continuing developments in glass technology during the 19th century, enabled the production of larger and larger sheets of glass. By drawing a ribbon of glass direct from the furnace and then cutting it down into sheets, glass could, for the first time, be mass produced. This coupled with developments in engineering and the use of iron as a structural material, resulted in the building of new forms in which glass featured strongly on a large scale. Developments in glass architecture during the 19th and 20th centuries are seen to span two periods with the first consisting of two phases.[21] Walter Benjamin wrote of the arcades built in the the first of these phases and stated that the need for buildings to accommodate an expanding textile industry, prompted their construction. There existed a resistance at this time which Benjamin referred to as "social presuppositions" to the building new forms of architecture which exploited the potential of the new materials and techniques available.

> *"With a few exceptions, such as the Crystal Palace in London built in 1851, the new type of construction consisted of long,*

narrow corridors, the whole of modest dimensions, hardly utilizing glass and its support, iron, except for the interior and exterior covering, ceiling, and roof. The other parts consisted of classical, and indeed somewhat outdated materials like marble"[22]

In the second phase, as industrialisation progressed, a more daring approach was adopted. Galleries replaced arcades and new buidings with the courageous spirit of the Crystal Palace emerged (Plate 8). The building of railway stations, structures which had no historical prescedence, enabled exploration of new designs. All of this paved the way to the formation of visionary ideas amongst Modernists at the turn of the century. Scheerbart encapsulates the new vision in his statement:

"Glass brings us the new age. Brick culture does us only harm" [23]

The Glashaus, a glass pavilion designed by Bruno Taut for the 1914 Werkbund Exhibition, celebrated glass as a material of beauty (Plate 9). Transparent, translucent, coloured and clear glass formed the walls, floors and ceilings, providing a play of light and optical effect. the power of glass demonstrated in this way was of great influence on architects of the time. This, like others of the more sophisticated houses of glass built during this period, were intended to have a limited lifespan. They would often be built for exhibition purposes and be demolished at the end. There did not appear to be a conviction at this time of creating permanent houses to live in in this way, revealing a continuing resistance to such ideas during this period.

Developments in engineering enabled a move away from the load-bearing wall means of construction which, by nature limited the maximum size of window area possible.

"The material history of architecture shows that throughout the centuries there has been a ceaseless struggle in favour of light against the obstacle imposed by gravity."[24]

Le Corbusier described this historical development as *'the struggle for light'* which ultimately has resulted in the ability to construct walls of glass pinned onto the supporting metal skeleton of a building. Initially this support structure was constructed of cast, then wrought iron and now steel. The walls of glass now perform no supporting role, becoming a transparent enveloping skin. The Fagus factory in Germany, designed by Walter Gropius was the first demonstration of the glass and steel façade (Plate 10). Later in 1922, Mies van der Rohe's model of the Glass Sky Scraper, exhibited in the Berlin annual Art Exhibition demonstrated the ultimate goal of the Modernist thinkers - the glass building (Plate 11). Every wall was clad in glass, but the idea remained just that until decades later when further technological developments tackled the problems of thermal loss and gain which were inevitable in the use of glass on this scale. Such difficulties were acknowledged by Scheerbart in 1914 when he wrote:

> *"the worst thing though is that walls are single and not double, in consequence the expense on heating is enormous. In the first instances it is advisable only to build glass houses in temperate zones, and not in the equatorial and polar regions."*[25]

2.6 Architectural exploration tended to be preoccupied with this application of large scale clear sheet glass, although following the Second World War, there was an explosion of progressive stained glass in Germany. Opportunities for a great many commissions arose in the building boom to reconstruct West Germany. This involved the rebuilding of churches, providing abundant opportunities for new stained glass design. With the desire to initiate a new beginning - a break with the past - there was an openness on the part of patrons to commission work of a contemporary nature.

The works of Georg Meistermann, and a little later, Ludwig Schaffrath and Johannes Schreiter, have greatly influenced contemporary stained glass. Bold abstraction and graphic use of lead-lines produced work which appeared to be very much of its time. Meistermann's work, characterised by expressionistic and spontaneous movement, demonstrated a new liberation of stained glass imagery and was to influence those who followed (Plate 12). Like Meistermann, Schaffraths work is, in the main, not concerned with painting on glass - he uses lead lines to create abstract imagery and form. The work, which alludes to mechanisation rather than organic form, found a place in ecclesiastical and, more widely, secular building - thus assisting in establishing a contemporary role for stained glass. In largely abandoning a painterly approach, using the material quality of both the glass and the lead to create *'weaving graphic images (which) become floating sculptures'*,[26] Schaffrath pushed the boundaries of the material and possible imagery (Plate 13). Innovative was the importance he placed on the exterior view of the windows he created which he saw to be equal to that of their interior appearance. In this way the glass would become an active architectural element, important to the exterior design of the building. Traditionally, stained glass has a passive role when viewed from the outside, appearing dull without the influence of transmitted light. Such questioning of the medium is at the heart of a dynamic approach inviting new solutions.

Martin Harrison, quoted at the beginning of this chapter, stressed the great influence this work has had on the approach of contemporary glass artists. As a result, similar works have been created and found a place in many contemporary buildings. This secularization of stained glass owes a great deal to the strength of Schaffraths approach. Harrison criticises, however, a tendency for artists to recreate the works of this pioneering artist at the expense of exploring new possibilities. Writing in the late 1970's, Harrisons words predate some innovative works which have taken place during the 1980's and 90's, examined in the form of case studies which follow. The commissioning process, often further inhibits the potential for the architectural integration of glass works and the potential to create works which challenge traditional notions of the nature of 'stained glass'. Dictated by the architect, such subjects are limited by his/her understanding of possibilities. This will be investigated further in later chapters.

Finding a role for stained glass in buildings where the traditional 'window' has been replaced by walls of glass, is a challenge for artists of our time (Plate 14). Current developments in glass technology offer vast potential to artists and architects open to exploring their implications. Stained glass artists, concerned with the aesthetic power of the medium, can benefit greatly from an openness to such potential. A survey by the US magazine *'Architectural Review'* of current technological developments concluded that:

> *'burgeoning developments in the science of glass outstrip the creative impulse on the part of architects to fully exploit the possibilities.'*[27]

For the majority of glass artists, this statement holds a similar poignancy. In Chapter 3 the work of contemporary artists who have found innovative solutions to the challenge of designing glass for architecture today is examined in the form of case studies. These artists continue the tradition of stained glass which is concerned with the power of glass to transform architectural space.

CHAPTER 3 : CASE STUDIES.

3.1

> *'In manipulating glass the artist is affecting fundamental aspects of architecture, fenestration, colour and light, and it can be difficult for an architect to conceive of these not being entirely under his control. However, when a good creative artist starts to work on them, a world can be created which many architects do not inhabit (and which makes a lot of them very nervous).'* [1]

Speaking at the *Glass in the Environment* Conference, held in London in 1986, Michael Wiggington set out the concerns of the event which aimed to encourage a dialogue between glass artists and architects. The reluctance of architects to commission artists was acknowledged, along with the importance of integration and collaboration.

> *'If we were, for example, to consider the artists as members of the building design team, rather than as some rare and exotic species invited, reluctantly or otherwise, as guests at the end of the design process, and if artists and designers themselves were to register and proffer solutions for some of the problems encountered in architecture by architects, collaboration would be much more commonplace.'* [2]

3.1.1 Such collaboration demands that the artist have an interest in, and sensitivity to, architectural concerns. It is true that not all artists working in the field of stained glass wish to adopt this approach. An alternative position was stated quite clearly by Ann Warff, the Swedish glass designer, at the same conference. Her work is concerned with self-discovery, producing individual works, unrelated to physical context. Although she has completed some architectural commissions, she views these works as "guests in architecture", autonomous works which in no way relate to the setting.

> *'These personal statements, these personal individual works, wish to be free, and cannot with ease be anchored in any particular architectural work: thank god..'* [3]

Similar to paintings on canvas which hang within architecture bearing no relation to their surroundings, Warff creates works using the traditional techniques of stained glass. Glass as a material can be used in endless ways with endless intentions guiding its manipulation. Stained glass, is clearly not by nature 'architectural', but can operate in this way when applied skilfully to the task. The view of the glass artist as the 'exotic creature', however, limits the artists potential to produce integrated architectural works. Rather, as Jochem Poensgen stated, the emphasis is on the creation of the...

> *'..sensational masterpiece created for the sole purpose of admiration.'* [4]

3.1.2 In the case studies which follow, the work of three artists will be examined. Each one has been selected as a result of their collaborative experience and their innovative approaches to the production of integrated architectural works. Each case provides insight into the working practice of the artists and their approach to the material. Innovative methods of construction are adopted by each artist in the fabrication of the works. It can be seen that this innovation is embarked upon in response to the demands of the buildings in question. Jochem Poensgen, at the 1986 *Glass in the Environment* Conference, discussed the need for the 'appropriate' in both the design and construction of glass for architecture. The appropriateness is determined through a dialogue between the artist, the architect/client and the building. An openness to new techniques and materials is vital in this.

> *'For years we stained glass artists were obsessed by the thought of finding the freedom and independence that is a prerequisite of our work. With this I mean that we had to abandon burdensome traditions, and find new, hitherto unknown ways. This was necessary and will always be necessary in the future.'* [5]

In the third of these studies the work of an American artist who has worked extensively with new developments in glass technology is outlined. Again, working methods are examined and of particular interest is his large scale applications of dichroic glass. Two architectural projects are detailed.

3.2 ALEX BELESCHENKO.

Born in Corby, Northamptonshire, 1951, Beleschenko is currently one of Britains leading architectural glass artists. During the past ten years a number of major works have been completed by the artist and characteristic of these projects has been an innovative approach to the material and its incorporation into contemporary architecture.[6]

Beleschenko states that his work is driven not by "any particular bent towards technology"[7], believing that "drawing with a toothbrush and charcoal is as feasible a method in the creation of a work of art"[8]. His work is ideas, rather than technique-led and methods he has chosen have served as practical solutions in achieving visual goals rather than as ends in themselves.

With a background in painting and print-making, his involvement with glass began in 1978 when he studied architectural stained glass at Swansea School of Art. Training here involved the traditional techniques of painting, staining and leading along with sand-blasting, polishing and acid etching. The technique of glass appliqué was also explored, which involves the gluing of coloured glass elements to a backing sheet of glass. Beleschenko was drawn to this method which enables the edge of the glass to be visible, more usually embedded and hidden in the lead-lines of traditional stained glass panels. In the desire to explore the way in which light can be held, diffused and refracted in endless ways both subtle and dramatic, no treatment or process is rejected. Working with light in this way, his work aims to bring something to the experience of individuals viewing a piece which does not necessarily depend upon their understanding of it as a work of art. Similar to the uplifting feeling experienced as one walks through a wood, observing the dappled, filtered light as it passes through the leaves of trees, his work seeks to stimulate the senses.[9]

His desire to abandon lead-lines which interrupt the flow of colour and texture of one glass to another, led to his experimentation with other methods of constructing glass panels. Certain technical problems had to be combated. Thermal expansion is such that coloured and clear glasses respond to different degrees and dimensional mismatch stresses are introduced. Problems were experienced in the technique of glass appliqué, with coloured glass becoming detached, or the backing sheet of clear glass shattering due to the stresses experienced as the the glued glass moved on the surface. The malleable nature of lead makes it able to deal with this movement in leaded windows. A further initial problem with appliqué was the dependance on glues whose life expectancies were unknown. Windows constructed in the 1960's using glue, later disintegrated when the adhesive perished.[10]

Beleschenko developed a method of laminating glass which had minimum reliance on adhesive and enabled the inclusion of a range of glass types. Rather like a glass sandwich, panels are constructed of two outer layers of float glass, with coloured/textured glasses enclosed between the two sheets. One of the outer layers is placed flat and strips of float are cut, placed on top and glued, framing the sheet. Within the frame the glass elements are placed, edge to edge, having been ground to allow them to abut each other tightly. The top sheet of float is then placed on top and glued to the inner glass frame.[11]

The commission for Stockley Park, Heathrow, completed in 1986, was the first public building to include glass constructed in this way (Plate 15). Arup Associates (architects) held a competition to select a design for the glass which was to give impact to the main entrance of the building. Although not totally convinced of the congruency of stained glass in a modern building of this nature, James Burland of Arup Associates was aware of the potential power of the medium. This was acknowledged, on his part, after observing the impact of light and colour on a group of children, entering an environment where stained glass was present.

The initial design submitted by Beleschenko and selected by Arup associates, was of a leaded window construction. In discussions which followed (these involved Beleschenko working for ten days in the Arup office) it was requested that leading was not used, due to the design of the building.[12] It was felt that this traditional method would not fit with the clean lines of the building facade. It was feared by Sir Philip Dowson (Arup), that interconnecting lead-work would appear too dominant in such a context.[13] The associations with the medieval roots of the tradition were to be avoided. The proposals were developed with a spirit of collaboration. Mike Lowe of Arup's stated:

> *'We were talking together as designers, rather than stained glass artist and architects and engineers, separately.'* [14]

Beleschenko, having been experimenting with the laminating technique, was then able to apply it in a large scale project. The panels were constructed in collaboration with the Derix Studio, Germany, who subsequently have used this technique to construct works designed by others (Plates 16 + 17). At the design stage, it was not known who the occupiers of the building were to be, this did not therefore influence the imagery. Beleshchenko believes strongly that...

> *'Public art must relate to the building; it must have a content'*[15]

Of influence here was the architectural geometry and the landscape surrounding the site. Arup's simple brief in terms of the content of the piece was that it should reflect the character of the landscape. The *'series of high-tec pavillions'*[16] at

Stockley Park are set around a lake. Glasses used in the window give an impression of rippling water in which trees, viewed through, appear as reflections. Beleschenko states that the individual coloured squares of glass, predominantly of green and blue, were designed to relate closely in size to that of leaves. The strength of the design is designed to give the building a sense of identity.

After completion, a computing company moved into the building, possibly drawn to the apparent references to computer-generated imagery. The small coloured squares appear like pixels on a visual display unit, each contributing to the larger picture.

Beleschenko's process of design is influenced greatly by the architectural setting; light source; available budget; and his ideas and feelings at the time. In this project he was called in at the 'detail planning stage' which occurs after the overall design of a building has been decided. The integration of this piece into the overall building design is the result of a willingness on the part of Arup Associates to collaborate and form a real dialogue with the artist, something so often missing in the commissioning of public art works.

Another more recent example of successful collaboration is in the vast areas of glass designed and constructed by Beleschenko for St Johns College Oxford. Architects MacCormac, Jamieson, Prichard, wanted to include artists in the design of a new part of the college and approached the Public Arts Commission Agency to select appropriate people. Glass screens were commissioned from Beleschenko, along with a burnished steel gate by Wendy Ramshaw and prints, which recorded the development of the project, were produced by John Howard.

The architect initially envisaged the use of plain clear glass screens in the atrium area of the building, as the intention was to admit the maximum amount of light. The building is set below the ground level of the exterior garden quadrangle and the architect viewed the project to be concerned with an underworld, consisting of the atrium and its surrounding rooms along with an overworld, made up of the terraced area above.

Beleschenko, inspired by the concept of underworld, decided to incorporate impressions of running water and crystalline rock structure into the design of the glass screens. Squares of totally clear float glass, imported from the USA, are sandwiched between outer sheets of toughened float glass, forming a glass laminate similar to that used in the Stockley Park commission (Plate 18). Each piece of clear glass, which is 10mm thick, was carved using a diamond saw, creating deep grooves which form a matrix pattern across the whole design. Edges were chipped away, producing varied optical effects, reflecting and refracting light in multiple ways. Small pieces of coloured flash glass were glued to the edges of each square, acting as spacers whilst also providing colour, seen from different angles, reflected in the chipped surface of the glass.[17]

The glass screens, unlike Stockley Park, were constructed entirely in Beleschenko's studio. This took a year to complete and involved the positioning of 60,000 pieces of glass, set within panels measuring 2.2m x 1.4m. A team of assistants numbering, at times, twelve was needed to enable fabrication.[18]

To eliminate the inclusion of dust between the laminated sheets, Beleschenko used a chamois to clean the glass which was then coated by a low adhesive film. This was removed as the outer sheet of float glass was lowered on to the assembly. When the panels were placed into a vertical position, a minimum amount of movement occurred as the pieces dropped into place. The final result achieves the architects desire to retain views through the screens, whilst creating an ever-changing play of light.

> *'The effect is magical, altering in transparency and colour according to your position and the time of the day; the screen changes from being an assembly of gem-like fragments, to a visual filter, to an almost opaque space-dividing element'* [19]

The success of the work again was reliant on strong collaboration between Beleschenko and the architect, enabling interpretation of the vision by both parties in unison.

> *'It is a stunning and most unusually successful example of collaboration between artist-craftsman and architect that enhances the work of them both with an intensity rarely seen since the Arts and Craft Movement'* [20]

This project, like all that Beleschenko embarks upon is characterised by a fresh approach to the medium coupled with a desire to create architecturally integrated works. With an experimental approach to the material, new techniques are developed as he strives to find practical solutions which visualise his ideas.

3.3 KESHAVA[1]

Keshava, who is otherwise known as Antonio Luis Sainz, is a glass artist living and working in Barcelona. Born in Logroña in 1952, he initially studied architecture at the University of Navarra from 1969 to 1975. He worked as an architect in La Rioja until 1983, when he moved to Barcelona to study stained glass and design at the Escuela Massana. His first exhibition, on completion of his studies was at the Institute of North American Studies, following which he visited the USA in 1987 to further study glass design until his return to Barcelona in 1988.[21]

As an architectural glass artist, Keshava has practiced in the regions of La Rioja, Navarra, Valencia and Cataluña. Over the past eight years, Keshava has developed a method of working with glass which serves his intention to unite glass design with contemporary architecture.[22]

Initially, the traditional method of leading glass elements together was used to construct his abstract works, as seen in his window for the *Delegacion de Hacienda de Logroña* 1989 (Plate 19). An experimental approach to his work led him to seek alternative construction methods, investigating bonding techniques, in order to achieve an aesthetic appropriate to the spirit of contemporary architectural design.[23]

His architectural background taught him that, in general, architects' knowledge of the potential of glass for architecture is limited. In the execution of building design and construction, standard glass products are used and an imaginative approach to the application of glass is all too often lacking. The desire to change this drives Keshava and much of his time is spent designing schemes which he presents in model form to architects in an attempt to expand their understanding of what might be possible.

Footnotes.

1. This case study was printed in the magazine of the British Society of Master Glass Painters *STAINED GLASS*, Issue 1 1996.

One such scheme for a railway station was presented to the architect, Josep Maria Fargas who, although unable to pursue the project, was impressed by Keshava's approach. In 1990, however, when Fargas was involved in the design of offices at Diagonal 640, Barcelona, Keshava was approached tentatively to examine the possibility of creating a very large scale window, measuring 22m wide by 25m high, for the entrance to the building. Having drawn up initial ideas, the commissioner of the building was consulted in January 1991 and, responding positively, it was decided that the the work should go ahead. The window, entitled *'The Awakening Planet'*, was installed in 1993 and is the largest and most important commission completed by the artist to date (Plate 20).[24]

Working on the theme of universality, the window refers to the design and function of the building; its location and its relationship to other buildings around the world. The computer was an essential tool in the execution and scaling up of the design, which consists of a satelite view of the earth, enveloped by swirling cloud formations. This sits directly above the rotating doors which form the entrance to the building. The vast image of the world occupies the lower two-thirds of the window, above which an abstract network of bonded coloured squares[2] extends, representing urban development. The streets of modern Barcelona are based upon this grid system and the roads designed by Cerdá to carry the densest traffic are identified in the design by three red lines which extend diagonally across the window. One of these, named Avinguda Diagonal, is the road on which the building is located.

In the lower third of the design, the rigid grid system gives way to a more random formation, which Keshava describes as 'real' and 'concrete' contrasting with the abstract idealised logic of the upper area of the design. The predominant form of the circle represents universality, referring to the communication world-wide between people, day to day, from offices of this kind.[25]

Footnotes.

2. Coloured glass is bonded to the clear using a two-part silicone adhesive. The silicone which provides a flexible bond, is able to accommodate the movement of the glass which expands and contracts at different rates with changes in climatic conditions. Using a sheet of adhesive vinyl, Kashava initially completely covers the clear glass providing a mask. Then the vinyl is cut and peeled off from the areas where the coloured elements are to be adhered. Sticky blocks of foam are placed around the edges of these areas to hold the coloured glass in place when gluing. The silicone is applied to the clear glass and the coloured glass is then pressed down firmly pushing out excess silicone onto the vinyl mask which when set, is removed.

The facade of the building consists of a vast reflective glass expanse. On approaching the building, which was visited for the purposes of the research in 1995, one is struck by the simplicity of this slim rectangular form. Buildings opposite are reflected on the face of the building.
Cut into this continous plane and recessed slightly, is the Keshava window. Most of the glass here is acid etched float, and appears matt in comparison to the high gloss of the rest of the facade. On entering the building, one is met by a vast reception area, from which the whole of the window can be seen - on ground level, and also as one ascends five floors in glass lift shafts. A dappled light fills the area and the acid etched glass has a breath-taking luminosity.

The window is made up of panels each of which measure 3.95m x 1.8m which are bolted to a steel frame which itself imposes a grid system over the entire glazed area. The square is repeated throughout the design and refers to its role as the established form in architecture. All architectural design, Keshava says, is based on this. The use of imagery and symbol in this work, thus refers to "the building; the city; the world"[26]

A control desk is situated in front of the entrance staffed by security personel. Due to the nature of the glass used in the window, the architect felt additional protection from the suns rays might be needed in this area. Coated glass, more usually seen on this scale is designed to achieve solar control. To compensate for the lack of this in this area, a moving sculpture was designed to act as a shading device. Controlled by a computer housed in the reception desk, this piece tracks the movement of the sun, slowly shifting its position to shield this area from direct light and heat. The design of the sculpture, which is based on a satellite, complements the predominant planet image of the window design (Plate 21). Made up of triangles of opaque glass, each one carrying bonded prisms and irridescent glass, the elements form a concave dish, supported on a steel framework. Cables running from the dish, support the form from an enormous steel structure, within which the sculpture rotates. One is struck by the stark contrast between the lightness and delicacy of the 'satellite' and the huge steel girders which support it. This box-frame structure also obscurs the view of the window from within the reception area. When interviewed, Keshava voiced reservations about such a heavy support system, and the steel glazing system, which detracts, to an extent, from the glass. His hope is that, for future projects, engineers will seek light-weight solutions.

Despite this, the impact of the work is great. To view glass design on this scale -

approximately 500 square metres - is extremely rare, making this one of the largest stained glass windows in Europe. The innovative approach adopted to construct both this, and its accompanying shading device make this an important work. Collaboration with the architect in the development of ideas and solutions to meet the particular demands of building, was vital in the creation of this integrated work. Keshava intends his work, embodying this approach, to be a part of a new generation of stained glass for contemporary architecture. Identifying the two past generations as, the gothic period and then the modernists, this work along with that of some of his contemporaries, signifies a third.[27]

> *'Problems of light and vision control, of spacial definition and colour, abound in architecture, and a skilful artist is just as likely to be creative in responding to these problems as an architect is, provided he takes the trouble to understand them'* [28]

The skilled glass artist brings specialist knowledge of the material and how it functions visually, in his/her approach to design. Acquired through experimentation and observation, an understanding of the light manipulating properties of glass makes the potential contribution of the architectural glass artist, a powerful one.

3.4 JAMES CARPENTER.

James Carpenter is an Amertican glass artist whose fascination for the material is at the heart of his experimental approach. When aged 16, he participated in a school trip and assisted commercial fishermen night fishing. The experience of looking into the sea, over the side of the boat, seeing his reflection along with points of dancing light, below which was a captured phosphorescence, has influenced his appreciation of the power of light. His work with glass has centred upon the exploration of light manipulation within architectural settings.

> *"I think the inherent interest is really about light. The material happens to be glass but the actual phenomena you're working with is light"*[29]

Carpenter initially entered Rhode Island School of Design with the intention of studying architecture. Dale Chihuly headed the glass program (part of the sculpture department) from 1969 and seeing work under way in this area, Carpenter became excited by the material. Working with Chihuly, various experimental sculptural projects were undertaken including one in which they froze glass tubing filled with fluorescent pink powder, in blocks of ice five feet high. The piece was observed over time as the ice melted, producing varying levels of fluorescence. Further work involved the use of neon, mercury and argon gases, enclosed in blown forms which created an environment, exhibited at the Museum of Contemporary Crafts in 1971.[30] Up until 1979, Carpenter designed vessels for Venini, on Murani island, he was also artist in residence at Steuben Glass in 1977. At Steuben, his interest in light was explored in deigns such as *'Double Volume'* in which he fused two blown forms together with the effect of creating a ring of refracted light at the join.[31] His interest gradually moved away from what he saw as the narrow concerns of American studio glass and towards the application of glass for architecture. With a residency at Corning, he was able to develop his experimental approach and investigate the potential of various developments in glass technology. He developed an interest in the potential.....

> *"..for a single piece of glass to incorporate innumerable functions."* [32]

Exploring photosensitive properties, melting chemicals into glass and exposing it to ultra-violet light, resulted in the production of a spectrum of colour. Working with glass technologists, Carpenter became aware of the artistic potential of developments made in space, electronics and chemical industries and how little exploited these technologies are in architectural design.

3.4.1 In 1978, Carpenter formed a company entitled James Carpenter Design Associates. Joining him were an architect and two industrial designers. Specialising in the design of glass for architecture, the first major work by the company was the design of the *'Spectral Light Dome'* for the Portland Centre for the Performing Arts (Plate 22). A national competition was won to secure the commission and the design consists of a thirty-five foot inner dome structure made of steel, supporting 500 strips of dichroic glass, which measure $^1/_4$" x 3" x 6'. The glass is illuminated as light passes through the clear glass covering dome.[33]

Inspired by a time-lapse photograph of the night sky, the work refers to the Greek tradition of the outdoor theatre, open to the dome of the sky. The glass strips are supported by brackets, attached to an internal steel dome structure. This was designed by Carpenter and his associates.

A commission for a Chapel in Indianapolis, is a further interesting use of dichroic glass forming a three dimensional grid on the interior of large float glass glazing which measures 30 x 10 feet. Horizontal and vertical planes of dichroic glass are bonded to the glazed area using a silicone adhesive. The result is a window which can appear colourless when the viewer is positioned directly before it - seeing only the edges of the horizontal and vertical planes of dichroic glass. In direct sunlight, however, it projects a dramatic display of coloured light into the chapel by reflection and transmission (Plate 23). In this way Carpenter presents a contemporary vision of the role of stained glass which traditionally he defines as...

> *"...dealing with the transmission of image, with the transmission and projection of myth into architecture"* [34]

Unlike the traditional transmission of the myth of saints and angels into such a space, Carpenters work presents an alternative:

> *'..in keeping with the twentieth century sensibility and spirit, a more rational but no less wondrous myth of sunlight in time and space.'* [35]

The Chapel window demonstrates clearly the unique properties of the glass in a simple yet dramatic way. Placing the glass horizontally and vertically, both the colours produced in transmission, and in reflection, are projected into the interior. The powerful impact of coloured light in this context follows a long tradition and yet the form the work has taken demonstrates a new solution, appropriate to the application of a new material and specific to the requirements of such a site.

> *'Carpenter is an unusual combination of technical specialist and artist'.*[36]

With his ability to see architectural applications in unrelated technologies, along with his interest in solving architectural problems Carpenter demonstrates a dynamic contemporary role for the architectural glass artist.

CHAPTER 4: INTO THE 21st CENTURY - DEVELOPMENTS IN GLASS TECHNOLOGY.

4.1 With the move away from the load-bearing wall and towards the glass skin, in the historical struggle for light, new problems are encountered which technologists continue to strive to overcome. As Paul Scheerbart acknowledged at the turn of the century, the glass building does not cope well with complex and changing environmental conditions. The search for solutions to these problems have formed the focus of glass research. A study by Richard Rogers and Partners in 1978, for Pilkingtons reached the following conclusions:

> *'It is no good having a sophisticted mechanical services system for a building and a poor skin performance.....A time responsive, variable quality skin system is the only logical answer to the problem. A building becomes like a chameleon which adapts. A properly equipped and responsively clothed building would monitor all internal and external variables, temperature, hygrometry and light levels, solar radiation, etc., to determine the best energy equation given these conditions and modify the building and its internal systems accordingly.'*[1]

4.2 Thin film technology applied to produce coatings on glass is currently the major means by which control of these factors is attempted. This technology will be covered in greater detail in Chapter 5. Research into variable transmission glazing is underway. Chromogenic glasses have sensitive coatings applied which respond to changes in environmental conditions. There are three main categories; 'photo chromic', which is sensitive to sunlight intensity; 'thermochromic', responsive to temperature; and 'electrochromic' which responds to application of an electric current. The glass can change from clear to opaque or reflective under stimulation.

Photo chromic glass responds to infra-red and ultra-violet radiation, becoming darker, thus reducing the level of light transmission. This glass has been used, to date, in spectacle manufacture, providing shading for lenses in high-level lighting conditions. Applications for architectural purposes are limited as in winter months when solar gain is desirable, the glass will continue to respond by becoming absorptive. As the response of the glass cannot be overriden by building occupiers, current research suggests that this particular chromogenic glass may not prove efficient for use in buildings.

Similar limitations are found with thermochromics. The optical properties of these coatings change by means of a chemical reaction which is thermally induced. There is continuing interest in this area, particularly in the application of thin films of metal oxides which transform to a metallic state under certain temperature levels. Potential for the use of this in shading devices is envisaged.

Electrochromic glass, which changes transmission levels of light and heat by means of an electrical impulse, appears to show the greatest potential in the current pursuit of the 'dynamic skin'. Transparent multi-layer coatings are applied to glass and with the application of a small electrical current to the electrochromic layer, the appearance of the glass changes from clear to tinted. The levels of solar and light transmission are thus changed. By reversing the current, the glass returns to clear. Control of the glass can be incorporated into the centralized service system of a building, but also can have the option for override by individual occupants to achieve control over local environments.[2]

Further work at laboratory level must be done to overcome technical problems before this product will be applied for architectural use. Studies by the Lawrence Berkely Laboratories, California, show that this glass 'constantly out-performs conventional systems'[3] in its savings on the energy costs expended on provision of lighting and cooling devices.

Liquid crystals produce a further chromogenic device activated by electric current. When no current is applied, the liquid crystal molecules rest in a disorderly structure which diffuses light, producing an opaque glazing panel. On application of electric current, the crystals realign themselves, with the result that the glass appears transparent (Plate 24). Power consumption of this device is higher than that of electrochromics, as continuous energy is required when in activated state.

Developments in holographic glazing, suggest great potential for the enhancing of daylighting in internal environments. The films, which are laminated between two sheets of float glass are transparent and can be designed to reflect any wavelength in the solar spectrum. Design of specific geometries to produce an holographic diffractive structure, can result in systems which track the sun and redirect light into the building increasing the spread of natural light and reducing dependency on artificial sources.[4]

The potential of producing a dynamic building skin which can operate as a medium for communication is also currently under examination. Electroluminescent displays consist of a stack of five thin films. When an electric current is applied between the two outer film layers, light is emitted. This technology is based on flat panel television and produces a pixelated matrix structure, which enables multicolour display. Although these devices usually incorporate an opaque, reflective, aluminium thin film, it is possible to replace this with a transparent layer to produce a glazing material.[5]

The future architectural potential of these technologies is vast and exciting. Further work must be done before they become a part of our eveyday experience. What this experience will consist of is currently the subject of fantasy, limited only by imagination. Similar to the initial excitement at the turn of the century expressed in the writings of Scheerbart[6] and others, there is a renewed visionary feel generated by the potential of these technologies as we approach the next millenium.

> *"Look up at a spectrum-washed envelope whose surface is a map of its instantaneous performance, stealing energy from the air with an iridescent shrug, rippling its photogrids as a cloud runs across the sun, a wall which as the night chill falls, fluffs up its feathers and turning white on its north face and blue on its south, closes its eyes but not without remembering to pump a little glow down to the porter, clear a view patch for the lovers on the south side of level 22 and turn 12 per cent silver just before dawn.'* [7]

With such sophisticated dynamism as the ultimate goal in achieving comfortable, efficient and beautiful buildings, its reliance on perfecting new technologies means that, currently, it remains a vision for the future.

4.3 Mechanical devices which offer a dynamic performance are presently explored by architects and engineers, along with 'passive' systems which seek to overcome problems of solar gain, heat loss and fluctuating light levels.

The Arab Institute in Paris, designed by Jean Nouvel is an interesting example of mechanical shading devices (Plate 25). Multiple irises open and close, to allow varying degrees of lighting to enter the building. Truly dynamic, this facade is opaque (constructed of steel), allowing shafts of controlled light to enter only through the holes created in the shading devices.

The Inland Revenue's offices in Nottingham (1995) operates an integrated system of computer controlled devices and passive systems which aim to accommodate changing environmental conditions and improve building performance. Hydraulically controlled lids to the glass stair towers, rise up to allow hot air to escape when necessary (Plate 26). Artificial lighting is introduced only when sensors detect a drop in daylightig levels. Beneath each window, light shelves are positioned which reflect natural light up, onto the ceiling. The undulating structure of this, disperses light around the interior, spreading it further than it would naturally fall, thus reducing the need for artificial lighting during the day.

The design for this building, by architect Sir Michael Hopkins, was selected following an architectural competition. It marks a change in the approach to current building...

> *'..the most prominent sign that British architects are moving away from the "bolting on a bit of greenery" approach towards an agenda that involves thinking about the environment from the very conception of the building."*[8]

This current awareness dates back to the energy crisis of the 1970's. Glass facades prove a cost efficient building material, resistant to corrosion and atmospheric pollution which affect many other finishing materials. The many coatings applied to float glass today, to achieve solar control create a passive system widely used in architecture. (see Chapter 5).

4.4 The Building Research Establishment has been involved in investigating the effectiveness of various systems devised to increase energy efficiency in buildings. One area of research is concerned with 'innovative daylighting systems'. Problems of uneven natural light distribution in buildings often mean that areas around glazing receive high-level lighting whereas deeper into architectural space, levels are low. This gloomy environment more usually demands the use of artificial light sources to improve conditions. Demands on energy consumption are thus increased.

> *'Innovative daylighting systems are designed to even out these effects, and thus improve the effectiveness of natural light as a source of illumination for building interiors'*[9]

Even buildings with vast amounts of glazing can suffer from problems of light distribution. Open-plan, large office interiors, termed 'floorscrapers' suffer considerably from this condition.[10]

Reports by M. E Aizelwood and P.J Littlefair of BRE[11], present results of the experimentation into the effectiveness of various systems within a controlled environment. Experimental rooms were constructed, measuring 9 metres in depth, 3 metres wide and 2.7 metres high. Windows were located at one end, and selenium photocells were positioned at regular intervals throughout the length of the rooms, at a working height of 0.7 metres, to detect and measure the internal distribution of daylight. Detailed results of the studies can be seen in Appendix 1. In the study by Aizlewood, the following four systems were tested.
'Light shelves', are horizontal solid fixings which have either a white or reflective coated upper surface. Fixed to either the inside or outside of a window, or sometimes both, the device reflects light into the room. Positioned against a window pane, a degree of shading occurs, blocking some direct light from falling into the room, close to the window.

'Prismatic glazing', made of either acrylic or glass, a sheet incorporating a series of prism forms is sandwiched between two outer sheets of glass within a double glazed unit. Daylight is redistributed within a room, directing it away from the immediate area close to the glazing.

'Prismatic film system' consists of a thin acrylic film with an etched surface, which is adhered to a plane of glass and can be fixed within a double glazed unit. Similar to primatic glazing, the surface is made up of tiny etched prisms which reflect and refract light.

'Mirrored louvres' are constructed of horizontal mirrored bands placed between two outer planes of glass. Each louvre has three reflective sides and light is reflected between each face with the result that at certain altitudes of the sun, light is admitted into the room, directed towards the ceiling. At other altitudes it may reflect light back, outside, providing shading. The fixed position of the louvres can be determined at the design stage so that performance suites the particular design of the room and lighting conditions.

Tested in summer, autumn/spring and winter, each system demonstrated varying performance levels. A problem with all but the light shelves, was the amount of light transmission omitted due to the structure of the systems. Prismatic film appears transluscent, obscuring clear views through. Similarly, the structure of prismatic glazing and that of mirrored louvres obstruct clear vision and transmission, as light is refracted and reflected from the multiple faceted surfaces.

For example, under overcast conditions when increased lighting is desired within a room, the primatic glazing systems and mirrored louvres transmit only 40% of available light. Prismatic glazing worked at its best in autumn and spring when light was projected far into the room, increasing lighting levels by over 100%. In winter, when the sun is lower in the sky, lighting at the back of the room is reduced by 50%, as light which would normally have penetrated this area is redirected on to the ceiling at the front of the room. Summer performance demonstrated that the system acts to exclude daylight, shading the area close to the window, with a lighting reduction of around 75%. Some light is reflected on to the ceiling which increases illumination in the back of the room but not sufficiently to compensate for the overall decrease in lighting.

Each system tested, demonstrated varying performances under different lighting conditions outlined in the report (Appendix 1). Conclusions drawn from this study stated that although the general amount of transmitted light is reduced by all of the systems, the redistribution of lighting generally improved conditions within the rooms.

> *'The total amount of light is less, but the usefulness of that light is increased.'*[12]

The 'passive' nature of these systems, is such that they do not adapt to changes in conditions and therefore respond more efficiently to some than they they do to others. Such changes are hoped to be accommodated by the dynamic skin of the future. It may be that this will not consist of one variable transmission glass which responds to the multiple demands placed on glazing. Rather, a number of glass products, designed to operate in different ways for differing climates may be developed and combined to achieve the dynamism required.[13]

Another innovative daylighting system, which is designed to channel daylight into badly lit areas of a building, is the light pipe.[14] Daylight is directed down the pipe from a multi-axis suntracker (heliostat) which consists of a mirror, the movement of which is computer operated. Following the path of the sun, the heliostat reflects light on to a redirecting mirror which then reflects it into the pipe.

> *'The light pipe is perhaps the most technologically exciting of innovative daylighting systems because of the long distances over which it can operate. Sunlight can in principle be channelled into virtually any area of a building'.*[15]

The reduction in lighting costs which this system offers is accompanied by a reduction in cooling costs also...

> *'..sunlight already has a higher light-to-heat ratio (luminous efficacy) than most forms of artificial light.. much of the sun's heat can be removed in the piping process'.*[16]

Along with the heliostat the light pipe is accompanied by an emitter, which disperses the light as it leaves the pipe. With the aim of distributing light throughout a space, prismatic emitters have been designed. *Bodmin Solar* of Germany design a range of 'solar light effect systems' which aim also to create dramatic lighting effects within buildings. These systems introduce colour into architectural space.(Plate 27)

Light pipes can simply be hollow tubes with reflective interiors. Polished metal has proved effective. Alternatively, bundles of fibre optics have been used to great effect although at present the cost of this is prohibitive[1]. Acrylic rods are a cheaper although slightly less effective than fibre optics. Transmission operates in a similar way, by means of total internal reflection.[17]

The complicated control system necessary to operate these systems is extremely costly at present, but further research may make them a more widely used method of improving the efficiency of buildings in the future.

The environmental factors highlighted here which have motivated the ever increasing sophistication glass design and daylighting systems, are important considerations for the architectural glass designer. Already, work commissioned must fit within existing glazing systems (see commissioned work, Chapter 6) and as these increase in sophistication, the nature of glass designed by the artist, if it is to have a place as an integral element of a building, must be appropriate. In the following chapter, thin film coating will be examined. This technique is used to produce specialist glass for architecture and is widely used today to tackle problems of heat loss and gain in buildings. Dichroic glass, produced in this way, will form the focus of further technical investigation. Analysis of its potential as an architectural medium will be examined in Chapter 6.

Footnotes.

The potential of fibre optics to move light within buildings has been the subject of research in Japan as outlined in Michael Wiggington's book *GLASS IN ARCHITECTURE* (published in 1996 by

Phaidon). Marketed in 1990, the device by Asahi entitled the 'Himawari' (sunflower), transmits daylight by means of a flexible hose, throughout a building. Light is gathered by a sun-tracking mechanism consisting of multiple lenses which collect and divert the light along fibre optics. Sockets within rooms, fed by the optical fibre, provide a source of daylight which can be plugged into with flexible fibre optic cable to release the light into the room.

CHAPTER 5 - THIN FILM TECHNOLOGY.

5.1 Dichroic glass is one of a family of high tech coated glasses. The strong visual impact of this glass, its unique qualities of transmission and reflection, led to its selection as the focus for research as an architectural medium. In developing an understanding of this material and its relationship to other coated glass already extensively employed architecturally (Plate 28), a study of thin film technology has been conducted. Coating processes and functions are outlined here by way of introduction, followed by an analysis of dichroic glass and its production.

The area of thin film coating developed rapidly after World War II, with advances in technology enabling increased possibilities. Much of the work in this area has been concerned with the field of 'fine optics' for instrument applications.[1] Architectural application has a shorter history, developing only within the last twenty-five years. Increasing control of the process enabled the coating of large areas of flat glass and the driving force behind developments in this area was the need to control heat loss and gain within buildings. Dramatic increases in energy costs in the 1970's made it imperative to increase the efficiency of buildings. The desirability of glass as a primary architectural material meant that it was necessary to overcome the reliance on expensive air-conditioning which counteracted the summertime greenhouse-like interior environment. Conversely, a solution to the loss of heat through the glass at night and in winter also had to be found.

By deposition of chemicals onto the surface of glass, it was possible to control both problems. Currently 5% of the total output worldwide of flat glass (1.2 billion square metres) is a 'speciality glass' in that it is body coloured, coated or modified in some way.[2] This percentage has rapidly increased over the past twenty years, indicating a growing interest in the application of thin film coatings. Glynn Williams (Pilkington), in his lecture to the Society of Glass Technology[3], 1990, stated:

> *'The indications are that this trend will continue, resulting in the development of more sophisticated products incorporating more layers with new materials.'*

As outlined in Chapter 4, research into sophisticated chromogenic glasses, which enable variable transmission, is currently underway, exploring further the architectural potential of thin film technology with implications for future building design.

5.2 COATING DEPOSITION.

For architectural purposes, coatings are intended to change the optical qualities of glass by altering the properties of transmission and reflection. The historical function of glass as shield to the elements whilst still admitting light, is thus extended, as it becomes an integral mechanism in the balance of energy within the building.

More widely, coatings are deposited onto glass and metals for other purposes, including :

- TO CHANGE MECHANICAL QUALITY for example, the improvement of scratch resistance by deposition of antifriction layers. Both silicon dioxide and titanium dioxide, perform this function.

- TO CHANGE CHEMICAL QUALITY increasing resistance by means of applying anticorrosion coatings, particularly for use on communication fibres and extreme optical glasses. Coatings can also increase the hydrophilicity of glass surfaces. This has been applied in the production of antifogging ski goggles.

- TO CHANGE ELECTRICAL QUALITY by deposition of semi-conductor coatings, removing static charge and producing for example, anti-fogging devices.[4] In the production of electroluminescent displays, a stack of five layers, resulting in light emission. Materials deposited include phosphor, silicon dioxide and aluminium.[5]

A wide range of coating techniques is currently in use, some of which were developed within the glass industry and others which have grown out of developments within the optical and electronics industries. These methods can be divided into two categories referred to as 'on-line' and 'off-line'. The former refers to coatings applied to the continuous ribbon of glass as it is manufactured and before it is cut into plates and removed from the production line. Off-line coating takes place after this stage, when plates of glass are coated in a separate procedure and often at a different location from its place of manufacture. Each procedure is suited to different methods of coating deposition which will now be outlined.

5.3 METHODS OF PRODUCTION

ON-LINE COATING

Certain conditions for on-line coating are provided as a result of the float process. These include the continuous movement of a ribbon of glass at a controlled temperature, along with the opportunity of application in a reducing atmosphere (inside the float bath) or in an oxidising one (within the lehr). The heat in these environments (900°C - 600°C in the float bath and 600°C to room temperature in the lehr)[6] make them ideal for coating processes which are thermally dependent. These include liquid spray deposition (LSD) and chemical vapour deposition (CVD). Coatings produced in this way tend to be hard and durable. Both techniques are ideal for deposition of oxides with the latter also suitable for deposition of metals. Problems of optical uniformity can occur, however, across surfaces wider than three metres. With LSD, there is also a problem of collection of the large volumes of solvent which accumulate during the process. Pilkington developed a CVD process in the 1970's which involved the production of a coating silicon, with its high refractive index, by means of the thermal decomposition of silane in a reducing atmosphere. using these methods, various reflective and low emittance glasses used to improve insulation of buildings are produced.

OFF-LINE COATING

One of the major methods of off-line coating deposition takes place under vacuum. The material to be deposited is transformed into vapour within a vacuum chamber to enable free-flow of particles onto the glass surface (Plate 29). The process by which the material is vapourised can differ, the two main techniques being 'thermal evaporation' and 'sputtering'. The first of these involves the placing of a material into evaporation boats within the chamber which are then heated, or directly bombarded with an electron beam. This technique enables the production of multi-layer coatings which tend to be rather fragile unless sealed within an outer layer of silicon dioxide. If not protected in this way, these coatings can only be used within sealed double glazing units.

The technique of sputtering was developed in the 1970's by Leybold Heraeus in Germany and Airco Timescal in the USA.[7] A number of large scale plants enabling the sputter coating of sheets of glass measuring 6m by 3m in two to three minutes are currently in operation. With cathode sputtering, the material to be deposited is bombarded with argon ions in an electrical dc field. This results in the evaporation of the material which condenses onto the glass. Coatings tend to be uniform and wastage of the material is minimum. Magnetron sputtering is a method which enables a deposition rate ten times faster than the cathode technique and, for this reason, has commercial advantages.

ANTI-REFLECTION COATINGS

In the coating of photo-optic devices and lenses, anti-reflection coatings are of great importance. Glass has a refractive index of 1.52 and reflects around 8.4% of received light, 4.2% from both the front and back surfaces. This property can be unwanted in the design of certain lens systems. The application of high performance wide-band anti-reflective (AR) coatings on to glass can reduce this level to around 0.1% - 0.3%. Currently, AR coatings are employed not only for optical instruments, but also on data display and television screens; picture framing and showcases; along with architectural glazing.[8]

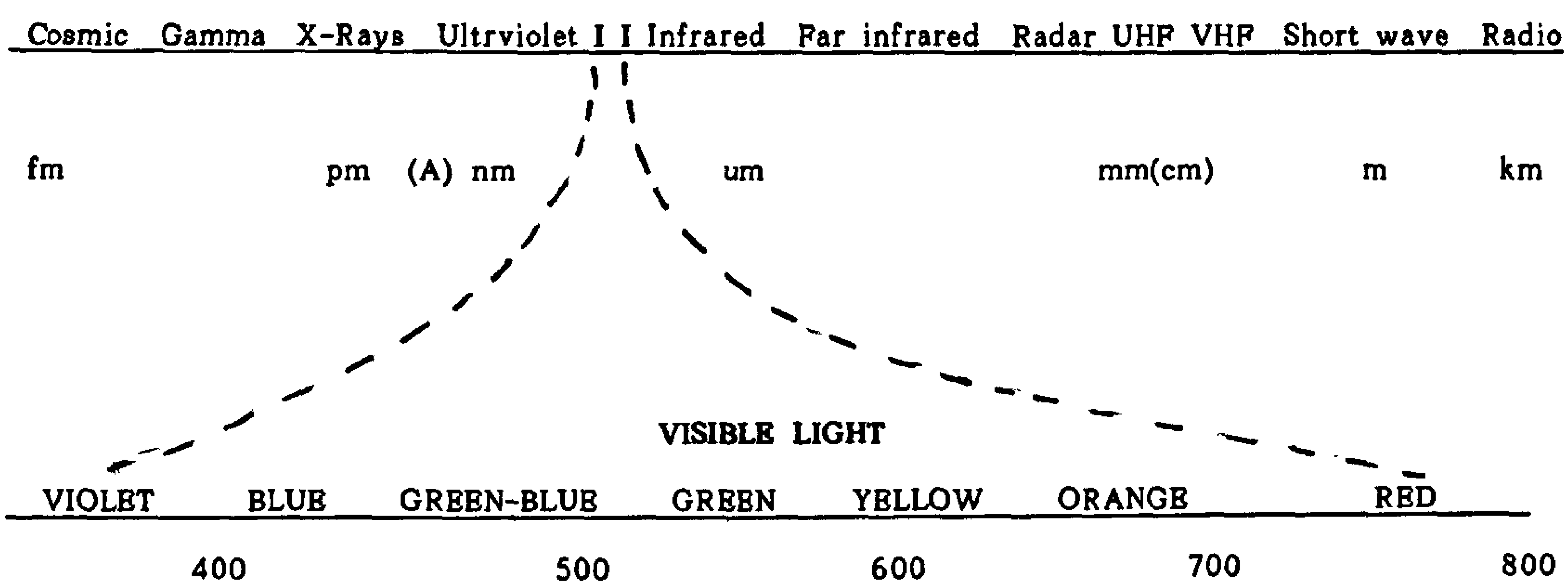
Reduction in reflection is achieved by the interference of light as it passes through thin layers of substances with a refractive index different to that of the glass substrate. By means of depositing multiple layers of alternating high and low refractive index, dielectric thin films, the transmission and reflection of wavelengths of light within the visible spectrum can be manipulated and controlled. To produce AR qualities, coatings are applied to both surfaces of the glass. Vacuum coating is the most suitable method of application, although problems are experienced with this method in large scale application. Dip coating, which by nature coats both sides of a substrate at once, has been used for larger scale application. This process involves the submersion of a sheet of glass into a bath of a solution of oxides. The sheet is then uniformly drawn into an atmosphere with a fixed content H_2O level. Condensation then occurs and the formation of a gel is achieved. the sheet is then heated to transform this into a transparent metal oxide coating. The process can be repeated to achieve multi-layer coating. The chemistry of this process is similar to that of the sol-gel process which has commercial advantages in its compatibility with automation and bulk output.[9]

5.4 MANIPULATION OF LIGHT

Coatings on glass are designed to manipulate the light in ways other than those which occur naturally as light passes through uncoated glass. As stated earlier, float glass manipulates light by reflecting back around 4% from each surface, whilst transmitting around 80%. Knowledge of the physics of light enables the calculations necessary in the design of coatings which enhance the natural qualities of glass.[10]

The spectrum of colours which appear in a rainbow or a prism, show clearly the separation of 'white' light into its component parts. Scientists discovered that light operates in a wave motion. Each of these colours distinguishes the differing lengths of light waves. The visible lightwaves revealed by the prism and the rainbow are only a small part of a much wider electronmagnetic spectrum which includes ultra-violet and infra-red, along with gamma and radio waves. All of these waves are termed 'radiant energy' and differ only in wave length. Light is, therefore, visible radiant energy.

Electronmagnetic Spectrum[11]



Electromagnetic wavelengths are reflected, absorbed, or transmitted when they hit any surface. One of four things are likely to happen to light as it strikes an object[12]:

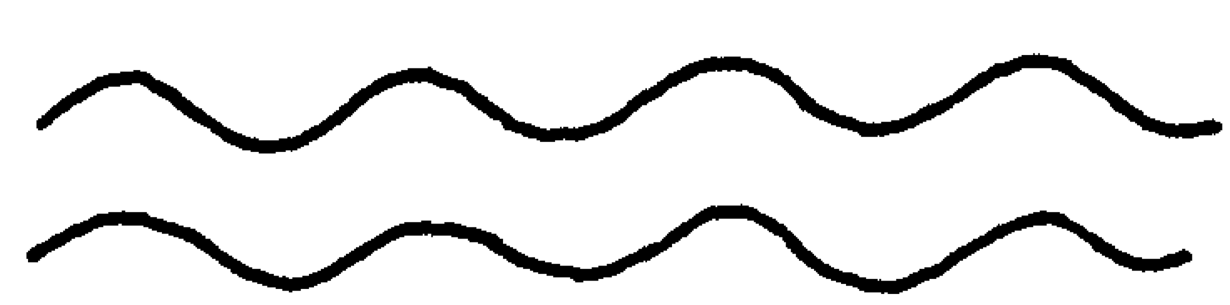
i) Specular Reflection. A flat and microscopically smooth surface, such as float glass, produces sharp, glossy reflection;
ii) Diffuse Reflection. An object with a rough surface reflects light in many directions as it hits the randomly positioned particles. Similarly, this can occur as the light passes through the object, resulting in diffuse transmission;
iii) Absorption can occur within the material, preventing wavelengths of light from travelling through;
iv) Transmission of the light directly through transparent objects.

The colour appearance of an object is a result of selective absorption. An object, for example, which appears green does so by absorbing the blue and red regions of the spectrum, transmitting green which is visible to the eye. Glass appears coloured either by the inclusion of oxides within it which absorb wavelengths of light, or, in the case of coated glass, by placing a material on the outer surface which interferes with light as it passes through.

5.5 INTERFERENCE

As stated earlier, the colours which make up 'white' light each have a different wavelength. Interference can result in some of these colours becoming visible to the eye and this is typically observed on a rainy day when colours appear in the patches of oil on a road surface. Light reflects upwards from the top of the oil film and from the interface between the film and the water. The length of the path to the eye depends on which surface the light is returning from. Thus, the result of two different wavelengths reflected from two locations can be that they reinforce each other, becoming 'in phase'. The resulting wave has double the amplitude of the individual ones and their joining is termed 'constructive interference'. 'Destructive interference' occurs when two wavelengths are 'out of phase' and they cancel each other out.

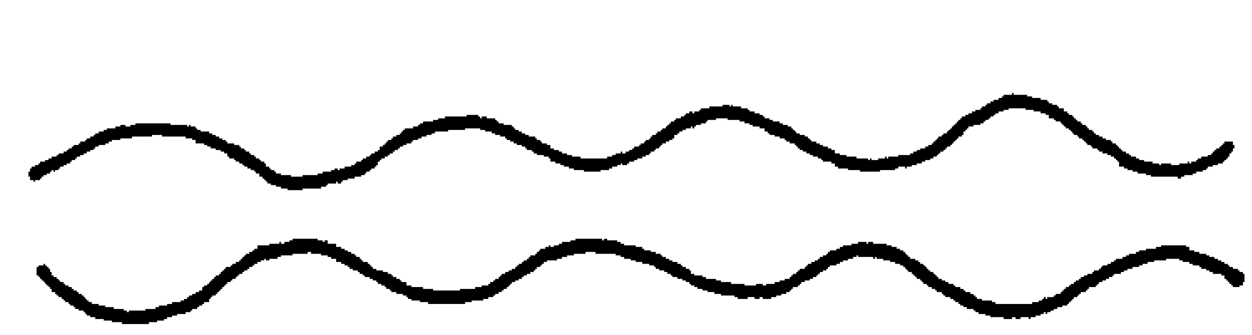
Fig.1



WAVE PATTERN CREATING CONSTRUCTIVE INTERFERENCE

Two waves of the same wavelength are said to be 'in phase' when the peaks and troughs of one coincide with those of the other, shown here in figure 1. Wavelengths are 'out of phase' when the peaks of one coincide with the troughs of another, figure 2.

Fig.2



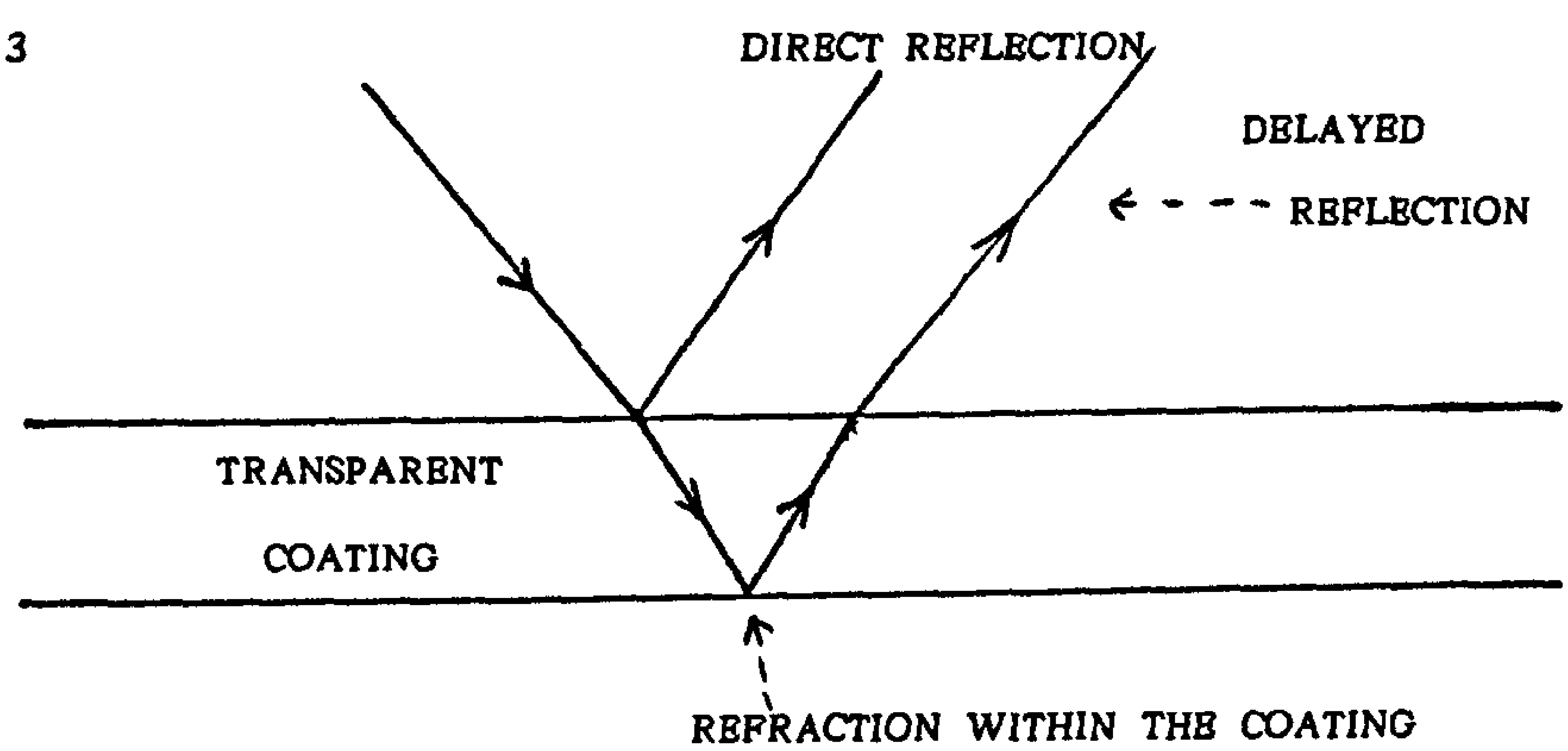
WAVE PATTERN CREATING DESTRUCTIVE INTERFERENCE

The result is the selection of wavelengths producing visible colour. On an oil film, bands of colours are often seen. This is due to a variation in thickness of the film, often from its centre to its periphery. Each thickness produces a different colour due to changing distances travelled by the light paths (see Appendix 1b).

5.6 INTERFERENCE COATINGS

Interference coatings utilise these processes and sophisticated coating design has resulted in precise control. The production of colours in dichroics is the result of control of constructive and destructive interference. In figure 3 the effect of light passing through a single transparent coating is illustrated.[11a]

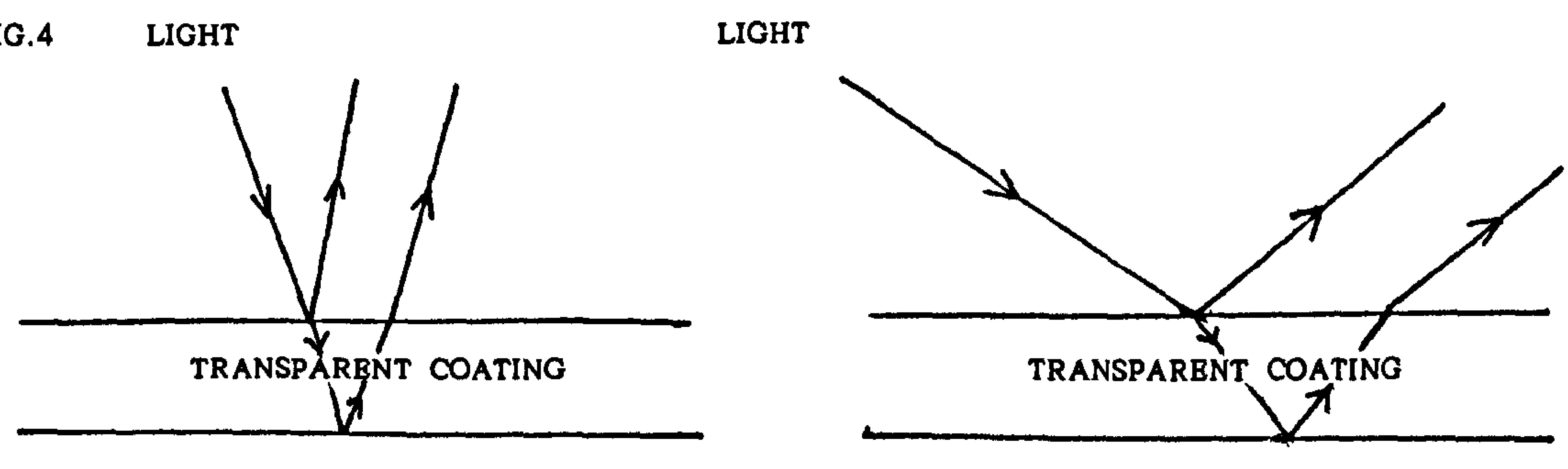
Fig.3



Light is seen here to be reflected from the top surface of the coating and again from the bottom surface. The length of delay between the direct and delayed reflected waves determines whether constructive or destructive interference occurs.

Path length, hence magnitude/amount of delay is influenced by the angle of incidence. Figure 4 and 5 illustrate this variation.

FIG.4

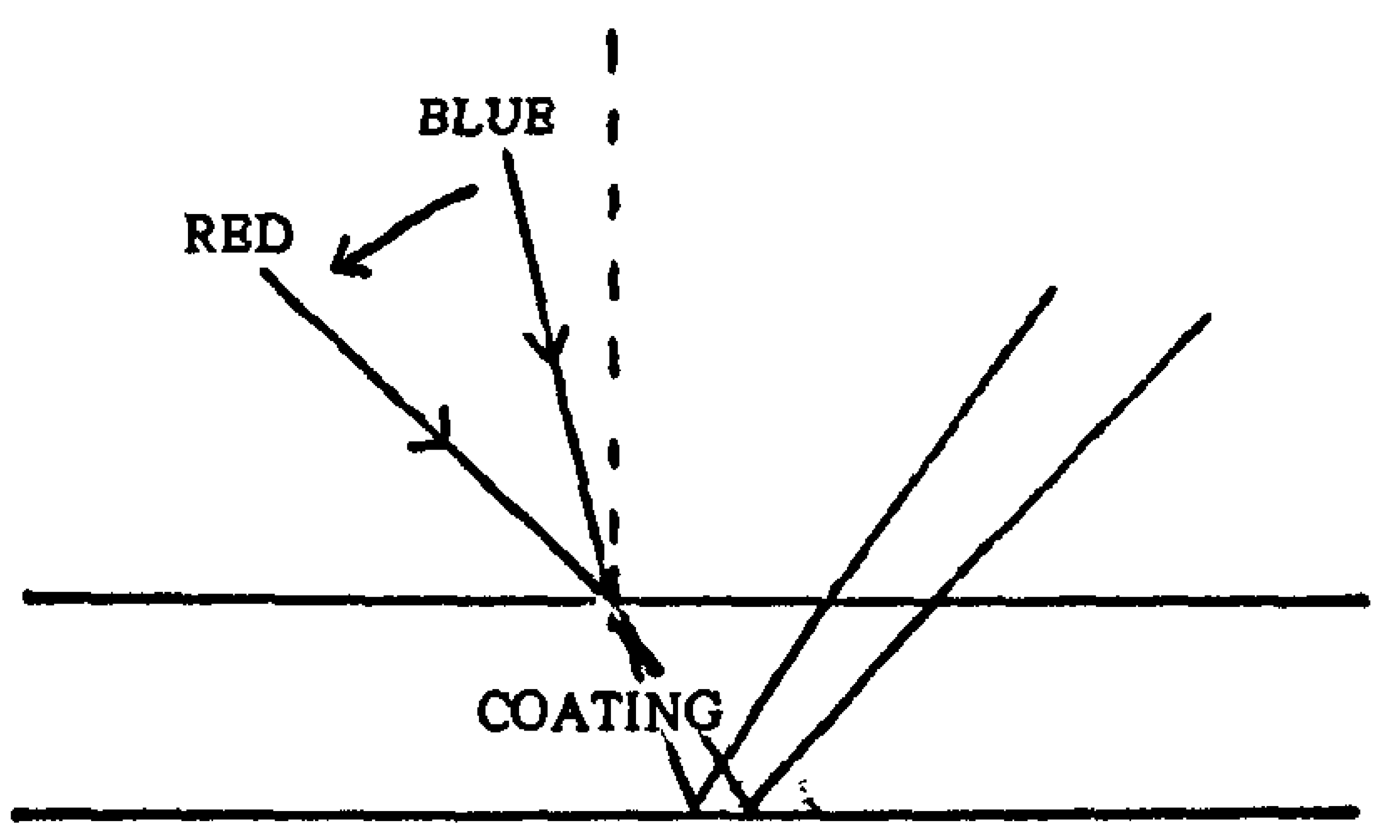


Delays of whole wavelengths result in constructive interference, with delays of half wavelengths resulting in destructive interference.

As the angle of incidence increases, the gradual increase in delay affects wavelengths of different magnitudes i.e. a 'short' delay would create a visible blue colour and a 'long' delay create a red effect. Moving from a vertical beam to a 'glancing' beam actually causes in a single coating a cyclic change from blue/violet to reds (figure 6)

FIG. 6

SHIFTING ANGLE OF INCIDENCE



5.6.1 COATING DESIGN.

A wide range of materials are deposited onto glass, each of which have differing refractive indices. It is the combined and accumulative effect of light passing through each layer and through the glass, which manipulates levels of reflection, transmission and absorption. Sophisticated software packages are commercially available which are used to design complex multi-layer systems. Examples of these are *Filmcalc* and *The Thin Film Designer.*[13] Such systems are used to design a vast range of performances, including anti-reflection coatings and dichroics.

5.7 DICHROIC GLASS.

'Dichroic' is of Greek origin and means 'two-coloured'[1]. It is used to describe coated glass designed to selectively reflect and transmit specific wavelengths of light. This dramatic glass, which appears one colour in transmission and another in reflection, was initially designed for use in the space industry[14] and has since found applications in optics and as absorbing filters for lighting systems.[15] Deposition of multiple thin film layers results in precise wavelength selection through control of constructive and destructive interference.

'The dichroic effect is generated by evaporating layers of transparent dialectric materials of differing refractive index to precisely controlled microscopic thicknesses. The effect is that a specific wavelength range of the visible light spectrum is reflected from the dichroic surface, and the remainder is transmitted through the substrate. Since the evaporated materials are transparent, the light is not absorbed as with pigments and paints, and this will create uniquely crisp and vibrant colours'.[16]

High levels of light transmission are characteristic as specified in the following table[17], along with wavelength selection:

DICHROIC COLOUR FILTERS

YELLOW	T	80%	530-760nm
	T	1%	410-475nm
MAGENTA	T	75%	400-460nm
	T	1%	530-560nm
	T	75%	650-730nm
CYAN	T	80%	420-565nm
	T	1%	630-720nm

Substrate: Heat-resistant TEMPAX

Glass thickness: 1mm

Thermal Load: 400C maximum

A common application is in the production of reflectors for tungsten halogen lamps (Plate 30). These are coated with dichroics designed to reflect visible light in the 400nm - 750nm range, whilst transmitting both near- and far-infrared light thus..

'...allowing heat energy to flow through the coating into the back of the fitting. This dramatically reduces the reflected/ projected heat energy' [18]

Control of wavelengths in both the visible and non-visible spectrum may enable future application of dichroics to produce windows designed to block infrared rays. Optical coating companies both in the U.K. and U.S.A recognise this potential although no such application is currently available.

The strong visual impact created by these coatings has inspired its artistic application, particularly in the USA (see appendix 2) Due to its dual capacity of reflection and transmission of coloured light the aesthetic potential of the glass as an architectural medium is immense.

5.8 ANALYSIS AND PRODUCTION OF DICHROICS.

In the early stages of the research, attempts were made to produce dichroic coatings within the University of Sunderland. Although a variety of interference coatings were produced, accurate control of coating thickness was not possible as the equipment was not fitted with a thickness monitor. The exercise was useful in achieving familiarity with the process of vacuum deposition but it was necessary to seek specialist assistance to achieve the degree of control necessary to produce the glass and an understanding of the physics involved.

In their role as co-operating establishment, Pilkington Technology Centre (Lathom, Lancashire), have provided technical support and assistance in the analysis and production of dichroic glass. This research has been necessary in achieving an understanding of the material which has informed design practice.

5.8.1 DESIGNING COATINGS.

Filmcalc software was used to model appropriate multi-layer stacks with the desired dichroic properties. Performance of the multi-layer coatings, calculated from the varying refractive indices of materials used, is presented in graph form, indicating the percentage of transmission and reflectance at different wavelengths (measured in nanometres). In the design of dichroic coatings for the purposes of this research, the visible range from 380 - 780nm was selected for analysis. The peaks and troughs plotted on the graph indicated the colours in reflection and transmission resulting from the materials and number of layers used. Optical thickness is calculated here. The programmes allow for the conversion of this into physical thickness.

Various sequences of high and low indices were explored and the results recorded. With the aim of producing a range of colours, those which appeared promising, showing strong colour in transmission and reflection, were selected and the designs followed.

5.8.2. COATING SAMPLES.

Coating samples measuring approximately 2 x 2ins demonstrated that it was possible, in most cases, to achieve the colours predicted by the computer programme, following the sequences and layer thicknesses prescribed. Where differences were observed, this was due to slight variations in thicknesses which occured during application.

The peaks and troughs illustrating the levels of transmission and reflection of each sample are recorded in both graph and numerical co-ordinate form (appendix 3).

Sample 1. Titanium dioxide (High refractive index), silicon dioxide (Low refractive index). Four layers were used measuring 410, 680, 410 and 170 angstroms thick, respectively. The result was a pale blue in transmission, which as the glass was tilted changed to a green/blue and then to purple at 45 degrees. Gold/purple in reflection.

Sample 2. Titanium dioxide, silicon dioxide. Ten layers : (410, 680) x 4 plus 410 angstroms titanium dioxide and 170 silicon dioxide. A much stronger blue was achieved in transmission which changed to a strong purple/pink at 45 degrees. Green/gold in reflection.

Sample 3. Titanium dioxide (H), Magnesium oxide (L). 18 layers : 9 x (H,L). Layer thicknesses : Titanium dioxide 650 angstroms, Magnesium oxide 710 angstroms. This was modelled to match the graph plotted on examination of 'magenta' (TFT Inc. USA - See Spectrophotometer analysis, appendix). The result was in fact blue in transmission, which was probably caused by inaccurate monitoring of layer thickness, resulting in a shift of colour along the spectrum.

Sample 4. Titanium dioxide - 780 angstroms, and Magnesium oxide - 710 angstroms. Ten layers in total. Blue in transmission, red/gold in reflection.

Sample 5. Ten layers : Titanium dioxide 780 angstroms, Magnesium oxide 850 angstroms. Blue in transmission, strong red/gold in reflection.

Sample 6. Repeating sample no.2 sequence. Result quite different - yellow in transmission, purple in reflection. Possible thickness variations.

Sample 7. Silicon dioxide (L), Titanium trioxide (H), Magnesium oxide (Medium).

1680angstroms 2110angstroms 1440angstroms

Twelve layers : (L,H,M) x4. Result : Magenta in reflection, green/blue in transmission.

Sample 8. Titanium dioxide (H), Silicon dioxide (L). Layer sequence and thicknesses:

450 H, 810 L, 410 H (880 L 570 H) x2 760 L, 400 H, 1790 L angstroms.
Result: Magenta in transmission, yellow at 45 degrees and green in reflection.

Sample 9. Titanium dioxide, Silicon dioxide. 460 H, 900 L, 460H (900 L, 700 H) x2 900 L, 460 H, 180 L angstroms. Result : Strong blue/green in transmission, purple at 45 degrees, gold in reflection.

5.8.3 CONCLUSIONS. The samples appeared to demonstrate the potential of using design software to achieve successful dichroics. The importance of the monitoring of coating thickness during application was clear. All samples were rotated during coating but it was not possible to heat the glass. This resulted in rather vulnerable coatings which can be scratched off.

Further experimentation revealed certain technical difficulties of repeatibility and application on larger scale glass samples (see appendix 4). This was initially displayed in the coating of sample 6 here, when exactly the same sequence of coatings was followed and yet the result was quite different from that achieved previously in sample 2. Problems encountered demonstrate the sensitivity of the procedure and the need for great accuracy in thickness monitoring. The equipment made available for this research at Pilkington was not set up to provide the degree of precision required.

Analysis of commercially produced dichroics gave further insight into their production. Similar sequences of high and low index materials were used, but heating the substrate during application gave a more resilient coating. The results of analysis of commercial samples can be seen in appendix 5. The number of coating layers applied to the commercially produced dichroics can be seen to be higher than in the tests above. It was intended in these tests to examine whether it was possible to produce the dichroic visual characteristics with a reduced number of layers. The large scale production and application of the material, often dependent upon cost, would be made more practicable with a reduction in the coating process.

The current commercial production of dichroics is generally concerned with small scale precision application and, as a result, available sheet sizes are limited in comparison to that of other coated glasses designed for architectural application (the maximum sheet size at the time of writing, available from stock at *Liberty Mirror* is 112cm x 129.5cm) The number of coatings applied and the precision involved, make this glass a relatively expensive material to apply on a large scale.

The sheet size currently available must be recognised and accommodated in the design of systems which explore the application of the material. In the following chapter, the visual qualities of the glass will be tested and recorded. Design practice with the material is then examined with application in the form of commissioned works and experimental models.

Footnotes.

1. The Lycurgus Cup, a Roman vessel produced in the fourth century AD, is an example of the height of technical achievement in ancient glass making, not only due to the intricate glass cutting producing complex imagery on its surface, but also because of a similar 'dichroic' property. This glass changes from magenta in transmitted light to a strong green in reflection, due to the inclusion of small amounts of gold and silver in the body of the glass. As with some other ancient techniques, a mystery surrounds the making of this glass which, as a result, is not in production today.

CHAPTER 6: TESTING THE MATERIAL.

6.1 The particular qualities of dichroic glass are such that there is vast potential for architectural application. The glass has the dual capacity to transmit and reflect colour, providing unique design opportunities. By working with the material in experimental models and applying it to the demands of commissions, the qualities of the glass are tested and recorded.

6.1.1 REFLECTION AND TRANSMISSION.

Initial exploration involved the construction of a simple white environment in which the glass was placed. Using a range of samples manufactured by *Liberty Mirror* (see appendix 6) the qualities of reflection and transmission of each piece were tested and recorded in Tables 1 and 2, appendix 7. The samples were first placed individually into the environment. Fixed into a supporting base which enabled the piece to stand vertically and receive incoming daylight, the effect of the light was recorded photographically.

> *'The visible result is that light transmitted through a dichroic surface will appear one colour and light reflected from it will appear as a complementary colour. As the angle at which the dichroic is viewed changes the colour that is transmitted and reflected also changes'* [1]

Moving the samples through 180 degrees, the changing effect of light transmission and reflection was recorded. This experiment demonstrates the change in visual appearance of the glass when viewed from different angles whilst also modelling the changing influence of the sun on the glass. Under normal conditions i.e. when the glass is fixed in a planar architectural setting, its position would be fixed with the light source (the sun's movement) shifting throughout the course of the day. This is reversed for the purposes of the experiment. Plate 30 and 31 shows the dramatic change in colour as the angle of light changes.

The transmitted colour of this sample ('red') changes from red to red/orange, then orange and through to yellow. The reflected colour is blue/green, which changes in intensity, becoming pale blue. The changing colour demonstrates the way in which visible wavelengths of light alter as the length of light path increases or decreases (see Chapter 5, section 5.6, : 'Interference Coatings'). The principles of interference are clearly demonstrated here with a shift along the visible spectrum caused by the changing angle of incidence.

As outlined in Chapter 5, the coating is seen to transmit wavelengths within a certain range of the visible spectrum whilst reflecting the rest.

In the photographic images recorded, the reflected colour can be seen to take on a dramatic intensity when projected into shadow. Projected onto areas receiving bright sunlight, this intensity is reduced.

The reflected colour was then tested further, positioning two samples within the environment, observing the effect of light passing through one sample, on to the next and then being reflected from both pieces. Each colour was tested against the others and the results are presented as Table 3 in appendix 6. It can be seen that the image reflected from a magenta sample positioned in front of a blue sample (so that there is partial covering of magenta over blue) produces a dramatic multi-coloured image. The blue sample reflects yellow, and where the magenta overlaps the blue, orange is created. The reflected blue green colour from the magenta is also visible.

6.2 From these tests it can be seen, firstly, that planar architectural application of the glass would display its dramatic colour differences. When viewed externally, in reflected light, the glass would appear one colour. Viewed from within, the transmitted colour would be visible. Colour change would occur, depending upon the observers angle of view. The strength of reflected colour makes the power and impact of the glass viewed from the outside, equal to the effects under transmission. Body-coloured glass, more usually used in the production of stained glass does not have this dual capacity and power and is in the main, designed to be observed internally[1]. Even in overcast conditions, ambient light is sufficient to produce the reflected colour, which changes only to the transmitted hue when lighting levels internally exceed the outdoor conditions. The reflective power of dichroics, therefore, present extended design potential.

Footnotes.

1. Consideration of the performance of stained glass, viewed from as part of the external appearance of a building has been important in some projects as outlined in Chapter 2. Ludwig Scaffraths work demonstrates the use of texture and relief to create a strong visual impact, responding to reflected light when viewed from outside.

The colour of light transmitted through the glass is seen to change as the angle of illumination shifts. This suggests that planar application will result a similar change in the illumination of interior space. Thus, at different times of the day, a room glazed with red dichroics, may change from yellow; through to orange; then to red; back to orange and again to yellow, as the sun projects a constantly changing angle of illumination. Placed within the building forming an internal screen, both the reflected and transmitted colours are seen to fall in the interior.

Further possibilities are created when more than one plane of glass is applied. Examination of this has shown the capacity to produce multiple reflected colours from two different samples. Without the influence of direct sunlight, the qualities of dichroics create a constantly active visual experience. As people circulate past dichroic screens, windows, etc the subtle shift in transmitted colour, is observed as their angle of view changes.

6.3 Bonding lenses and prisms to the surface of the glass manipulates further the optical qualities. The transmitted colour can be seen to shift, for example from magenta to yellow, with the application of a prism cut to a 45° angle. Sample A, illustrated in appendix 8, demonstrates this. The light passing through the prism is refracted, creating this colour shift. Experiments using prisms cut at less dramatic angles did not have this effect.

An optical lens bonded to Sample B (illustrated in appendix 8), demonstrates additional design potential. Etching away some of the dichroic coating, by masking a sample using an adhesive vinyl and then cutting away some of the mask to expose the coated surface, the glass is then sand-blasted, removing the thin film coating and leaving a white etched surface area. Bonding the lens to the glass using a clear silicone adhesive, makes the white etched area become transparent. The glue fills all of the tiny abrasions on the etched surface which had acted to diffuse the light, making it appear translucent prior to bonding. The addition of various glass elements to the surface of dichroics in this way, resulting in the manipulation of optical effect demonstrates further exciting possibilities for the artist working with the material.

6.4 COMMISSION 1. The opportunity to test the material in a live commission first arose in year two of the research programme. Exploration of the potential of the glass, within the constraints placed upon the commission, was recorded and is presented here in the form of an analysis of the whole process involved in the design and construction of the piece. Observations following completion of the commission are made and conclusions drawn.

6.4.1 ANALYSIS OF DESIGN PROCESS.

SUNDERLAND CITY TRAINING AND ENTERPRISE COUNCIL, WINDOW COMMISSION.

Background. The university was approached in November 1993 by Sunderland City TEC, (formerly Wearside TEC) requesting the design and construction of an internal 'feature window' for their new Business and Innovation Centre which was already in the building stage. The site chosen for the building was on the bank of the river Wear at Southwick, an area cleared following the demolition of the shipyards. With regeneration as its aim, the Training and Enterprise Council wanted the building to be forward looking and innovative. They describe their 'mission' as follows:

> *'...to contribute to the regeneration of the area by creating a partnership between public resources and private enterprise to foster the development of training and enterprise initiatives.*
> *Innovation and enterprise on Wearside needs to be cultivated in order to expand the manufacturing base of the area with the ultimate result of real job creation...The Business and Innovation Centre will be the catalyst to make this happen.'* [2]

The Brief. The arched-shaped window was to be positioned in an internal wall above the reception area of the building and stretch from the first to the second floor. In recognition of the anger and unhappiness amongst local people, in reaction to the government decision to end shipbuilding on the Wear, it was felt that a level of sensitivity was necessary if the community were to accept the new building on this site. As a result, it was decided by City TEC management, that no reference to ship building should be made in the design of the window. Sunderland's long history of glass making, an industry which is surviving in the region at present, was felt to be a more appropriate theme. The brief then, was to design an arch-shaped stained glass window celebrating this history.

The Building. Constructed of brick, steel and glass, the building takes the form of a central hub, housing a reception, administative offices, a boardroom and restaurant. Leading off from this central area are four 'arms' which consist of industrial units for small businesses. The design of the building draws on aspects of classical design in its use of proportion and symmetry, along with the 'high-tec' use of glass and steel, particularly noticible in the entrance design and that of the central court. (Plates 32 + 33)

Designing the Window. Before beginning to design, the site was visited. At this stage much of the exterior of the central hub area was in place. Internally, the floors were in place but there were no dividing walls and the space was filled with scaffolding. The architect, Mario Minchella, described where the wall would be, within which the feature window would be situated. It was difficult to visualise exactly how this area would look, in the dark damp interior of the buildings shell. Access to further information including; a plan of the window's position; photographs of the completed building in model form; publicity material; along with my own impressions gained during the visit, enabled work on the design to begin.(see appendix 9) It was requested that a design should be submitted in early January so that it could be presented to the management committee of the TEC. This allowed a design period of approximately two weeks.

Various factors were of influence in the design of the window. From the outset it was my intention to include dichroics and this was an important factor in the way I approached the project. Other practical and prescribed constraints can be outlined as follows:

CLIENTS BRIEF: It was stressed in the brief that this was to be an arched-shaped 'feature window', which made no reference to shipbuilding, but celebrated the development of technology through glass. Thus, constraints were placed upon the nature of the content of the design along with the size and shape of the window.
COST: A limited budget influenced the choice of glasses incorporated into the design along with the chosen method of construction. The size of the window was such that it was important to limit the amount of expensive glass included. Leading, it was decided, would be the most appropriate construction method, allowing the bringing together of many different types of glasses.

TIMESCALE: Ambitiousness of design and demanding nature of construction had to be realistic. Although gluing and plating, as a construction method, could have been an option, the experimentation necessary for successful execution of this technique (which would have marked an embarkation into a new technical area for me) was prohibitive at this stage.

NATURE OF BUILDING: The architectural style of the building, with both classical and high-tec references influenced decision making as it was my intention to design a window which would integrate with the overall spirit of the building. The themes of innovation, optimism and looking to the future, along with recognition of history and past achievements, informed my approach to design.

POSITION/FUNCTION OF WINDOW: The siting of the window had to be taken into account for the following reasons:

i) the window was to stretch from the first to the second floor, which meant that the central area would fall between floors and therefore recieve no transmitted light.

ii) being an internal window, no direct sunlight would be recieved - only borrowed light from the glass front of the building and from a small window on both the first and second floors.

iii) safety regulations prescribed that a protective layer of toughened glass be placed in front of the panels on the office side. The depth of space between this layer and the leaded panels could limit the use of glasses with high relief.

iv) the view through the window from the first and second floor had to be considered. Directly opposite the site of the window, on the other side of the reception area, there would be a brick wall which would be in view from the first and second floor.

Approach to the design of the window was influenced by these constraints. I decided to formulate the design using abstract geommetry and refer to the history of glass technology by including a vast range of glasses, both old and new. Following the classical inspiration within the design of the building, it was decided in the early stages of the design process to work with a broadly symmetrical structure constructed of squares, circles and curves, which responded to the overall determining arch-shape (Plate 34). The structure of the design aims to lead the viewer through the historical development of glass making. The progression can be summarised as follows.

6.4.2 Starting at the base of the design, a mouth-blown 'crown' of glass can be seen (Plate 35). This is an example of one of the earliest methods of producing glass for windows. This 'plate' of glass is formed by spinning the blowing iron, forcing a bowl-shaped glob of hot glass to spread outwards into a flat disc. Surrounding the crown is a thin border of coloured hand-made glass of the kind used extensively in medieval stained glass windows. Both the crown and these

coloured glasses were made in Sunderland at Hartley Woods.
Working outwards from here, two Victorian discs of glass can be seen, manufactured by Joseph Bell, and featuring embossed patterning. The outer semi-circular area is made up of hand-made reamy antique glass, also known as 'water glass' due to the fluidity of it's texture.

Leading up through the central area of the panel is a grid-like arrangement of clear and tinted glasses, beginning at the base with early hand-made pieces, working through to twentieth century machine-made patterned glasses. Amongst the hand-made samples are various antique pieces and an example of 'Norman Slab'. This larger pale green tinted glass sample was produced by blowing a bubble of glass into a square shaped mould. The block was then cut down to form 'slabs' of glass. This technique was developed in the 19th century and was termed 'Early English' by the company, E.S.Prior, due to its similarity to medieval glass. Chance brothers gave it the name Norman Slab also for this reason.

Amongst the machine made samples are examples of Victorian glass and some produced in the 1930's. Recent patterned samples of glass no longer in production feature, along with a range of contemporary patterned pieces produced by Pilkington Glass. Various bevelled pieces also feature, providing pin-points of light. Bevels have been used by stained glass artists in both the nineteenth and twentieth centuries, becoming increasingly popular for use in contemporary abstract design.

The central section of the window, between the lower two horizontal bars of the frame, receives no transmitted light, as it is situated between the first and second floors of the building. To activate this area, various glasses are included which have a high level of reflectivity. This includes mirrors and coated opaque glasses, along with transparent textured glass.

Before reaching the concentration of colour at the top of the window, two information discs appear ('compact discs'). This provides a contrast to the Victorian glass discs at the base of the panel and demonstrates the importance of glass in the contemporary development of information technology.

The coloured section consists predominently of dichroic glass, which surround a disc of 'float' glass, the contemporary method of producing window glass. This provides a contrast to the mouth-blown disc at the base of the window.

Along with dichroic coated glass, the outer grey area of the window is made up of 'Suncool Classic', a coated glass produced by Pilkingtons (see appendix 10). This is one of the range of environmental control glasses, produced to assist in the thermal control of buildings (see Chapter 5).

Viewed from the reception area, the window is seen in its entirety. The extensive use of reflective glass enables a sense of uniformity, despite the inclusion of glasses of greatly contrasting character. The borrowed light from the glass wall of the entrance area activates the window and helps to disguise the central void between floors. Conventional stained glass windows are designed to be seen in transmission. Face light of the kind described here, serves to obliterate the subtle qualities of the transmitted light passing through the glass. The positioning of this window, therefore, demanded a different approach. Rather than work against the conditions, the use of coated glass in the window, exploits the face light, producing reflection. The 'Suncool Classic' becomes a grey mirrored surface in reflected light. This complements the reflected colours of the dichroic glass area.

From the offices on the first and second floors, only part of the window is visible. It was my intention to make each of these sections of interest in their own right. The lower section includes the greater proportion of antique glass (Plate 36) and so its character is different to that of the section visible on the second floor (Plate 37). This is predominantly made up of machine-made and coated glasses. The use of textured glass in both sections serve to fragment the view of the brick wall opposite, which when viewed head on, brings additional colour into the composition. The 'Suncool Classic' appears grey when viewed in transmission, from the office area.

6.4.3 Observations Since Installation.

As is usually the case in commissions like this, there are influences on the appearance of the window which could not have been predicted prior to installation. Details in relation to the level of the ceiling on the first floor and positioning of electric lighting within this, changed during the period of construction. As a result, when viewing the window from reception with office lights on behind, bright square areas are visible through the lower section of the window.

The central void area, it was agreed, would be faced with a white plastic board, in front of which the panels would be placed. This would give a level of reflected light in the space behind the panels which, it was felt, would help diguise the lack of transmitted light received in this area. When it came to installation, however, it was found that this backing board was in fact a dark grey - an amendment to the plan had been made without my knowledge. As a result, the grey Hartley Woods glass, along with the textured clear, appear much darker than intended.

DICHROIC AREA. In order to make up the colour changes required across the dichroic section, some handmade coloured glass plated with irridised glass was used. The irregular surface of the irridescent pieces, compliment the samples of textured dichroics from Bullseye Glass. Scattered amongst these are the flat highly reflective samples of dichroics made at Pilkingtons. The planned spectral changes can be best understood when viewed head on in transmitted light. Due to the nature of dichroics, at other angles this changes. Interrupted by the hand-made/irridised pieces which do not shift in colour, the power of this dramatic shift is weakened and the area is broken up. The result is a variety of performances across the surface which although rich in themselves, are not the intended outcome. This could only have been achieved if this area had been entirely made up of dichroics and the result would have been quite different. The dichroic area in reflected light can be seen in Plate 38. At the time of construction, and stage of research this was not possible.

The use of leading as a construction method in this project meant that the design had to be broken up to incorporate support bars. Leaded panel are flexible when complete and during transportation and installation damage can occur to vulnerable areas of the panels. For this reason, it is advised that the size of panels be limited so that they can be easily handled. Also within a panel, larger areas of glass be split and leaded along its their most vulnerable break lines, so that flexibility is given without damage to the glass. The result of adhering to these technical constraints is that additional lead-lines are added, which interrupt the design. In this window, perhaps too cautious an approach, has resulted in a number of horizontal lines, some with steel support bars attached, which break up areas of the design, initially intended to be clear of such interruption. Vertical lines in the bottom section of the window were also not in the original design and are purely there for technical reasons.

Further study since the completion of this project, disputes such a cautious approach to leading. Alex Beleschenko's work which has involved research of construction methods, demonstrates how similar projects can be resolved without the use of lead-lines. He argues that the strength of glass is often underestimated by glass artists, fearing breakage and cracks. Many of the additional lines in this window, he felt, were unecessary as the steel framework in which the panels are set provide rigid support. Also, the larger sweeping areas of glass in the original design, would have given integral strength to individual sections, negating the need for strengthening bars.

Approaches to this method of construction varies in the work of artists. Certainly conclusions drawn from this project are that the use of lead works against the design in certain areas and an alternative, more sparing approach would have been appropriate.

6.4.4 CONCLUSIONS.

The commission proved interesting in highlighting the impact of a variety of constraints on the eventual outcome of a project. It was a useful opportunity to explore the use of coated glass, a relatively new material, within the traditional medium of stained glass design. The clients response to the window has been extremely positive, despite the many problems highlighted in my own observations which demonstrates a degree of success in achieving a design solution to meet the prescribed brief.

Acting as a model for observation of the relative performances of the glasses used, the project has been a valuable source of information. Examination of the problems met in utilising the chosen construction method, indicated the need for further research into alternative methods, appropriate to the nature of the material and design. This aided in defining further areas of the research programme.

6.5 COMMISSION TWO. Following a visit to the studio of the Spanish artist, Kashava (see Chapter 3), where the method of bonding glass to glass using an optically clear silicone adhesive was discussed, it was decided to employ this technique in the completion of a second glass commission during the research period. This project involved the design of glass panels to surround two doorways at the entrance to a modern languages department for a School in Morpeth, Northumberland. As in the Sunderland commission, the building was near completion when the appointment of an artist took place. Northumberland County Council (the commissioning agent) operate a 'percent for art policy' which ensures that a percent of the building costs of projects is allocated to the inclusion of some form of art work. Unfortunately the appointment of an artist can tend to be a last minute proceedure.

6.5.1

The architect requested that the glass used be either of a pale tint or colourless in order to minimise the reduction of incoming light to the north facing entry. This request, along with a very limited budget and safety considerations, led to the use of toughened float glass with sand-blasted detail. The incorporation of words which releated to 'modern languages' was also requested and these were to be selected by the student/staff of the school. Sand-blasting proved a cost-effective method of meeting this request. The addition of bonded glass elements gave further definition to the design adding colour and interesting optical effect.

It was requested that the outer door surround should be eye-catching when approaching the building and for this reason, I felt it appropriate to incorporate dichroic glass into the design. At first, the use of dichroics along with other coloured glasses was considered. This was ruled out after further consideration and review of the performance of non-dichroic glass in the Sunderland commission. Body tinted coloured glass would not respond well to the reflective conditions on the exterior of the building and so it was decided that only dichroic glass detail should be used, to achieve a uniformity and strength to the design when viewed from outside.

6.5.2 Working on the theme of *communication* an abstract design based on the structure of a circuit board was produced. The outer door surround incorporated dichroic glass and the words and phrases selected by the school (Plate 39). The internal doorway echoed this design in a simpler form (Plate 40). Using only colourless glass additions of small lenses and squares of glass, a monochrome effect was achieved. The application of clear glass pieces to sandblasted glass with an adhesive (U.V glue or silicone) was tested. The result was to create transparent detail on the white of the sandblasted surface (Plate 41). The use of this technique on the internal door surround enabled view through from the interior to the colour and detail of the external glass panels.

Following the method prescribed by Kashava (see Chapter 3), the additional glass elements were bonded to the panels, after the sand-blasted design had been applied. Adding the detail in this way, enabled the edges of the glass to remain visible, catching the light and creating a further dimension in the form of low-relief. Without the border of black lines around each colour a different aesthetic is achieved (Plate 42).

Various tests were completed before the application of the technique in this project. First, an appropriate silicone for the planar bonding of glass to glass, available in the U.K. had to be identified. There are various optically clear silicone adhesives available but many are designed for the bonding of glass edge to edge. Planar tests with these found that, over time, following bonding, star-like shapes would appear, trapped between the glasses. This was due to contraction of the silicone during curing making it unsuitable for such application. A two-part silicone, similar to the one used by Kashava, available in the U.K. provides high fluidity which reduces the problem of trapping air bubbles between the glass. This cures uniformly giving an optically clear result ideal for planar application (see appendix 11).

The door surrounds, already in place when I was appointed to complete the commission, were blue powder-coated metal. Clear glass panels were already in place, the commissioned work was to be fixed internally into the existing framework. The existing beading was removed and spacer bars were placed between the clear glass and the commissioned work, with an additional narrow beading placed around the frame to hold the glass in place. Fixed in this way it, was possible to enclose the relief work within the unit, protecting these pieces and leaving a smooth plane of glass exposed. Thus, cleaning and maintenance was made easy.

6.5.3 Observations Since Installation.

The dichroic details on the exterior door surround pick up the reflected light very effectively, appearing like illuminated shapes when viewed from outside (Plate 43). The use of dichroic glass only, on the exterior, make the contrast in reflected colour and transmitted colour a strong feature in the experience of the work. From within, the colours appear as blue and magenta, from outside, golds and greens are seen. The use of other body-tinted glasses dispersed amongst the dichroics would have diminished this strength.

The commission provided an opportunity to test out an alternative method of construction which proved to be a successful and appropriate solution for this project. Using dichroic glass in this way, as small additional elements providing detail, meant that the glass could be used throughout the design of the outer doorway, despite the limited budget.

A later commission due for completion in July 1997 also employs this technique. A series of vertical 'louvres' made of toughened float glass are etched to create a free-flowing matrix design inspired by the history of mathematics. Commissioned by the University of Newcastle, the louvres stand open achieving interesting optical effect of pattern overlay. Dichroic glass and prisms bonded to the surface of the glass create colour. Plate 44 shows the design in model form and plate 45 shows a sample piece including dichroics and prisms.

6.6 COLLABORATION.

The commissioning process experienced in the completion of the windows for Sunderland City TEC and Northumberland County Council, involved the artist being brought in almost at the completion stage of the building. The architects and clients had identified the position, size and nature of the artwork they wanted for the building and, as such, various constraints were placed upon the input made by the artist. In the case studies outlined in Chapter 3, the importance of collaboration with architects and engineers is a common theme in the completion of innovative and architecturally integrated works by these artists. Often at the commissioning stage it is too late to suggest much beyond the imagination and expectations of the commissioning agent. Robert Sowers, in his book *'Stained Glass an Architectural Art'*, discusses the issue of collaboration and the level of involvement of the artist. He sets out the following spectrum of possibilities:

> *'Let us review the possible alternatives: at one extreme the artist may, like Matisse at Vence, more or less be his own architect; or the artist may be called in at the very beginning of a project, just as a structural engineer or anyone else with specialist knowledge is called in. He is after all a specialist in his field, or should be - the stained-glass artist is amongst other things a kind of lighting engineer. Or the architect may completely design his building and then commission art for it; or finally he may be, like Le Corbusier, his own artist.'* [3]

The options open to the artist brought in following the buildings completion can be limited, as stated earlier, by the imagination of the architect. The ideal time to involve the artist in the process is the subject of debate. Ed Carpenter, an American architectural glass artist, has completed both collaborative and non-collaborative projects. His approach to the latter he describes...

> *'..as being in the spirit of collaboration...I have the opportunity to work with the building, when its a good building, that I take very seriously.'* [4]

Working within such constraints, then, the glass artist may respond to the particular demands and qualities of a building creating work which, as Jochem Poensgen stated can...

> *'contribute in bringing a given space ever closer to its own'* [5]

Consideration of the particular qualities of a space can lead to the creation of such works by the skilled glass artist, despite a lack of collaboration from the outset.

An opportunity to experience the potential of working as part of a design team arose mid-way through the research programme. A project devised by an MA (Art in Public) student at the University of Sunderland, invited students of architecture (University of Newcastle) to work along side art students in the preparation of designs for the renovation of a building in Allenheads, Northumberland. The aim was to encourage collaboration and open up a dialogue between the parties involved.

The listed building had been mining offices but had been unused for sometime. The proposal was to convert the building into a community resource and information centre. The architects were presented with the project two weeks before the artists were brought in. They visited the site and came up with initial proposals for its conversion. Four artists, three of them sculptors, and myself were invited in at this stage. Three schemes were selected from the proposals presented by the architects, following which, the artists gave a presentation of their work to the architects so that they could become familiar with working methods.

As the architects had designed the general changes to be made to the building and established the themes and concerns they were interested in incorporating into the schemes, it was up to the artist to respond to their designs and suggest detail. Broader than the more usual commissioning experience, the artists contribution was to become a member of a design team in which changes to the detail of the proposed designs could be negotiated. Some of the artists who did not have personal experience of commissioned projects felt uncomfortable entering the proceedings at this stage. Having to respond to the overall designs already set out by the architects was alien to their usual working practice.

Although there were problems with some preconception on the part of the architect students as to the role of the artists, in general this could be discussed. Initially, some of the architects envisaged a very narrow input from myself as glass designer, suggesting that this would be to design some leaded lights for the building. This demonstrated the fixed ideas held by some regarding the nature of stained/architectural glass. Through discussion, a greater understanding was achieved and it was possible to make a broader contribution.

Due to the nature of the building, certain constraints were set from the start of the project. The exterior appearance of the building had to be retained (Plate 46) and so design involved the imaginative use of the interior space. Visiting the site the group was faced with a rather dark oppressive interior, which all of the architects attempted to tackle by creating a greater sense of space and light in the three design schemes. As a result, there were numerous opportunities for the incorporation of various glass elements into the schemes and these were discussed and worked on collaboratively. The importance of maximising light within the building gave opportunities for the incorporation of coated glass as a means of introducing light and colour into the building.(Plate 47)

6.6.1 EXTENDING THE FALL OF NATURAL LIGHT.

The existing loft area of the building was to house studio and workshop spaces. Building restrictions limited the possibilities of introducing light into this area as the roof was to remain largely unchanged. Working with the architect on one of the schemes, the idea of moving light from an adjoining extension which had a glass roof, was explored. The use of mirrored louvres, angled to catch the light and reflect it into the roof space appeared to offer an effective solution (Plate 48).The positive effect of mirror louvres as a means of reducing reliance on electric lighting is outlined in the review of mirror systems by P.Littlefair.[6] The introduction of coloured light appealed to the architect. Models were constructed incorporating dichroic glass and their effectiveness was tested. Shafts of light were reflected in different directions acccording to the angle at which the louvres were set. A double louvre which was edged with mirrored glass multiplied the impact of the glass (Plate 49).

In the same scheme, a light shaft was designed by the architect to form the central area of the building, from which corridors would lead. Glass tiles in the original roof would serve to admit light at this point. the design had strong references to the history of the building and the area, utilising mining imagery. Within the shaft, the architect wanted a large wheel to be suspended, horizontally, which rotate casting shadows on the walls of the shaft. This imagery, rooted in the past, was discussed and with the intention of adding to this a contemporary optimism, relating to the theme of regeneration, it was decided that dichroic glass blades should be slotted into the wheel, like spindles. Positioned on an angle, the blades would catch the light and reflect shifting patterns of colour onto the walls of the shaft below (Plates 50 + 51).

For another of the schemes, the architect wanted a glass wall to be designed which could change from opaque to clear to allow for changes in use of the room. After discussing the use of chromogenic glasses and considering budget restrictions, it was decided that a mechanical solution be sought. Based on a vertical louvre system, I designed a wall which incorporated strips of opaque and clear glass. One strip of opaque glass was joined along the edge to a strip of clear to form a right angled section. These individual units pivoted at this join. When all the opaque strips were aligned, vision through the wall was obscured. Pivoting to align the clear strips, resulted in transparency (Plates 52 + 53). The interesting structure of the wall led to the construction of a further model incorporating dichroic glass. Dramatic light effects were created as light was reflected and transmitted from the multiple planes of glass. Pivoting the sections resulted in exciting shifts in the fall of light (Plates 54 + 55). Although not appropriate for this project, the dichroic wall is an interesting use of the material which emerged as a consequence of it.

The result of this project was that the final designs produced by the architects had been influenced by the experimental work completed by the artists. The artists were able to respond to the building, its particular qualities and its problems. Lighting was a crucial area which opened up many opportunities for the involvement the glass artist. Problems of trying to increase the amount of natural light in certain areas of the building, or obscure vision whilst retaining light, I found an ideal opportunity to apply knowledge of the material qualities of glass. The use of dichroics in this project, moved away from the traditional incorporation of coloured glass, decoratively, into planar window design. The power of introducing light and colour into architectural space is thus explored in alternative forms.

6.7 EXAMINATION OF FURTHER FORMS.

Following on from this project, the fall of natural light within the atrium area of the City TEC building was examined. Despite the size of the glazed roof in this area, light did not extend to the walkways below in sufficient quantities to negate the use of electric lights during daylight hours (Plate 56). Conversations with building users highlighted this as a problem, stating that it was necessary to use electric lighting throughtout the day, with the obvious consequences of energy consumption and users discomfort.

A simple model of the area was constructed and a glass and steel structure suspended around the atrium. Strips of dichroic glass along with mirrors were positioned at varying angles and the resulting light effects were recorded. By altering the angle of the glass it was possible to project light further into the space, onto the levels below (Plates 57 + 58). Although simple in construction, the device displayed potential for extending the influence of natural light in this space. The inclusion of dichroics enabled the introduction of coloured light .

Further work with three dimensional forms designed to reflect and transmit light has been done. These simple structures illustrated here intend to create dramatic light effect with possible applications for improving overall lighting levels.

The 'dichroic light shelf' (Plate 59), inspired by the light shelves tested at the Building Research Establishment (see Chapter 4), consists of a horizontal plane of dichroic glass, with vertical fins attached to the upper surface. Light is reflected up into a room from the horizontal plane, whilst the fins project light further on to the walls, depending upon the suns angle.

The 'spiral reflector' (Plate 60 + 61) consists of strips of dichroic glass on a light steel support. The form twists so that each glass element receives light. Reflected light is thus projected in multiple directions.

The 'dichroic and UV filter tower' (Plate 62) is a stack of horizontally placed glass elements. Like a multiple light shelf, the reflected and transmitted light is bounced between the levels and into the surrounding space. The UV filters appear deep blue in transmission, changing to red at an angle of 45^{o}. In reflection the filter appears mirrored and therefore projects 'white' light.

The three dimensional forms explored here have possible applications used in conjunction with the light pipes, described in Chapter 4. Acting as emitters, in a similar way to those designed by *Bodmin Solar,* these structures could create a play of natural light and colour within a buildings interior.

Drawing on the method used by Alex Beleshenko (see Chapter 3) to incorporate various glasses within a laminated panel, further experimentation has been completed to examine the application of dichroic glass within glazing units.

Vertical and horizontal strips of dichroic glass are bonded between two outer sheets of float, with strips of float glass sealing the edges of the unit (Plate 63). The dichroic structure here is inspired by the Chapel window in Indianapolis designed by James Carpenter (see Chapter 3). Similarly, when viewed head on, the panel appears colourless. Dramatic light effects occur in sunlight, when the transparent box suddenly projects a spectrum of colours in multiple directions. As a glazing panel it is envisaged that such a unit could be incorporated into glazing systems forming an integral part of a building.

Plate 64, shows a similar device in which the louvres are fixed at an angle of 45° placed on top of this unit. Appearing like a partially open louvre, the colour of the glass can be seen head-on. The angle of the planes of glass redirect some of the light striking the panel, projecting light upwards, whilst transmitting coloured light into the space beyond.

Taking the idea of the louvre further, a unit was produced consisting of 16 horizontal strips of dichroic glass, each of which could be rotated through 360°. The dichroic glass used has a transmitted colour of yellow and reflected colour purple. By changing the position of the individual louvres, paths of reflected light could be projected through all angles. The transmitted light remained constant and dependant on the position of the light source. In plates 65 and 66 the changing paths of light can be seen. Movement of the louvres could be controlled electronically to produce dramatic changing light effects[1].

Each of these glazing units may have applications in the partial shading of areas of buildings, complementing other shading devices. The louvres could be positioned to reflect light back, shading the interior[2](Plate 67). Similar to the 'mirrored louvres' described in Chapter 4, these systems could also be used to direct light into a building, increasing the light fall within. With the incorporation of dichroic glass in these units, coloured light is projected into space. Incorporating other coated glasses with varying levels of reflection, 'white' light could also be manipulated and extended in this way.

Footnotes.

1. Moveable louvres are reviewed by P.Littlefair in his paper *Innovative Daylighting : Review of Systems and Evaluation Methods.* Their advantage over fixed systems is made clear. The cost effectiveness of motorised systems is to be the subject of further testing.

2.The Occidental Chemical Centre (Niagara Falls, New York), constructed in 1980 incorporates aerofoil louvre blades which sheild the building from the sun. The outer skin of the building is double glazed and the inner skin single. A five foot space between houses the louvres. A solar cell on some of the blades triggers movement. A similar method could be used to power the movement of the dichroic louvre. In this case, the white opaque louvres, reflect the suns rays out of the building providing shading. Venetian blinds have also been applied in a similar way between the inner and outer skins of a building, for example, in the Solar Dairy, Mysen Germany. Pilkingtons produces sealed blind units for internal windows and partitions ('Plyglass Luxaclair'). These systems are manually operated.

The innovative daylighting systems, tested at the Building Research Establishment (see Chapter 4), demonstrated that overall lighting conditions could be improved under their application. The passive nature of the systems, however, limited their effectiveness under changing lighting conditions. The rotating louvre system, above, is a dynamic solution which could adapt to conditions, projecting light further into the interior when light available is low, and reflecting light away, providing shading when necessary.[7] The systems tested at the B.R.E are designed to *'enhance lighting levels for the working environment'* [8] and are concerned with the dispersion of 'white' day light. The incorporation of dichroic glass in similar sytems, with its particular qualities of reflection and transmission, has enabled exploration of the introduction of colour.

CHAPTER 7: THE ARCHITECTURAL APPLICATION OF THE MATERIAL

7.1 The empirical approach, based on observation and experiment, which has been adopted throughout the research, has enabled a knowledge of the potential of the material to be amassed. Application within architectural settings has been within the constraints set by the commissioned works completed and these have been identified and recorded. To further examine the architectural potential of the material, a notional project has been constructed. Working within the context set by the study of historical precedence and current developments in architectural design and technology, an appropriate building was identified as the subject for this project. It was decided that the building should be made up of vast areas of glazing, embracing the continuing *'struggle for light'* in a contemporary form. The issues involved in the design of glass for such a building would be addressed, with the intention of achieving a thorough application of the qualities of dichroic glass within this setting.

7.2 THE NATIONAL GLASS CENTRE.

Due to be built in Sunderland in 1997, the design for this building, by Gollifer Associates, was the winner of a Europe-wide architectural competition (Plate 49). The aim of the building is to house under one roof, gallery spaces; a working glass factory and independent workshops.

> *"Laid over these elements soars a vast shimmering glass plateau, overwhich visitors will be able to walk...and gaze beneath their very feet the world of a working glass factory. At the prow of the plateau, visitors will be able to view the river Wear cutting through the landscape, tied together by two heroic Victorian bridges as it flows into the green grey North Sea.*
> *Combining these visual and practical elements into one unique assemblage, the National Glass Centre will create a complex world of vertical and horizontal transparency."*[1]

The design of this predominantly glass building, sets numerous technical challenges in order to create a comfortable and energy efficient space. Mechanical and Electrical engineers, Battle McCarthy state:

> *'The National Glass Centre would be an ideal showcase for the latest glass technology'*[2]

The aim of the building; to be a celebration of glass (both aesthetically and technically), provide an ideal and appropriate venue for the application of dichroic glass. The project enables the testing of the material within a transparent building and thus tests its performance under such conditions. Being a notional project, it is not possible to become a member of the design team and collaborate fully in the design process. Communication with the architects and engineers, however, has taken place during the project with the aim of designing an integrated work as a result.

Responding within the framework of the aims and objectives for the building set by the design team, there is a flexibility and scope in the choice of site within the space and the scale the work might take.

> *' The Centre is an open building using glass in dramatic ways... The building image should be memorable, both from afar as Architecture and from the first hand experience of a visit. It should be an inspiring building - the flagship of the future development of the area.'* [3]

Through discussions with the architects, engineers and the Tyne and Wear Development Corporation, who are commissioning the building, the background and technical information necessary for completion of the project was amassed.

7.3 THE BUILDING DESIGN.

The building will occupy a site which formerly had housed ship building yards, cut out of the sloping land on a bank of the river Wear. (Plate 68 + 69)

Approaching the entrance from this incline, the building appears to emerge from ground level forming *'a glass hill to walk up'* [4]. This is the roof of the building which projects upwards. Entering the building from this side, visitors approach the foyer (Plate 70). Beyond this, the space opens out to form a ten metre high gallery running the length of the building. From here views out onto the surrounding landscape can be taken, through the vast glass facade of the building. Below, too, activities within the retail and refreshments areas can be observed. Standing at this point, the viewer is surrounded by glass. The roof above, the walls to each end of the gallery and the facade running the buildings length - all are planes of glass (Plate 71 + 72). The plans of the building can be seen in appendix 12.

7.4 Due to the nature of the building - its 'vertical and horizontal transparency' - the engineering design team have investigated the environmental factors which must be considered. The position of the building is such that the facade faces south east. Consideration of the influence of the sun informs their decisions of appropriate materials to use which will maximise comfort for building users and minimise heating and cooling costs. Using Thermal Analysis Software[5], the geographical coordinates of the site are recorded and the design of the buildings mass is entered. Simulation of the changing influence of the sun is then achieved, casting shadows from the building which change according to time of day and season. This is calculated using an algorithmic formula for approximate solar position[6]. The shading analysis highlights areas of the building receiving maximum sunlight and thus identifies where it may be necessary to install devices to combat problems of glare and overheating.

> *"It can be seen that the solar radiation is directly onto the glazed facade of the building in the early morning and that the overhang on the facade provides partial shading from the high angle midday sun and that the facade is in shadow in the late afternoon"*[7]

This information is detailed in the images created using this software in appendix 13. For the purposes of the research, these images provide a valuable tool in assessing appropriate areas which may be targetted for the application of dichroics. Knowledge of the material suggested that areas which would receive direct sunlight but which would also produce shaded regions would enable the glass to perform at its best. The depth of reflected colour from the glass in tests has been shown to increase dramatically in shaded areas, bleaching out or becoming barely visible in uniform high level lighting (see Chapter 6). With the aim of creating a dramatic play of light, the reception area of the building was identified for investigation following discussions with members of the design team. A work creating dramatic and changing light effect in this area would contribute to the powerful impact of the building on visitors entering the space and conform to the design teams aims, outlined above, both to 'use glass in dramatic ways' and to create a 'memorable' experience.

7.5 Technical details obtained from the architects plans led to the construction of a 1 to 20 scale model of the central section of the building. The model was constructed of sheets of fibre board, forming the rigid internal walls and floor. Glazing was achieved using planes of 4mm thick float glass. The internal structure was painted white so that the influence of the glass could be clearly observed and recorded. Structural elements supporting both the roof and the facade were simulated in the model, by etching the glass. The grid matrix formed by the supporting elements was applied to the glass by first cutting a stencil from vinyl adhered to the surface and then sandblasting the revealed glass areas. The white etched areas prevent light transmission and cast shadows onto the interior space, simulating the effect of shadows from supporting girders (Plate 73).

The reception area consists of a wide walkway flanked by walls on both sides, with a glass roof above. It was anticipated, having examined the shading analyses that this area would produce the degree of shadowing desired whilst also receiving good levels of direct sunlight.

7.6 To simulate the influence of the sun on the model, a tungsten photography lamp was positioned to the east of the model. The exact positioning of the lamp, its height and distance from the model was determined by observing the shadows cast and comparing them to the shading analysis images. Having established an accurate position to simulate the lighting conditions expected at 9am, mid-summer, the lamp was moved to establish its height and position at 12 noon. Having marked the positions of these two points in relation to the static model, it was possible to measure out the positions the lamp should take in the intervening hours. The height of the lamp was measured at 9am and at 12 noon and the rate of increase over the distance travelled was calculated. From this, the position of the lamp at 10am and 11am was calculated. An equal ratio of height to distance travelled was used to calculate the declining position of the light source post-12 noon. All of these sites were marked so that the procedure could be repeated accurately. A sequence of light simulation was thus established, beginning at 9am and ending at 2pm. This examines the duration of daylight hours during which time the maximum influence of light and shade is observed in this area of the building.

Initially, the influence of light on the model was observed and recorded photographically, building a knowledge of the changing influence of the sun on the space. Following this a sample of dichroic glass was selected to be tested within the space. The transmission and reflection levels of the sample of 'magenta' dichroic glass was analysed by Pilkington Technology Centre and the results of this can be seen in appendix 14.

With the aim of exploring the material as an integral element in the building, working within the existing glass planes of the roof and walls, various options were investigated.

During the early stages of the project a meeting with Gordon Shrigley, architect at Gollifer Associates, took place in which possible applications of the material were discussed. A document was presented (see appendix 15) which outlined planar applications and other methods which had been the subject of earlier work, outlined in Chapter 6. There was a definite preference stated during discussion for the design of an integrated work which formed part of the buildings structure, and this informed my approach to the project. The ability of dichroics to give dramatic effect within a glass building, with high levels of light and few deep shadows, was questioned by Gordon Shrigley who felt it would be useful to test the glass in the proposed way.

Samples of dichroic glass were placed at various positions on the roof and façade, the resulting effects were observed. Planar use of the glass, for example as flat panels fixed within the structure of the façade, although creating a strong reflected colour visible on the exterior of the building, did not facilitate projection of reflected light into the interior space. Alternative methods of application had to be considered. Earlier 'tests' of the material in which strips of glass had been explored in the form of louvres (see Chapter 6), etc, informed my approach to design. Selecting the roof area above the reception as an appropriate area for the fixing of the glass, the application of dichroics was investigated.

The grid system, determined by the supporting elements, on the model measure 5cm x 5cm, being one metre square full scale. Multiple strips of the chosen dichroic glass measuring 5cm x 1cm were positioned on the roof of the model. Placed vertically, standing upright on the 5cm long edge, the strips become louvre blades within the grid formation. Possible arrangement of the glass blades was then investigated. Two of the options are outlined here as 'schemes', each of which are tested in the space under the simulated lighting conditions.

7.7 ROOF SCHEME 1.

With the aim of exploiting the reflection and transmission qualities of the glass, throughout the course of the day, the glass elements were positioned in a repeating configuration. Viewed from above, two rows of the central area of the grid were chosen for the positioning of the glass. Beginning above the location of the reception and extending beyond the balcony area to above the foyer area, the glass was placed in a regular repeating pattern. Two strips of glass were placed in each square of the grid. The first were positioned horizontally, the next vertically, then diagonally (left to right) and finally diagonally again (right to left). This configuration was repeated four times in both rows of the chosen area of the grid system. Alternating the positions of the glass in this way, it was thought, would enable both reflection and transmission of certain elements at each hour of the day.(Plates 74 + 75)

9am. Transmitted magenta light falls onto west facing wall of the reception area, extending out onto the south east facing wall of the balcony area (this runs parallel to the facade of the building). Reflected green light is projected onto the opposite west facing wall of the reception area.

10am. Transmitted magenta light now appears on the floor of the reception area, next to the point at which the floor meets the west wall. Superimposed onto the magenta area are flashes of green reflected light. This begins to extend also onto the ground floor area directly below.

11am. The transmitted light moves deeper into the floor area of the reception. Green reflected light continues to be visible on this area. The reflected green light moves further west in the ground floor area below.

12 noon. Magenta transmitted light moves to cover the central area of the reception where the desk will be situated. Flashes of green appear across areas of magenta. Transmitted light is visible on the ground floor area, immediately below the balcony. Reflected green light is projected on to the west wall of the reception area and onto the western end of the ground floor area.

1pm Transmitted magenta moves on to the eastern wall of the reception. Reflected green light appears strong in the deepening shadow opposite where it touches the floor and the western wall. Shafts of light are projected around the corner onto the south east facing wall of the balcony area. This extends out onto ground floor area, west of the reception, directly below the balcony. Transmitted magenta is cast onto the ground floor to the east of the reception.

2pm. Lengthening shadow from the western wall creates intense green colour in the reflected light patterns. Shadows on the balcony now highlight the intense green reflected light moving from the wall onto the floor here. Transmitted magenta moves higher up the eastern wall and is cast down onto the ground floor below. Interesting superimposition of colour occurs due to the alternating positioning of the glass blades.

This scheme demonstrated the potential of the qualities of transmission and reflection despite the highly illuminated context. Sufficient shadowing occurs to allow both colours to appear in varying intensity throughout the course of the day. (The visual recording of Scheme 1 forms part of the research presentation).

7.8 ROOF SCHEME 2.

Using the same repeating configuration of glass elements, focusing on a concentrated area of the roof section, the aim was to assist in the shading of the reception desk by modulating the light falling in this area. Plate 76 shows the selected layout of the glass in Scheme 2 (Time lapse photographs of this study have been used to create animated sequences which can be observed on the interactive programme, forming a part of this research presentation). Plates 77 to 84 show the shifting influence of colour and shadow in the reception area, viewed as one enters the building.

9am. Deep shadow cast by the eastern wall provides shade to the reception desk. Transmitted magenta extends beyond this onto the western wall, whilst a dramatic play of green light is observed opposite on the shaded east wall. This extends in dramatic shafts of light on to the balcony wall area. The intensity of colour here is seen to be weaker due to the lack of shadow in this area.

10am. As the shadow shortens the transmitted magenta is seen to follow path, moving onto the floor area whilst still extending up the eastern wall to roof level. Reflected light is seen on the opposite wall.

11am. Covering two-thirds of the floor area, whist still extending from floor to roof level on the western wall, the transmitted magenta continues to progress across the reception, meeting the retreating shadow. Reflected light is seen opposite with some light reflecting back onto the highest point of the reflected magenta area.

12 noon. The transmitted magenta light covers the whole of the floor area where the reception desk would be situated and begins to extend up the eastern wall. The amount of reflected light in this area is reduced. Projected out onto the ground floor, towards the facade, there is a play of green light.

1pm. The shadow of the western wall lengthens and reflected light intensifies on the floor and wall. Transmitted light covers approximately two thirds of the floor area and extends up the eastern wall to roof level. This transmission also is seen to turn the corner, falling onto the south-easterly facing wall of the balcony. Again green light is projected onto the ground floor towards the glass facade of the building.

2pm. With the shadow lengthening further, the magenta transmitted light ascends the eastern wall towards the balcony, where it spills out on to this walkway. Reflected green is seen projected onto the balcony area also. No cross over of colour occurs, the two are seen clearly and distinctly - magenta on white, in transmitted light and green on the dark ground created by shadow.

In Scheme 2 the glass is situated beyond the reception desk, beginning above the balcony area. This positioning enabled the transmitted light to fall onto the desk area. By placing the glass directly above the desk, it was found in preliminary tests, that the angle of the sun projects the colour beyond the desk area towards the entrance to the building. Moving the glass around the roof area enabled the most effective siting for the glass in this scheme to be determined. Early morning and mid to late afternoon, the reception area is in shadow, cast by the walls on each side of the reception desk. Positioning the glass across the roof from wall to wall, served to cast modulated coloured light on to the reception, during the hours of direct, intense sunlight. It is envisaged that the glass louvre blades would be fixed to the metal support structure which forms the dramatic grid matrix of the roof. Laminated for safety purposes, the dichroic glass could be drilled and fixed with steel fittings to this structure.

7.9 PROJECT REVIEW

Working with the scale model under simulated lighting conditions, made it possible to become familiar with the particular qualities of light and shade which will be experienced within the building. The influence of the glass could be examined and design options tested. Concerns, at the start of the project, about the performance of the glass under the strong daylighting conditions within a glass building were found to be valid to an extent - in some areas the reflected colour appeared to pale and lose intensity, as highlighted in previous tests. The degree of shadow falling within the space throughout the course of the day, however, was greater than envisaged. The supporting structure of the roof casts a dramatic grid matrix shadow across the space and the internal walls also give strong, shifting shadows. The reflected light falls in ever-changing formation, onto the shadowed areas of the space and intensity of colour is created. The constantly changing influence of light and shadow on the space would have been difficult to anticipate without the construction of the model and the simulation of sun light. The project demonstrates the effectiveness of the glass as a modulator of light within the building, creating the intended dramatic effect in the reception area.

Liaison with the engineers gave access to the shading analysis which proved invaluable in the simulation of solar impact on the model. Although approximate solar position can be calculated without the use of a computer programme, the three-dimensional modelling achieved with the software provides greater accessibility for the designer (see appendix 16). In solving the practical problems posed by the architects design, the engineers examine the potential products and mechanisms available to achieve a comfortable, efficient building. Gavin Stamp at the *Glass in the Environment Conference* (1986), made a rather damning assessment of the success of the attempts to create comfort within contemporary 'glass houses'[8]

> *'The moment huge sheets of glass are used, they are hung with net curtains'* [9]

Proposals from the engineers to combat the solar gain problem at the National Glass Centre include horizontal fixings (metal grills) to the facade and horizontally fixed blinds to the roof. These solutions appear rather crude compared to the many possibilities currently being developed (see Chapters 4 and 5).

The application of dichroic glass in the model achieved the desired dramatic aesthetic whilst also revealing potential in the use of reflective glass structures to redirect light and assist in shading. Rather than the more usual planar application of coated glass, the positioning of the glass vertically to the horizontal plane of the roof maintained transparency (the desired view through the roof) whilst, within the building, the fall of light was manipulated and diverted from its natural path.

In this project, although the primary concern was to create a dramatic aesthetic for the National Glass Centre, the approach adopted and the forms which result demonstrate the great potential which exists for the involvement of the artist in addressing contemporary architectural problems. Certainly, the need to apply a creative approach to the large scale use of glass in order to achieve transparency and comfort is clear.

In his recently published book *Glass in Architecture* Michael Wiggington explores both the historical and contemporary application of glass. Presented as case studies are buildings in which the use of glass has been interesting and innovative.

> *'Significantly, in most of them either a special glass has been designed, or a new technique developed to serve the concept.The message here is that with technical understanding and prowess comes the potential of virtuosity and great beauty.'* [10]

The importance of understanding the material and what it can do is at the heart of the creative approach, as much today as it was in the production of glass for Gothic cathedrals. It is unrealistic to expect the development of new glasses for each new building, but an inventive application of existing materials may produce effective solutions.

The application of dichroic glass to this particular building demonstrates the exciting architectural potential of this relatively new material. The approach to the design taken during the project is very much a response to the architecture and the natural conditions experienced within the building. In documenting each stage of the design process, useful insight for other practitioners is revealed and personal practice developed further. Communication with other design professionals throughtout the project demonstrates the value of the collaborative approach in the creation of integrated architectural works.

CHAPTER 8: SUMMARY AND CONCLUSIONS.

8.1 The selection of dichroic glass as the focus of research, initiated the identification and analysis of a number of areas of study which unite to inform and direct practice. In this final chapter, each area of research is summarised and its contribution to the research as a whole and influence on practice examined.

8.1.1 The historical study of the role of stained glass in architecture was important in establishing the context within which this research programme has been carried out. In this study the importance of light is revealed as the phenomena with which artists, designing glass for architecture, are primarily concerned. Rather than viewing stained glass in isolation, the review of its role over the centuries is clearly linked, in the study, to developments in building design and technology throughout history. In this way, the architectural functions of the glass are defined. The particular position from which this research is pursued is clearly expressed in the close linking of developments in stained glass with developments in architectural design. The integration of glass designed by an artist with its architectural setting is thus revealed as a vital issue in the research.

8.1.2 This theme is explored further in Chapter 3 with the study of the practice of contemporary glass artists. A broad spectrum of approaches to the medium of stained glass is revealed. The words of Ann Warff provide an interesting contrast to the struggle for integration. Viewing her work as self-contained pieces which do not relate to their settings - as *"guests in architecture"* - her approach to the medium of stained glass is similar to the approach of a fine artist to painting. A clear distinction is revealed here between this approach and that of the *architectural* glass artist. The emergence of this as an appropriate term to describe the work of artists interested in architectural issues is clearly revealed in this comparative study. Identification of this distinction is important in establishing the position from which this research is carried out and provides useful insight for other practitioners in the field.

In-depth case studies of three other contemporary artists serve to demonstrate innovative approaches to the design of glass for contemporary architecture. In each of these cases, methods and techniques developed illustrate a spirit of invention and a desire to push the potential of the medium. A range of issues involved in the process of designing work to commission are revealed in this detailed study. The importance of collaboration with architects, engineers and other design professionals emerges in each case study. Knowledge of the issues revealed in this comparative study informs practice and this is clearly demonstrated in the approach to the application of dichroic glass adopted during the research programme.

8.1.3 A review of developing glass/building technologies and the various concerns directing their research provides useful insight for the architectural glass artist. The need for economically and environmentally efficient buildings has led to the development of a range of technologies in the steps towards creating a 'dynamic skin' for architecture. This concept of creating an active building exterior, which is sensitive to changing climatic conditions, is an exciting one and one which has major implications for the future direction of architectural design. Awareness of the changing nature of architectural glass and emerging technologies is vital for artists wishing to be engaged in the design of glass for contemporary buildings.

Sophisticated mechanisms designed to make innovative use of daylight are reviewed along side this study. Again, driven by the need for environmentally friendly and economically desirable solutions to building design, these devices aim to reduce the dependency on electric lighting within buildings, by enhancing and extending the influence of daylight on interior space. The importance of an awareness of these developments for the architectural glass artist - whose work is essentially concerned with light - is clear. In the review of systems, new opportunities for artistic intervention are revealed. As the window disappears, with the development of the glass skin, other sources of light emerge in new building design. Natural light, diverted into the depths of a building by light pipes or fibre optic cables, enters and is dispersed through 'emitters'. The design of appropriate forms to receive and emit this light provides new opportunites for the application of the artists skills. Knowledge of these emerging technologies and architectural concerns are influential in the approach adopted in the experimental work and architectural application of dichroic glass during the research.

8.1.4 In developing an understanding of the nature of dichroic glass as a material, useful insight was gained with the support of Pilkington Technology Centre. Developments in coating technology were studied and the production of a range of dichroic glass samples revealed the sophisticated process involved in the design and application of thin layer coatings. Examination of the methods adopted to produce specific colours gave a greater understanding of the nature of the material and the high level of control necessary in the successful production of dichroic coatings. Insight into how the dramatic visual qualities, which characterise dichroics, appear as they do was achieved in the study of the physics of light and, more specifically, interference. This study served to build an understanding of how the material operates. Understanding of the nature of the material informs the assessment of its potential as an architectural medium.

The investigation of the material technology of dichroics, then, serves to provide an understanding of the magical aesthetic qualities of the material chosen as focus in the research. This understanding assists in guiding personal practice with the glass.

8.1.5 Initial testing of the potential of the material involved the documentation of the visual qualities of the glass in controlled environs with a shifting light source. The recorded observations of the changing appearance of the glass and the reflected and transmitted colours provide a technical guide for other designers interested in using the material and a starting point for personal practice.

Methods were developed during the research to enable the recording of the qualities of the glass and to explore the design potential of the material. The construction of model environments became an important element in the practice with the material. This enabled control of lighting, and the simulated application of the material on an architectural scale. Recording the results photographically meant that models could be dismantled and reconstructed in the exploration of a range of forms using a limited amount of materials.

This technique of exploration through the model is a valuable method which other practitioners may find useful. The model is seen to be an economical method which enables the development of a creative approach to the material. In this process, the artist is freed from the numerous restrictions which operate when designing a commissioned work. Amongst these, issues of budget, scale and clients preference were seen to be of influence in the documented analyses of the design processes for the commissioned windows completed during the research programme.

The commissions, although modest in scale, provided opportunities to apply the glass in 'real' settings which proved useful during the research programme. The restrictions on the creative involvement of the artist highlighted in these projects demonstrate clearly the limitations which operate when there is a lack of opportunity for collaboration with architects in the design process. In each case, although the commissions were within newly constructed buildings, the artist was brought in at the final stages of construction, when most of the fundamental design decisions had been made. The scale and nature of the 'art work' is thus determined, to a large extent, before the artist is appointed. These commissioned projects then, whilst providing opportunities for the application of the material, also enabled first hand experience of the kind of constraints which, all too often, the glass artist must work within.

8.1.6 The importance of a collaborative approach revealed in the contextual study, directed the choice of the final project. Although not a 'real' commissioned project, communication with the design team during the planning stages enabled a greater freedom of approach, characteristic of collaborative work.

The nature of the building chosen provided a challenging test of the possible contribution an artist might make within a building constructed predominantly of glass. One of the essential aims of the design for the National Glass Centre: to create *a world of vertical and horizontal transparency* provided the opportunity to test the impact of dichroics within such a setting. The project enabled application of the knowledge of the material gained during the experimental work, within a constructed model of the Centre, working with the qualities of light and shade particular to this building. Communication with members of the design team enabled a level of engagement with the building which had not been possible in the commissioned work carried out during the research.

The application of dichroic glass in the research model of the National Glass Centre involved the successful exploitation of the qualities of the material observed in the experimental work completed during the research. Rather than applying the glass in a planar way, positioning the glass vertically against the horizontal plane of the glass roof enabled the full appreciation of the unique light manipulating quality of this glass. Both transmitted and reflected light is projected into the building creating an intriguing, ever-changing, wash of coloured light throughout the building during the course of a day. Planar application of the glass would result in the reflected colour being observed on the outside of the building only, in daylight conditions and the full impact of this contrast on the interior would have been lost.

Communication with the mechanical and electrical engineers highlighted shared areas of study in the design process. The study of the influence of light exposes to the engineers problem areas within the building which may be subject to high levels of direct sunlight. This suggests to them the need to design (or apply ready-designed) devices to divert light from these areas with the aim of creating a more comfortable internal environment for building occupiers. The shading analyses comfortable internal environment for building occupiers. The shading analyses completed by the engineers provided valuable information to work from in deciding the appropriate location for dichroic glass within the building. This study suggests that given a truley collaborative approach the interest of the architectural glass artist in the manipulation of light could join with and enhance the functional approach of the engineer. The result could be a richer more creative approach to the solving of architectural problems.

The application of dichroic glass in the model demonstrated the dramatic aesthetic created by applying the glass within a building of this kind. Light was projected into the building by the strategic postioning of the glass, creating a play of colour which shifted throughout the space during the course of the day.

In this project, the communication with the design team and the knowledge of the material, succesfully united in a direct response to the building, achieving the aim of a dramatic visual experience for building users.

Sir Alastair Pilkington, speaking at the *Glass in the Environment Conference* (1986) stated his strong belief in the 'partnership' necessary between architects, glass technologists and artists in the exploration and application of glass.

> *'I am very concerned that the artist is included in this. I feel artists are so vulnerable, particularly if they are working on their own, and yet their contribution is critically important to true architecture.'* [11]

8.2 During the course of the research, then, the various strands of study have united to develop an innovative approach to the artistic application of a relatively new and exciting material to the contemporary architectural context. Study of historical and contemporary prescedence has guided thinking and involvement with Pilkington Technology Centre has informed technical understanding of the material and of appropriate construction methods. Application of the material through collaborative work (Chapter 6) and in the Glass Centre project, has led to the development of forms which, whilst exploring the aesthetic of this unusual glass, examine also its function as an architectural element. The design process is thus informed by contextual study and technical knowledge, coupled with a direct response to architecture.

In the final project, the freedom to explore the potential of the glass within a challenging contemporary building was enabled without the level of constraint which operates when artists are invited in at the end of a project. The value of the 'partnership' described by Alastair Pilkington is revealed in this approach and its influence on individual practice made clear.

Documentation of the various strands of research and their relationship to personal practice provides valuable insight for other practitioners approaching the application of dichroic glass within an architectural setting. Liaison with glass technologists, engineers, architects and artists has resulted in the bringing together of a number of specialist perspectives which have assisted in the development of an appropriate response to the architectural application of the material. In bringing together these specialisms, links are made which go some way to demonstrate a richness in approach which can be achieved through greater communication and collaboration.

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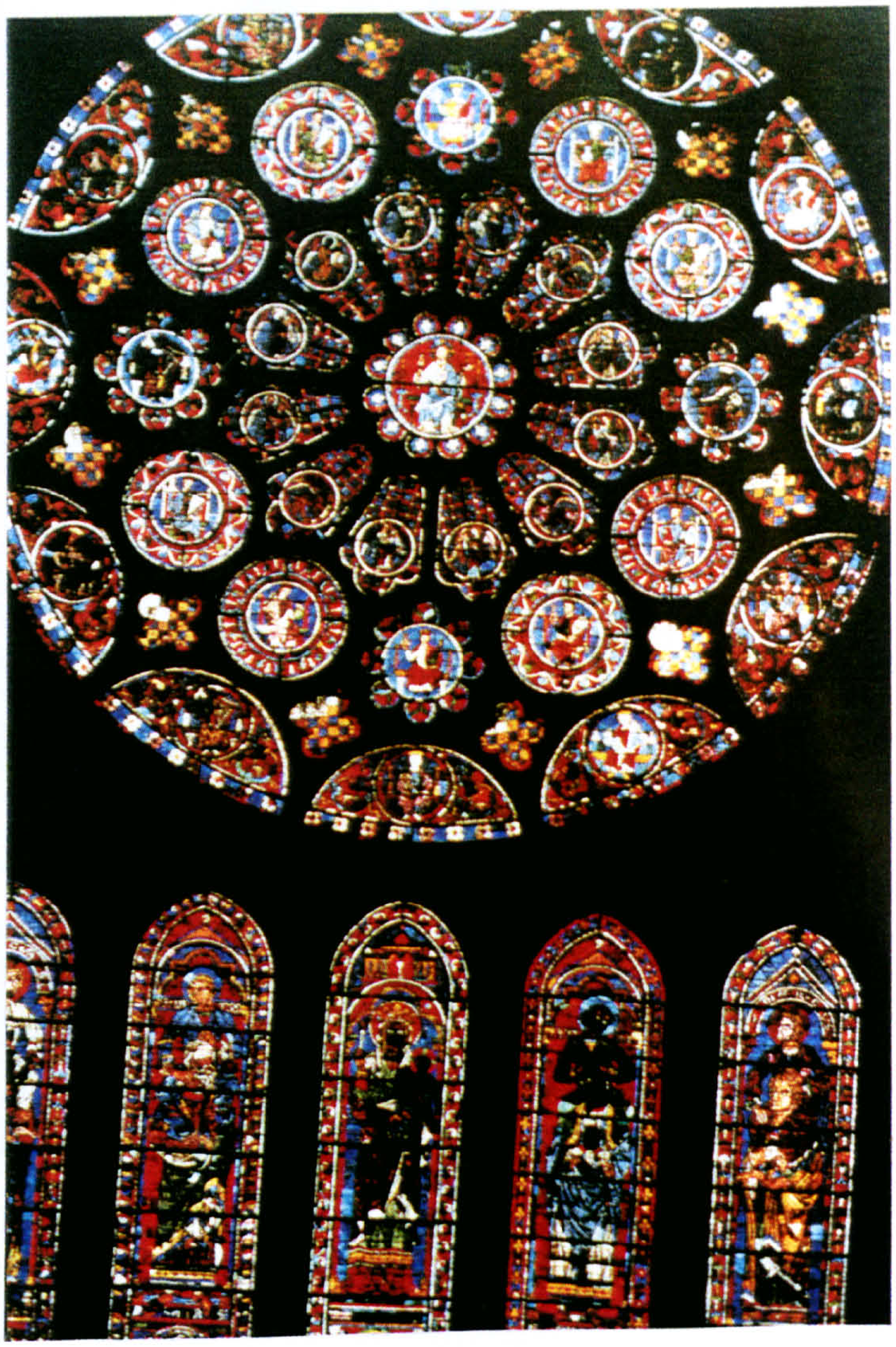
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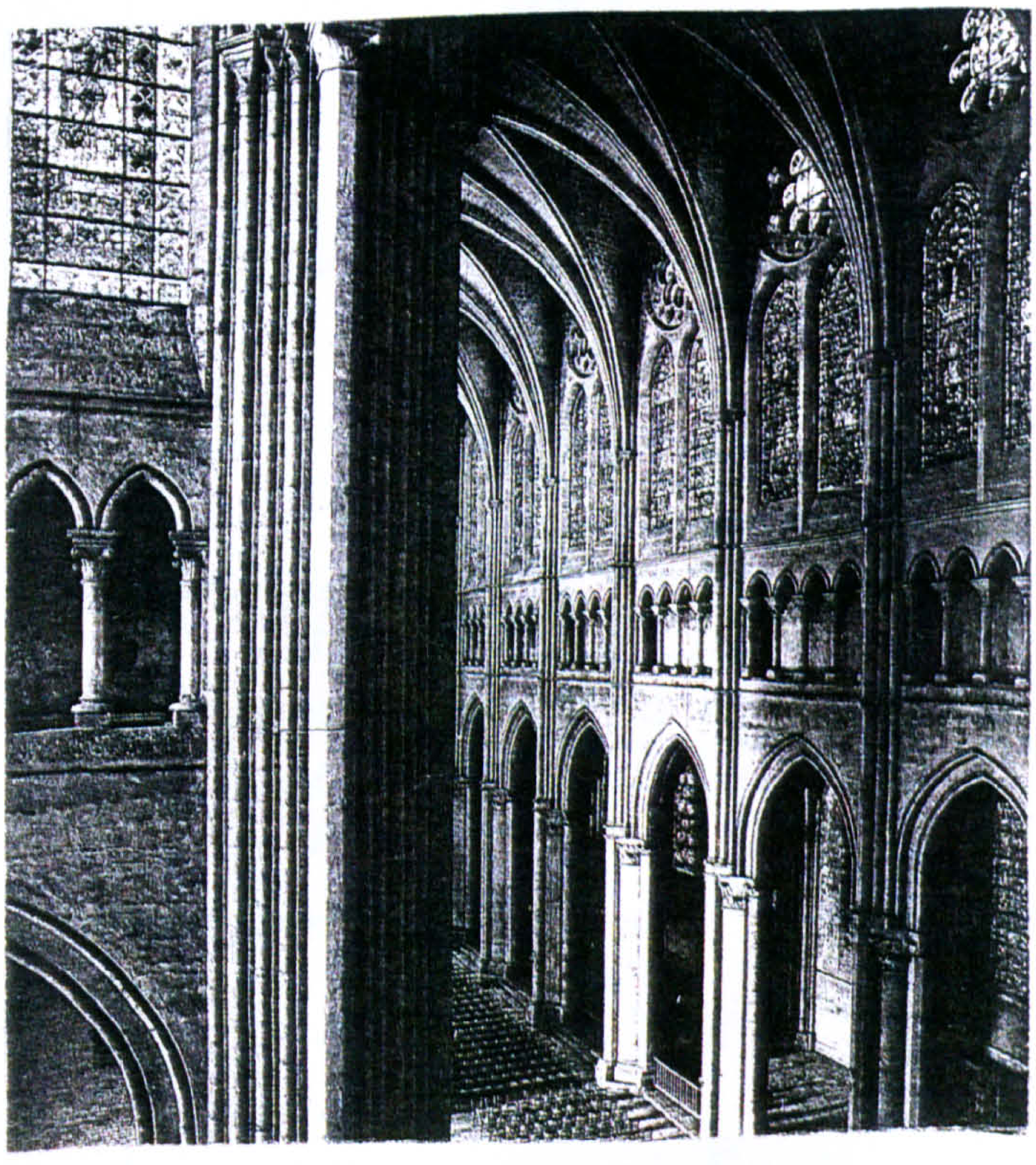
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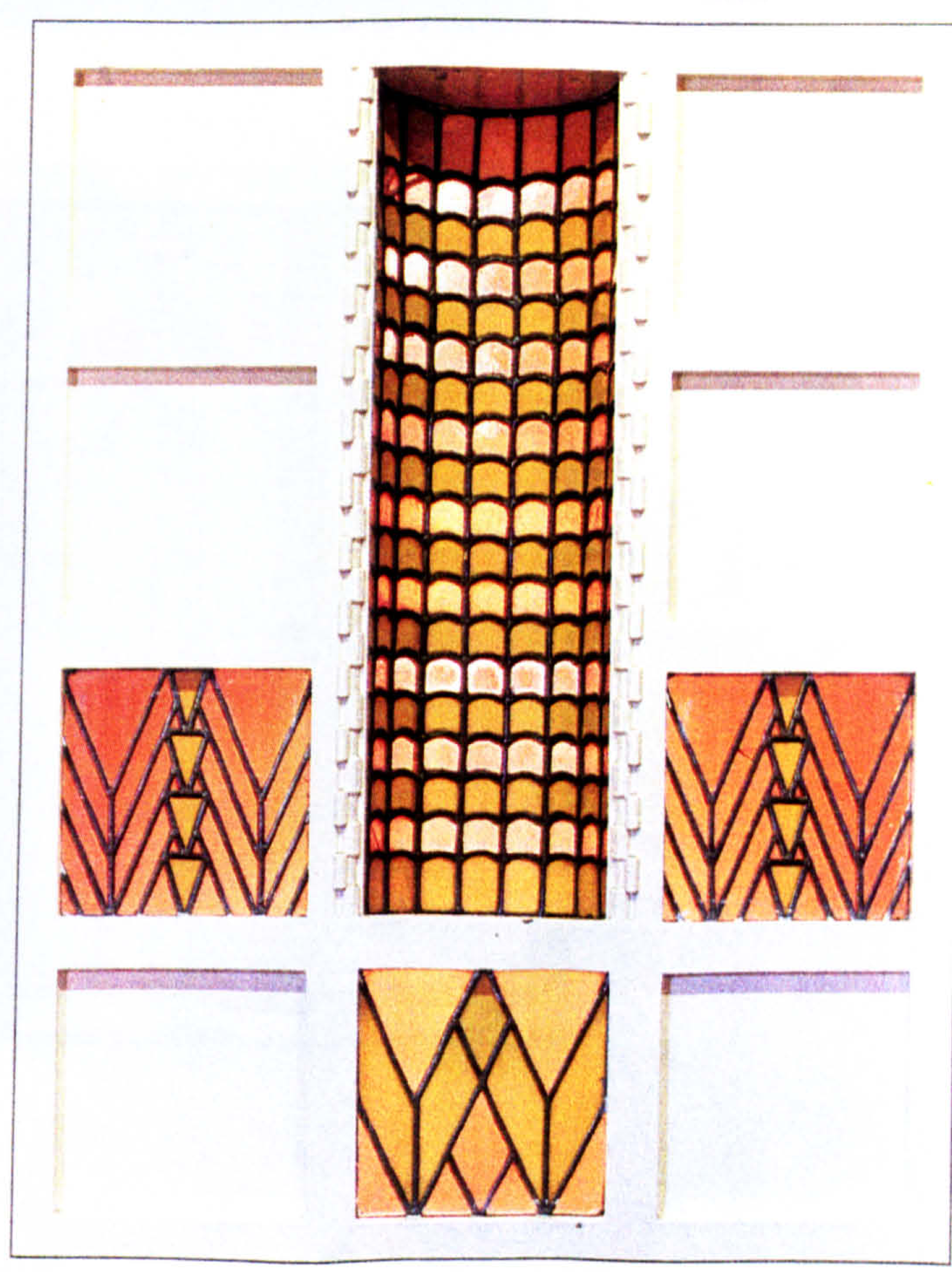

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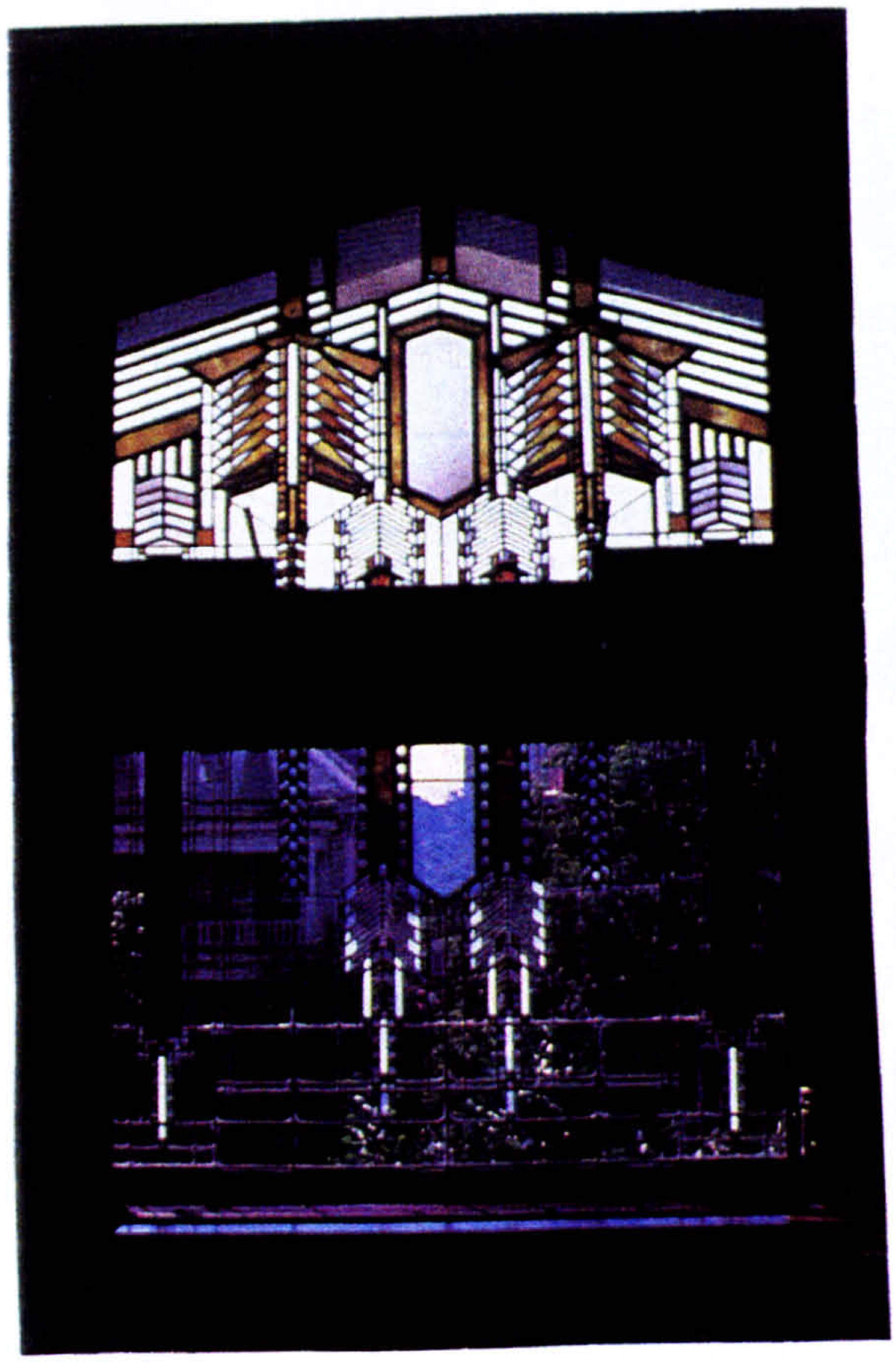

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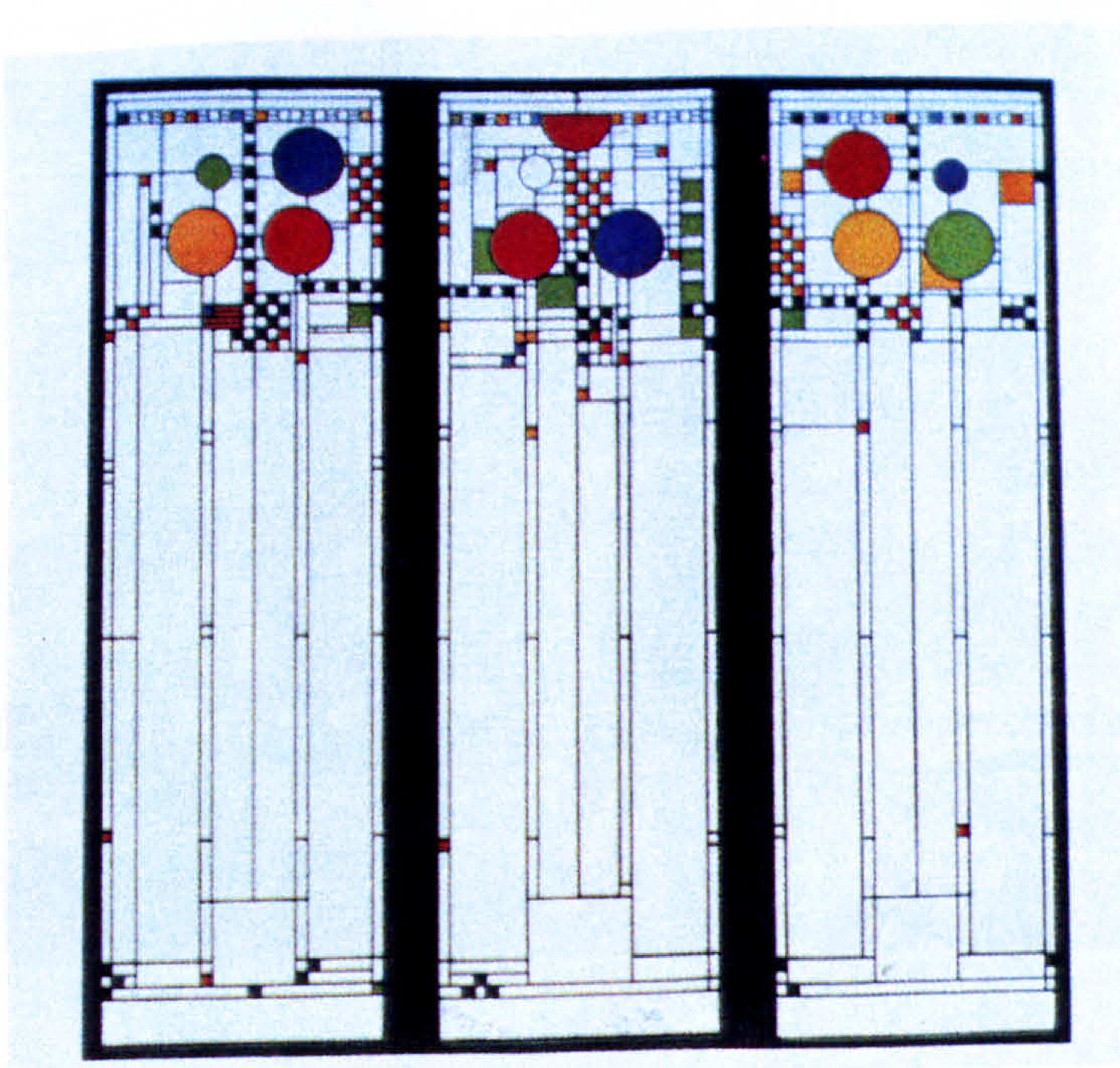

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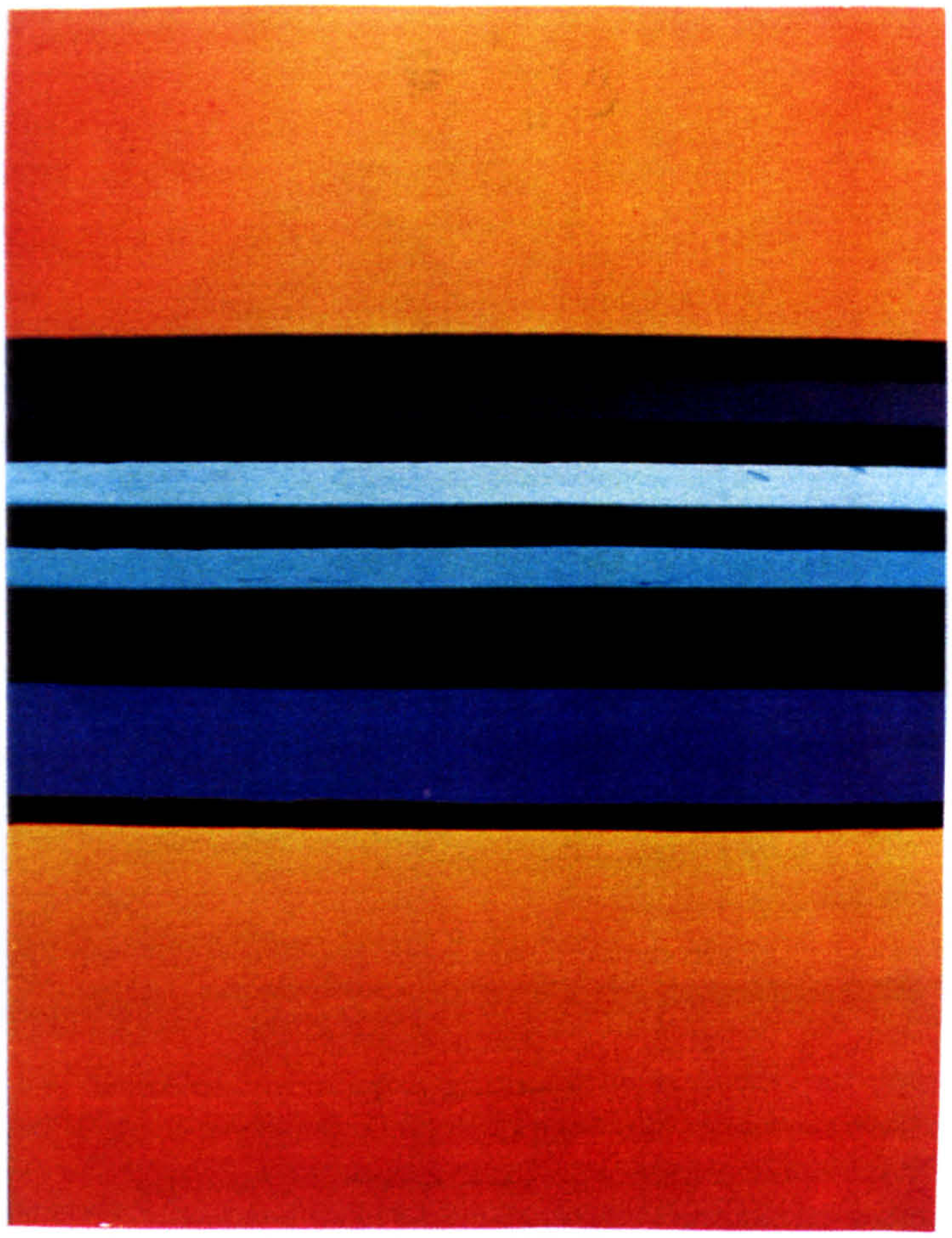

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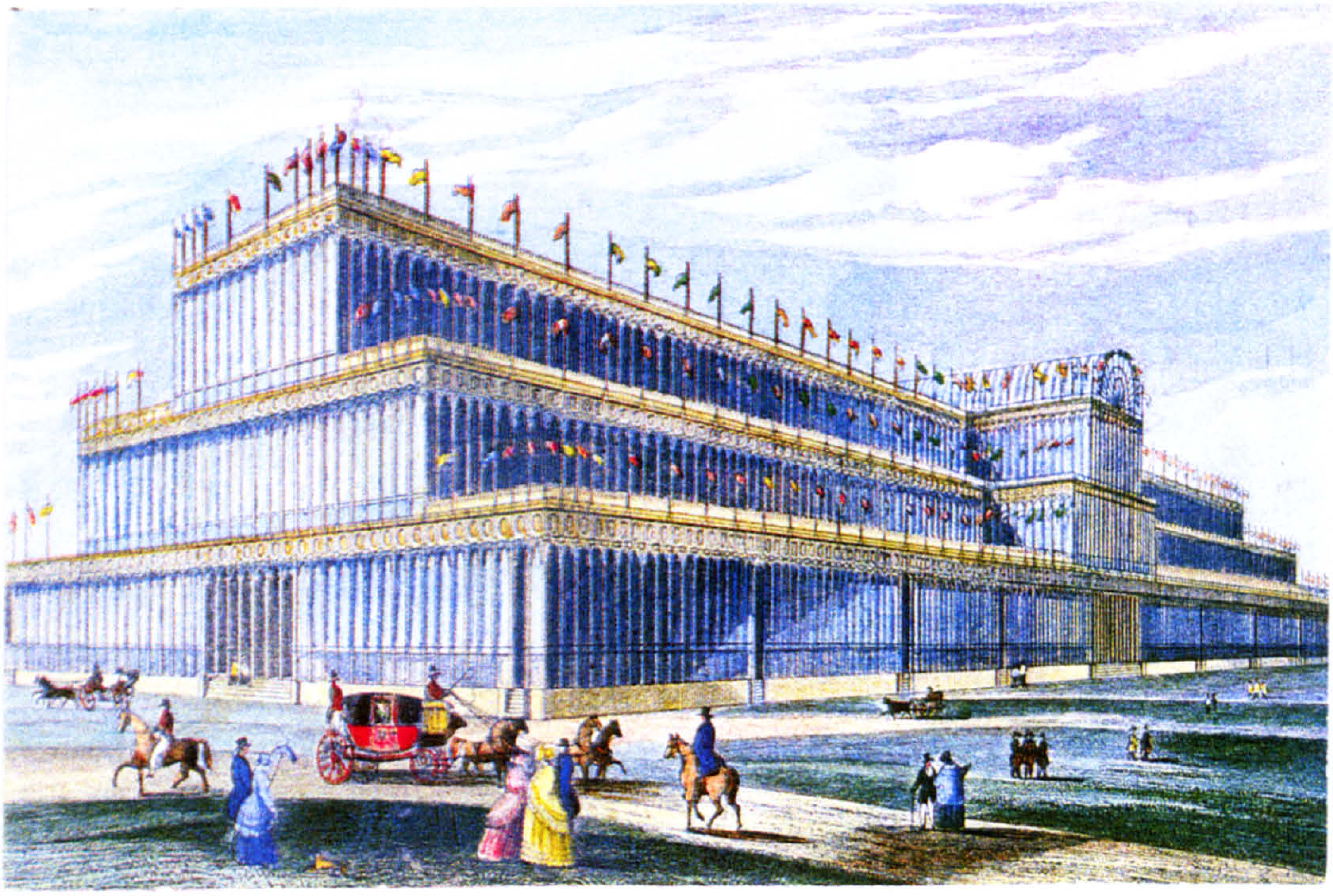

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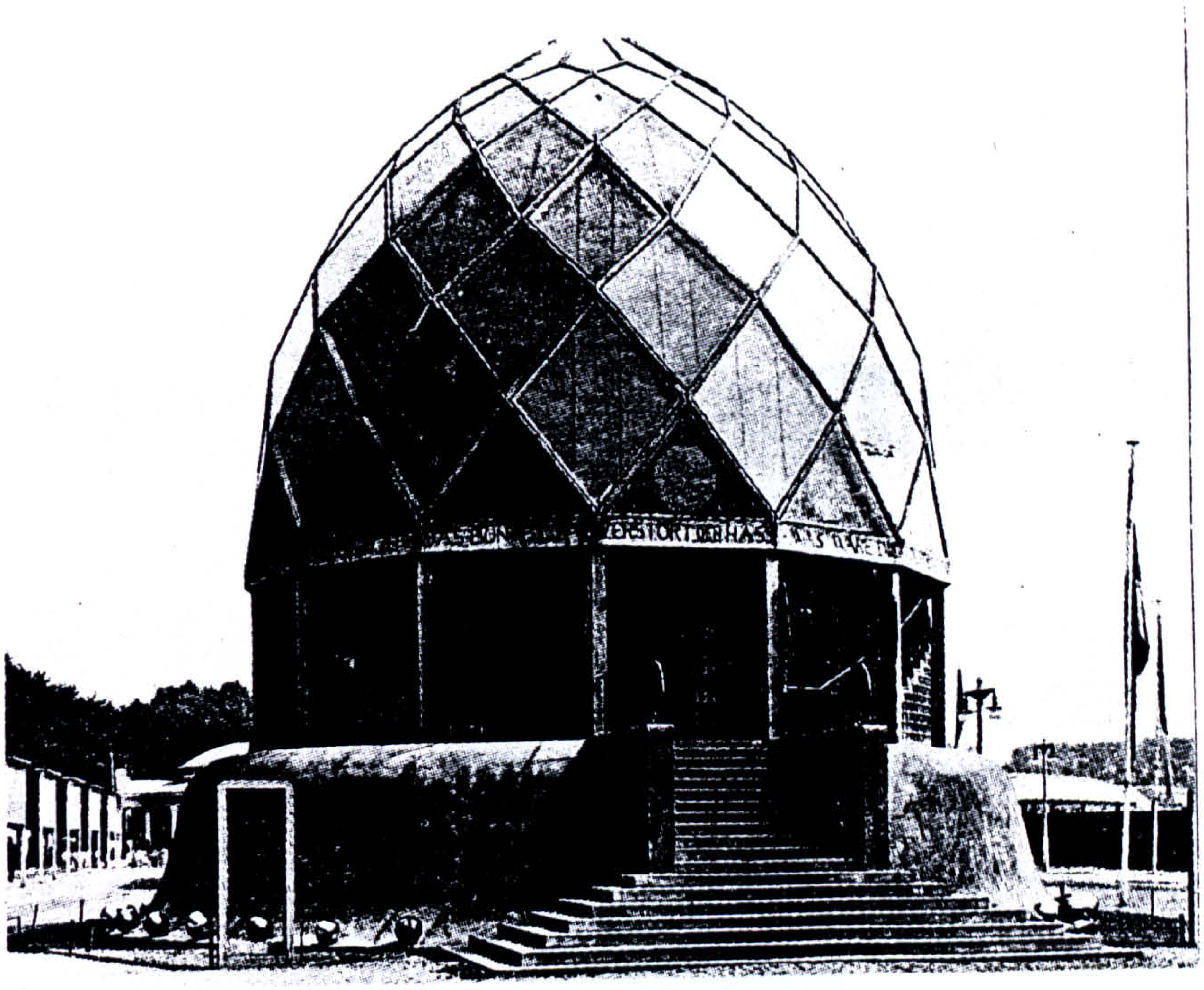

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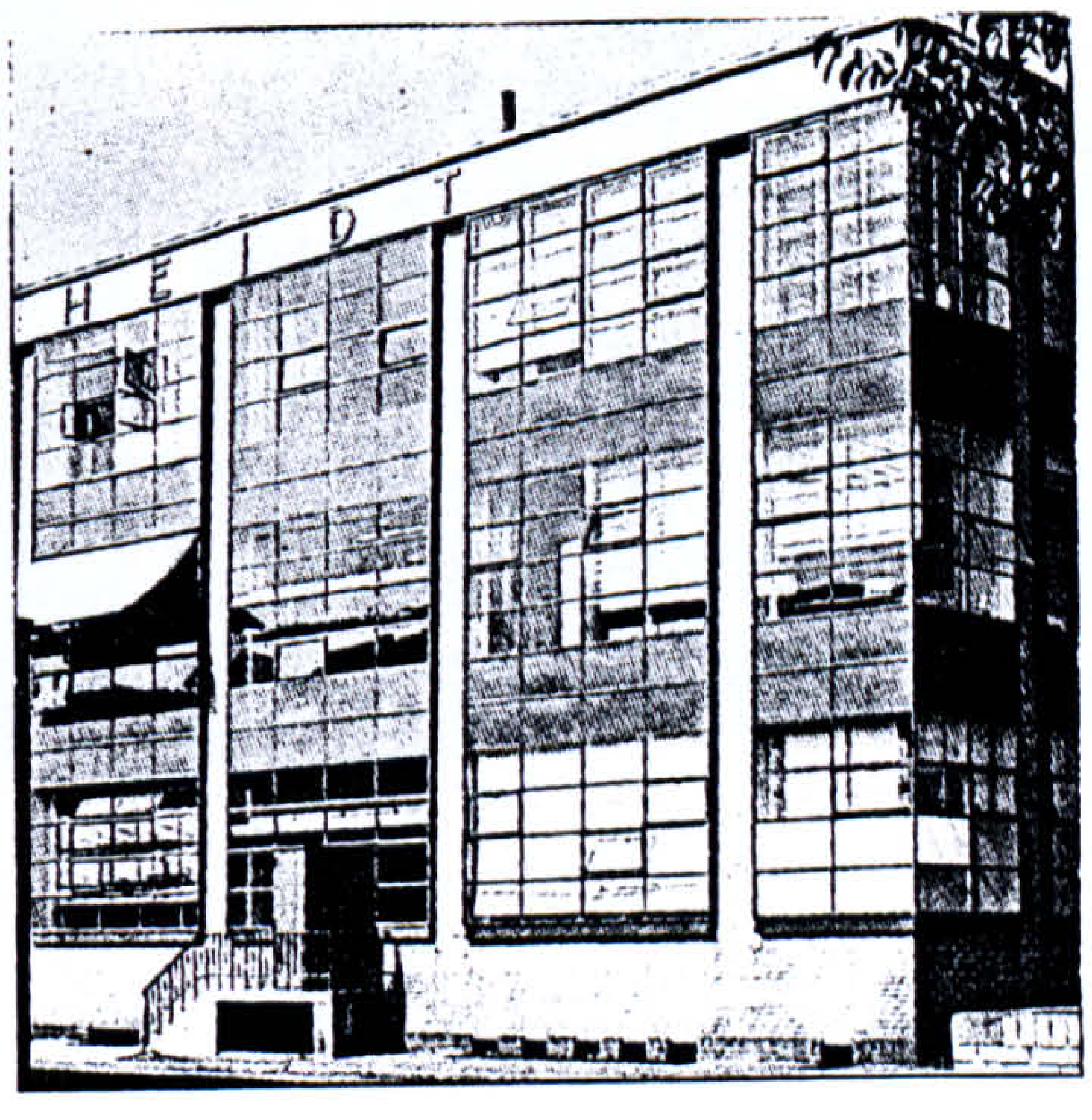

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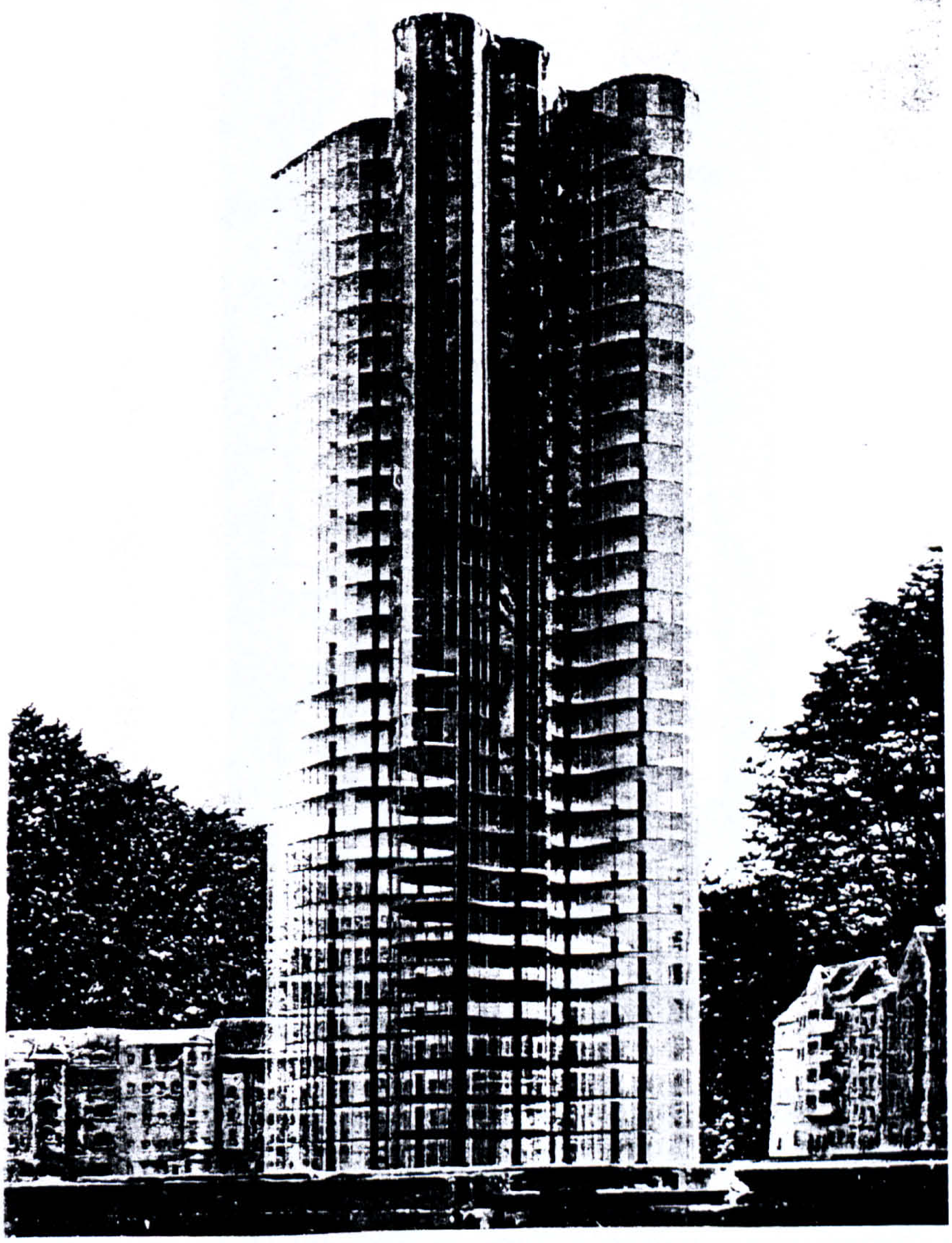

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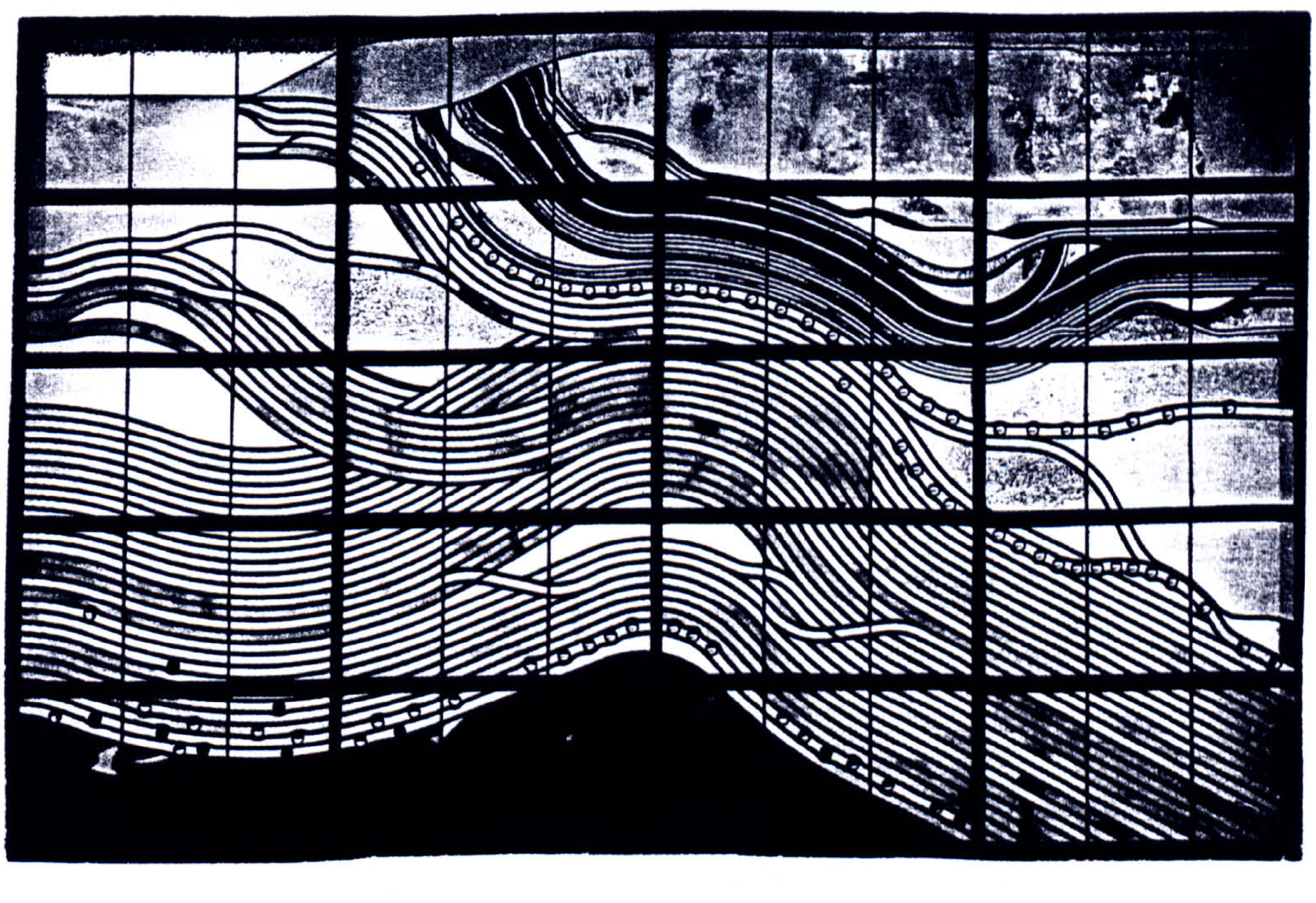
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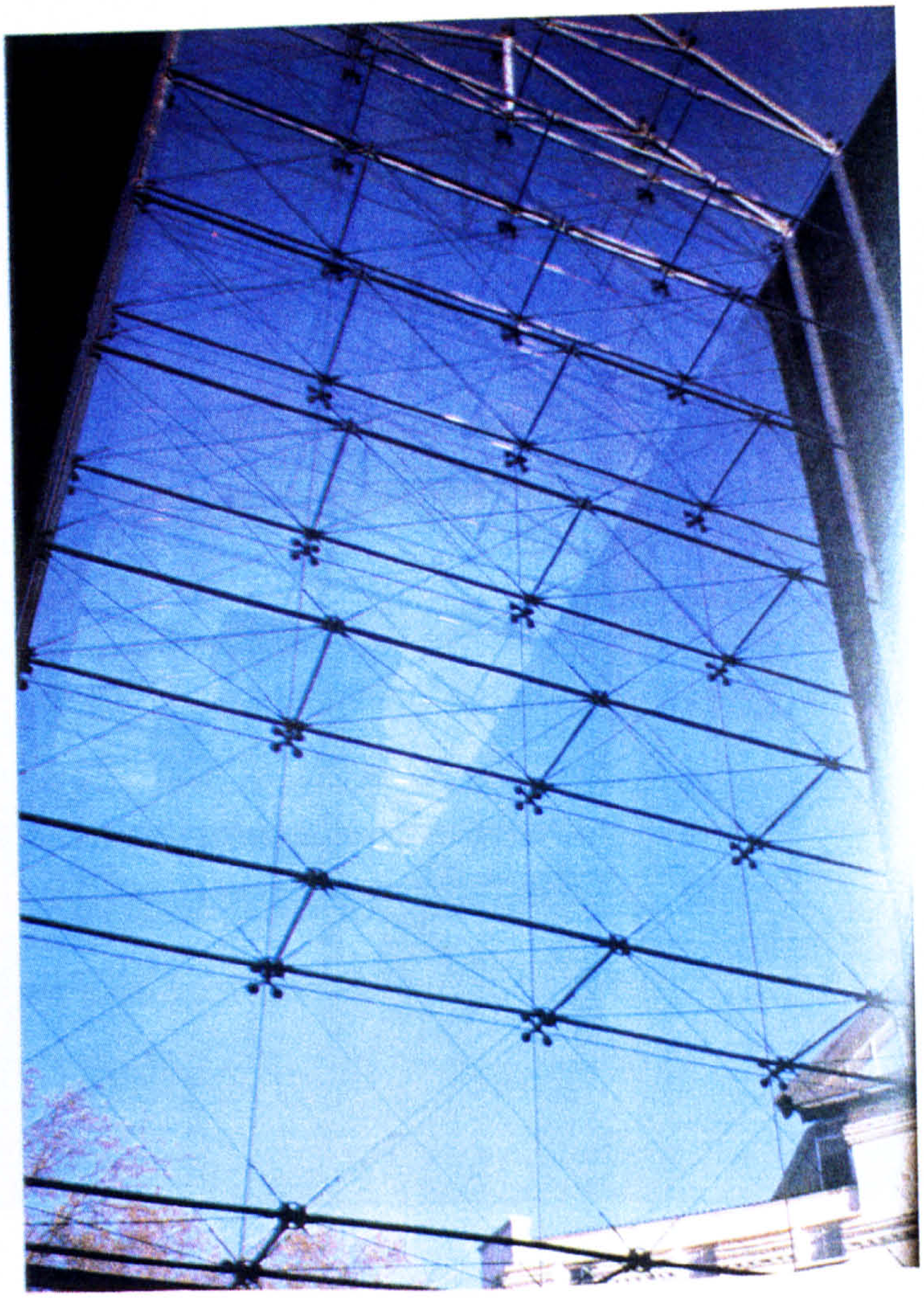

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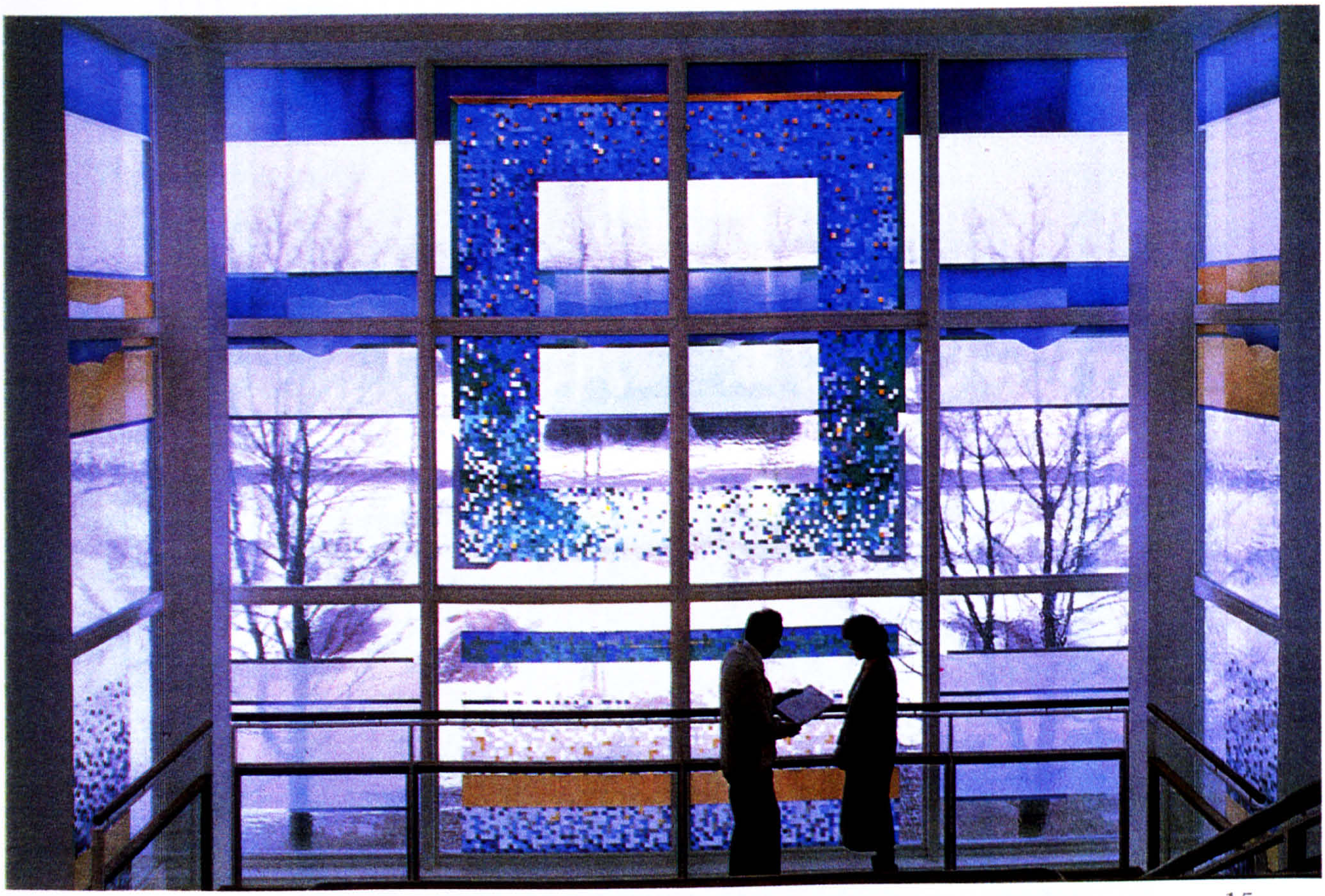

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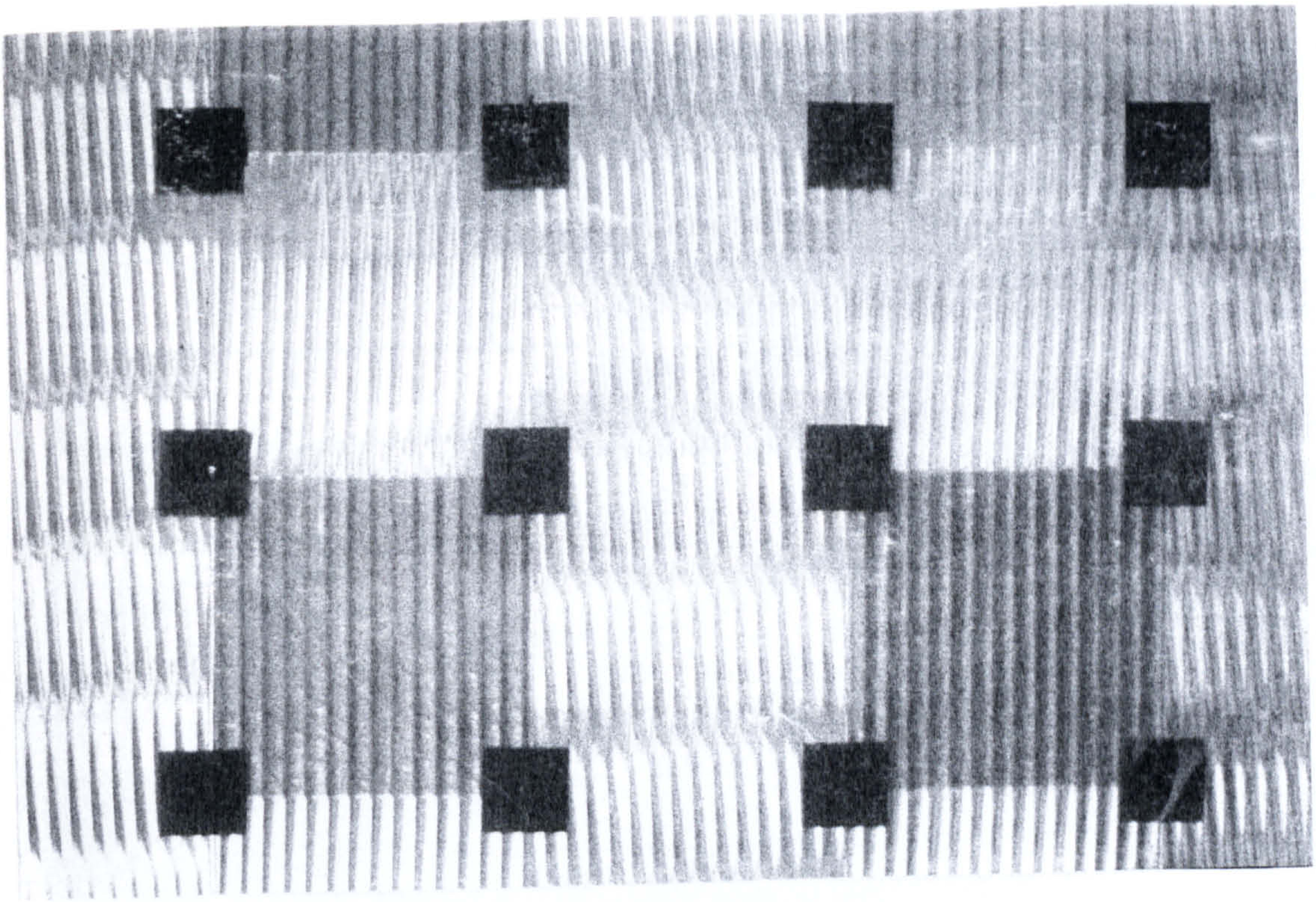

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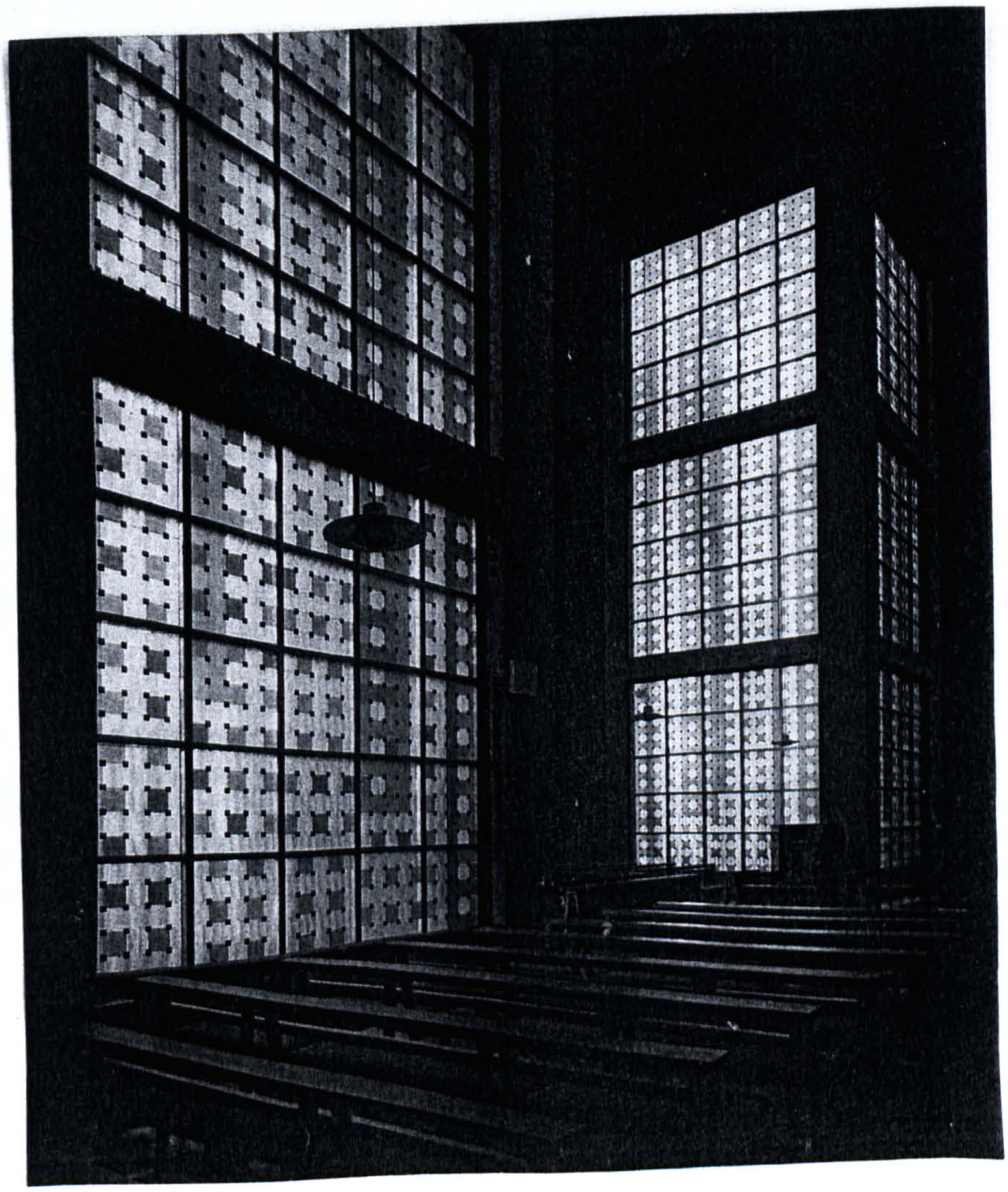

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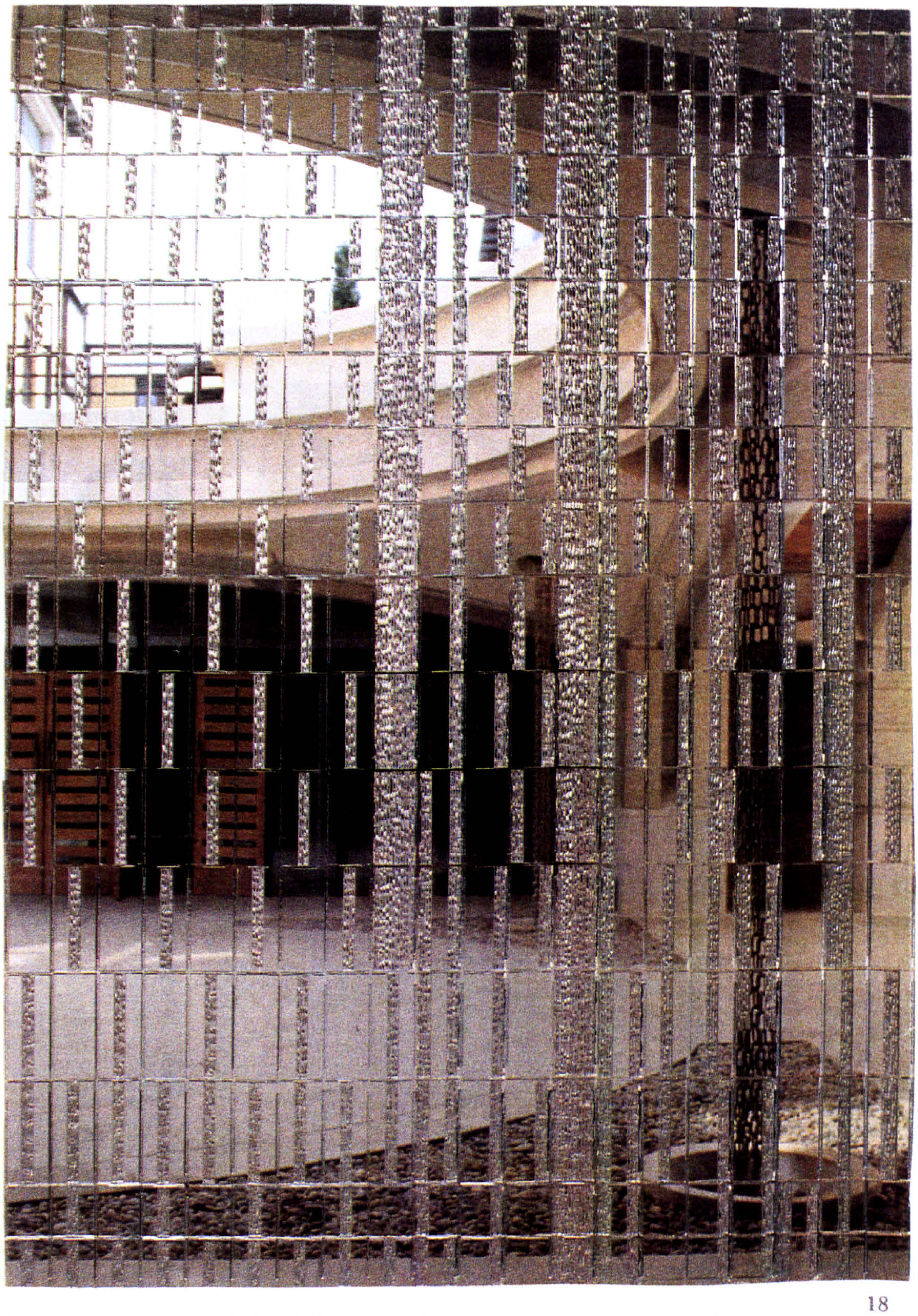

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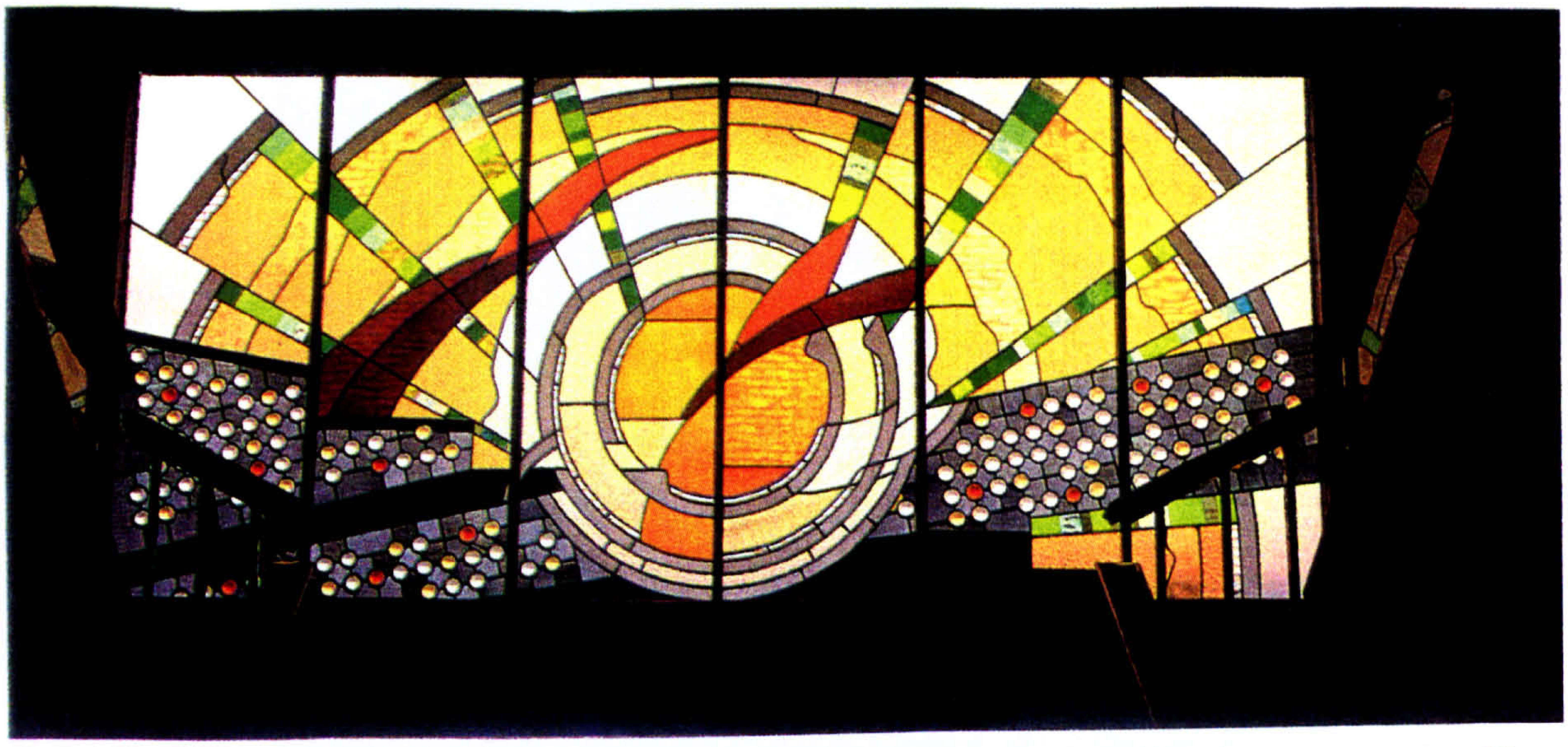

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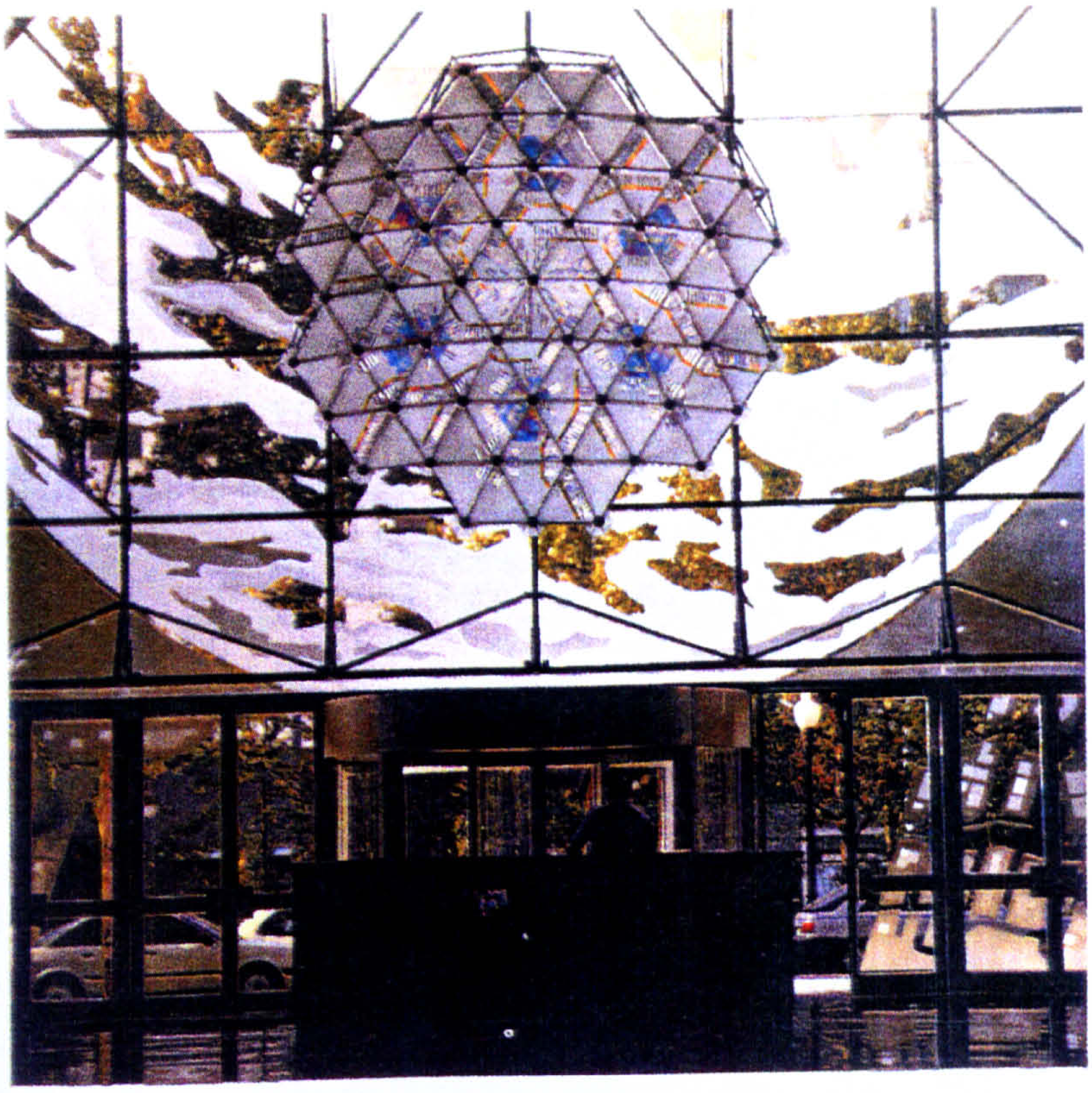

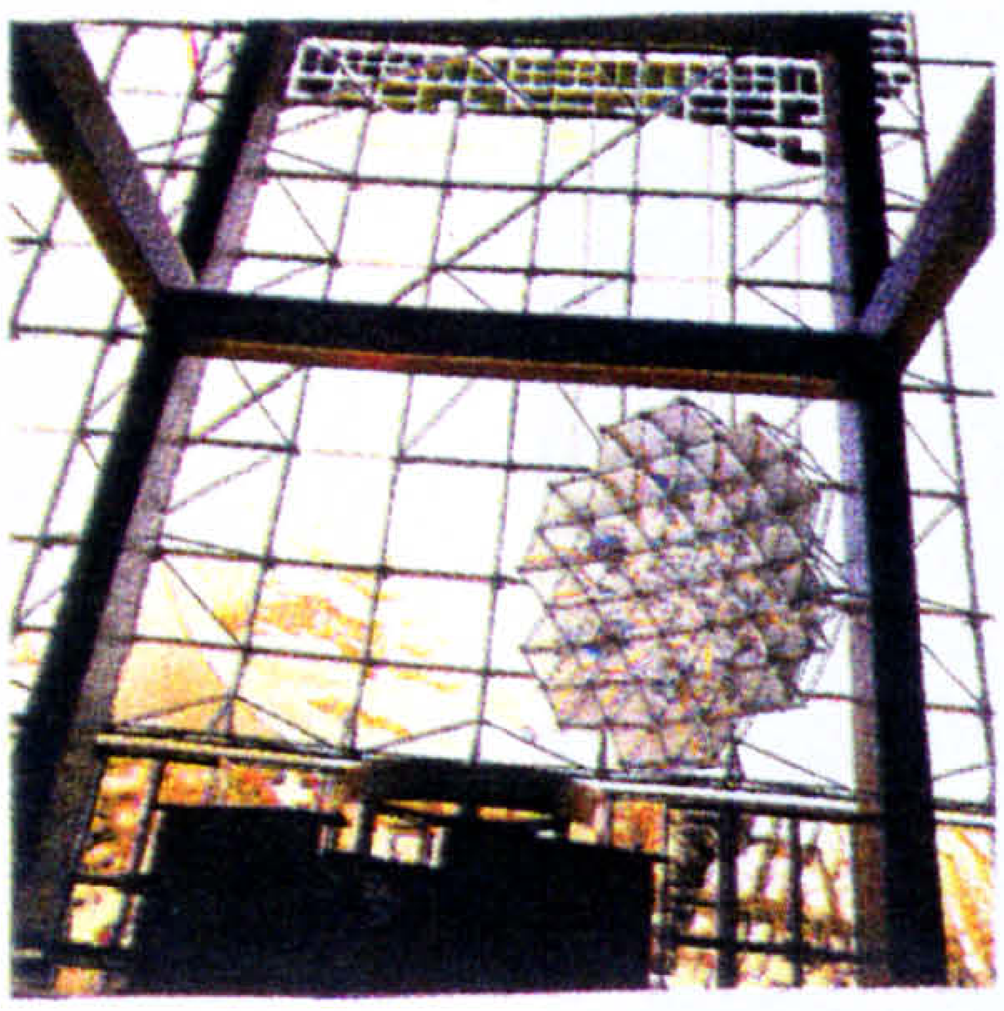

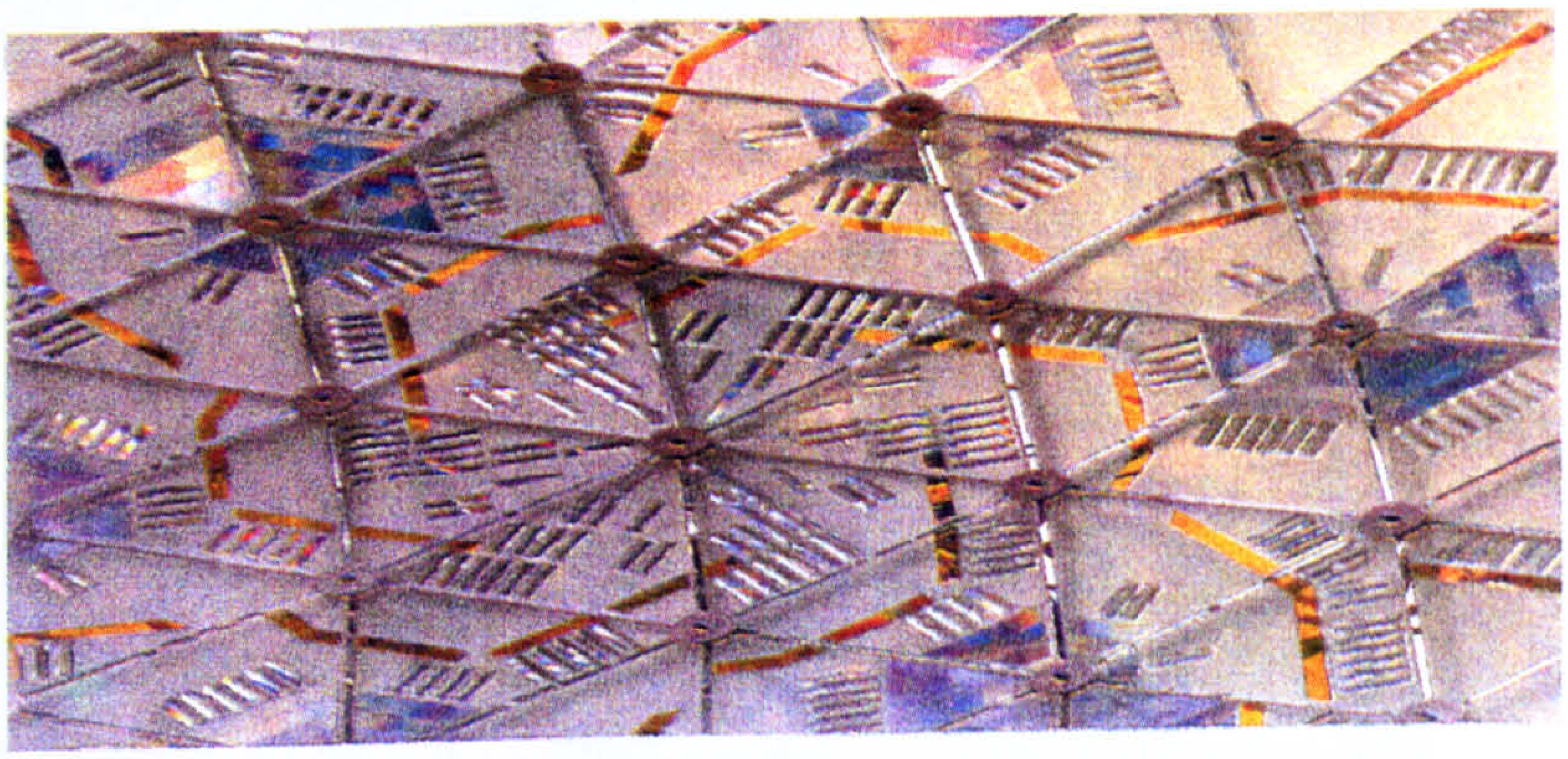

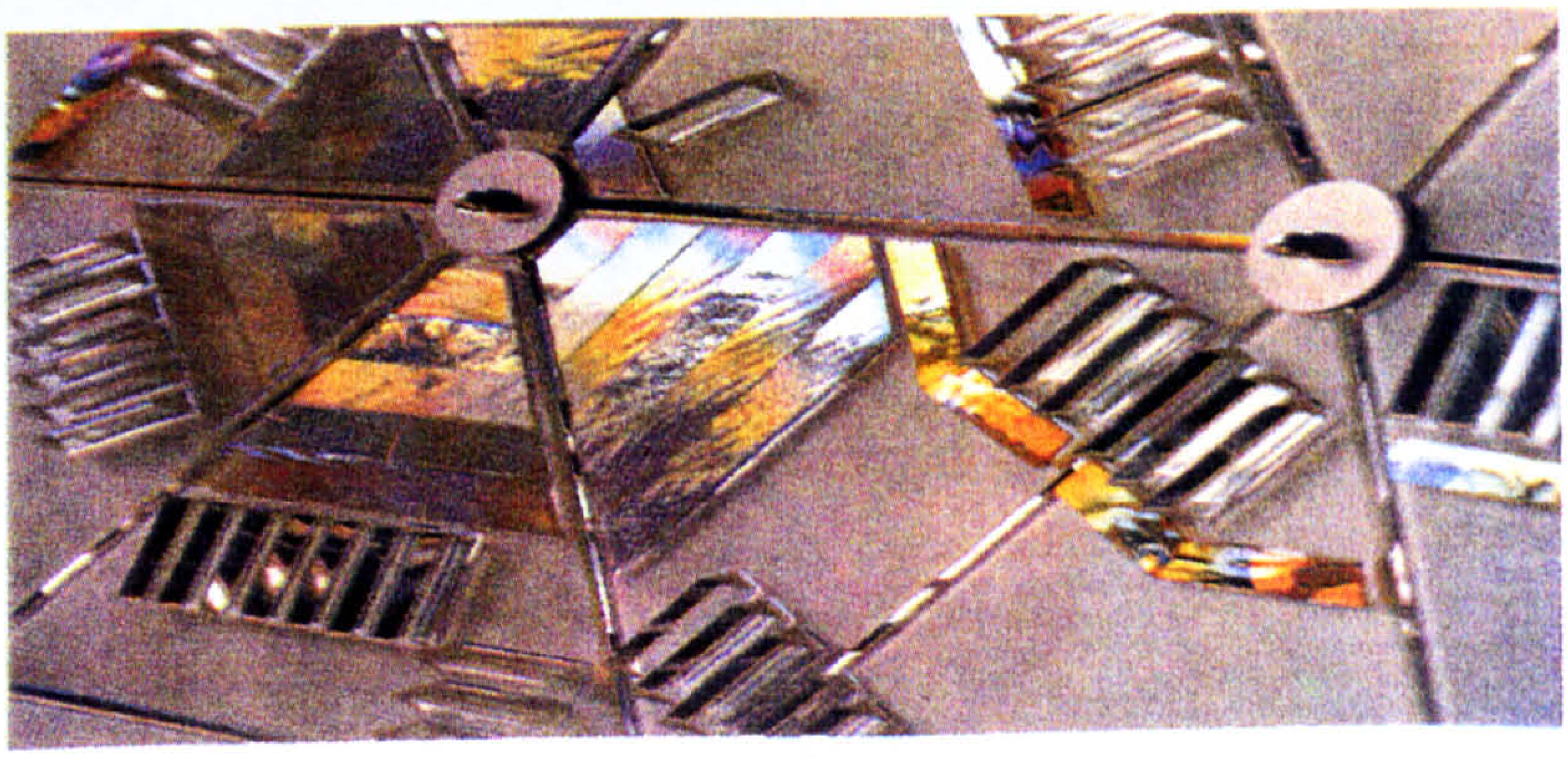

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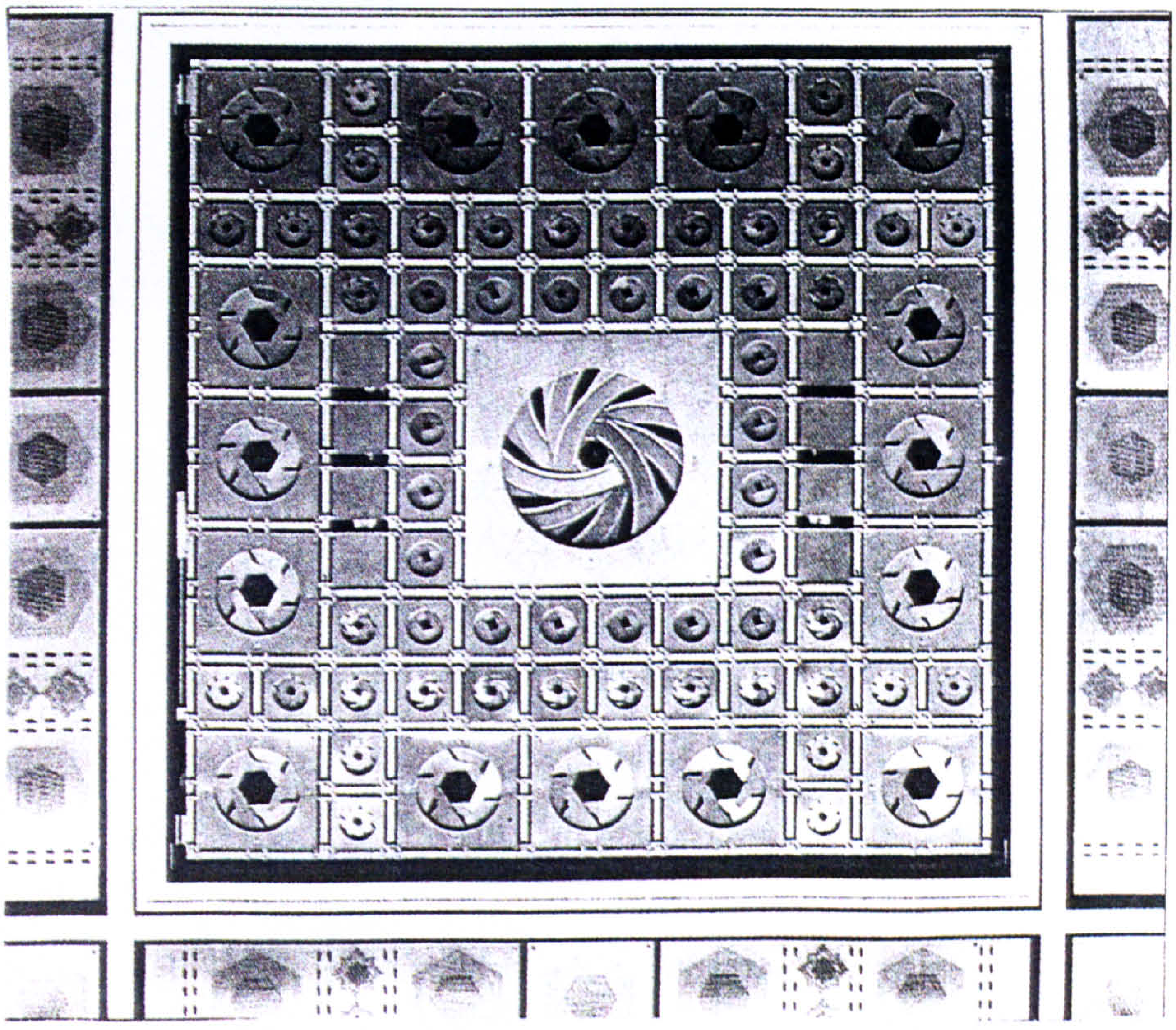

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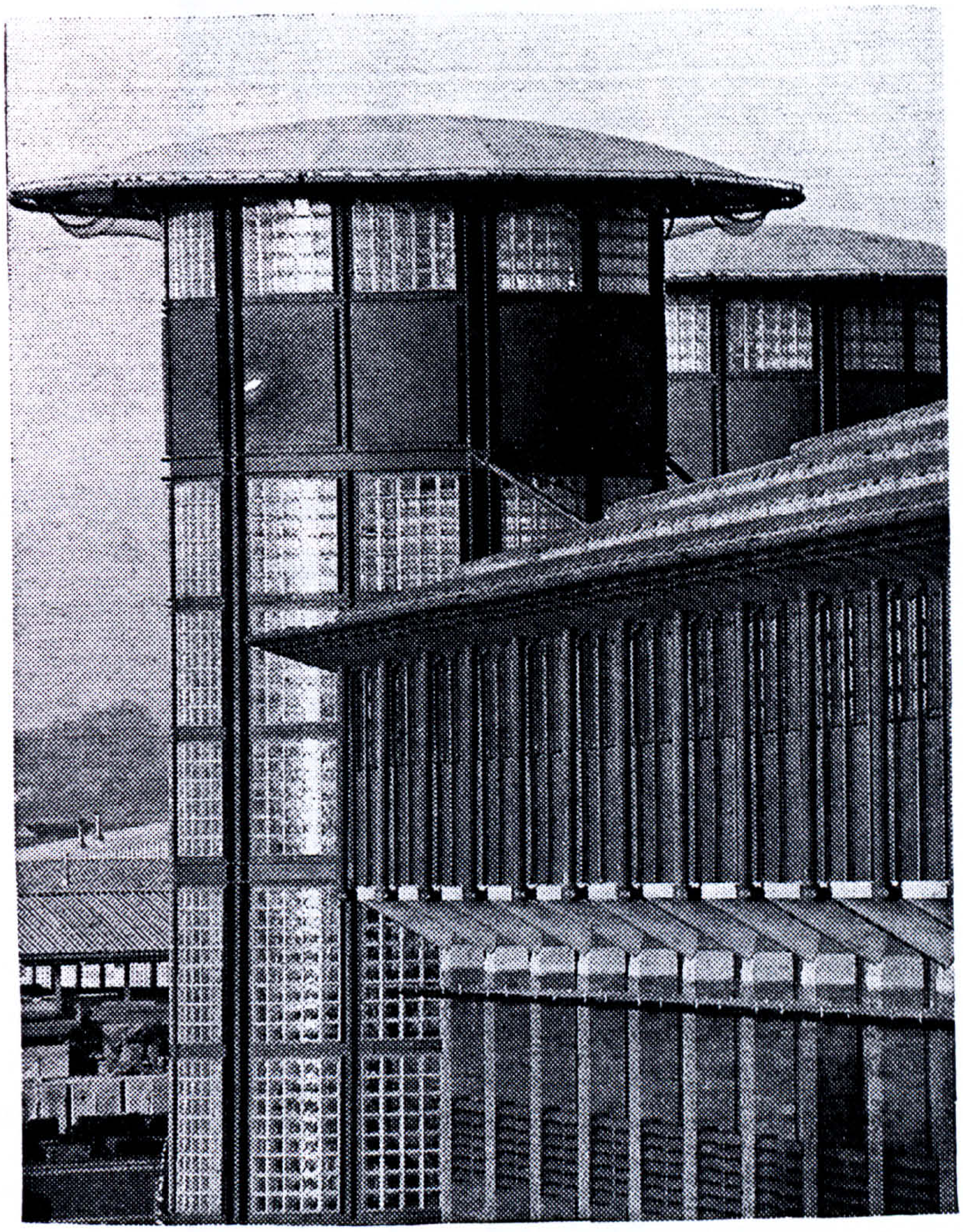

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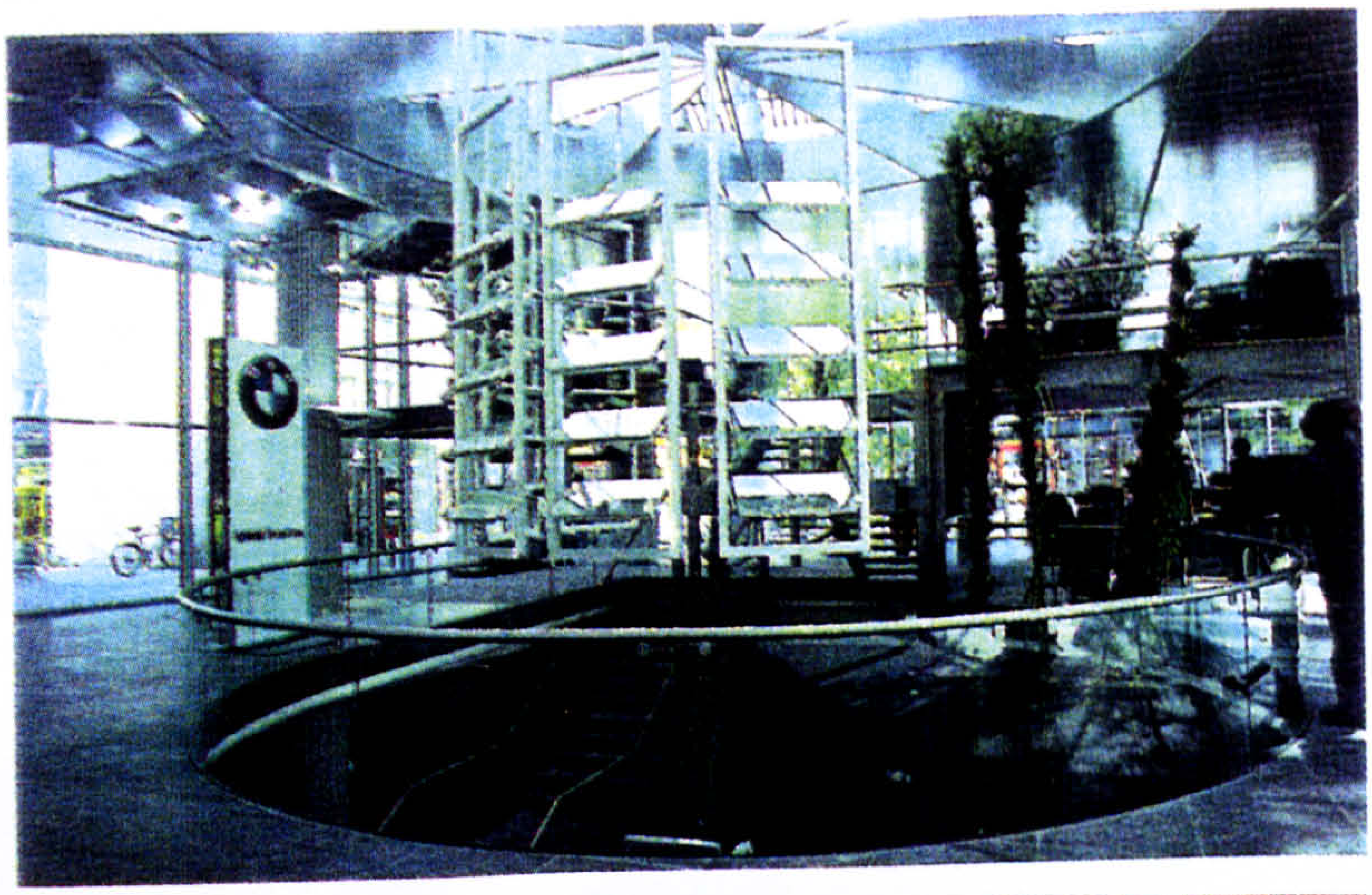

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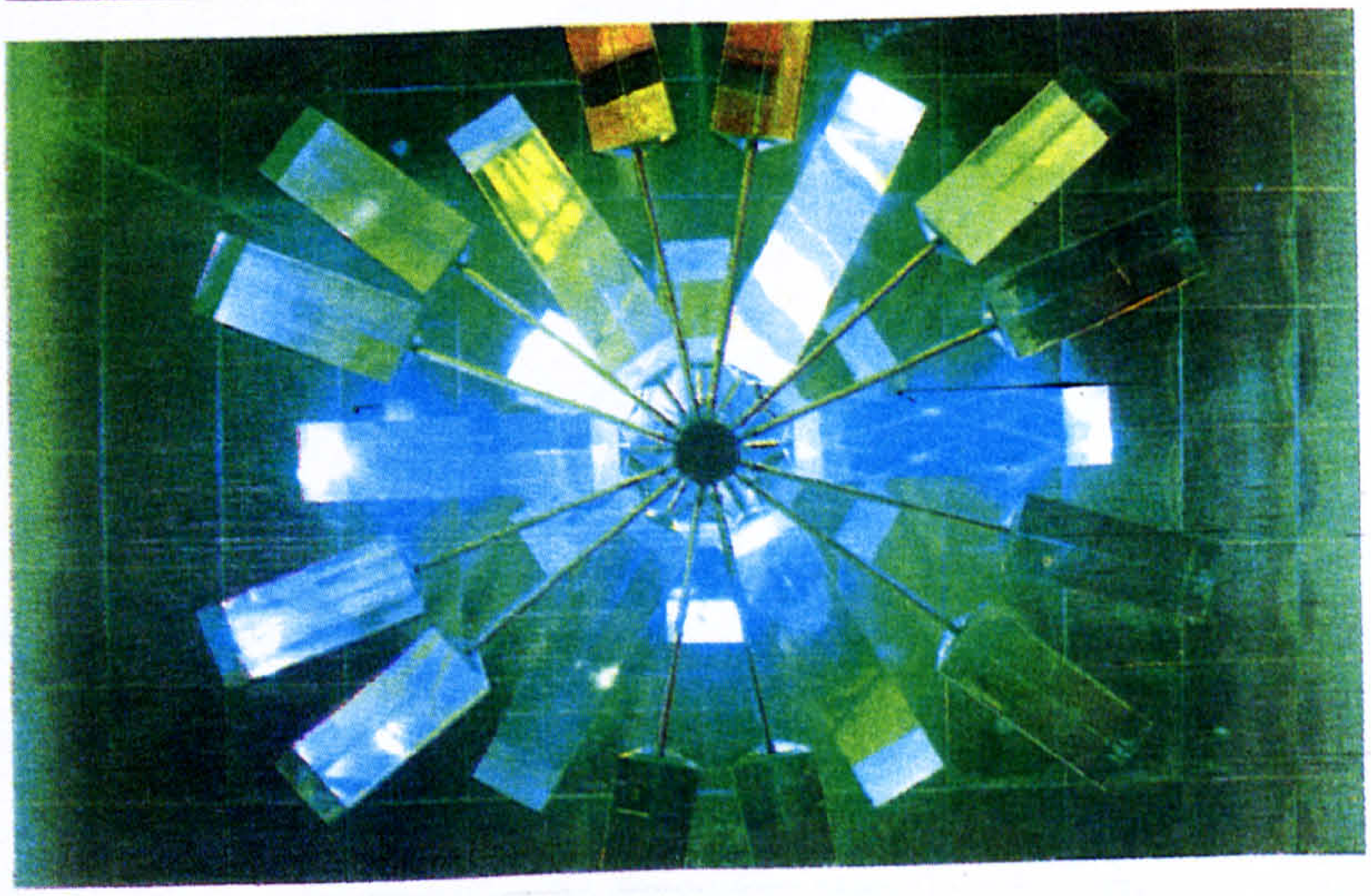

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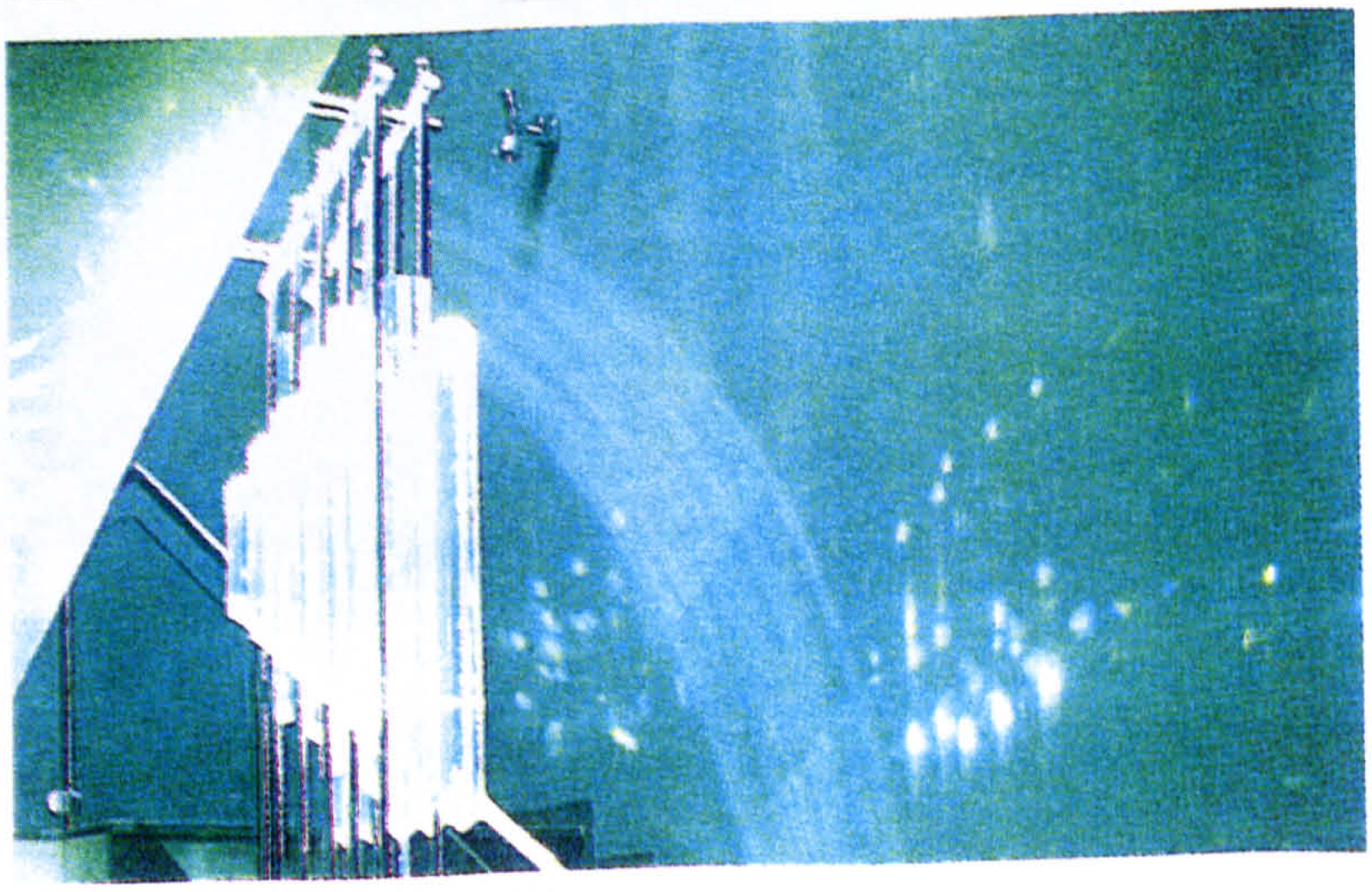

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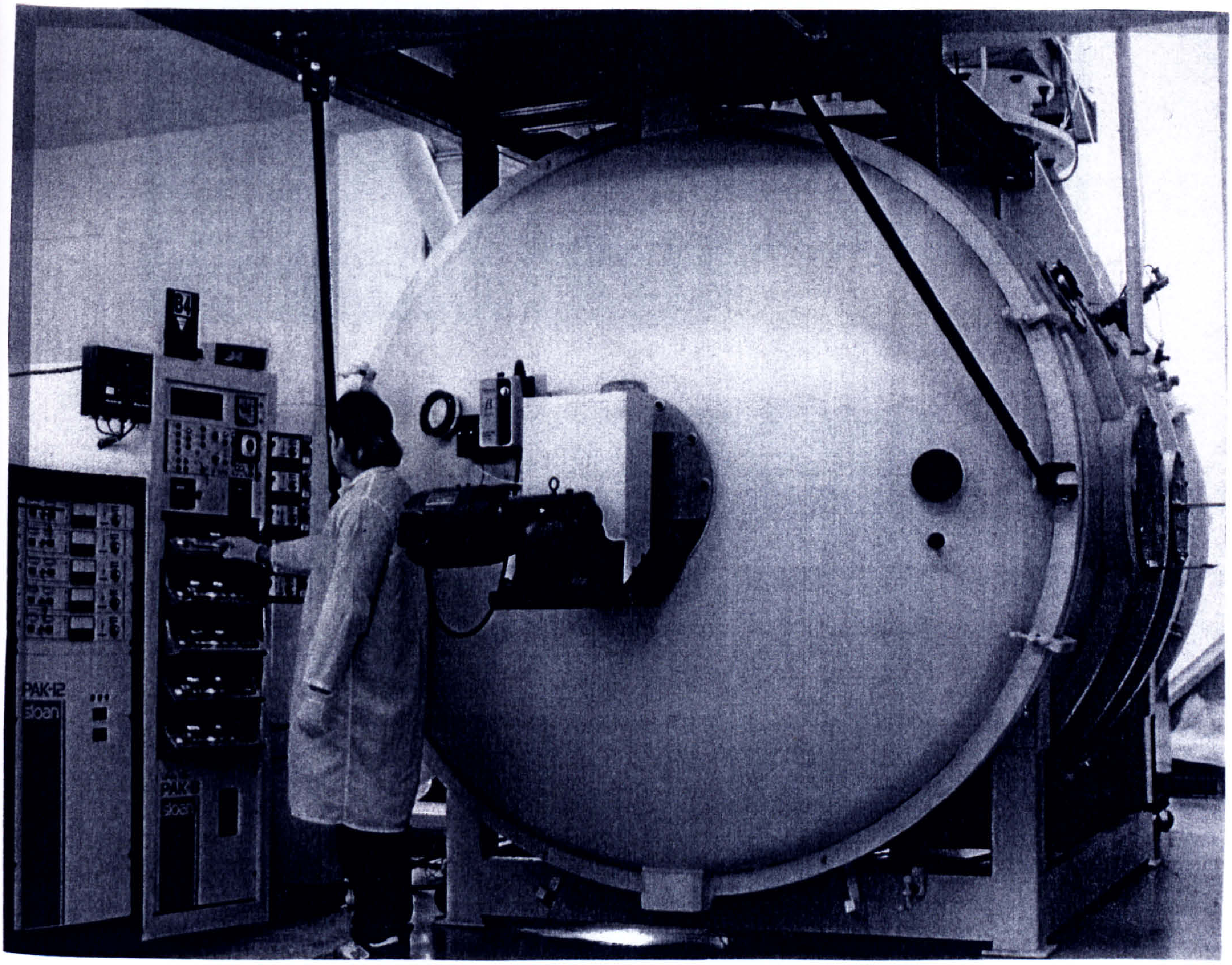

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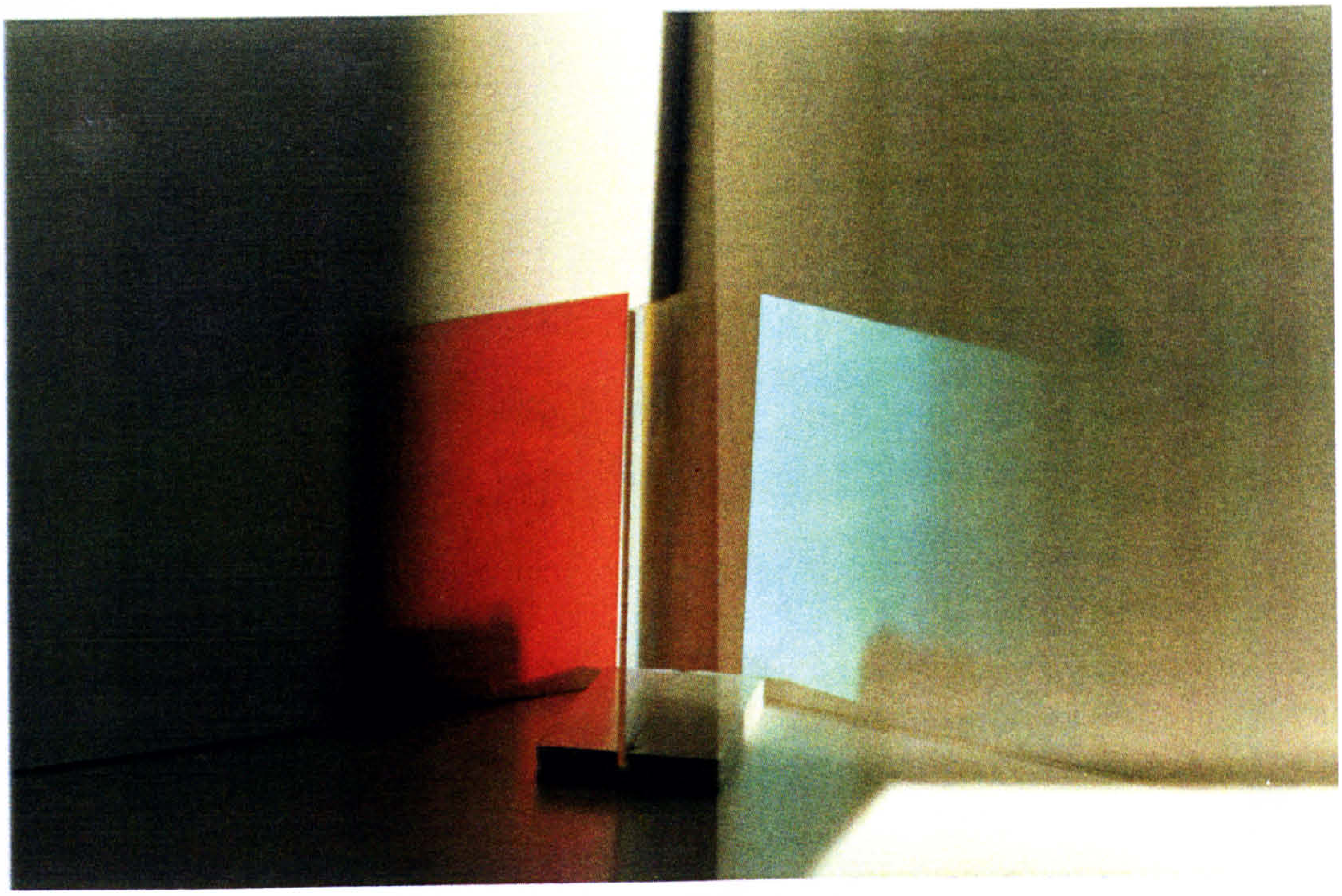

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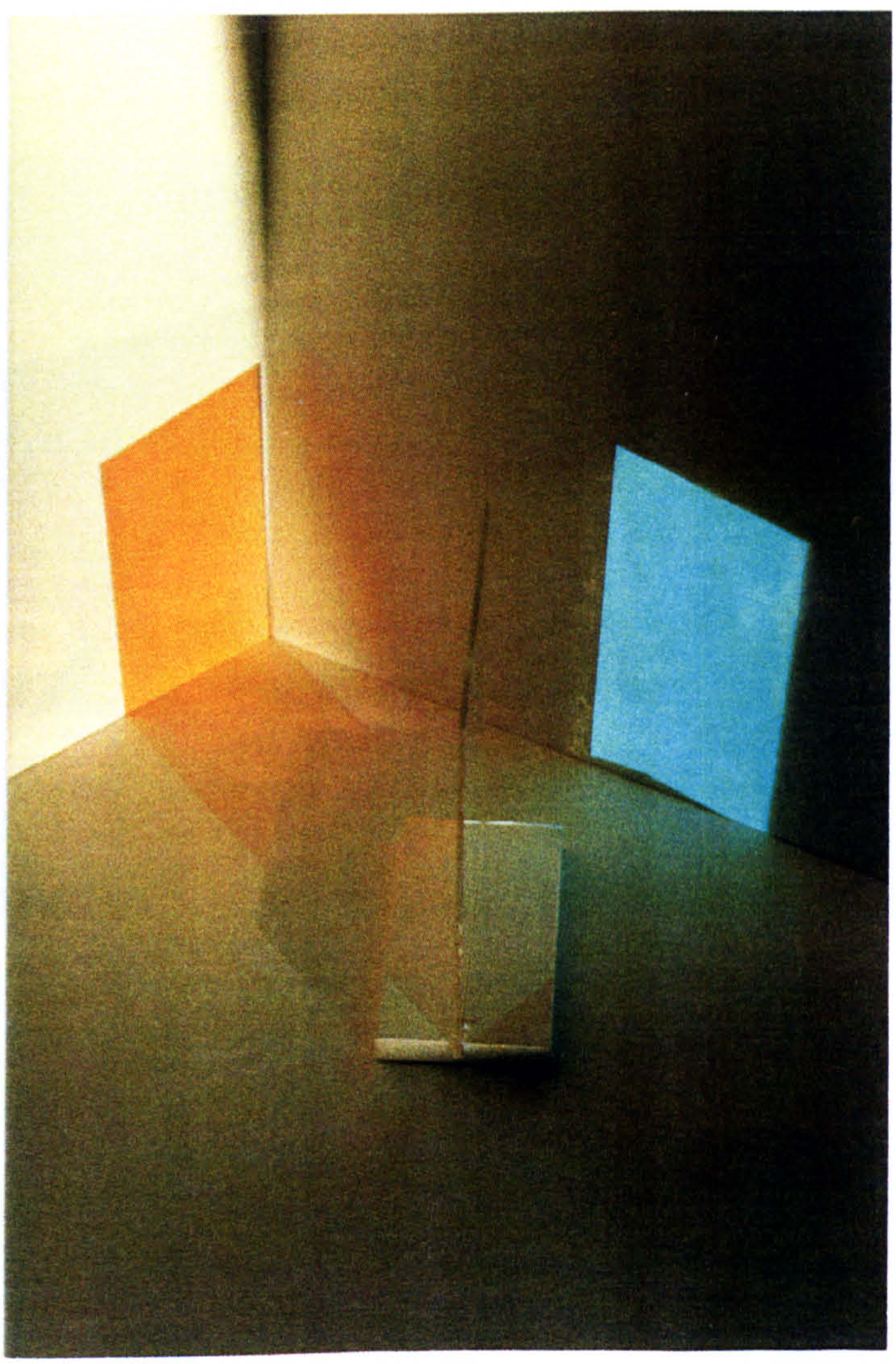

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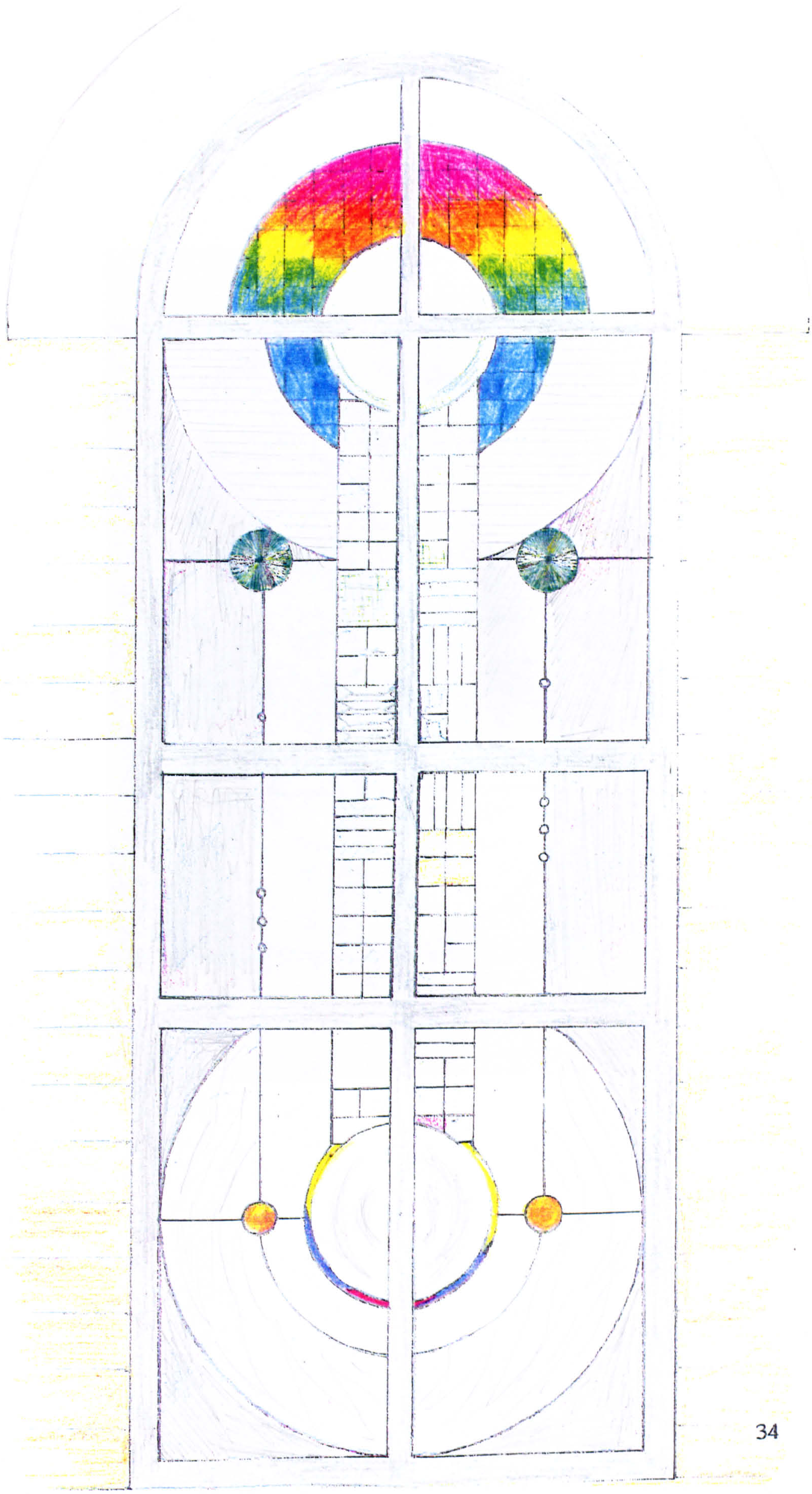

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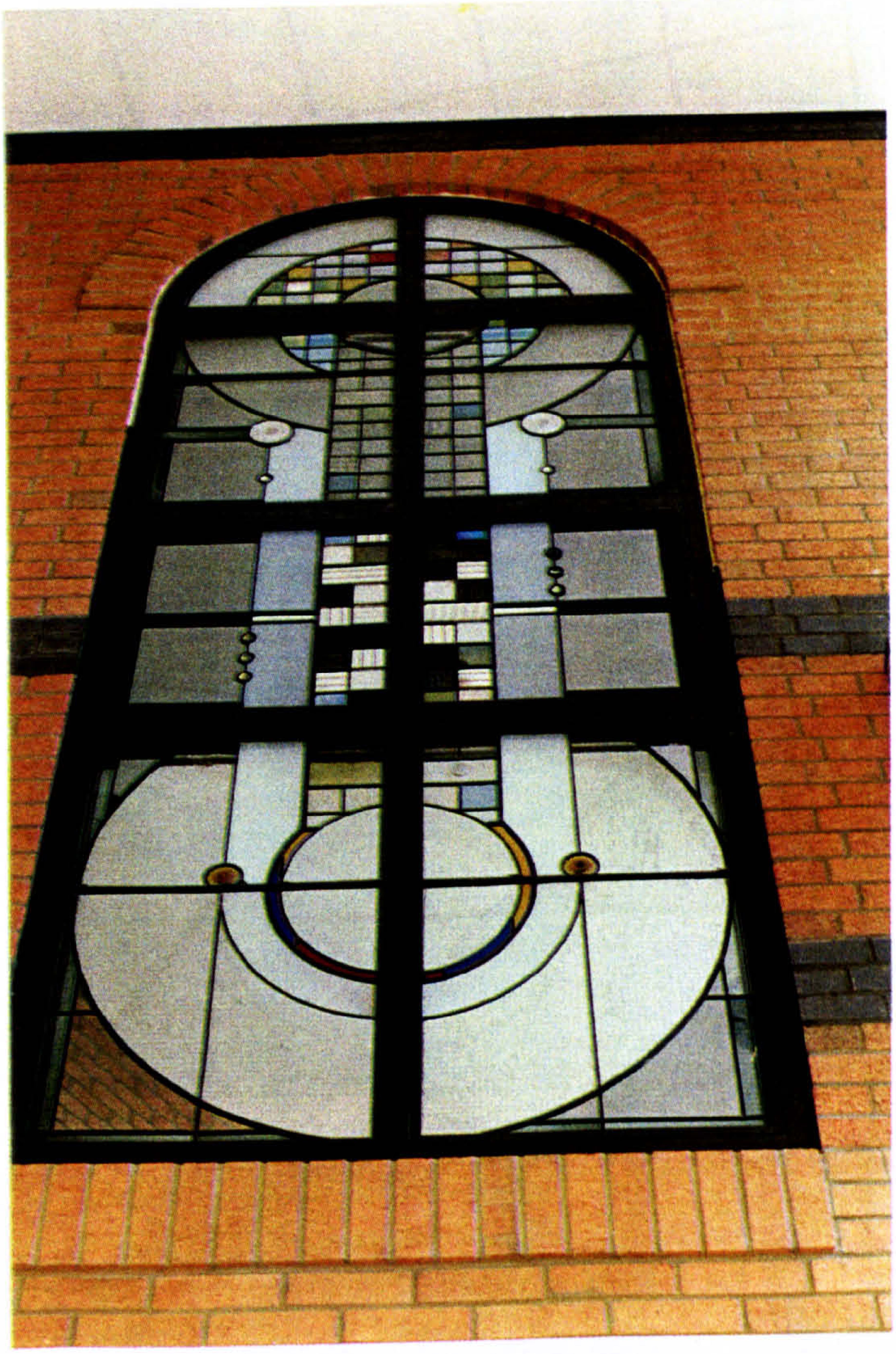

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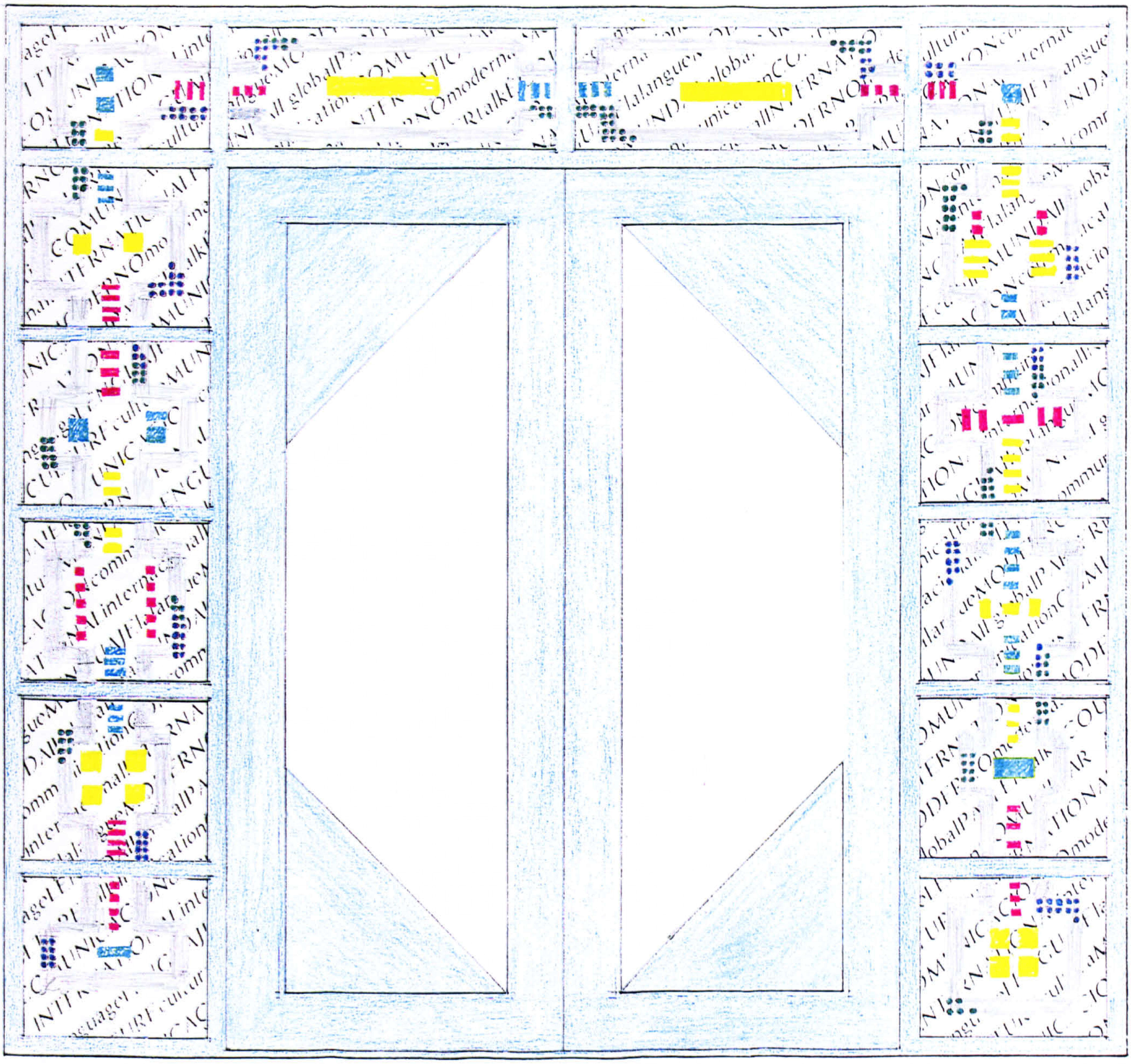

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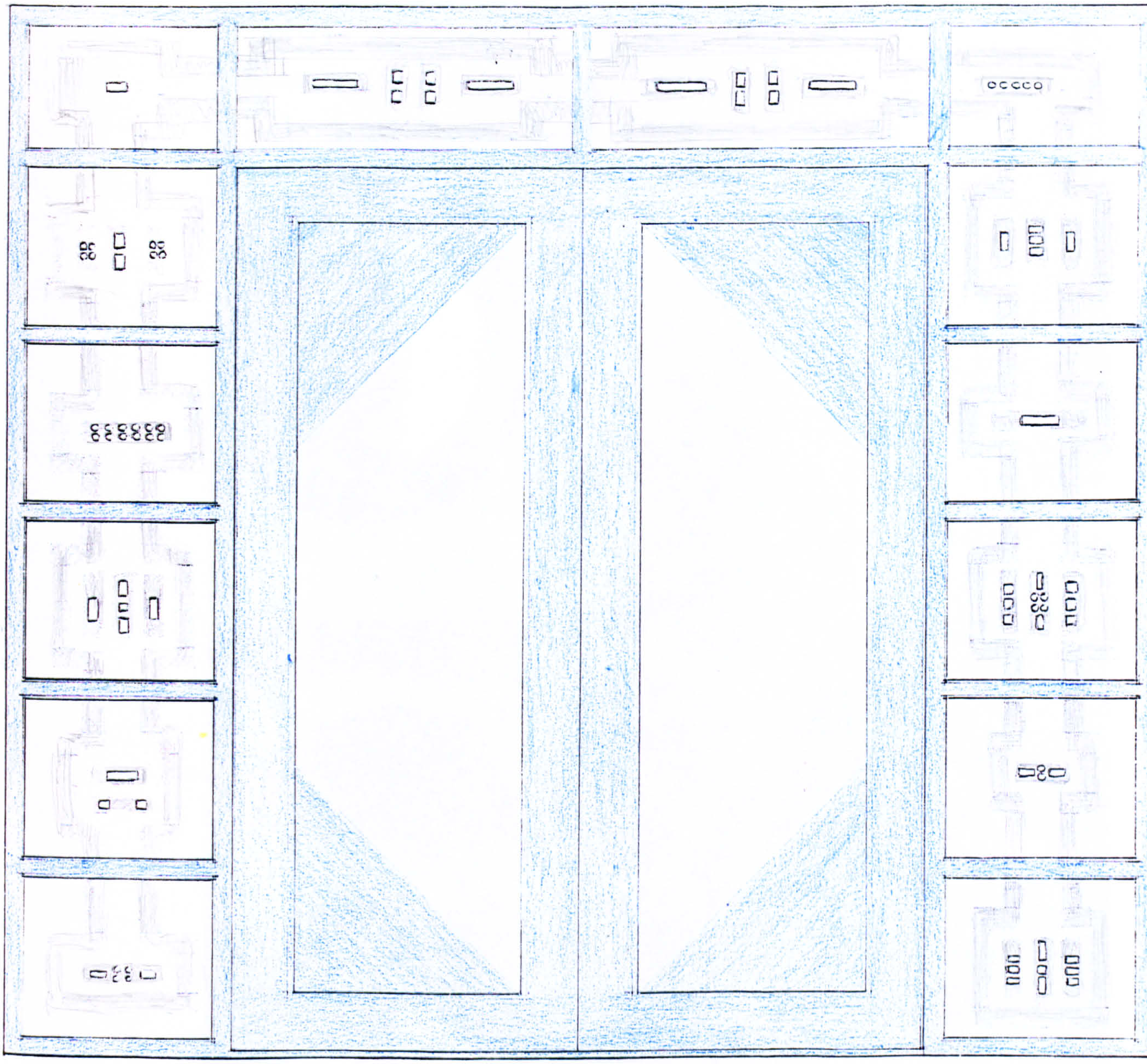

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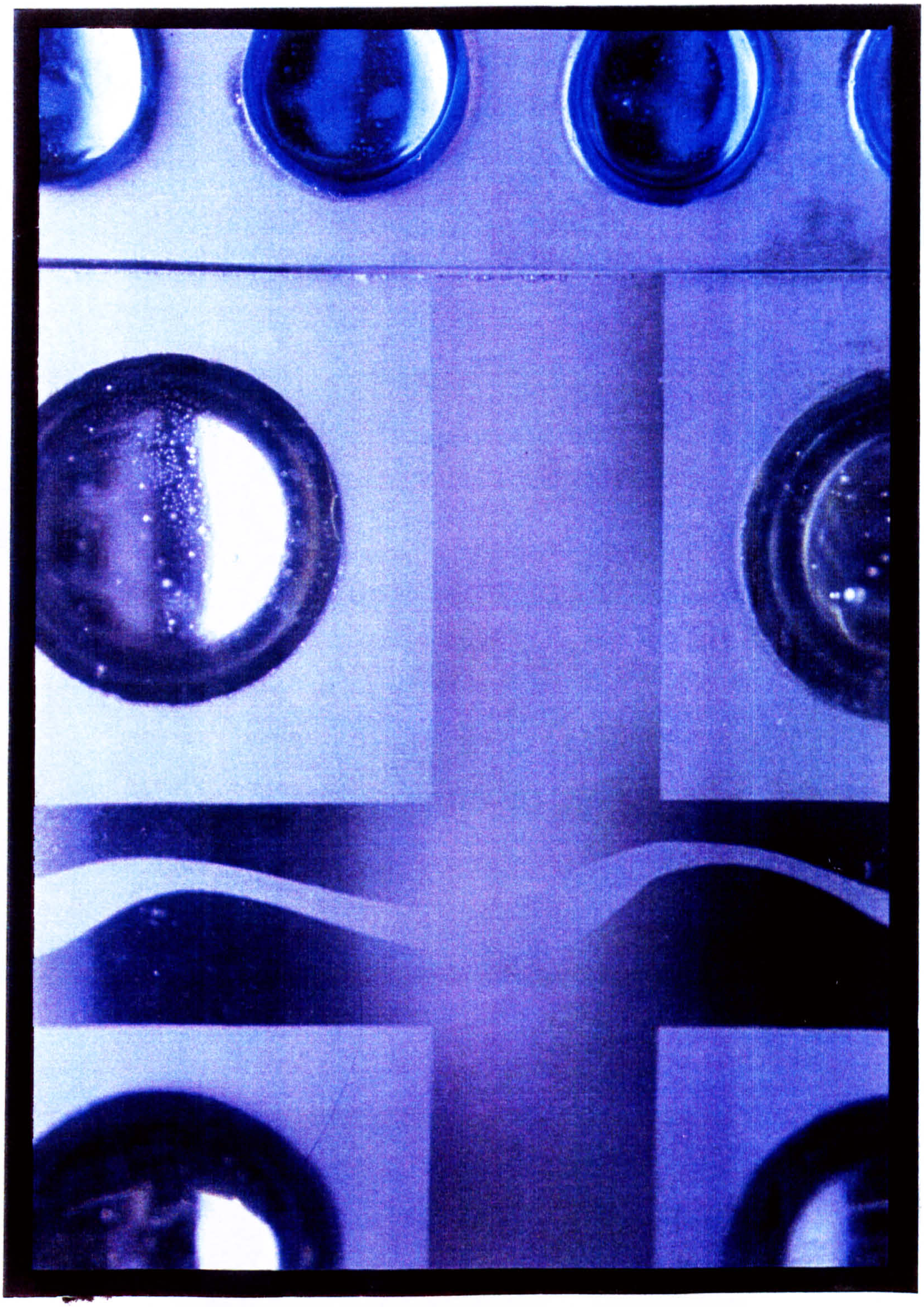

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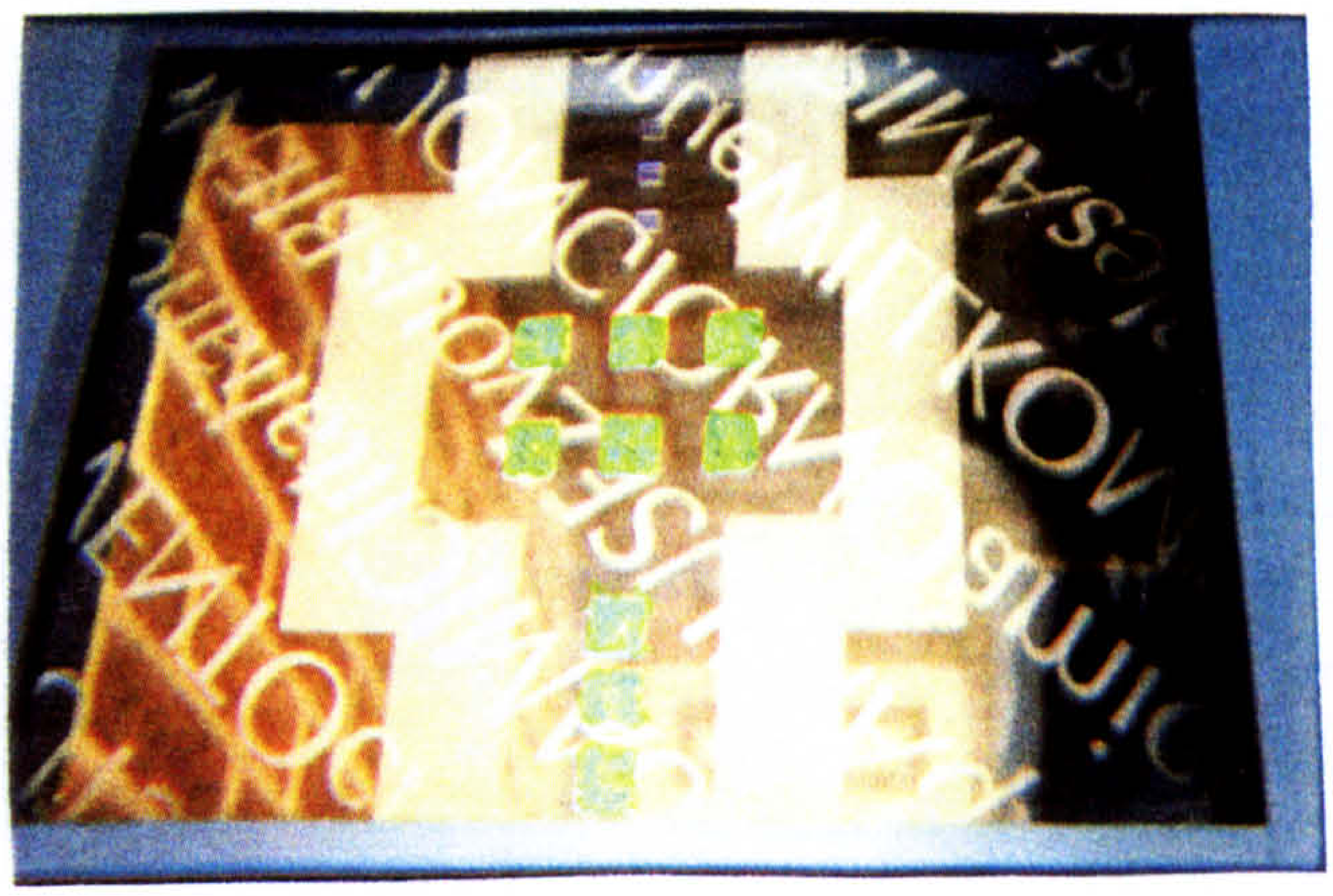

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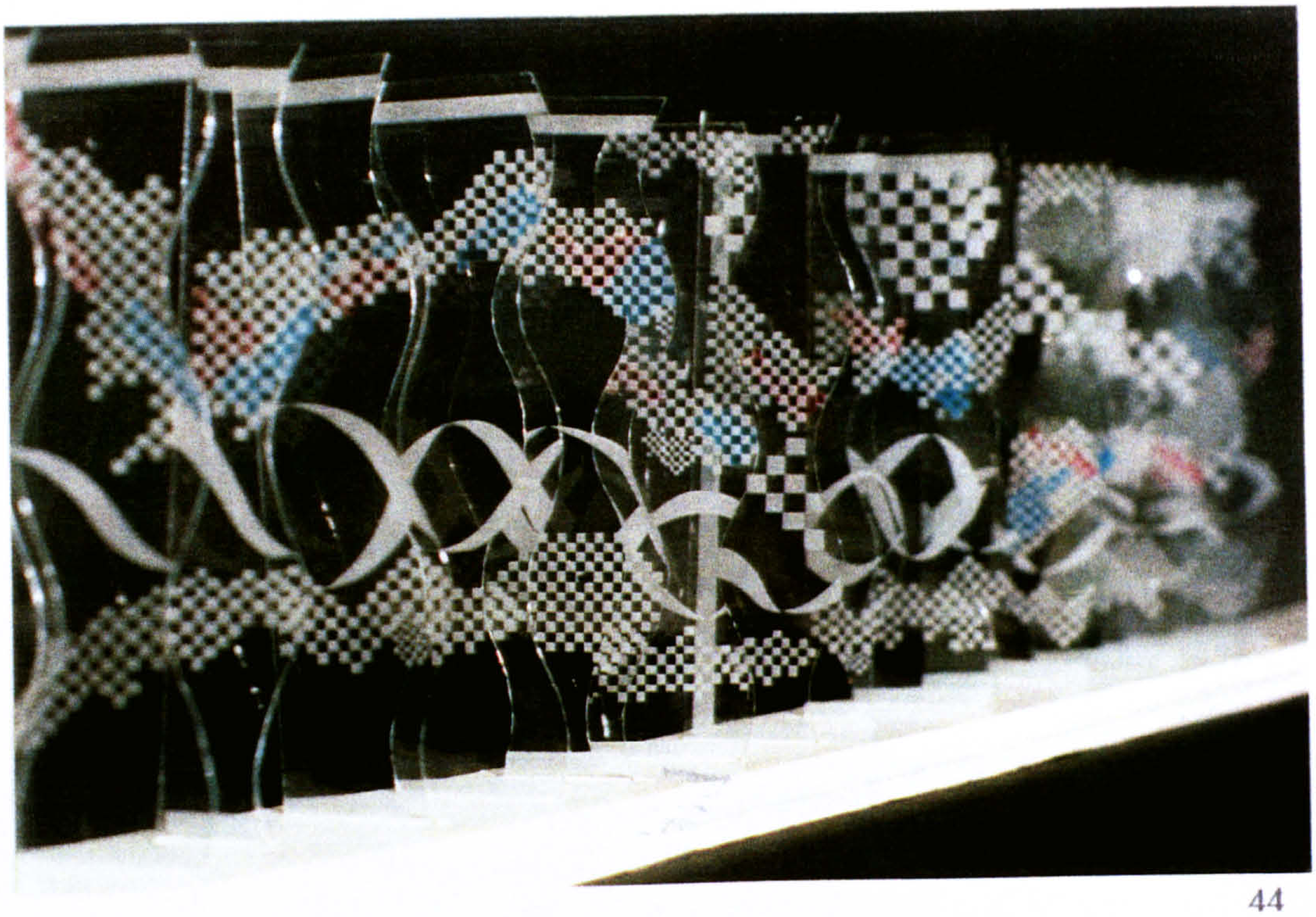

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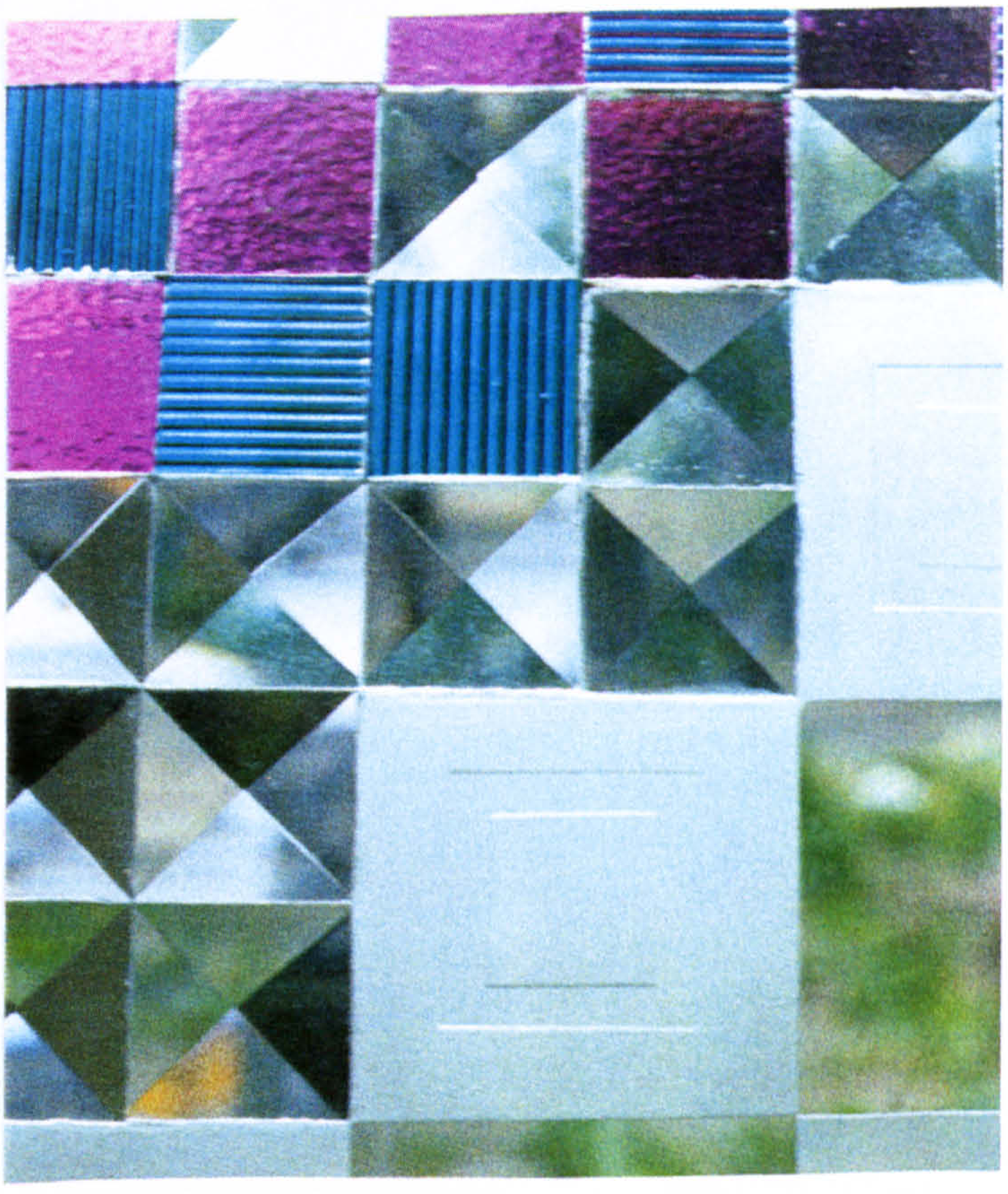

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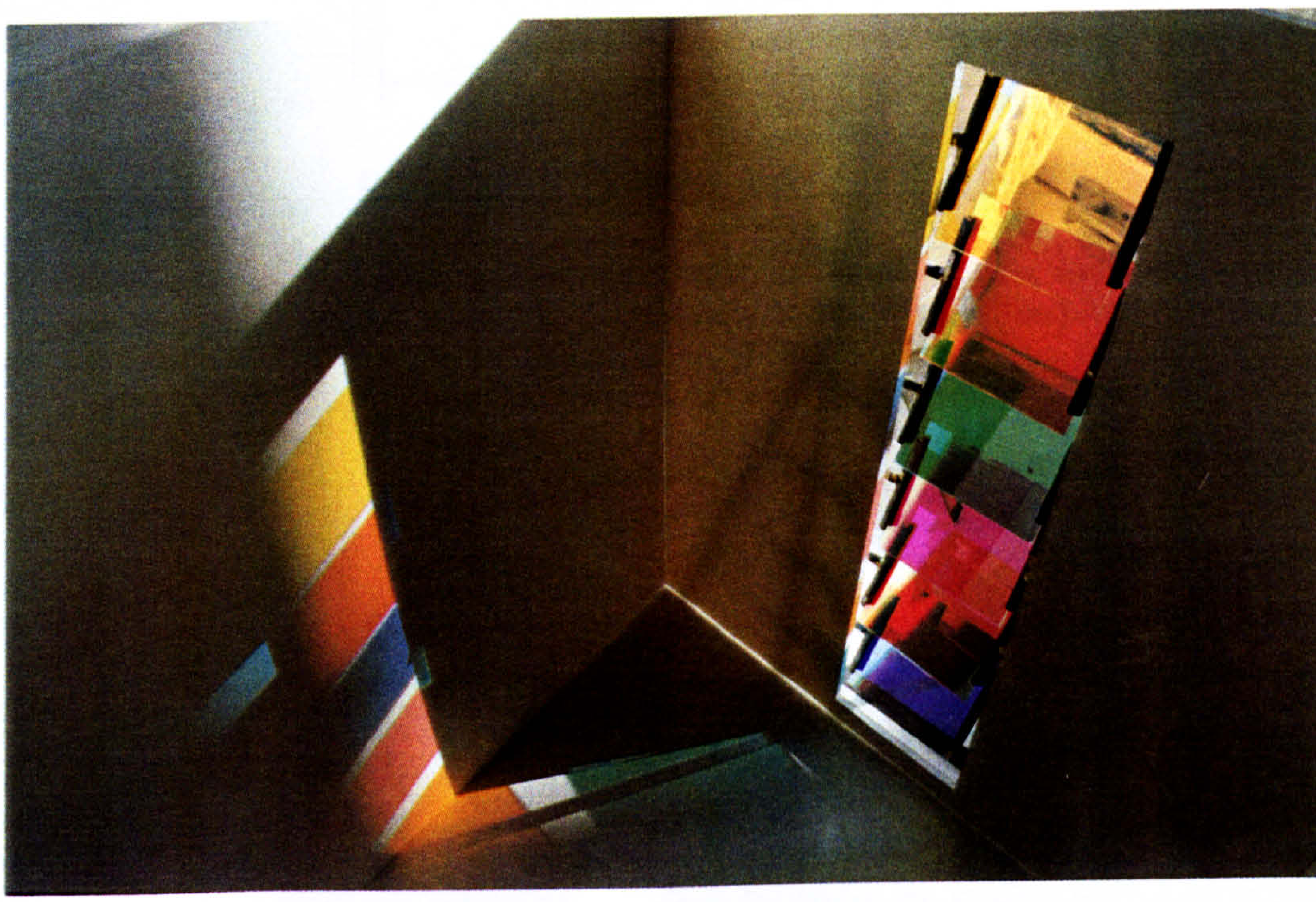

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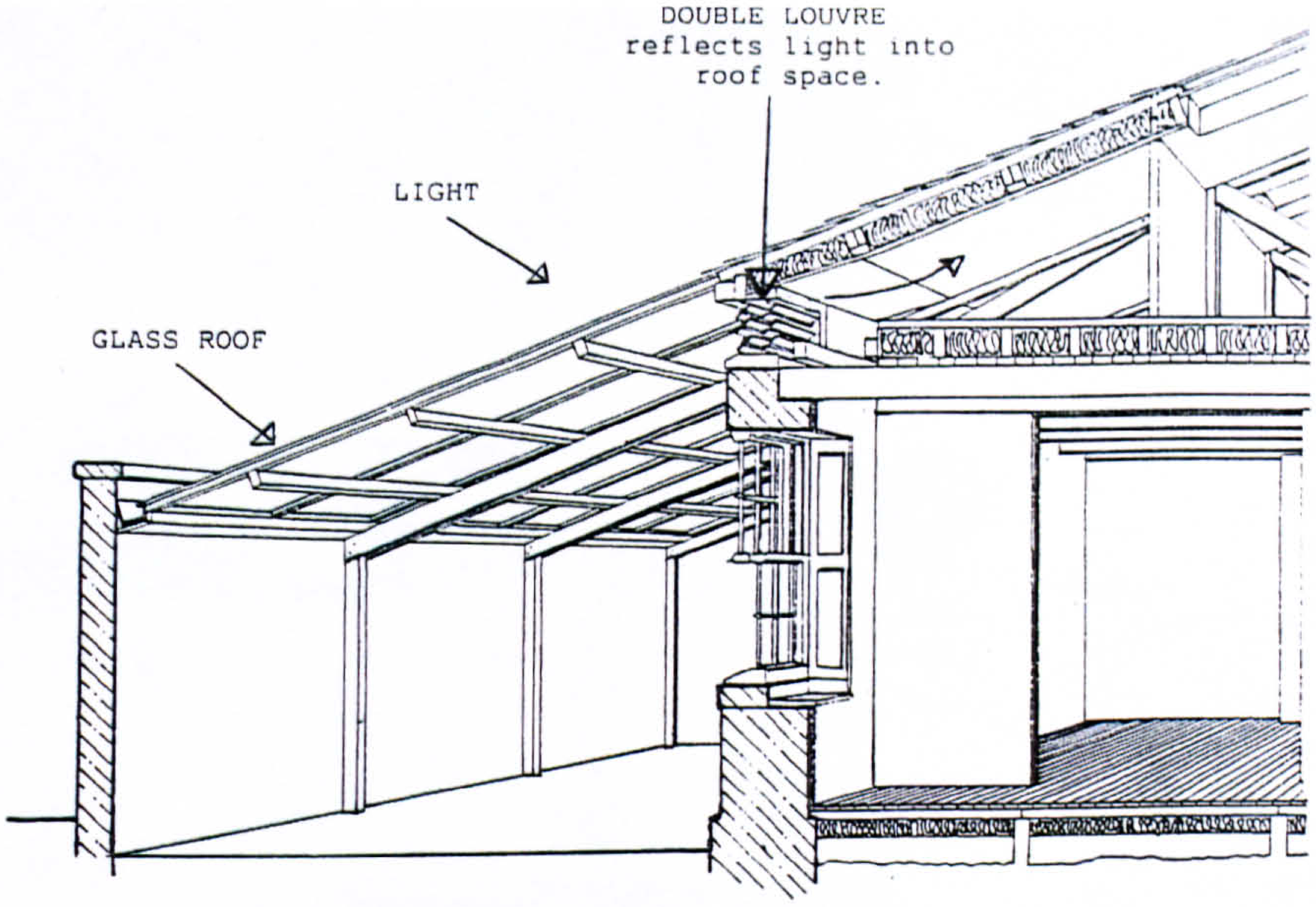

EXTENDING THE FALL OF LIGHT.

Light is diverted from one space into a badly lit area by means of reflection. Coated glass, strategically placed heightens illumination. Dichroic glass also enhances the environment providing a play of coloured light.

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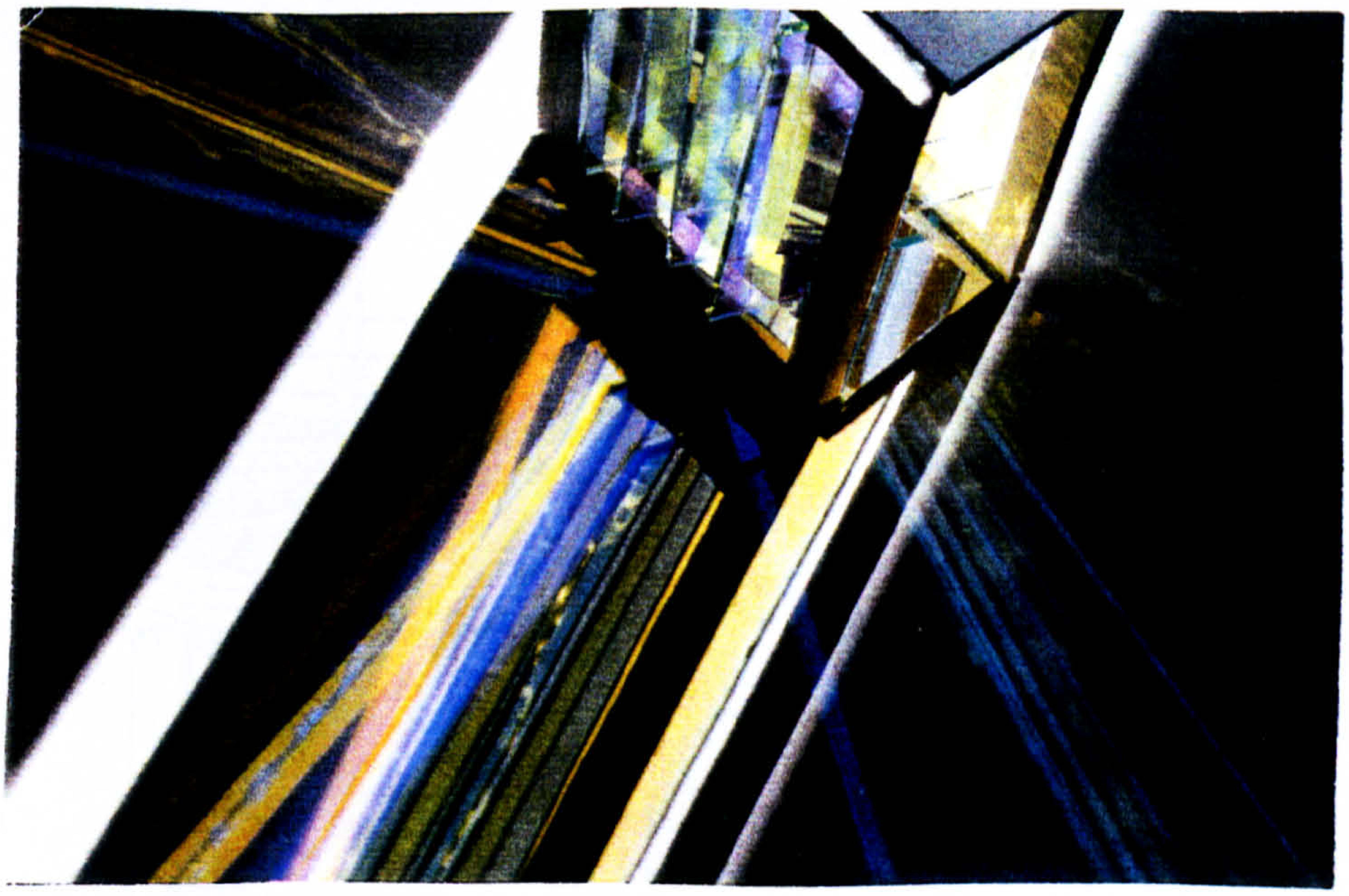

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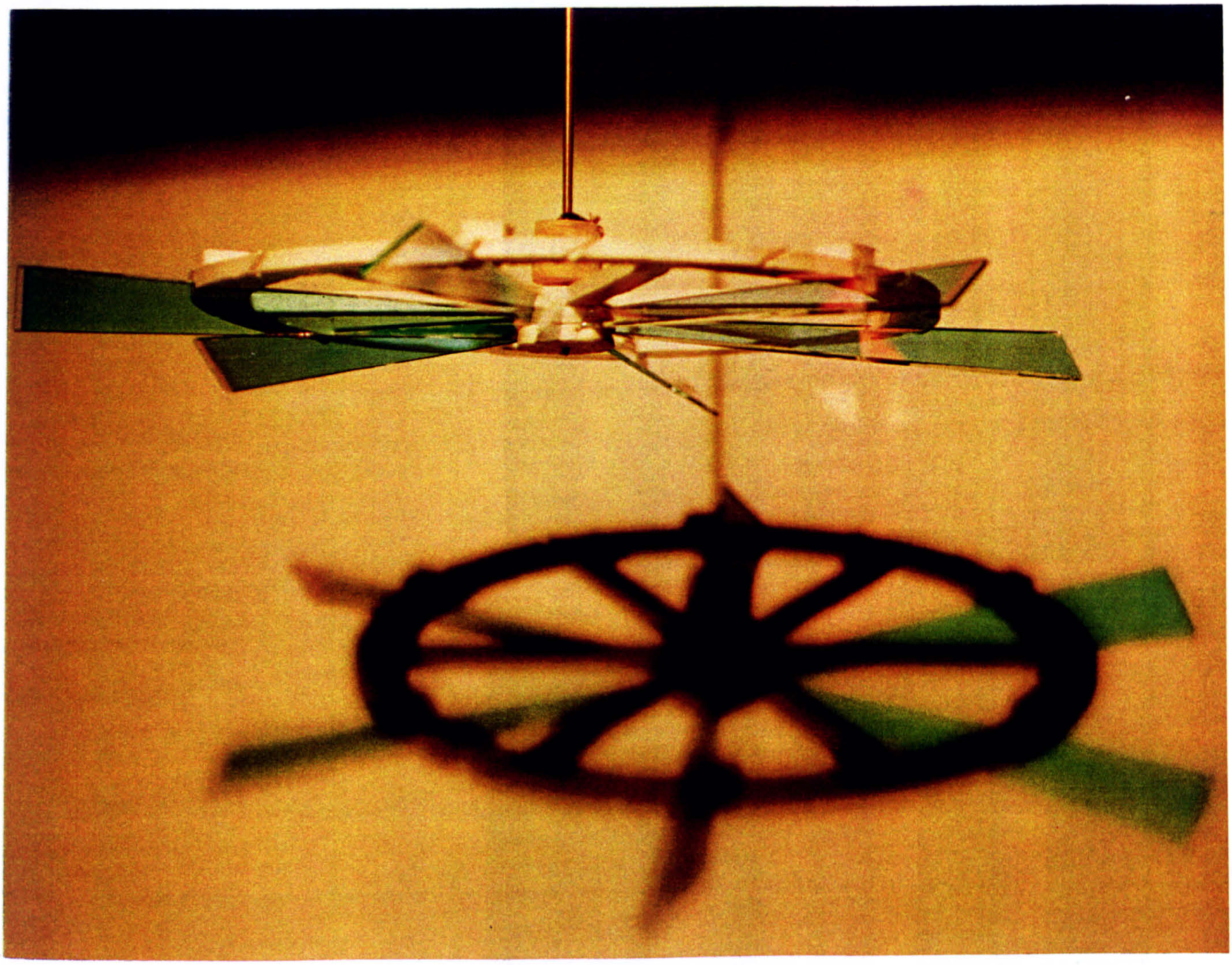

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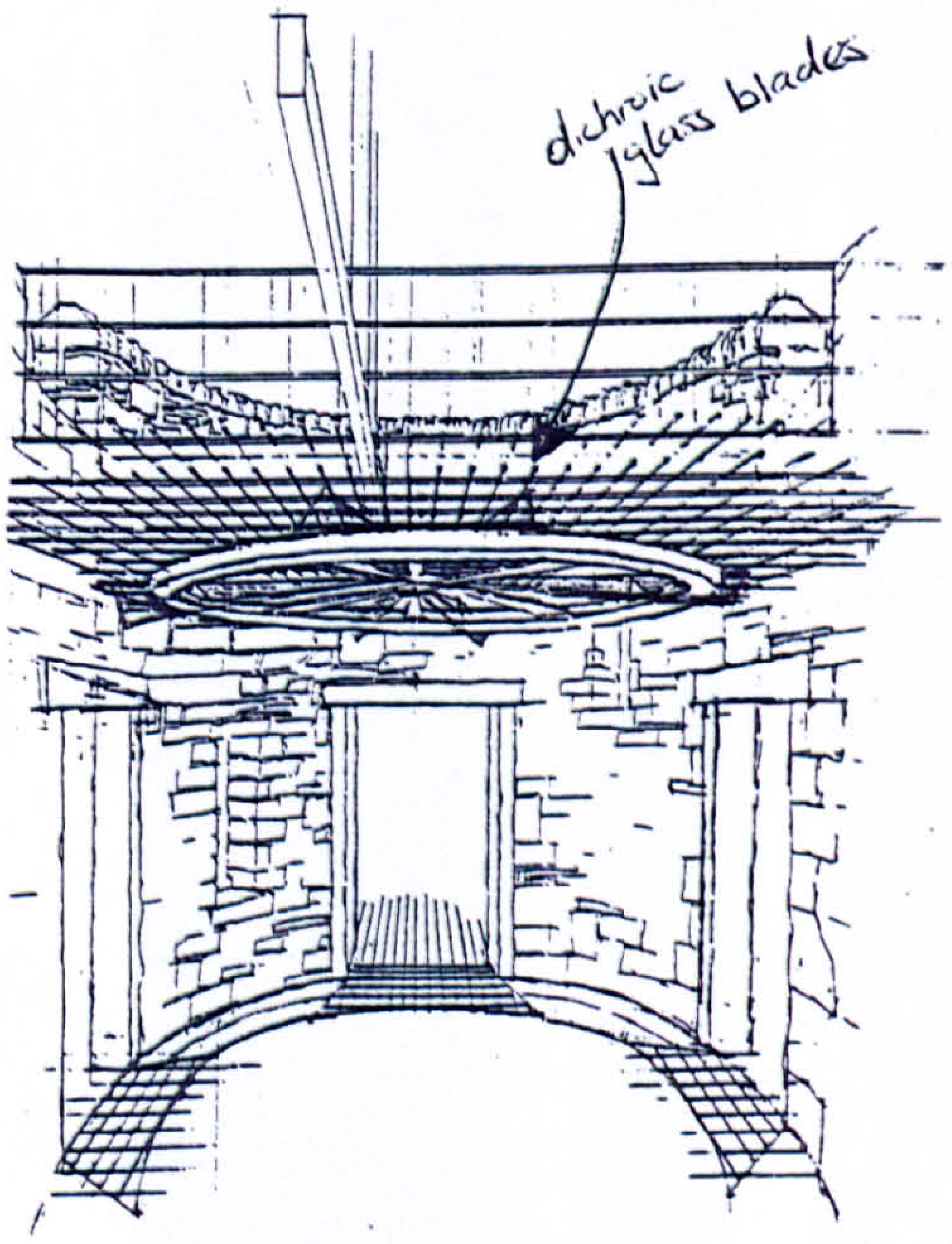

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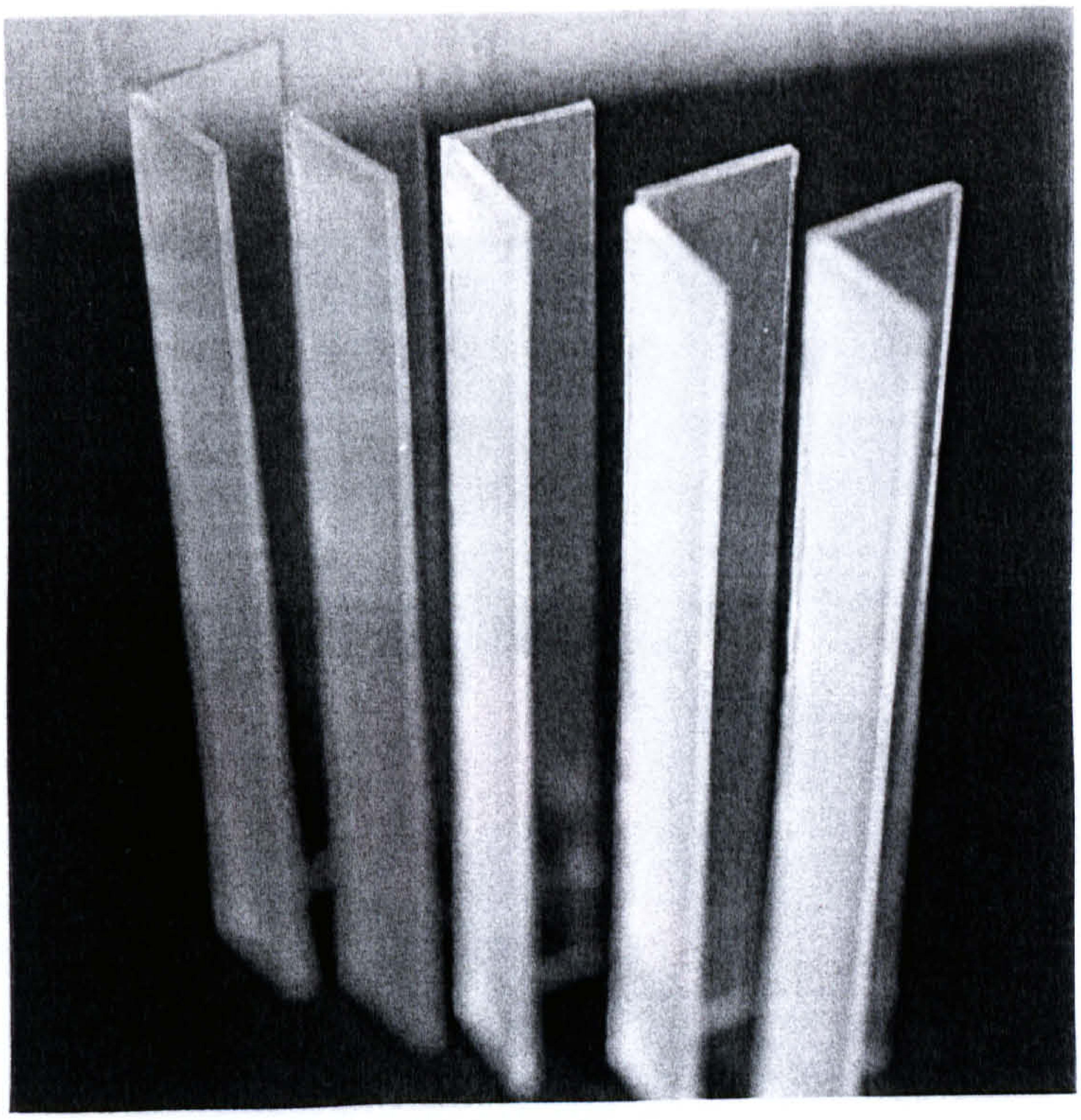

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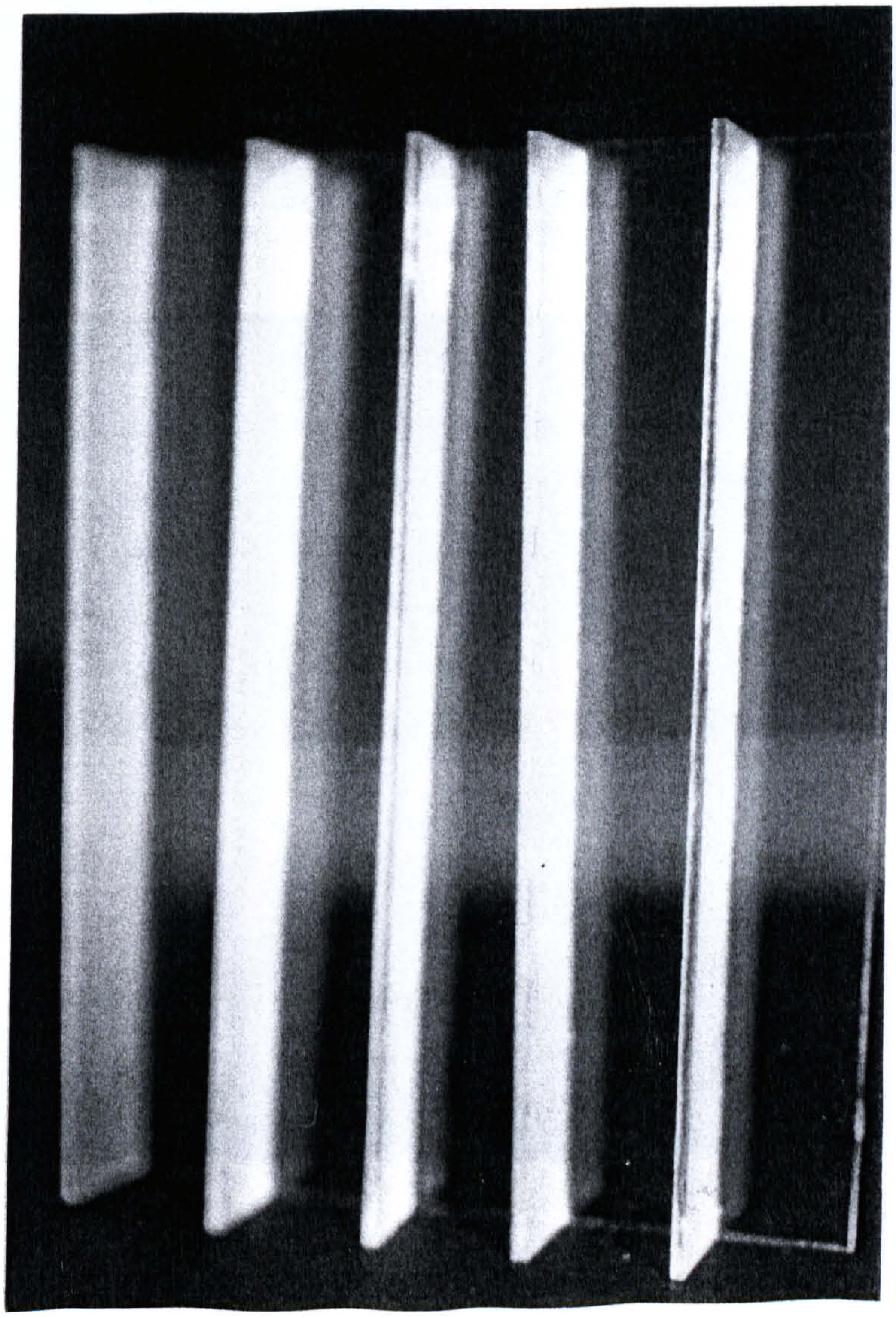

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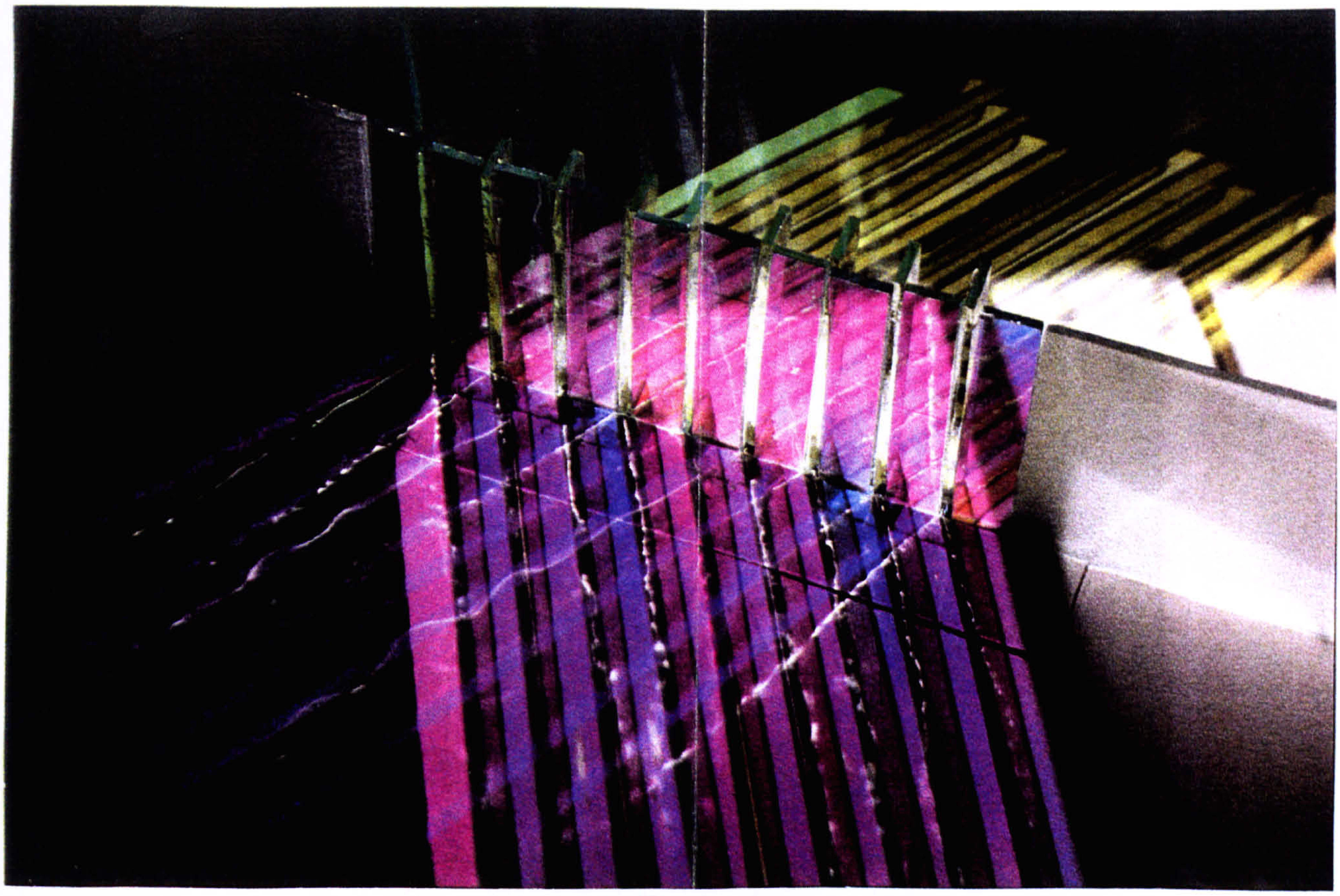

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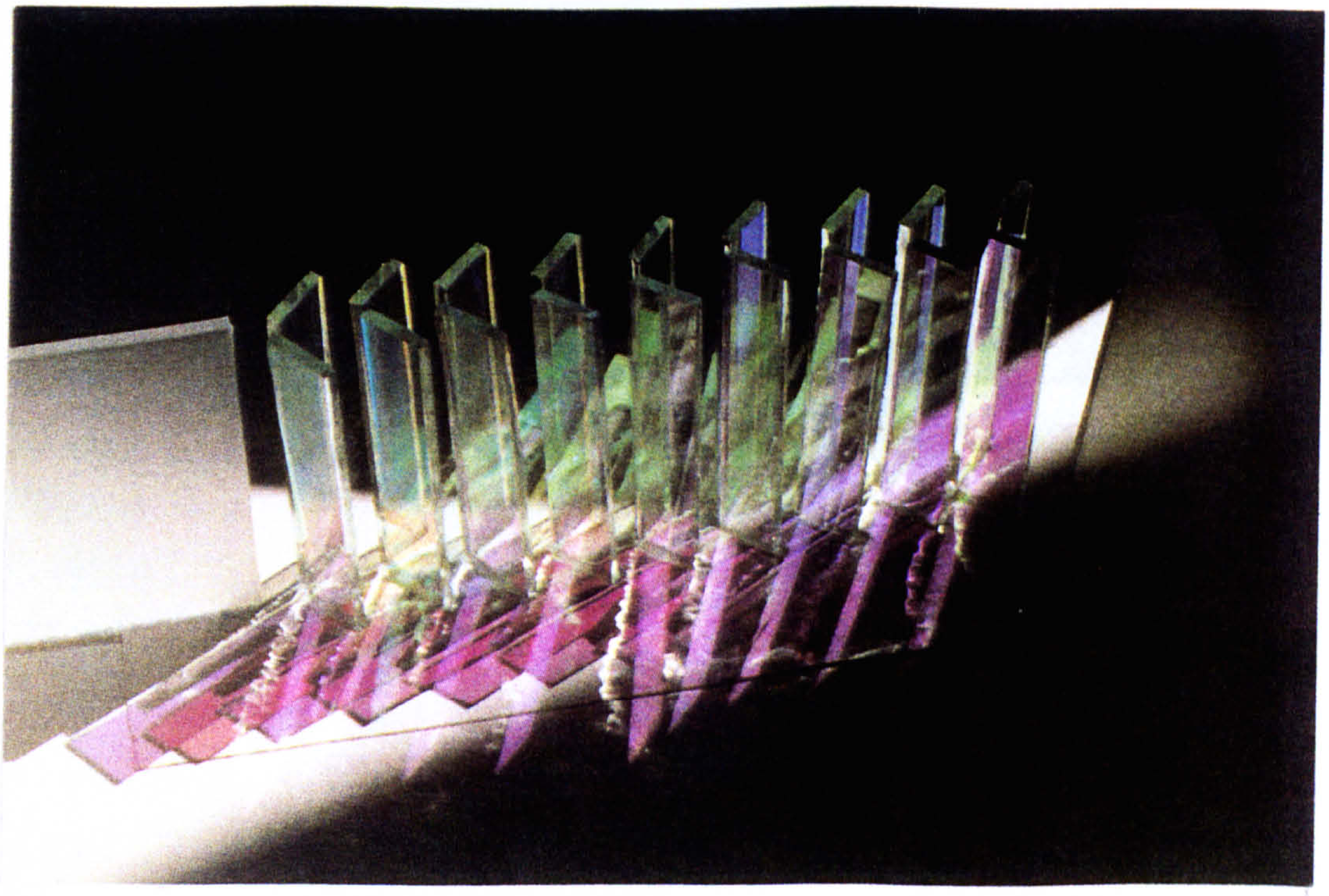

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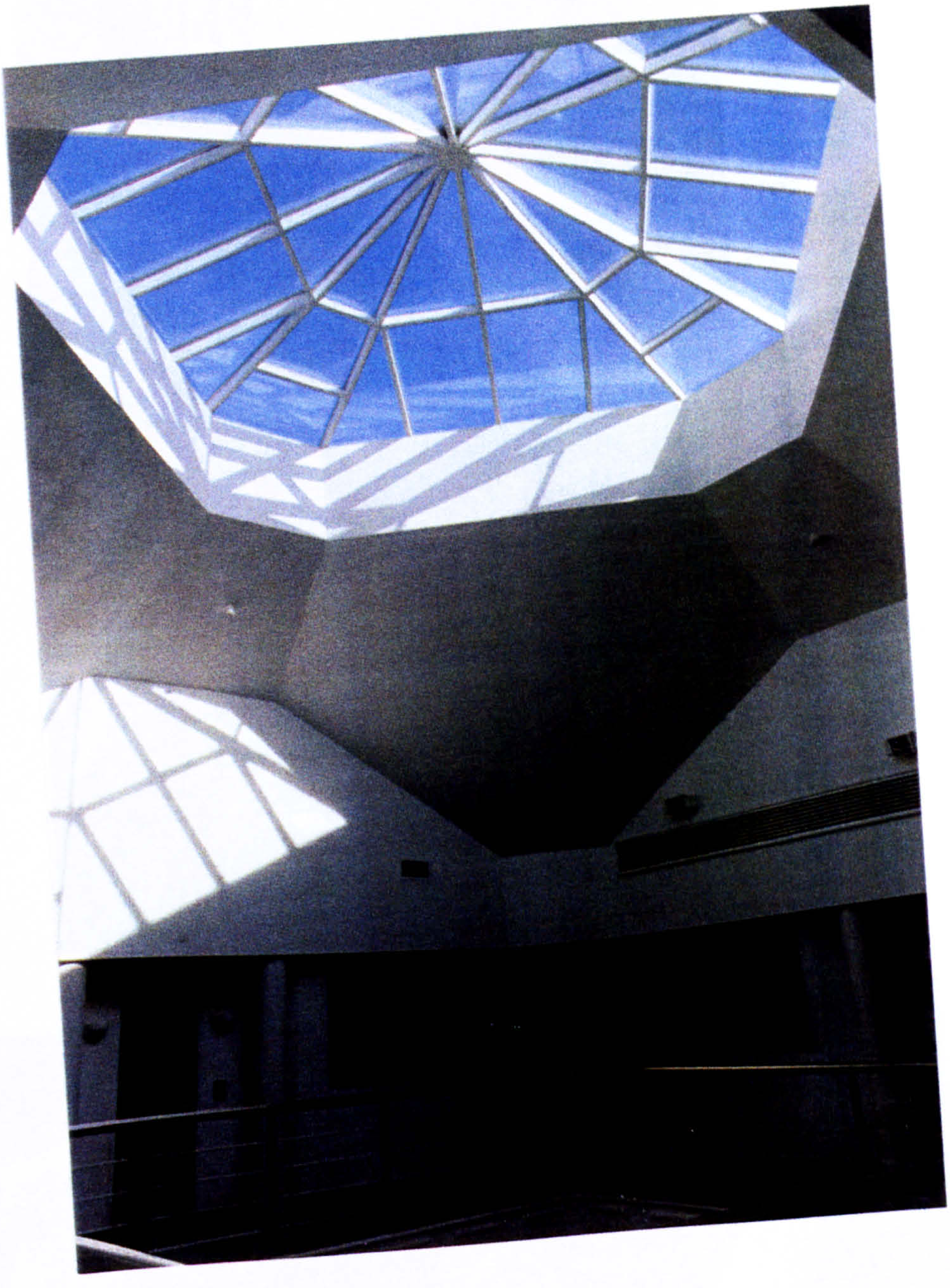


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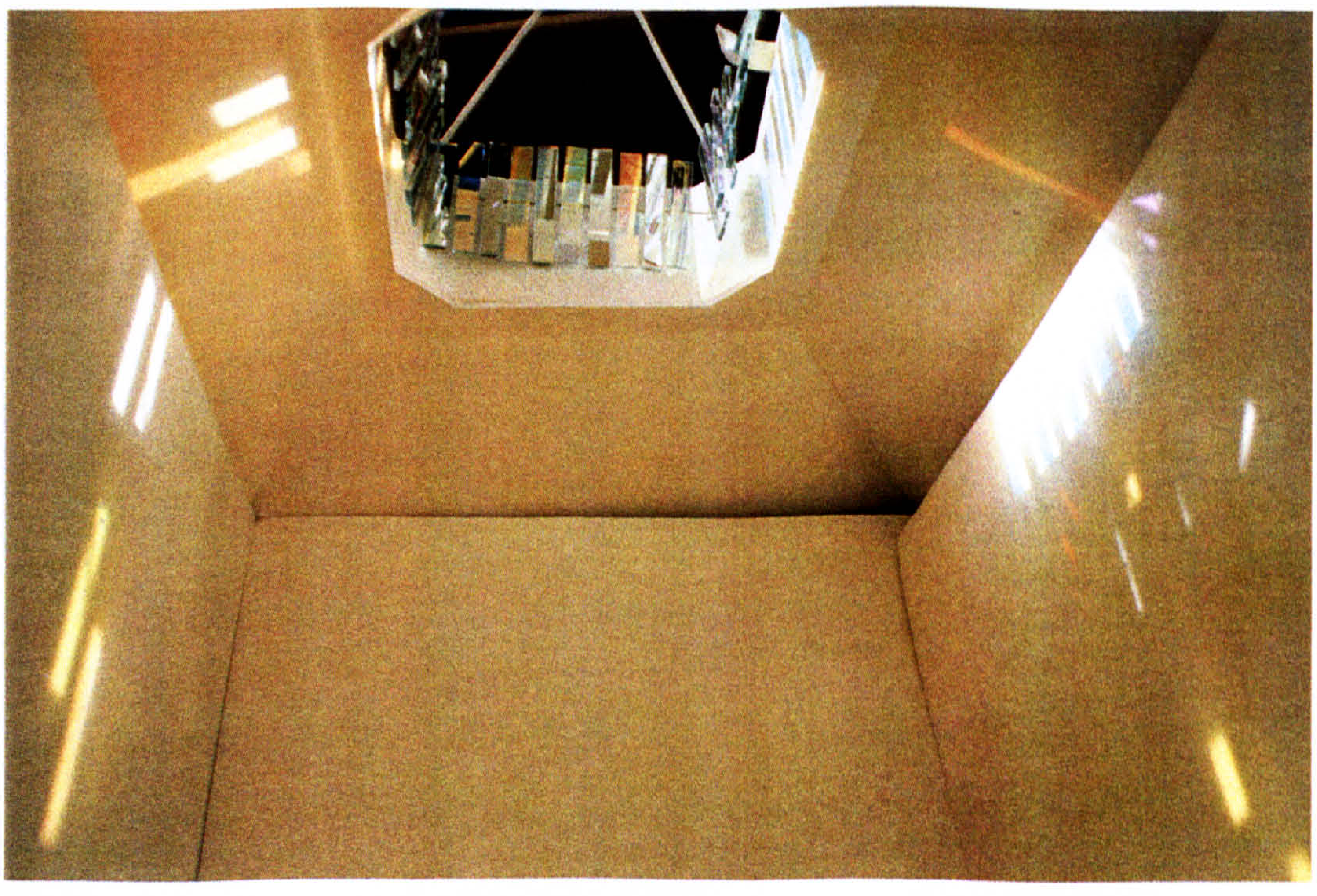
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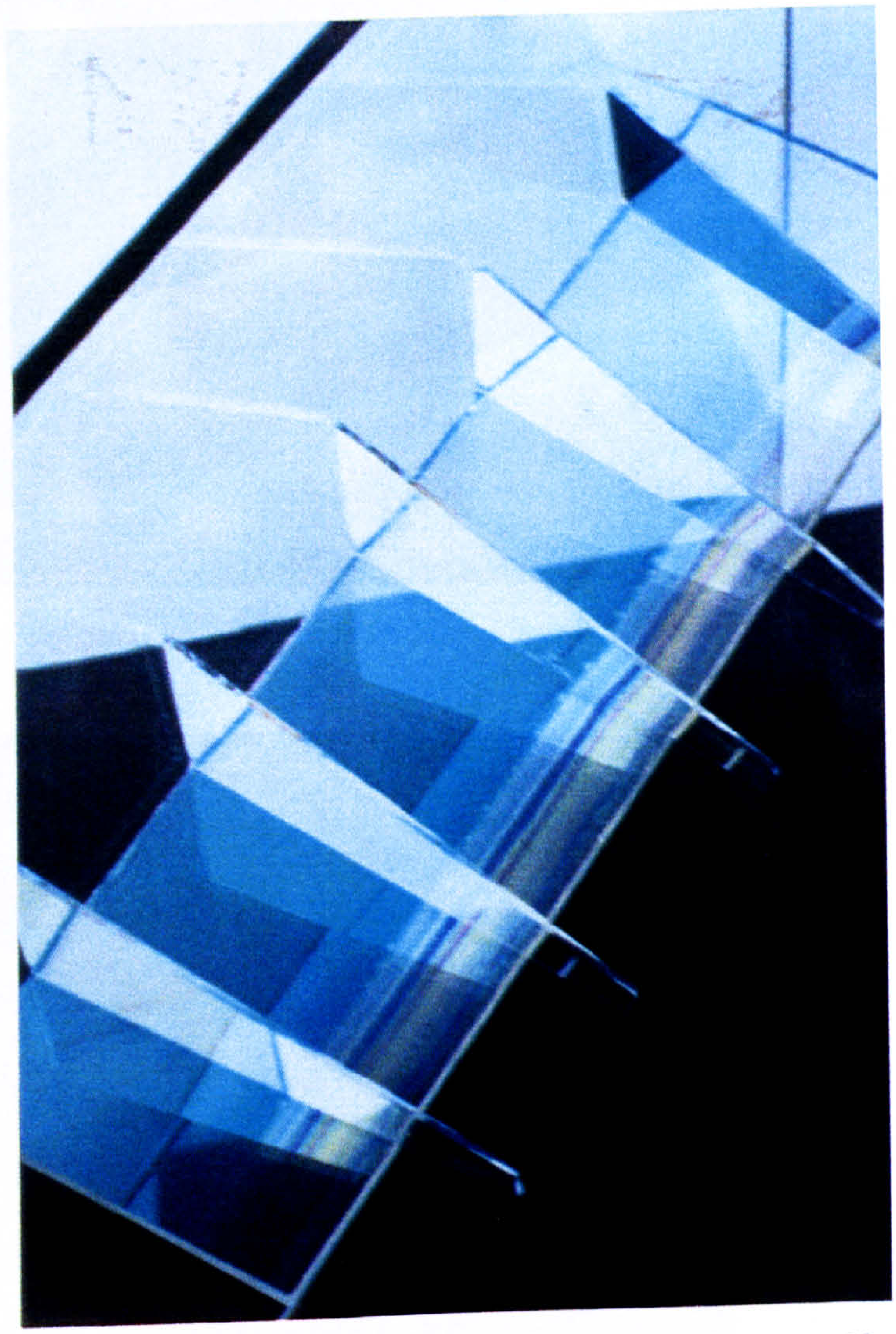

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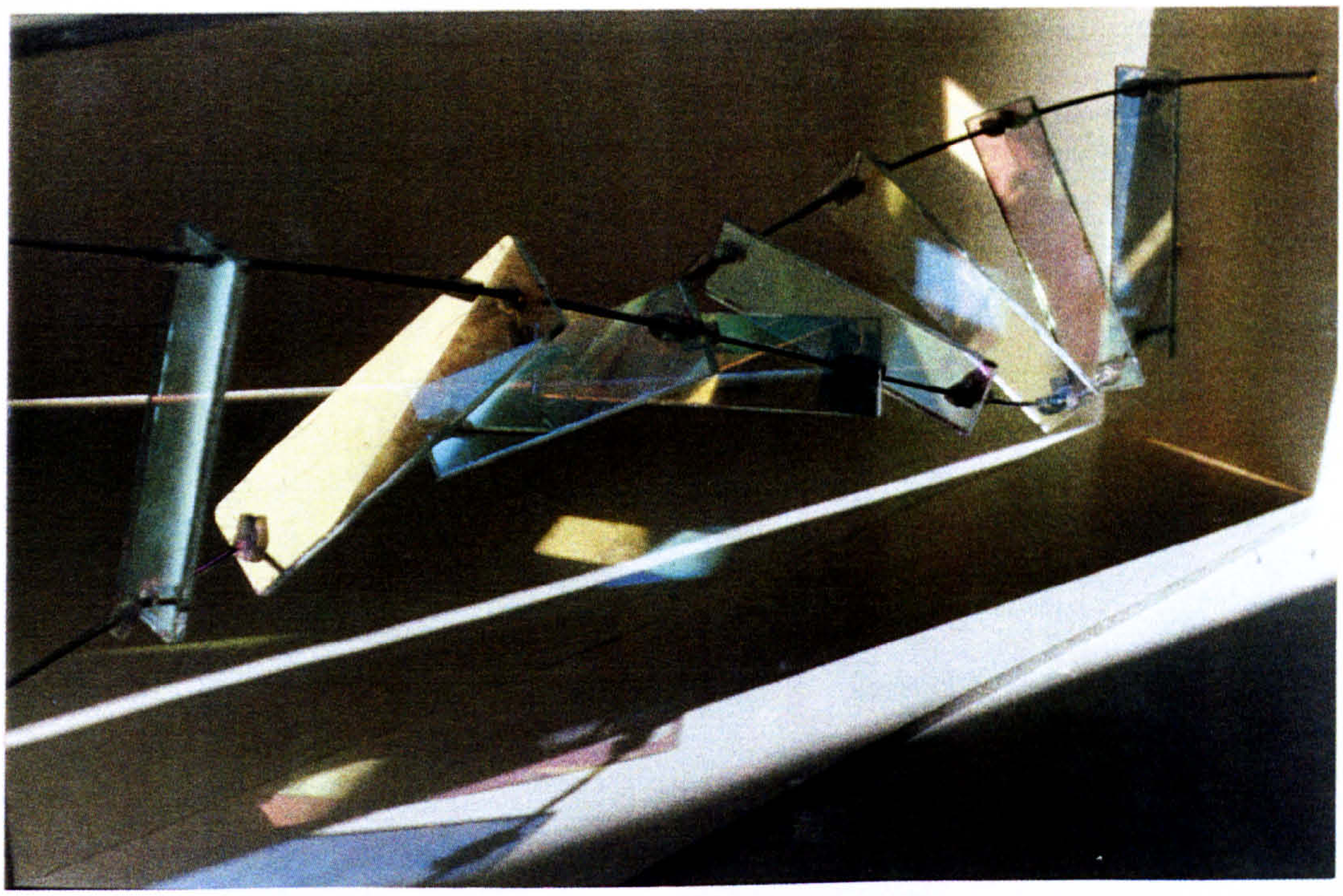

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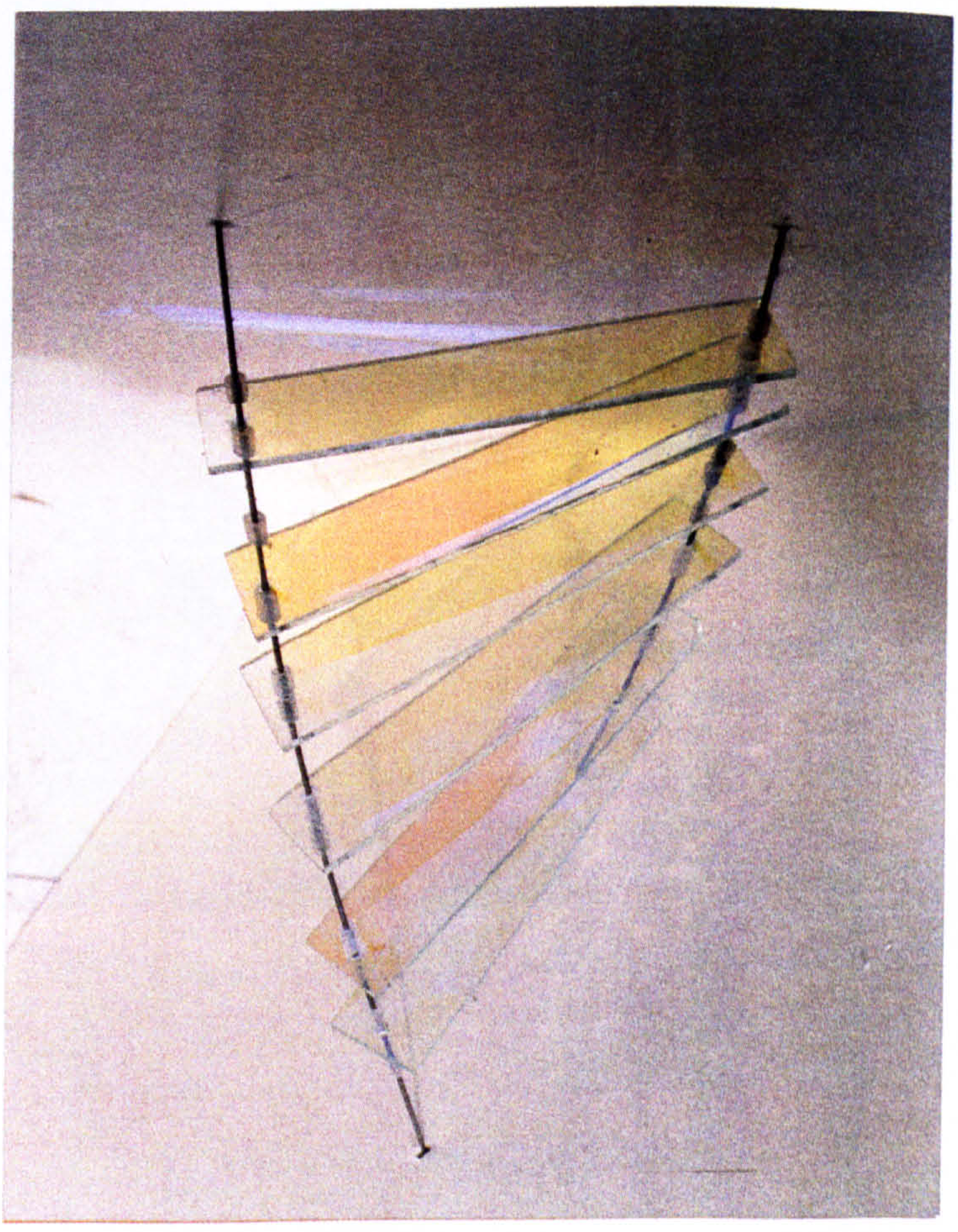

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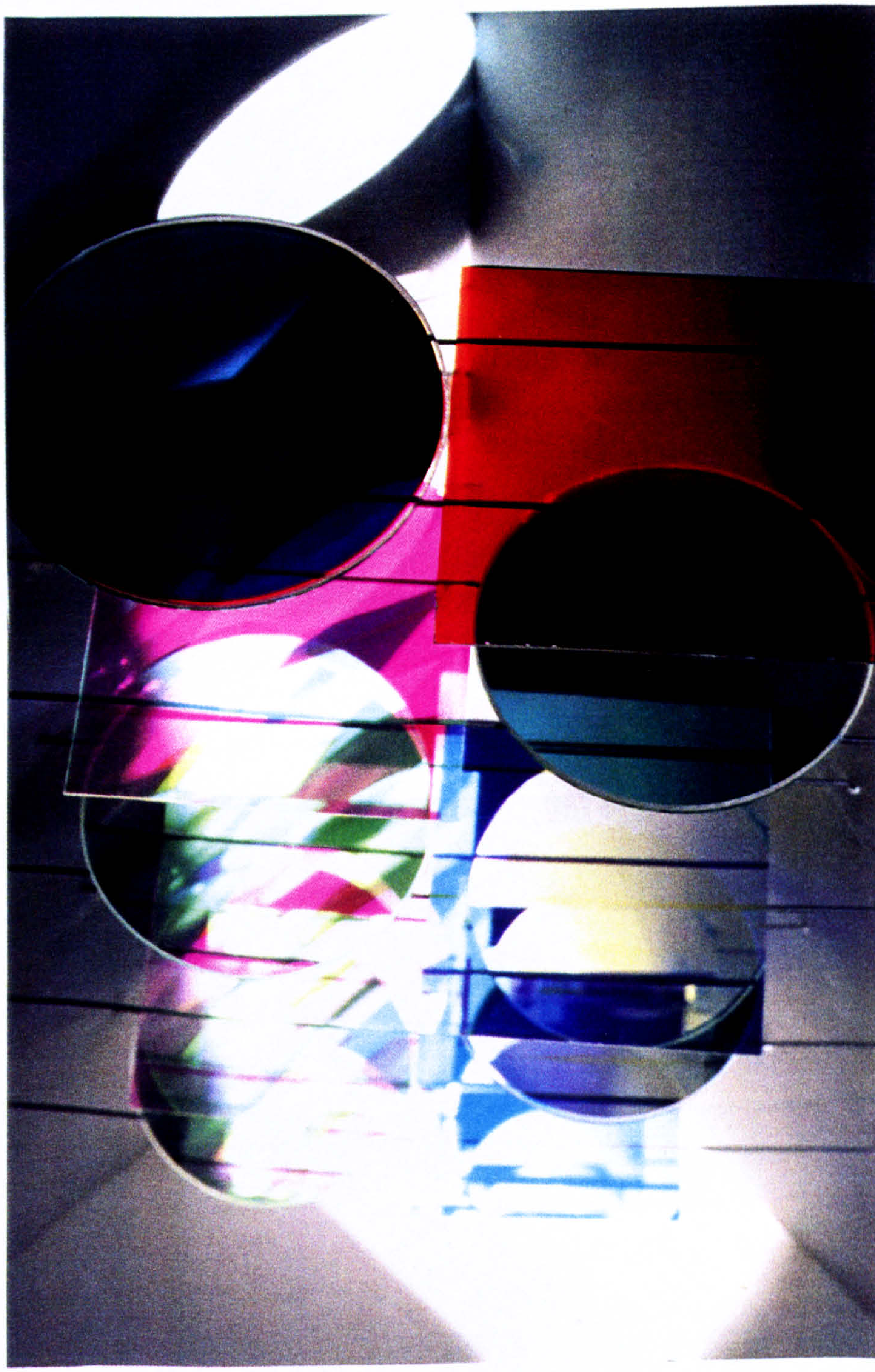

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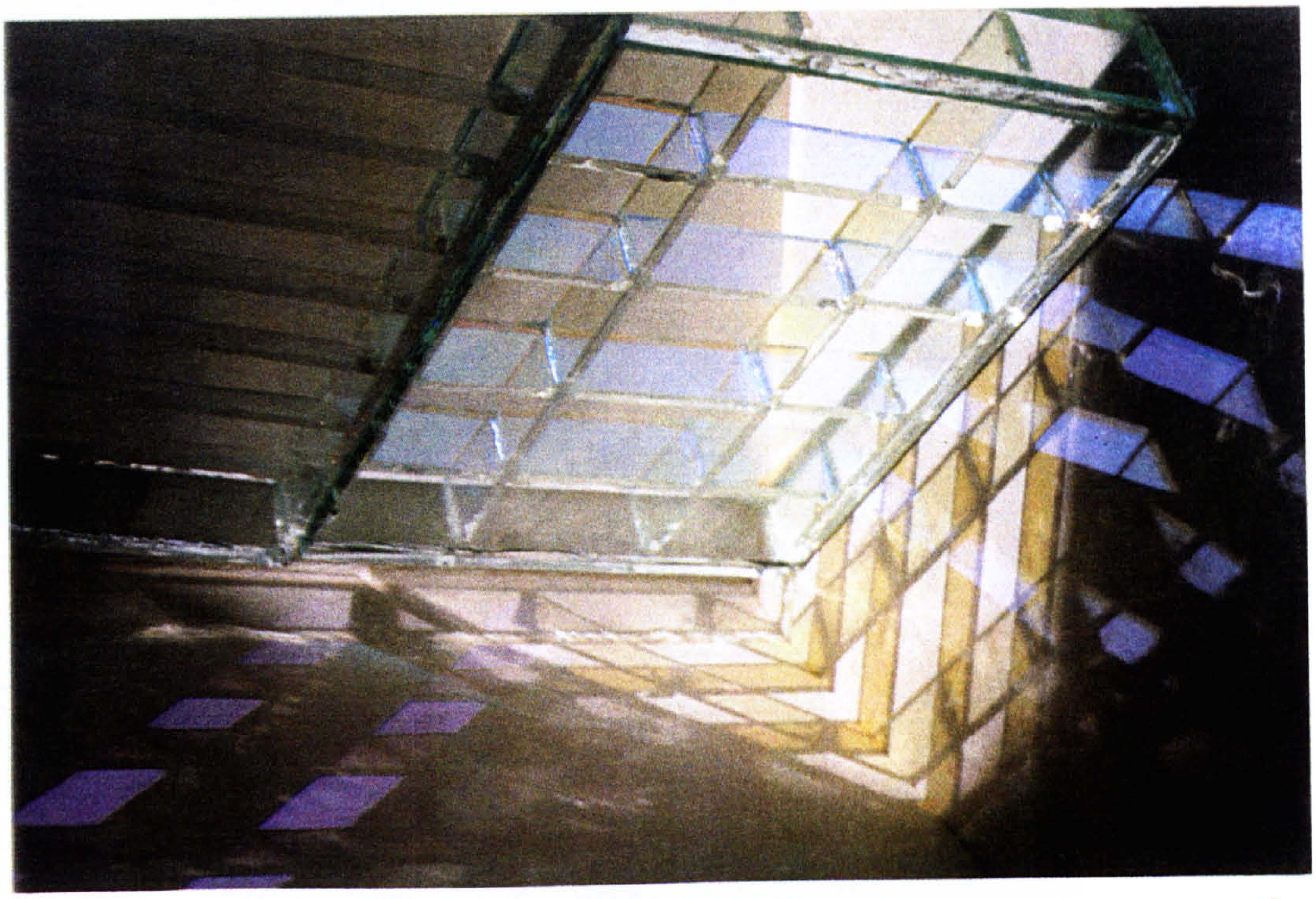

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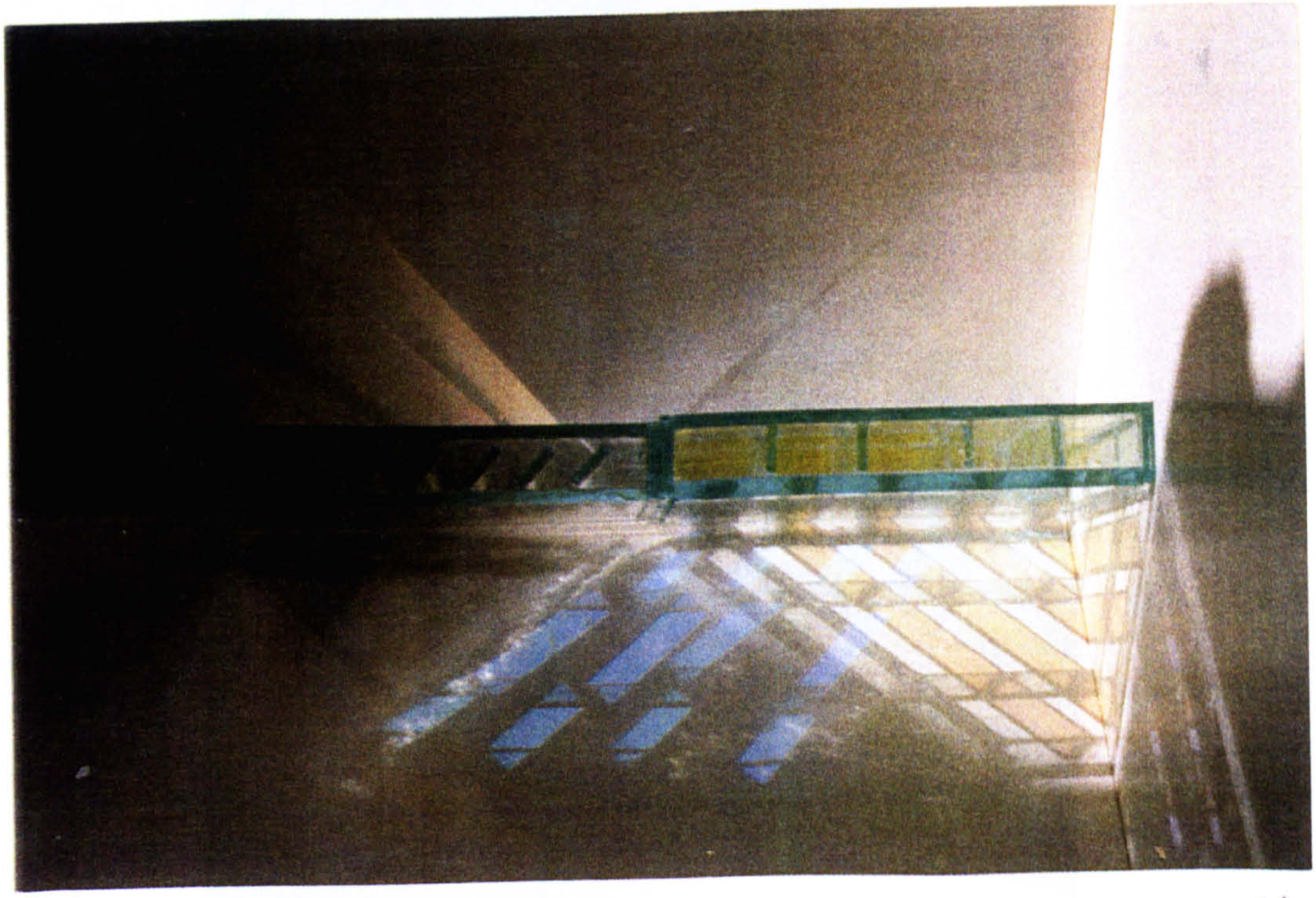

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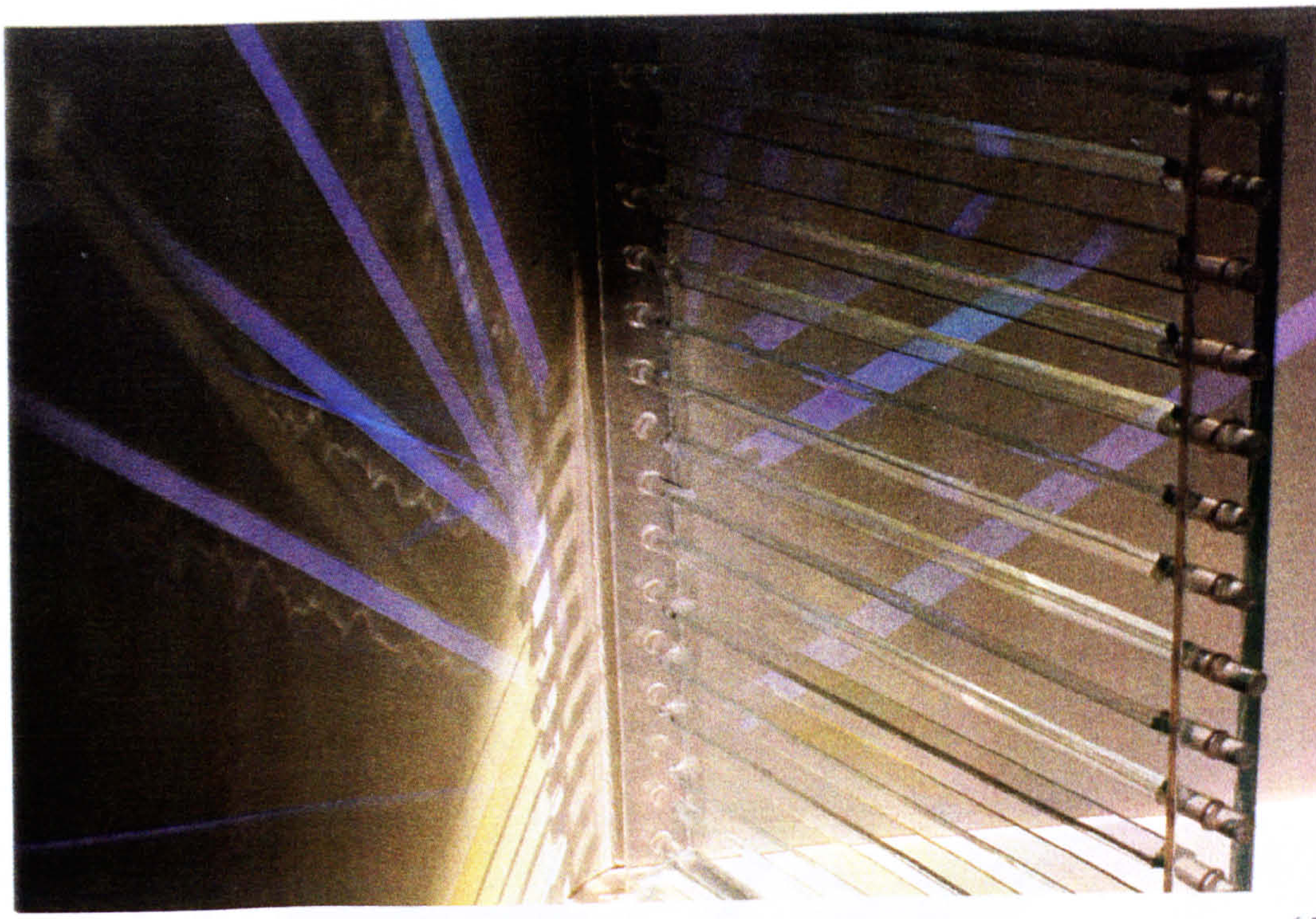

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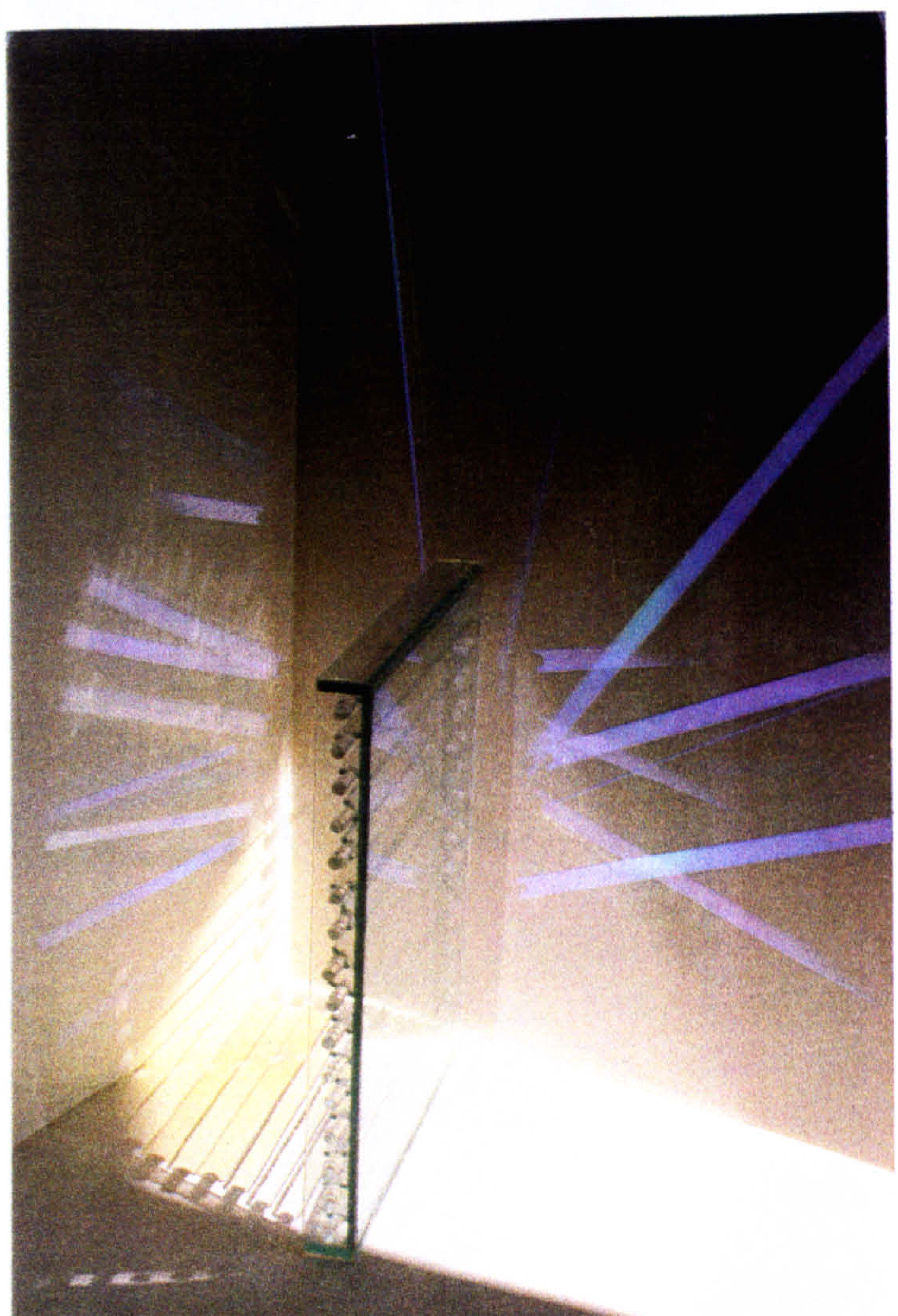

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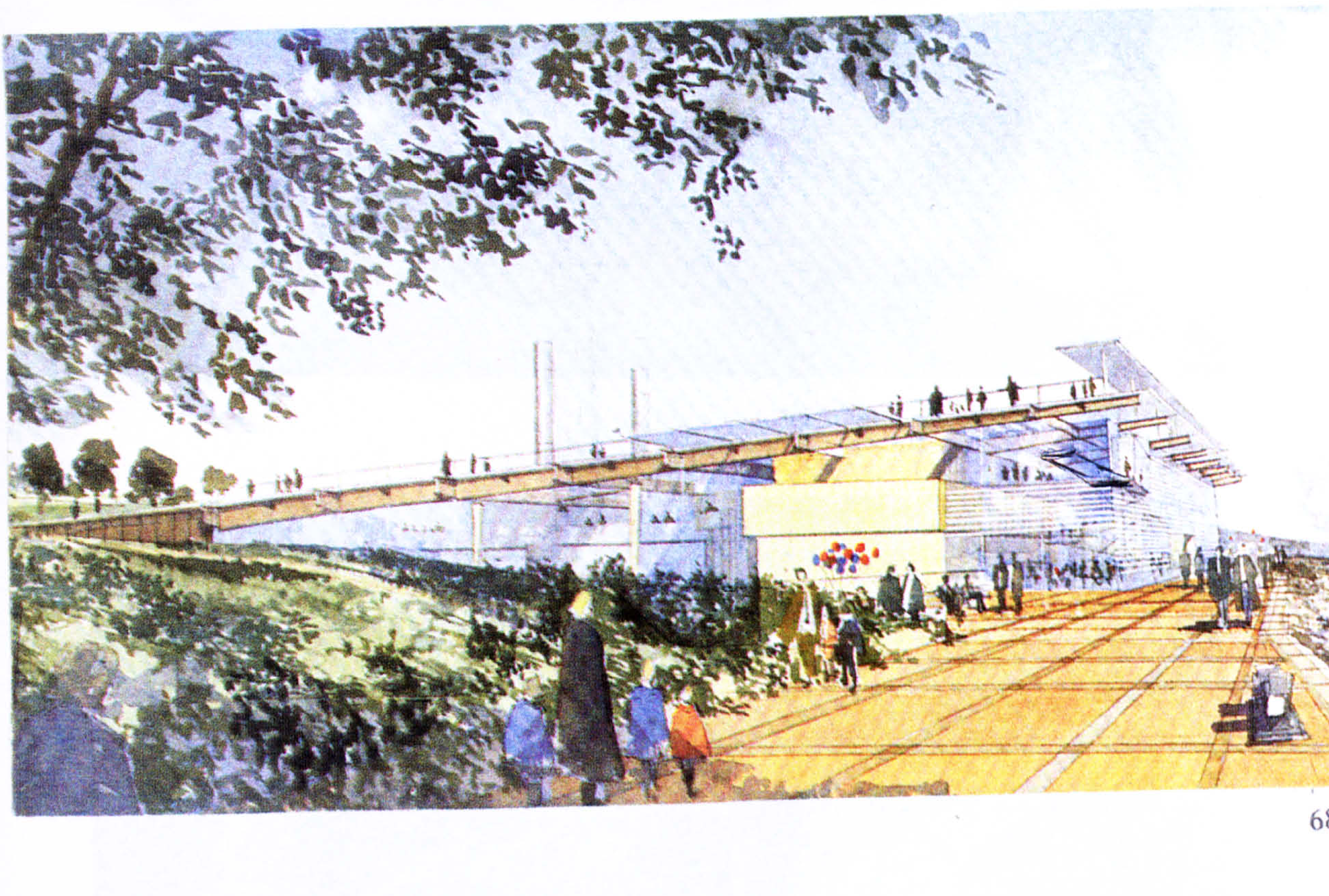

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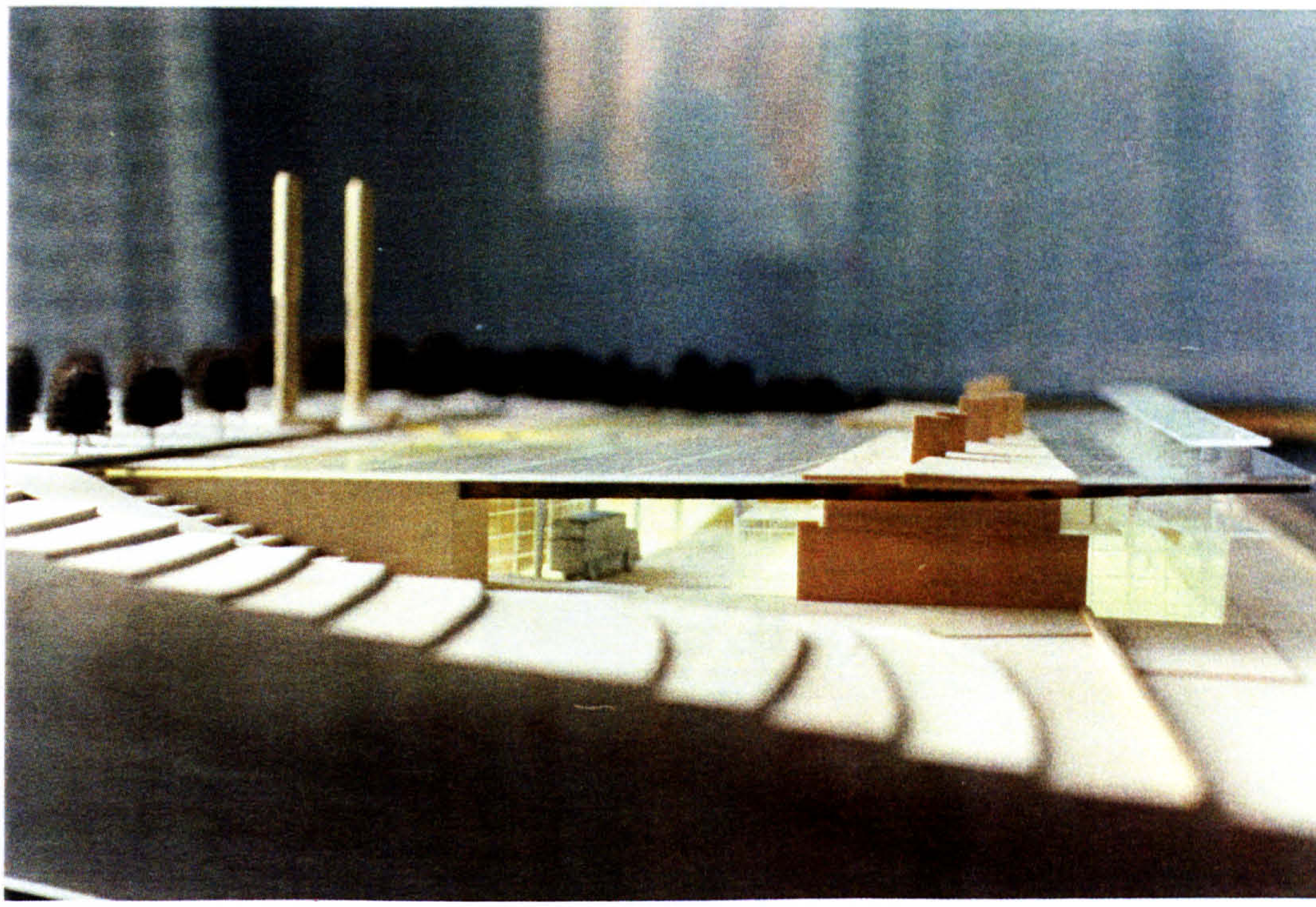

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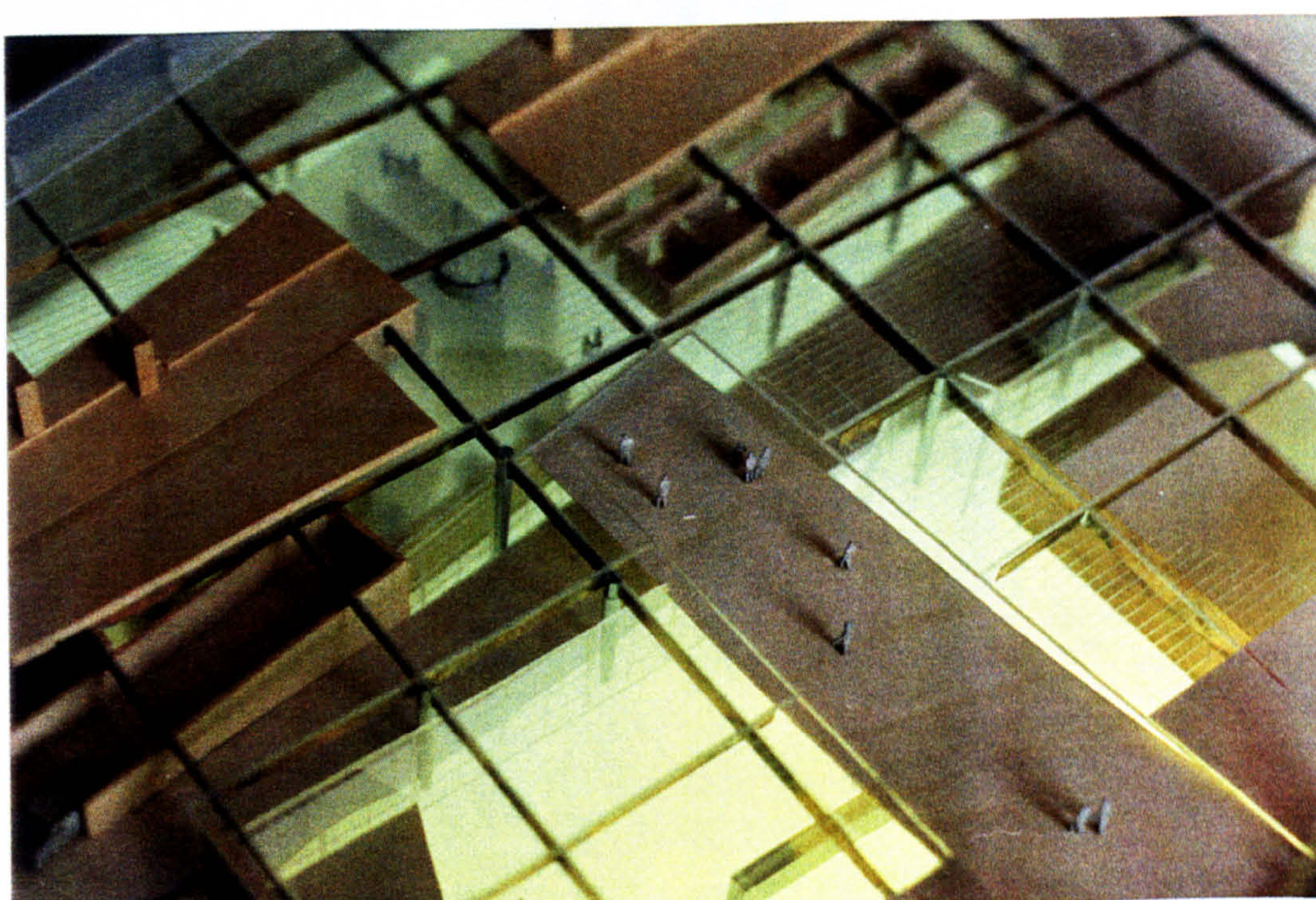

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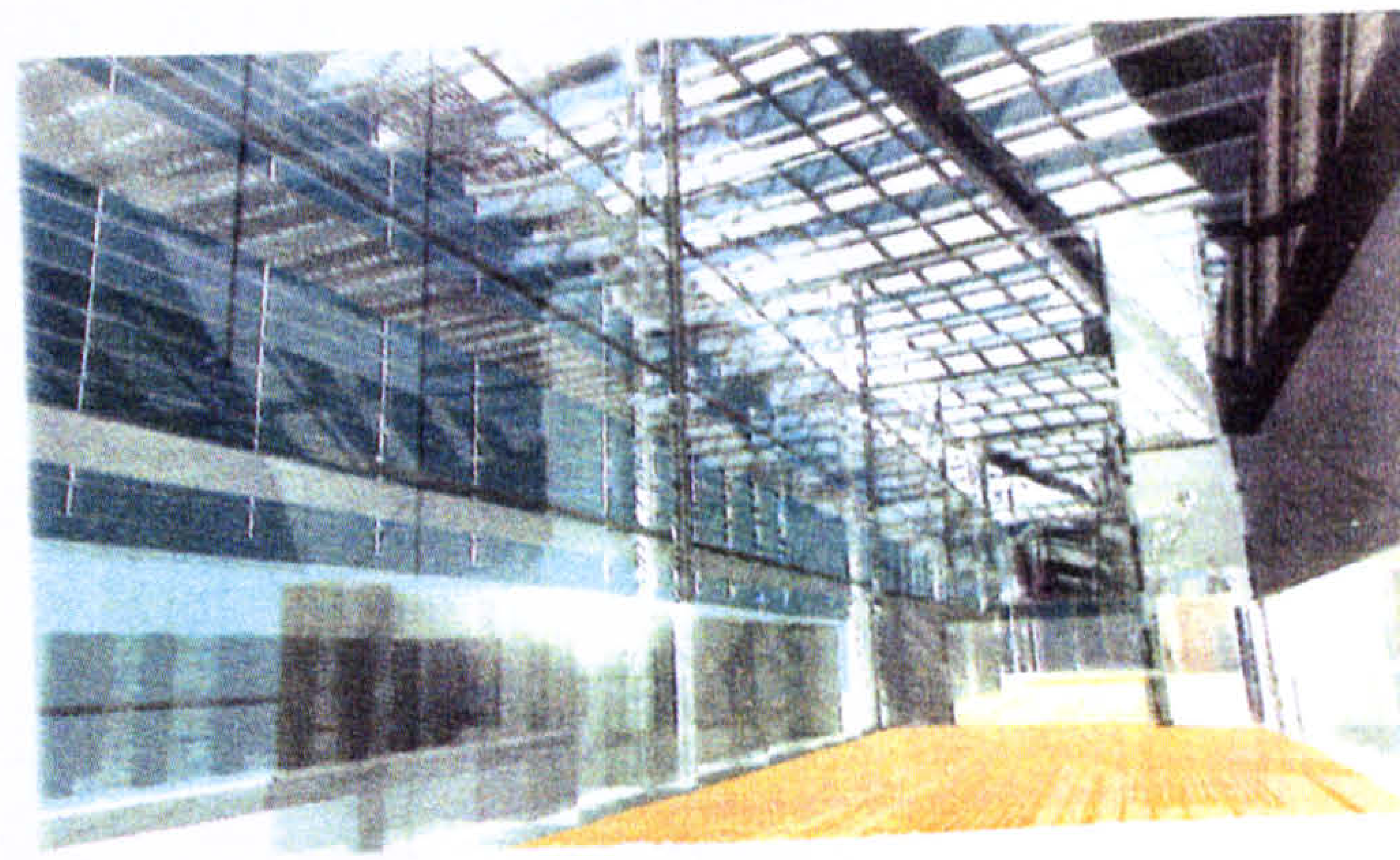
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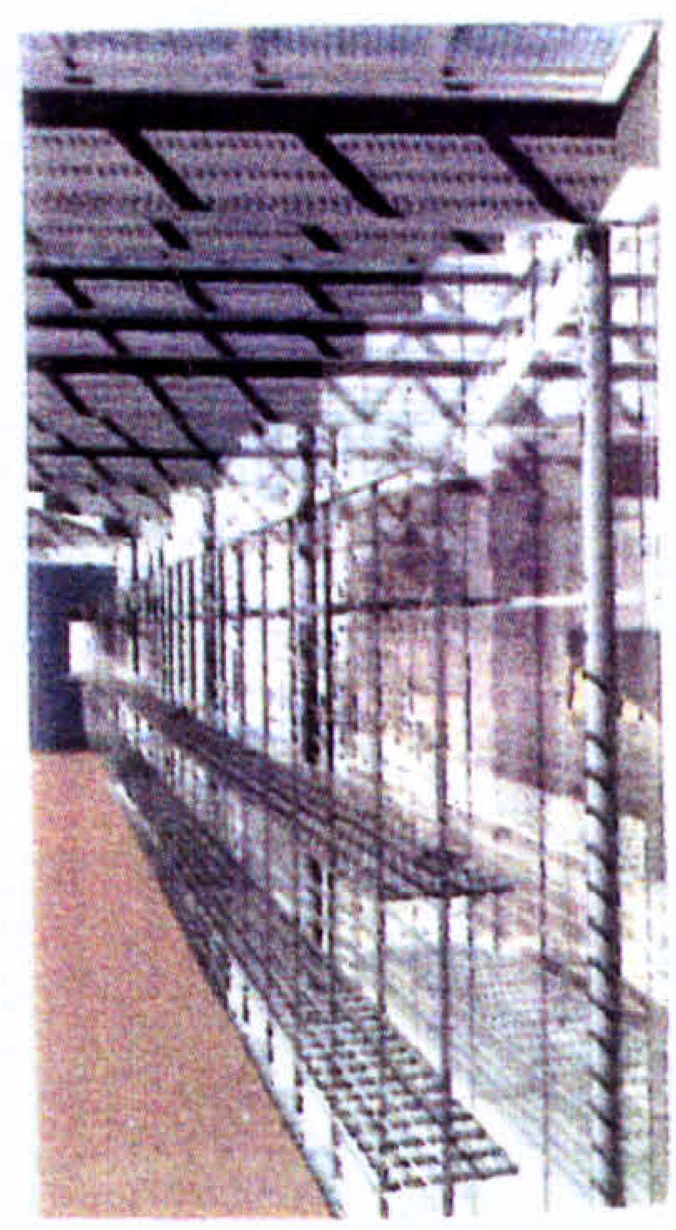
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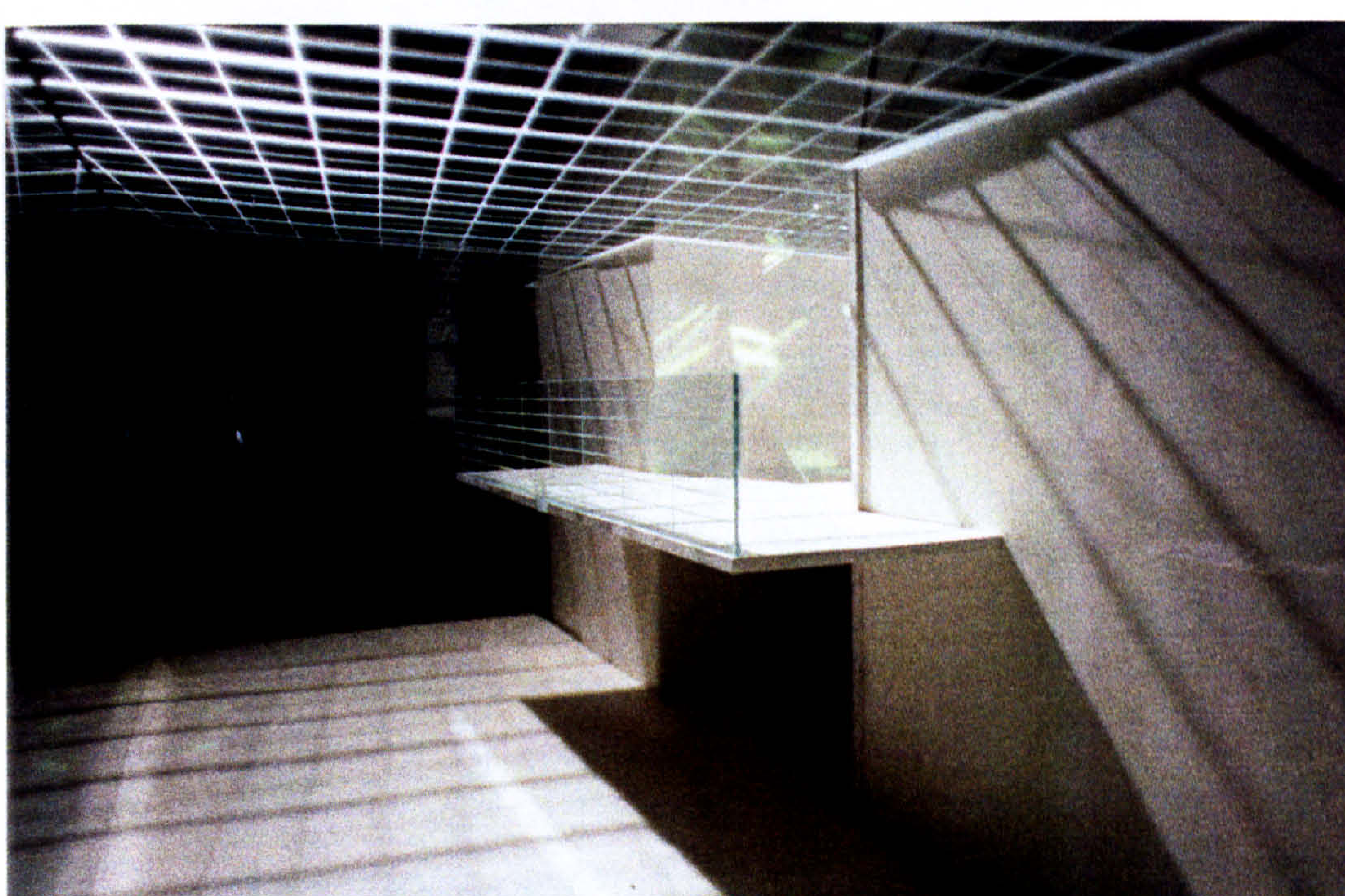
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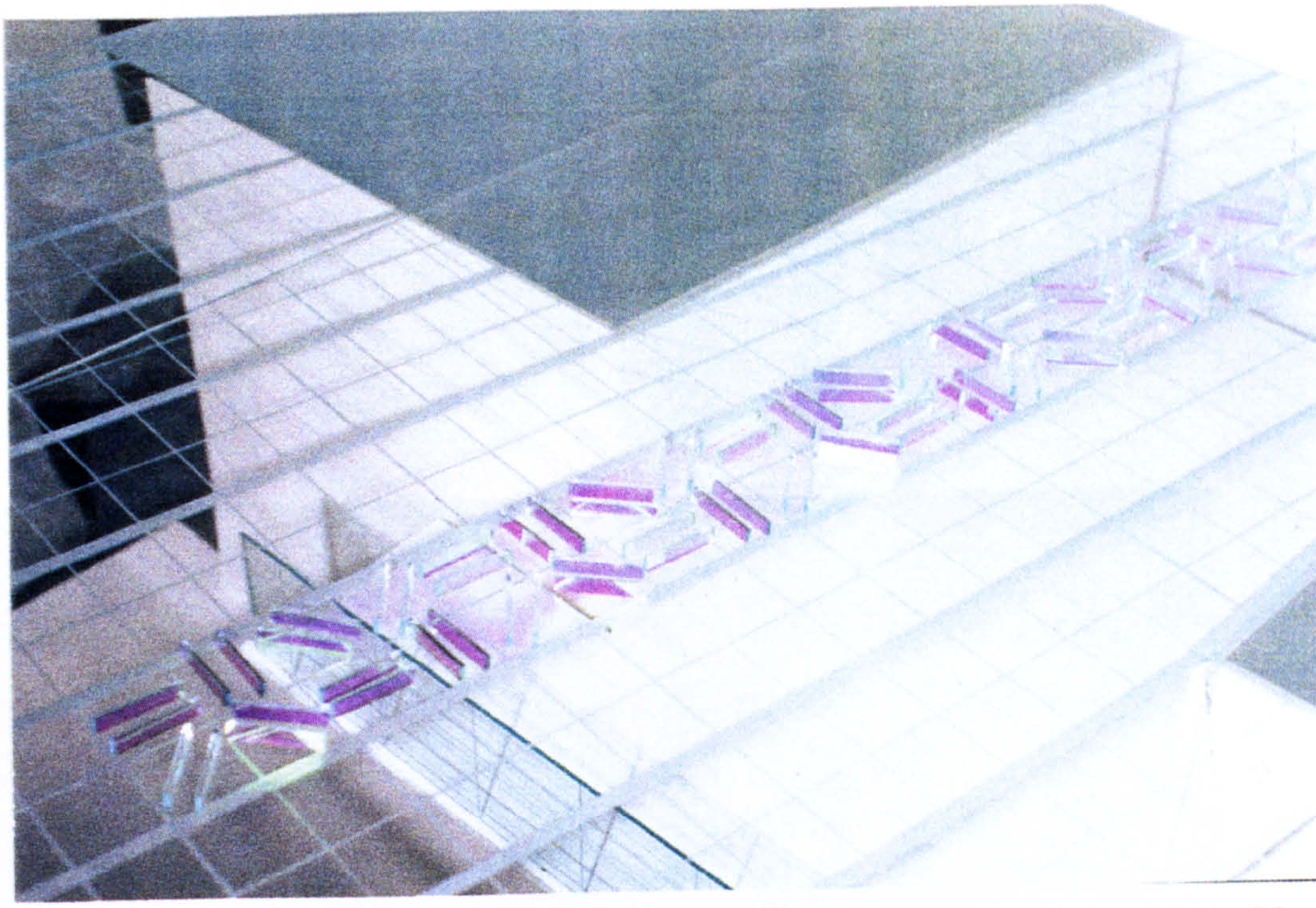

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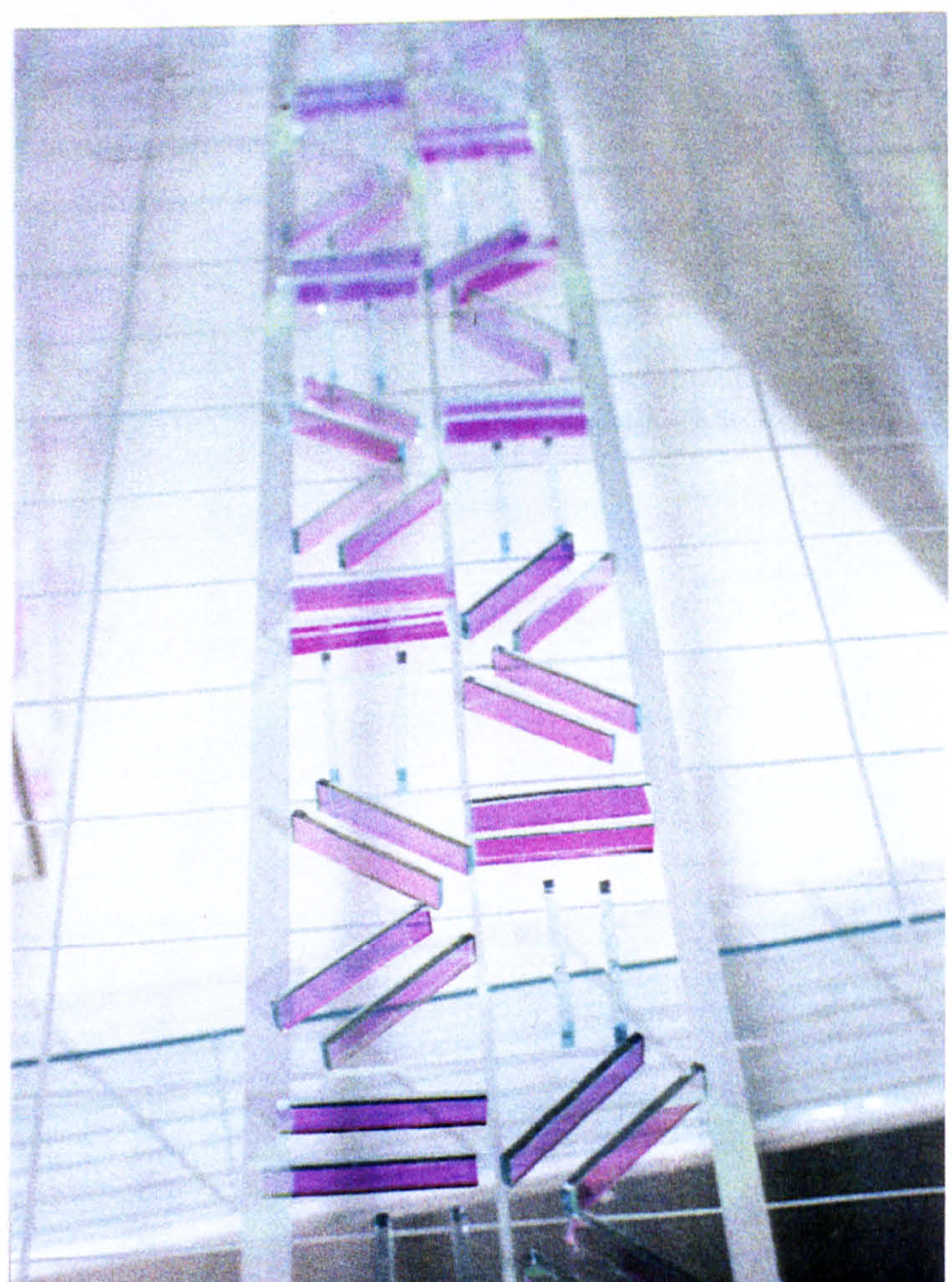

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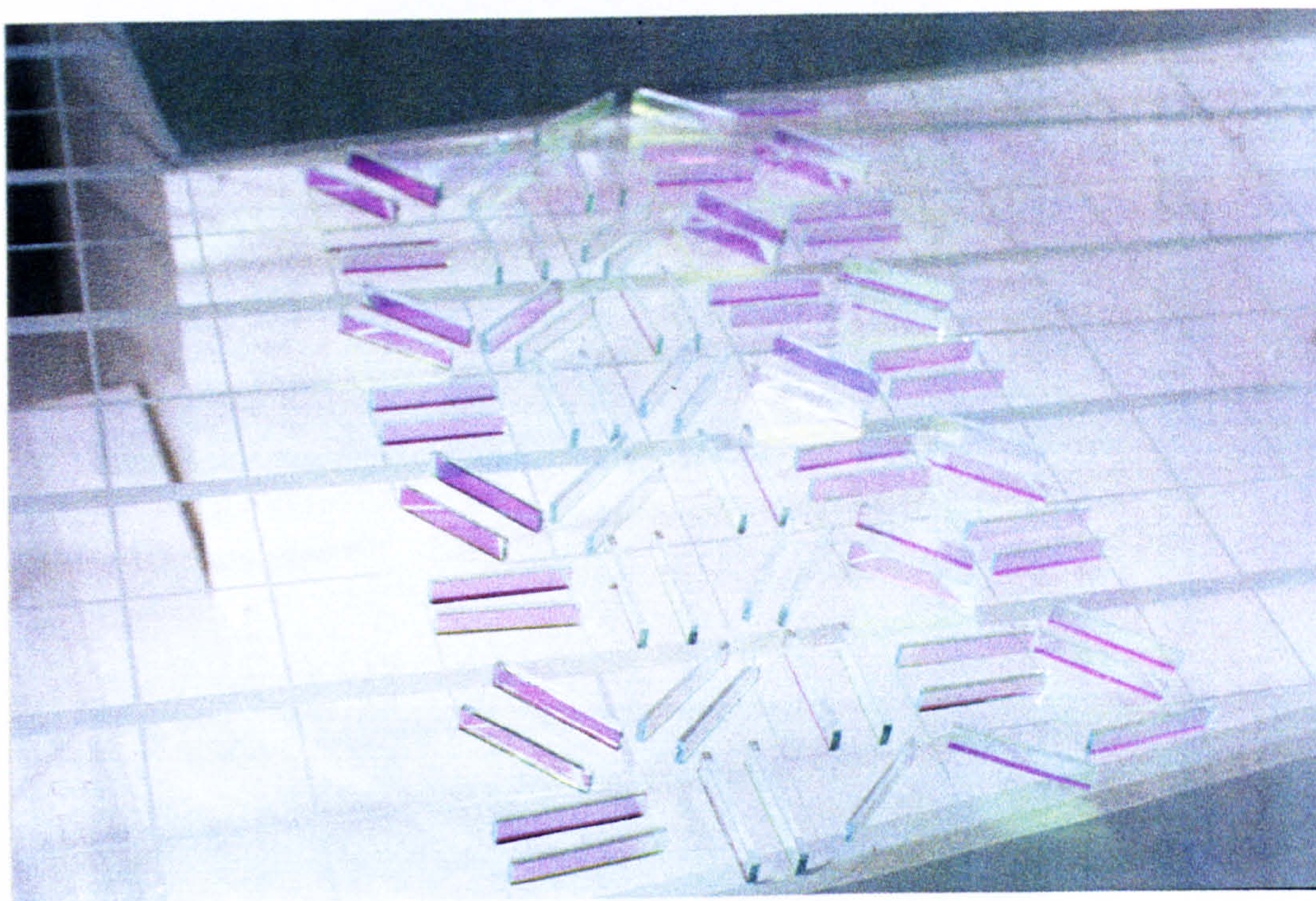

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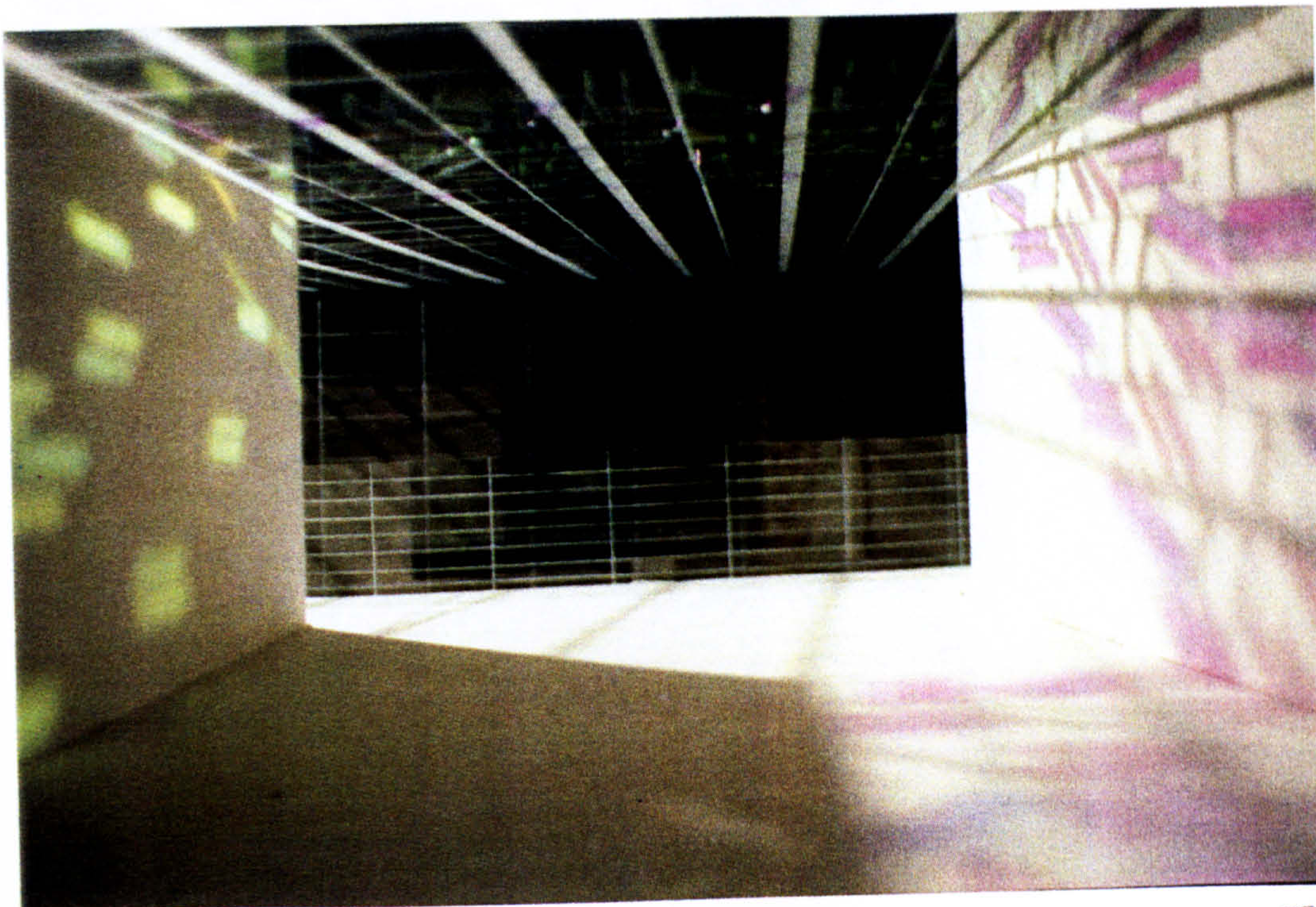
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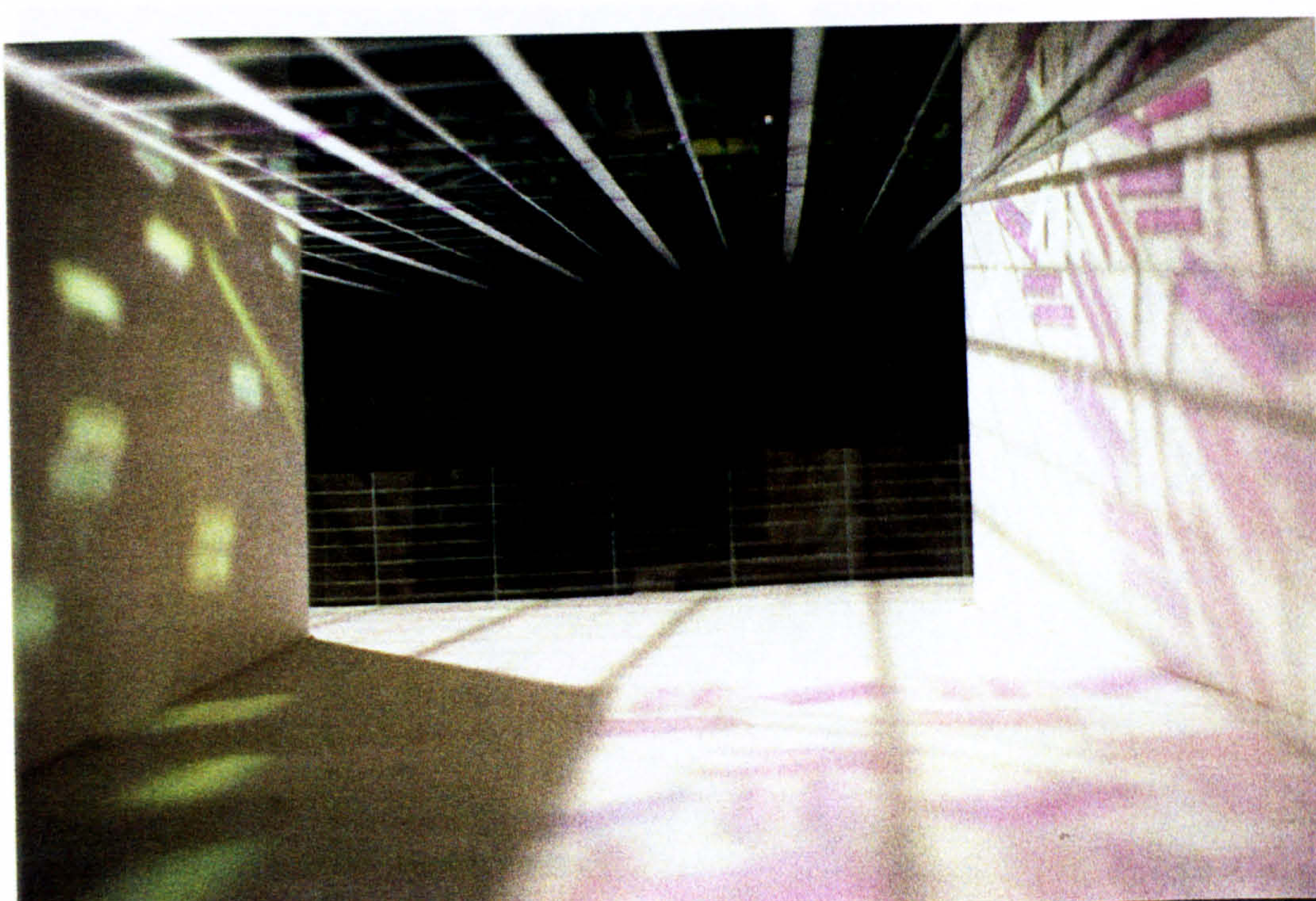
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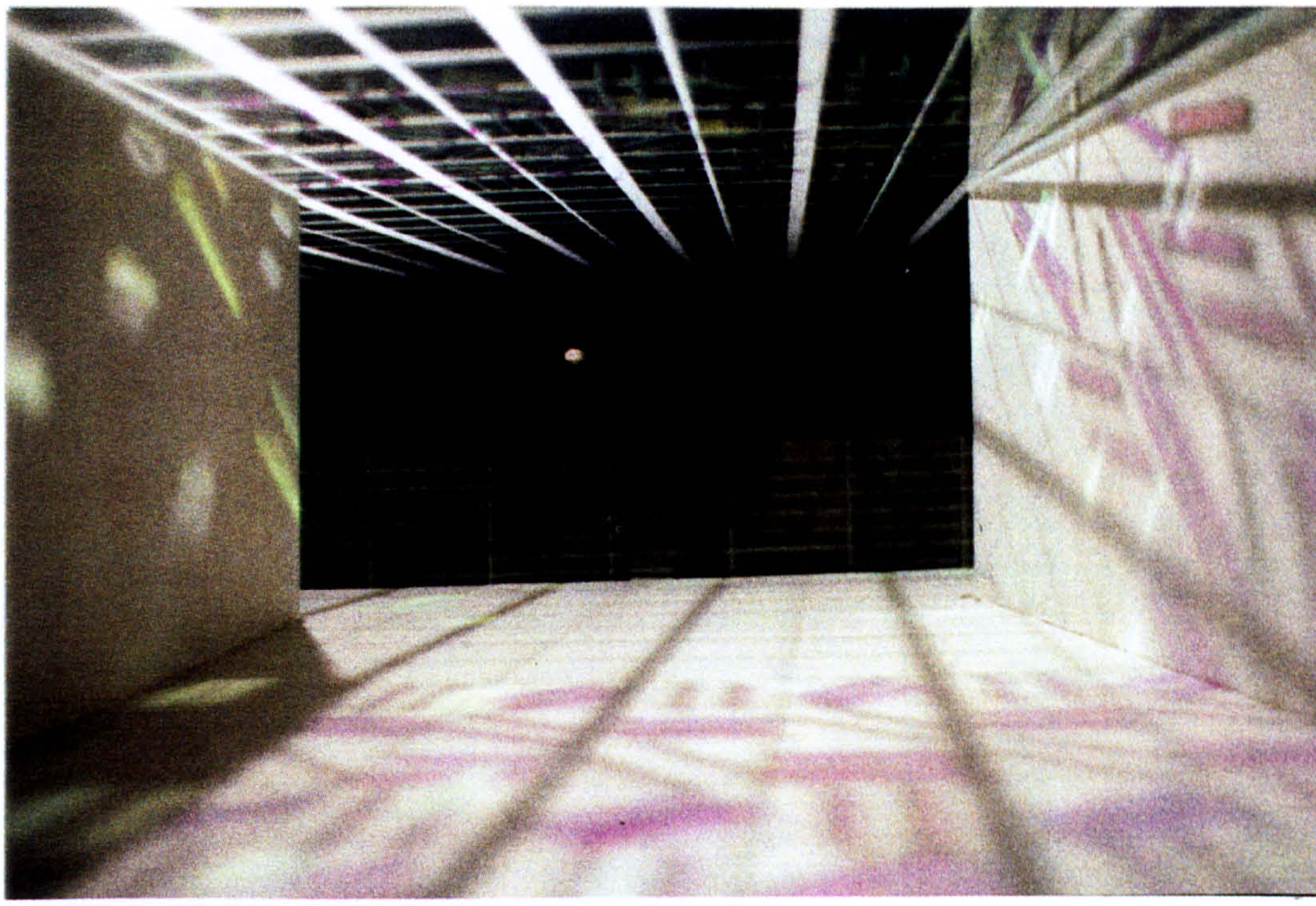

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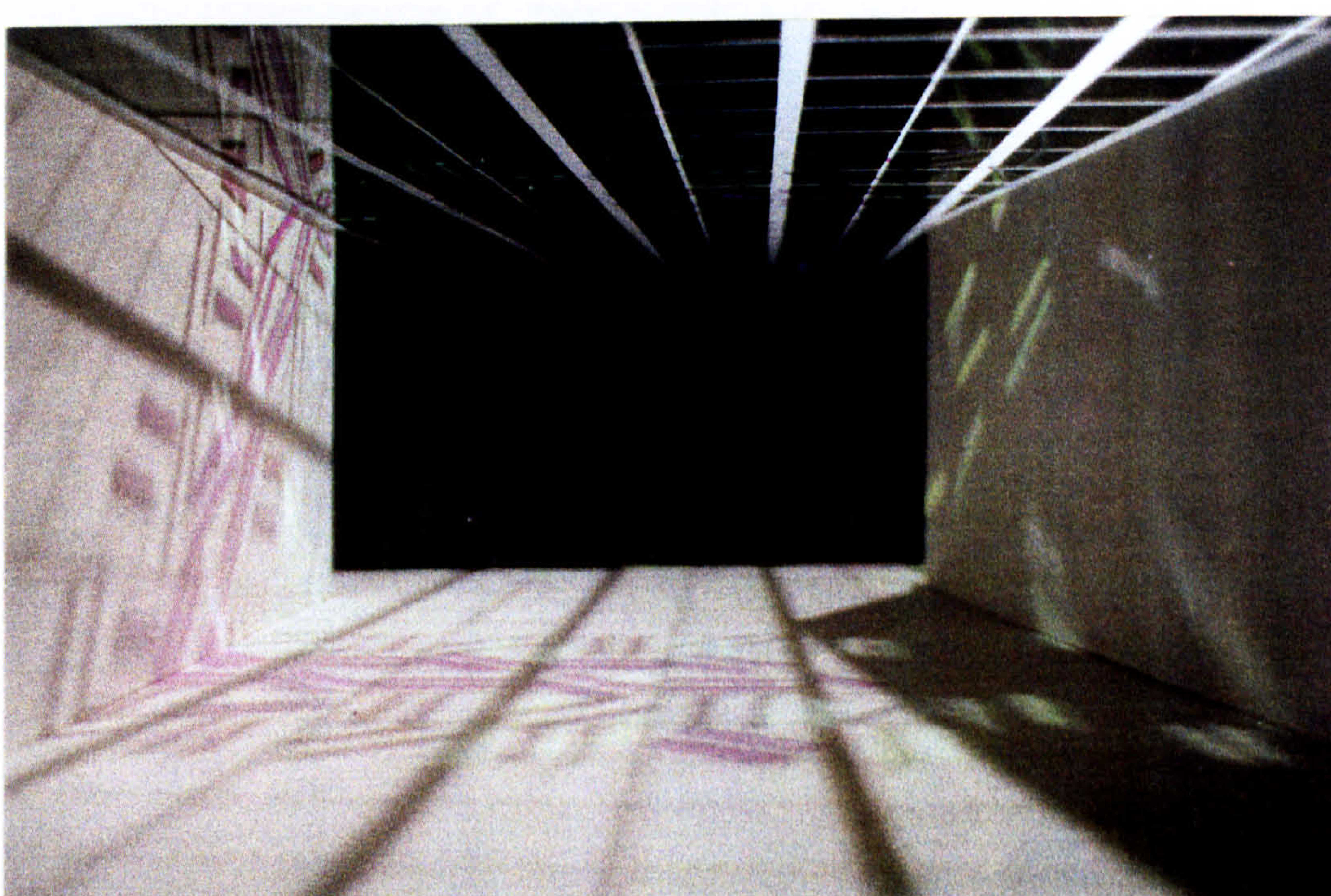

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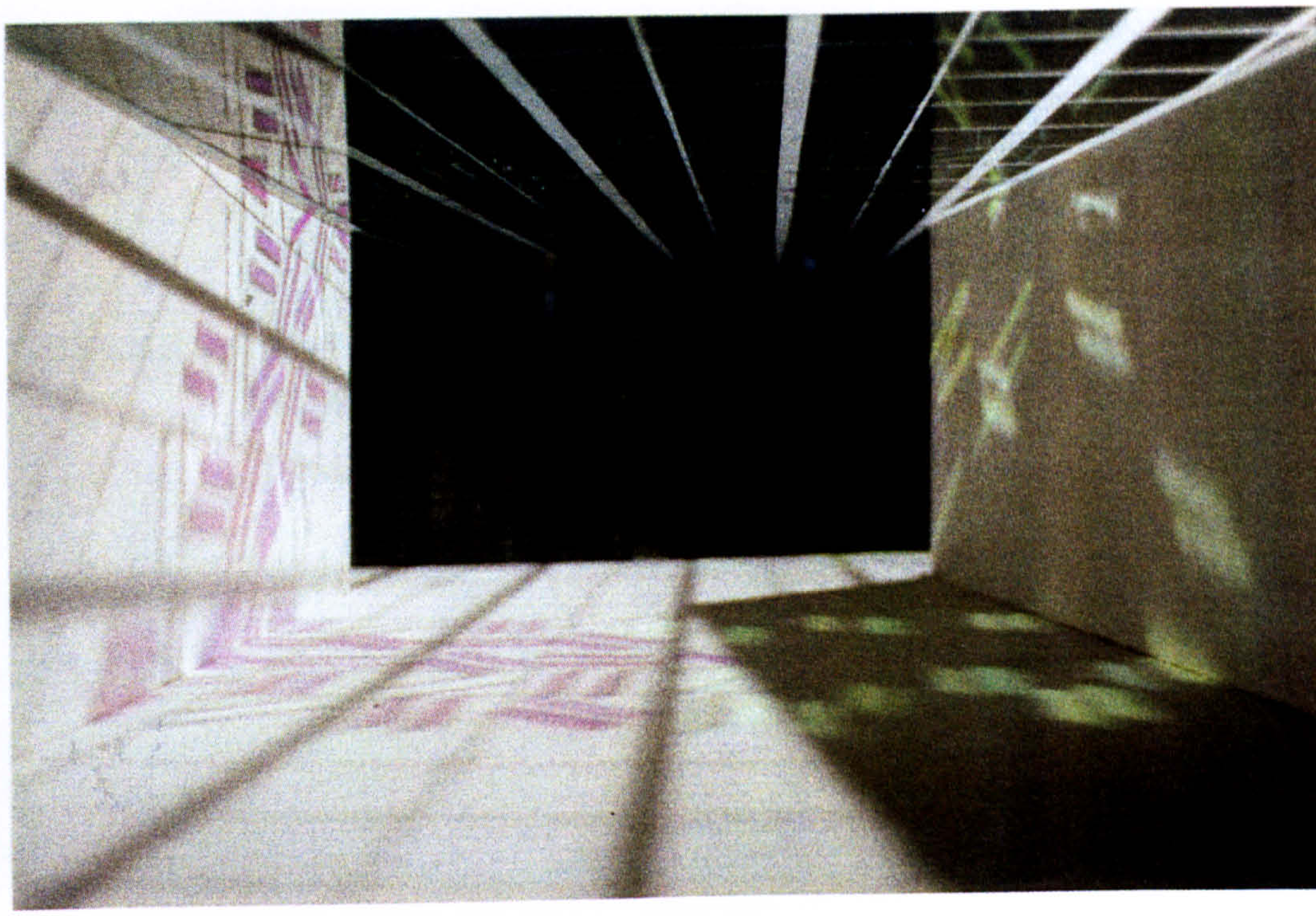

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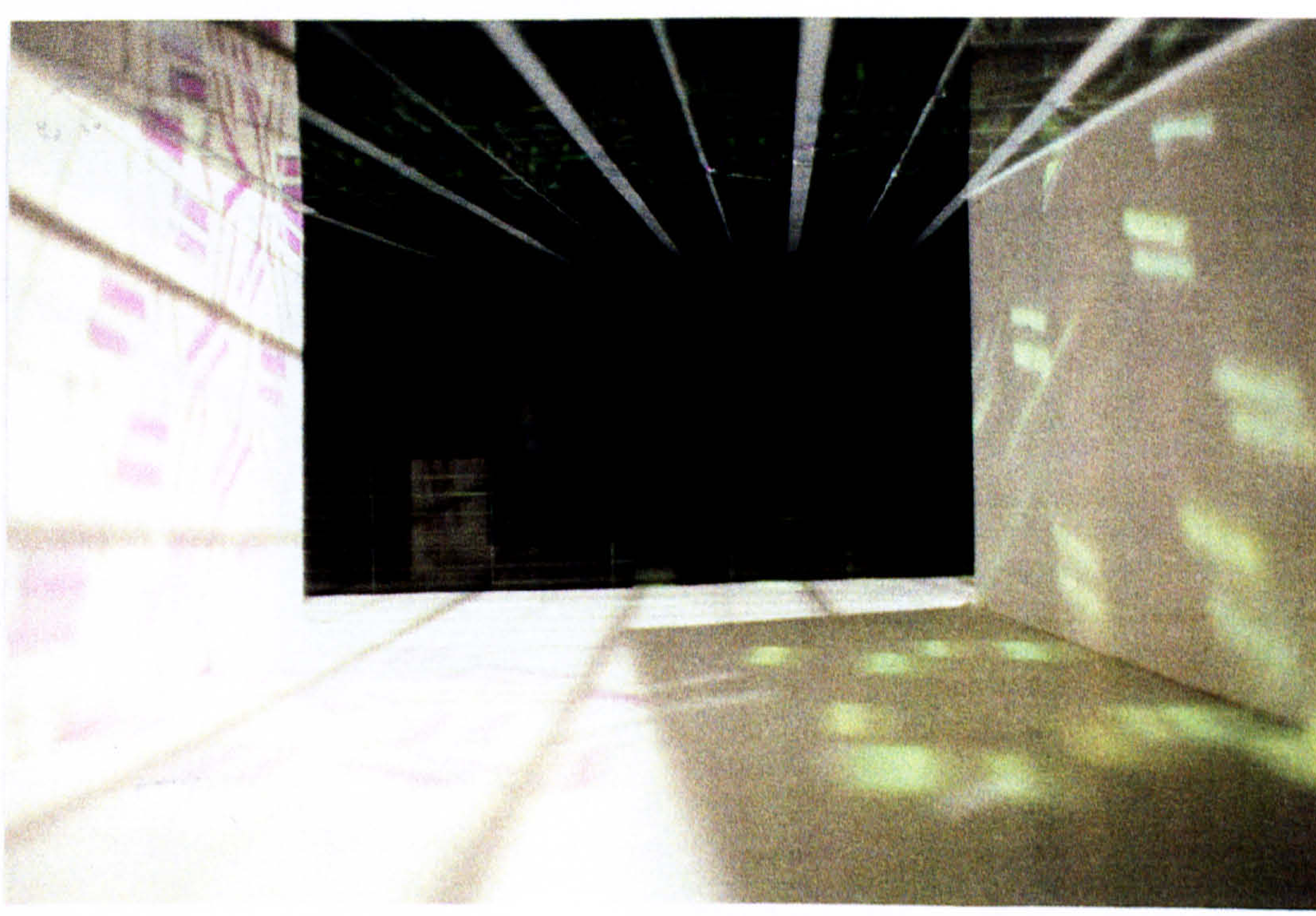

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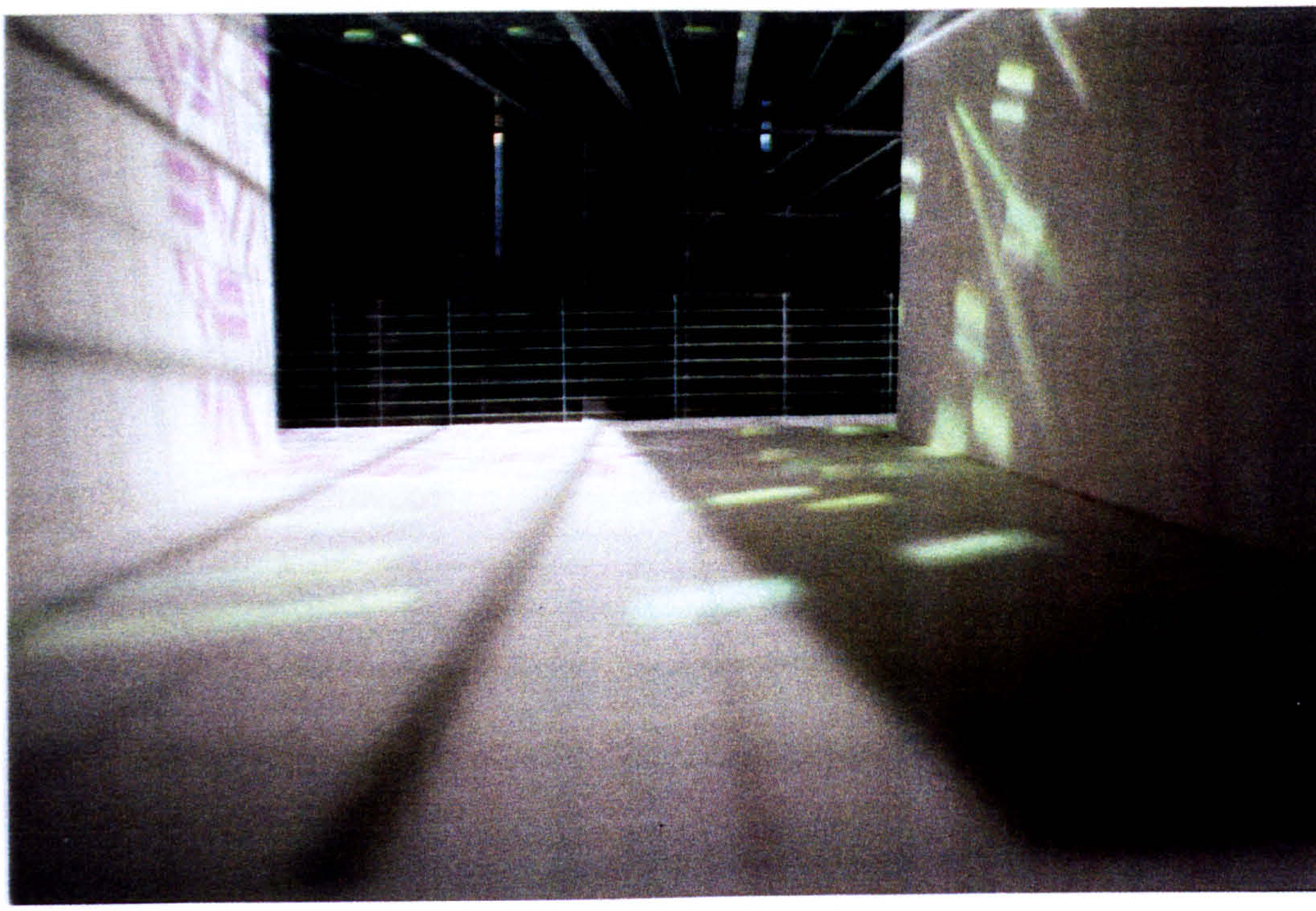

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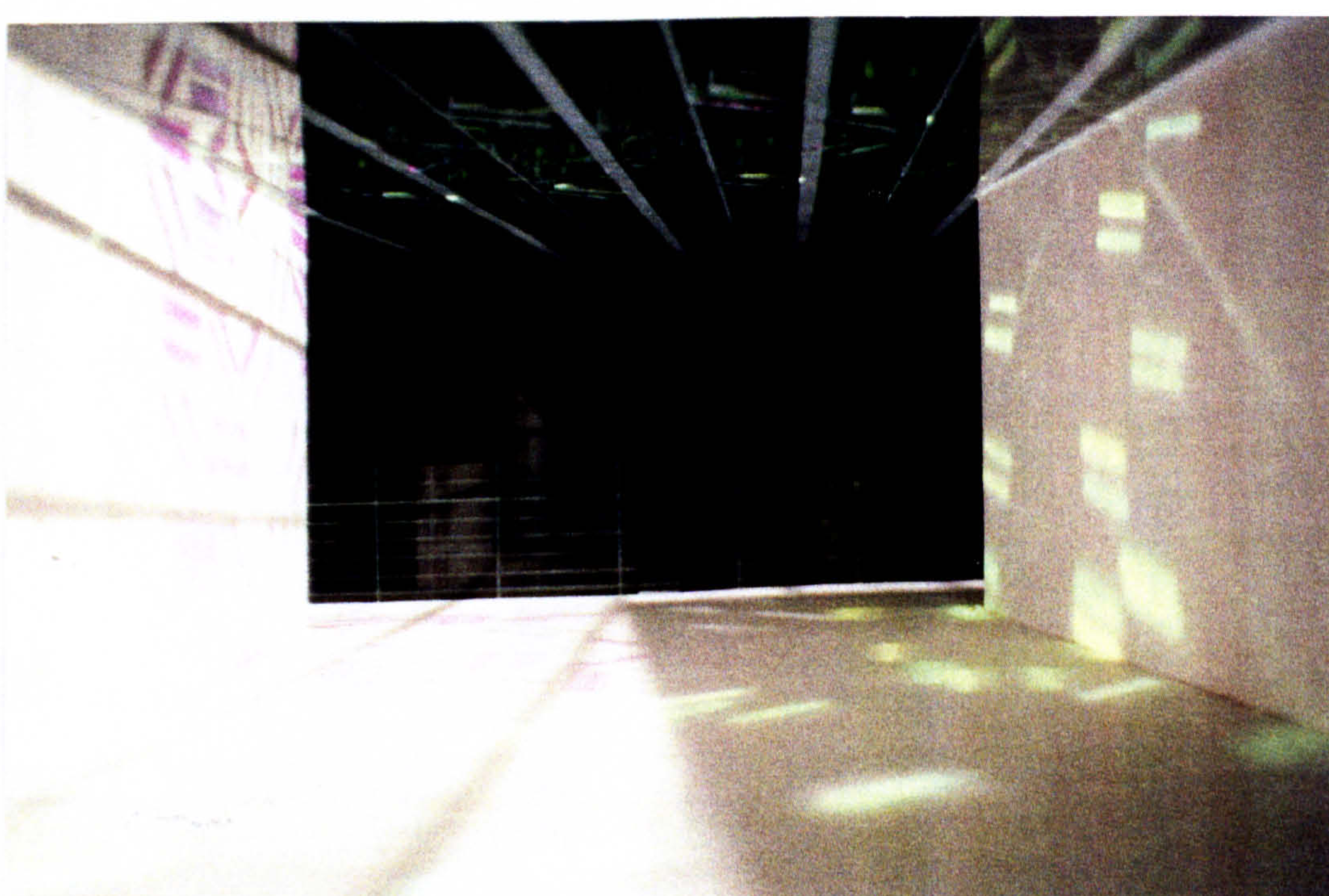

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APPENDIX 1

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INFORMATION FROM THE WORLD WIDE WEB.

Next Up Previous Index

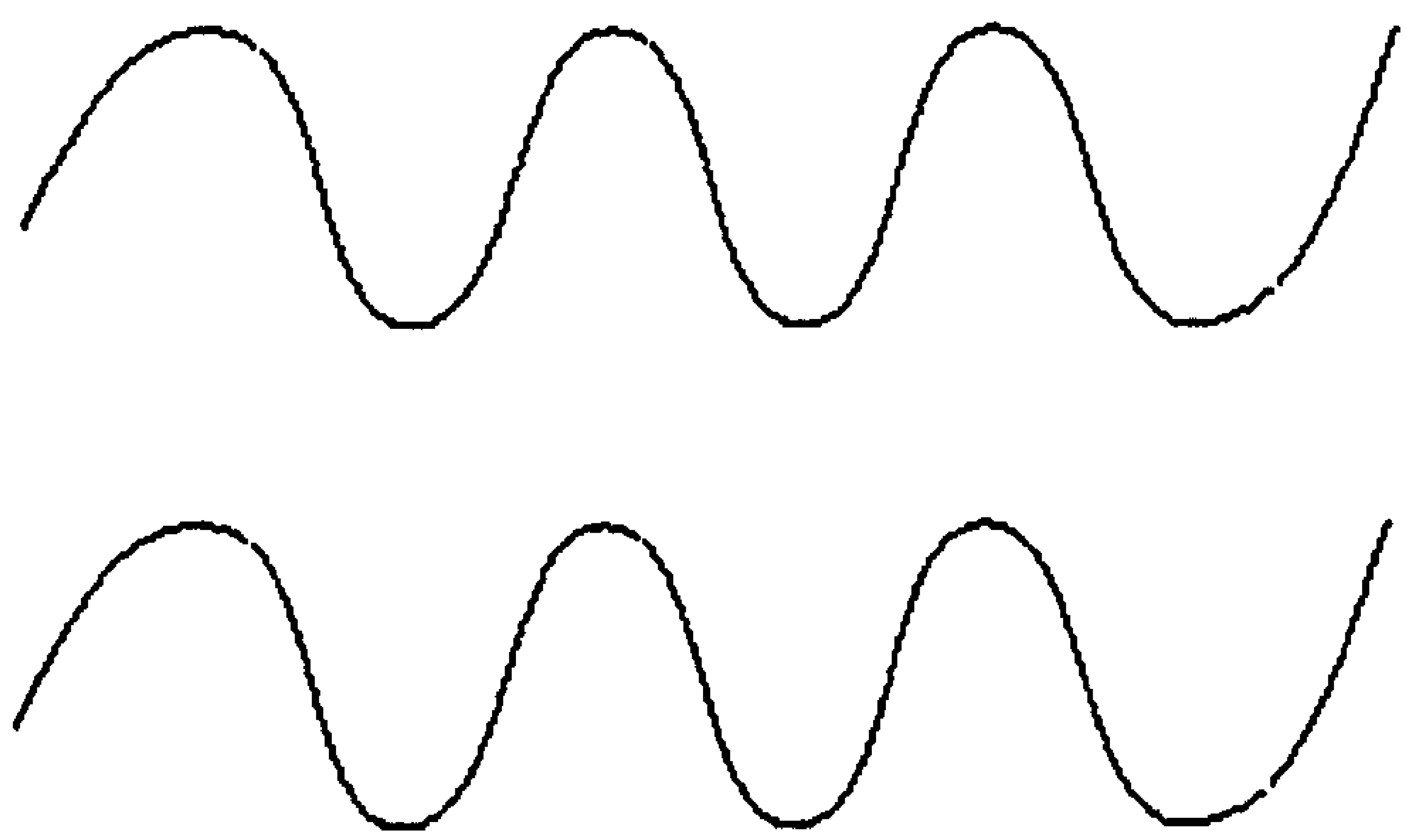
Next: Young's Double Slit Experiment **Up:** Wave Properties of Light **Previous:** Diffraction

Interference

Definitions

- Two waves (of the same wavelength) are said to be **in phase** if the crests (and troughs) of one wave coincide with the crests (and troughs) of the other, as in Fig. 22.8.

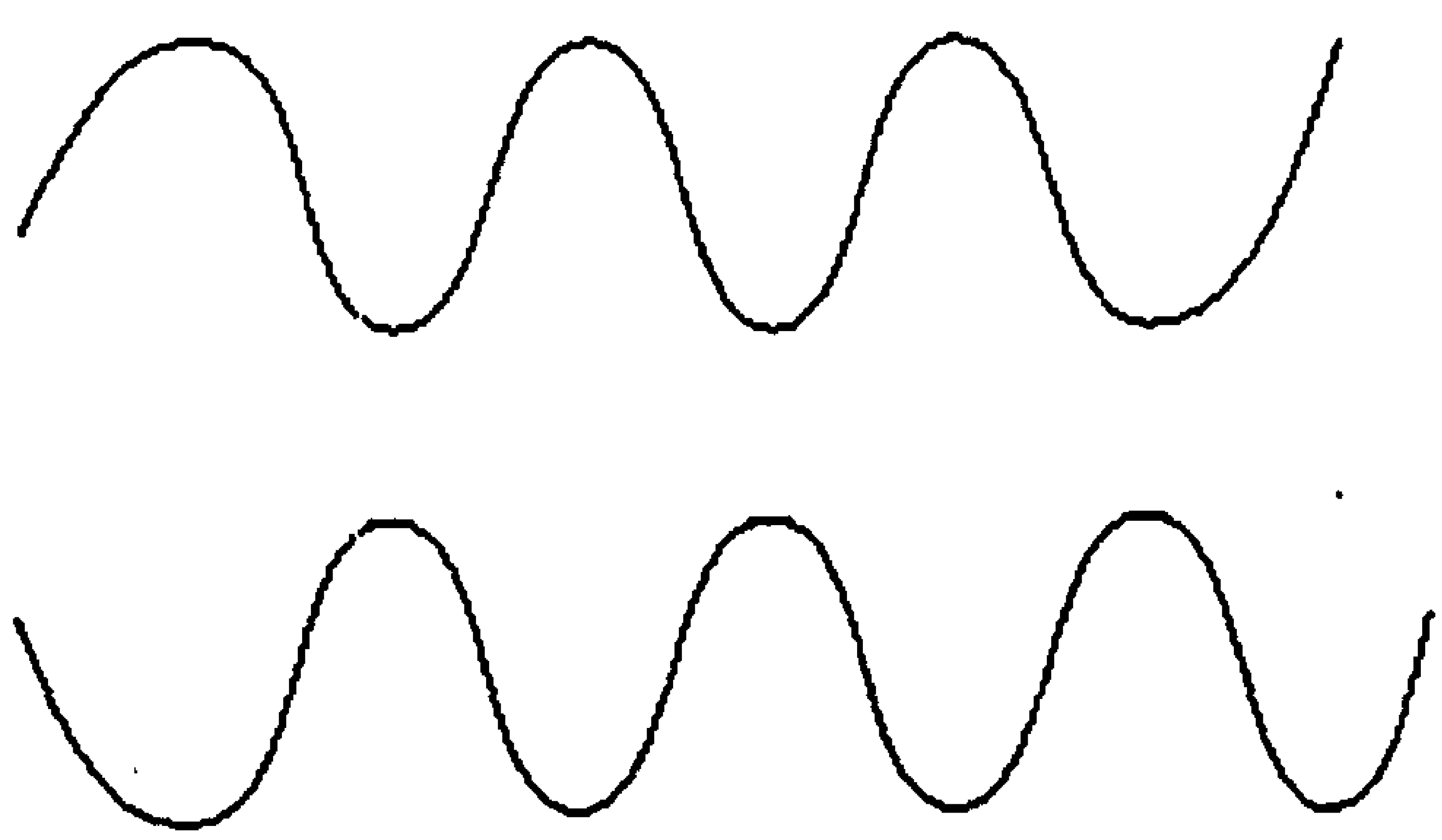
Figure 22.8: Constructive interference



In this case the resultant wave would have twice the amplitude of the individual waves - one says that **constructive interference** has occurred.

- If the crest of one wave coincides with the trough of the second, as in Fig. 22.9 they are said to be completely **out of phase**,.

Figure 22.9: Destructive interference



In this case the two waves would cancel each other out - one says that **destructive interference** has occurred. At a point of constructive interference the net amplitude of the two waves is a maximum, whereas at a point of destructive interference, the net amplitude is a minimum. Of course, one could also have situations in between these two extremes.

Idea: If two identical waves of wavelength λ start out in phase, travel at the same speed for a distance of r_1 and r_2 respectively, where $r_1 > r_2$, the crests of the one wave will be behind the crests of the other by a distance of $r_1 - r_2$. The condition for constructive interference when the waves recombine is

APPENDIX 18

$$r_1 - r_2 = m\lambda ,m = 1,2,....$$

The condition for destructive interference is

$$r_1 - r_2 = (m + \frac{1}{2})\lambda ,m = 1,2,...$$

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APPENDIX 1B 2

Physics 102 Lecture 19

Spring 1996

The lectures can be downloaded in various formats.

Return to the UIUC Physics Page, Physics 102 Page, Lecture and Assignment Schedule , or the Lecture Notes

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Lecture 19

Wave optics: Interference and Diffraction

Wave can be added together either **constructively** or **destructively**. The result of adding two waves of the same frequency depends on the value of the **phase** of the wave at the point in which the waves are added.

Electromagnetic waves are subject to interference. For two sources of electromagnetic waves to interfere

1. The sources must have the **same frequency** and **polarization.**

2. The sources must be **coherent.**

3. The **superposition principle** must apply.

Young's double slit interference

In the double slit experiment, a single source is split in two, to generate two coherent sources.

When the light from the two sources is projected on a screen, an interference pattern is observed.

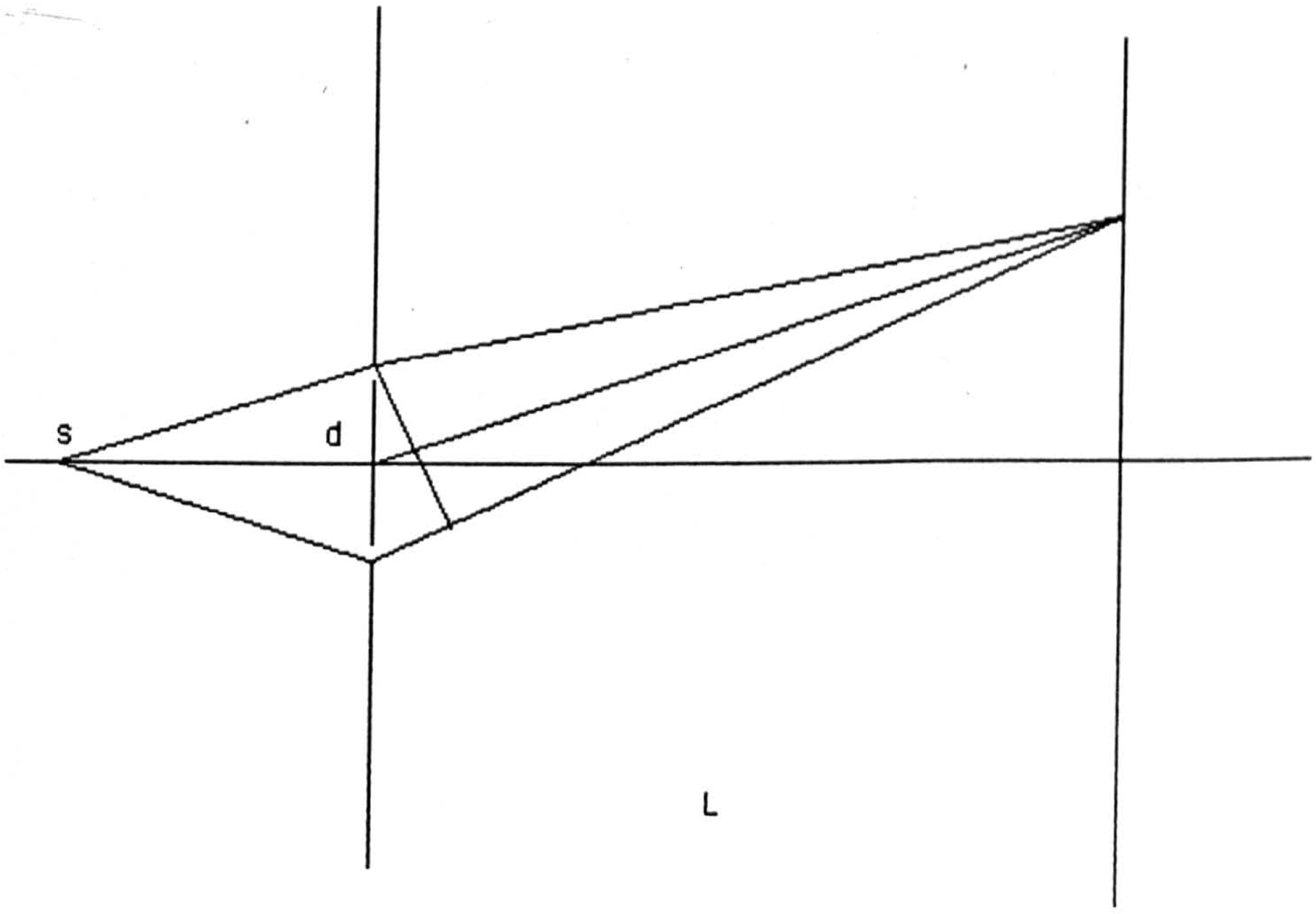
To explain the origin of the interference pattern, consider the distance traveled from the two sources. At the center of the screen the waves from the two sources are **in phase.** As we move away from the center, the path traveled by the light from one source is larger than that traveled by the light from the other source. When the difference in path is equal to **half a wavelength, destructive** interference occurs. Instead, when the difference in pathlength is equal to a **wavelength, constructive** interference occurs.

The condition for constructive interference is

d=d sin [[theta]]=m [[lambda]] with m=0, +/-1, +/-2

d is the distance between the two slits.

APPENDIX 1B 3



The condition for destructive interference is

d=d sin [[theta]]=m(1+1/2) [[lambda]] with m=0, +/-1, +/-2,

Bright lines appears at

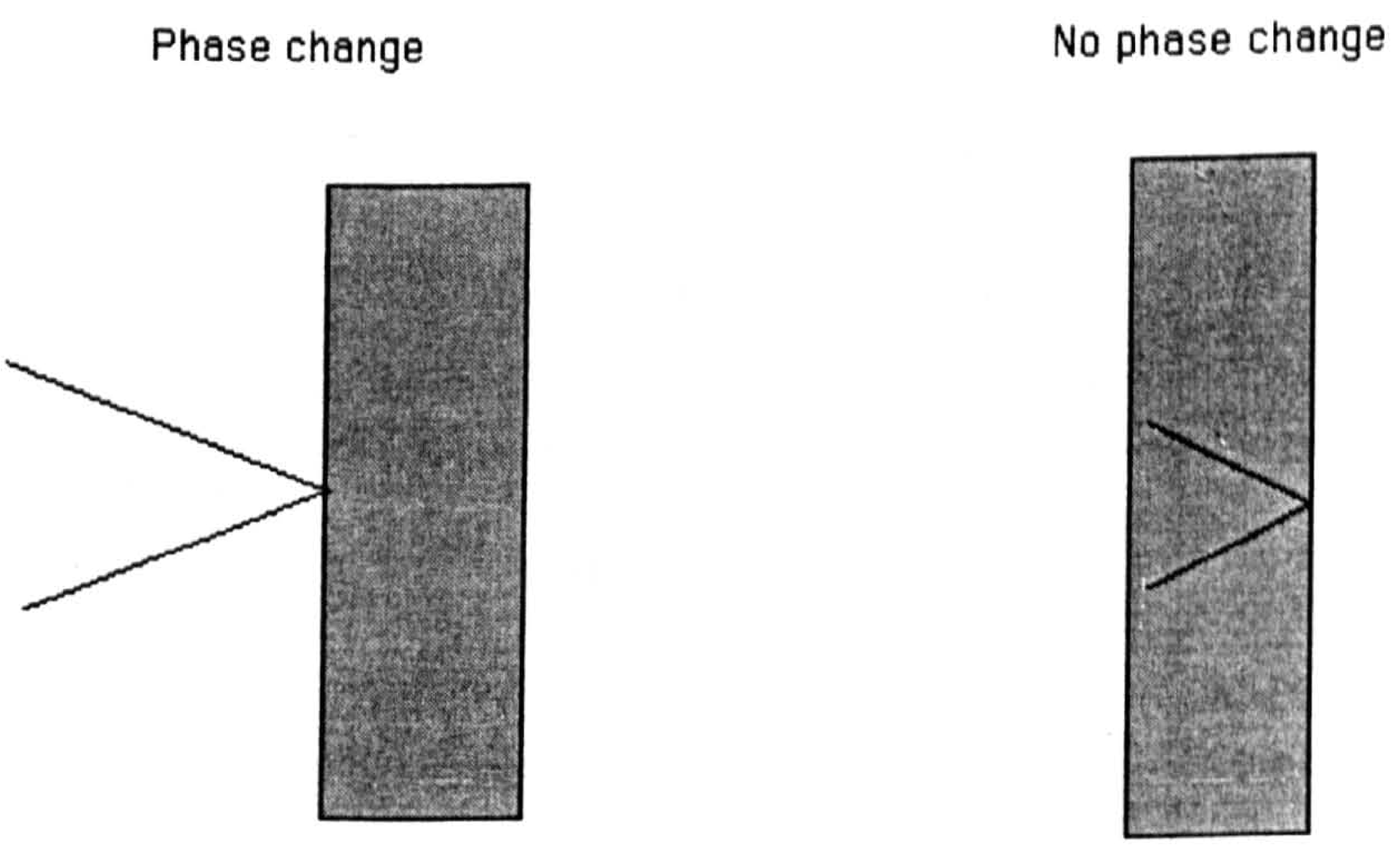
ybright=m[[lambda]]L/d

Dark lines appears at

ydark=(m+1/2) [[lambda]]L/d

Change of phase due to reflection

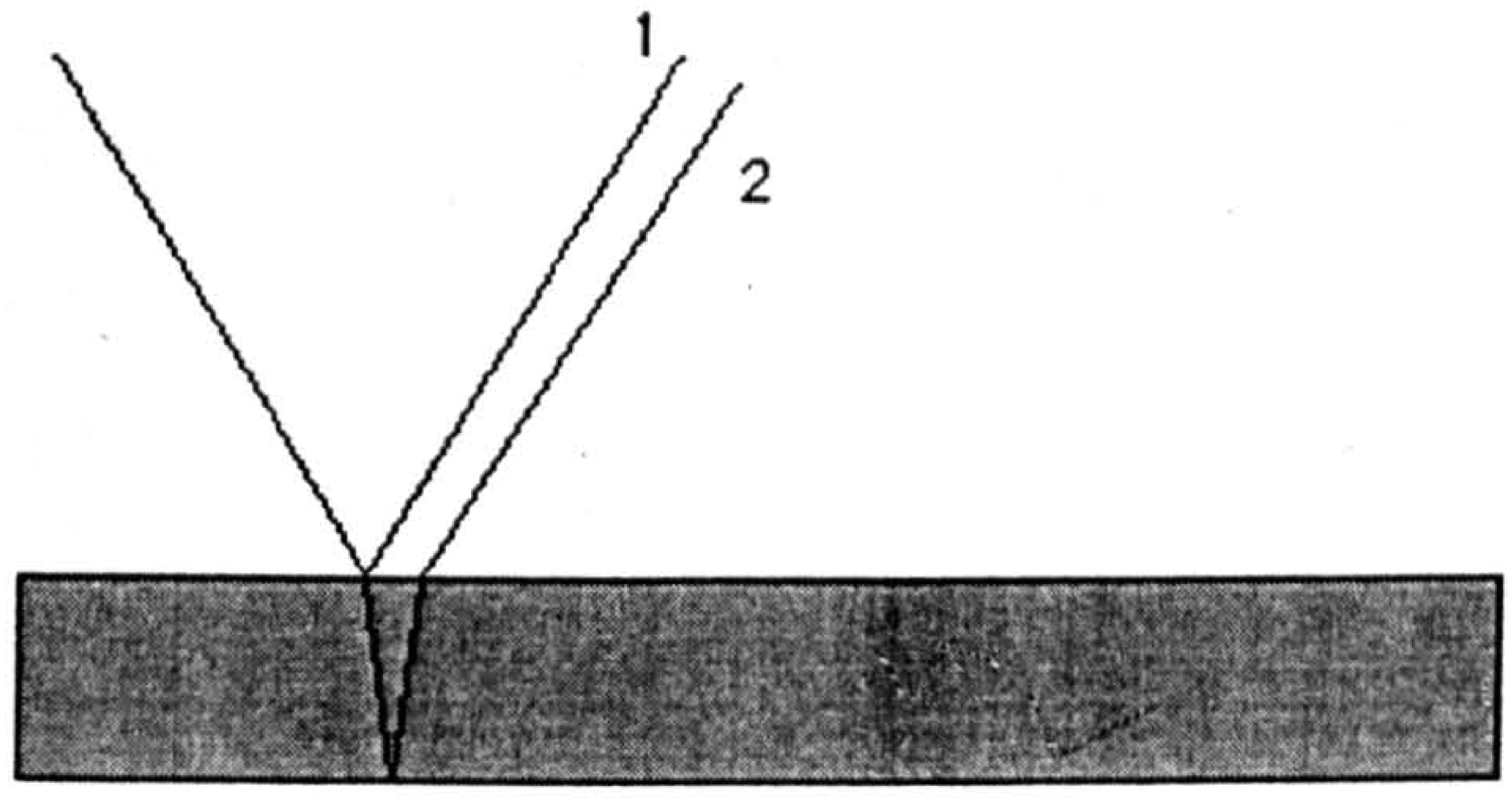
An electromagnetic wave **undergoes a change of 180deg.** upon reflection from a medium of higher index of refraction than the one in which it was traveling



Interference in thin films

APPENDIX 16 4

Consider the reflected and refracted rays at the surfaces of a thin film



Ray 1 undergoes a 180 phase shift upon reflection (if n of the film is larger than in the air)

Ray 2, does not undergo a change in phase, but it travels a longer distance 2t. The wavelength of light in the medium is [[lambda]]/n=[[lambda]]n.

If

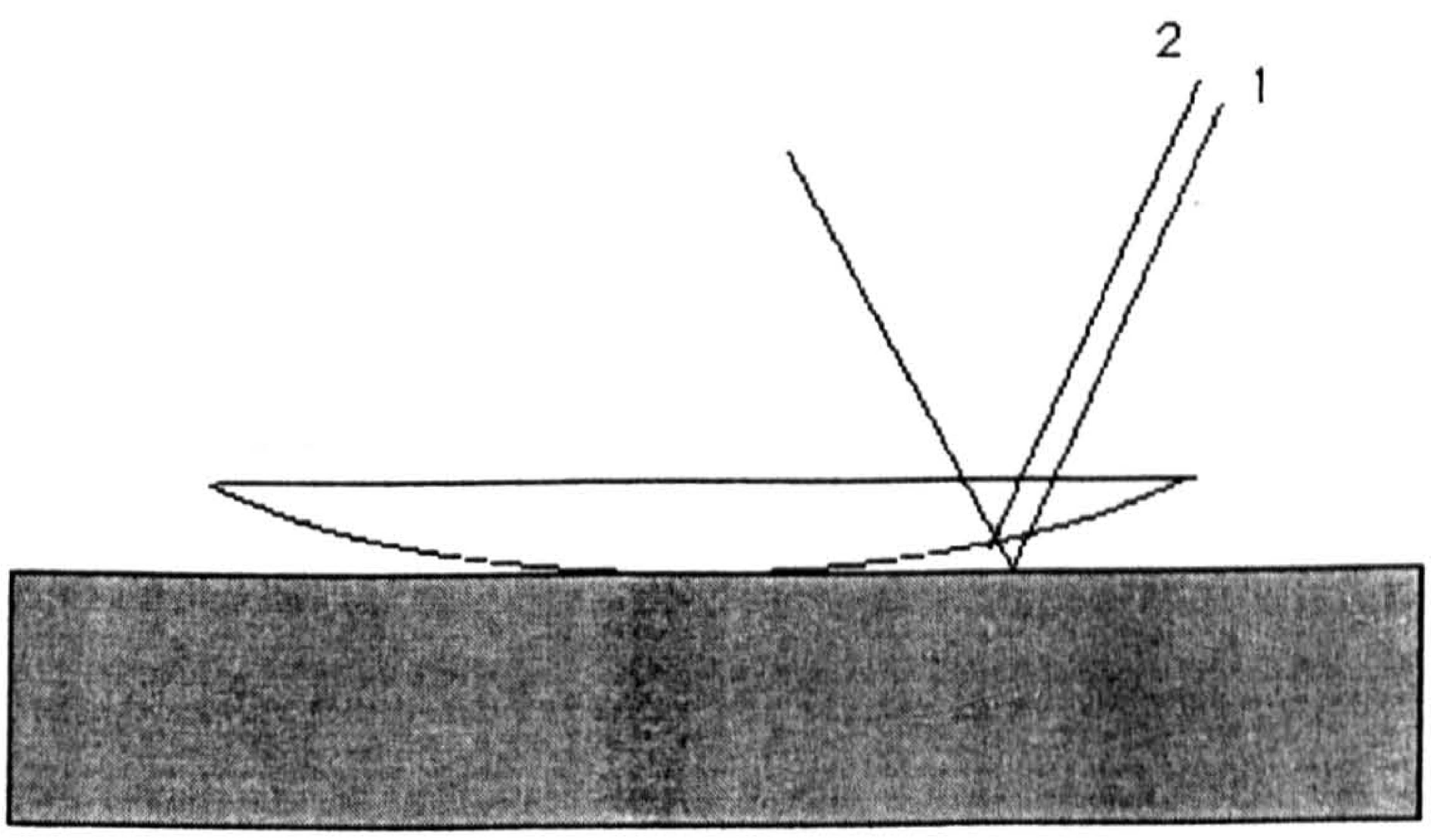
2t=(m+1/2)[[lambda]]n

then constructive interference occurs. Instead when

2t=m[[lambda]]n

destructive interference occurs.

Newton's ring



Ray 1 undergoes a phase shift of 180

Ray 2 undergoes no phase change.

The condition for interference is the same as that for the thin film. The center is **dark**, because of destructive interference.

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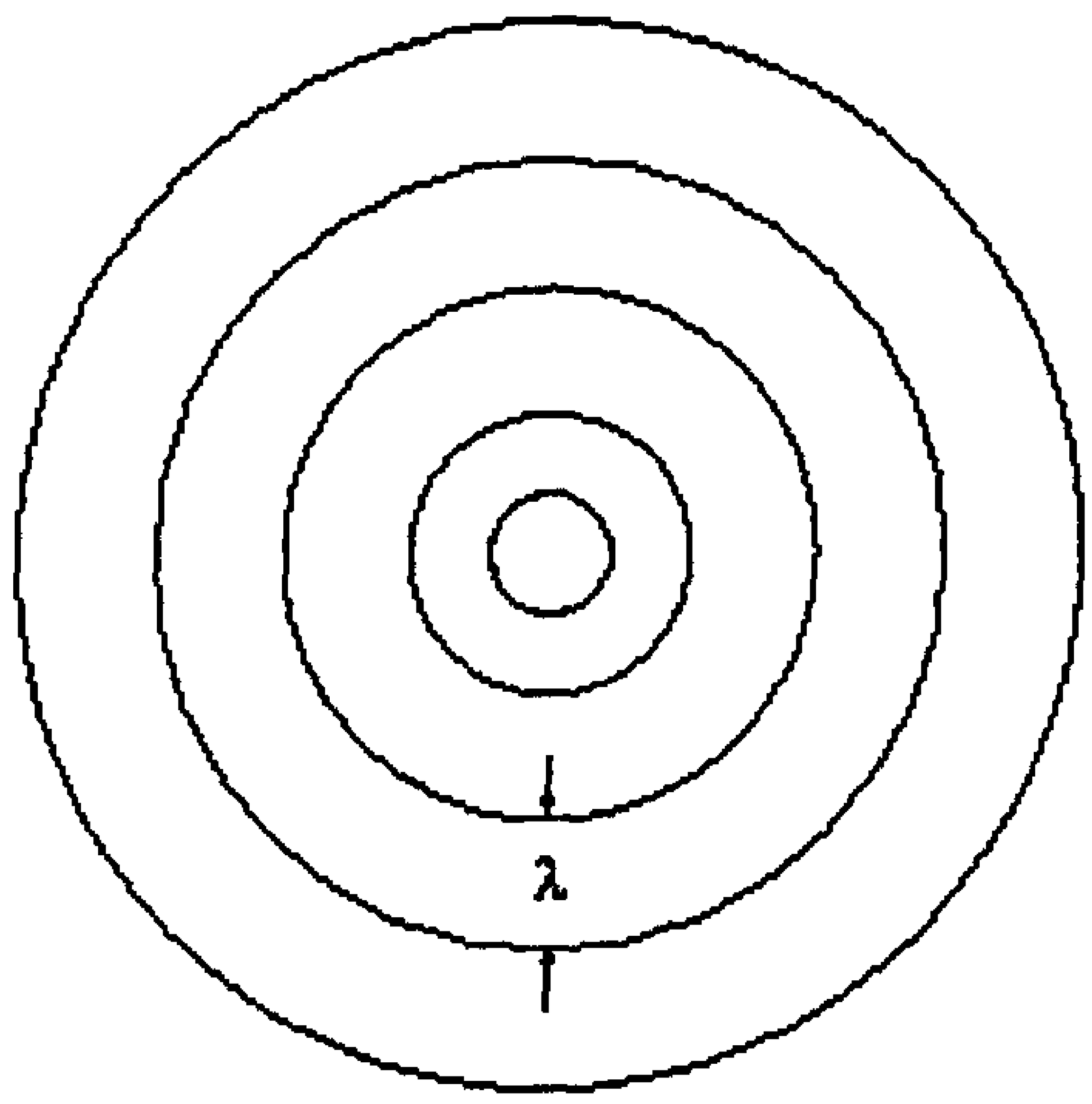
Next Up Previous Index
Next: Reflection **Up:** Wave Properties of Light **Previous:** General Properties of Light

General Properties of Waves

We first introduce some terminology associated with waves. Let us imagine that we drop a rock in the middle of a still pond and watch the waves emanating out from the center. From above the wave crests might appear as in Fig. 22.2.

Figure 22.2: Wave crests as seen from above



We assume the wave pattern is regular, and consider the following characteristics of these waves.

Definitions

- The **wavelength** (λ) is the distance between neighbouring crests or troughs.
- The **speed** (v) is the rate at which the crests (or troughs) move forward.
- The **Period** (T) is the time that elapses between passing crests (or troughs). The period can be expressed in terms of the speed and wavelength:

$$T = \frac{\lambda}{v}.$$

- The **frequency** (f) is the number of crests (or troughs) that pass by per unit time. It is equal to the inverse of the period:

$$f = \frac{1}{T} .$$

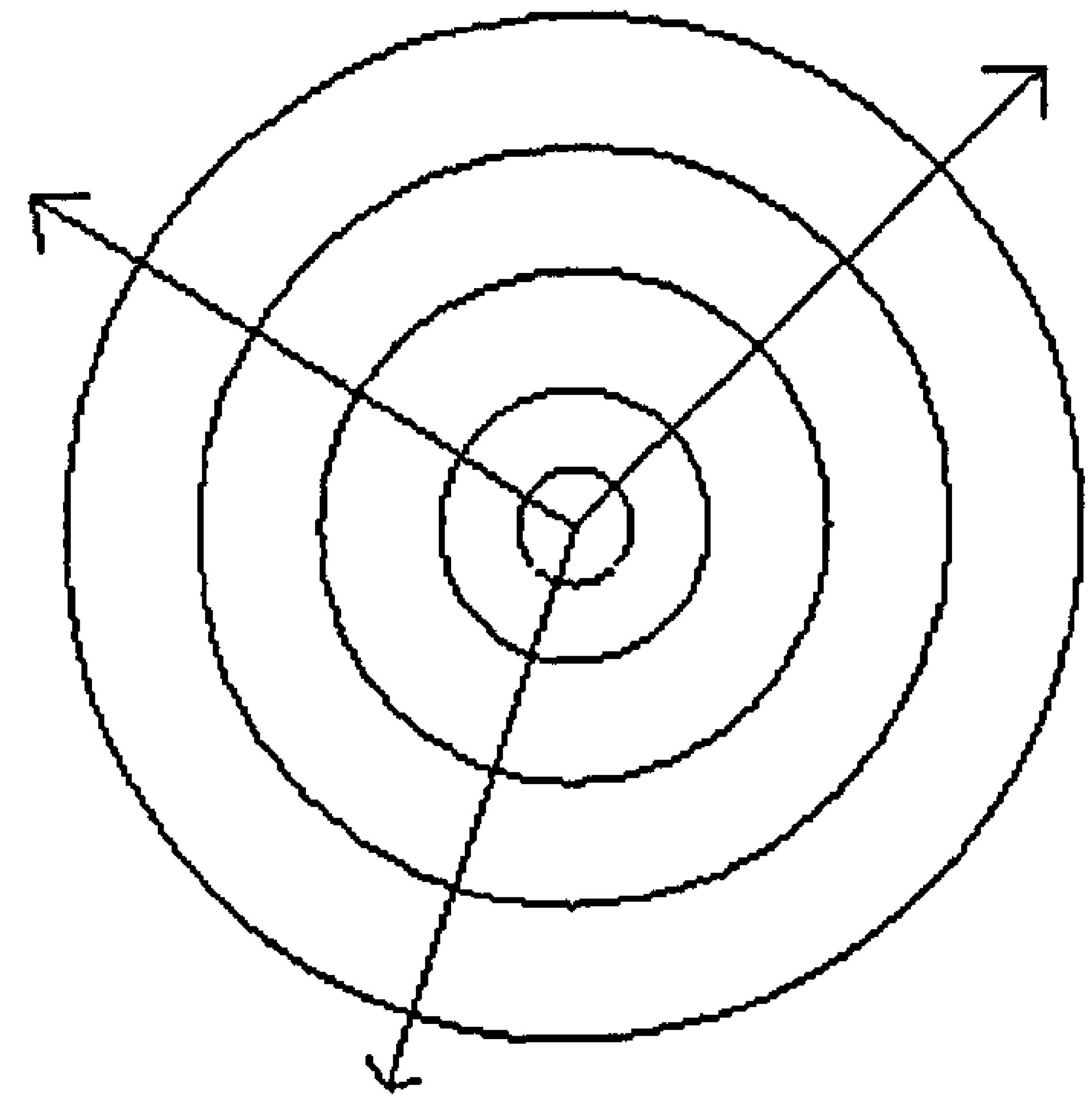
Using the expression for T above we get the useful expression:

$$v = f\lambda.$$

APPENDIX 1B 6

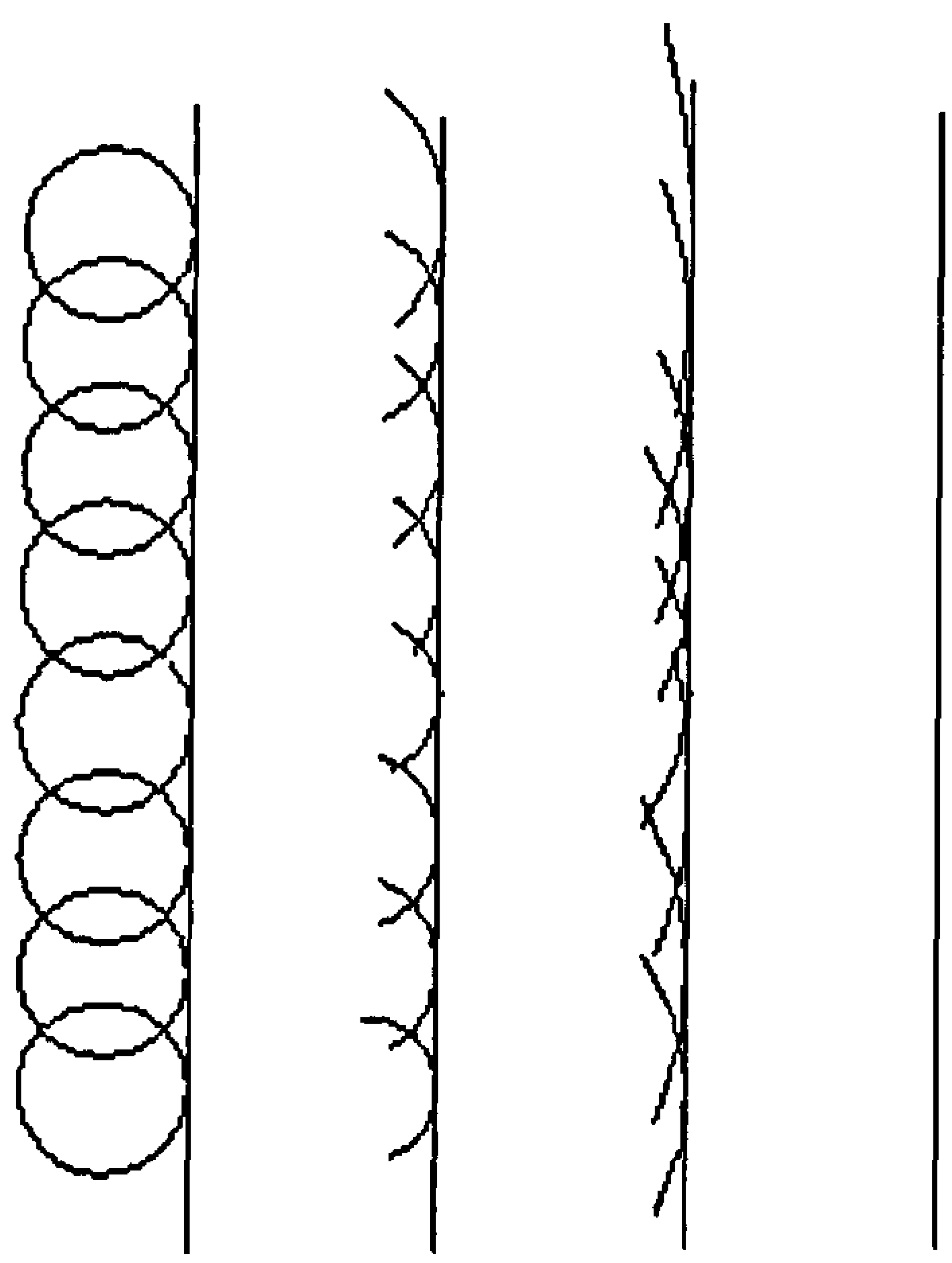
- A **ray** is a line drawn from one wave crest to another which intersects each crest at right angles, as in Fig. 22.3. For light waves, the rays always point in the direction of the motion. Rays therefore provide a useful representation for describing the motion of light waves.

Figure 22.3: Relationship of rays to wave crests



Note: Wave crests coming from a point source (eg. if you drop a rock in the middle of a still pond) give rise to circular waves as shown in Fig. (22.2). If one has very many point sources close together and in a straight line, they give rise to **plane waves**, whose crests all lie in a straight line. (See Fig. (22.4))

Figure 22.4: Plane waves formed by many point sources



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APPENDIX 1B 7

Why do beautiful bands of color appear in the tiny oil slicks that form atop puddles on a rainy day? More specifically, why does each band have a different color, and why do the various bands remain distinct?

Jorge Numata
Monterrey, Mexico

The following answer comes from Dinesh O. Shah; he is Charles A. Stokes Professor of Chemical Engineering and Anesthesiology at the University of Florida at Gainesville:

"When you see an oil film on the road on a rainy day, it gives rise to bands of beautiful colors for the following reason:

"Small amounts of oil are usually present on the road surface (for instance, lubricating oil from cars, trucks and bicycles). When it rains, drops of oil float on the layer of water that collects on the road because the density of oil is less than that of the water--the same reason that wood floats on water. Commercial oil formulations usually contain a surfactant, an additive that causes the oil drops to spread out into a thin film atop the water. That film is thickest in the center of the patch, or oil slick, and thinnest at the periphery.

"Light reflects upward both from the top of the oil film and from the underlying interface between the oil and the water; the path length (the distance from the reflection to your eye) is slightly different depending on whether the returned light comes from the top or from the bottom of the oil film. If the difference in path length is an integral multiple of the wavelength of the light, rays reflected from the two locations will reinforce each other, a process called constructive interference. If, however, the rays reach your eye out of step, they will cancel each other out due to destructive interference.

"Sunlight contains all the colors of the rainbow--the famous ROYGBIV (red, orange, yellow, green, blue, indigo, violet). Each color of light has a different wavelength. Hence, a given disparity in the path length will cause constructive interference of certain colors, whereas other colors will not be observed because of destructive interference. Because the oil film gradually thins from its center to its periphery, different bands of the oil slick produce different colors."

More Physics Questions

Back to Ask the Experts

APPENDIX 1B.

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APPENDIX 2

DICHROIC GLASS

A REPORT ON THE FINDINGS OF A VISIT TO THE UNITED STATES OF AMERICA
AUGUST 1993.

LAURA JOHNSTON - RESEARCHER, ARCHITECTURAL GLASS
UNIVERSITY OF SUNDERLAND.

SPONSORED BY NORTHERN ARTS.

INTRODUCTION.

My interest in dichroic glass began after reading of the work of Jamie Carpenter in the June/July 1991 edition of *American Craft* magazine. This artist worked with Corning and developed colour coatings for glass which he has since incorporated into major architectural commissions including the 'Spectral Light Dome' in the Portland Center for the Performing Arts, Oregon, USA.

Later I read of small companies in the USA producing dichroic glass for the art/craft market. My own research is involved in developing the potential of this technique as an architectural medium and my own experimentation has resulted in the production of multicoloured coatings on glass. I decided a trip to the USA would be useful in establishing the scale of interest in this technique and the directions currently being taken in this area. I was also interested in discovering the methods of coating used and to have the opportunity to discuss my work with experts in this area.

Companies producing the glass include Thin Film Technology, Inc; Thin Layer Coating, Inc; and Allen H.Graef - Dichroic Glass. The second of these companies works alongside Bullseye Glass Co. and produces coatings on their range of compatible glass for kiln work.

THE GLASS.

Dichroic (two-colour) glass has the unique quality of shifting from one colour to another, depending upon the angle from which it is viewed. In transmitted light the glass has a primary colour when viewed from straight on, and a secondary colour when viewed from an angle of around 45 degrees. In reflected light, the glass then becomes a third colour. For example, a glass may appear blue in transmitted light, purple when viewed from an angle and yellow-green in reflection. The colour is created by the deposition of thin films of 'dielectric' materials such as magnesium, titanium and silicon. Each layer of material interacts with one another, allowing the transmission of certain wavelengths of light and the reflection of others. By calculating the refractive indices of the materials used and their interrelationship, any colour on the visible spectrum can be created.

THE PROCESS.

Each company produces coatings by means of vacuum evaporation. The vacuum is necessary to allow for the free flow of particles from the source to the glass. Without a vacuum, particles would collide with other elements within the environment and coating quality would be poor. This method is used in industry as a means of depositing coatings on a wide variety of products. The purpose of the coatings vary and include those for optical use, wear-resistance on machine parts, and along with dialectric materials, those with conductive and resistive properties are also deposited. The vacuum depositing machine is made up of a chamber, which looks rather like a domestic water tank, backed up by electrical monitering equipment and mechanical pumps to remove air. The chamber size is variable. The ones used by companies in the USA ranged from around 18" in diameter to 8' diameter x 14' deep.

Glass is clipped into a frame within the coating chamber, which rotates during the process of coating deposition. Each sheet rotates individually whilst also travelling around the chamber, as Allen H. Graef described, the movement is like that of planetary rotation. The movement of the glass is integral to the production of an even coating. In the bottom part of the chamber a crucible is placed, containing the material to be evaporated. The chamber is then closed and the process of achieving a high vacuum environment begins.

Air is removed from the chamber with the use of a mechanical pump, producing a low vacuum. This is followed by the removal of any remaining gases using a cyropump which results in the production of a high vacuum. In order for the material to adhere to the glass surface, the substrate must then be heated to 300 degrees celsius. Having achieved this, the coating process begins.

Evaporation of the material is achieved by shooting it with an electron beam. This is electronically controlled and monitered so that enough material is evaported to produce a coating of the desired thickness. Thin films are approximately 700 angstroms in thickness, which is around ten billionths of a metre. The precision required in multilayer coating is at the upper end of the capability of the machines used and, consequently, must be constantly monitered and interpreted by the operator. Pressure, time and temperature are critical. The rate of evaporation is also important as a too rapid evaporation can effect the shape of crystals forming on the glass surface.

To produce the colour intensity desired, around twenty to twenty-five coatings are applied. When complete, air is admitted into the chamber and the glass is allowed to cool before the chamber is opened and unloaded.

The whole process can take between three to four hours. The size of sheet glass coated is limited, as a larger area results in less control over uniformity. One company told me that the maximum size of glass successfully coated using this method is 24 x 24 inches. To produce an even coating on an area any larger than this would demand multiple sources from which the material is evaporated. Another disputed this, stating that problems of uniformity are encountered on anything larger than 12 x 12 inches. The size of sheets generally produced for retail are between 12 and 16 inches in diameter and three to four sheets are coated at one time.

The methods used by the companies have been refined over the years. Gary StAmour, of Thin Film Technology Inc. told me that control of coating evenness was the major obstacle to overcome. Material evaporated from a static source travels in paths which fan out in three dimensions from it's source. Dennis Schmitz, President of Thin Layer Coating Inc, described this pattern of evaporation as the 'Neutzin Sphere'. This results in differences in coating thickness, as the distance the material travels to a static substrate is variable. Early samples produced showed a spectrum of colour across the surface of the glass. Each colour band represented a difference in coating thickness. This was analysed and documented and with the development of a rotating system, evenness was achieved along with the control of thickness and colour.

THE PRODUCT.

Each company produces a range of colour coatings including blue, magenta, cyan, green and yellow (TFT). The coatings can be applied to glass of any texture and colour, though this effects the way the coating operates. For example, coating onto black glass results in the loss of transmitted colour, with reflected colour only being visible. On deeply textured glass, the coatings are effected by the modulating surface, so that the reflected colour can be visible in transmitted light, along with the primary and secondary colours.
Sheets of dichroic glass, 16" x 16" in size, sell at wholesale for between 90 and 135 dollars. Smaller pieces, measuring 4" x 4" are sold by Bullseye for around 10 dollars and 'stringers' (thin rods of coated glass, approx.1/16" thick x 4" long) are sold in packs of nine for 5 dollars.

THE MARKET.

Dichroic glass is growing in popularity in the USA. Due to the high cost of the material, it is currently most popular for use in jewellery and bead making. The glass is bought direct from the coating companies and from Bullseye Glass Co. who sell their own glass, coated by Thin Layer Coating Inc. The range of compatible glasses produced by Bullseye has led to a developing interest amongst those working in the area of kiln-forming. Architectural use of the glass produced by these companies is limited at present, with some artists incorporating dichroic elements into leaded panels. Thin Film Technology Inc. were approached by an architect who had the idea of colour coating Pitzburg Corning's Glass Block Products. These blocks have been used for many years in buildings, forming walls and screens and are available with both smooth and a variety of textured surfaces. Thin Film Technology Inc. now coat these blocks with the range of colours available from them. In doing so, they found that the colour is enhanced by painting the sides of the blocks black. This product is now marketed by Spectrum Block Products Inc, Irvine, California.

THE COMPANIES.

Thin Film Technology Inc, Buellton, California. This company offers a complete vacuum coating and substrate patterning service. Although they produce dichroic glass, this forms only a small part of their business.

Allen H. Graef - Dichroic Glass, Long Beach, California. Supplies dichroic glass to the art glass industry.

Thin Layer Coating Inc, Clackamas, Oregon. Operates a range of coating services for industry along with producing dichroic coatings for glass. Bullseye Glass Co. work with TLC to produce dichroic coatings on their range of Tested Compatible glasses for kiln working.

The Dichroic Fusing Source, Oregon City, Oregon. This is a subsidiary service offered by TLC Inc, and deals with the needs of the individual craftsperson, supplying dichroic glass for fusing along with small kilns and tools, etc.

Ultra Vitrum Studio, Clackamas, Oregon. This is a glass studio operated by TLC Inc. Facilities are available for both kiln forming and blowing and artists working at the studio experiment with the glass coated by TLC. This provides a link between the manufacturer and user of the product and enables learning on both sides.

Bullseye Glass Company, Portland, Oregon. Founded in 1974 by three glass blowers, Daniel Schwoerer, Boyce Lundstrom and Ray Ahlgren, this company aims to supply the traditional glass market whilst also exploring new methods of glass working. Early research took place at the Bullseye Fusing Ranch, from which the range of Tested Compatible Glasses for kiln working was developed. This was the first company in the world who aimed to cater specifically to the needs of the kiln worker. Information gained from this research was compiled by Schwoerer and Lundstrom and published as a sourcebook of theory and technique entitled *Glass Fusing Book One*. This company continues to grow, having tripled in size over the past five years. Despite its forward looking approach, the glass produced at Bullseye continues to be 'hand crafted'. Nearly 1000 sheets of glass a day are produced using a single roll process and each sheet is inspected individually five times before packaging. Compatibility is tested by analysing stress in the sheets produced.

The company is currently focusing on kilnworking and aims to raise the standard of work produced in this area. Lani McGregor, Bullseye's sales manager, states that blown glass is currently seen to be superior to kilnworked pieces. Bullseye aims to change this by producing compatible glass, encouraging experimentation and organising exhibitions in this area which promote standards of excellence..

Bullseye have recently opened a research studio, to encourage experimentation. There is a full time research worker and artists are encouraged to come and explore new possibilities. When I visited the company I was told that Narcissus Quagliati is currently working with the research department attempting to produce glass panels incorporating imagery, using hot sheets of glass laid over an arrangement of glass shapes. Some technical problems were being experienced in the annealing of these pieces. Although this artist was not incorporating dichroics into his work, I was shown examples of kilnformed and blown work which included dichroic glass.The work in the research area was aiming towards inclusion in a forthcoming kilnwork exhibition at Bullseye in September 1993.

ARTISTS.

Jewellery Makers.

There is a renewed interest in bead making in the USA, inspired by the work of Phonecian bead makers. This is one of the oldest glass art forms. At Thin Layer Coating, Inc. I was shown torch worked pieces by Pat Franz who, I was told, is the best bead maker in the world. One piece which stands out in my mind was a bead less than an inch in size, which incorporated intricate marine imagery including fish and plant life.

Dichroic bead sticks are produced by Thin Layer Coating Inc, and are becoming popular for use by jewellery makers. The sticks can be heated with a torch and wrapped around glass beads to produce bands of vibrant colour.

Yvonne Buijs, an Artist working in Washington, uses dichroics as an integral element in her work. She fuses the glass into blocks which are then cut and polished to produce gem-like qualities.

Jonathan Hamilton, who works in Oregon, uses dichroic glass to produce jewellery using imagery inspired by the colours and qualities observed from studying insects. When fusing dichroic glass, a crackle effect is achieved which, in Hamiltons work, is used to suggest the cellular structure of insect wings.

Hotworking.

Zoe Adorno of San Jose, produces sculptural pieces by first fusing and slumping the glass, incorporating imagery at this stage, then, whilst the glass is hot, removes the piece from the kiln and hand forms the glass, whilst wearing protective asbestos clothing!

Virginia Gabaldo, produces large fused assemblages of dichroic and irridised glass. She has a painterly approach to her work,

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celebrating richness of colour, form and texture. The surface of the pieces are worked on, often by airbrushing Tracing Black to produce shaded areas. By using black glass with a dichroic coating, black outlines can be achieved, as, at full fuse temperature, the black glass spreads beyond the limits of the coating. Gabaldo has also found that using coated clear and opal glasses for fusing, makes the inevitable crackle effect less visible.

James Novak produces work which is made up of blown forms which are later coated and assembled using UV glue. In this way, he is able to retain the qualities of dichroic coatings which are altered during firing.

Architectural Glass.

Peter McGrain produces leaded panels which incorporate large amounts of dichroic glass. In his work he produces imagery approaching the dichroic surface in a similar way as one would work with flashed glass. Areas are masked and sandblasted or acid etched, producing gradation of tone. By plating sheets of coated glass, complicated imagery can by built up, with great depth of tone and variety of colour.

David Wilson, in his installation at the National Conference of Bishops Chapel, Washington, DC, uses sheets of dichroic glass along with bevelled pieces. This abstract design contrasts strongly with the McGrain's figurative approach. Wilson presents the dichroic glass as areas of colour, without working into the surface. In this way, the qualities of the glass, with it's shifting colour, are exploited. At night, in reflected light, the dichroic glass changes again, the third colour becoming visible.

James Carpenter has used dichroic glass in his architectural works and presents a third approach to the use of this material. His installations do not involve the use of lead work as a means of connecting the glass pieces together, rather, his three dimensional works are assembled using structural silicone or by attaching the glass to steel frameworks. His 'Spectral Light Dome' at the Portland Center for the Performing Arts demonstrates the latter method. This installation, made up of 500 strips of dichroic glass, is located above the rotunda area of the New Theatre Building. Metal clips suspend the pieces from a dome-shaped grid. The work is based on the idea of a time lapse photograph of the universe and the concept for the work is derived from the Greek tradition, in which the dome of the sky forms the roof of the outdoor theatre. The strips of glass are 5 and 3.5 feet in length. Carpenter's work with dichroics began in 1977 whilst he was a resident artist at Corning Glass Works and in the completion of his commissions, he works with a manufacturer who does not produce dichroic coatings for retail sale. By adapting the process used commercially to produce standard anti-reflective coatings, sheets of dichroic glass measuring three metres by three metres are made. This process involves deposition of coatings by means of electron sputtering, rather than the process of vacuum evaporation, employed by commercial producers of the glass.

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CONCLUSIONS DRAWN FROM VISIT.

The trip was extremely useful in establishing the scale of interest in dichroic glass which, it seems, is steadily growing in the USA. In the completion of the Mphil stage of my study, it is necessary to establish the extent of research completed to date in this area. I feel the trip was sucessful in achieving this aim.

Technical Information.

The companies visited, although open to an extent in their answers to questions, were guarded when it came to details of materials and quantities used to produce the coatings. Each company had individually researched the area to get to their current stage of production. There was no sharing of information during this time and there were differences in opinion as to who was first to produce the glass, who is the main producer, etc. Some resentment was voiced of other companies 'jumping on the band wagon'! The impression I got was that this is a very competitive market and that each company is trying to establish control.

From the information I received, certain questions were answered which will be invaluable in the development of my research. These include: the importance of sample rotation; the heating of the substrate to enable coating adhesion; and the identification of some materials used. By visiting coating laboratories, I was able to examine the machinery used and assess the importance of sophisticated monitering equipment.

The results of the research by these companies can be summarised as follows :

1. The production of a range of single colour sheets of glass for retail sale, limited in size to 16" x 16".

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2. Application of designs - Thin Film Technology have developed a process which allows patterning with multiple dichroic colours, using metal stencils as masks between coatings.

Current Artistic Application.

Having discussed the use of the glass with both the manufacturers and Bullseye Glass Co., I was able to learn how this product is being used and the kind of experimentation being carried out by individual artists.
This can be summarised as follows:

1. Fusing - Bullseye have recorded the effect of fusing on the coatings applied to their range of Tested Compatible glasses. Changes in colour have been observed along with a 'crackle' effect which has been exploited in the work of artists.

2. Surface treatment - Peter McGrain has examined the potential of creating imagery by etching, sandblasting and plating.

3. Coating 3 Dimensional pieces - artists wanting to retain the un-fired qualities of the coatings have explored this method.

4. Coating using electrode sputtering - James Carpenter has developed this process working with a manufacturer which results in the production of glass 3m x 3m. This is not commercially available.

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It is clear that the area of dichroics has attracted alot of interest in the USA and a considerable amount of work has been done by companies to produce a marketable product. Experimentation by artists in this area is growing with the availability of the material and the awareness of its particular qualities.

The potential for extended use of this material remains great. In terms of its architectural use, the development of sophisticated masking techniques to allow for image production, united with development of the process for large scale application, could lead to exciting design possibilities.

Problems to Overcome.

In order for my research to achieve its current goals, it is important for me, firstly, to overcome problems of achieving single colour production and, secondly, to achieve large scale coating application.

Experimentation to date has resulted in the production of multi-coloured coatings on glass. To enable control of colour, evenness of thickness must be achieved. This will involve devising a method of rotating the samples during coating. To increase the durability of the coatings, it will be necessary to heat the samples during the process. I am currently investigating the possibility of achieving this, using the available machinery at the University of Sunderland. Equipment here, however, is not as sophisticated as that used in the USA and it may be that this will inhibit the success of the coating application. Should this be the case, it may be necessary to look outside of the University for access to appropriate equipment.

Once control of colour is achieved, development of masking techniques can then be explored and the full potential of this process for architectural use can be examined. Ultimately, application of these findings must be achieved on a scale suitable for architectural use. It is likely that co-operation from industry

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will be necessary at this stage. The feasibility of this will be discussed with Pilkington plc who have agreed to co-operate with the University in the completion of the research.

If it is found that achieving control of colour is not possible using the resources available to me, the programme of research and current goals set will have to be reassessed. It may be possible to continue, working on a small scale, with commercially produced dichroics. Exploration of their architectural potential could be explored using models. Surface treatment of this glass could take place by means of further coating application, etching and sandblasting which would allow some exploration of the application of designs and imagery on to the glass. Research of this nature would put forward a body of information demonstrating the architectural potential of the glass, which could be achieved with access to appropriate equipment and facilities.

The direction the research will take, then, is dependant on the success of achieving colour control using available machinery. I envisage that it will be possible to assess this before commencing the second year of MPhil study.

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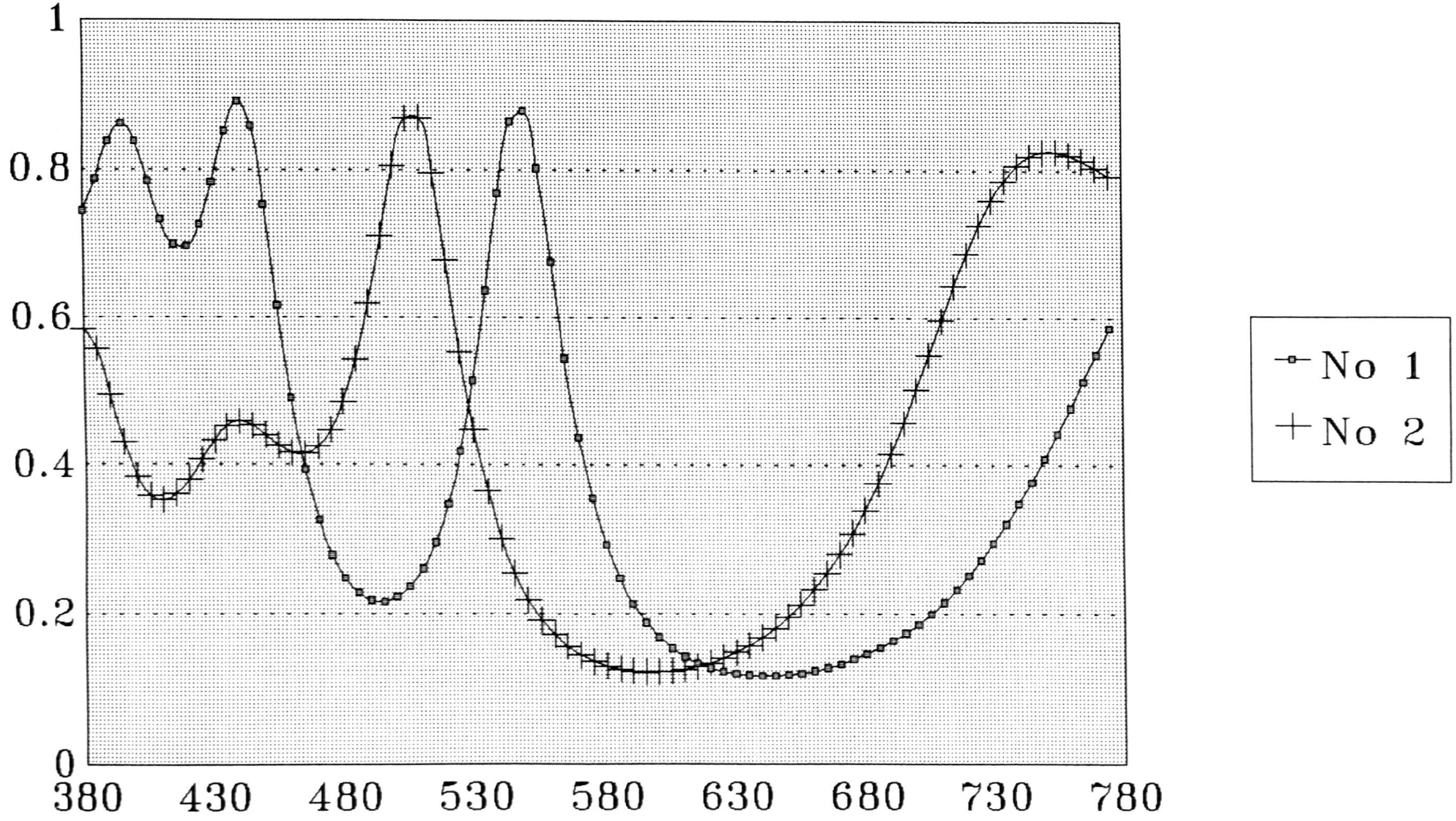
Transmission of dichroic filters

Pilkington Research Lathom



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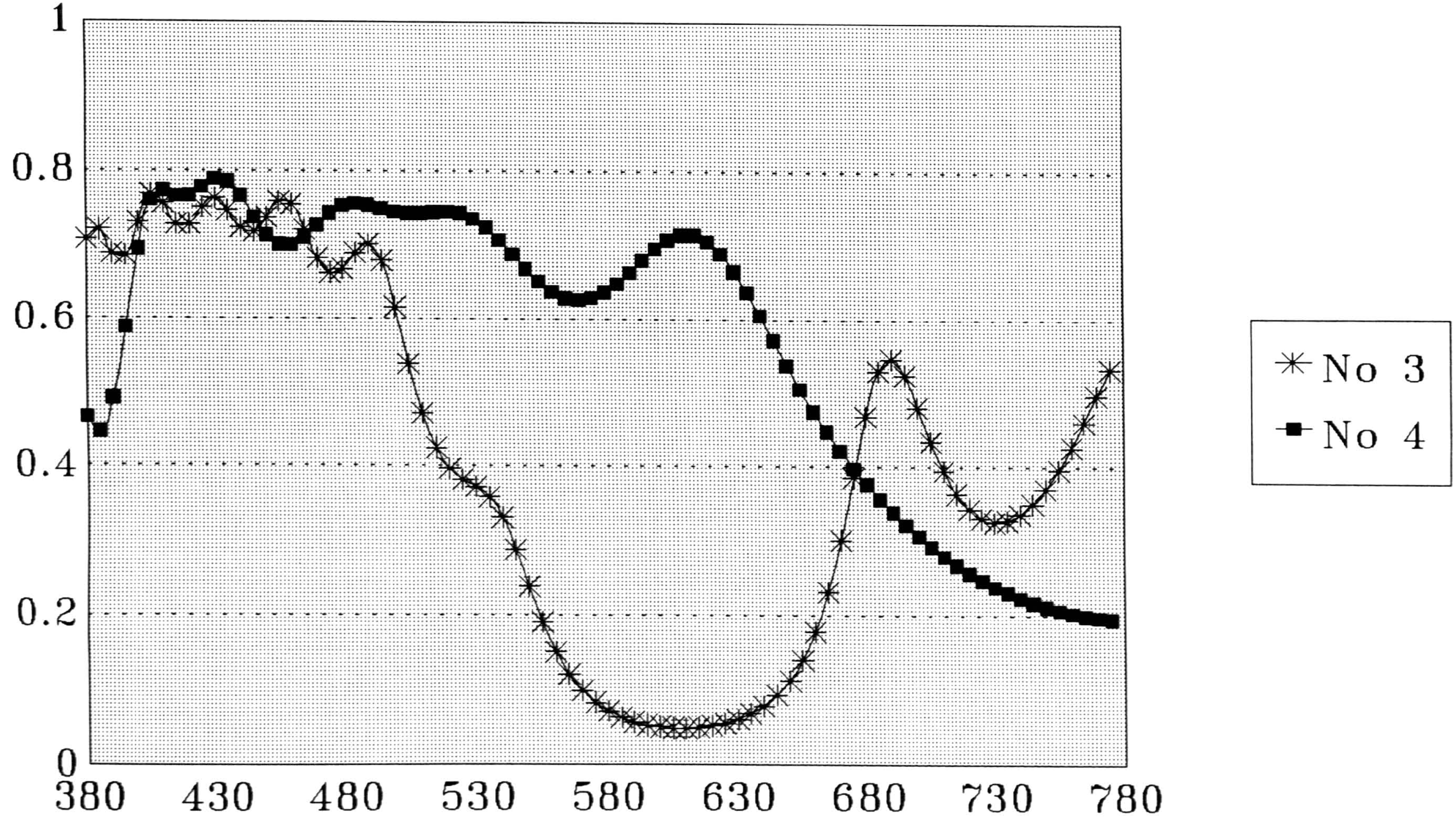
Transmission of dichroic filters

Pilkington Research Lathom



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APPENDIX 3

Transmission of dichroic filters

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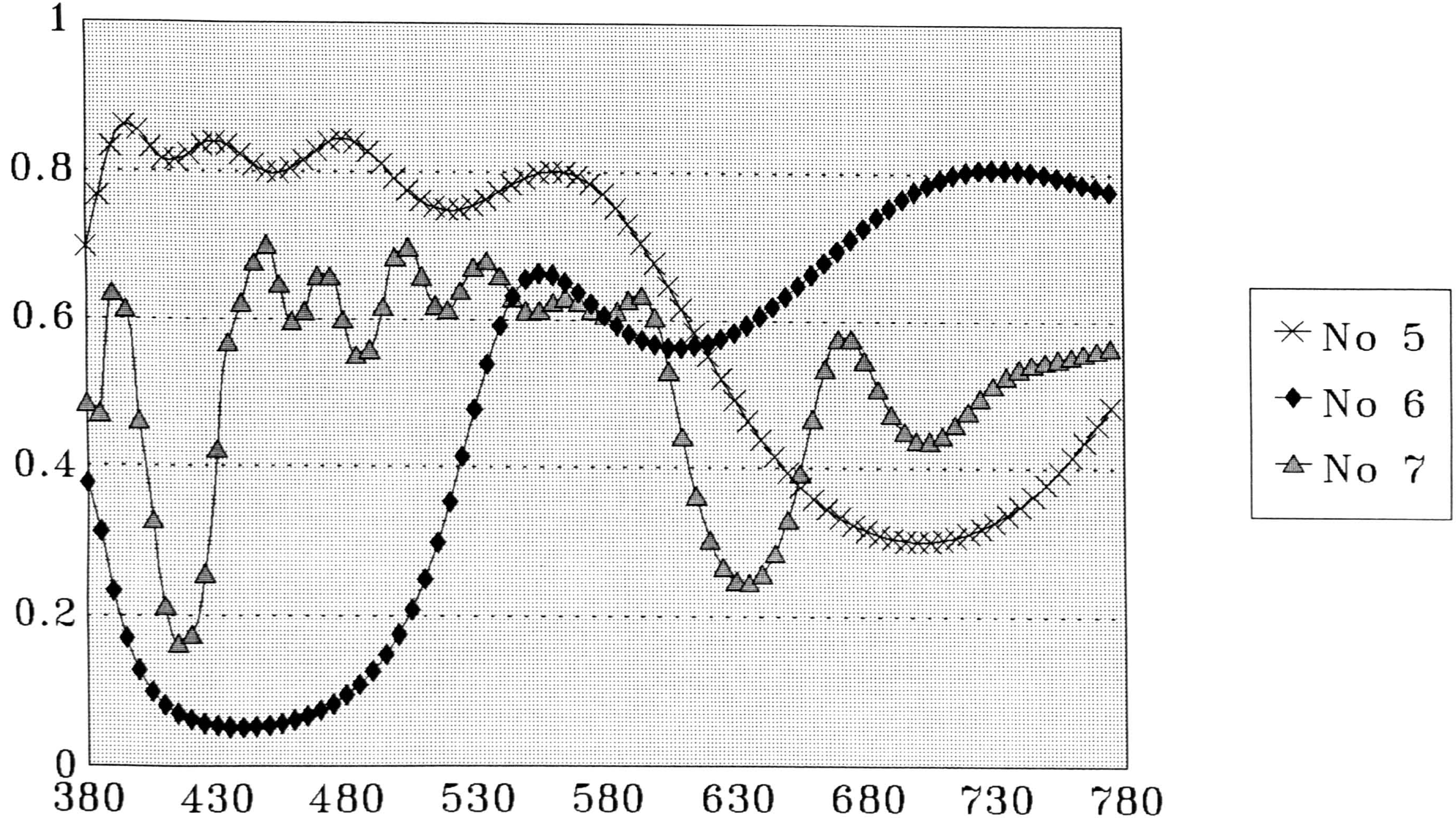

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Transmission of dichroic filters

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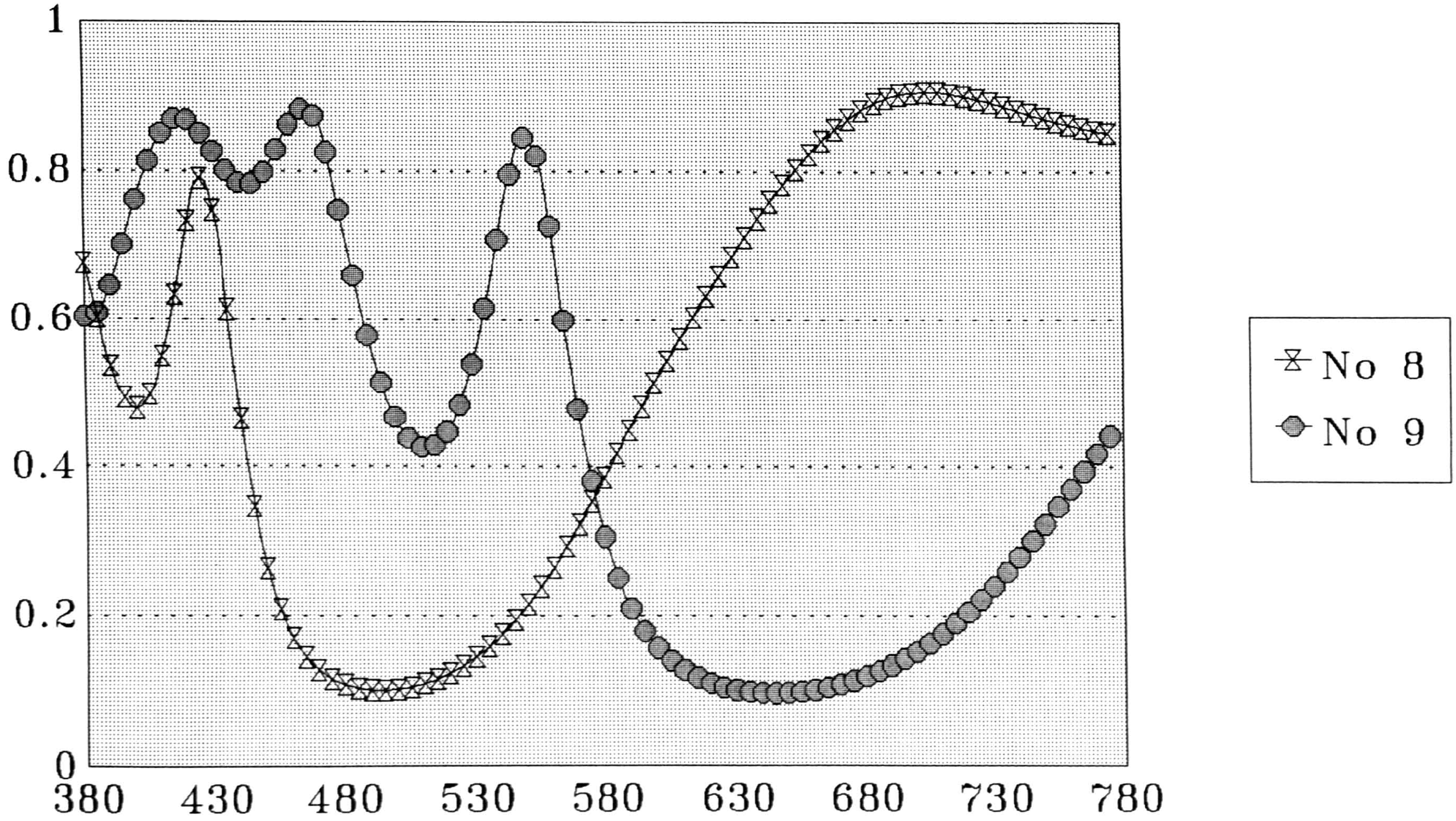

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Dichroic Glass

Research Carried out at Pilkington Glass Ltd.

LAURA JOHNSTON - RESEARCH.

PILKINGTON : 22ND - 26TH NOV.

DESIGNING COATINGS. I began the week working with Malcolm Copeland, using 'Film Star' and 'Film Calc' computer software. These programmes calculate the performance of multi-layer coatings, based on the varying refractive indices of materials used. Information is presented in graph form, indicating the percentage of transmission and reflectance at different wavelengths (measured in nanometres). For my purposes, the visible range from 380 - 780nm was selected for analysis. The peaks and troughs plotted on the graph indicated the colours in reflection and transmission resulting from the materials and number of layers used. Optical thickness is calculated here. The programmes allow for the conversion of this into physical thickness

Various sequences of high and low indices were explored and the results recorded. Those which appeared promising, showing strong colour in transmission and reflection, were selected and the designs followed.

COATING SAMPLES. Nine glass samples measuring approximately 2 x 2ins were coated during the week. The results demonstrated that it was possible, in most cases, to achieve the colours predicted by the computer programme, following the sequences and layer thicknesses prescribed. Where differences were observed, this was due to slight variations in thicknesses which occured during application.

The peaks and troughs illustrating the levels of transmission and reflection of each sample are recorded in both graph and numerical co-ordinate form (see following pages).

Sample 1. Titanium trioxide (High refractive index), silicon dioxide (Low refractive index). Four layers were used measuring 410, 680, 410 and 170 angstroms thick, respectively.. The result was a pale blue in transmission, which as the glass was tilted changed to a green/blue and then to purple at 45 degrees. Gold/purple in reflection.

Sample 2. Titanium trioxide, silicon dioxide. Ten layers : (410, 680) x 4 plus 410 angstroms titanium trioxide and 170 silicon dioxide. A much stronger blue was achieved in transmission which changed to a strong purple/pink at 45 degrees. Green/gold in reflection.

Sample 3. Titanium trioxide (H), Magnesium oxide (L). 18 layers : 9 x (H,L). Layer thicknesses : titania 650 angstroms, Mg oxide 710 angstroms. This was modelled to match the graph plotted on examination of 'magenta' (TFT Inc. USA). The result was infact blue in transmission, which was probably caused by inaccurate monitering of layer thickness, resulting in a shift of colour along the spectrum.

Sample 4. Titanium trioxide - 780 angstroms, and Magnesium oxide - 710 angstroms. Ten layers in total. Blue in transmission, red/gold in reflection.

Sample 5. Ten layers : Titanium trioxide 780 angs, Mg oxide 850 angs. Blue in transmission, strong red/gold in reflection.

Sample 6. Repeating sample no.2. Result quite different - yellow in transmission, purple in reflection. Possible thickness variations.

Sample 7. Silicon dioxide (L), Titanium trioxide (H), Magnesium oxide (Medium).
1680angs 2110angs 1440angs
Twelve layers : (L,H,M) x4. Result : Magenta in reflection, green/blue in transmission.

Sample 8. Titanium trioxide (H), Silicon dioxide (L). Layer sequence and thicknesses : 450 H, 810 L, 410 H (880 L 570 H) x2 760 L, 400 H, 1790 L angstroms. Result : Magenta in transmission, yellow at 45 degrees and green in reflection.

Sample 9. Titanium trioxide, Silicon dioxide. 460 H, 900 L, 460H (900 L, 700 H) x2 900 L, 460 H, 180 L. Result : Strong blue/green in transmission, purple at 45 degrees, gold in reflection.

CONCLUSION. The samples demonstrate the potential of using design software to achieve successful dichroics. The importance of the monitering of coating thickness during application is clear. All samples were rotated during coating but it was not possible to heat the glass. This has resulted in rather vulnerable coatings which can be scratched.

Mathematical Calculation of Coating Thickness.

Where n = index and d = thickness, λ = wavelength.

$$nd = \frac{\lambda}{4} \quad \text{(Quaterwavelength)}$$

Therefore : $$d = \frac{\lambda}{4n}$$

Example: $$Ti = \frac{550}{4x2.3} = 93nm \text{ (nanometres)}$$

$$Si = \frac{550}{4x1.48} = 59.70nm$$

By changing the wavelength in the formula, colour change is achieved. The wavelength determines the position of the peak on the spectrum graph.

ANALYSIS OF TWO SAMPLES : Magenta and Yellow, Thin Film Technology Inc. USA.

SPECTROPHOTOMETER.

This unit enables the analysis of the levels of UV, solar heat and light transmission and reflection of glass samples along with colour. The range in nanometres = 295 - 2600.

The unit consists of a chamber in which two light beams are shone. With the chamber empty, a reading of 100% is given. Glass is cleaned and then placed flat against the cell holder in the path of the beams. The samples are then scanned and a print out analysis is given. The graph illustrates the high level of light and solar heat transmission particular to these samples. Within the visible range, 380 - 780nm, peaks and troughs can be seen to fall at points on the spectum dictating colour.

(See plotted chromaticity diagram).

SPECTROGARD - Measurement of Optical Properties.

This is a robust system with an integrating sphere which is very good for assessing transmission through textured glass where light is scattered. Reflection can also be measured.

Light passes into the white sphere inside the unit and then through the sample, to measure transmission. ISO standard calculations are used and the transmittance data is rounded up to a whole number. For these samples, the colour reading was very high - well over fifty (using the a* b* method of classification). Lightness is also measured : 'L'. This scale is from black = 0 to white = 100.

Reflection is measured as light bounces back from sample into the sphere. Before sample is placed within the unit, the reflection reading is set to zero by placing a black cap over the area where the sample will be placed. A reading of 100% is then taken by inserting a mirror here. The reflection from the sample is then tested against these parameters.

The values of transmission + reflection + absorption must be equal to 100.
A low absorption will mean a high level of reflection.

(See Transmission and Refletance Data).

SAMPLE 1.

The analysis shows alternating layers of SiO_2 and what may be $ZrTiO_4$. This zirconium titanate can be seen on the graph as the brown and purple lines. The plotting of these signify that the two compounds form a single layer at each interval, where SiO_2 registers zero.

There are eight layers of silica and nine of zirconia titanate. It can be seen from the graph that the composition of ZrTi changes during the coating sequence. Layer 1 shows a slightly higher proportion of Zr than Ti. This relationship gradually changes and in layer 17 Ti can be seen to have increased to more than twice as much as the Zr present (approximately 50% and 24% respectively). The analysis works through from the top outer layer to the glass substrate and therefore layer 17 was the first to be deposited.

The multi-layer sequence consists of alternating high and low refractive index materials:

Vitreous Silca = 1.46

TiO = 2.6 (as rutile), ZrO = 2.17

SEN estimate of overall coating thickness = 15671A +/- 154. This differs from the total given from Auger analysis = 12615 +/- 600A. Such a large discrepency in this instance is due to problems during the Auger analysis, involving fuses within the machine blowing. The analysis, which appears to be around 20% below that of the SEN, is likely to have been effected by this, the SEN approximation should be seen to be a more accurate record.

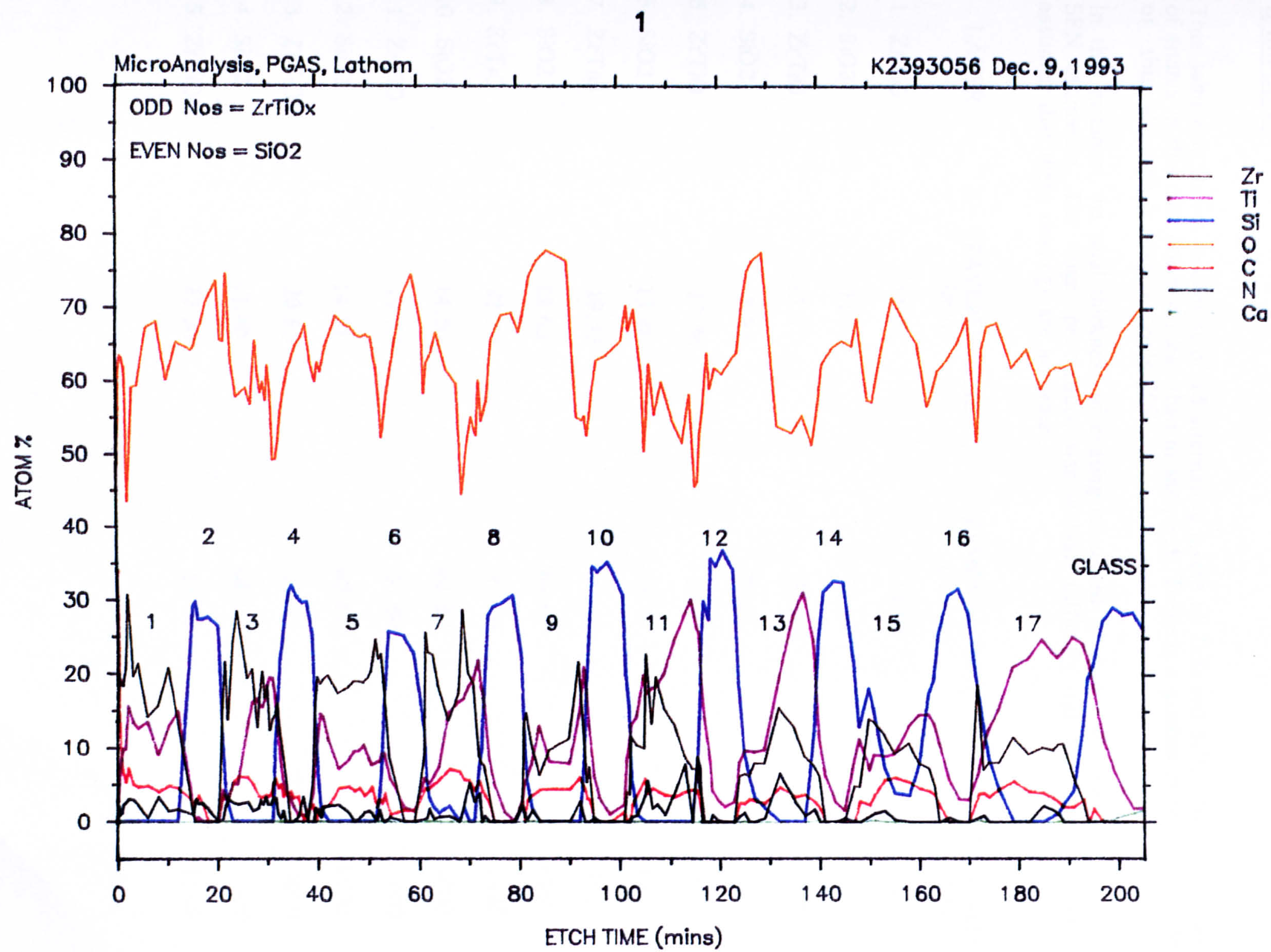

Figure 5.

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SAMPLE 2.

This sample is shown to consist of 15 alternating layers of ZrTi and SiO2. The overall levels of titania in this case are much less than in sample 1. There is a gradual increase in the level of this, although it never exceeds 20%.

In this instance, the total thickness of coating calculated by Auger analysis, is close to the SEN estimation. The Auger proceedure was without difficulty this time and so it can be assumed that these readings are accurate.

LAYER	TRAVERSE TIME (min)	REMOVAL RATE (A/min)	THICKNESS (A)
1. ZrTiO	11.72	51.98	610
2. SiO2	11.72	70.06	820
3. ZrTiO	15.07	51.98	780
4. SiO2	8.93	70.06	630
5. ZrTiO	17.86	51.06	910
6. SiO2	13.40	68.82	1080
7. ZrTiO	19.53	51.06	1000
8. SiO2	15.63	68.82	1080
9. ZrTiO	22.30	51.06	1140
10. SiO2	14.50	68.82	1000
11. ZrTiO	19.53	51.06	1000
12. SiO2	14.51	68.82	1000
13. ZrTiO	20.65	51.06	1050
14. SiO2	13.40	68.82	920
15. ZrTiO	22.30	51.06	1140

TOTAL = 14000 +/- 1000A

No. 2

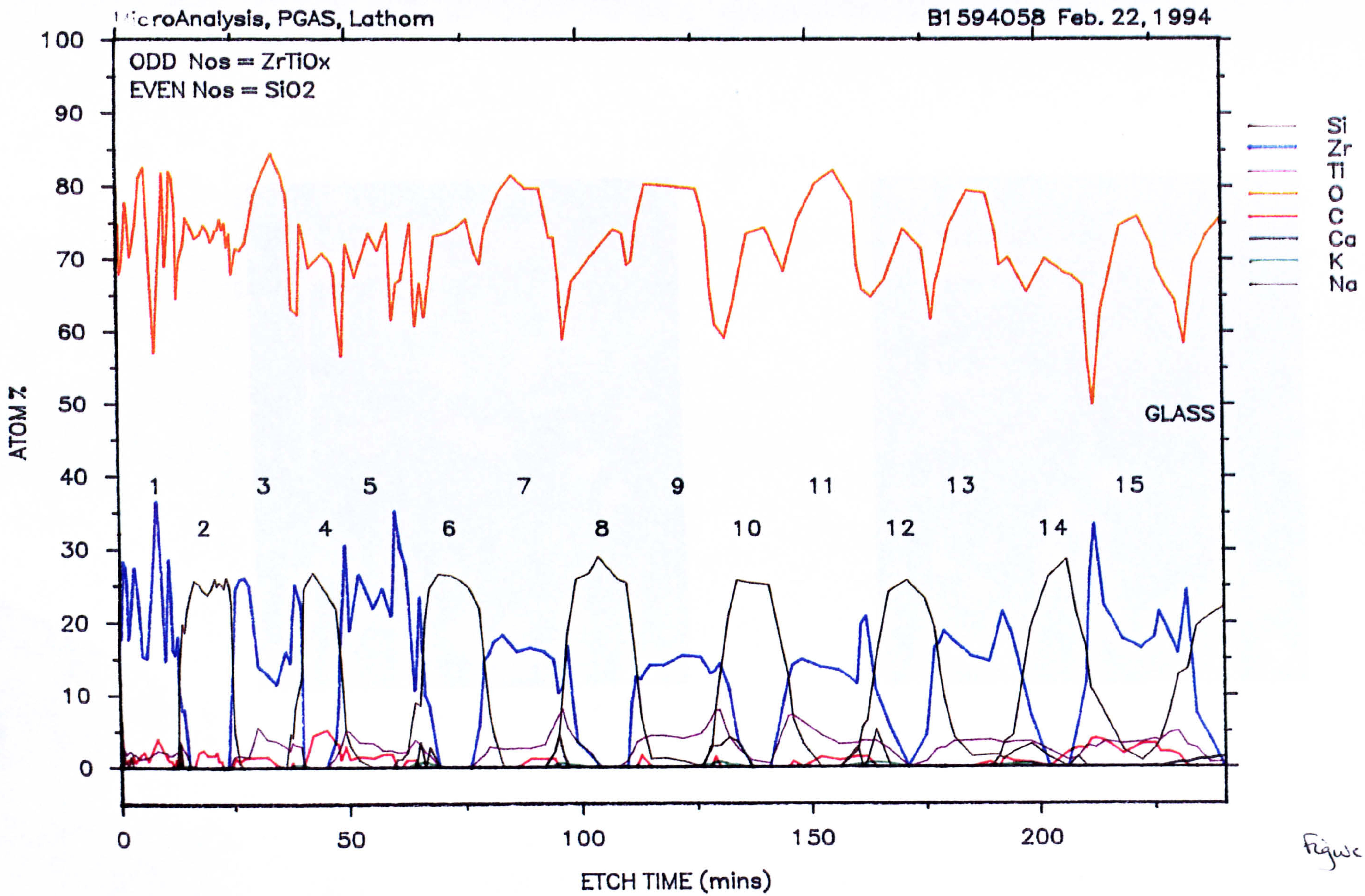

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Figure 6.

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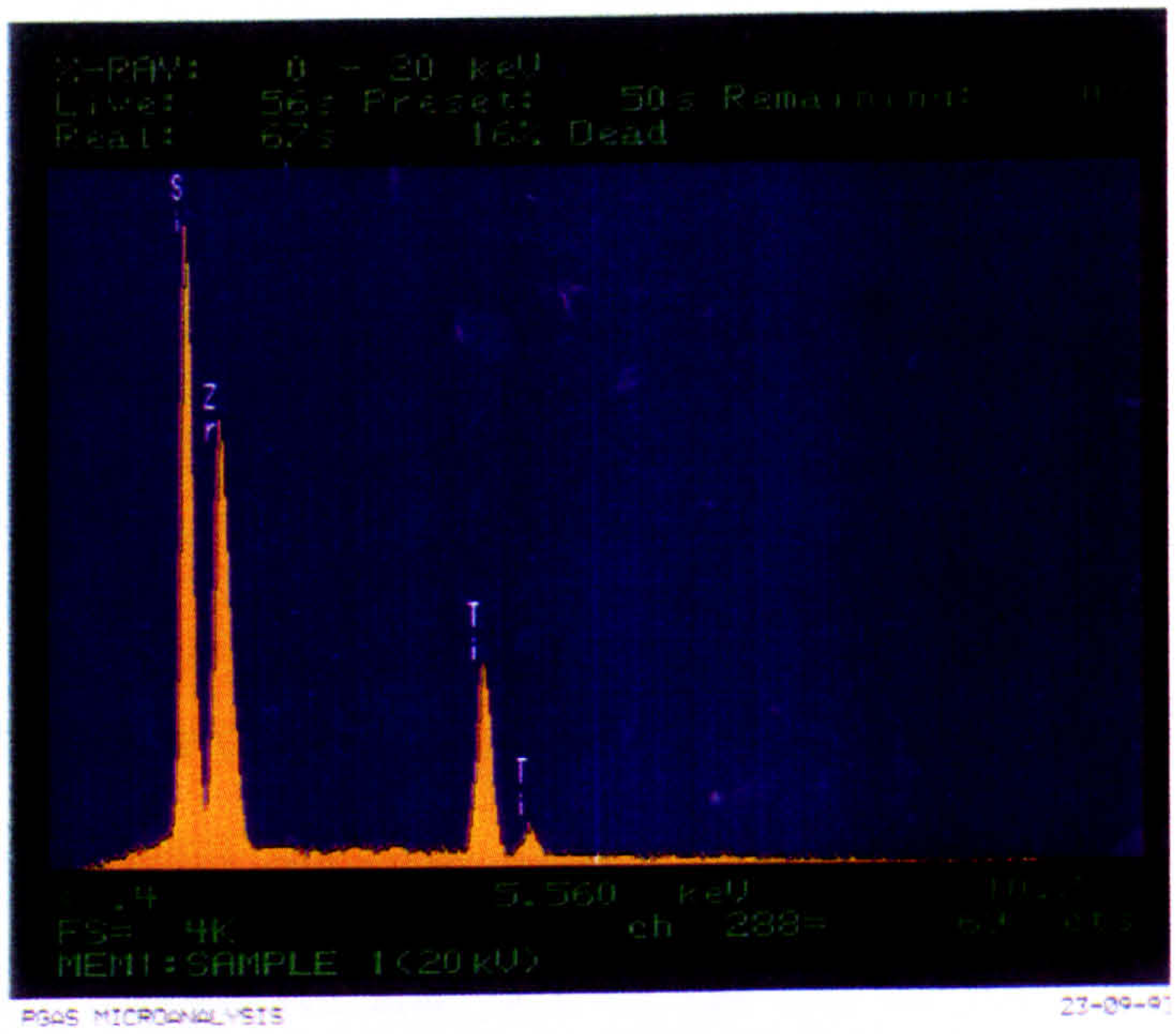


Figure 1.

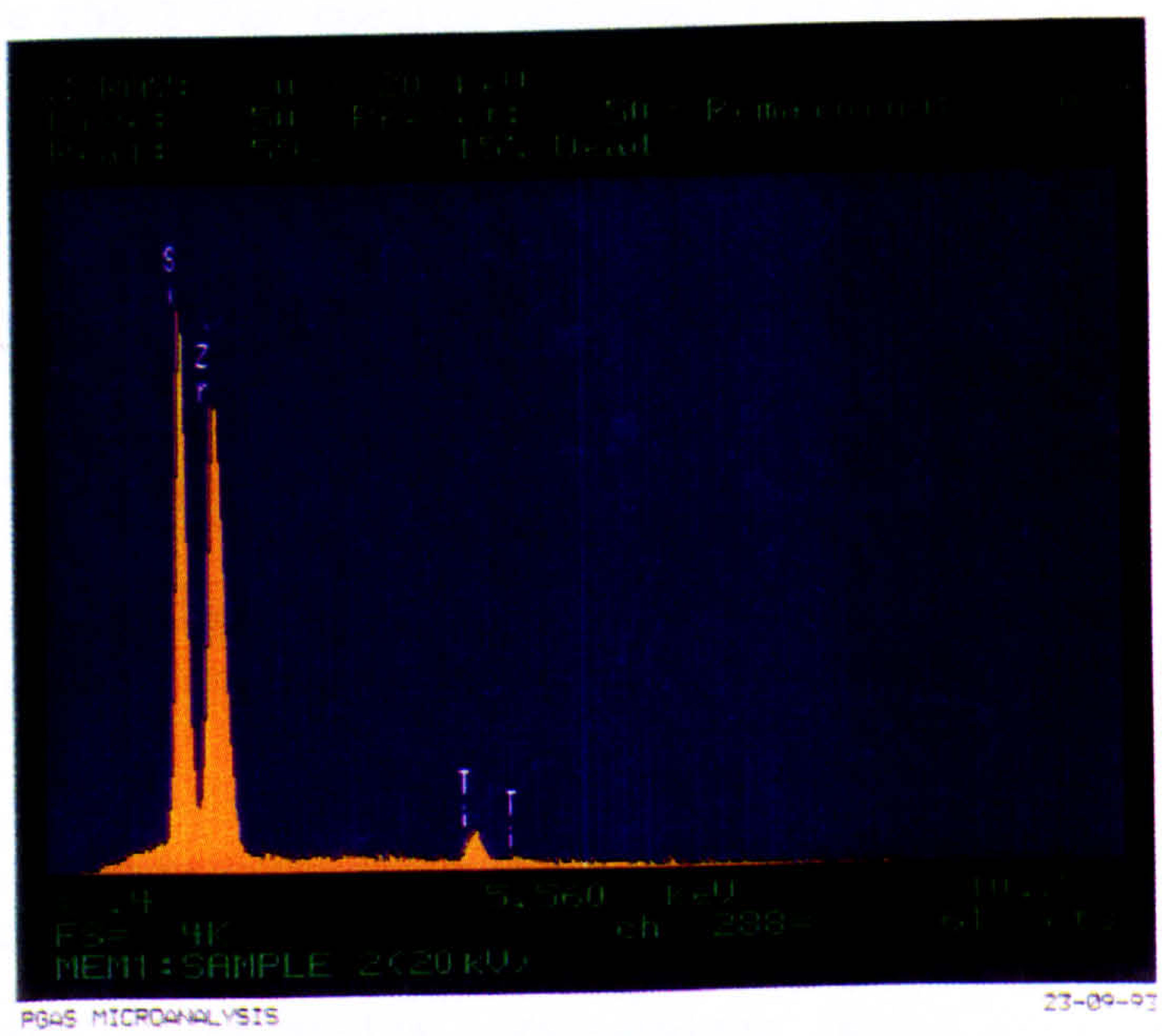


Figure 2.

APPENDIX 4

AS

PILKINGTON

Pilkington Technology Management Limited
Group Analytical Services Pilkington Technology Centre
Hall Lane Lathom Ormskirk L40 5UF Lancashire England
Telephone 0695 50000 Telex 629909 Fax 0695 54508

Date:
24.02.94

Account:
R.534.APA.34010

ANALYTICAL REPORT

Origin: OPTO-ELECTRONIC TECHNOLOGIES

Sample No: OET 1245

From: S. A. GILFEDDER
R. A. CHAPPELL

Description: MULTI-LAYER COATINGS ON GLASS - 21.9.93

Two samples of iridescent coatings on glass were submitted for layer characterisation, #1 exhibited a yellowish green colour in reflected white light whilst #2 had an orange colour. They were examined by three techniques, energy dispersive analysis in the SEM to identify what materials were present in the coatings, microscopy of fracture cross-sections in the high resolution SEM to determine number of layers and total coating thickness and Auger depth profiling to determine layer sequencing, individual layer thickness and detailed composition.

SEM/EDA EXAMINATION

Figures 1 & 2 are the X-Ray spectra obtained from #1 and #2 respectively. The elements Si, Zr and Ti were found both times, but much less Ti from #2. The absence of Ca in both spectra shows that the electron beam had not penetrated through to underlying glass and that both coatings must have at least one micron in thickness.

HRSEM CROSS SECTIONS

The micrographs in Figures 3 & 4 show that #1 had about 17 layers, #2 about 15. In both cases there was a fairly even alternation between two types of layer, one with columnar crystallinity, the other amorphous.

Total layer thicknesses for 1 & 2 were 15671 ± 154 Å and 14685 ± 215 Å respectively, (average of 10 measurements on each micrograph).

AUGER PROFILING

Results of Auger Profiling were as shown in Figures 5 & 6, Tables 1 & 2. Sample 1 was found to have 17 layers, 9 layers of 'zirconium titanate' alternating with 8 layers of silica. Sample 2 had 15 layers, 8 of 'zirconium titanate', 7 of silica. No separate layers of zirconia or titania were found. Zr and Ti always occurred together in the same layer. The name zirconium titanate serves only as a convenience however for a variety of Zr/Ti ratios were found in such layers. Thus in layer 1 of #1 Zr just exceeded the Ti whilst in layer 17 of the same sample Ti was about

J. Siddle

Circulation

Authorised by Group Chief Analyst

APPENDIX 4

ANALYTICAL REPORT

Sample No: (cont.) OET 1245

twice the Zr. There were also real variations in Zr/Ti ratio within a single layer, there generally being more Zr at the top of the layer than at the base of it. Assuming that there was on average, a progressive decrease in the relative ZrO_2 content of the 'zirconia titanate' layers in #1 from top to bottom, we may suppose that the refractive index of these layers also changed from about 2.40 at the top to about 2.56 at the bottom.

The TiO_2 contents of the 'zirconium titanate' layers in #2 were much lower overall, in line with the SEM/EDA data. There may be some evidence for a slight increase in the TiO_2 contents of these layers, top to bottom. Judging by average composition, layer 1 in #2 may have had a refractive index of about 2.17 and layer 15 a refractive index of about 2.29.

The alternate SiO_2 layers in both samples were low index material ($\mu \sim 1.46$).

Tables 3 & 4 provide estimates of individual layer thicknesses in #1 and #2, the total for #2 (14000 ± 1000 Å) accords well with the HRSEM results (14685 ± 215 Å). The total for #1 (12615 ± 600 Å) is in poor agreement with the HRSEM total (15671 ± 154 Å) but the Auger profiling of this sample suffered from a number of interrupts (filament failures) and is likely to have errors in its thickness estimates.

Although it is possible to calculate average layer thicknesses by dividing the Auger or HRSEM totals for #1 and #2 by 17 or 15 respectively, this is thought to be misleading for the variations in layer thickness shown in Tables 3 & 4 are thought to be real. The HRSEM micrographs also show that layer 17 of #1 was unusually thick for example and its upper layers were thinner than average. Similarly for #2 both HRSEM and Auger results both show the upper layers to be thinner than average and the lower layers to have been of equal thickness.

R A Chappell
[signature]

Circulation

Authorised by Chief Analyst

APPENDIX 4

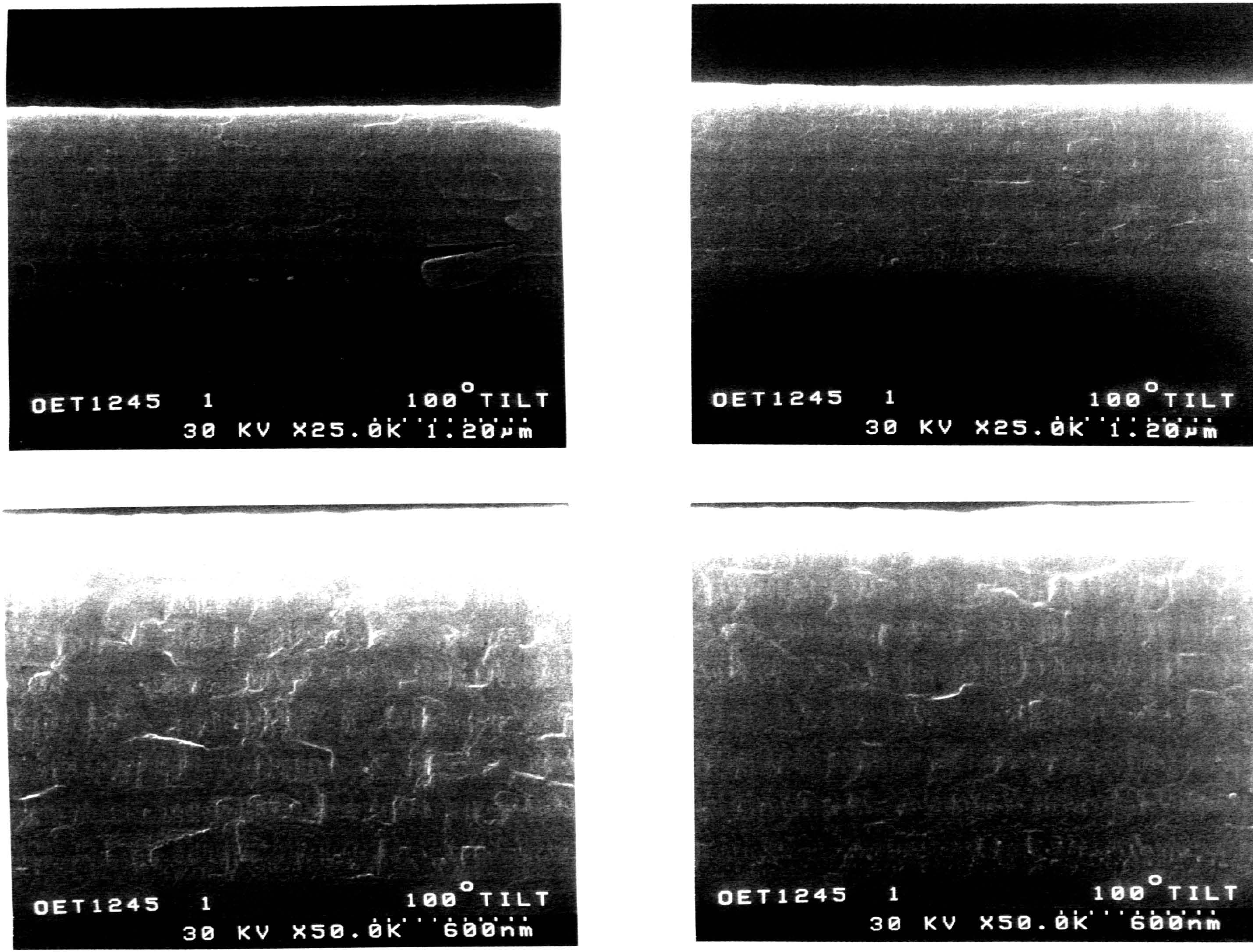
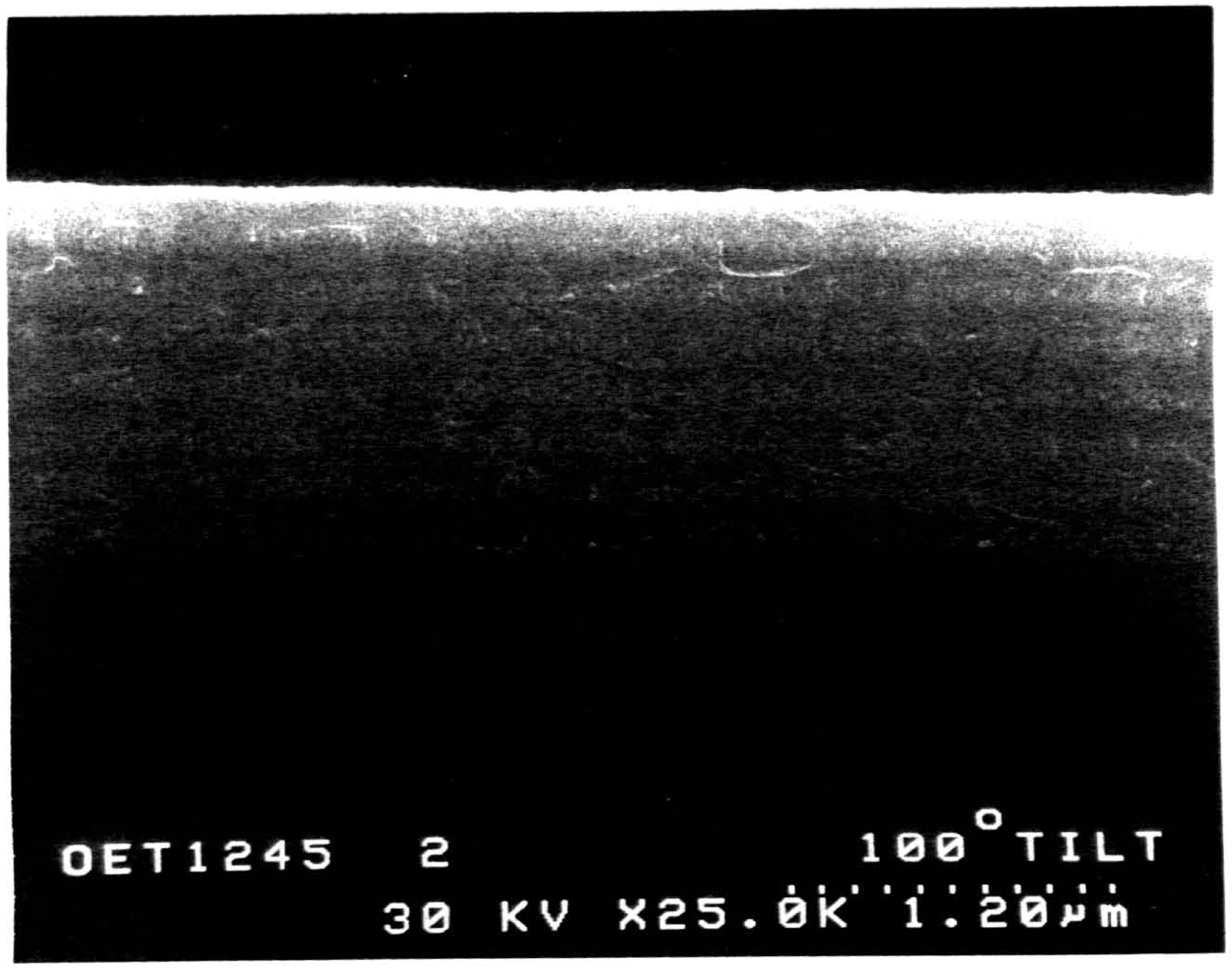
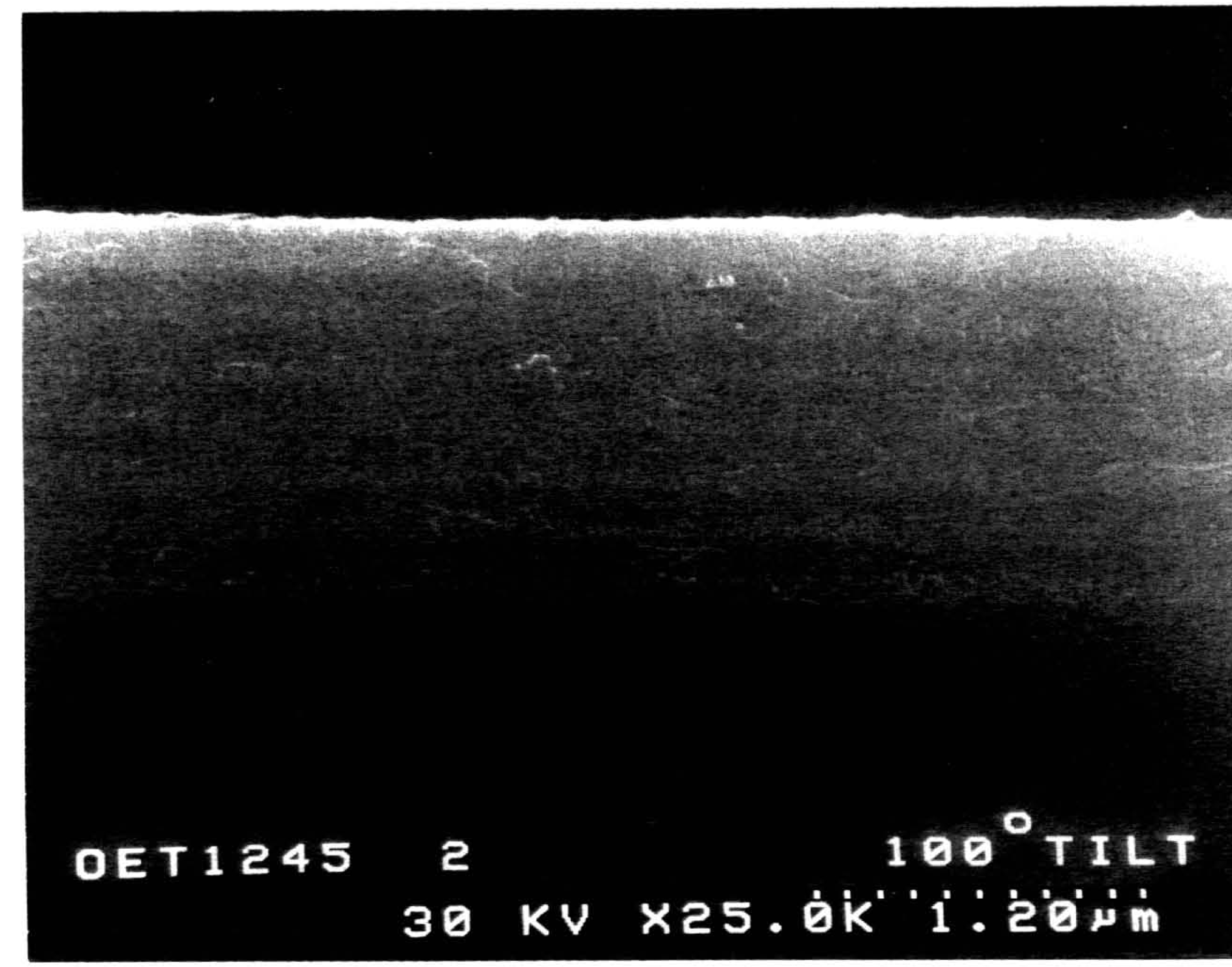
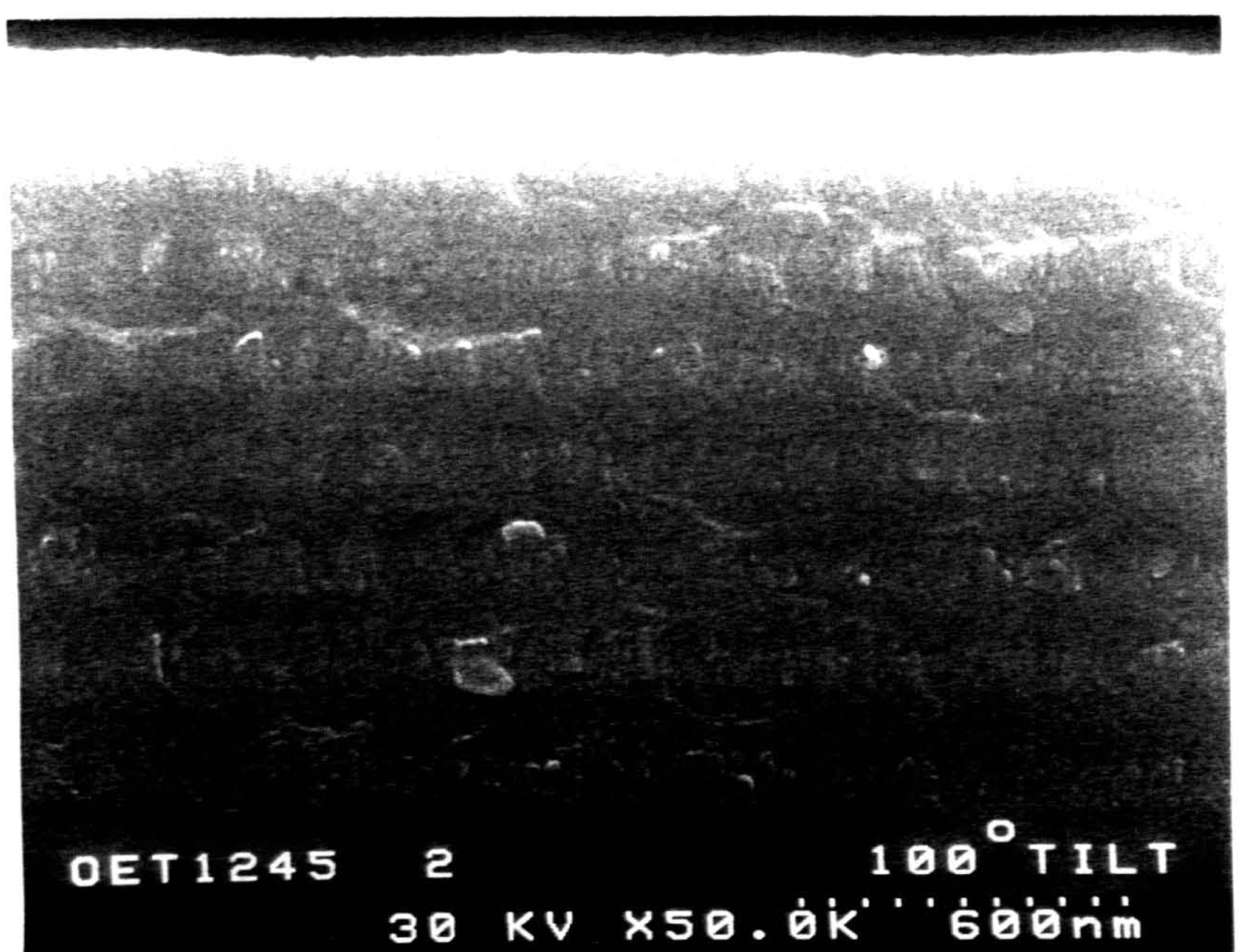


FIGURE 3

APPENDIX 4


OET1245 2 100°TILT
30 KV X25.0K 1.20µm


OET1245 2 100°TILT
30 KV X25.0K 1.20µm


OET1245 2 100°TILT
30 KV X50.0K 600nm

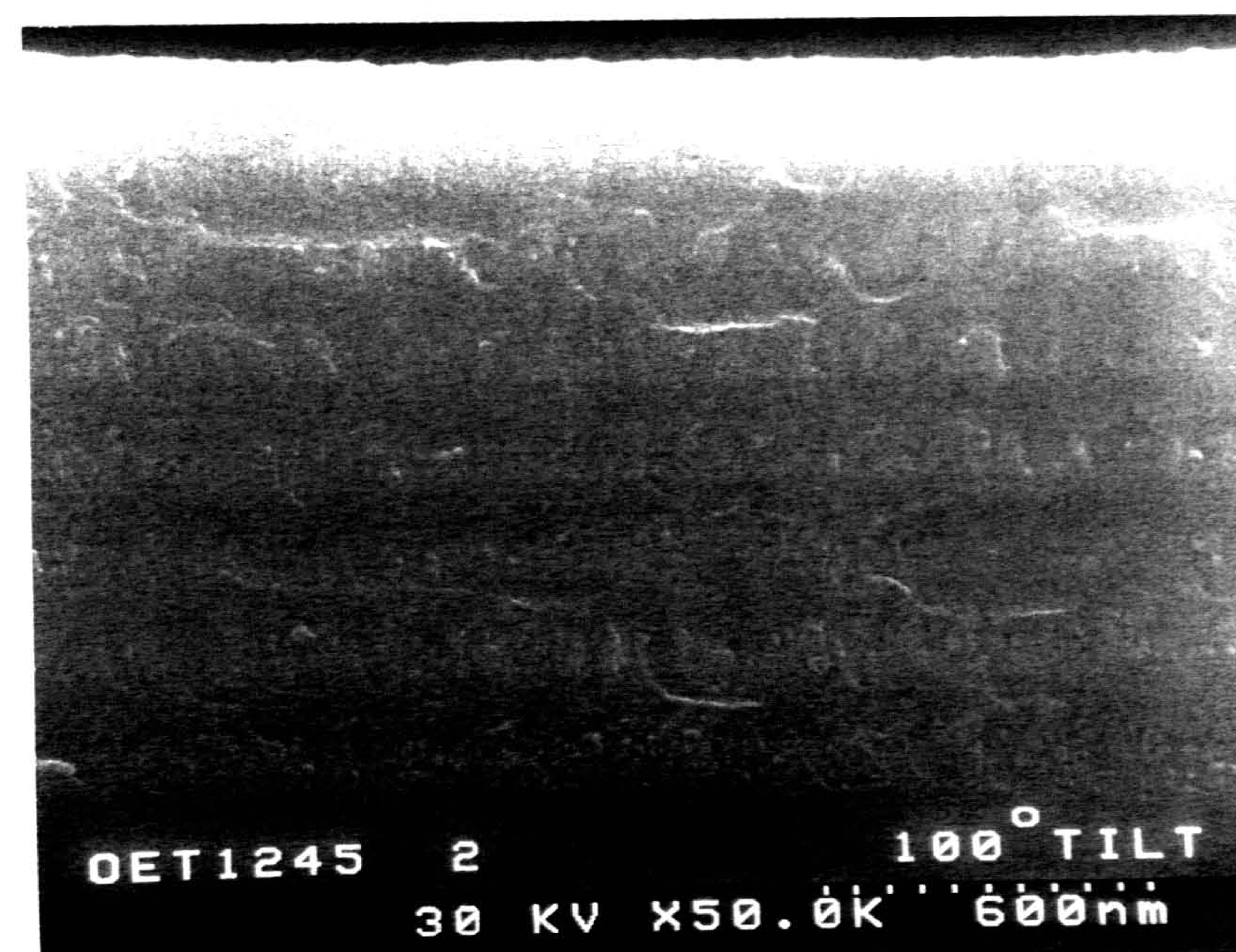

OET1245 2 100°TILT
30 KV X50.0K 600nm

FIGURE L

APPENDIX 5

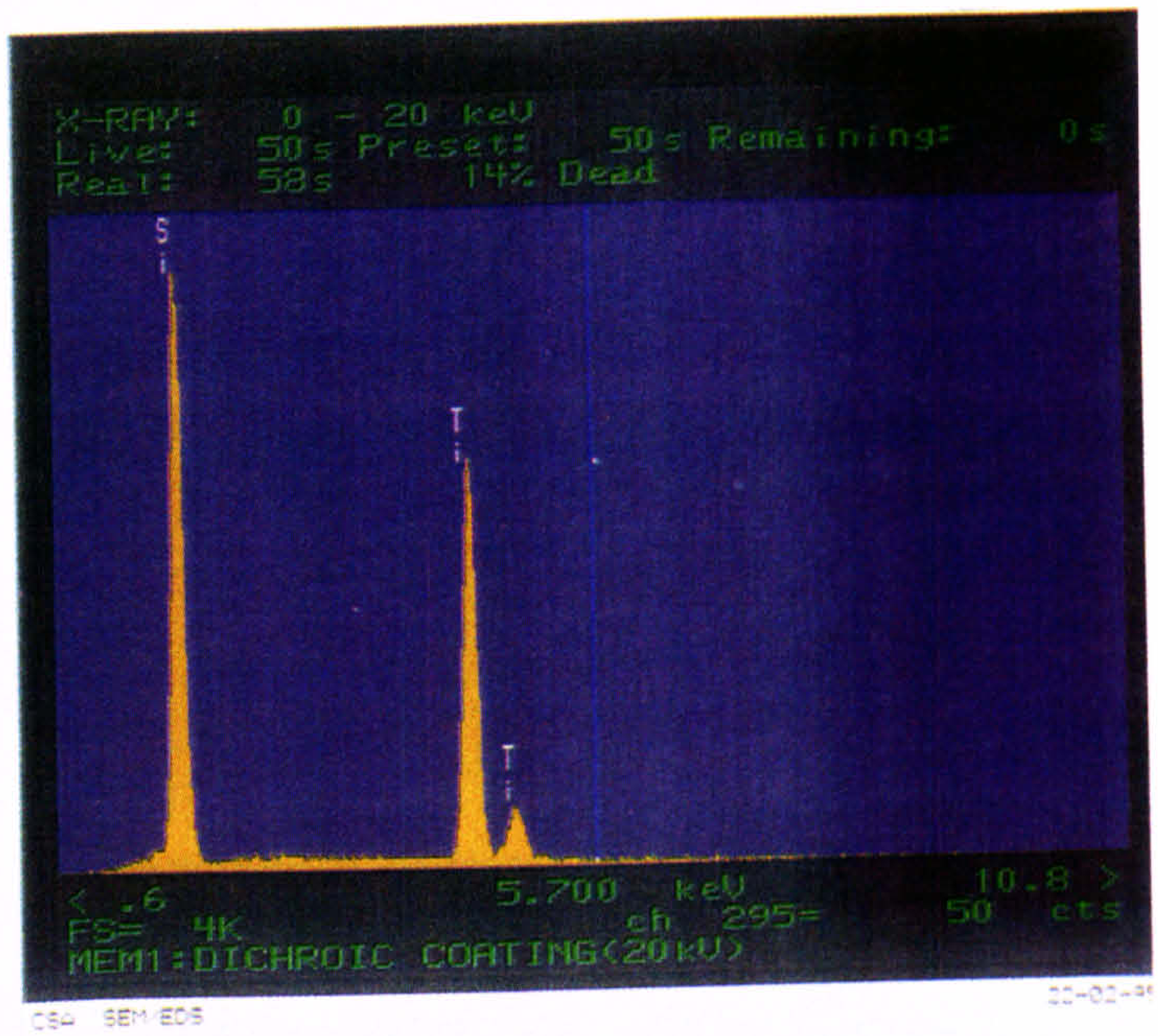
APPENDIX 5

A sample of dichroic glass produced by OCLI Optical Coatings Ltd (Scotland) was sent for analysis at Pilkingtons.

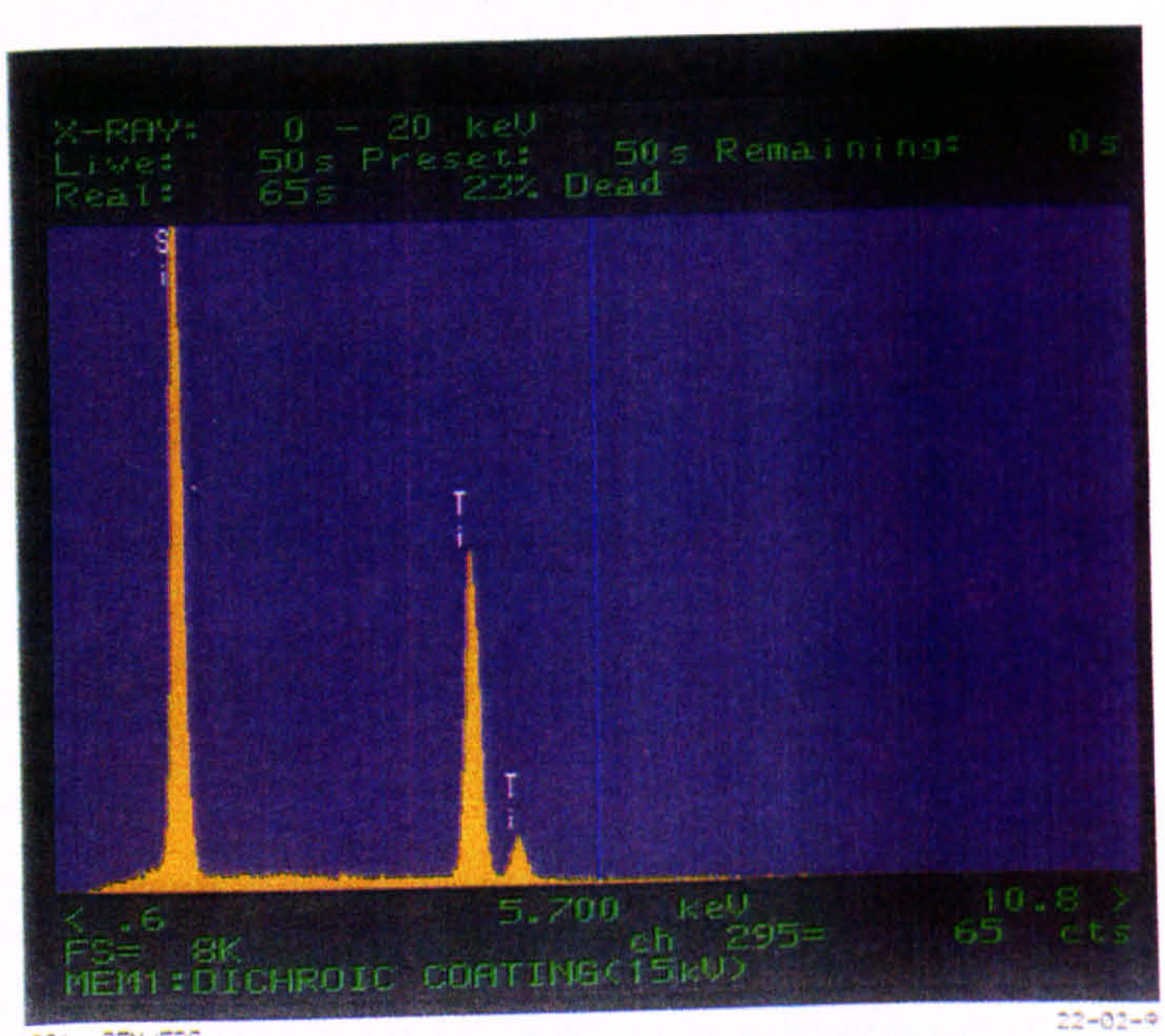
Analysis by means of high resolution scanning electron microscopy (HRSEM) along with energy dispersive analysis of electron beam induced X-ray emission (EDAX), took place.

The black and white photographs which follow are the result of HRSEM and show the edge view of individual coatings which make up the stack. Thirty-two layers were found to be present, and individual layer thicknesses were recorded. The coatings were identified as alternating layers of Silica/Titania with the first layer presumed to be the high refractive index material Titania. The analysis by EDAX revealed the nature of the coatings and are presented here in colour.

The number of layers used can be seen to be much greater than the average number deposited on samples produced as part of the research.

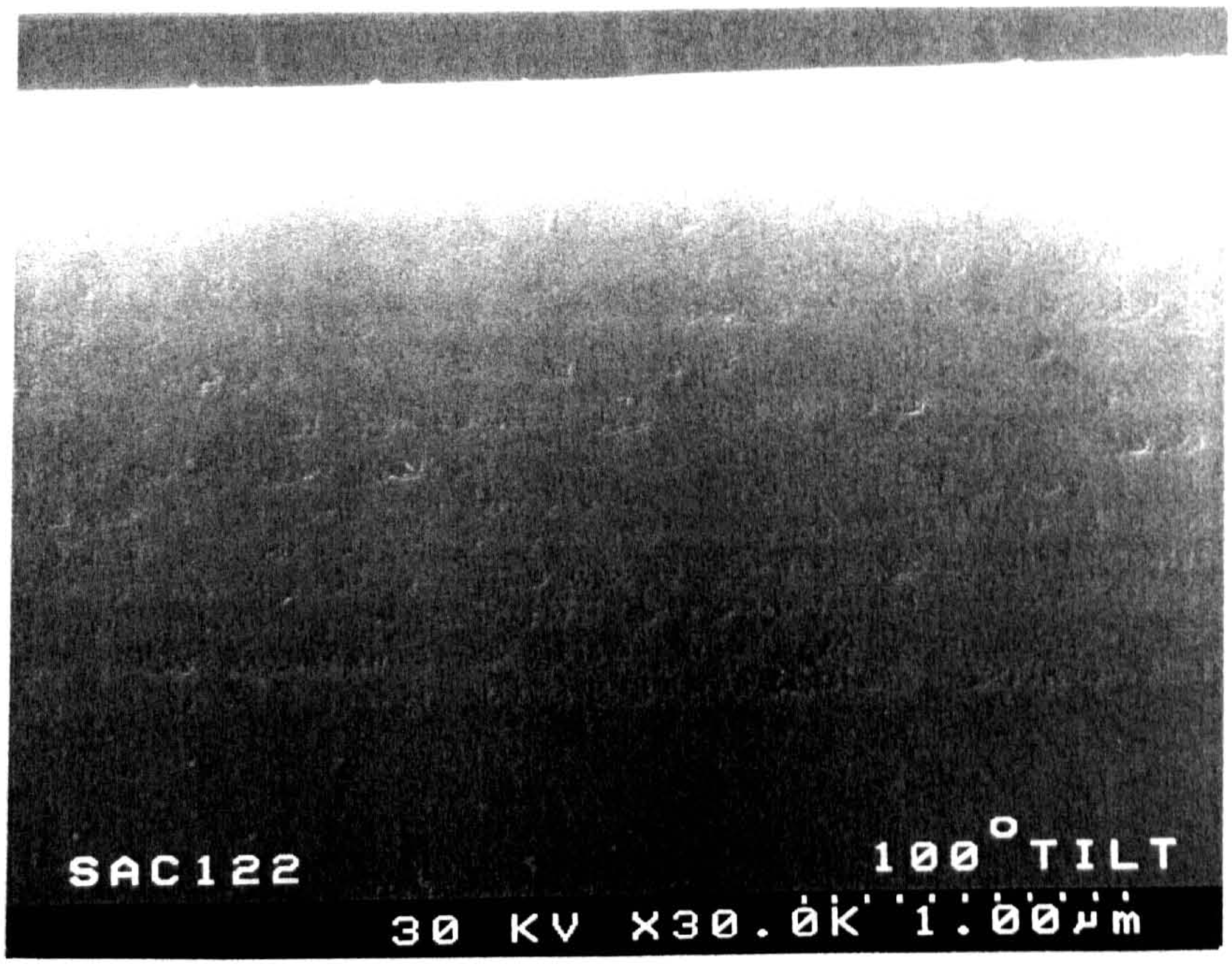


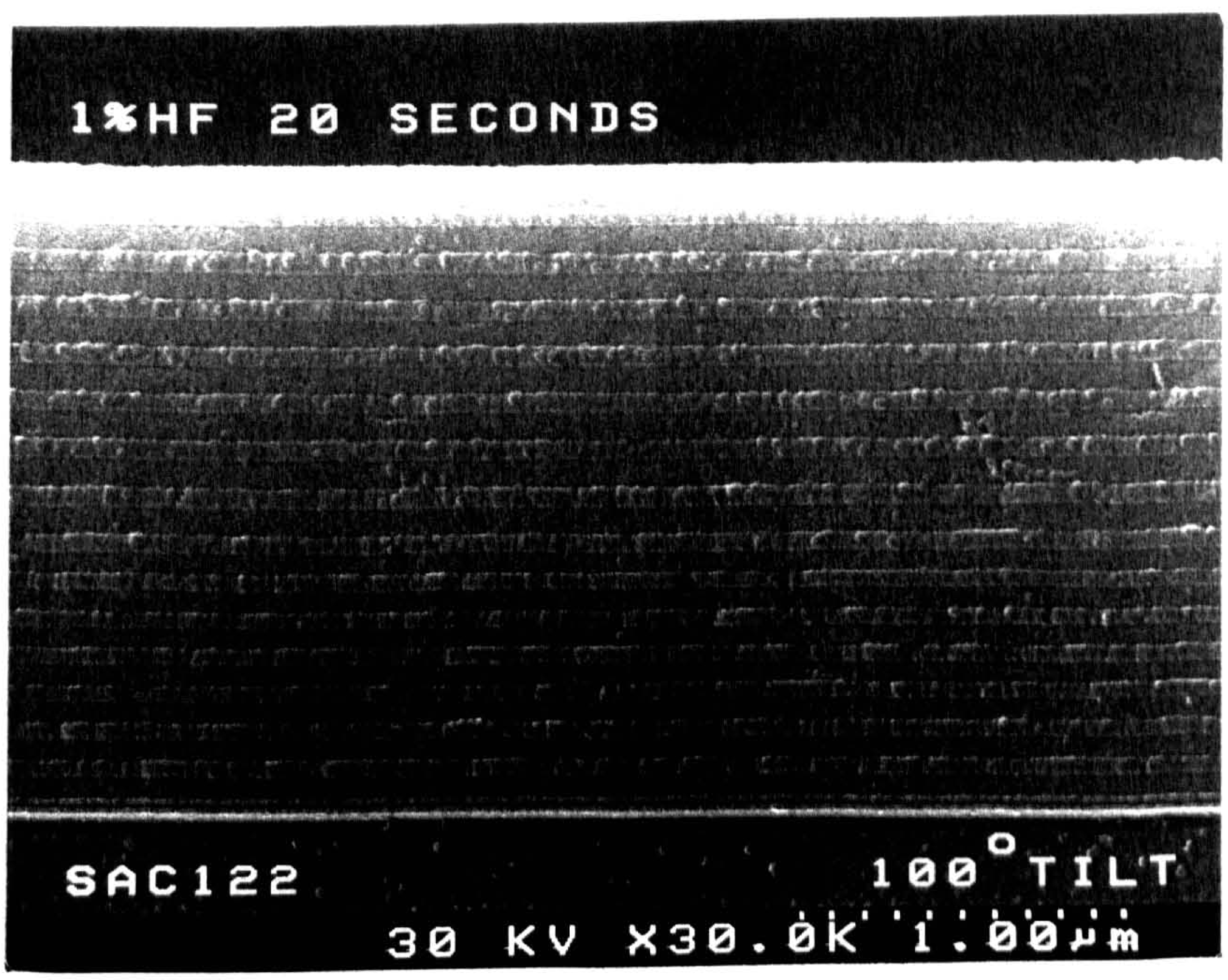
20kV

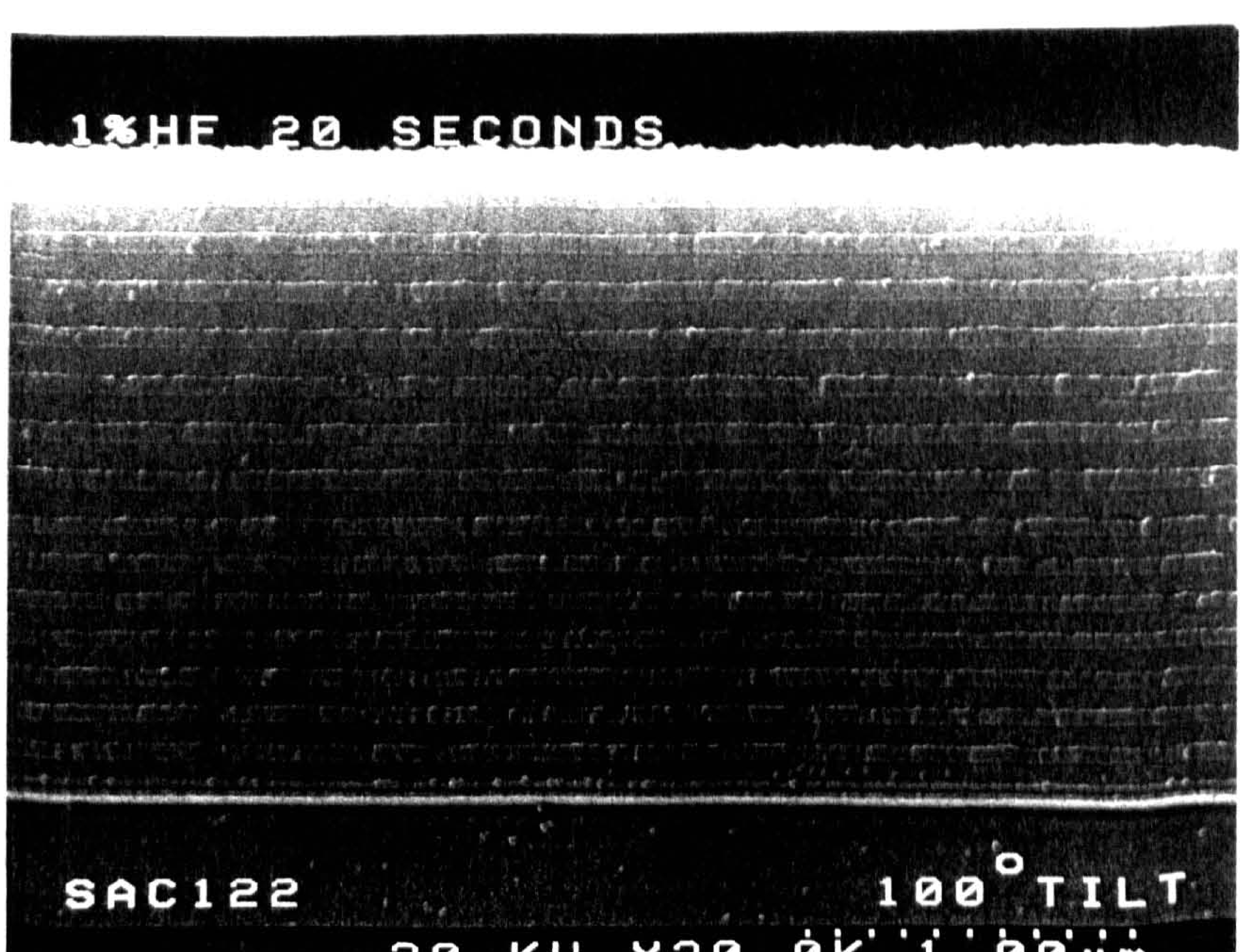


15kV

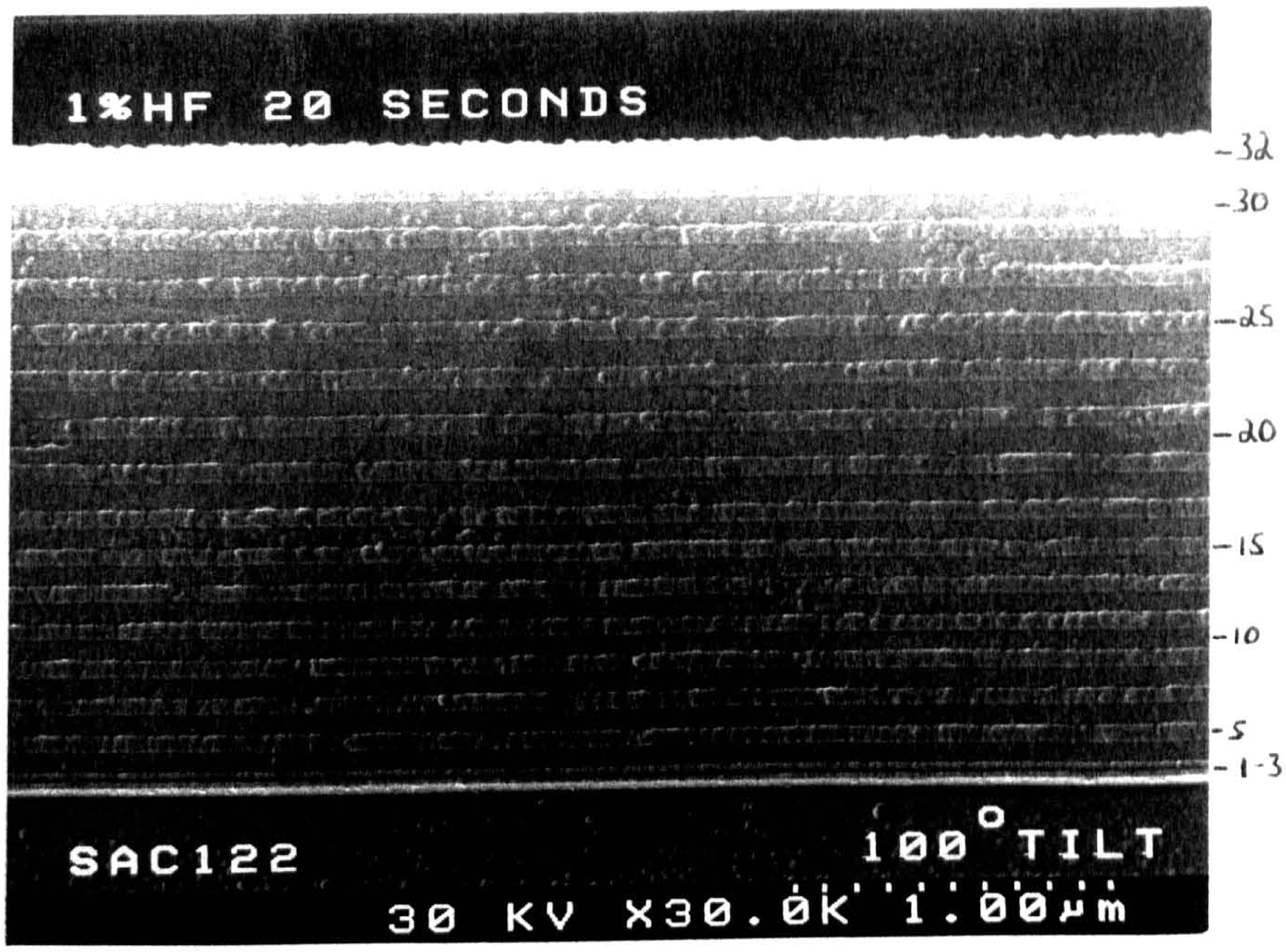
APPENDIX 5.

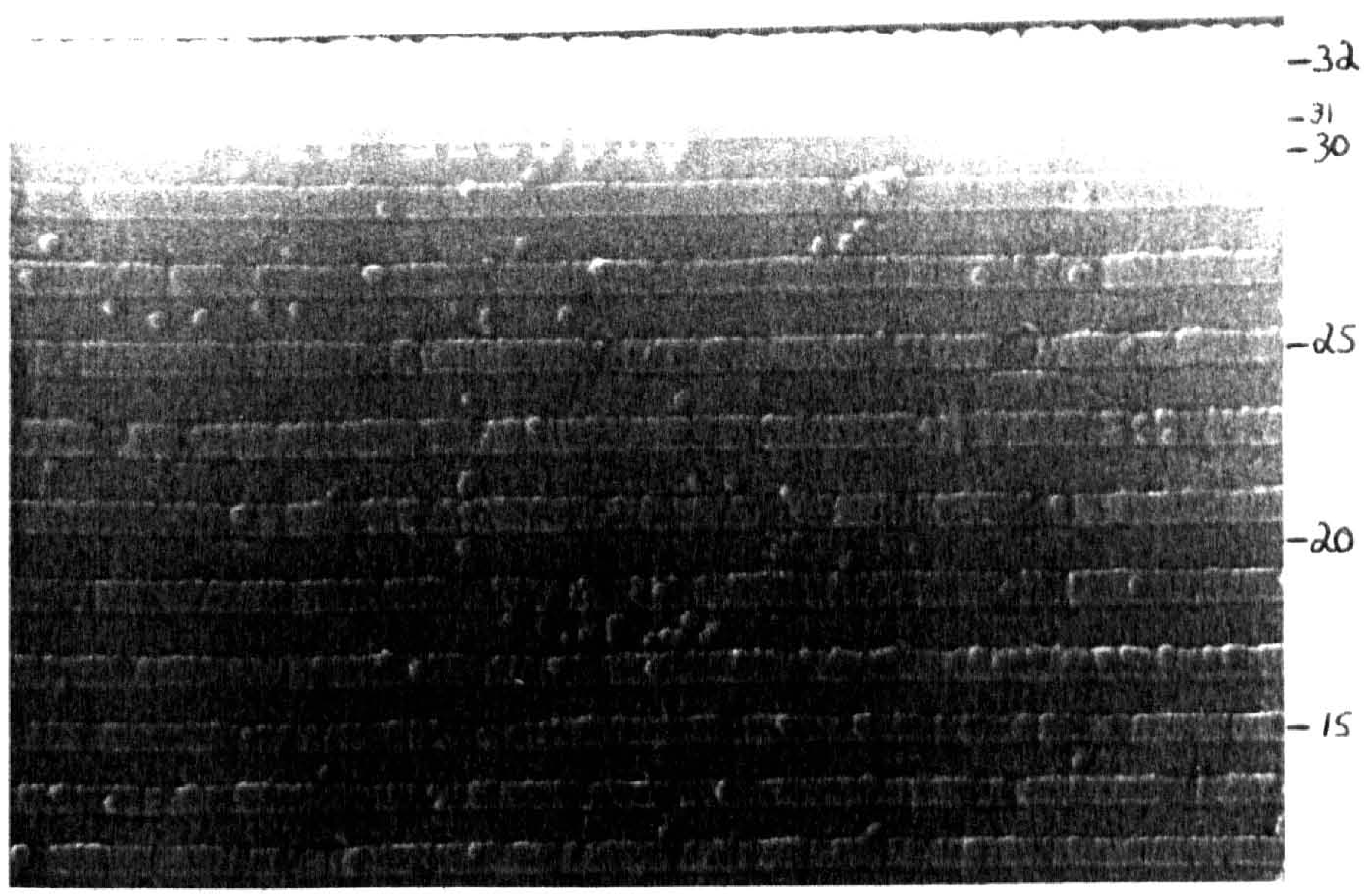

SAC122
100°TILT
30 KV X30.0K 1.00µm

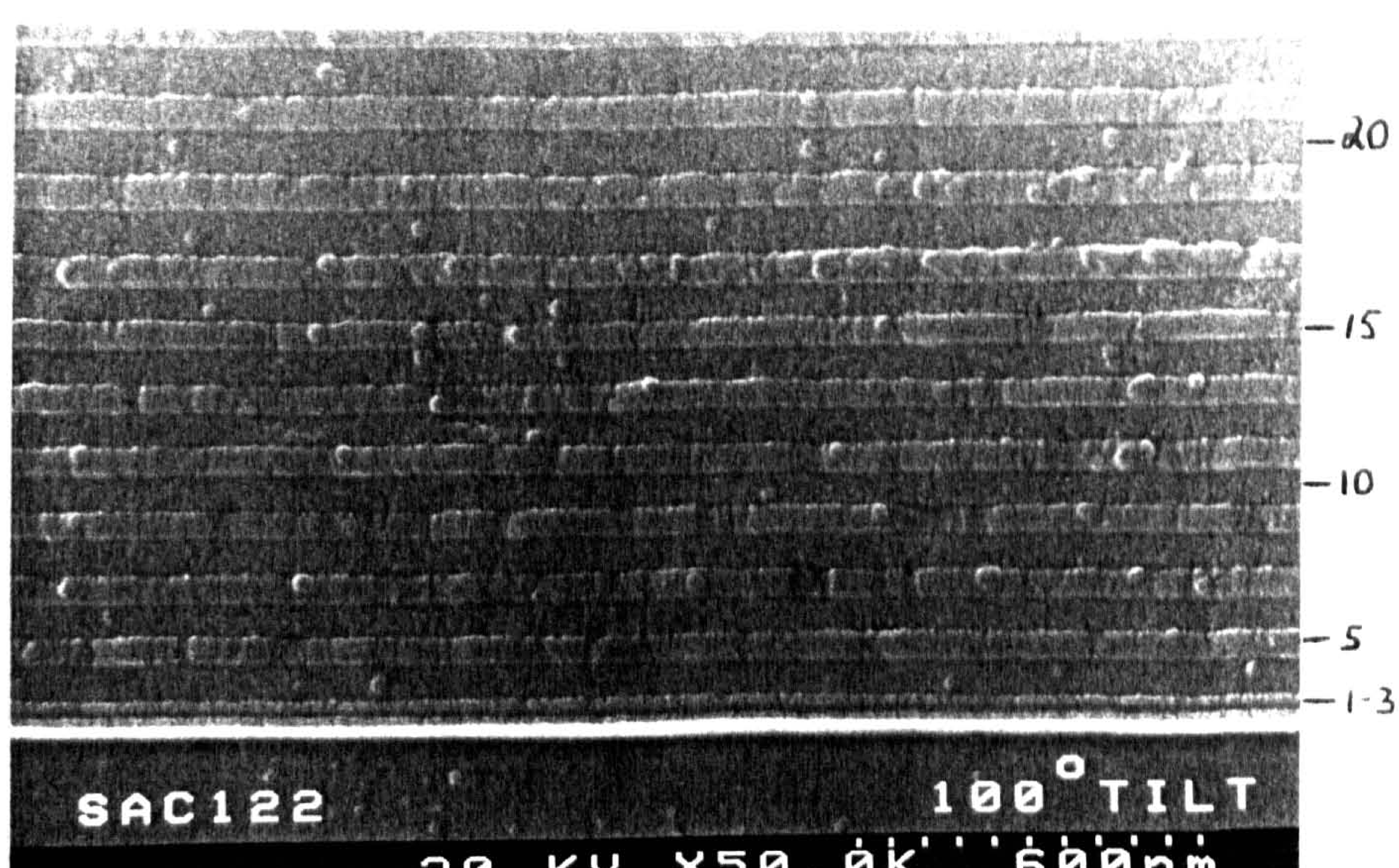

1%HF 20 SECONDS
SAC122
100°TILT
30 KV X30.0K 1.00µm


1%HF 20 SECONDS
SAC122
100°TILT
30 KV X30.0K 1.00µm

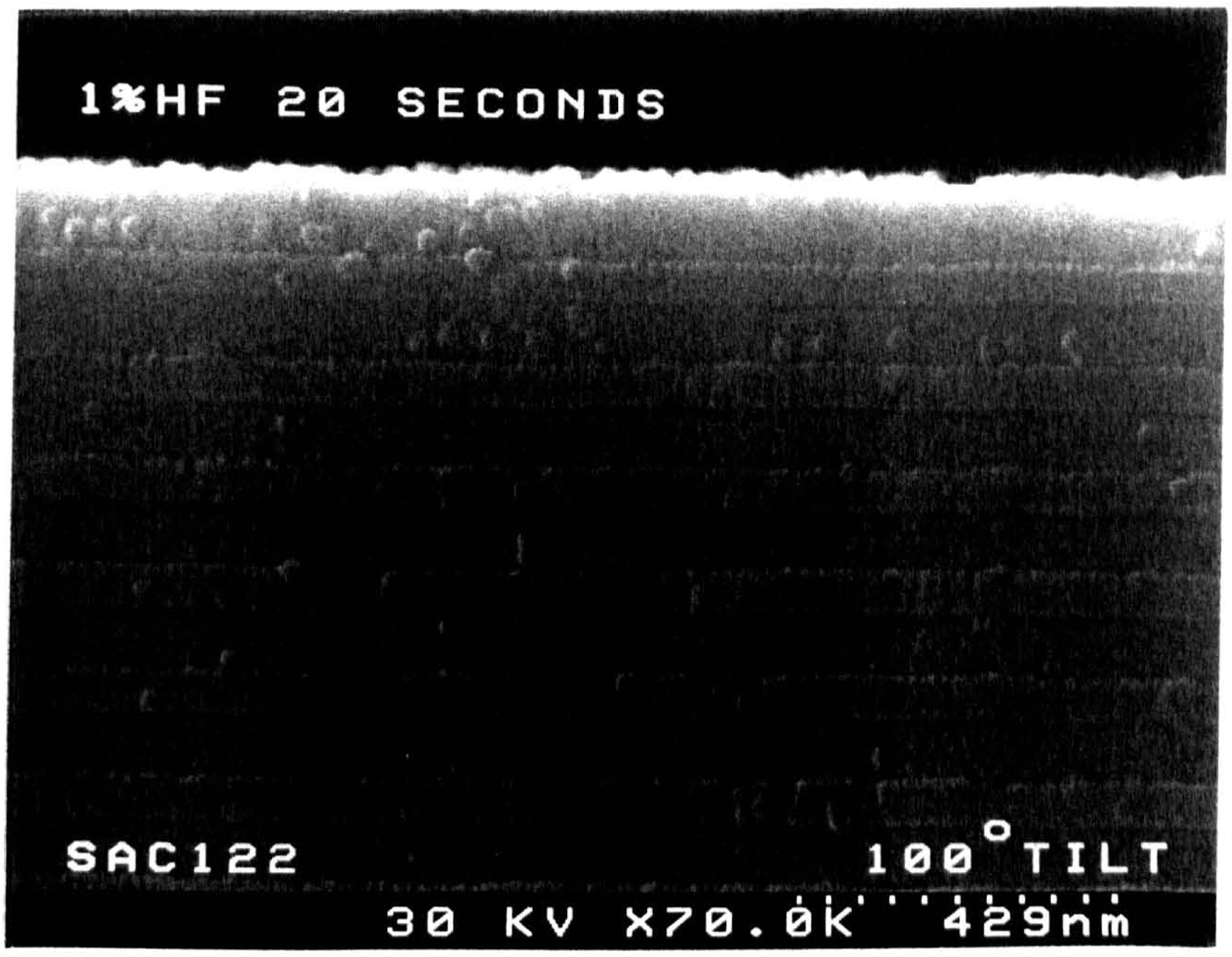
APPENDIX 5

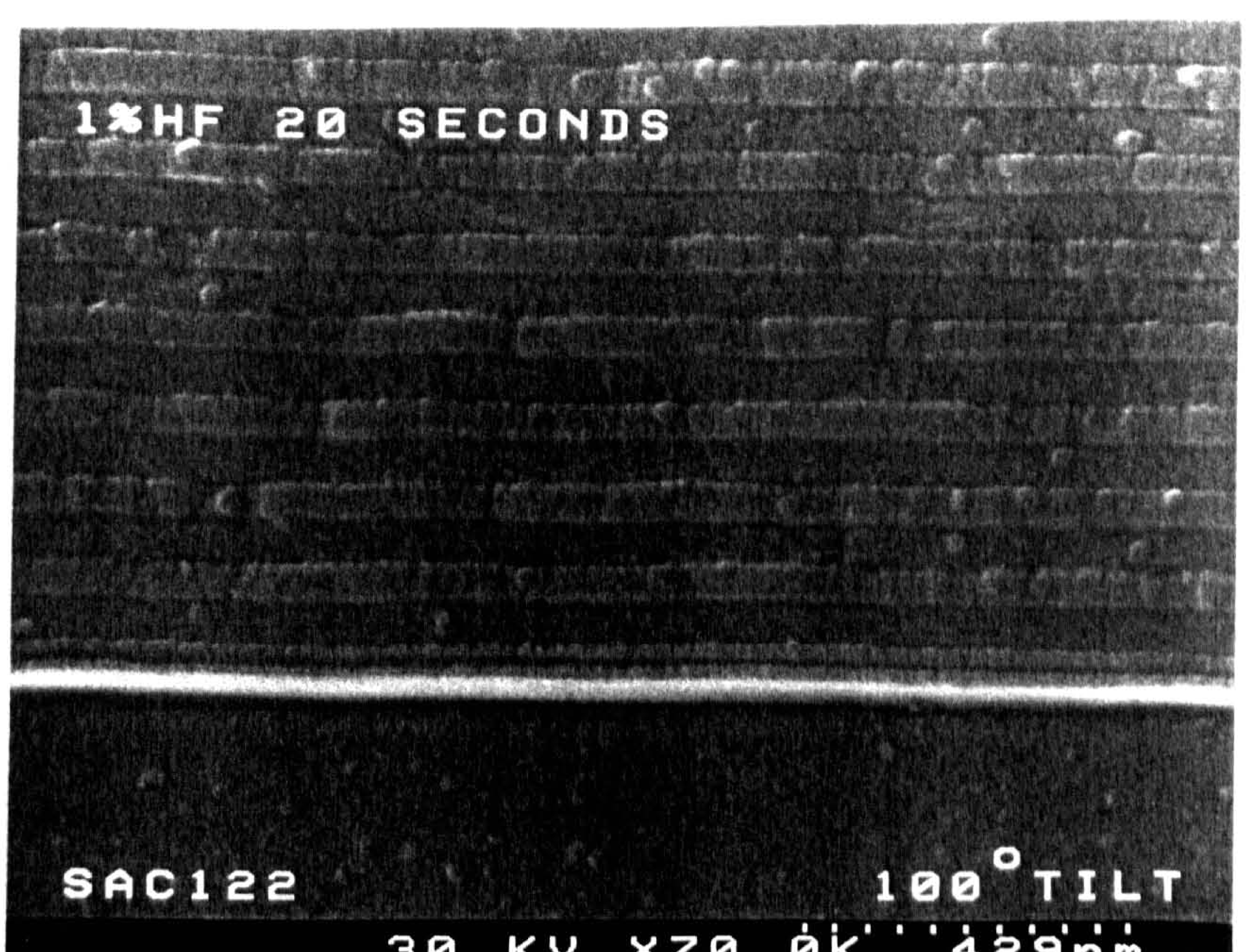

1%HF 20 SECONDS
SAC122
100° TILT
30 KV X30.0K 1.00μm
-32
-30
-25
-20
-15
-10
-5
-1-3


-32
-31
-30
-25
-20
-15

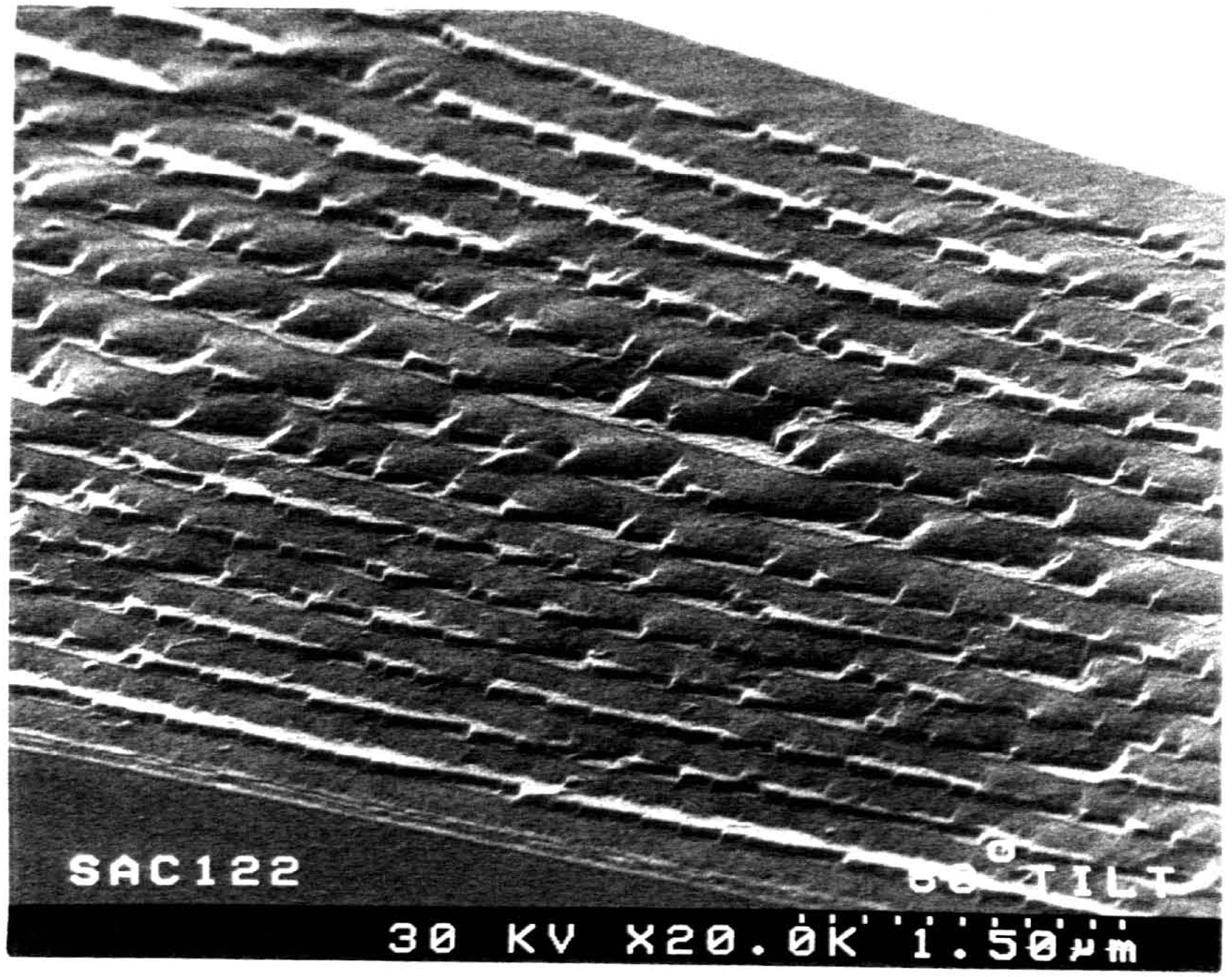

-20
-15
-10
-5
-1-3
SAC122
100° TILT
30 KV X50.0K 600nm

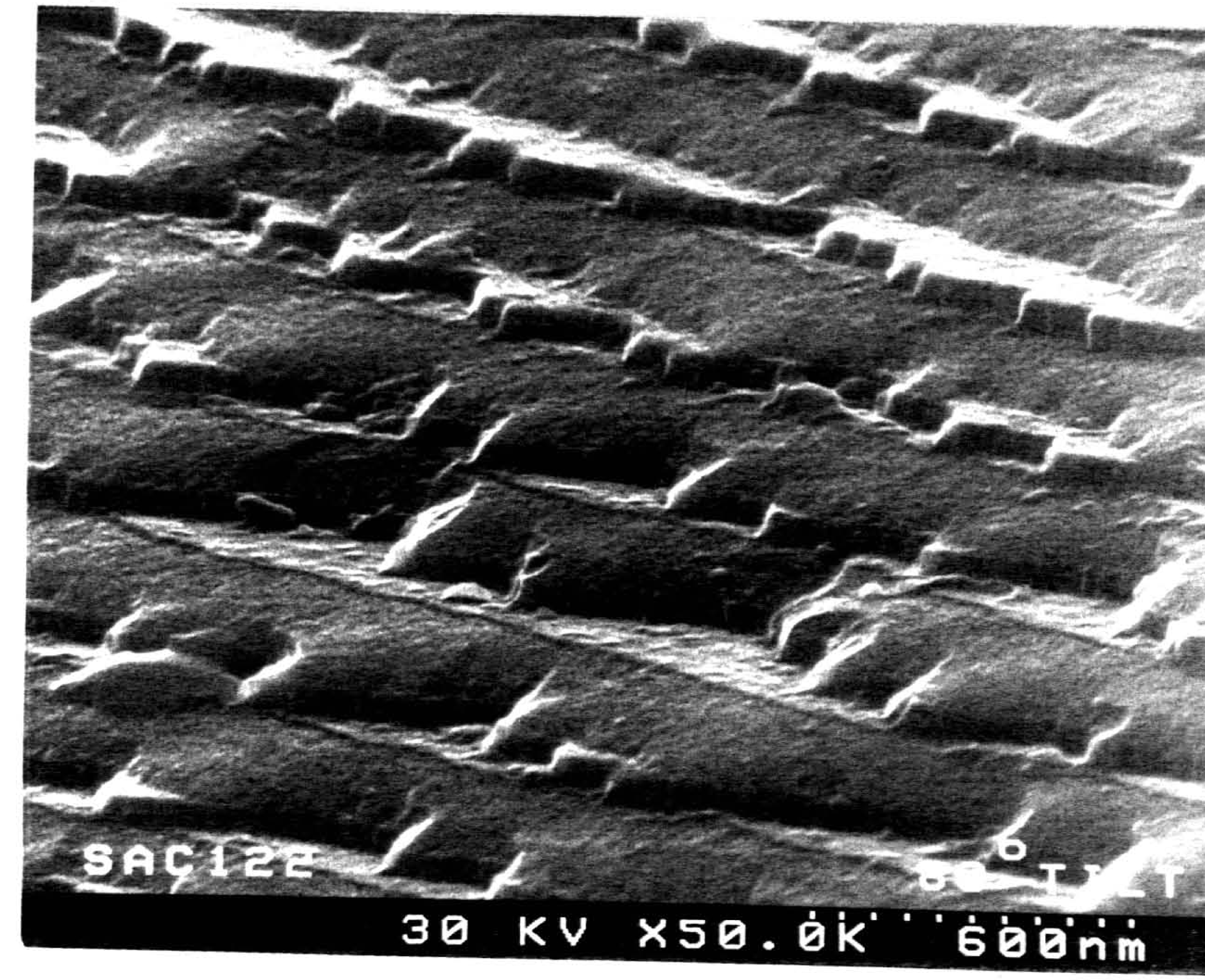
APPENDIX 5


1%HF 20 SECONDS
SAC122
100°TILT
30 KV X70.0K 429nm


1%HF 20 SECONDS
SAC122
100°TILT
30 KV X70.0K 429nm

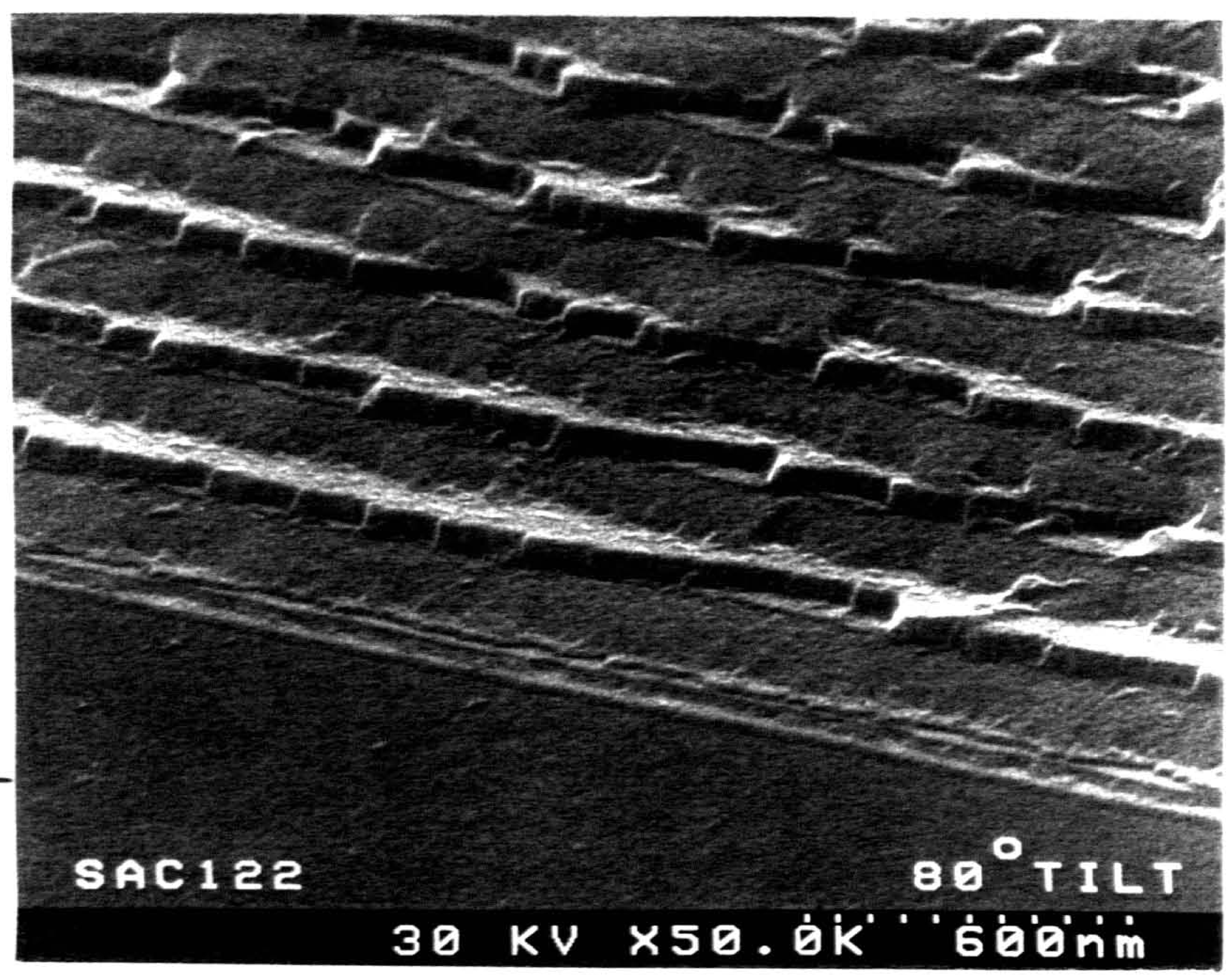
APPENDIX 5

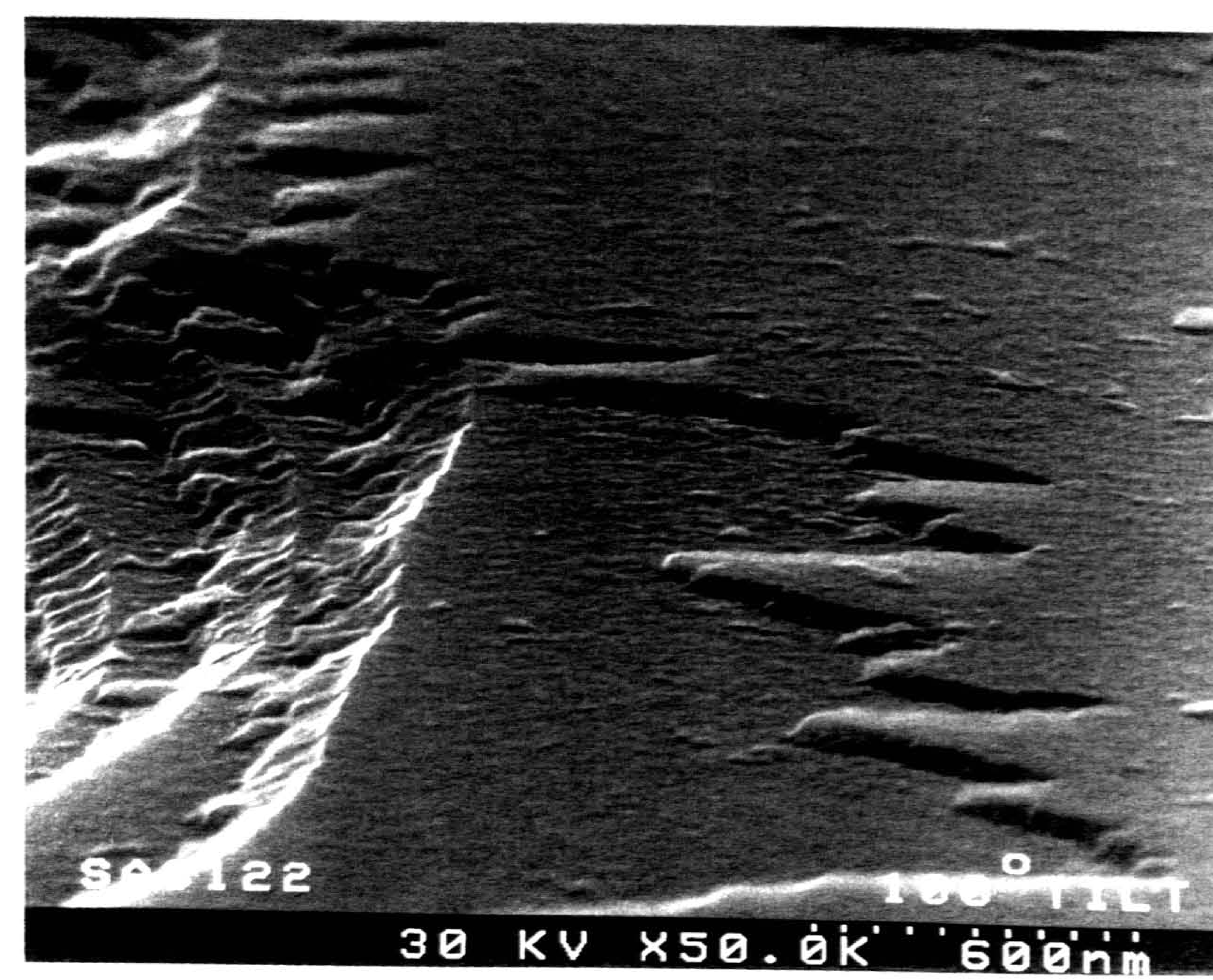




APPENDIX 5

GLASS





5

SAC 122

LAYER No.	THICKNESS Å
1	200
2	100
3	150
4	660
5	480
6	660
7	510
8	660
9	465
10	720
11	480
12	615
13	495
14	675
15	495
16	630
17	540
18	870
19	615
20	840
21	600
22	825
23	630
24	825
25	615
26	870
27	525
28	915
29	615
30	795
31	570
32	1230
TOTAL	19875

The figures given are intended only as a guide as measurement took place at only one possition on the x50,000 cross section photograph.

There is likely to be more error associated with layers 1-3 because they are so thin. Also layers 31 (due to flare) and 32 (the HF etch may have reduced the thickness of this) may not be accurate.

(ANALYSIS BY M.BAINES, PILKINGTON, 24.2.95)

APPENDIX 6

Reflection and Transmission

TABLE 1 and 2
Six samples from Liberty Mirror are rotated through 180°, recording their colours in reflection and transmission at 20° intervals. The results are documented in table form below.

TABLE 1.

REFLECTION.

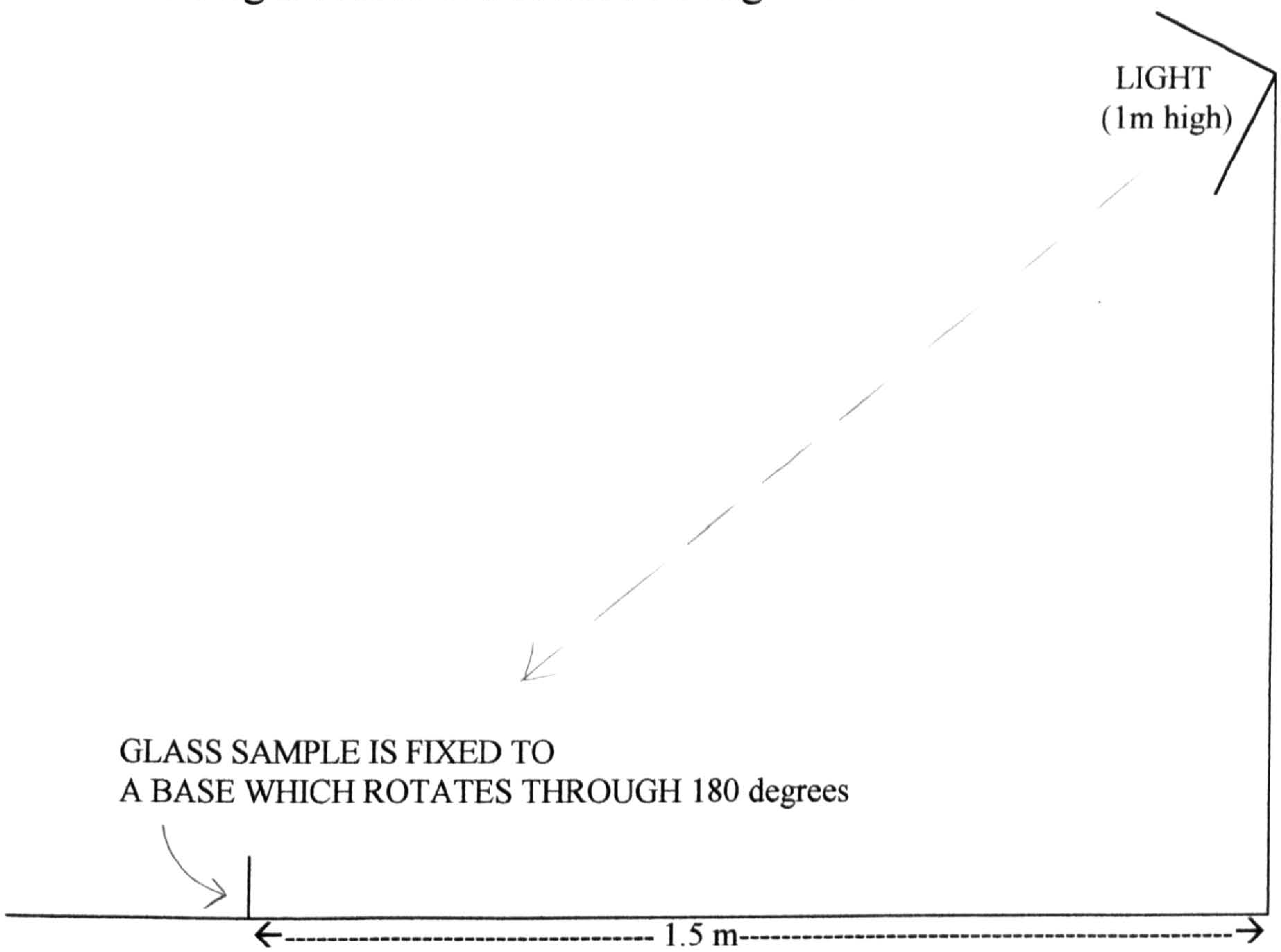
NAMED COLOUR	0°	20°	40°	60°	80°	100°	120°	140°	160°	180°
MAGENTA	Pale Green	Pale Green	Pale Blue	White/ Blue	White/ Violet	White	White/ Blue	Pale Blue	Pale Green	Pale Green
YELLOW	Electric Blue	Electric Blue	Blue/ Violet	Violet	Pale Violet	White	Pale Violet	Blue/ Violet	Electric Blue	Electric Blue
GREEN	Pink	Pink	Pale Pink	White	White	White	White	Pale Pink	Pink	Pink
CYAN	Red	Red/ Orange	Orange	Yellow/ Orange	White	White	Yellow/ Orange	Orange	Red/ Orange	Red
RED	Cyan	Cyan	Cyan/ White	Cyan/ White	Pale Violet/ White	White	Pale Violet/ White	Cyan/ White	Cyan	Cyan
BLUE	Yellow/ Gold	Yellow/ Gold	Yellow/ Green	Yellow/ Green	White/ Green	White/ Green	Yellow/ Green	Yellow Green	Yellow Gold	Yellow/ Gold

TABLE 2.

TRANSMISSION

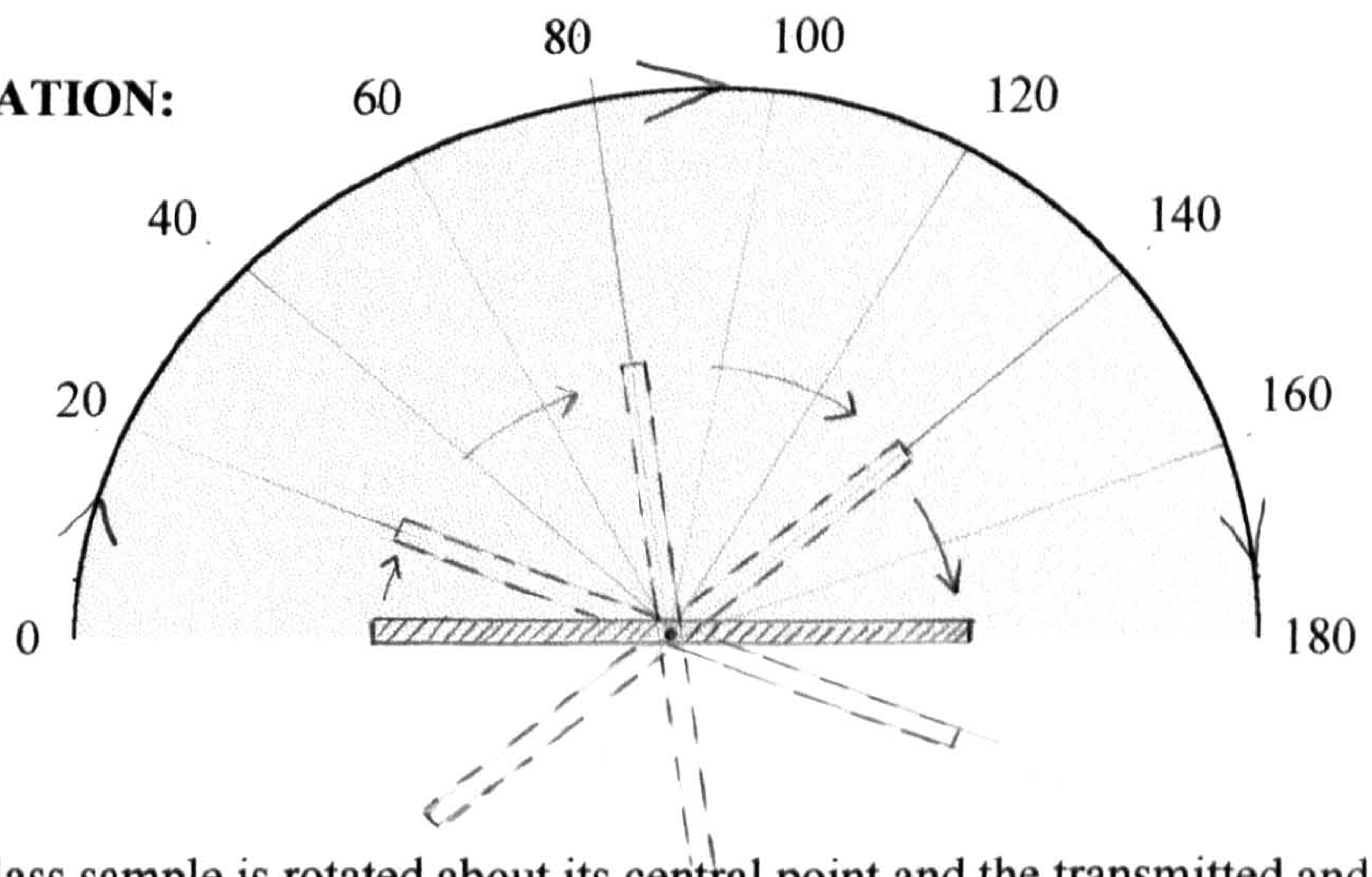
NAMED COLOUR	0°	20°	40°	60°	80°	100°	120°	140°	160°	180°
MAGENTA	Magenta	Pink	Pink/ Orange	Yellow/ Orange	Yellow	Yellow	Yellow/ Orange	Pink/ Orange	Magenta	Magenta
YELLOW	Yellow/ Orange	Yellow/ Orange	Yellow	Yellow	Pale Yellow	Pale Yellow	Yellow	Yellow	Yellow/ Orange	Yellow/ Orange
GREEN	Green	Green	Blue/ Green	Blue/ Violet	Pink	Pink	Blue/ Violet	Blue/ Green	Green	Green
CYAN	Cyan	Cyan	Deeper Cyan	Cyan/ Blue	Blue/ Violet	Blue/ Violet	Cyan/ Blue	Deeper Cyan	Cyan	Cyan
RED	Red	Red	Red/	Yellow/	Yellow	Yellow	Yellow/	Red/	Red	Red
BLUE	Blue	Blue	Blue/ Violet	Violet	Pink	Pink	Violet	Blue/ Violet	Blue	Blue

Glass Samples measuring 5cm x 5cm are placed directly in front of a light source and rotated through 180°.



Sample illustrated here is positioned at 0 degrees

ROTATION:



The glass sample is rotated about its central point and the transmitted and reflected colours are recorded at 20 degree intervals.

APPENDIX 7

PILKINGTON
TECHNICAL MIRRORS

HI-EFFICIENCY DICHROIC FILTERS

The dichroic effect is generated by evaporating layers of transparent dielectric materials of differing refractive index to precisely controlled microscopic thicknesses.

The effect is that a specific wavelength range of the visible light spectrum is reflected from the dichroic surface, and the remainder is transmitted through the substrate. Since the evaporated materials are transparent, the light is not absorbed as with pigments and paints, and this will create uniquely crisp and vibrant colors.

The visible result is that light transmitted through the dichroic surface will appear one color and light reflected from it will appear as a complementary color. As the angle at which the dichroic is viewed changes, the color that is transmitted and reflected also changes.

Specifications

Stock Sizes	23" x 44" x 1/16" Thick Float Glass 44" x 51" x 1/8" Thick Float Glass 44" x 51" x 1/4" Thick Float Glass
Colors (Transmitted)	Blue, Green, Red, Yellow, Magenta, Cyan

Capabilities

- Engineering is available for certain materials with odd sizes and shapes.
- Variations on size, color and material

Revised 11/26/96

APPENDIX 7

Pilkington Technical Mirror Corp.
851 Third Avenue Brackenridge Pennsylvania 15014 Telephone (412) 224-1800 Fax (412) 224-8754

PILKINGTON
TECHNICAL MIRRORS

Scope

These specifications apply to the coatings when they are applied to glass with an index of refraction of 1.523. For custom applications, transmission and reflectivity tolerances, and wavelength considerations can be specially tailored to customer's requirements.

Materials and Workmanship

(a) The coating process shall cause no injury to the glass surface which would cause rejection of the optical element under other applicable specifications. Any optical element which has met the requirements of other applicable specifications prior to coating shall not be rejected after coating because of fine hair lines or other defects in such optical element which are made more visible by the coating.

(b) The coating shall have substantially low absorption of visible light.

Reflection

The coated element shall reflect from the front surface at least 90% of the incident light at the specified wavelength which includes a tolerance of +/- 10 millimicrons. Our capabilities range from 90% reflectivity up to 99% at the specified wavelengths. Representative spectrophotometric curves for some of our standard coatings are shown.

Adherence

No visible part of the coating shall be removed by the cellulose tape test described here:

Test: The tacky surface of cellulose tape shall be carefully placed in contact with a portion of the coated surface and firmly rubbed against that surface. It shall then be quickly removed with a snap action that exerts the greatest possible stripping action on the mirror film.

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Hardness

No evidence of film removal or film abrasion shall be visible to the eye when any one or all of the following tests are applied:

(a) The coated optical element shall be carefully washed first in a solution consisting of one (1) ounce of sulphated alcohol, one (1) ounce 15 Baume normal ammonium hydroxide, and one (1) gallon water; then cleaned in acetone or grain alcohol and dried with lens tissue or soft cloth. The temperature shall not exceed 80°F.

(b) A thick paste of U.S.P. precipitated chalk and water shall be applied to the coating and allowed to dry, and then wiped off with a soft cloth.

(c) A pad of clean dry cheese cloth (previously laundered) 3/8 inch in diameter, 1/2 inch thick, bearing with a force of one pound on the coating shall be rubbed across the coated element in any direction 150 times.

Note: During the above tests, care should be exercised to prevent contaminating abrasives contacting the coated surface causing slight sleeks.

Durability

No evidence of film deterioration visible to the eye shall result from one or both of the following tests:

(a) The coated element shall be placed in a thermostatically controlled cabinet with a salt atmosphere at a temperature of 95°F. plus or minus 4°F. for 48 hours. The salt atmosphere shall be obtained by allowing a stream of air to bubble through a salt solution containing about 1 1/2 pounds of sodium chloride per cubic foot of water.

(b) The coated element shall be placed in a thermostatically controlled humidity cabinet with an atmosphere of at least 95% relative humidity and at a temperature of 120°F. plus or minus 4°F. for a continuous period of 24 hours.

Water Resistance

No evidence of film deterioration visible to the eye shall result from the following test:

A drop (0.05 milliliter) of distilled water shall be permitted to dry at room temperature on the coated surface and the coated surface shall then be cleaned with acetone or grain alcohol.

Effect of Temperature

The coating shall function satisfactorily and shall not be damaged by exposure to an ambient temperature of minus 60°F. and plus 500°F.

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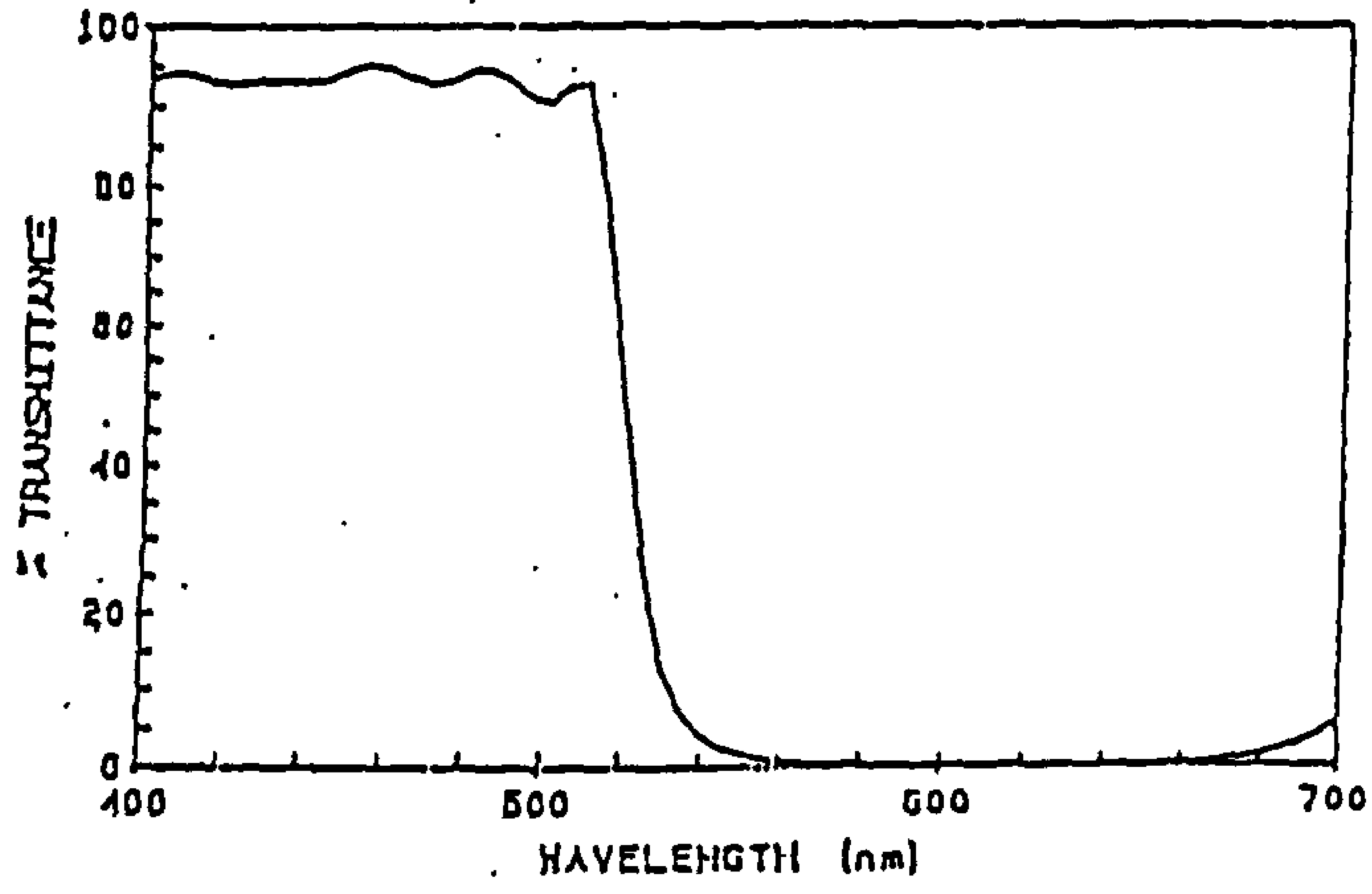
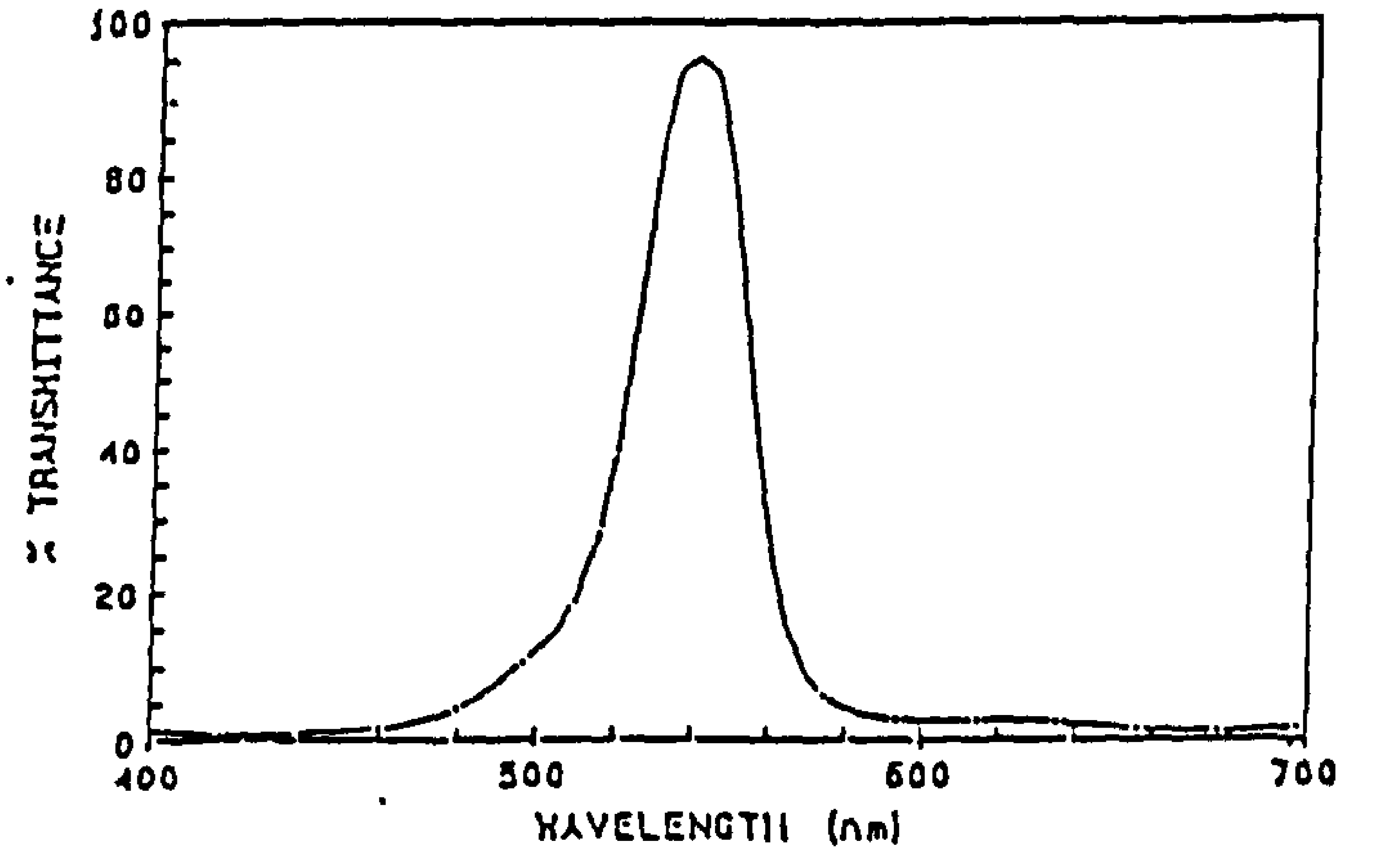
PILKINGTON
TECHNICAL MIRRORS

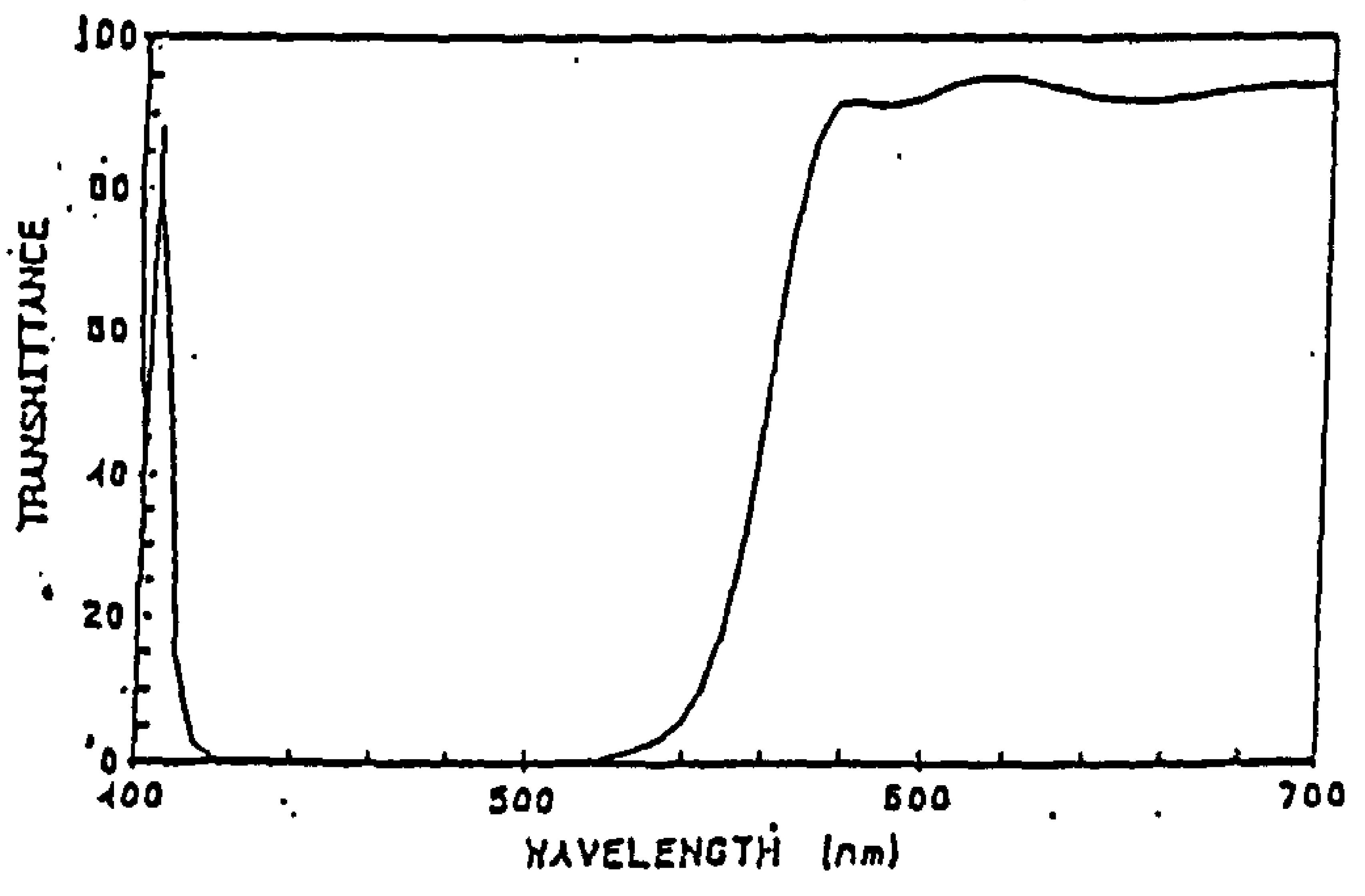
BLUE DICHROIC



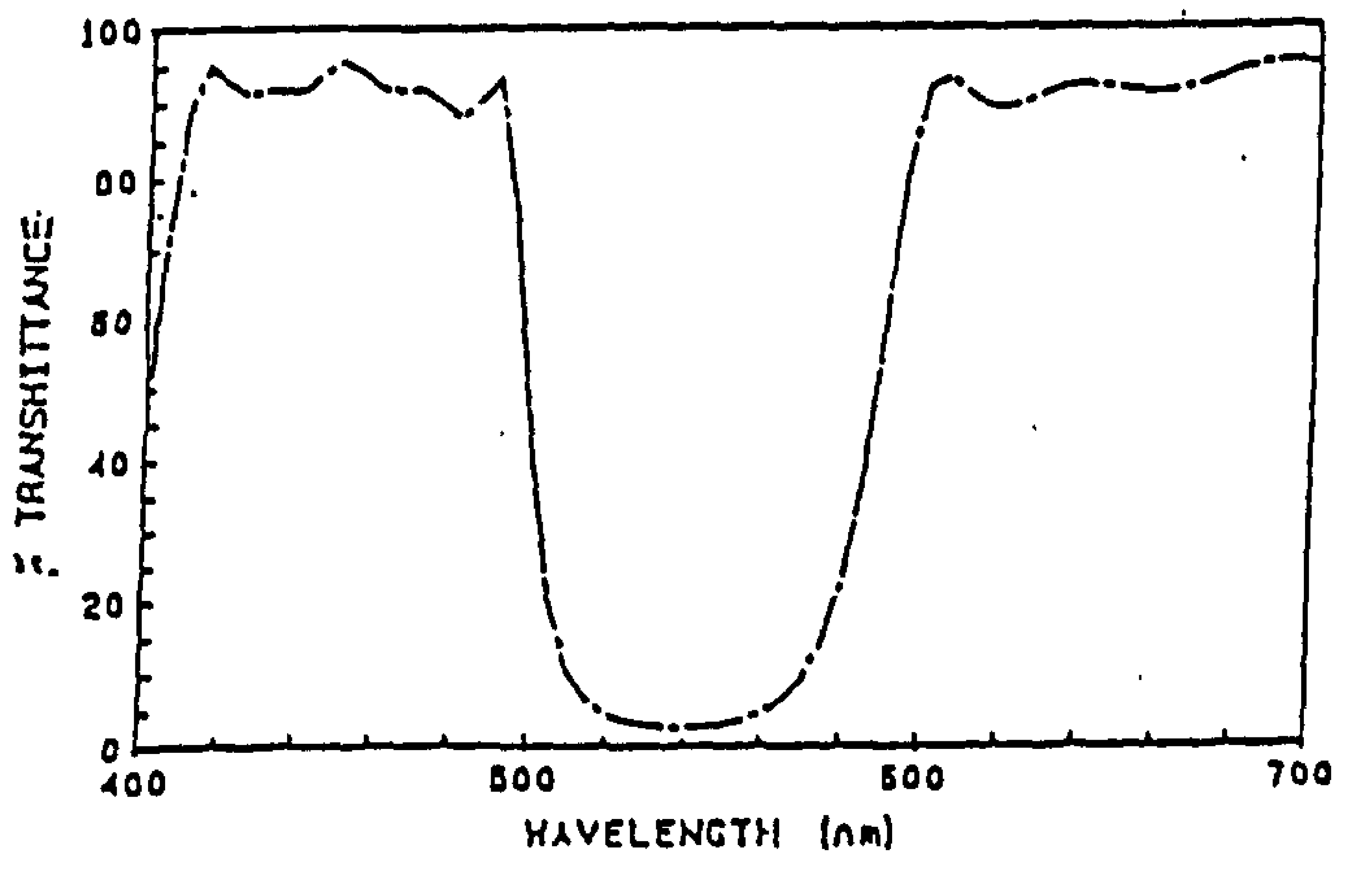
GREEN DICHROIC



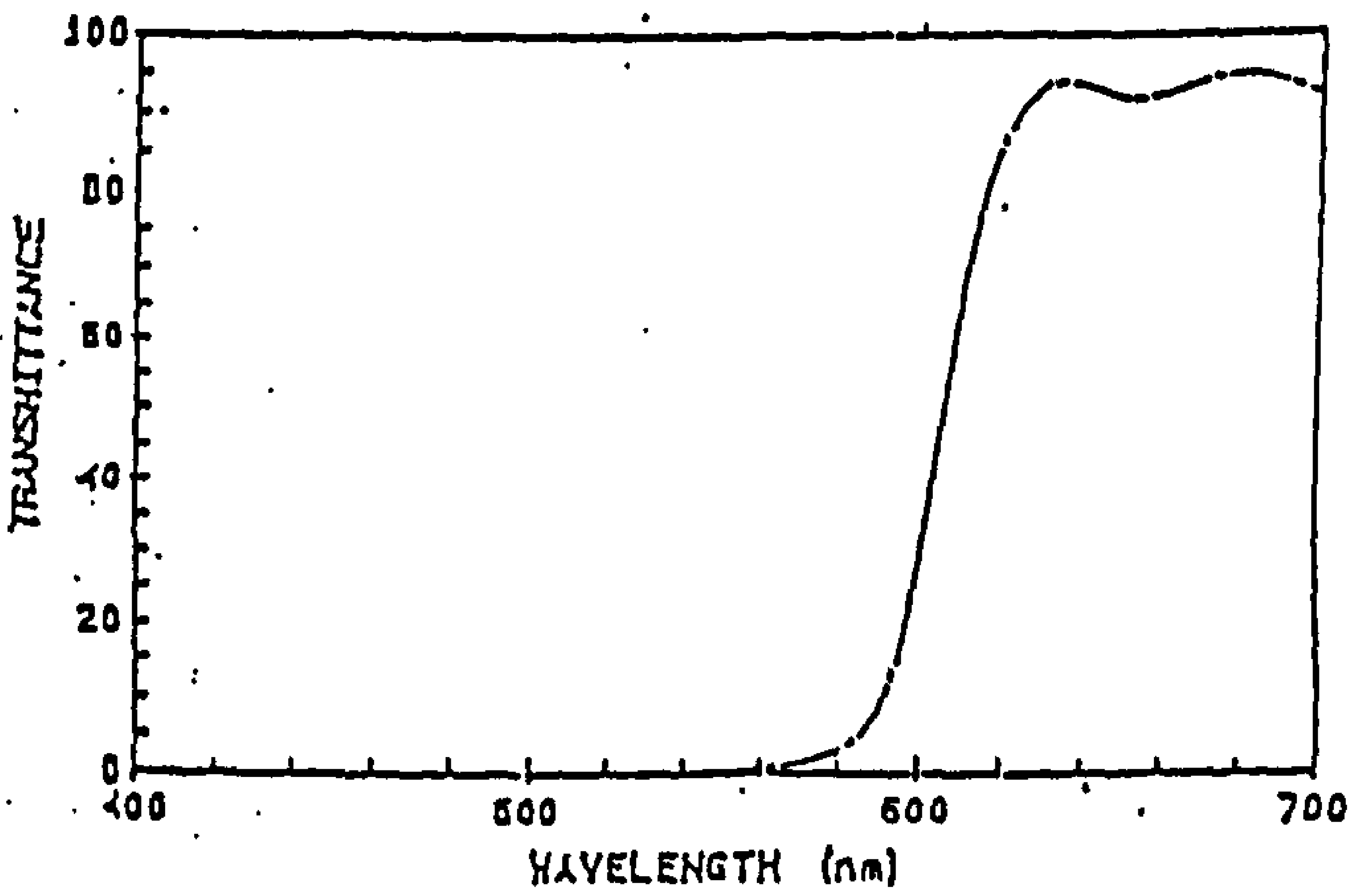
YELLOW DICHROIC



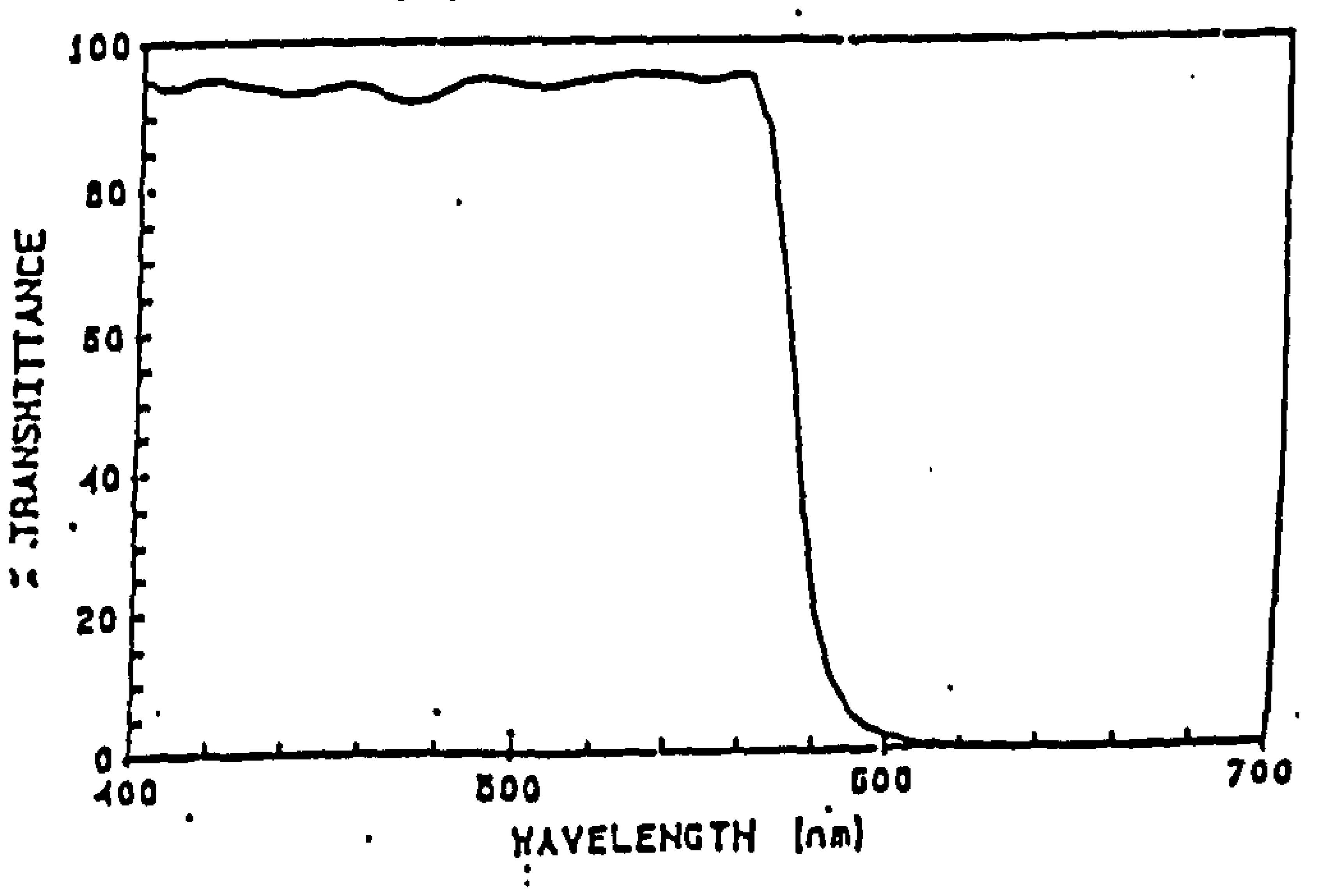
MAGENTA DICHROIC



RED DICHROIC



CYAN DICHROIC



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APPENDIX 8

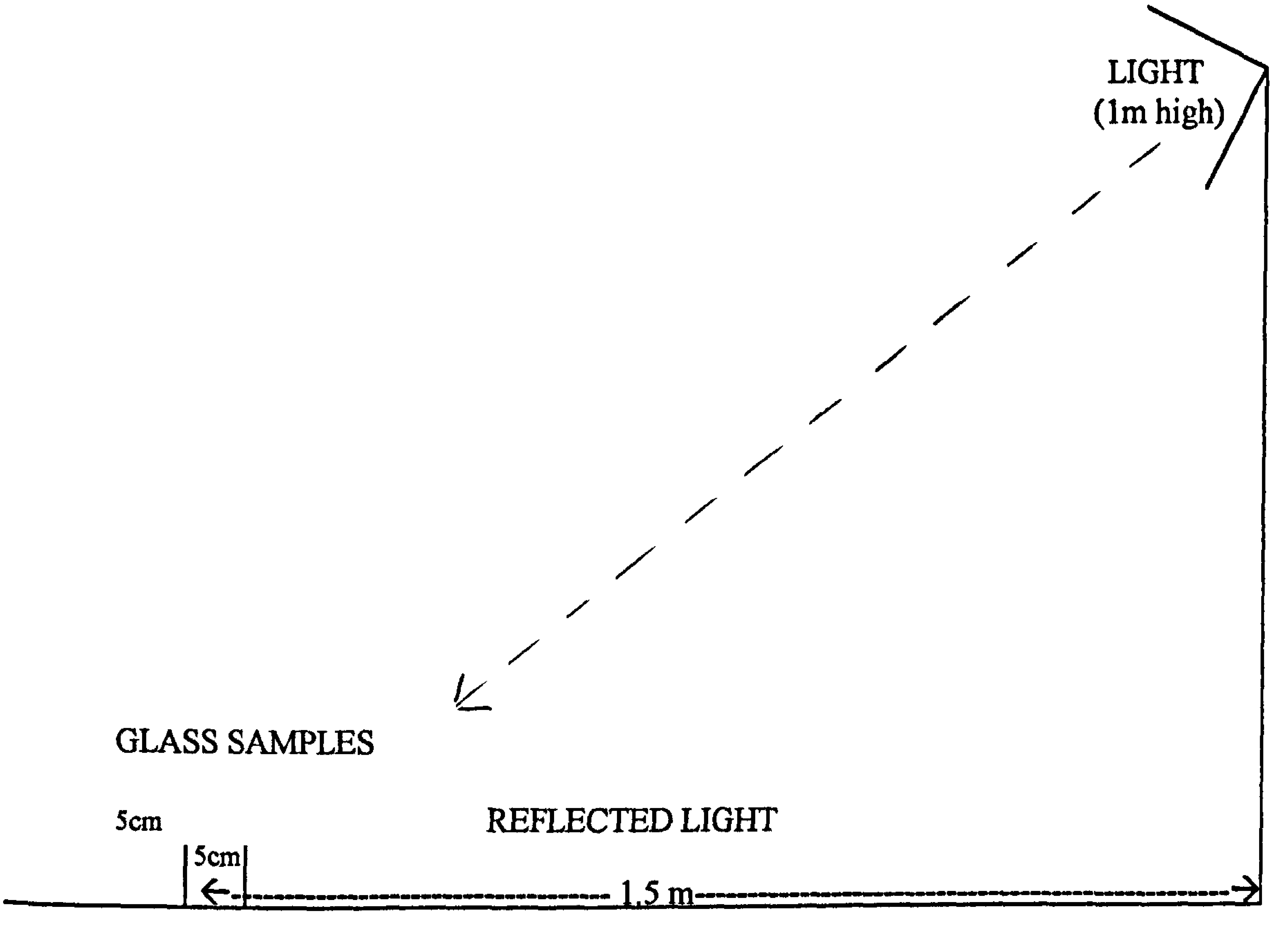
TABLE 3.

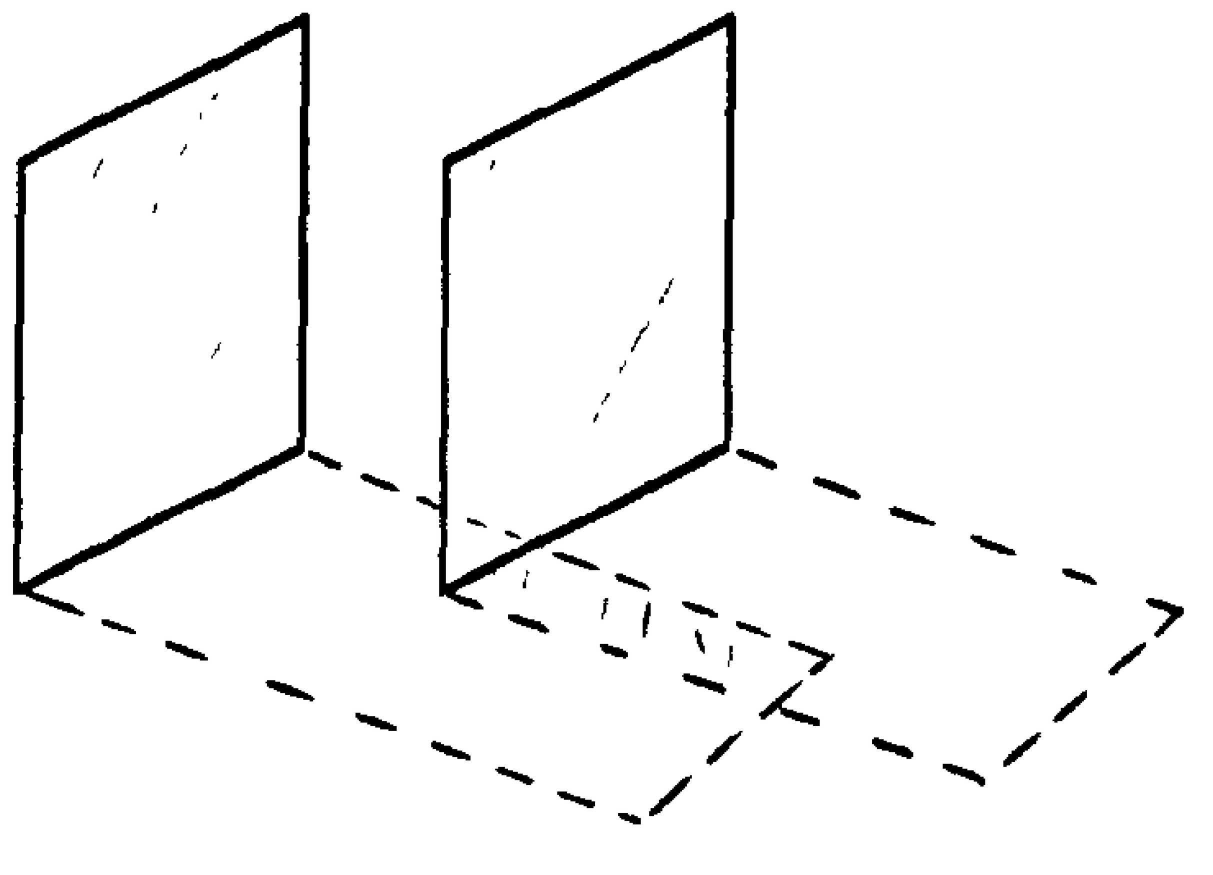
Using the Liberty Mirror samples again, the effect on the reflected colour was tested when one sample was placed behind the other, off-set so that the colours partially overlap. Here it was possible to see the reflected colours from each sample and the reflected colour created where the samples crossed.

	Colours Placed infront of the Samples Listed in the left-hand Column.					
	CYAN	RED	GREEN	BLUE	YELLOW	MAGENTA
MAGENTA	PALE YELLOW	PALE CYAN	PALE NEUTRAL/ CREAM	PALE YELLOW	CYAN	x
RED	NEUTRAL/ WHITE	x	PALE CREAM	PALE BLUE/ VIOLET	PALE GREEN/ CYAN	PALE COOL PINK
BLUE	YELLOW/ ORANGE	PALE/ ORANGE	NEUTRAL/ PALE CREAM	x	PALE YELLOW	COOL YELLOW/ CREAM
CYAN	x	PALE PINK	PALE PINK	YELLOW	PURPLE	PALE GREEN/ YELLOW
YELLOW	MAGENTA	PALE CYAN	x	PALE CREAM	PALE LILAC	NEUTRAL GREEN/WHITE
GREEN	BLUE	YELLOW	x	BLUE	YELLOW	MAGENTA

The diagram on the next page illustrates the optical set up used in this test.

Glass Samples measuring 5cm x 5cm are placed directly in front of a light source.

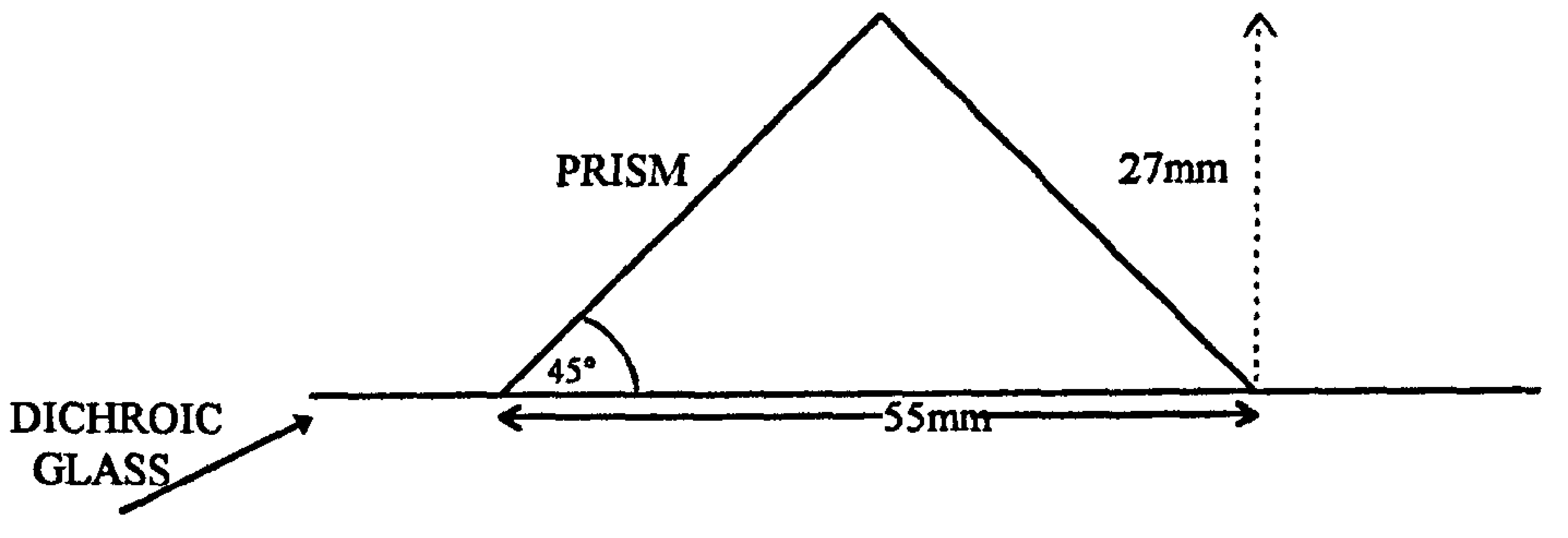


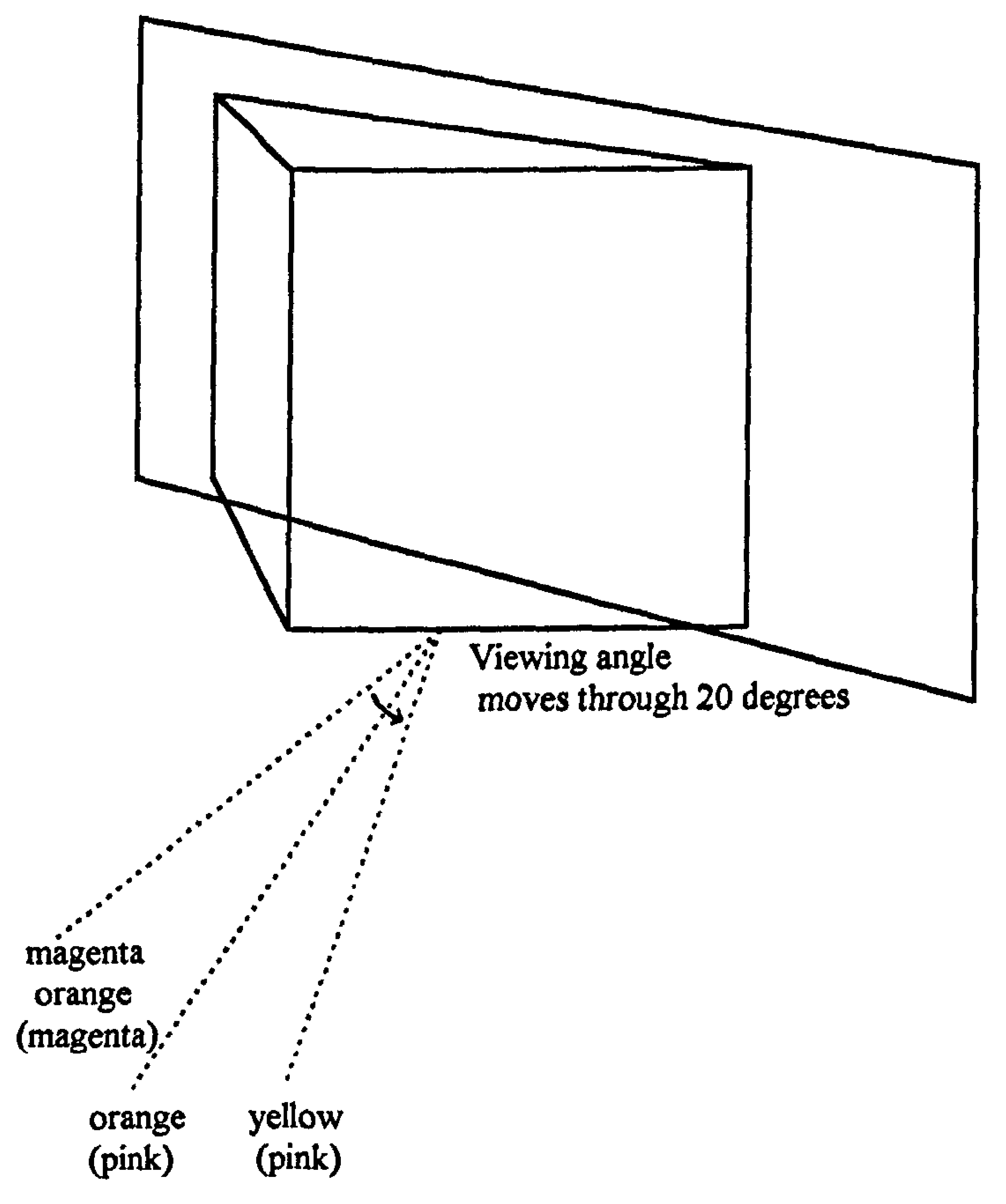


Glass Samples are placed one in front of the other, off-set so that the reflected colour of each is clearly visible along with the colour mix created by overlap of reflection.

Appendix 8 : BONDING GLASS TO GLASS.

Sample A: A prism bonded to a 'magenta' sample produced interesting optical effect.

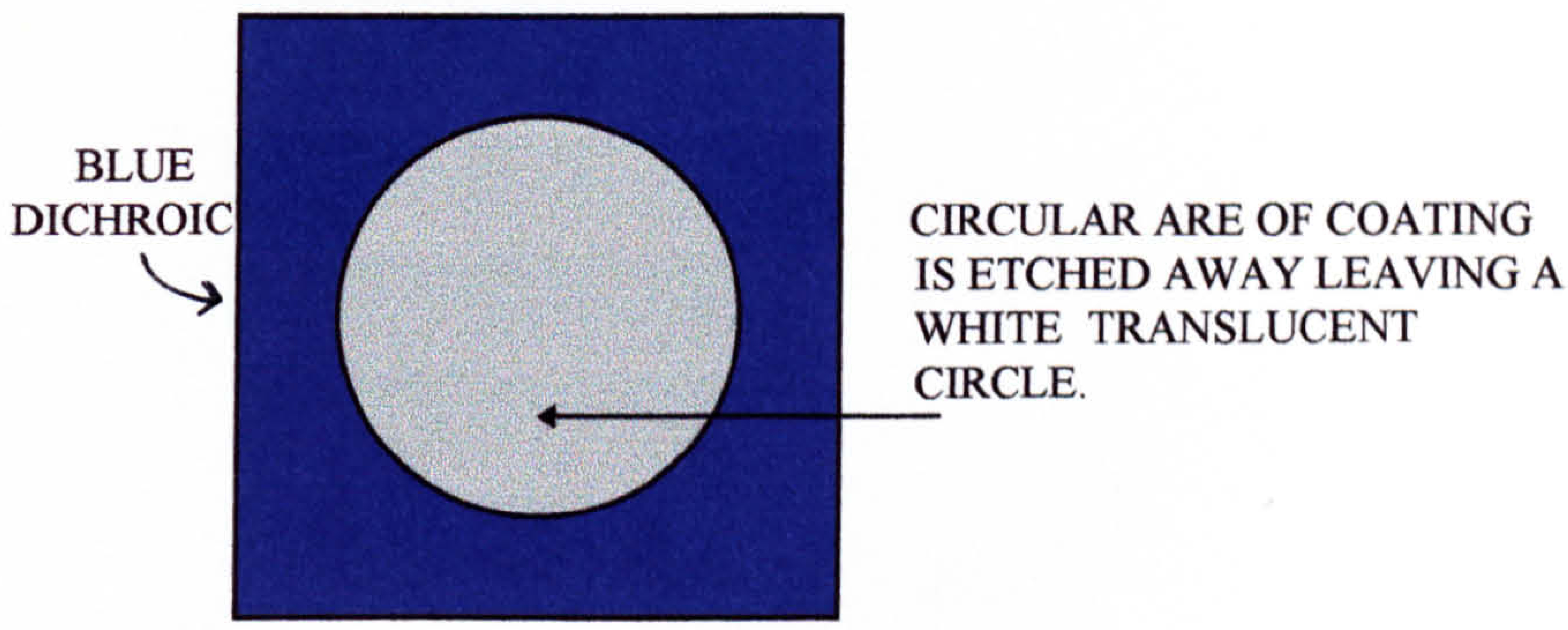




Appendix 8.

Sample B:

A circular area of coating is etched away leaving a white area in the centre of a blue sample.



A 55mm DIAMETRE OTICAL LENS IS BONDED TO THE ETCHED AREA

THE TRANSLUCENT AREA BECOMES TRANSPARENT ALLOWING CLEAR VIEW THROUGH.

APPENDIX 9

Mario Minchella Architects

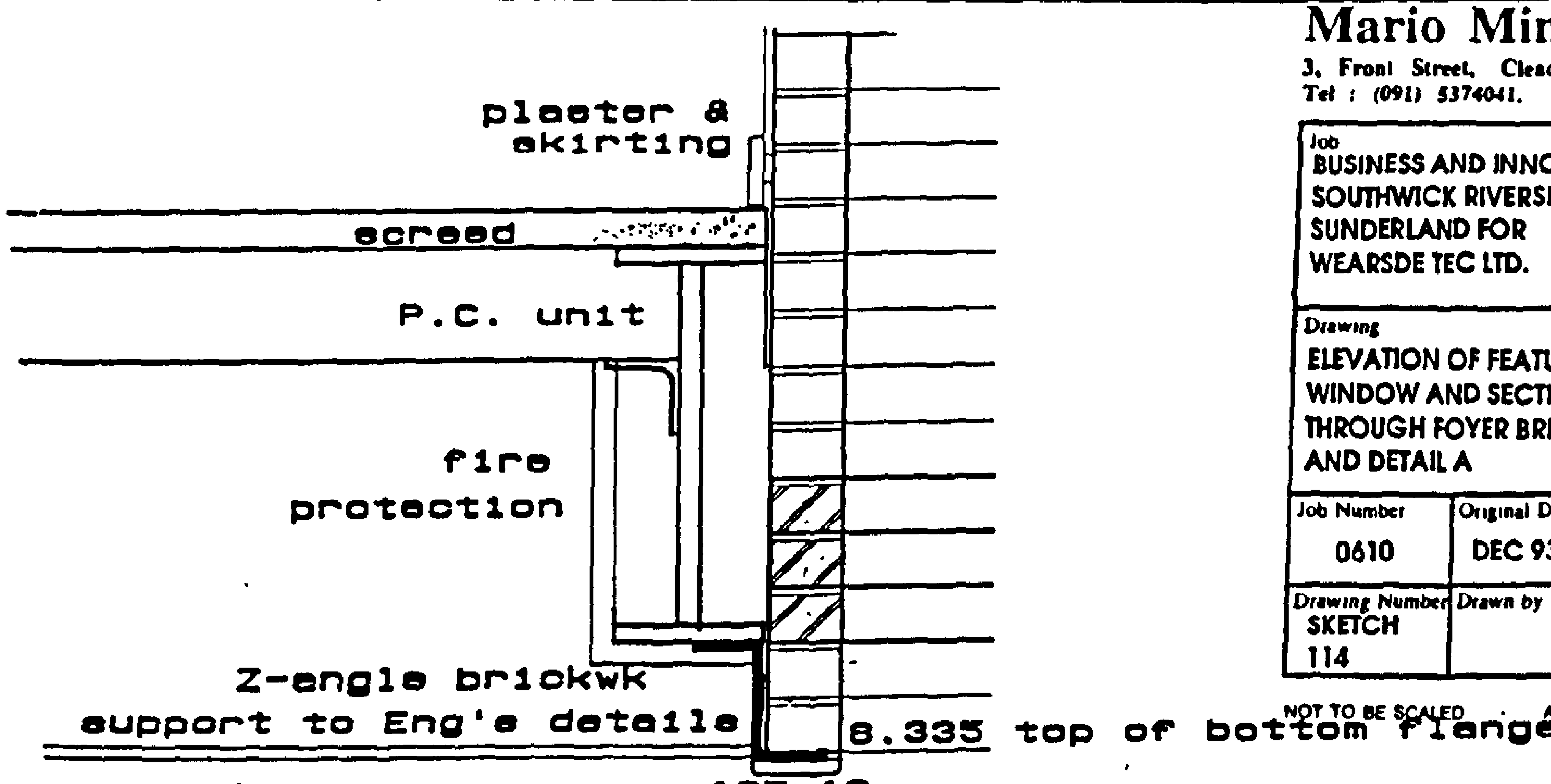
3, Front Street, Cleadon Village, Sunderland SR6 7QE.
Tel : (091) 5374041. — Fax : (091) 5190448.

Job
BUSINESS AND INNOVATION CENTRE
SOUTHWICK RIVERSIDE
SUNDERLAND FOR
WEARSDE TEC LTD.

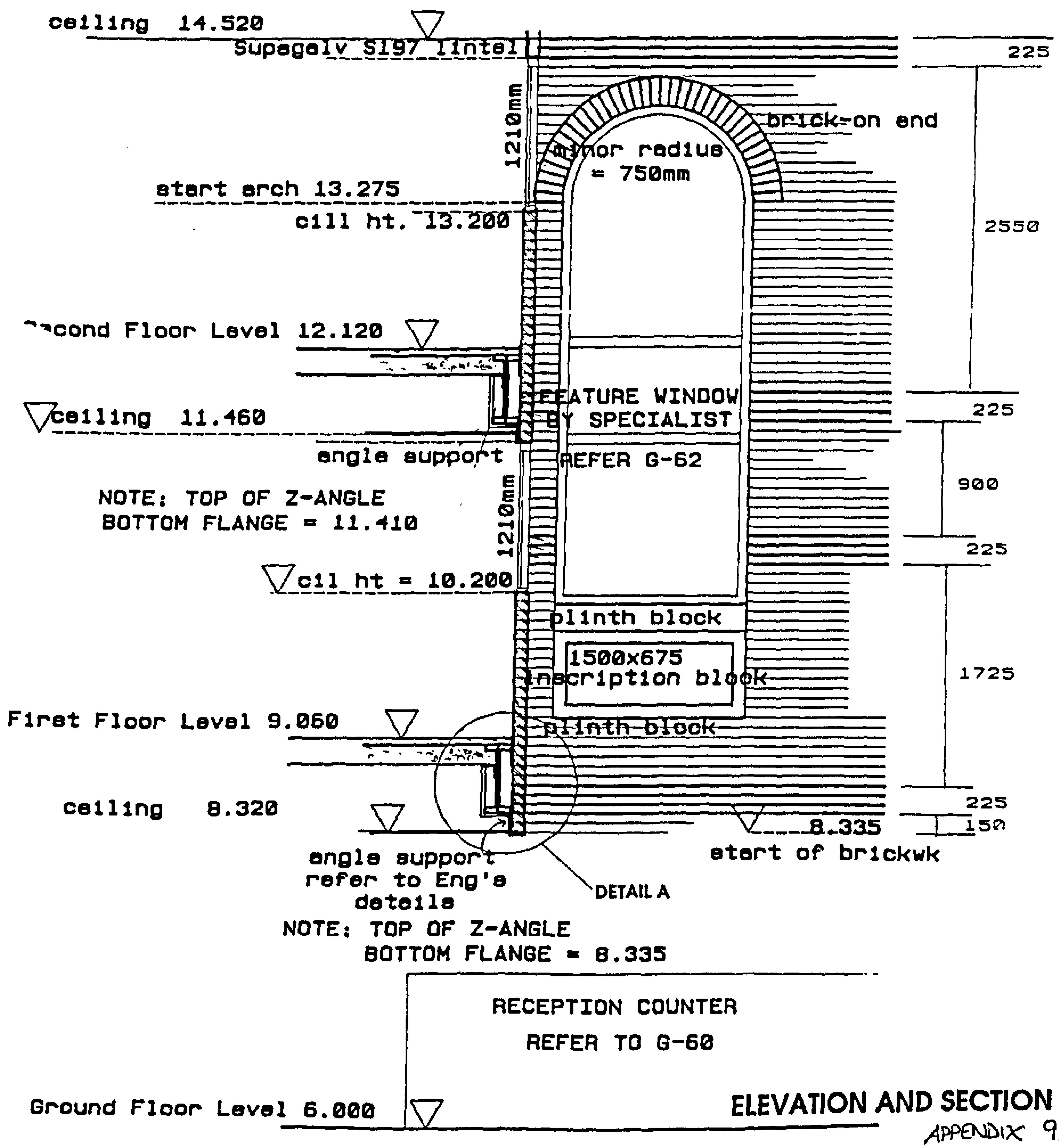
Drawing
ELEVATION OF FEATURE
WINDOW AND SECTION
THROUGH FOYER BRICKWORK
AND DETAIL A

Job Number	Original Date	Scales	Revision
0610	DEC 93	1:10 1:33	
Drawing Number	**Drawn by**		date
SKETCH 114			

NOT TO BE SCALED — ALL DIMENSIONS TO BE CHECKED ON SITE



DETAIL A 1:10



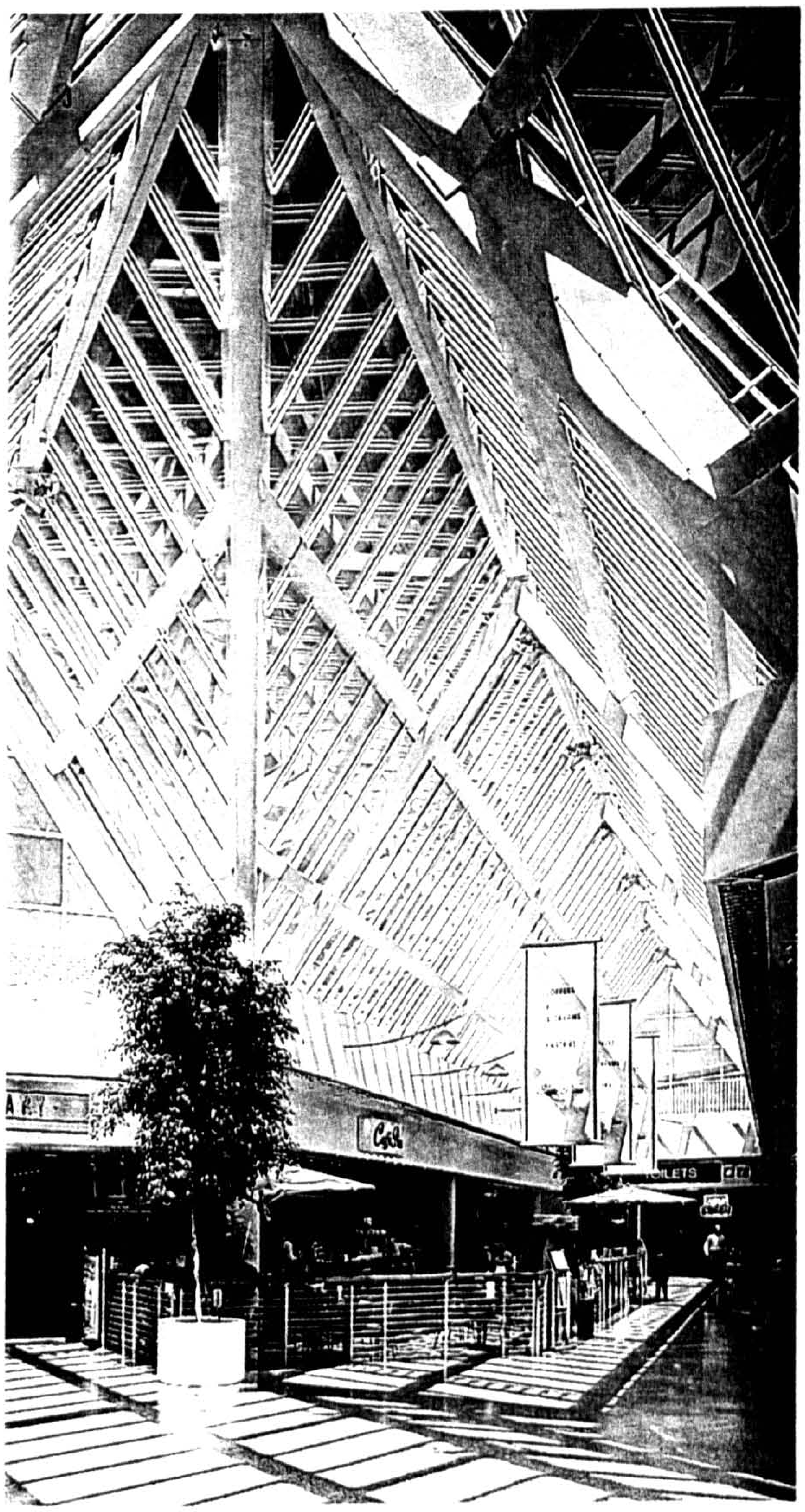
ELEVATION AND SECTION 1:33

APPENDIX 9.

APPENDIX 10

CI/SfB (31) Ro6 (M5)
May 1997

Glass for Solar Control



Pilkington SUNCOOL *High Performance*

Pilkington SUNCOOL *Low Reflection*

Pilkington SUNCOOL *Classic*

Pilkington ECLIPSE

Pilkington REFLECTAFLOAT

Pilkington ANTISUN

Pilkington Spandrel Panels

PILKINGTON

APPENDIX 10

Glass for Solar Control

Clear glass is ideal for admitting light and keeping out the weather, but is neither an effective barrier to solar energy, nor a good thermal insulator.

Pilkington Solar Control Glasses address this problem by providing designers with a range of products and performances to meet most environmental requirements – solar control, daylighting, thermal comfort and energy conservation.

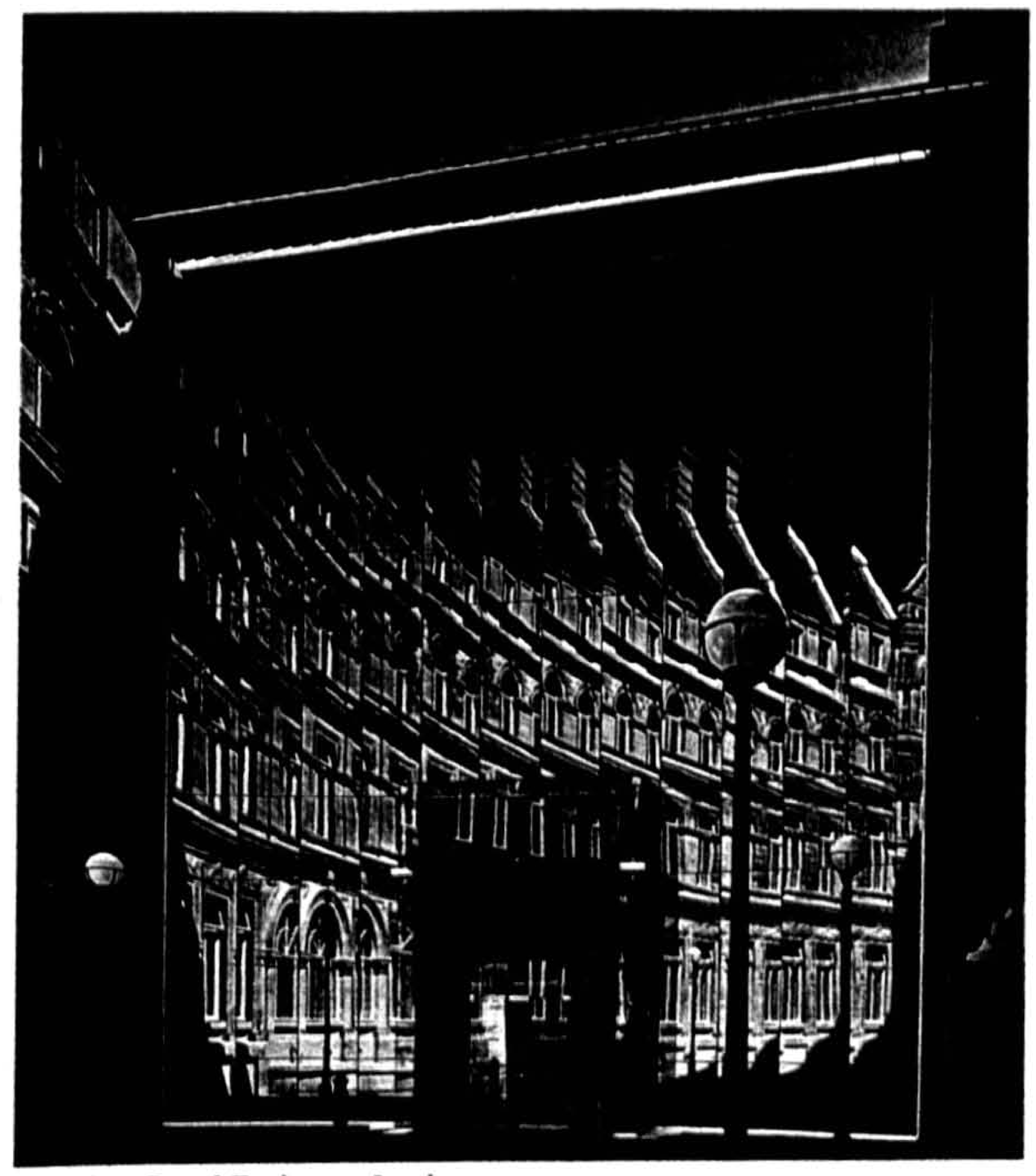
Vigilant House

APPENDIX 10 2

Putting you in control of your environment

Buildings need to provide a comfortable environment for their occupants, keeping them cool in summer, warm in winter, whilst at the same time making the building an 'efficient performer' in the use of energy for heating, cooling and lighting.

Pilkington Solar Control Glasses offer a wide range of performance options which enable the designer to balance these often conflicting needs, whilst the wide range of colours and glass types – reflective, neutral, body tinted – ensure that the aesthetics of a building need not be compromised, especially when used with contrasting or harmonising spandrel panels.



Guardian Royal Exchange, Leeds

Glazing Orientation	Principal Application	Primary Function						
		Environmental Control						
		Solar Control	Thermal Insulation	Noise Control	Fire Resistance	Safety and Security	Privacy and Decoration	Mechanical Strength
Vertical	Curtain Wall	•	•	•				•
	Window	•	•	•		•	•	
	Door				•	•	•	
	Barrier					•		•
	Partition			•	•	•	•	•
	Vision Panel				•	•	•	
Non-Vertical	Sloped Wall	•	•			•		•
	Roof Glazing	•	•			•		•
	Canopy					•	•	•
	Floor				•	•		•

APPENDIX 10 3

The Complete Solar Control Solution

Product Description

Pilkington SUNCOOL *High Performance*

Only available as Insulating Units, these coated glasses provide a high solar control performance, with the highest level of thermal insulation. Appearance in reflection: Blue, Bronze, Clear, Green, Grey, Neutral and Silver.

Pilkington SUNCOOL *Low Reflection*

The durable coating on these glasses combines low external reflection with high solar control performance. The coating also possesses low emissivity properties for improved thermal insulation. Appearance in reflection: Blue, Bronze, Green and Grey.

Pilkington SUNCOOL *Classic*

A range of high performance, reflective products with a durable surface coating applied to clear or tinted glasses. Appearance in reflection: Blue, Bronze, Green, Grey and Silver.

Pilkington ECLIPSE

A series of four reflective, medium performance solar control glasses with a durable coating applied during manufacture to a range of clear or tinted glasses. The coating can be glazed to either the interior or exterior of the building to provide an extended range of different colour effects. Appearance in reflection: Blue/Green, Bronze, Grey and Silver. Bright Silver (coating to exterior).

Pilkington REFLECTAFLOAT

A medium performance reflective product which has its durable coating applied during glass manufacture. Appearance in reflection: Silver.

Pilkington ANTISUN

A range of low to medium performance, body-tinted float glasses. The solar control properties and colour densities vary with thickness. Appearance in reflection and transmission: Blue, Bronze, Green and Grey.

Pilkington Spandrel Panels

A range of opaque, toughened glasses developed to harmonise or contrast with the full range of Pilkington Solar Control Glasses. They are available in single and double glazed forms – with or without insulation – and can incorporate selected solar control glasses, or the Pilkington ARMOURCLAD range of ceramic coated glasses.

The Pilkington ARMOURCLAD range is available in eight colours: Black, Harmonic Blue, Bronzetone, Cactus, Graphite, Grey and Harmony Bronze.

Advantages

Pilkington Solar Control Glasses:

- Reduce solar heat gains with a full range of high, medium and low performance options
- Offer choice of high to low light transmittances
- Provide varying degrees of reflectance including low reflectance
- Available in a wide range of colours and appearances to meet aesthetic design requirements
- Can be used in Pilkington Insulating Units in combination with many other glasses, including PILKINGTON K GLASS for improved thermal insulation
- Available in toughened or laminated form for safety and security
- Can be used in a range of harmonising Pilkington Spandrel Panels
- Comprehensive range of solar control performance options

APPENDIX 10
4

Pilkington SUNCOOL *High Performance*

High performance insulating units offering total environmental control

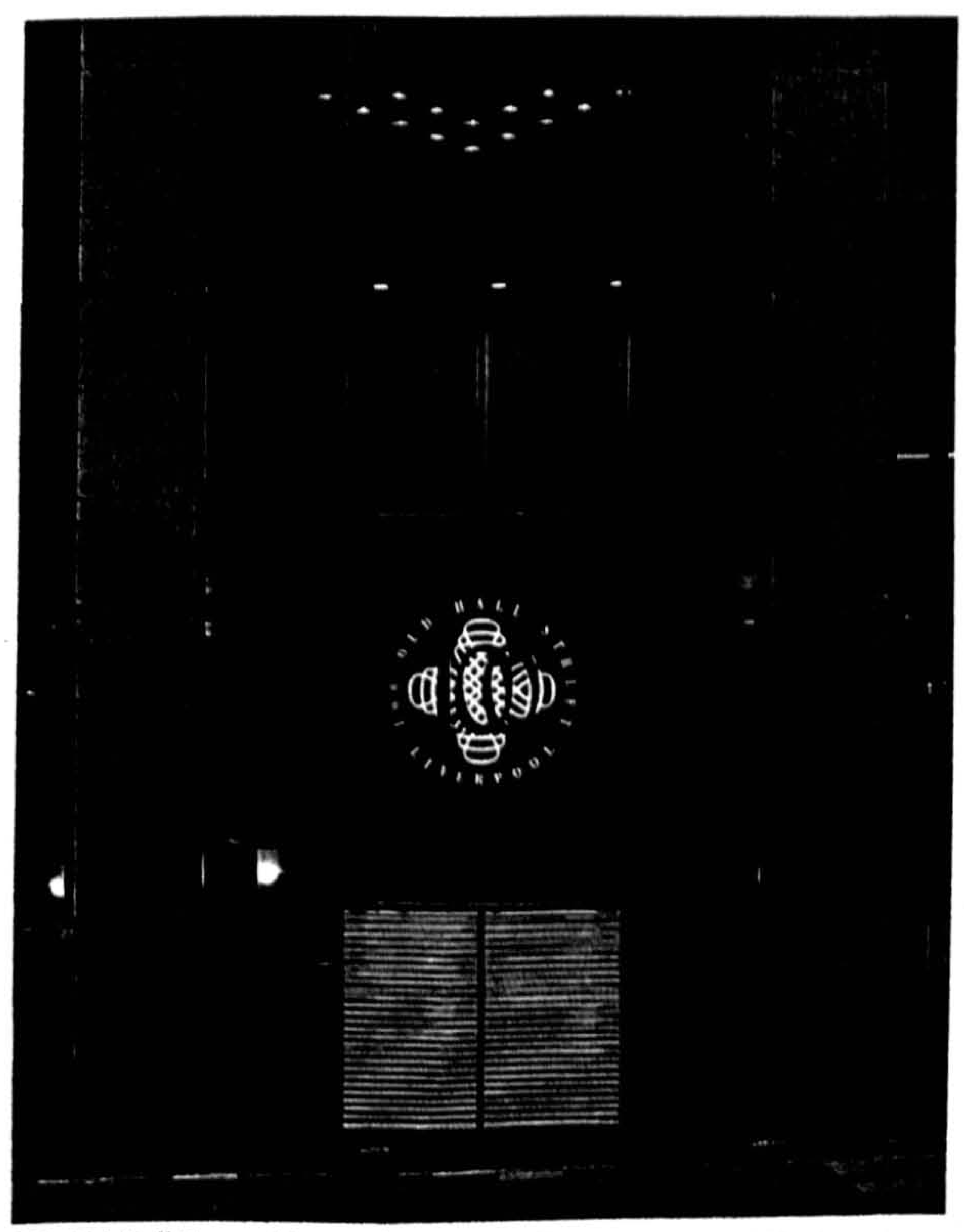
- Very high Solar Control performance
- High light transmission and low heat transmission with highest level of thermal insulation
- Cost effective solution for achieving low energy consumption
- Colours: Blue, Bronze, Clear, Emerald Green, Green, Grey, Jade Green, Neutral, Olive Green and Silver
- External reflections ranging from a low 9% (Neutral) to 43% (Silver)
- Light transmissions vary from 63% (Clear) to 20% (Grey) giving excellent light/heat ratios
- Ideally suitable for large areas of glazing where the need is to control solar gains whilst still providing high light levels
- Pilkington SUNCOOL *High Performance Clear* – a high light transmission glass with a clear appearance and a high degree of solar and thermal control – developed to meet the demands of recent design trends

Boots HQ, Nottingham

Pilkington SUNCOOL *Low Reflection*

Reflecting less than an ordinary clear glass insulating unit

- High Solar Control performance
- Medium to low light transmission
- Ideal for projects where reflective glasses are undesirable
- Low reflections allow these glasses to blend with, and complement, other building materials
- Colours: Blue, Bronze, Green and Grey
- Very low external reflections between 5 and 12% – less than a clear insulating unit (14%)



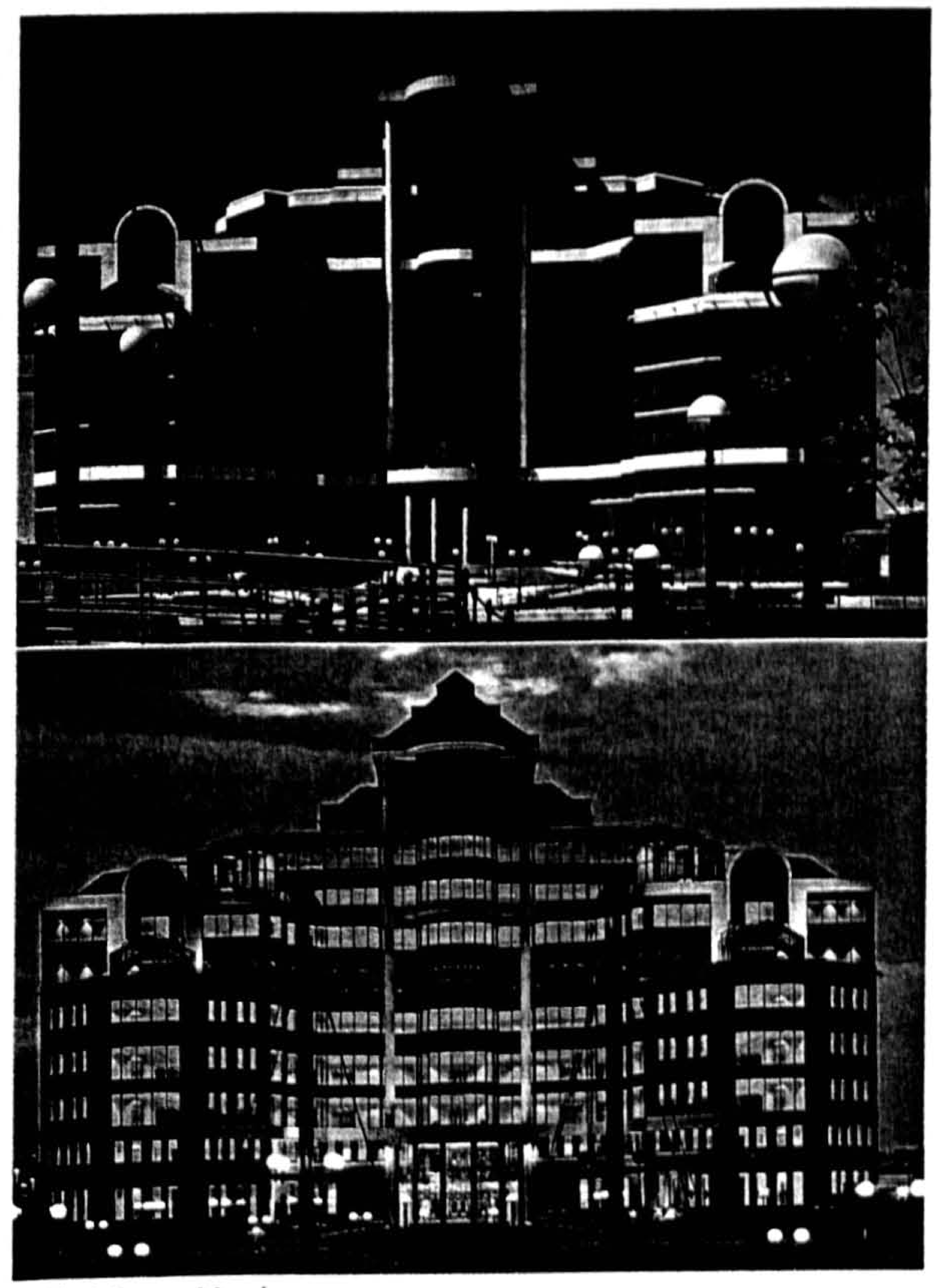
100 Old Hall Street, Liverpool

APPENDIX 10
5

Pilkington SUNCOOL *Classic*

Comprehensive range of reflective Solar Control Glasses

- High Solar Control performance
- Medium to low light transmittance
- High to low reflection
- Five basic colours – Blue, Silver, Bronze, Green and Grey – providing 21 different shades
- Provides an attractive solution to all applications where the solar heat entering a building needs to be controlled



Salford Quays, Manchester

Pilkington ECLIPSE

Reflective Solar Control Glasses in a range of dramatic colours

- Medium Solar Control performance
- Medium to low light transmittance
- Highly reflective
- Choice of six bright and dramatic colours – Clear, Blue/Green, Bronze, Grey, Silver and Bright Silver – which can be glazed either way round to create a variety of visual effects
- Durable coating
- A comparatively low cost solution with a high visual impact

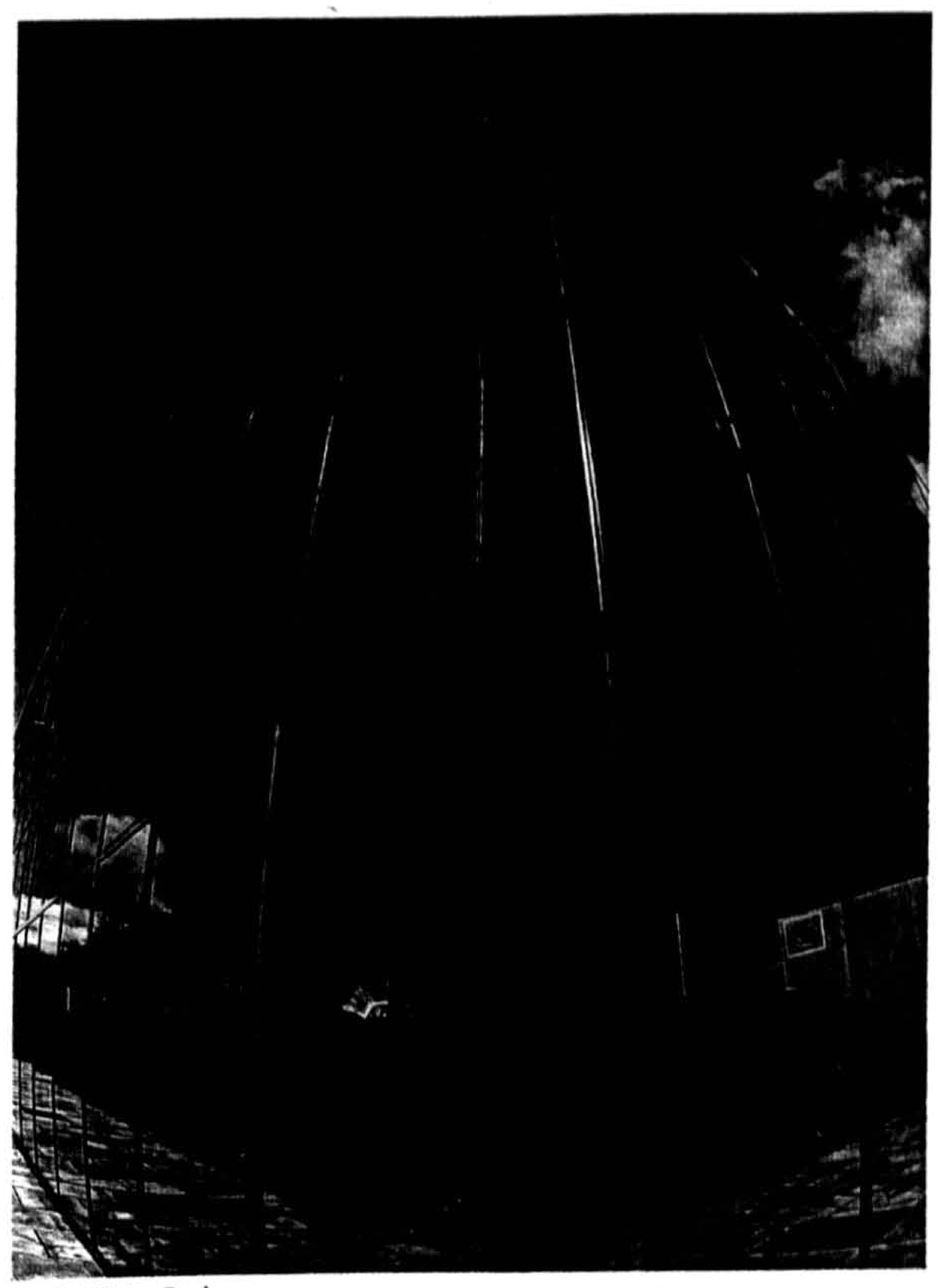
Hyatt Hotel, Santiago

APPENDIX 10
6

Pilkington REFLECTAFLOAT

A Solar Control Glass with a coating applied on line during the float glass manufacturing process

- Medium solar control performance
- Medium light transmission
- High light reflection
- Bright silver appearance in reflection
- Bronze in transmission
- Durable coating – can be single glazed
- A low cost solution with a high visual impact

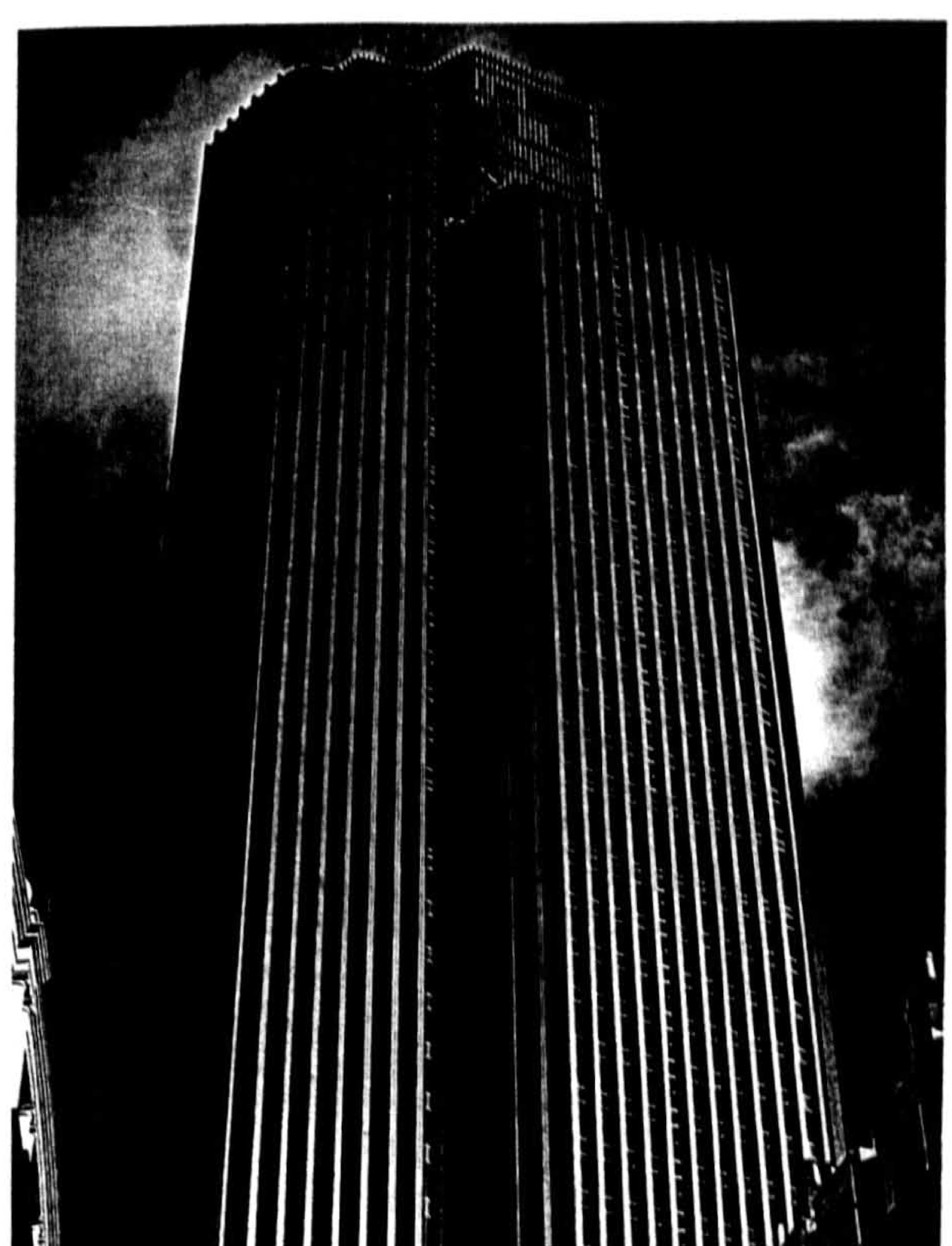


Bath Clinic, Bath

Pilkington ANTISUN

A range of body tinted, heat absorbing solar control glasses

- Medium to low Solar Control performance
- Range of high to low light transmission
- Tinted throughout their thickness
- Very little internal or external reflection
- Choice of four colours – Blue, Bronze, Green and Grey
- Solar Control properties and colour density vary with thickness
- Subdued colour range complements other building materials and natural surroundings



Natwest Tower, London

APPENDIX 10 7

Selection Table – Glass for Solar Control

The following selection table is based on the parameters of:

Colour	– Clear or Neutral, Silver, Green, Blue, Grey, Bronze
Solar Control	– low (shading coefficient > 0.5%), medium (0.35% < shading coefficient ≤ 0.5%), high (shading coefficient ≤ 0.35%)
Light transmittance	– low (≤ 0.25%), medium (> 0.25%, ≤ 0.5%), high (> 0.5%)
Light reflectance	– low (≤ 0.15%), high (> 0.15%)

The product selections are based on the performance of the solar control glass when used in insulating units in combination with PILKINGTON K GLASS, except for the Pilkington SUNCOOL *High Performance (HP)* glasses, which are always supplied in insulating units and already have low emissivity properties

Product	Colour	Solar Control			Light Transmittance			Light Reflectance	
		High	Medium	Low	High	Medium	Low	High	Low
Pilkington SUNCOOL *HP* Neutral	Clear or Neutral		•		•				•
Pilkington SUNCOOL *HP* Clear				•	•			•	
Pilkington Clear Float (for reference)				•	•				•
Pilkington SUNCOOL *HP* SILVER	Silver	•				•		•	
Pilkington SUNCOOL *Classic* 30/42		•				•		•	
Pilkington ECLIPSE on Blue/Green #1		•				•		•	
Pilkington SUNCOOL *Classic* 20/34		•					•	•	
Pilkington SUNCOOL *Classic* 10/23		•					•	•	
Pilkington ECLIPSE on Grey #1		•					•	•	
Pilkington REFLECTAFLOAT			•			•		•	
Pilkington ECLIPSE on Bronze #1			•				•	•	
Pilkington ECLIPSE on Clear #1				•		•		•	
Pilkington ECLIPSE on Clear #2				•		•		•	
Pilkington SUNCOOL *HP* Green	Green	•				•		•	
Pilkington SUNCOOL *HP* Emerald		•				•		•	
Pilkington SUNCOOL *HP* Olive		•				•			•
Pilkington SUNCOOL *LR* 34/43	Green	•				•			•
Pilkington SUNCOOL *LR* 26/37	Green	•					•		•
Pilkington SUNCOOL *Classic* 17/32		•					•	•	
Pilkington SUNCOOL *Classic* 08/25		•					•	•	
Pilkington SUNCOOL *HP* Jade			•		•				•
Pilkington ANTISUN Green*			•	•	•				•
Pilkington ECLIPSE on Blue/Green #2	Blu/Grn		•			•		•	
Pilkington SUNCOOL *HP* Blue	Blue	•				•		•	
Pilkington SUNCOOL*Classic* 30/39		•				•		•	
Pilkington SUNCOOL *Classic* 20/33		•					•	•	
Pilkington SUNCOOL *LR* 19/37		•					•		•
Pilkington SUNCOOL *Classic*13/32		•					•		•
Pilkington SUNCOOL *LR* 27/43		•					•		•
Pilkington SUNCOOL *Classic* 40/50			•			•			•
Pilkington ANTISUN Blue				•		•			•
Pilkington SUNCOOL *Classic* 26/40	Bronze	•					•	•	
Pilkington SUNCOOL *Classic* 10/24		•					•	•	
Pilkington SUNCOOL *HP* Bronze		•					•		•
Pilkington SUNCOOL *LR* 23/43		•					•		•
Pilkington SUNCOOL *Classic* 12/32		•					•		•
Pilkington ANTISUN Bronze*		•	•	•		•	•		•
Pilkington ECLIPSE on Bronze #2			•				•	•	
Pilkington SUNCOOL *HP* Grey	Grey	•					•		•
Pilkington SUNCOOL *LR* 21/42		•					•		•
Pilkington SUNCOOL *Classic* 10/32		•					•		•
Pilkington ANTISUN Grey*		•	•			•	•		•
Pilkington ECLIPSE on Grey #2			•				•		•

\# The indicators #1 and #2 show the Pilkington ECLIPSE coating on surface 1 or surface 2 of the unit (counting from the outside). Other coated glasses are recommended to not have the coating on surface 1.

* Depending on thickness. Thicker Pilkington ANTISUN Glass gives higher solar control with lower light transmittance.

Note. Pilkington SUNCOOL LR = Pilkington SUNCOOL Low Reflection

Descriptive Code – A pair of numbers signifying the properties of glazing. The first number is the visible light transmittance and the second is the total solar radiant heat transmittance.

APPENDIX 10

8

APPENDIX 11

CONLOC SK 713

Product Description

Liquid, clear addition cure two-part silicone for planar bonding of glass to glass.

Regardless of the layer thickness it does not shrink during polymerisation and forms a tough elastic cured product that is resistant to ageing, weathering and UV-radiation.

Application

CONLOC SK 713 does not adhere primerless, i.e. all adhesion surfaces must be pretreated thinly with EGO-Primer 713 prior to bonding. Mix both components (A:B=9:1 parts by weight) homogenously in a plastic tub. avoid contact with tin and zinc. Air bubbles that might be entrapped during mixing escape on their own shortly after application.

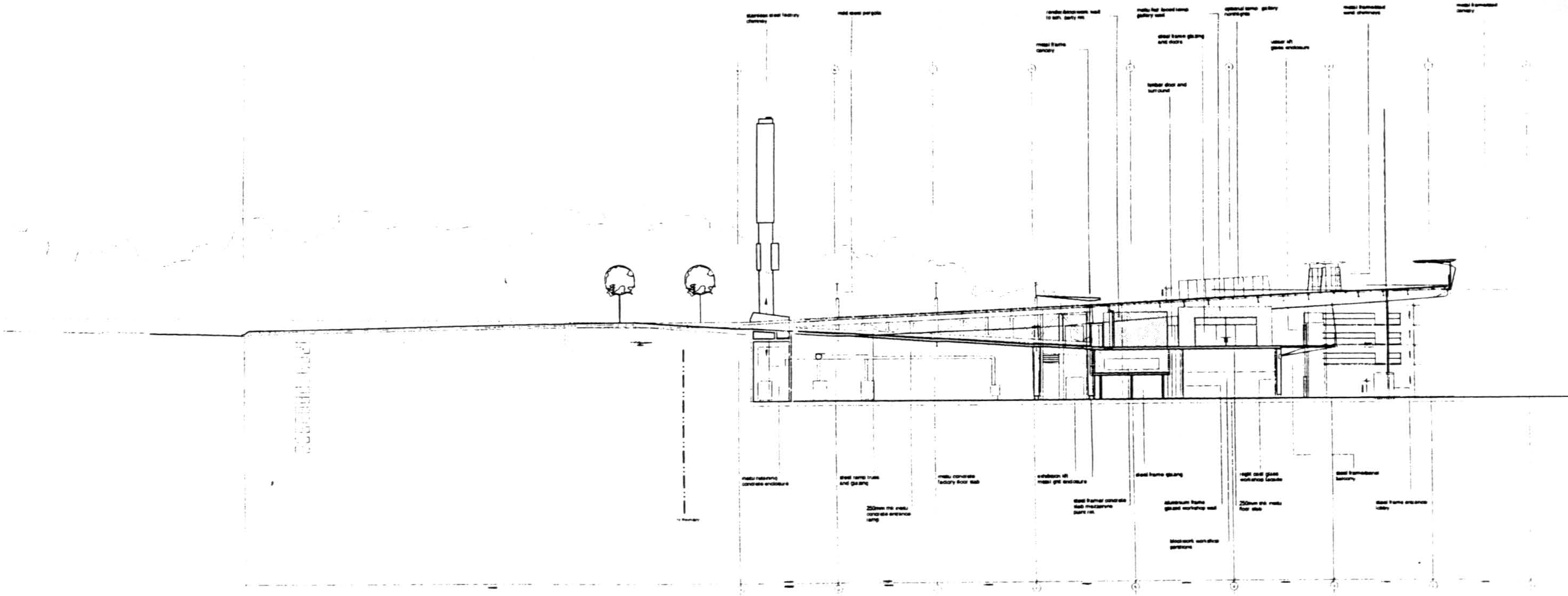
APPENDIX 12

1. Main Entrance
2. Pre-Foyer Display
3. Foyer and Reception Desk
4. Gallery
5. Void over double height space
6. Temporary Gallery
7. Story of Glass exhibition
8. Secondary gallery
9. Marketing area
10. Conference room
11. Ramp to lower level
12. Roof
13. Chimneys
14. Solar Shading Panel
15. Retail Space
16. River Entrance
17. Cafe
18. Viewing Platform

Wear Elevation

Scale: 1:100

APPENDIX 12



Location: St Peter's Riverside Sunderland

for The Tyne & Wear Development Corporation, Sunderland

Associate Architects: RYDER NICKLIN PARTNERSHIP

LIVERSIDGE Landscape Architects

The National Glass Centre

Status: STAGE D

GOLLIFER ASSOCIATES ARCHITECTS

Drawing Title: **Section A - A**

95 AD11

22.03.96

1:200

95

AD11

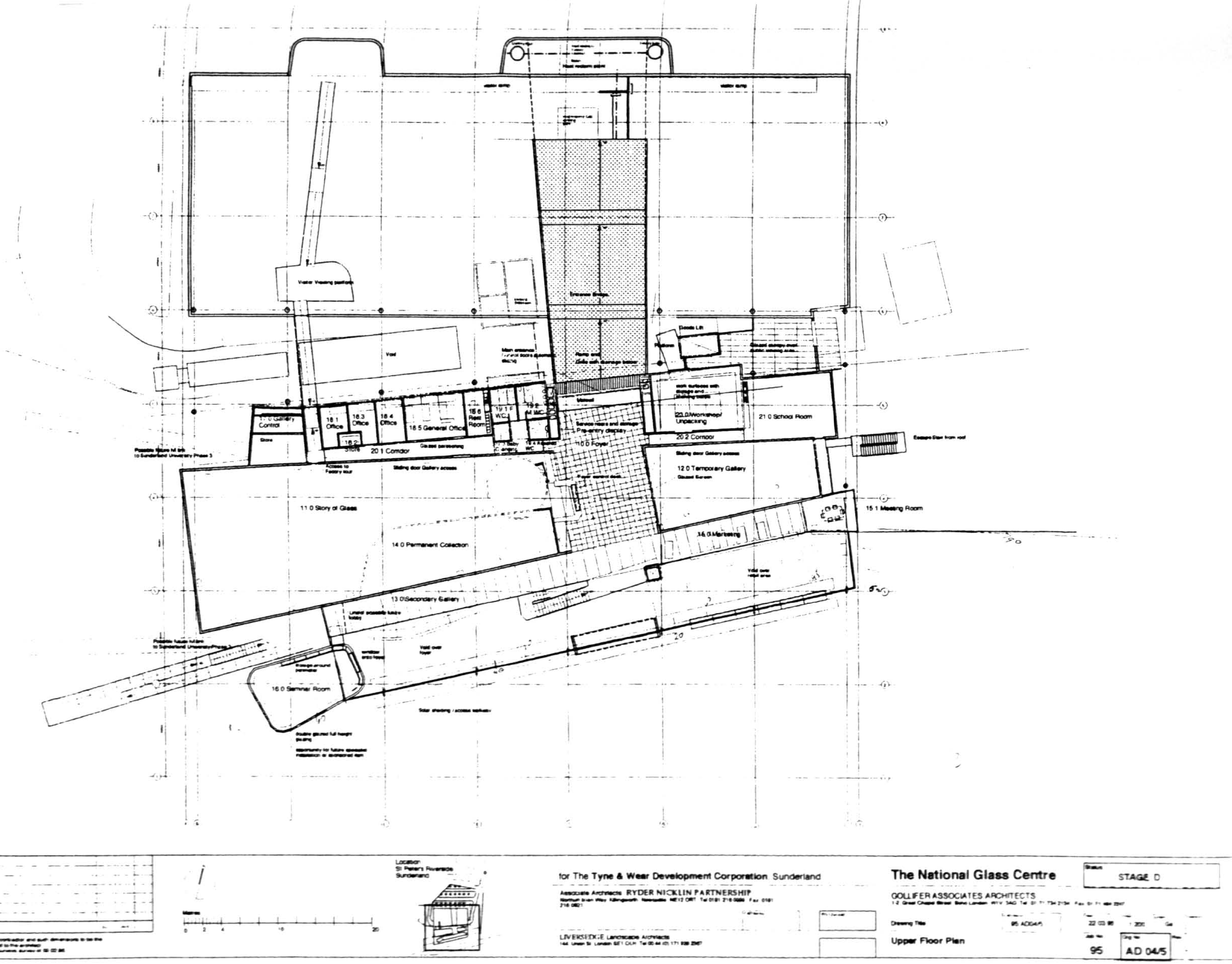
APPENDIX 12

2

APPENDIX 12

3

APPENDIX 12



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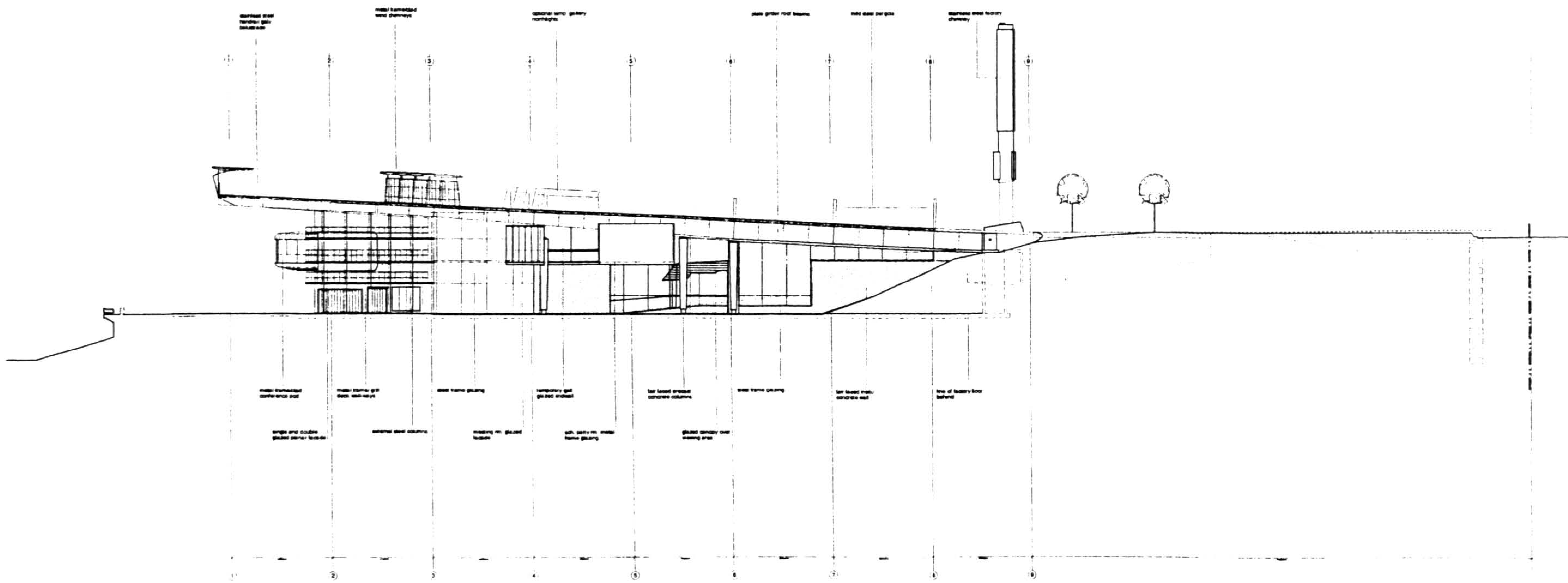


Location
St Peter's Riverside
Sunderland

Metres
0 2 4 6 8 10 20

for The Tyne & Wear Development Corporation, Sunderland

Associate Architects RYDER NICKLIN PARTNERSHIP

LIVERSEDGE Landscape Architects

The National Glass Centre

GOLLIFER ASSOCIATES ARCHITECTS

Status: STAGE D

Drawing Title: North East Elevation

95 AD 08

22 03 96

1:200

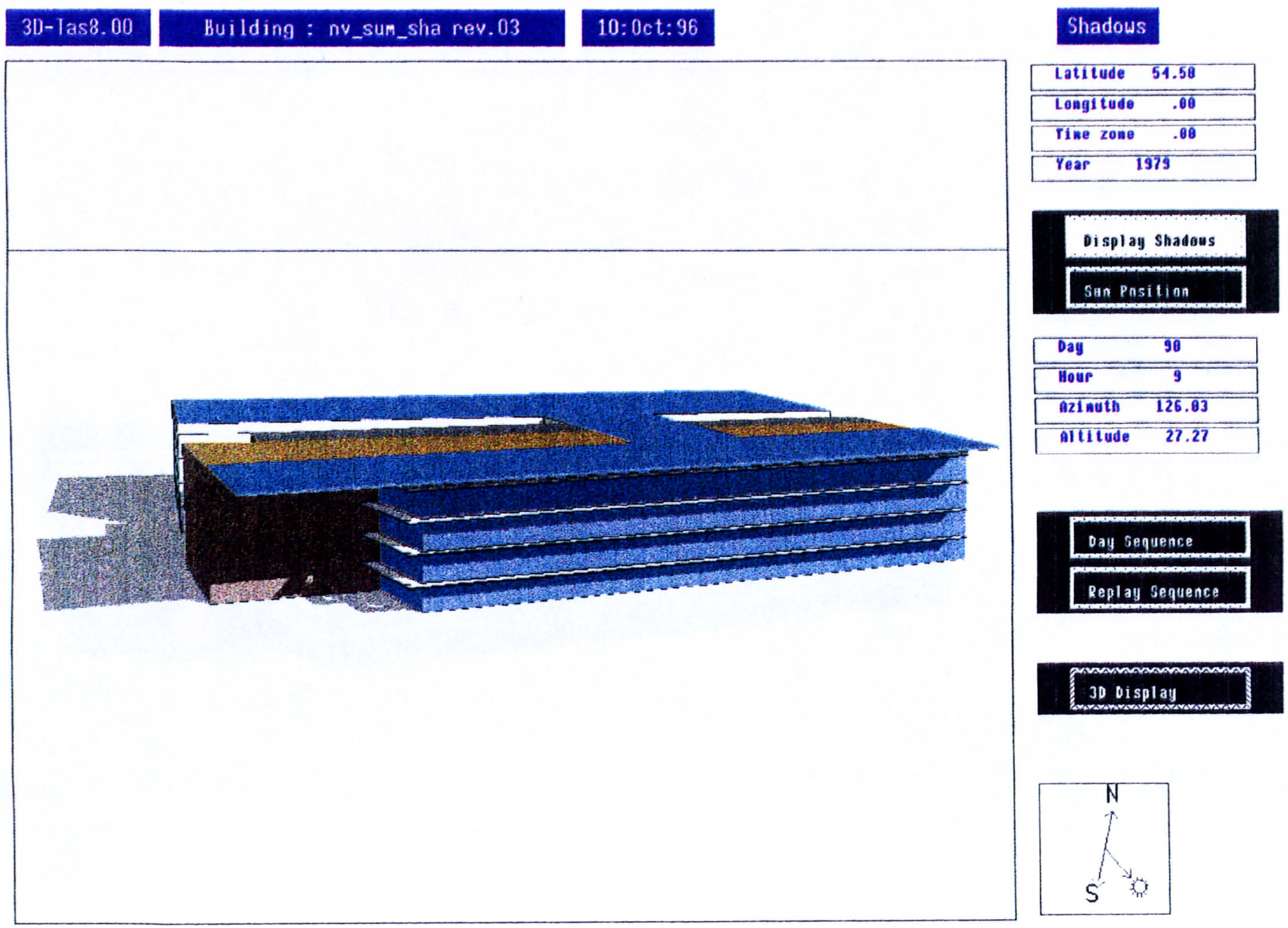
Job No: 95

Drg No: AD 08

APPENDIX 12

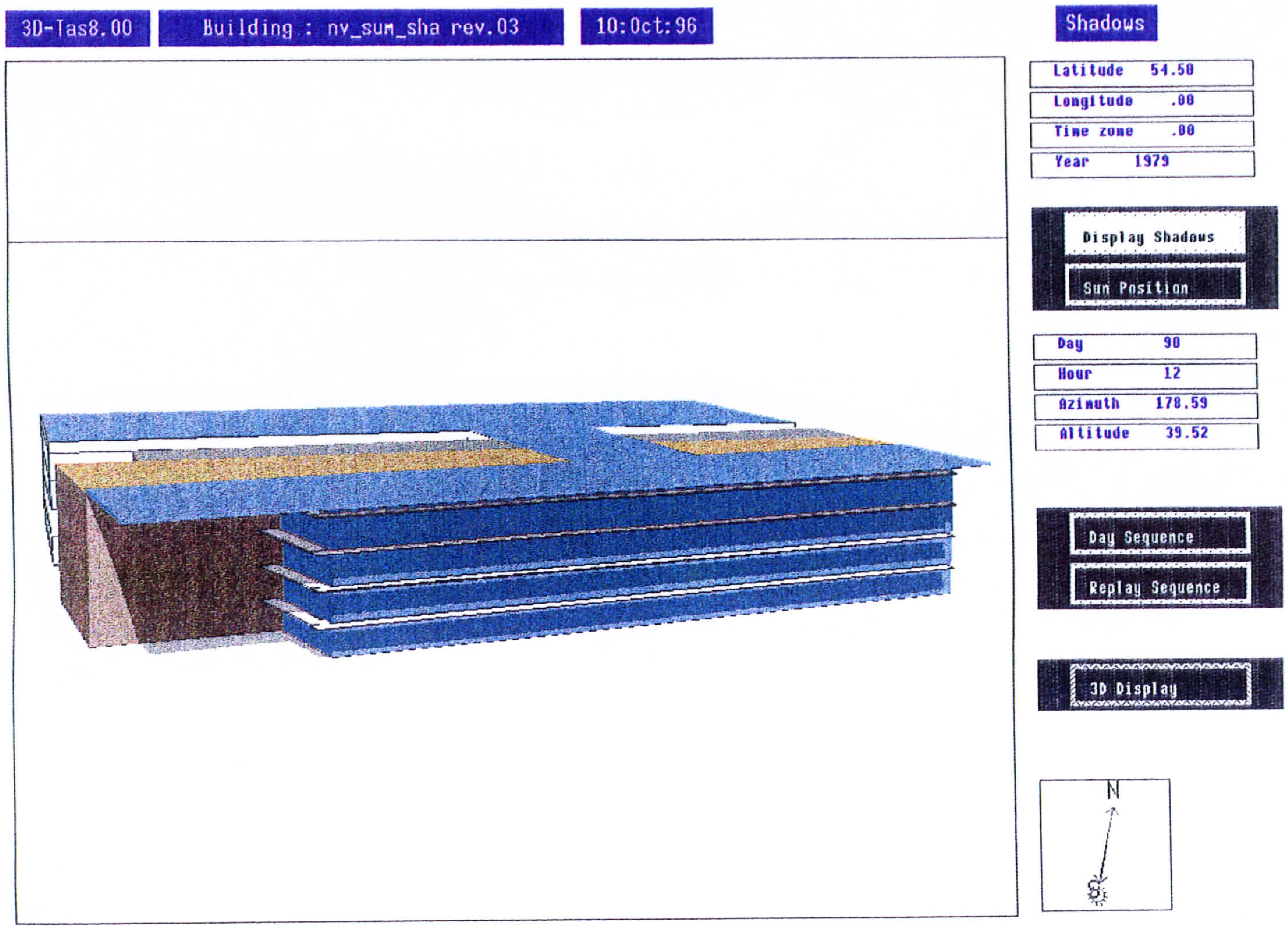
5

APPENDIX 13



MID-SPRING / MID-AUTUMN
9 AM

APPENDIX 13



MID-SPRING / AUTUMN
12 AM

APPENDIX 13

MID -
SUMMER
9 AM

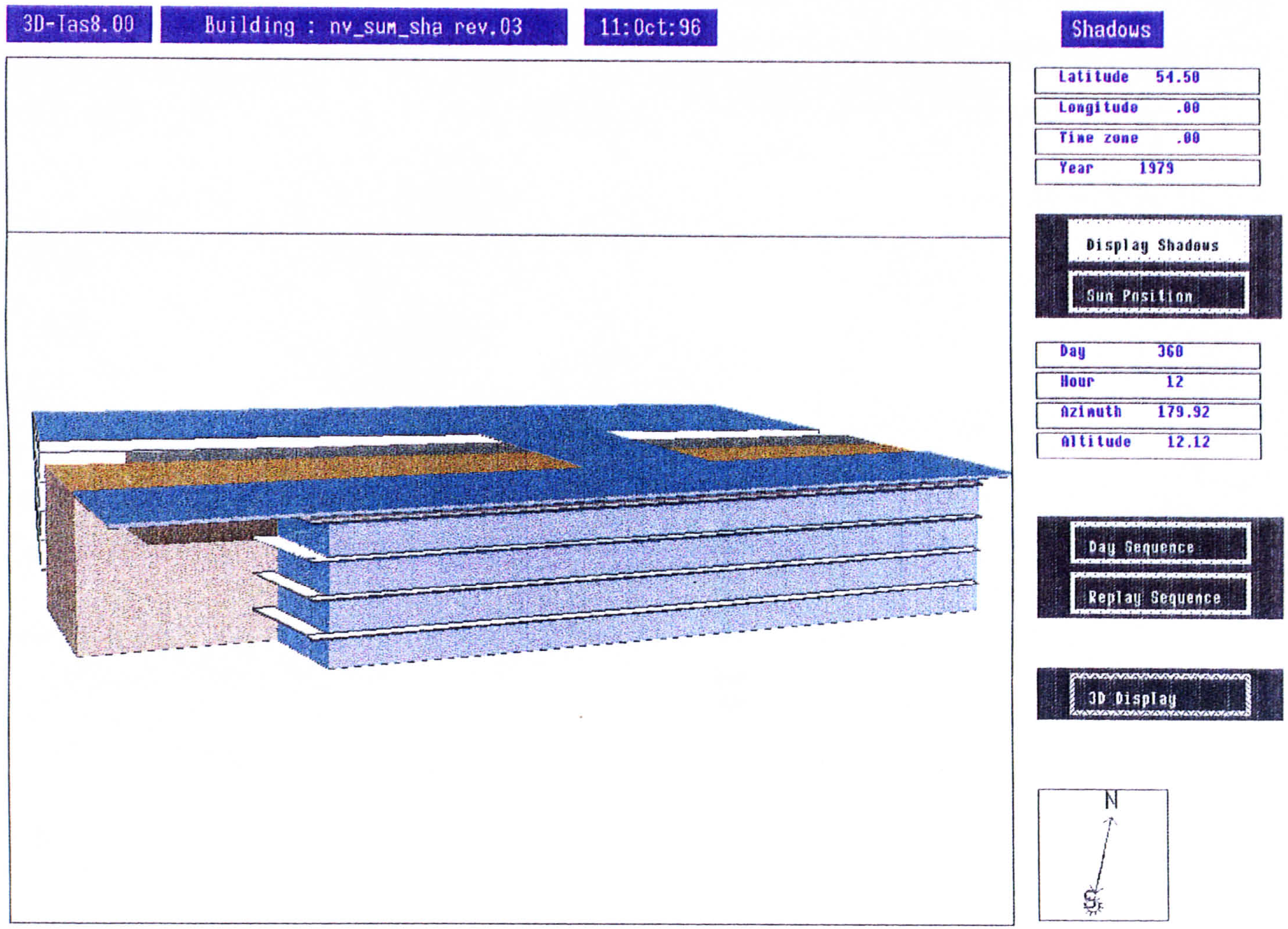
APPENDIX 13

MID-SUMMER
MIDDAY

APPENDIX 13

MID-WINTER
11 AM

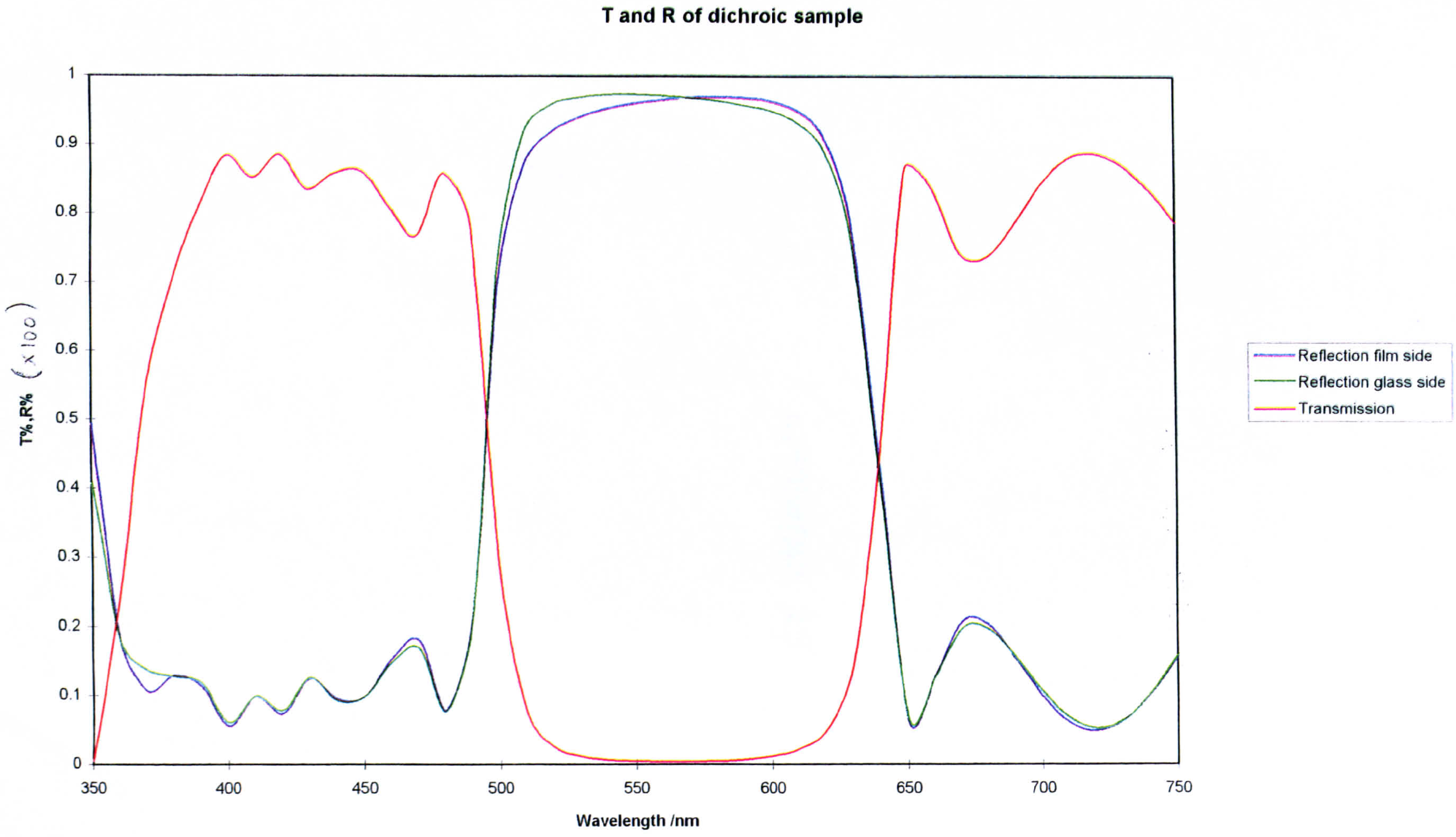
APPENDIX 13



MID-WINTER
12 AM

APPENDIX 13

APPENDIX 14

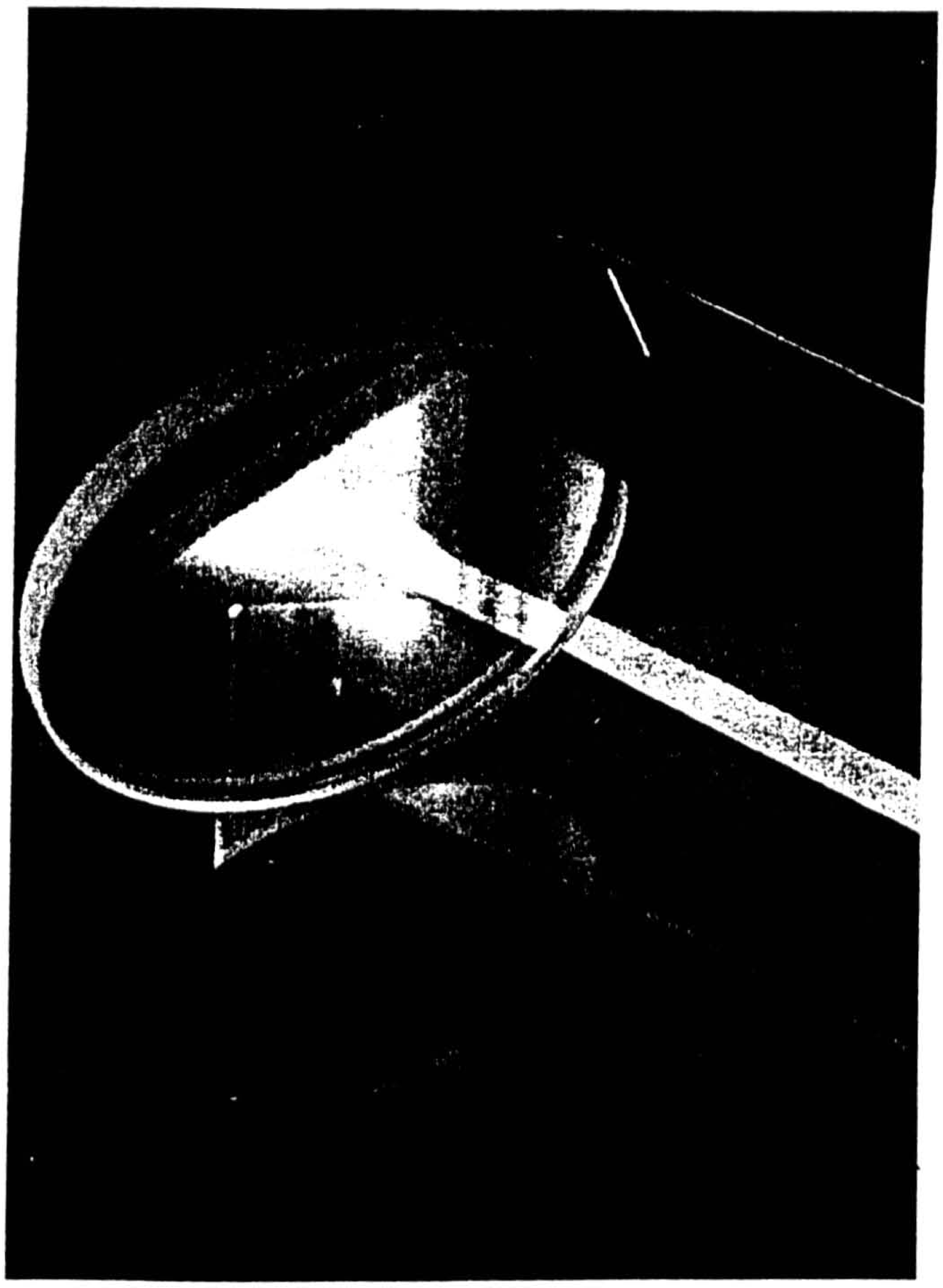

T and R of dichroic sample
T%,R% (x100)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
350
400
450
500
550
600
650
700
750
Wavelength /nm
Reflection film side
Reflection glass side
Transmission

APPENDIX 14

APPENDIX 15

FROM RESEARCH BY LAURA JOHNSTON

'The Innovative Application of the Coated Glass Surface in Architecture'.



DICHROIC GLASS

REPORT ON THE POTENTIAL APPLICATION FOR THE NATIONAL GLASS CENTRE

Laura Johnston - Architectural Glass, 9 Summerhill Terrace, Newcastle upon Tyne NE4 6EB

Tel: 0191 272 54 89 / 232 23 66

APPENDIX 15

INTRODUCTION.

Dichroics are produced by applying multiple thin film layers of oxides onto glass. Using materials of differing refractive indices, in various thicknesses and sequences, wavelengths of light are selectively reflected and transmitted. Any colour in the spectrum can be created and the glass has the unique quality of transmitting the selected colour, whilst reflecting its opposite. When viewed from an angle of 45 degrees, a further colour change occurs when viewed in transmission.

The properties of dichroic glass offer enormous potential for architectural application and some work has been done in this area, mainly in the USA. This topic has been the subject of my PhD research since 1993. The research, which is practice-led, examines the innovative application of coated glass in contemporary architecture and is concerned with both the aesthetic and practical potential of the material.

Aesthetically, the material has unique qualities which lend themselves to abstact contemporary design and offer a means of incorporating colour and coloured light, reminiscent of stained glass, into the modern building. Whereas traditional stained glass appears incongruent in such a setting, dichroic glass offers new potential for exploring the power of light and colour.

The reflective quality of the glass offers further potential for the redirection of paths of light within architectural space and thus has the capacity to extend and enhance lighting, with possible implications for energy saving.

With this approach to my research, I have investigated various methods of applying the glass for architectural use. Some of these I feel would complement the innovative design of the National Glass Centre.

I will now go on to outline and illustrate applications which may be of interest. Referring to technical information in the Stage C report, completed by Battle McCarthy, along with some knowledge of plans and having viewed the model at Glassex, I suggest possible situations for the glass within the building.

This should give a feel of the kind of approach I have taken. Development of ideas outlined here for specific inclusion in the NGC, I envisage, would involve a collaborative approach with architects and engineers to ensure integration into the overall design and construction of the building.

PLANAR APPLICATIONS.

Sheets of dichroic glass available in the UK measure 1m square. Imported from the USA (Liberty Mirror) sizes are 44" x 51" x 1/4". Colours available are blue, green, red, yellow, magenta, cyan (see sample 1).

This glass can be laminated and fixed into planar glazing systems. Used on the exterior, the glass would appear one colour from the outside as people approach the building. Viewed from the inside the glass appears a totally different colour. The reflected colour is strong and would be seen at a distance, drawing attention to the building. When internally lit at night the transmitted colour will be viewed externally, with the reflected colour being seen by building users. Incorporated into the outer walls, possibly as strips running ground to roof, the glass could be used as detail to emphasis the unique structure of the building. Night lighting the exterior of the building could pick out this dramatic colour and detail.

As panels incorporated into the glass roof, the glass will transmit coloured light onto internal walls and floors which will change in hue and intensity as the sun travels around the building during the day.

INTERNAL SCREENS or walls made up of the glass transmit and reflect opposing colours. As people cirulate past the wall, they observe the subtle shift of colour, viewed form different angles. The wall appears alive and constantly changing (see fig.1).

Bonding lenses and prisms to the glass, manipulates these qualities. Sample 2, demonstrates the way in which the transmitted colour can be seen to change from magenta to yellow, when viewed through the prism. Sample 3 shows the potential of bonding a lens to the glass, having etched away some of the dichroic coating, producing interesting optical qualities. Treating the surface in this way and adding such details could be used to further enhance the glass, used as walls and screens. By adding such elements to the glass, light transmitted into the building can be manipulated further, producing interesting effects. Glass elements are bonded using a two-part silicone adhesive. This has an elastic quality allowing the differing rates of expansion and contraction to occur without the glasses suffering stress and consequent cracking - a problem common when using other glass adhesives. The product is optically clear and resistant to ageing, weathering and UV-radiation.

Moving away from the use of the glass in flat panel form, the dichroic glass wall in fig.2, is made up of planes of glass bonded to form a right-angle section, each of which pivots at the join. This wall opens and closes to allow ventillation and creates multiple, shifting light patterns.

I have done some further experimental work incorporating the glass into what could be termed **Double Glazed** units. Here I have bonded strips of dichroic glass between the two outer planes of float. Sample 4 has horizontal and vertical strips enclosed which, when viewed head on, do not appear coloured. Dramatic lighting effects occur in sunlight, when the clear transparent box suddenly projects a spectrum of colour into the building. Light reflects from the all sides of the multiple planes and is transmitted through others, with the result that light is dispersed in all directions. The magic of this simple structure can be seen in fig. 3 and imagined as roofing or wall units . This structure expands on the simple idea of 'light-shelves', which project light further into architectural space. Although not usually constructed of glass, the horizontal reflective planes in this piece perform this function whilst also adding aesthetic power and colour.

A further 'double glazed' piece (sample 5) incorporates horizontal strips of glass placed on a 45 degree angle, appearing like a partially open louvre. This can be seen in fig.4, placed on top of the sample 4. In this piece the dichroic colour can be seen head on. The angle of the planes re-direct some of the light passing through the panel. This could be placed in situations within the building where it would be advantageous to project light towards another area. Alternatively, as seen in fig.5, this unit may be used to assist in shading an area of the building, reflecting back some of the light which would ordinarily pass through a flat glazing panel. Used in this way, this unit could complement other shading systems installed in the building.

Taking the idea of the louvre further, I have produced another unit in which each horizontal strip of dichroic glass can be rotated through 360 degrees. The dichroic glass used has a transmitted colour of yellow and a reflected colour purple. By changing the positions of the individual strips, light can be projected in all directions. In fig.s 5-6 the changing paths of light can be seen. The movement of such a piece could be controlled electronically, possibly using power reaped by photovoltaic cells. Programming a timed movement into the piece could result in multiple possibilities. A subtle wave-like motion could occur, each individual strip rotating after the other. Dramatic, changing, light effects could be produced, possibly to occur at certain times of the day, according to the position of the sun. Such a panel could be incorporated into the roof, seen on entering the building, providing a breathtaking play of light. This piece, emphasising the exciting nature of the material, would provide a fitting introduction to the Centre devoted to a material which is essentially all about this phenomena : light.

3 DIMENSIONAL STRUCTURES.

With the aim of harnessing and dispersing light and colour, a three dimensional structure constructed of glass elements with a steel support structure, could be designed, possibly for the reception area. The form would be designed to respond to the natural fall of light and could incorporate dichroics along with other glasses, for example prisms and lenses, positioned within the piece to catch and disperse lightfall. Areas which are likely to receive high levels of light might benefit from such a piece which could redirct the light, protecting, for example, those at the reception area, from such intensity. In fig.7, a work by the artist Keshava of Barcelona can be seen. Here he designed a single-glazed glass wall for a building. Along with this a glass 'satellite' was designed the purpose of which is to act as a shading device in the entrance area. Using opaque glass, light is blocked giving a degree of protection. The prisms and coloured glass here are mainly decorative. The satellite moves slowly around the area, following the path of the sun. Developing this idea, the form would utilise the properties of prisms and coated glass to redirect light, thus protection is given, whilst also providing interesting and dramatic light effect around the immeadiate area.

In fig.8 and 9 some simple 3D forms can be seen. Supported by thin steel the glass is the dominant element. Figure 8 incorporates UV filters(sample 6) along with dichroics. Highly reflective and blue-red in transmission, this glass complements the dichroics.

APPENDIX 16

APPENDIX 15

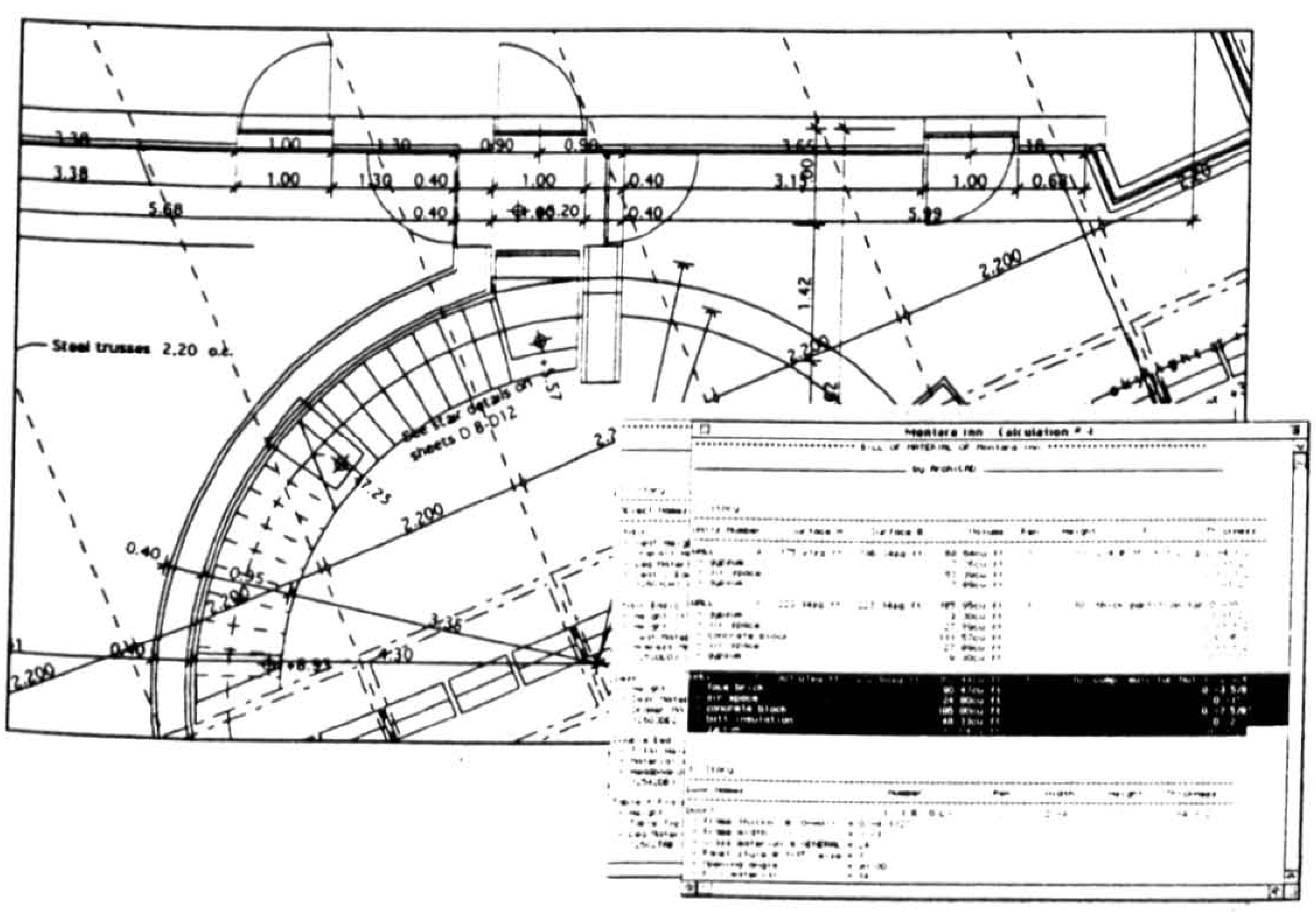
ArchiCAD®

MAKES THE DIFFERENCE

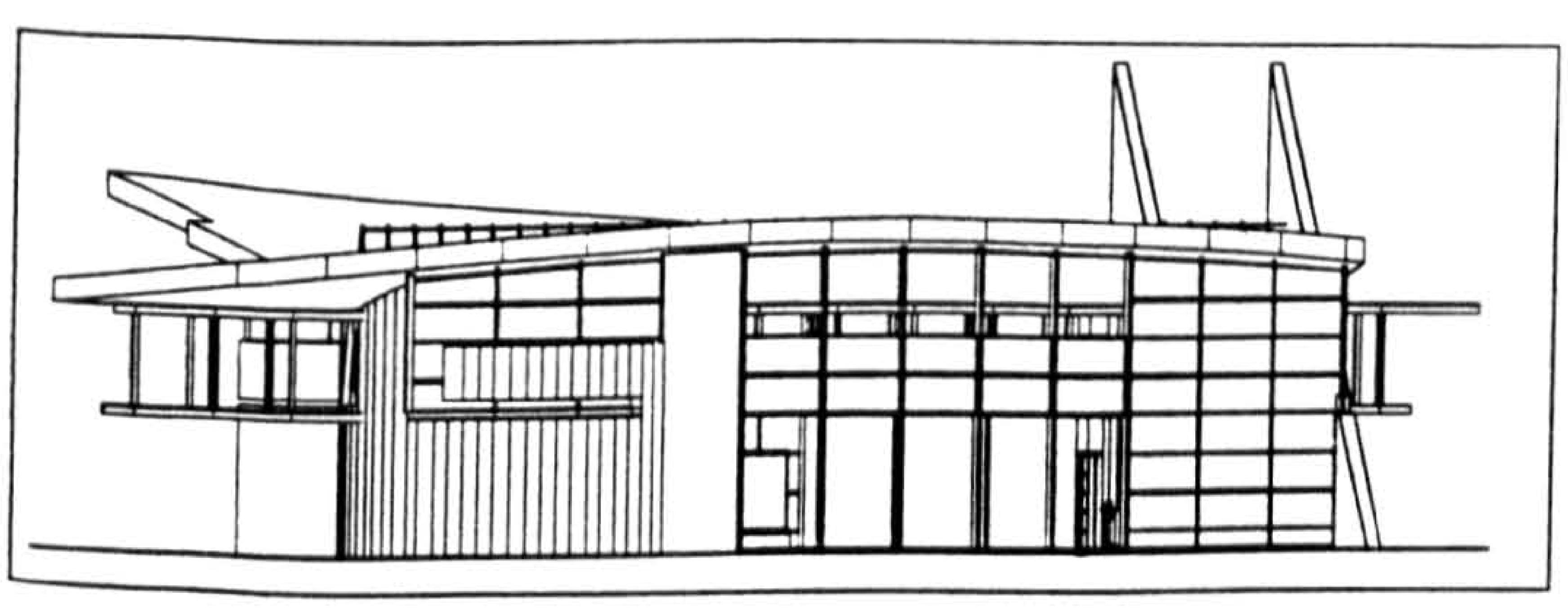
Designing and documenting a building, whether a house or a skyscraper, means communicating two types of vital information to two distinct audiences, the "buyer" and the "builder".
The buyer needs simple plans, renderings, animations and budgets in order to be sold on the project. The builder needs complete construction documents and precise material take-offs to construct it.

ArchiCAD offers complete information tailored for both the buyer and the builder and integrated in a single file so that all of the information remains up-to-date while you are exploring alternatives.
ArchiCAD features an attractive and easy-to-learn interface employing tools that are meaningful to the profession. Its meticulous design anticipates the way you work and leaves you in control at all times.
ArchiCAD can reduce the time you spend communicating your design by up to 50%, and it can save you and your client even more money and liability by resolving on-site conflicts before they occur.

ArchiCAD features full drafting tools for the production of construction documents. More importantly, ArchiCAD's complete integration means that anything drawn in the floor plan is automatically updated in 3D, elevation/section views and the bill of materials. Files can be directly printed or plotted in black & white or color.



ArchiCAD fully renders perspectives, 3D sections and animations including shadow casting with optional light sources and background.
Accurate sun studies can be generated for any location, date and time.



ArchiCAD continuously tracks all of the elements in a project and automatically generates quantity take-offs. Specifications can be assigned to each element (prices, manufacturer, labor cost, finishes, etc.). The bill of materials can be printed directly or exported to any spreadsheet or word processing program.

ArchiCAD files can communicate with major CAD, graphics and database programs. Full compatibility with common file formats (DXF, DWG, etc.) and the availability on major operating systems insures that your files can be transferred with no data loss to colleagues, clients or authorities.

Over 16,000 copies of ArchiCAD have been sold worldwide in more than 60 countries and 16 languages.

Operates on:

Intel 486 and Pentium-based Computers
operating systems: Windows 3.1, Windows for Workgroups 3.11, and Windows NT.

DEC Alpha Stations
operating system: Windows NT.

Apple Macintosh and Power Macintosh
operating system: Mac OS.

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